STUDY ON THE USE OF

MOBILE NUCLEAR POWER PLANTS FOR GROUND OPERATIONS

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"Unleash us from the tether of fuel."

— Gen. James Mattis, former commander of the
1st Marine Division, during the drive to Baghdad, March 2003

Executive Summary

This study was commissioned by the Army Deputy Chief of Staff (DCS), G-4 to analyze the potential benefits and challenges of mobile nuclear power plants (MNPPs) with very small modular reactor (vSMR) technology and to address the broader operational and strategic implications of energy delivery and management. The Under Secretary of Defense for Acquisition, Technology and Logistics released the Defense Science Board (DSB) Task Force final report on Energy Systems for Forward/Remote Operating Bases[1] in 2016. The DSB observed that energy is, and will remain, a critical enabling component of military operations, with demand continuing to increase over time.[1] This study supports the DSB's recommendations and considers the political, economic, social, technological, environmental, and legal/regulatory (PESTEL) factors associated with a future, near-term decision involving the deployment and employment of MNPPs.

Employment of mobile nuclear power is consistent with the new geopolitical landscape and priorities outlined in the US National Security Strategy (NSS) and the 2018 National Defense Strategy focusing on China and Russia as the principal priorities for the U.S. Department of Defense (DOD). The Army recognizes the fundamental change in the character of warfare with a confluence of evolving threats and an increasing technology sophistication of our adversaries spanning the competition continuum, as opposed to the obsolete peace/war binary[2]. This study finds that as a technical matter, nuclear power can reduce supply vulnerabilities and operating costs while providing a sustainable option for reducing petroleum demand and focusing fuel forward to support Combatant Commander (CCDR) priorities and maneuver in multi-domain operations (MDO).

Energy is a cross-cutting enabler of military power and nuclear fuel provides the densest form of energy able to generate the electrical power necessary at forward and remote locations without the need for continuous fuel resupply. Key points of the Army vision include high-intensity conflict where the Army must be ready to conduct major large-scale combat operations (LSCO) against near-peer competitors. MNPP supports strategic and operational deployment and can meet the anticipated power demands in both highly developed mature theaters, such as Europe, and immature theaters and lesser developed areas globally. Multiple studies identify that air and

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[1] Defense Science Board (DSB). 2016. *Task Force on Energy Systems for Forward/Remote Operating Bases, Final Report*. U.S. Department of Defense, Washington, D.C. http://www.dtic.mil/dtic/tr/fulltext/u2/1022571.pdf.

[2] Joint Chiefs of Staff. 2018. *Joint Concept for Integrated Campaigning*, 16 March 2018. Executive Summary, p. vi, para 1, lines 3-4 and p. 4 para 1, line 1. http://www.jcs.mil/Portals/36/Documents/Doctrine/concepts/joint_concept_integrated_campaign.pdf?ver=2018-03-28-102833-257.

ground delivery of liquid fuel comes at a significant cost in terms of lives and dollars[1,2,3]. Approximately 18,700 casualties (or 52 percent) of the approximately 36,000 total U.S. casualties over a nine-year period during Operation Iraqi Freedom and Operation Enduring Freedom[2] occurred from hostile attacks during land transport missions. This observation gives credence to DOD initiatives to evaluate and deploy alternatives to petroleum-based fuel systems[1].

MNPP is a viable option where:

- Fuel logistics and storage of Class III curtails CCDR options, increases complexity, and/or imposes substantial economic challenges.
- Infrastructure requires large-scale power (e.g., ports, airfields, rail, other transportation supporting infrastructure, industry etc.).
- Mission assurance is required or where "islanding" is desirable (providing continuous power to a location even though energy from an electrical grid/external power source is no longer present).
- Energy intensive systems (e.g., forward radar site operations) require significant power.
- Power is desired to support defense support to civil authorities (DSCA).
- Access to an established or stable electrical grid is unavailable or where the electrical grid requires reinforcement or reconstitution to support intermediate staging bases, logistics staging areas, and/or medium to large base camps.

The MNPP is a classic example of disruptive innovation[4]. The introduction of an MNPP is precedent-setting but disruptive innovation is not without unique regulatory and licensing challenges within the current governance structure. The concept and development of an MNPP relies upon interagency support to navigate the existing regulatory framework applicable to new reactor design and the transport of nuclear materials. The existing regulatory body of work is centered on fixed facility-type nuclear power plants that are non-mobile and employ legacy technology, and, movement of fuel or small quantities of nuclear material (e.g., test samples, isotopes, etc.) internationally.

These challenges are not insurmountable given the national-level desire to expand the nuclear energy sector, reducing barriers to develop and deploy new reactors[5]. The Army and DOD possess the skill sets and experience necessary for detailed coordination across a broad array of stakeholders including the U.S. Department of Energy, U.S. Department of State, and U.S. Department of Transportation to resolve interdepartmental issues such as nonproliferation, safety,

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[1] Defense Science Board (DSB). 2016. *Task Force on Energy Systems for Forward/Remote Operating Bases, Final Report.* U.S. Department of Defense, Washington, D.C. http://www.dtic.mil/dtic/tr/fulltext/u2/1022571.pdf.

[2] Daehner EM, J Matsumura, TJ Herbert, JR Kurz, and K Walters. 2015. *Integrating Operational Energy Implications into System-Level Combat Effects Modeling, Assessing the Combat Effectiveness and Fuel Use of ABCT 2020 and Current ABCT.* RAND Corporation, Santa Monica, California.

[3] Army Environmental Policy Institute. 2009. *Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys, Final Technical Report.* Army Environmental Policy Institute, Arlington, Virginia.

[4] In business, a disruptive innovation is an innovation that creates a new market and value network and eventually disrupts an existing market and value network, displacing established market-leading firms, products, and alliances.

[5] Executive Office of the President of the United States, Science & Technology Highlights, p.7.

transportation, and fuel availability. A DOD-led interagency team approach offers the best chance of success for resolution of non-technical matters.

The MNPP concept is based on new, advanced, and safe technology currently available from the commercial and government sectors which should be further refined within the DOD and at the interagency level. This study recommends the DCS G-4:

- Present the MNPP concept through the Commander, Army Futures Command (AFC) and the Vice Chief of Staff, Army (VCSA) to the Chief of Staff, Army for further consideration.
- Express Army support for a DOD prototyping effort by the Strategic Capabilities Office (SCO).
- Identify MNPP for future Joint Requirements Oversight Council (JROC)/Army Requirements Oversight Council (AROC) consideration.
- Continue to refine MNPP analysis using SCO prototyping efforts to:
  - Support Joint operations
  - Leverage DOE laboratory support
  - Evaluate the scope and resource impacts to the Army
- Advocate for MNPP acquisition through the National Defense Authorization Act (NDAA) Section 804, Middle Tier Acquisition for Rapid Prototyping and Rapid Fielding or entry into the Joint Capabilities Integration and Development System (JCIDS) process and designation as an acquisition program of record.

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Acronyms and Abbreviations

AEA	Atomic Energy Act
ARO	Army Reactor Office
AROC	Army Requirements Oversight Council
CFT	cross functional team
DCAs	Defense Cooperative Agreements
DLA	Defense Logistics Agency
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOS	U.S. Department of State
DSB	Defense Science Board
EPZ	emergency planning zone
FOA	field operating agency
FOAK	first-of-a-kind
FOB	forward operating base
HA-LEU	high assay – low enriched uranium
HEU	highly enriched uranium
HTGR	high-temperature gas reactor
IAEA	International Atomic Energy Agency
ISO	International Organization for Standardization
JROC	Joint Requirements Oversight Council
LEU	low enriched uranium
MDO	multi-domain operations
MILCON	military construction
MNPP	mobile nuclear power plant
NNSA	National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
OCONUS	outside the continental United States
PESTEL	political, economic, social, technological, environmental and legal/regulatory
SMRs	small modular reactors
TRISO	tristructural isotropic
TRL	technology readiness level
USACE	U.S. Army Corps of Engineers
USANCA	U.S. Army Nuclear and Countering Weapons of Mass Destruction Agency
vSMR	very small modular reactor

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1.0 Introduction

The 2017 National Security Strategy of the United States of America describes China and Russia as challenging American power, influence, and interests, and attempting to erode American security and prosperity (National Security Strategy of the United States of America, December 2017). The implications of the U.S. response to these challenges are by nature wide-ranging, both domestically and internationally. This study begins the investigation of the use of very small modular reactors (vSMRs) for mobile nuclear power plants (MNPPs) as energy-producing resources for forward operating sites.

The Army G-4 commissioned this study to inform Army leadership of the potential challenges and opportunities of employing MNPPs. It is a high-level examination of the political, economic, social, technological, environmental and legal/regulatory (PESTEL) aspects and regulatory and licensing issues associated with having an MNPP program employ (vSMRs). This study partially addresses the following issues/recommendations previously reported:

- A possible Joint Requirements Oversight Council (JROC) requirements submission resulting from the 2016 Defense Science Board (DSB) report (DSB 2016). The DSB report recommended exploring nuclear energy at forward and remote operating bases, and with expeditionary forces, as a means to reduce the U.S. Department of Defense's (DOD's) liquid logistics burden in support of worldwide operations.
- A 2017 DOD-funded study, *Future Contingency Base Operational Energy Concepts to Support Multi-Domain Operations,* which identified future growth in remote/forward operating base electrical power demand as an issue (Fowler et al. 2018).
- The Senate Armed Services Committee request for information derived from the National Defense Authorization Act (U.S. Senate Report 2017) to "…work with the U.S. Department of Energy's (DOE's) Office of Nuclear Energy to engage in research, development, demonstration, and deployment of micro-reactor concepts, also known as very small reactor concepts, with electric power generation of 10 megawatts or less, for meeting the strategic needs of the DOD, including, where appropriate, powering remote bases and forward operating bases, and for commercial applications in remote areas."

This study presents the history of mobile power plants in the Army (Section 2); the concept of mobile power plants (Section 3); a technical description (Section 4); and an assessment of the PESTEL elements and barriers to adoption (Section 5). Conclusions are presented in Section 6 and references are compiled in Section 7. Appendices provide greater technical and policy detail.

1.1 Background

Today, the United States is in a worldwide competition with emerging and resurgent global powers, aspiring regional hegemons, and non-state actors seeking to challenge aspects of the post-Cold War international order. For the foreseeable future, adversaries will continue to combine conventional and non-conventional methods to achieve their objectives creatively. Many will operate below a threshold that invokes a direct military response from the United States while retaining the capability to escalate to more conventional armed conflict if desired (Joint Chiefs of Staff 2018, p. v).

The Army faces a fundamental change in the character of warfare with a confluence of evolving threats with increasing technological sophistication spanning the competition continuum, an alternative to the obsolete peace/war binary (Joint Chiefs of Staff 2018). First among these threats is the return of great power competition with China and Russia. This competition threatens our nation's core interests and may result in the return of protracted, large-scale combat operations (LSCO). To meet these threats, Army readiness requires lethal, resilient, and agile forces ready to rapidly deploy and fight in contested environments, operate effectively across the entire competition continuum, and win decisively as part of the Joint Force against near-peer adversaries in large-scale combat operations and high-intensity conflict (U.S. Army 2018; Suits 2018). Warfare will become more violent, lethal, and swift; creating more consequential risks in terms of casualties, cost, and escalation beyond armed conflict.

The Army will face these challenges in all domains of battle, in all types of terrain, and particularly in urban centers. Political stresses affecting international stability and security will develop new areas of competition in which adversaries seek to expand influence and threaten the balance of power. Finally, fiscal instability threatens to limit the Army's ability to prepare for this complex environment, forcing it to choose between the priorities rather than operate cohesively among them. With the reemergence of long-term strategic competition with potential near-peer adversaries like China and Russia, U.S. joint force forward locations and operating bases serve to counter long-term adversarial coercion tactics and act as a strategic stabilizing force providing the predictability necessary for sustaining a favorable regional balance of power. Should deterrence fail, these same forward locations can support, receive, and project military power to fight and win.

Forward and remote locations allow the United States to deter and compete with near-peer adversaries below the threshold of war; however, the future world order will see a number of states with the political will, economic capacity, and military capabilities to compel change at the expense of others (Joint Chiefs of Staff 2016, p. ii). Adversary forces will be augmented by advanced command, control, communications, intelligence, surveillance, reconnaissance, information technologies, lethal precision strike and area effect weapons, and the capacity to field first-rate technological innovations (Joint Chiefs of Staff 2016, p. ii). The proliferation of weapons and other technologies include a variety of surface-, air- and submarine-launched ballistic and cruise missiles enabling near-peer challengers to accurately attack forward bases and deploying U.S. forces and their supporting logistics at ranges exceeding 1,000 nautical miles (DOD 2012). Because the principal MNPP locations are envisaged to be employed at major aerial ports of debarkation, seaports of debarkation, and forward operating bases (FOBs) where intelligence-gathering capability and protection from enemy interdiction by air, ground, naval and cyber forces are greatest, an MNPP is less likely to be captured, damaged, or destroyed than liquid fuel resupply convoys.

Adversaries may also attempt to disrupt the ability of the United States to conduct overseas military operations through attacks on major nodes of the global trade and logistics network such as large container ports or major airports (Joint Chiefs of Staff 2016). Some adversaries might also attempt to attack military bases and facilities to disproportionately degrade the ability of the United States to generate, deploy, and maintain the Joint Force (Joint Chiefs of Staff 2016). The survivability of the joint sustainment system will be critical. For land-based logistics especially, the challenge will be to ensure the survivability of the infrastructure (DOD 2012, p. 33) and the ability to reconstitute bases and other infrastructure required to project military force, including points of origin, ports of embarkation and debarkation, and intermediate staging bases (DOD 2012, p. 34). Forward and remote sites must be smaller, networked, and sustained by a much reduced logistical footprint.

The MNPP provides a new conceptual approach to the challenge of increasingly demanding logistics requirements in an era of constrained and degraded resources (Joint Chiefs of Staff 2015, p. v). Nuclear energy can offset electrical power currently generated using petroleum fuel to meet future logistics challenges. In terms of energy, these challenges include how to adequately support globally integrated operations, given the combination of four ongoing trends: 1) the increasing logistics demand of U.S. joint forces and operations; 2) constrained resources, both overall and within the logistics force structure; 3) the growing complexity of logistics operations; and 4) the proliferation of advanced anti-access/area-denial capabilities by adversaries that would degrade logistics capabilities and capacities (Joint Chiefs of Staff 2015, p. v-vi). The MNPP provides a high-density energy source capable of producing significant amounts of electrical power to meet essential electrical generation without having to divert petroleum fuel from maneuver.

1.2 Energy as an Enabler

Power/energy is a cross-cutting/cross-functional enabler of the current, next, and future fight and integral to Army modernization priorities. Improving power/energy capabilities and energy independence are cited in the Chief of Staff, Army (CSA) Sustain and Train Priorities (Internal Army). The MNPP delivers independent megawatt power, using an alternative to petroleum power generation, to enable air and missile defense capabilities, long-range precision fires, a future electrified force, and other modernization priorities. The MNPP can reduce the logistics footprint and lessen reliance on contested or extended supply lines while increasing reliability, access to power, and redundancy (U.S. Army 2017, p 45) to support key activities and linkages at echelons-above-brigade. Alternative fuels and advanced power generation decrease demand for fossil fuels providing the future force with improved endurance and a greater self-sustaining capability.

Since the early 1900s, electrical generation at forward and remote locations has been provided by gasoline- or diesel-powered generators. Historically, theater logistics support in particular, required electrical power generation at the megawatt to multi-megawatt level. The Capstone Concept for Joint Operations (CCJO) Joint Force 2020 (Joint Chiefs of Staff 2012) adeptly recognizes that energy is the largest share of logistical requirements. Improving how forces use energy, especially reducing demand for liquid fuel and developing operationally viable alternative energy sources, decreases the amount of combat power that must be dedicated to transporting those forces.

In 2015 and 2016, the Pacific Northwest National Laboratory (PNNL), a national laboratory within the DOE complex, was requested to provide scientific and technological assistance in their role supporting the United States Army Logistics Innovation Agency (USALIA), the Field Operating Agency (FOA) of the Department of the Army Deputy Chief of Staff, G-4 (Logistics). PNNL conducted a technical study, compliant with the structure and organization of a Joint Capabilities Integration Development System (JCIDS) capabilities based analysis (CBA), to evaluate future energy requirements, systems, and dynamics associated with forward operating locations. Operational energy demand in support of multi-domain operations (MDO) at forward locations is expected to grow significantly, resulting in an approximately 37 percent increase in fuel demand by 2027 (Fowler et al. 2018).

Electricity is normally provided by a stationary power plant, with commercial generators installed as part of the camp's military construction (MILCON) effort, and operated and maintained by a service contract, although some locations have employed combinations of leased and or mobile generators as government-furnished equipment (GFE). Power generation capacity is determined by electrical demand, backup power needs, design, and ability of the camp to distribute generated power. Fuel storage and logistic lines of supply are targets for enemy exploitation. Near-peer threats have the capability to exploit this vulnerability and can attack U.S. replenishment lines of supply, as well as forward area logistics bases/sites supporting combat operations. Dispersal of functions to multiple smaller sites or base clusters is often preferred as a means to ensure redundancy but it also increases force protection demands on units and manpower. Achieving a balance of protection and dispersal is influenced by an opponent's ability to interdict supply lines to a particular location or by outright attack on a location with long-range fires[1]. The availability of large (megawatt) amounts of power at a site could alter this situation to the DOD's advantage. With the development of directed energy weapons, U.S. forces have the ability to use high-power lasers for defensive purposes against long-range missile and rocket fires. This same electrical power could also enable an electromagnetic gun to provide long-range fires similar to the U.S. Navy's 155 mm rail gun, which will have a 110 nautical mile (204 km) range (BAE Systems 2018).

Nuclear power can reduce liquid supply (fuel and water) and associated transport risk vulnerabilities, operating costs and provide improved reliability (Merrifield 2018) across the spectrum of conflict, while enabling development of future capabilities by providing significant amounts of electrical power on demand for lethality, mobility, and protection. Reducing exposure to interdiction of the fuel supply is possible by substituting a more energy-dense fuel source that does not require frequent replenishment[2]. Nuclear fuel has the highest energy density (Table 1.1) and is employable in an MNPP that can meet forward or remote site needs while reducing demands on the liquid fuel supply chain. Depending upon the reactor design chosen, an MNPP could operate for 10-20 years (or more) on a single fuel loading.

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[1] Near-peer competitors all possess long range rocket, cruise, ballistic or hypervelocity missile systems with precision guidance.

[2] A hypothetical site requiring 13 MW of electrical base load power would consume approximately 16,000 gallons of fuel per day, every day. This replenishment equates to a vehicle/trailer liquid supply chain of roughly four M969 5,000-gallon fuel trailers or seven M978 2,500-gallon HEMTT tankers per day. A single 40-foot MNPP would eliminate this daily demand and associated transport and storage requirements, for up to 20 years.

Table 1.1. Energy Density

Generator Fuel Energy Density Comparison	
Fuel Type	**Energy Density (kJ/kg)**
Gasoline	44,000
Kerosene	43,300
Diesel	43,200
Uranium 235	67,300,000

Minimizing a location’s liquid fuel demand for electrical power generation not only reduces operational force requirements for security/delivery of fuel but also enables significant amounts of existing fuel to be freed up for operational and tactical use by U.S. forces in vehicles and aircraft, extending reach and capability immediately without having to grow additional logistics infrastructure. The fact that nuclear fuel can displace large amounts of liquid fuel is not a new concept. In the mid-1950s, the Army developed the concept of a nuclear power energy depot using a compact reactor to power synthetic fuel manufacturing on-site in the field, to create a substitute hydrocarbon fuel for military vehicles (USACE Baltimore, *Army Nuclear Power Program, 1969, 2014*). Also examined were mobile power production concepts and reactors for forward and remote site electrical generation. Demand for electricity is projected to grow significantly through 2050 and beyond as newer capabilities are deployed (Fowler et al. 2018). Generating power to meet projected demand is a challenge for conventional liquid fuel generators, which add cost and complexity to logistics.

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2.0 Mobile Power Plants in Army History

The need for electrical power to support expeditionary and contingency operations is not a new challenge to the Army or DOD. DOD and its precursor, the War Department, employed large-scale mobile power plants in World War II, the Korean Conflict, and Vietnam. Even then, the Army employed floating power barges to provide large-scale base power at forward sites and ports supporting deployed forces. In providing electrical power, mobile power plants are established through purchase or contract and may operate at any number of locations in support of conflicts, and peacetime operations, providing stationary electrical power to facilities, camps, or stations as required. In the past, the configuration of these power plants ranged from ships and barges to multiple large diesel generators, and transportable, mobile nuclear power devices.

2.1 Army History with Nuclear Power

The Army examined nuclear power opportunities and ran its own nuclear power program in the mid-1950s through 1977. A number of concepts were examined, from compact reactors for mobility purposes to mobile power for field forces. In 1963, the nuclear power energy depot concept envisioned a compact reactor to provide power for synthetic fuel manufacturing during field operations for military vehicles, and subsequently built a series of eight reactors for testing, training, and proof-of-concept purposes. Of the eight reactors, five were of a portable or mobile type. Of these portable/mobile devices, three were designed as stationary, but portable, power plants for large-fixed or semi-stationary facilities and two reactors were designed to be mobile. These five systems were successfully operated in both test and operational environments to gain operating experience and experiment with potential employment concepts. The three portable systems are described as follows.

- Reactor system PM1 successfully powered a remote mountain top air/missile defense radar station near Sundance, Wyoming for six years. The site was selected because it was remote, far removed from the 1962 commercial electric utility grid where winter road conditions did not safely permit fuel truck access.
- PM2A successfully demonstrated the ability to assemble a nuclear power plant from prefabricated components at a remote location. It was transported to Camp Century, Greenland in parts, assembled and successfully operated for three years, providing uninterrupted electric power before returning to the United States.
- PM3A was an Army reactor power station built for and operated by the U.S. Navy to provide electric power, heating, and desalinization for McMurdo Station, Antarctica from 1962-1972 (National Science Foundation 1980).

The two mobile power plants were designated MH-1A and ML-1.

- MH-1A was a barge-mounted power station[1] located at Gatun Lake in the Panama Canal Zone from 1968-1977, where it provided electricity and fresh water in support of canal zone operations.

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[1] The barge was a modified WW II Liberty ship (ex SS *Charles H. Cugle*, renamed the STURGIS) whose engine was removed in converting it to a power barge.

- ML-1 was a true mobile power plant (Figure 2.1). Its main advantage was the ability to substitute a single nuclear fuel load to displace and eliminate the need to transport the equivalent of 400,000 gallons of liquid fuel. Unlike the other Army reactors, ML-1 did not use water for coolant, substituting a sealed reactor design with pressurized gas (nitrogen) to drive a closed cycle gas turbine. This design made possible a significant reduction in both size and weight, enabling it to be truck-mobile. The reactor could fit in a standard International Organization for Standardization (ISO) container for ease of shipment by standard military transportation systems (ML-1 2018; Adams 1995). System reliability issues caused program delays and resulted in project cancellation in 1966 as the fiscal demands for the Vietnam War grew (Suid 1990, p. 93).

Figure 2.1. ML-1 Reactor circa 1962

The Army Nuclear Power Program (ANPP) was initiated as a result of a Joint Chiefs of Staff action in 1954, establishing the requirement for nuclear power plants. The ANPP was charged with the responsibility of developing ground nuclear power plants for the Army, Navy, and Air Force (Table 2.1). This program transitioned into the Army Reactor Office (ARO) in 1992, which is tasked to implement the Army Reactor Program (ARP) to ensure that Army reactors are operated in a safe, secure, and reliable manner from activation through de-commissioning. ARO resides within the U.S. Army Nuclear and Countering Weapons of Mass Destruction Agency (USANCA), an Army G-3 Field Operating Agency. Today, the ARO's primary focus is the disposal of legacy (non-mobile) reactor facilities and oversight of Army operated test reactors used for nuclear survivability testing of DOD systems. None of the mobile/portable reactor systems managed by the ARP/ARO are in operation. All have been deactivated or disposed of. While the current Army reactor program and its entities such as G-3/5/7, ARO and the Army Reactor Council[1], remain engaged in nuclear matters, the Army has the history and ability to regenerate subject matter expertise and hands-on proficiency in the areas of physical security, storage, training, certifications, transportation, consequence management, and policy. Under the ANPP, the Army created the military occupational specialty code (MOS 52 H/J/K/L/M) to identify duties and responsibilities of reactor operators and support staff. These nuclear unique positions were reduced and eliminated with the closure of reactors in the 1970s and 1980s.

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[1] Army reactor council members: G-3/5/7, Chief of Engineers/USACE, the Surgeon General, Assistant Chief of Staff for Installation Management, Provost Marshal, Director Army Safety, Army Test and Evaluation Command, U.S. Army Nuclear and Countering Weapons of Mass Destruction Agency and Army Commands possessing nuclear reactors.

Table 2.1. Army Reactor Program – Portable/Mobile Reactor Systems

Plant[a]	Operating Location	Net Power, megawatt (electrical)	Activation Date	Deactivation Date
PM-1	Sundance, WY[b]	1.0	1962	1968
PM-2A	Camp Century, Greenland	1.6	1961	1964
PM-3A	McMurdo Base, Antarctica	1.5	1962	1972
ML-1	Developmental Testing	0.3	1962	1966
MH-1A	Panama Canal Zone	10.0	1965	1977

[a] All reactors except MH-1A used highly enriched uranium

[b] PM-1 pressure vessel was entombed on site and is managed under an Air Force Safety Center Permit.

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3.0 The Mobile Nuclear Power Plant Concept

An MNPP is a small manufactured mobile electrical power system designed to produce electricity by nuclear fission. As envisioned, the MNPP would consist of a vSMR and balance of plant equipment with nuclear fuel packaged for easy movement and operation at multiple locations over its operating lifetime. The MNPP would not operate during movement, and is active only when stationary and connected to a site's electrical microgrid. While location power requirements vary (projected between 2 and 20 MW), a modular design allows combining MNPPs to meet greater electrical demand. MNPPs are configured for rapid setup, rapid shutdown, and ease of movement.

Because it contains nuclear fuel, an MNPP's life cycle has specific events not normally associated with non-nuclear systems. At the beginning of its life, an MNPP is pre-tested at the factory and commissioned into service to verify nuclear fuel loading and proper operation. It is then transported to various operating sites as needed. Its small size allows transportation via multiple means—trailer-mounted, containerized rail, military truck, watercraft, or aircraft—to operating sites worldwide (Figure 3.1).

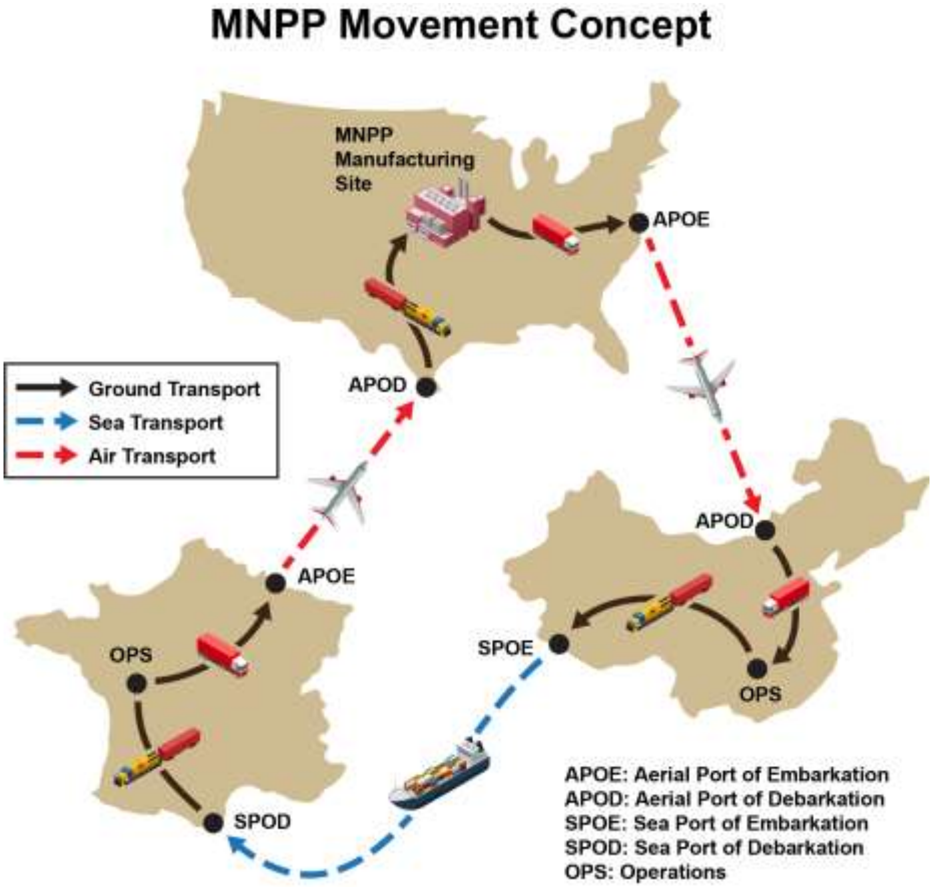

Figure 3.1. MNPP Movement Concept

At the end of its fuel life (projected at 10 to 20 years), the MNPP is returned to the United States for refueling and reuse or disposal. Unlike most existing commercial reactors today, MNPPs have the requirement for multiple startup, shutdown, and movements via different modes of transportation during their 10-to-20-year operating lifetime. This mobility characteristic is precedent-setting in the commercial nuclear industry.

While the Army experimented with a mobile reactor design in the early 1960s, current commercial reactor designs and philosophy, as well as supporting nuclear regulatory and domestic and international transport systems have not fully developed the necessary framework and rule sets for a land-based mobile system. Adjusting the framework and rule sets to accommodate a mobile reactor solution will require innovative approaches and updates to existing legal agreements, and a refocusing of current commercial nuclear industry views and perceptions governing nuclear power plants.

The MNPP represents a disruptive contribution to critical, emerging operational capabilities. The MNPP's ability to support larger locations with megawatt-level power demand provides room for projected electrical demand growth in support of current and future capabilities (directed energy and electromagnetic guns, water desalinization, and fuel production [Suid 1990, p. 88; NETL 2018]) and missions (Fowler et al. 1990).

Some key performance parameters and design considerations of an MNPP concept are:

- Sized for transport by different strategic, operational, and tactical military platforms (C-17 aircraft, ships, Army watercraft, and military truck).
- Designed to enable multiple movements in austere locations, throughout its operating life (e.g., passively or actively vibration-resistant during transport).
- Once installed, provides stationary "load-following" and conditioned electric power as well as possibly process heat. Capable of meeting a camp's variable electrical base power load demand.
- Provides electrical power for mission systems (e.g., sensing, computing, and communications), life support (heating, ventilation, air conditioning, lighting, etc.) quality-of-life functions, and other future applications (e.g., electric weapons, manufacturing, water or fuel production) during contingency operations in remote locations.
- Provides electrical supply for vital equipment when shut down (e.g., via passive-decay heat conversion to electricity).
- Does not require special or extensive on-site construction or unique material handling equipment.
- Must be simple in design and operation. Reactor design and fuel must be inherently safe and accident-forgiving.
- Installation and connection to supported location power distribution system should be a turnkey operation and have "plug and play" simplicity.
- Must have characteristics enabling minimum downtime for periodic instrumentation and sensor replacement or refurbishing, without requiring direct exposure to the nuclear fuel system.
- Ease of shut down for maintenance and transport.
- Minimize auxiliary/balance of plant components (tubing, equipment, tanks, pumps, and heat exchangers) that require additional maintenance and decrease operational reliability.
- Factory fueled with system operating life of 10-20 years without refueling.
- If battle damaged, the plant design and materials employed in its construction cannot generate and impose excessive training and equipping burdens on forward area first responders or site medical facilities.

- Limited to low enriched uranium (LEU) fuel (preventing material and technology diversion to produce a nuclear weapon if captured or stolen) supports international nuclear nonproliferation efforts (Treaty on the Non-Proliferation of Nuclear Weapons 2010).

While this list can guide Army requirements development, additional analysis, coordination, and experimentation will inform the refinement and development of more detailed requirements such as acceptable startup and shutdown times, optimal movement configuration, contractor logistics support (CLS), operator training and education on reactor design, operation, nuclear fuel, technologies, and material.

Operationally, the MNPP gives combatant and ground component commander's additional options in setting a theater logistically, enabling theater access, and supporting theater engagement operations. From a theater engagement perspective, clean nuclear power eliminates the issue of conventional exhaust emissions, a concern of host nations committed to reducing emissions internationally. Militarily, the ability to provide a small, mobile, prime power source, with significant electrical generation capacity to accommodate future electrical demand growth, and does not add to liquid fuel logistics burden, is significant. A factory-fueled MNPP eliminates the need to divert a significant portion of the fuel pipeline to electricity generation, enabling the unconsumed fuel to be available for maneuver force use. This is a significant sustainment and maneuver advantage as MNPPs are envisioned to operate unrefueled for 10-20 years. Over a decade of continuous low-intensity combat and stability operations, existing central power plants have been constructed and managed as real property facilities. Currently, central power plants take a significant amount of time to fund and construct, and are large and immobile. Such facilities, and their fuel sources, are easily identified and targeted.

While existing central power plants and spot generation have successfully supported operations in contingency and enduring FOB locations over time (including over a decade of continuous low-intensity combat and stability operations), it begs the question of how power generation would perform differently in a future high-end engagement. Peer and near-peer enemies have the capability and capacity to disrupt energy supplies and therefore limit U.S. options. Fixed facilities can be easily targeted. Small, mobile solutions complicate identification and targeting and can be relocated to support reconstitution of key capabilities and activities (electricity for port and airfield operations) following an attack. In a prolonged competition among great powers, MNPPs provide operational flexibility in displacing a substantial portion of liquid fuel (currently required for electricity generation), thus expanding alternatives in support of maneuver and options available to a theater commander.

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4.0 Mobile Nuclear Power Plant Technical Description

An MNPP consists of four major component sub-assemblies: the reactor, its nuclear fuel, its control system, and the balance of plant equipment (network of tubings, fittings, valves, and components and structures coupling with and controlling heat exchanger/turbine and generator assemblies). Together, these convert heat from the nuclear reactor into electrical power (Figure 4.1).

The reactor itself consists of the containment vessel, the core and its fuel, coolant, a moderator (a material in the core that controls the neutron energy at which fission occurs, and thus the chain reaction), and controls that enable the core to maintain and control fission and produce power at adequate rates. LEU nuclear fuel generally provides the thermal energy for power production.

The balance of plant receives thermal energy from the core and converts it into electrical energy through a heat exchanger and conventional turbo generating equipment that produces electricity for distribution. Depending on thermodynamic cycle and design, transfer of heat is accomplished by a working fluid (e.g., atmospheric air, carbon dioxide gas, or helium) that captures heat from the core through a closed-loop circuit and transfers heat between the reactor and heat exchanger/turbine. The control system monitors both the MNPP and power grid demand, adjusting reactor operations and output generation to match electrical load demand in real time.

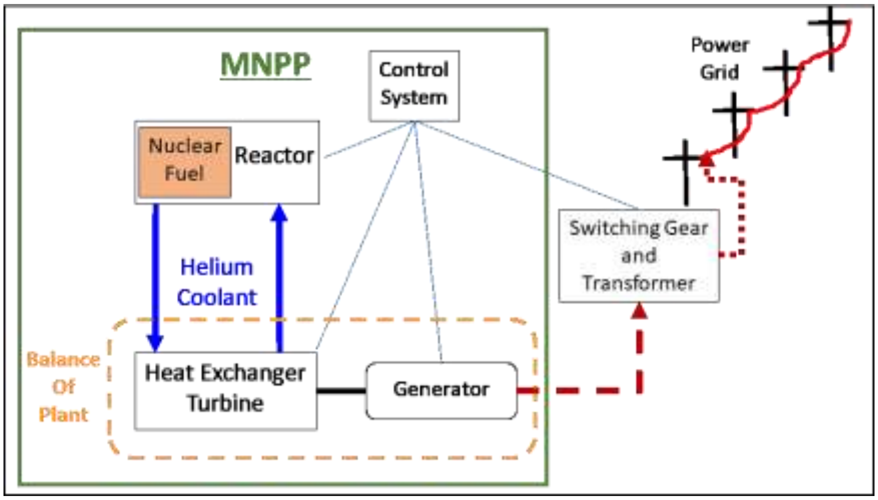

Figure 4.1. Components of a Mobile Nuclear Power Plant

As mentioned in its report, the DSB examined a few vSMR reactor designs and technologies with near-term potential to meet DOD needs (DSB 2016). Of these, only two designs were seen as potentially portable enough to meet DOD transportability needs. A further review of vSMR regulatory applications from firms seeking to provide a similar class of device identified three other vendors with near-term designs undergoing Canadian Nuclear Regulatory pre-licensing activities (Canadian Nuclear Safety Commission 2018). Collectively, these five designs reflect, existing technologies that reinforce the DSB assertion that adequate mature technologies are available. Most designs integrate existing off-the-shelf products for balance of plant, controls, and power generation, which reduces the need for additional research and development (R&D) work to design and prototype an MNPP device. Furthermore, the new vSMR reactor designs are much simpler than existing commercial power reactors. New designs and technologies enable them to exhibit high levels of inherent safety using techniques such as small nuclear fuel inventories and natural passive cooling processes in their design, instead of active pumps or compressors, resulting in improved reliability, and the minimization of accident scenarios such as core meltdown (McGinnis 2018). Backup power for monitoring control and safety is design-dependent and should be addressed with vendors as part of future design analysis efforts.

Four of the five system designs use a variation of the high-temperature gas reactor (HTGR), while another employs a heat pipe design. All have a corresponding reduction in systems, structures and components[1]; a very small footprint for physical plant; and use a Brayton thermodynamic cycle[2] with helium, nitrogen, or carbon dioxide as a coolant. Four of the five employ the same type of encapsulated melt-tolerant fuel[3]. Improved reactor safety is also provided by using ambient air as the ultimate heat sink for removal of reactor waste heat.

Tristructural isotropic (TRISO) fuel is favored in four of the reactors for safety purposes. While not the only fuel type option available for consideration, it has unique and highly desirable encapsulation and nonproliferation properties worth noting. TRISO fuel is a uranium fuel kernel encased in carbon and ceramic layers that prevent the release of radioactive fission products during use. These protective coatings also ensure against the possibility of fuel meltdown (Figure 4.2). Section 5.4 and Appendix D provide additional information on TRISO fuel.

The selection of TRISO fuel is an important safety feature for the majority of designs reviewed. By encapsulating fission contaminants, TRISO fuel dramatically reduces the risk of contamination release into the local environment, enabling a reduction in the size of a reactor's safety zone footprint. This is essential for facilities such as a commercial mining camp or forward location where personnel must work close to the reactor. Designed not to crack under stress from thermal expansion or fission gas pressure, industry designers clearly understand the value of TRISO fuel in safely avoiding contaminant release in an accident. While the DOE and the nuclear industry are pursuing R&D investments in multiple fuel encapsulation techniques, TRISO fuel is commercially available internationally, and can be available domestically with a sufficient demand signal (X-energy 2018). Additionally, TRISO fuel has been used with success and has aggregated operational experience in reactors in the United States (Fort St. Vrain in Colorado and Peach Bottom in California).

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[1] The Holos reactor design employs a "closed-loop" turbo-jet engine, replacing "combustors" with a reinforced, sealed, fuel cartridge. This design is similar to nuclear engines successfully tested by GE in U.S. government sponsored programs back in the 1950s and 1960s.

[2] The Brayton cycle is a thermodynamic cycle named after George B. Brayton, an American engineer. Consistent with conventional turbo-machinery, a closed Brayton cycle system employs a constant-pressure heat engine operating with compressor(s), power turbine(s), and generator to convert thermal energy contained in the working fluid (usually helium or carbon dioxide) to electricity.

[3] Tristructural isotopic (TRISO) fuel is a spherical particle of uranium fuel encased in carbon and ceramic layers that prevent the release of radioactive fission products during use and ensures against the possibility of fuel meltdown under loss-of-coolant and other off-normal scenarios.

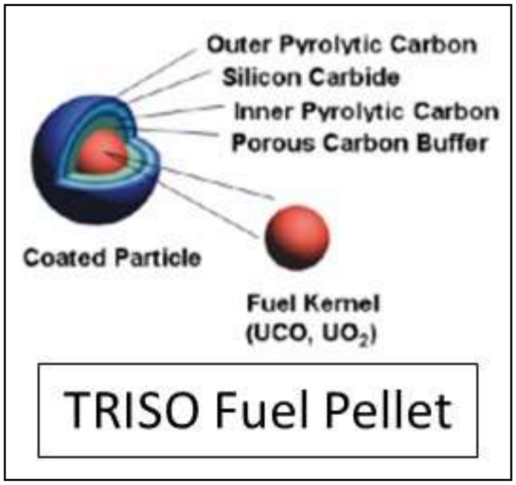

Figure 4.2. TRISO Fuel Composition

Combining newer inherently safe[1] reactor designs incorporating features with improved materials and safer fuel enables a significant reduction in the reactor and power conversion system footprint. These designs also offer enhanced protection and reliability of critical components while simplifying and improving nuclear plant operations. These ongoing commercial design efforts indicate that the technology and system level sub-components are present and sufficiently mature for a possible near-term Army MNPP program that can meet Army/DOD needs. While modern reactor designs do benefit from current technology and materials, it is important to note that these micro-reactor designs and their balance of plant have not yet been built. Additional effort may be needed to complete design and build of a device, or to reduce development or operating risk. DOE technical expertise will be needed, mainly in developing technical requirements, requests for information/proposals and in evaluating vendor responses. The manufacture of fuel for an MNPP device, is well understood. Enrichment and fabrication of a fuel type eventually chosen, is not expected to pose a developmental risk.

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[1] "Inherently safe" reactor design features reduce the risk of an accident and are required by the U.S. Nuclear Regulatory Commission to improve operating safety.

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5.0 PESTEL Assessment

The following analysis examines the impact and issues generated by the development of an MNPP solution by the Army. This macro-level examination of each area of PESTEL—political, economic, social, technological, environmental and legal/regulatory—helps provide context and identify key issues that can be examined later in the sections on potential courses of action and barriers/hurdles to adoption. Each PESTEL area is discussed in depth in this section and the highlights are presented in a gold-colored box at the beginning of each detailed discussion.

5.1 Political Assessment

Efforts to reconstitute America's nuclear industry are essential to support any near-to-mid-term Army and DOD MNPP effort. Political support is essential for three specific lines of effort:

- Nuclear fuel availability
- Regulatory environment being supportive of commercialization of new reactor designs
- Advanced reactor designs.

Of these, the nuclear fuel issue is the most critical. Nuclear fuel is a DOE responsibility and an area requiring senior DOD/Army leader attention. The Army and DOD have a significant dependency on DOE and its effectiveness at developing, producing, disposing, and potentially recycling nuclear fuel economically.

Overall, any MNPP effort will require a "whole-of-government" approach for success.

Despite failed construction of two light water reactors (LWR) reactors in South Carolina, and Chapter 11 bankruptcy filing by Westinghouse Electric, the current political environment for nuclear power is favorable. Nuclear power enjoys strong support from both the current administration and Congress. President Trump has made the maintenance of a strong and vibrant U.S. nuclear industry a priority (The White House 2017b). There is significant support to not only revive America's nuclear industry, but expand the U.S. domestic nuclear industry sector and its capabilities. The administration and DOE are developing a long-term vision and supporting plans to deliver focused outcomes (the President of the United States 2017). Energy Secretary Perry believes nuclear energy development can be a national game-changing opportunity through a focus on technology development and advances in capabilities such as small modular reactors, or SMRs (The White House 2017a). While the desire for America to regain its leadership role in nuclear energy is important economically and politically, it is also "a massively important issue for the security of America and the security for America's allies…." (The White House 2017a).

To support the commercial and federal nuclear sector, the administration has undertaken a number of efforts to affect the domestic nuclear energy sector. First, funding for nuclear energy research was boosted $190 million as the administration moves to increase engagement with private sector technology development efforts. An example of this is the transfer of technology from federally funded R&D to the private sector to promote economic growth and national security (Executive Office of the President of the United States 2018). Another area is DOE's Agreements for Commercializing Technology program, which removes barriers and facilitates commercial industry working with DOE's national laboratories.

Congressional focus has been on the U.S. national power grid with a broad approach to electricity generation from multiple energy sources. The mission and scale are significantly different from any DOD MNPP solution optimized for small-scale, non-grid power. Interest in supporting both national defense goals and other national nuclear capabilities is possible (Murkowski and Perry 2017). As with other initiatives, the ability of nuclear power to reduce some operating costs is of interest and requires engagement early to inform congressional members and leadership on intent, goals, and outcomes for any development or prototyping efforts.

Congress appears generally supportive of strengthening domestic nuclear industry through appropriations and legislation. In early 2018, two nuclear bills were introduced and are working their way through Congress—S.97 - 115th Congress: Nuclear Energy Innovation Capabilities Act of 2017 and S.1457: Advanced Nuclear Energy Technologies Act. Both bills appear to have bipartisan support. As of the publication of this report, S.1457 awaits a Senate action. S.97 was passed into law on September 28, 2018. S.97 is particularly noteworthy as it directs the Secretary of Energy to carry out demonstration projects relating to advanced nuclear reactor technologies to support domestic energy needs. A companion effort, HR 5260, was also introduced. If passed, the Army and DOD could potentially leverage work from these demonstration projects. Additionally, S.512, the Nuclear Energy Innovation and Modernization Act, seeks to modernize the regulation of nuclear energy by directing the U.S. Nuclear Regulatory Commission (NRC) to modify the licensing process for commercial advanced nuclear reactor facilities. This would be accomplished through DOE cost-sharing grants to fund a portion of NRC review fees. Furthermore, it would require the NRC to develop a technology-inclusive, regulatory framework encouraging greater technological innovation for advanced reactor programs. Finally, four new bills were introduced in the House supporting nuclear competitiveness and national defense[1]. Of these, H.R. 6140 supports increased fuel enrichment levels[2] to support U.S. government obligations and U.S. industry efforts at developing and deployment advanced reactors.

On May 8, 2018, at a Senate Energy and Natural Resources Committee meeting examining Puerto Rico's electric grid, members noted that the reliance on diesel generation resulted in operating costs of 20 cents per kilowatt hour. Senator Martin Heinrich (D-NM) stressed the need for new generation, cheaper than relying on diesel generation. As this situation is quite similar to that DOD encounters at existing enduring and contingency bases, congressional support and funding for a DOD-led MNPP effort with commercialization potential is not only possible, but arguably worth further exploration.

Efforts to reconstitute America's nuclear industry are essential to support any near-to-mid-term Army and DOD MNPP effort. Political support is essential for three specific lines of effort:

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[1] The four bills are: HR 6140, the *Advanced Nuclear Fuel Availability Act*; HR 6141, a pilot program to site, construct, and operate micro-reactors at critical national security locations and for other purposes; HR 1320, *Nuclear Utilization of Keynote Energy Act*; and H.R. 6351, the *Advancing U.S. Civil Nuclear Competitiveness and Jobs Act.*

[2] Currently commercial nuclear fuel is enriched to 5 percent. Increasing this to 20 percent supports advanced reactor development and deployment while meeting non-proliferation limits. For a discussion on the enrichment issue, see Appendix D.

- Nuclear fuel availability
- Regulatory environment being supportive of commercialization of new reactor designs
- Advanced reactor designs.

Of these, the nuclear fuel issue is the most critical. Nuclear fuel is a DOE responsibility and an area requiring senior DOD/Army leader attention. The Army and DOD have a significant dependency on DOE and its effectiveness at developing, producing, disposing, and potentially recycling nuclear fuel economically. The U.S. government needs a domestic enrichment source with the capability to produce high assay-low enriched uranium (HA-LEU) (Appendix D) to support civilian and military needs[1]. Uranium enrichment for both weapons and naval propulsion purposes[2] must be from domestic sources. DOE and DOD are examining future solutions to address uranium enrichment and nuclear fuel production for navy and weapons purposes in the next 10-15 years. A modest scale program to deploy an MNPP capability within 5-10 years, would potentially require significant amounts of HA-LEU for fuel much earlier than this. The current U.S. industrial base has only a single manufacturer enriching nuclear fuel today. That manufacturer, URENCO-USA, is focused on the electric utility market. URENCO-USA has capacity for additional work but would require a modification to their existing NRC license to enrich/produce an HA-LEU product. Enrichment to support military needs would be an incremental addition to existing commercial enrichment production, adding workload to existing plant capacity. Support for higher enrichment would require NRC licensing and some facility upgrades with a lead time of approximately five years[3]. This approach would support potential prototyping and initial production timelines enabling an MNPP capability demonstration by 2023 as well as capability to support follow-on high-volume fuel production for a modest- to large-scale deployment of an MNPP system, if desired. While this approach presents the lowest cost for fuel enrichment, it requires negotiations with URENCO's owning governments[4].

A second option for enrichment is the acceleration of a domestic enrichment capability to support an MNPP prototyping effort and follow-on MNPP production and deployment. The U.S. nuclear industry has the capability to support such an effort if an adequate demand signal exists and long-term production volumes are sufficient for long-term profitability. Bringing such an enrichment capability online is possible within 5-7 years[5]. A U.S.-owned domestic enrichment capability would bypass potential foreign government peaceful-use restriction entanglements, enabling support to other national security/defense needs, as well as MNPP electrical power production. Political support for this approach, which strengthens and supports U.S. industry is high.

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[1] LEU cannot be extracted and repurposed for nuclear weapons (DSB 2016, p 38).

[2] Weapons or U.S. Naval reactor fuel require high levels of enrichment. See Appendix D for detail.

[3] McCabe K. 2018. Telephone discussion with Melissa Mann, President, URENCO USA Inc. and Kerry McCabe (Engineer, Pacific Northwest National Laboratory), March 27, 2018, Ft. Belvoir, Virginia. Copy of conversation notes included in project files.

[4] Germany, the Netherlands, and the United Kingdom.

[5] McCabe K. 2018. Telephone discussions with Melissa Mann, URENCO-USA, Scott Nagley, BWX Technologies and Dan Poneman, Centrus) and Kerry McCabe (Engineer, Pacific Northwest National Laboratory), March 27, June 8, and May 30, 2018, Ft. Belvoir, Virginia. Copy of conversation notes included in project files.

Lastly, DOE is pursuing the reestablishment of a U.S. origin enrichment capability, but DOE's timeline is in the late 2030 period or beyond[1]. DOE's preliminary plan is at an early stage and does not take into account any MNPP requirement. DOE is focused on support to defense missions (primarily weapons and naval propulsion) in the period 2038 and beyond. The potential to incorporate an Army MNPP program into DOE's existing planning efforts is not fully characterized. Future enrichment needs must be worked with the National Nuclear Security Administration within DOE (NNSA). Acceleration of a national capability is a political decision that would need to be informed at the interdepartmental level.

In addition to fuel, reactor design efforts have increasing political support. Support for advanced reactor designs is being handled by DOE through various means. In addition to normal support to the nuclear industry designers through the national laboratories, DOE has initiated funding opportunities for new reactor and technology designs through several Funding Opportunity announcement such as ARPA-E. These opportunities are being pursued along with the commercialization efforts mentioned above to generate new technologies and capabilities. While DOE focuses on the U.S. national power grid and its associated issues, leveraging existing work as well as policy and funding adjustments are possible to support development and fielding of an Army/DOD MNPP in the near term.

Interagency support in the nuclear regulatory environment is needed in two areas. First is assistance in adjusting international agreements to support an MNPP. Doing this will require collaboration among DOD, Department of State (DOS), DOE, and the NRC. Secondly, guidance from the administration and potential changes to NRC authorities and funding support may be necessary for enabling staff to assist in addressing international agreements and other issues outside of the NRC's existing scope. Success in these areas would potentially enable international commercialization of an MNPP design with global business and geopolitical opportunities for the United States.

Within DOD, the political environment is favorable for an MNPP solution that supports the increasing energy needs of combatant commands and their forward locations. The Office of the Undersecretary of Defense for Research and Engineering supports developing and demonstrating an MNPP capability as it would assist the United States in maintaining a competitive advantage compared to Russia and China in the development and employment of advanced nuclear reactors for military and civil applications (Freedberg 2018; Griffin 2018a; Griffin 2018b). Regarding the operational employment of an MNPP within the joint force, a more critical analysis that looks at not only the political, but the social and environmental challenges associated with deciding if, when and where best, or where not to employ an MNPP device is required. Given an ever-changing, fluid political landscape where relationships with allied nations—not to mention non-state actors and near-peer competitors—are occasionally other than harmonious, the sensitivities involved in transporting, locating, and operating an MNPP over protected air space, waters, and on foreign soil, with or without permission from the host, is always a strategic-level decision requiring DOD and interagency coordination.

Overall, any MNPP effort will require a whole-of-government approach for success. When discussed with DOE, DOS, and the NRC, all were supportive of an MNPP project for this study.

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[1] McCabe K. 2018. Telephone discussion with Audrey Beldio, NNSA NA-192 (Office of Domestic Uranium Enrichment) and Kerry McCabe (Engineer, Pacific Northwest National Laboratory), July 2018, Ft. Belvoir, Virginia.

Development of an advanced-design MNPP with its supporting technologies is seen by the U.S. nuclear industry as a significant national milestone. As MNPP devices have broad utility for both military and civilian interagency use, the development of a safe, mobile, advanced design system effectively exported to other countries, would strongly support American interests, the U.S. nuclear industry and American workers in the global power market. The device's mobility is particularly useful for supporting responses to civilian authorities like the U.S. Department of Homeland Security (DHS) or the Federal Emergency Management Agency (FEMA) in a humanitarian assistance and disaster relief scenario such as a hurricane, or for unforeseen events such as a large-scale power outage from manmade or natural events. As a result, the political environment at the interagency level is assessed as favorable for collaboration and work on an MNPP.

5.2 Economic Assessment

Fuel availability and cost are directly dependent on the success of industry to stand up a national capability to cost effectively mass produce HA-LEU fuel commercially.

The economics of an MNPP differ from conventional liquid fuel power generation. Comparison of an advanced nuclear power plant to existing liquid fuel generators can provide some reasonable cost estimates. Figure 5.1 compares total costs (operating and capital) for one proposed nuclear design compared to diesel fuel at three price points.

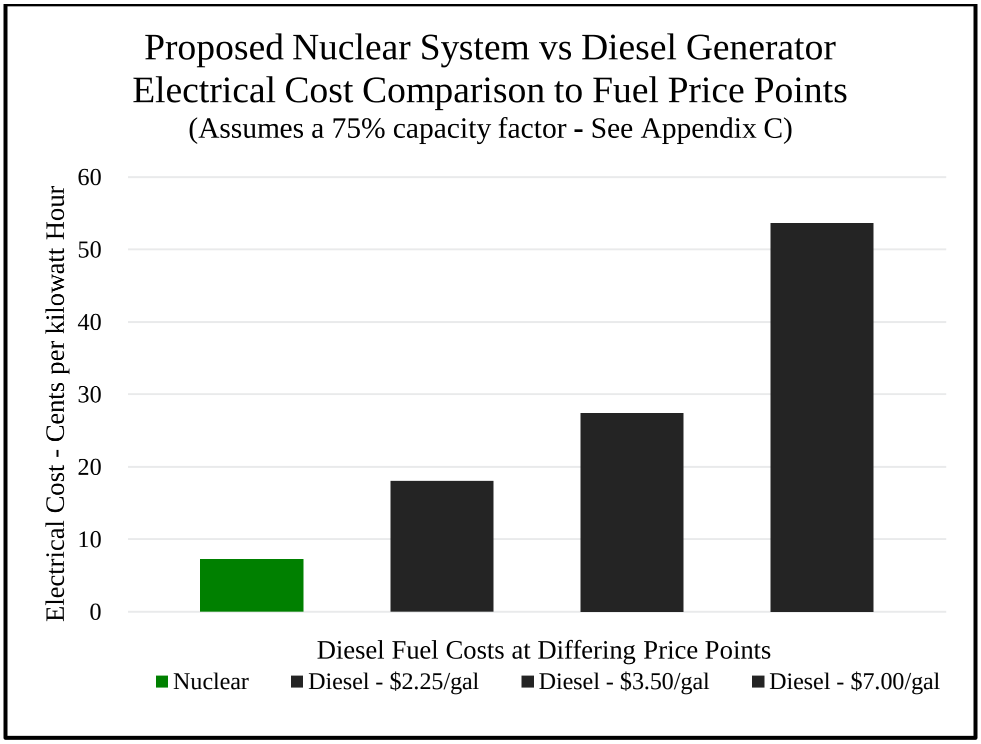

Figure 5.1. Electric Cost Comparison of Proposed Nuclear versus Diesel Generation

For this analysis, actual cost data from the Defense Logistics Agency (DLA) fuel and support contracts along with mature engineering estimates were used for cost comparison against one MNPP design. Several systems were evaluated for this report (Holos, MegaPower, USNC, etc.). Of these, the Holos design had the most mature cost data to enable analysis.

The Holos system[1] design uses integral power conversion systems derived from off-the-shelf aviation, power-turbine and waste-heat-recovery components. The vendor was willing to share test, design, and cost estimating data[2]. Information on end-of-life/cleanup costs was provided by the U.S. Army Corps of Engineers (USACE) and DLA provided fuel consumption and cost data enabling a comparison of nuclear (Holos) generation with actual liquid fuel generation at multiple remote and FOB sites. Results indicate that Holos has a 62 percent cost advantage over conventional liquid fuel generation power solutions across the range of power utilization options (see Appendix C).

Significant barriers exist for new nuclear power designs. These barriers have constrained the nuclear power industry and market to a few existing large-scale and or special-purpose reactor designs and a handful of nuclear fuel producers (Merrifield 2018). First-of-a-kind (FOAK) design reviews for a new reactor can range from 25,000 or more hours for design and licensing review to approval.

The NRC estimates cost and time for performing a design, siting, and environmental review at approximate $10 million and 35 months; but this estimate is highly dependent on the actual design selected, the licensing approach pursued and as a result could vary significantly[3]. Economic benefit calculations are dependent on accurate estimates for nuclear fuel and FOAK costs that include NRC regulatory and licensing work for approval to manufacture and operate. All three represent major cost components of any nuclear energy program, and will require interagency coordination, collaboration, and support for success. Planning and cost containment, particularly for spent nuclear fuel, are essential to cost avoidance in not generating long-term liabilities for the Army. Similarly, effective planning to minimize regulatory costs is essential as NRC and DOE support work add significant cost. Costs for regulatory staff and experts to understand a design and license/permit[4] will be significant, but can be controlled through advanced proper planning. Compared to current nuclear plants, the scale and simplicity of MNPP design facilitates reduced workload and time required for design licensing certification and approvals. This scale advantage also extends to other areas such as development for manufacturing, prototyping, and testing. While licensing and regulatory costs are significant for new reactor designs, they are essential to ensure the reactors are safe to operate, and maintenance and operator training are appropriate for the specific design.

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[1] Disclaimer: This is not meant as implied endorsement or support thereof for a particular design or vendor.

[2] HolosGen LLC provides analysis, research, design, fabrication and testing for energy systems and components. HolosGen has designed Holos, a mobile nuclear power plant, to address military-specific requirements and the military market. HolosGen derives their power conversion component economics from experience in testing large diesel-electric locomotive waste heat recovery systems.

[3] Email from John Segala (Advanced Reactor and Policy Branch, NRC) to Kerry McCabe (Engineer, Pacific Northwest National Laboratory), Subject – Question on New Reactor Regulation/Licensing costs, May 3, 2018. Ft. Belvoir, Virginia. Copy of email included in project files.

[4] The NRC issues a license to operate a reactor/site commercially and Army Reactor Office issues a permit to operate. While the terminology is different, both provide authority to operate a reactor.

Nuclear fuel is purchased upfront, unlike hydrocarbon fuel, which is purchased in volume over time. Nuclear fuel takes up a fraction of the space, yet has the equivalent energy of hundreds of thousands of gallons of liquid fuel, eliminating significant shipping and handling costs. In addition, modern nuclear power plant designs have the ability to automatically reduce fuel consumption based on demand. When a location's demand is less than the MNPP's capacity, the MNPP automatically reduces its nuclear fuel consumption to match electrical generation demand, with a net effect of extending MNPP operating life. In the Holos case, this initial fuel load life extension could be as much as 8-10 years. This feature presents a significant advantage over conventional liquid fuel generators on remote sites within the operational energy environment.

While multiple nuclear fuel options exist, the development of a healthy, sustainable, long-term commercial fuel supply chain is essential for long-term success. Currently, the ability of the U.S. nuclear industry to produce enriched fuel in high volume, at a reasonable cost is limited. While commercial nuclear fuel is generally enriched to 3 to 5 percent ^{235}U concentration, MNPPs will need HA-LEU fuel, which is not currently available. HA-LEU is typically enriched between 12 and 19.75 percent[1]). Therefore, fuel availability and cost are directly dependent on the success of industry to stand up a national capability to cost effectively and mass produce HA-LEU fuel commercially. Initially, DOE can lend support to the effort and has a number of options for providing enrichment and fuel fabrication support, ranging from down blending of existing highly enriched uranium (HEU) in government stocks, to possibly recycling[2] spent naval fuel, or promoting the commercial manufacturing of new fuel through increased demand and long-term fuel contracts. All these options come with differing costs and schedules that have various impacts on MNPP affordability. Avoiding unacceptable fuel (and program) cost escalation requires planning, coordination, and interagency support from those involved in larger national nuclear fuel efforts. Identification of any cost-sharing opportunities with DOE should be explored and pursued at the interagency level.

The last area for cost concern is spent fuel and reactor disposal. Both of these have significant potential to incur long-term liabilities and necessitate senior leader oversight. The Army has a number of legacy nuclear program sites containing decommissioned reactors with minor levels of contamination that were never addressed fully. Past budgetary decisions to defer decommissioning and cleanup coupled with cleanup standards that changed over time, have increased costs and created long-term liabilities. This situation would have been avoided with prompt decommissioning and cleanup. These legacy facilities differ from an MNPP because they were large facilities that were not designed specifically to simplify decontamination and decommissioning. In contrast, a small mobile reactor will be designed to have significantly lower complexity for cleanup and decontamination with lower costs that can be forecast and properly pre-planned. Modern reactor designs and fuel technologies can reduce or eliminate many of the types of contamination issues by reducing the number of systems, structures, and components that can become radioactive as a result of operations; shrinking the volume of systems exposed to primary cooling systems; and selecting materials that are easy to decontaminate. A philosophy

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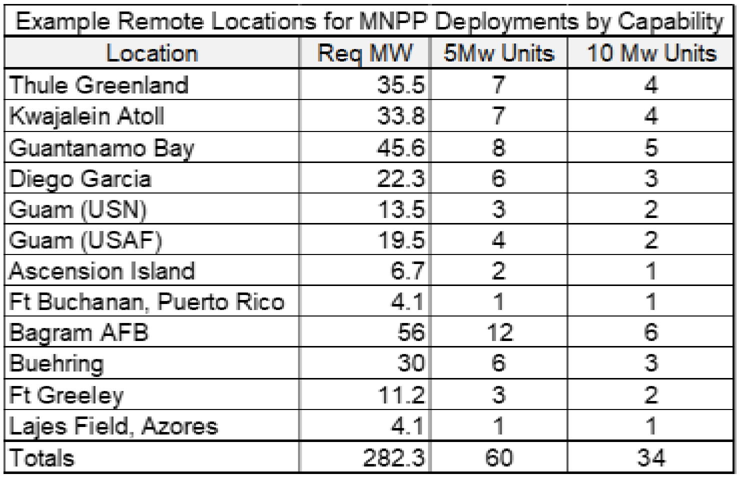
[1] LEU is enriched up to 20 percent ^{235}U. HA-LEU is typically taken only to 19.75 percent to account for statistical error and make sure it does not cross the 20 percent threshold (*International Nuclear Fuel Cycle Evaluation. 1980)*

[2] U.S. Navy spent fuel is highly enriched and could be down-blended to HA-LEU levels after processing to remove fission burnup poisons. This approach has not been attempted and would require development and proving out a full recycling process to meet Army needs. Cost and time to develop this recycling option are currently unknown.

of design for disposal should be pursued in early contract, design, and prototyping to minimize nuclear unique decommissioning and disposal life cycle costs. Supporting this, improved options for effectively funding end-of-life cleanup activities should be investigated, examined, and pursued by DOD. Current methods of funding decommissioning work are based on the small, legacy nuclear program and may be insufficient for a fleet of MNPPs over a more than 20-year period. A look at how the NRC manages this issue would provide a good starting point for developing DOD options. Examples used by the NRC include concepts such as pay-as-you-go over time, or pre-paying into a separate decommissioning fund that is specifically set up to handle reactor end-of-life events (10 CFR 50). The NRC’s fee is formula-based and could serve as a starting point for developing a potentially similar DOD effort for MNPPs.

Finally, potential procurement quantities of MNPPs were estimated to determine the magnitude and impact of device and fuel production on commercial industry (Table 5.1). This effort is only an attempt to determine if MNPP fuel demand quantity is sufficient to support long-term commercial production economics. The listing of example locations[1] for Table 5.1 is not all inclusive of potential deployment locations. It only includes sites that had data to support the economic analysis. Additional locations that would be ideal for MNPP support, such as Kandahar, Afghanistan, are not included in this initial economic analysis due to a lack of data. Location power demand and MNPP quantities to support it are dependent on a variety of factors including site location and grid power availability, site power demands and criticalities, backup power needs, MNPP size and capabilities, and funding available. The Army and DOD need to sponsor a field data collection effort and follow-on study of forward and remote site electrical requirements before any authoritative MNPP requirement quantity (and supporting Army acquisition objective and costs) can be determined.

Table 5.1. Potential Procurement Quantity Estimate



Example Remote Locations for MNPP Deployments by Capability

Location	Req MW	5Mw Units	10 Mw Units
Thule Greenland	35.5	7	4
Kwajalein Atoll	33.8	7	4
Guantanamo Bay	45.6	8	5
Diego Garcia	22.3	6	3
Guam (USN)	13.5	3	2
Guam (USAF)	19.5	4	2
Ascension Island	6.7	2	1
Ft Buchanan, Puerto Rico	4.1	1	1
Bagram AFB	56	12	6
Buehring	30	6	3
Ft Greeley	11.2	3	2
Lajes Field, Azores	4.1	1	1
Totals	282.3	60	34

Technical and economic information for most sites is not available or complete, inhibiting a thorough analysis and definitive answer. For the purposes of this study, a rough estimate was made to enable basic analysis. The methodology used to determine a potential procurement quantity was to examine selected remote, outside the continental United States (OCONUS) locations with higher-than-grid power costs that had a current demand of more than 4 MW of electrical power (King et al. 2010, p. 61). Generic 5 MW and 10 MW MNPPs were then compared to existing plant size and average annual energy use (which did not include peak demands that will need to be factored in for thorough analysis) and adjusted with backup and critical power estimates, and other potential locations. The estimate for the procurement is 35 to 105 units of 10-MW generating capacity, and 61 to 108 units of 5-MW generating capacity. The total requirement could be units from one capacity level, or a mix of the two capacity levels.

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[1] For location energy requirements see Appendix A of Fowler et al. 2018.

Infrastructure requirements and costs to operate MNPPs are unknown at this time but could be significant, depending on DOD and commercial business models and factors. Existing nuclear responsibilities and processes would need to be reexamined and adjusted. Some adjustments could be significant. Example areas affected include: manning, training, quality control, radiological controls, radiological health, nuclear qualified maintenance personnel, and program supervisory personnel. A future study on this topic is needed, and recommended in Appendix I.

5.3 Social Assessment

- It is essential to develop and communicate factual information on MNPP design, safety features, transport, operations, and the military and civilian benefits.
- Communicating facts on safety, transport, and risks to foreign militaries and governments in proper context is crucial to success.
- The DSB report recommended: "The Secretary of Defense should designate the Army as the Executive Agent for all of the nuclear energy applications recommended in this study and provide adequate resources to accomplish the mission."

The return of nuclear power to the Army and DOD will have a significant impact on the Army, our allies, the international community, commercial power industry, and the nation. U.S. nuclear industry growth affects the nation economically and geopolitically. With nuclear industry growth, there is significant potential for generating thousands of jobs. The development of exportable, safe, modern, reactor designs and services benefit not only national economic interests but also social attitudes and geopolitical relationships. A movement towards increased reliance on nuclear power from MNPP development, could spur worldwide jobs in high tech, electric utility, specialized manufacturing, and uranium mining industries, while reducing dependence on petroleum and decreasing carbon dioxide emissions. Additionally, the academic disciplines relating to nuclear power would be revitalized and once again become a source of professionals for the rest of the world. In sum, the social aspects of nuclear technology development would be deep and wide, and would enhance the economic prosperity of the nation.

Today, commercial nuclear operating experience has been limited to large and complex first-, second-, and third-generation pressurized and boiling water reactors with non-encapsulated fuels. These designs rely on complex redundant control and cooling sub-systems whose operators are highly trained to avoid accidents involving the release of volatile contaminants and the overheating and melting of their fuels. A small simple modern reactor with inherently safe design can be built to eliminate legacy reactor failure points and minimize the potential for MNPP operating and transport hazards.

Safety and transportability are envisioned as major design elements of an MNPP. Like other military unique equipment, MNPP training will require some specialized focus and or operator certification for setup, operation, shutdown, movement, and emergency procedures. However, this requirement is not anticipated to be as demanding as that of a nuclear weapon. Nuclear reactor-specific operating procedures and operator certification of soldiers and/or contractors is anticipated to be simplified by the use of cyber-hardened, automated, modern reactor designs using proven components and LEU encapsulated fuel. It should also incorporate nuclear hazards training on the device during movement and if attacked and damaged. A review of past practices from the earlier ML-1 system would provide a good starting point for safety and transport training development. Security and protection during both movement, and at an operating site, are also issues identified for further study once a standard MNPP design is selected. Similar to conventional power generation systems, MNPP designs should permit the use of standard forms of field engineering protection from attack (e.g., revetments, entrenching—with or without overhead cover). The ability to protect the device is further enhanced by its anticipated external configuration (in a 40-foot ISO container or smaller), which reduces visual signature and enables rapid simplified protection measures.

Communicating facts on safety, transport, and risks to foreign militaries and governments in proper context is crucial to success. Highlighting these issues will be a full-time job for at least a decade or longer. The Naval Nuclear Propulsion Program has individuals assigned to communicate, advocate, and work treaty, port access, and other intergovernmental issues. The establishment of a small team (within the MNPP Project Management Organization or DOD) to manage the communication and education function should be examined and considered if and when an MNPP program is initiated. Establishing outreach and strategic communications as a core competency is essential for international transport, theater, and host nation access as well as informing and ensuring U.S. and foreign public opinion.

A second area for significant social change concerns the Army's service authorities. The DSB report recommended: "The Secretary of Defense should designate the Army as the Executive Agent for all of the nuclear energy applications recommended in this study and provide adequate resources to accomplish the mission." (DSB 2016). The duties and responsibilities as the lead requires resourcing and policy development as well as public communications and outreach. A nuclear power program manager will need to be identified also, along with a supporting regulatory organization—all of which will require staffing and be authorized to conduct interagency (NRC, DOE, etc.) interface and coordination. While not an authority per se, the decision assigning a program manager would fall to the Army Acquisition Executive, possibly informed by an Army Requirements Oversight Council (AROC) or Joint Requirements Oversight Council (JROC) decision.

Program management naturally aligns to existing organizations responsible for mobile electric power sources, such as the Project Manager Expeditionary Energy & Sustainment Systems (PM E2S2). Early PM involvement with requirements development and interagency (DOD/DOE) coordination is needed. As an option, the PM should consider use of NDAA Section 804, Middle Tier Acquisition, to rapidly prototype/field capabilities distinct from the traditional acquisition system. Middle Tier of Acquisition (MTA) designated programs are not subject to the Joint Capabilities Integration Development System (JCIDS) or DoD 5000.01 except as provided in implementing guidance contained within Section 804. Regardless of the program management office designated for MNPP development, and the acquisition path chosen, authority for direct communication with interagency counterparts and alignment of authorities are essential. In the case of assignment to PM E2S2, this would entail aligning DODD 4120.11, "Standardization of Mobile Electric Power (MEP) Generating Sources."

Current mobile electric power (MEP) generating source definition limits PM E2S2's mission to standardize power no higher than 750 kW. The project manager does, however provide a medium voltage (prime power) 840 kW generator exclusively for the U.S. Army Corps of Engineers. A 2-20 MW MNPP would exceed the current MEP definition and also affect the current practice of using stationary non-tactical generator sets installed as real property equipment at contingency and enduring site locations.

Finally, contingency construction planning, practices, standards, and funding processes will need to be updated along with doctrine. The development of a standardized, mobile, nuclear-fueled prime power system will generate some operational concerns, even though its employment would not differ from current practice. Like any other first-time capability, adjustments to doctrine, operational contracting, training, and other areas will be necessary. The U.S. Army's Maneuver Support Center of Excellence (MSCOE) and USACE[1] would function as user proponents for the capability, working with U.S. Army Training and Doctrine Command (TRADOC) and with Headquarters Department of the Army (HQDA) direction to update contingency planning, contracting and construction policy, procedures, plans, and MILCON approvals for prime-power (nuclear) support in forward locations. In addition to contingency locations, OCONUS enduring facilities should plan for MNPP support in coordination with their host nation through Status of Forces Agreements, Defense Cooperative Agreements and interagency (DOE) support, upgrading and adjusting their power grids over time to take full advantage of MNPP generating capacity.

5.4 Technological Assessment

Technology for an MNPP encompasses both materials and system design (reactor and power generation), fuel, controls, and testing. Investment in new and unique materials is healthy for the economy, but Army/DOD should generally avoid R&D in this area, allowing DOE with its core competencies in reactor materials improvement to lead such efforts.

The Army understood the need for a technological solution to minimize demand for, and transportation of, bulk liquid fuels for maneuver forces in the 1950s. The ability of modern nuclear technology to provide electrical power, provides a solution that reduces joint force logistics asset vulnerability, without adversely affecting maneuver options and operations. Attacks on liquid logistics are expected in counterinsurgency operations and MDO environments. Displacement of liquid hydrocarbon fuel by nuclear power helps reduce fuel transport requirements and associated casualties. MNPP technology can generate significant amounts of electrical power that easily support current electrical demand, as well as projected future growth from emerging directed-energy (e.g., high-energy lasers, microwave, and rail guns) weapons. Farther into the future, MNPPs can support future vehicle electrification drive concepts seen emerging in the commercial market.

The 2016 DSB assessed technology as sufficiently mature to develop an MNPP (vSMR); a subsequent market/technology investigation conducted for this study identified additional examples of relevant technology. As a first step, DOD would need to develop definitive requirements for industry design teams to develop responsive designs and supporting technologies. Of the key characteristics listed earlier, transportability, safety, power produced,

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[1] USACE 249th Engineer Battalion has the Army "Prime Power" mission

simplicity of operation (including placing the device into, and out of, operation), and fuel issues (type, enrichment, and endurance/life) are likely the main driving features for a military device.

The nuclear industry is focused on building power plants to support the national commercial grid. In the last few years, the focus has moved away from large-scale construction/power plants towards smaller, factory-built, somewhat transportable devices that could provide quality and cost advantages. This SMR effort is a utility-scale approach with large SMR designs optimized for fixed facility applications. While these SMR-scale systems are too large for an MNPP application, lessons learned have been leveraged for the vSMR market, which is of interest for military applications. Thus, current technology is generally sufficiently mature to support MNPP design development efforts without Army/DOD needing to introduce new materials or additional R&D prior to prototyping. Near-term solutions are possible with components and subsystems at a technology readiness level 6 (TRL-6) or above maturity level. State-of-the-art MNPP designs are possible, but not common, as they are considered niche market products for remote villages or mines, and few firms are pursuing this business market segment. A by-product of this situation is that those firms working in the mining or remote site market generally do not want to reveal or share design data as their intellectual property represents a competitive advantage. A DOD prototyping effort could motivate these companies to participate.

Technology for an MNPP encompasses both materials and system design (reactor and power generation), fuel, controls, and testing. Investment in new and unique materials is healthy for the economy, but Army/DOD should generally avoid R&D in this area, allowing DOE with its core competencies in reactor materials improvement to lead any such efforts. While the DOE civilian enterprise normally is not focused on producing an MNPP for military application, a competitive prototyping approach within the DoD R&D system might be a cost-effective way to advance MNPP design quickly without unduly affecting ongoing Army modernization efforts. The Strategic Capabilities Office reporting to the Undersecretary of Defense for Research and Engineering could provide a suitable level of leadership support for demonstration of a military MNPP.

While many vSMR designs are conceptual, and require substantial developmental effort to complete a detailed design, DOD can leverage a number of maturing reactor designs that are being developed for the commercial marketplace. Few designs lend themselves to an air-transportable, mobile, turnkey, “plug and play” MNPP device, but the mining sector has proposed devices with most of these characteristics. An examination of three current designs undergoing regulatory review for the Canadian mining market identify small-sized HTGRs as a preferred technology solution. HTGRs can use a number of gases as coolant (e.g., helium, carbon dioxide, argon, nitrogen). Commercial power plant designs for the mining sector support very remote locations and tend to favor few refueling opportunities, or prefer to have a reactor with a lifetime fuel supply. All designs favor newer and safer encapsulated fuel technologies such as TRISO fuel for safety. The commercial marketplace has driven both technology and design trends towards highly safe reactors with a significantly reduced footprint and simplified operations and operator training. Extensive operation experience with new gas-cooled advanced reactor designs can eliminate the need for large liquid water cooling sources (lakes, rivers, sea). For Army purposes, reactors using passive cooling are ideal for worldwide transport and operations as they do not require a source of liquid for cooling. Through clever design, these newer reactors employ techniques such as passive cooling to eliminate reactor heat buildup ensuring safety. Such “walkaway” safe designs are proven, have significant operating experience and, with the reduction of complex balance of plant equipment for cooling, improved reliability.

HTGR technology is well-known, but not common, primarily due to regulatory FOAK costs and the commercial nuclear industry’s focus and experience with highly efficient, large, LWR power plants. Smaller MNPP class HTGR devices can be developed and produced, but do not operate as cost-effectively (on a $/kWh basis) as larger, utility-scale power plants, and are not cost-competitive against large-scale grid power generation. For remote site, military and mining purposes however, this reduced operating efficiency and higher kWh cost, are counterbalanced by the unit’s smaller size, mobility, and remote site power economics. Operations in remote locations accept higher generating costs as the price of doing business.

Economics, not technology, has limited industry interest in this market space. Research and analysis of 2-20 MW reactor designs complete enough for a “pre-licensing” regulatory review, have identified four vendors that are developing mature solutions in this market space. All four companies examined for this study, and potentially others, have vSMR design concepts that can be modified or developed into more mobile solutions to support a military-funded development and or procurement effort.

Nuclear fuel options for an MNPP are complex. Existing U.S. government fuel stockpiles do not contain enough fuel supply to support the scale of a DOD MNPP program. New fuel sources must be sought and developed. DOE is working national nuclear fuel issues for the U.S. government with interagency and commercial stakeholders. DOD should be part of this discussion. Any Army or DOD MNPP program may benefit from the success of industry or U.S. government efforts to establish HA-LEU enrichment supporting fuel production. An understanding of enrichment and the nuclear fuel cycle is necessary before examining technical options and approaches to enrichment opportunities and type fuel.

Nuclear fuel manufacturing requires enriched material that is then fabricated into a final fuel product. Enrichment artificially increases the content of a fissionable uranium isotope. A number of bilateral agreements limit enrichment levels to less than 20 percent, this material is classified as LEU. Enrichment to 20 percent and above is called HEU, which theoretically can be used to produce a nuclear weapon. These classifications have differing protection, shipment, and security requirements. For fuel purposes, higher enrichment does two things. First, it reduces the amount of material needed for a given power output as it allows for more compact reactor designs. This is highly desirable for mobility. Second, higher enrichment allows for longer operating periods and reduced refueling cycles. Although naval propulsion reactors use HEU fuel, operational security constraints practically limit an MNPP application to the use of LEU. This choice supports nuclear nonproliferation goals and reduces security costs, simplifying transport and reactor operations. HA-LEU is enriched up to 20 percent (typically no more than 19.75 percent) and enables an MNPP reactor to have a 10-20 year service lifetime without refueling.

The domestic U.S. nuclear industry does not currently produce HA-LEU in large quantities. DOD and DOE both need HA-LEU production capabilities for a number of existing treaty purposes. DOE HA-LEU requirements can be met using either foreign or domestic production as they are not defense-related. DOD may not have this flexibility. DOE has a goal to revive domestic production capabilities to support government stockpiles of nuclear fuel being consumed, but is hampered by lack of market demand in creating and sustaining domestic commercial production capabilities. Without a sufficient demand signal for production quantities of HA-LEU, a sustained long-term domestic nuclear fuel production capability is questionable. While industry production was hampered by a lack of demand, current emerging market conditions can incentivize industry to engage. Long-term demand for fuel from a defense MNPP program is one example of an emergent market need and could help support the economic business case.

For enrichment of uranium, three options exist. First is new enrichment from a commercial source. For non-weapon, electrical-power purposes, this fuel can come from any commercial vendor. URENCO-USA, a foreign-owned firm, enriches uranium in the United States.

A second option is a new domestic commercial enrichment capability that can be developed from currently dormant commercial vendors. Pursuing this option would require additional time to re-open and modify government-owned, commercially operated (GOCO) shuttered facilities, install new centrifuge production lines, and train staff on updated manufacturing processes. This effort would take about five to seven years to begin low-rate initial production of enriched products in small mass-production scale volumes. Production could be ramped up incrementally over a two-to-three-year period to meet MNPP demand levels.

The third option is a DOE plan to develop a domestic U.S. industrial capability for enrichment in support of other DOD and DOE needs. DOD and DOE must comply with U.S. obligations in civil nuclear cooperation agreements and the enriched uranium must be domestically produced[1]. Planning for this option has only just started and no firm information is available. The goal is to meet defense needs in the 2040 time frame. Accelerating this effort would require interagency and U.S. government direction and support.

For all these options, there is a delay in bringing any capability online. Choosing the first option—employing the existing foreign-owned vendor—has a three-to-five-year lead time, necessary to secure NRC approval and upgrade existing facilities to enrich HA-LEU and fabricate TRISO fuel in mass production volumes. This option is estimated to cost roughly $100-200 million.

The second option has initial cost estimates in the range of $240-380 million for facility equipping and setup. The third option, the nascent DOE plan, developing a wholly U.S. origin HA-LEU production capability would likely exceed $200 million and take 10-15 years (GAO 2018). While DOE has no plan to accelerate their planning on enrichment efforts, the possibility of accelerating it could exist if directed by the U. S. government to meet DOD demand for fuel. In all cases, it would be prudent for DOD to employ long-term contracts. This would allow vendors to amortize facility costs over a long-term production contract and potentially reduce the initial manufacturing base setup cost to DOD and the U.S. government.

To support an initial prototyping effort, another near-term DOE option to produce enriched uranium exists. The process, referred to as down blending, would use existing stocks of HEU material (weapons or fuel) reprocessed and blended with recovered uranium or low-grade LEU into HA-LEU. This option has no long-term utility for MNPPs as it is limited by the amount of available HEU in U.S. government stocks. Down blending, as a bridging strategy, can provide HA-LEU for initial testing—and potentially for low rate initial production (LRIP) units—until commercial enrichment and processing sources are fully online. Down blending HEU produces

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[1] Uses include DOD and DOE research, testing, and production of component products supporting nuclear weapons.

about 4 kg of HA-LEU for every 1 kg of HEU used. The cost is approximately 25 percent of the cost of new enrichment (Figure 5.2).

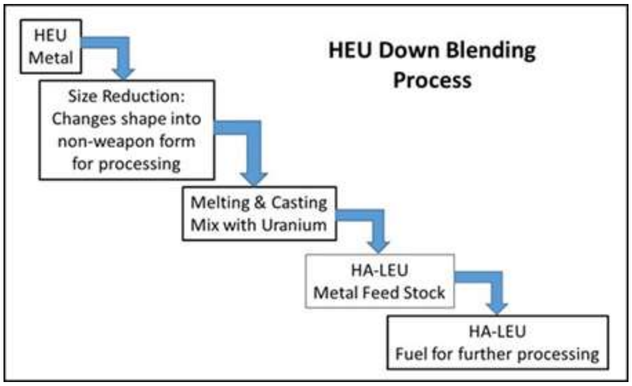

Figure 5.2. Enrichment and Down Blending Process

Another option with long-term potential is future recycling of spent U.S. Navy HEU ship fuel, by down blending it for MNPP needs. This would make use of valuable material that is considered waste today, and enable the reduction of the amount (and cost) of spent U.S. Navy fuel in DOE storage. While it is an option, recycling the U.S. Navy's spent HEU will require additional study and analysis before it can be considered feasible. A similar process was used to convert former Soviet weapons material into commercial fuel for U.S. reactors, but additional effort would be needed to remove pollutants from spent U.S. Navy fuel. This processing is being developed by DOE and would need support to investigate its feasibility and to develop a process to pursue. If successful, this approach would provide fuel and other advantages as it would reduce and recycle the amount of waste HEU stored by the U.S. government. While the recycling option is outside the scope of this study, experts have estimated that the preliminary work for doing so would require a minimum of more than five years of R&D and testing.

Reactor designers may choose from multiple fuel types, but all four commercial reactor designs undergoing pre-licensing review employ TRISO fuel. TRISO is an encapsulated fuel designed to avoid the release of radioactive volatile elements that are the by-products of nuclear fission. If not encapsulated, these elements could be released and contaminate the surrounding area in an accident or during normal operations. Volatile fission product release is a health and safety concern and needs to be evaluated in any design concept. Until detailed studies characterizing the effects and dangers of volatile fission product release and their effects on health and safety in the military environment can be conducted, it is strongly recommended that military systems use an encapsulated fuel. DOE has the lead for developing technologies to support fuel encapsulation for safety and should be tasked to work this issue with the Army at the interagency level. DOD should engage DOE to continue to seek improved technological solutions over time that support DOD's needs.

TRISO is a mature Technology Readiness Level-9 (TRL-9) existing solution for fuel encapsulation. TRISO contains the uranium fuel material inside a triple-coated sphere (known as a TRISO particle), less than 1 mm in diameter. The uranium center core is coated by a layer of carbon, which is then coated by silicon carbide, and that is coated by an outer shell of carbon. The effect of the coatings is to give each tiny fuel particle its own primary containment system. This containment prevents the release of toxic, radioactive contamination into the atmosphere. TRISO fuel particles are then packed and fabricated into larger fuel assemblies for a reactor.

Work on automated and remote control of MNPPs is needed to minimize operator requirements and improve control and regulatory and maintenance reporting of deployed systems. Leveraging existing commercial nuclear industry experience in the development and use of automated supervisory control, monitoring, and reporting systems can reduce operator requirements and workload. The techniques and technologies for this exist, but are not commonly fully integrated. DOE and NRC have experience with the integration of diagnostics/prognostic condition assessment systems for nuclear reactors. Automating supervisory control systems to conduct maintenance scheduling, monitor component health and prognostics while providing equipment condition assessment, increases system resilience and FOB energy resilience. Collaboration in this area should be pursued along with a DOE and DOD focus on cyber hardening. Operating an MNPP in a multi-domain operational environment, particularly if remote monitoring and control is desired, makes cyber hardening a priority. DOE national laboratories have significant and current experience at developing effective approaches for layered cyber defenses to protect automated control systems. DOD should leverage DOE's and other government and industry experience early during prototyping to understand effective approaches and techniques, integrating them as needed. Collaborating and integrating military and commercial expertise in this area are essential.

If an MNPP is pursued, a series of interagency cross functional teams (CFTs) will need to be established on a series of technical subject areas. CFTs are necessary to leverage and synchronize requirements and technical efforts. Multiple agencies have mature tools to support modeling and simulation for prototyping efforts. CFTs should be leveraged and interagency support pursued, particularly for technical areas such as reactor survivability and consequence management. Examples of CFTs include the National Aeronautics and Space Administration's (NASA's) modeling effort and capabilities to examine reactor impacts from destruction during spacecraft launch and flight. Sandia National Laboratories also have capabilities to conduct early modeling of the impact and effects of a ballistic/blast attack on a reactor. Use of this model could provide significant insights into an MNPP's design for survivability and contamination minimization prior to any live fire testing.

Testing is another area where the establishment of CFT would be most profitable. Both DOE and NRC have processes and technology efforts ongoing that can inform MNPP technical and operational testing. Idaho National Laboratory and other DOE laboratories have the necessary technical capabilities and test equipment available to support developmental, technical, and operational testing. Early interagency coordination of test schedule, requirements, and personnel can keep testing, licensing, and regulatory FOAK costs and schedule under control. The use of modeling would position any prototype for early success in live fire testing. Extensive testing for a new reactor design will be needed to validate operating procedures and provide assurances for safe operation. The cost and effort are significant and represent a barrier to adoption for commercial industry, but DOD acquisition can synchronize technical communities and favorably affect schedule and FOAK cost control through a staged approach to development and testing.

The use of full-scale test rigs and subcritical testing for critical power operations can reduce FOAK costs and facilitate schedule and regulatory information needs. Initially, the DOD test community can conduct much of this testing without nuclear fuel. A CFT approach, with prior coordination and regulatory approval, could support the information needs for both testing and the regulatory process, while simultaneously validating safety and technical performance. Detailed test planning with a device's developers, NRC, DOE, and other stakeholders, must be done early to identify, capture, and manage all the essential quality assurance requirements necessary for supporting subsequent system development stages for technical and regulatory purposes. By certifying this early work with the regulator/licensing authorities, development efforts would then have the appropriate rigor and credentials to satisfy later developmental efforts requiring higher-hazard authorizations such as areas operating with nuclear fuel. Developing a staged approach to design approval, modeling, prototyping, and testing reduces program and schedule risk as well satisfying regulator information requirements and safety concerns. Such an approach would reduce the chance of FOAK cost escalation, but also requires significant design maturation and development of production-level drawings to support modeling and test planning. Setup and coordination of technical CFTs for this are possible and should be undertaken as early as possible following a decision to pursue an MNPP.

5.5 Environmental Assessment

- An MNPP operating environment is complex and consists of human, organizational, environmental, and operational components. Safe operation in all of these areas is a key issue.
- As a new addition to operating forces, understanding and communicating nuclear safety is essential for a successful MNPP program.

An MNPP operating environment is complex and consists of human, organizational, environmental, and operational components. Safe operation in all of these areas is critical. Nuclear power, like other hazardous materials generates occupational health and safety concerns as well as consequence management issues. In a military operating environment, it is training that enables soldiers, civilians, contractors and their leadership to operate as safely as possible given explosive and toxicity risks from fuel, ammunition, chemical, and other hazardous materials. Modern reactor designs and fuels can minimize risks, but some hazards will still remain, necessitating adequate training. Standards and training on the hazards of nuclear material must be updated and promulgated on a regular basis, as required. As a new capability to operating forces, understanding and communicating nuclear safety are essential for a successful MNPP program. The Army routinely communicates and manages safety information for other hazards such as explosives (fuel and ammunition), electrical power, or weapons and equipment operation. The Army does not routinely publish information on nuclear power safety to its soldiers, families, and DOD civilian workforce. To publish information will require the Army Safety Center (ASC), the Army Public Health Center (APHC) and ARO to work together in identifying, monitoring, and communicating nuclear health-related issues to commands, soldiers, and their families. Collaboration between these organizations and DOE is necessary to share and communicate information on nuclear safety technical matters with leadership and program office staff and key information to service members and families. Supporting these efforts is the nuclear regulator, the NRC, or ARO. Nuclear industry regulators have not yet licensed an MNPP design for widespread use and have little experience in understanding any unique attributes or operating conditions. As such, a number of first-time safety issues will need to be worked through as new designs are licensed and approved. For an MNPP, examples of these issues include reactor mobility and transport, potential for battle damage, safer reactor and fuel designs and their impact on reducing emergency planning zone (EPZ) size, and potential environmental concerns and regulatory issues[1] related to siting an MNPP. Other traditional issues such as long-term spent fuel disposal are national-level issues that await long-term resolution.

Transport and battle damage are two of the key safety issues for a deployable MNPP. Any MNPP design selected must prevent the reactor from going critical when it should not, such as during movement/transport. Radiation shielding must sufficiently protect personnel involved during movement and transport without becoming a burden. Transport and operational commands will require a full understanding of the design and risks in moving the device properly to facilitate host nation access and operational employment. DOD and commands working defense cooperative agreements (DCAs) and host nation coordination will require expertise to effectively communicate and alleviate safety concerns with host nation officials who frequently have no experience in nuclear matters. Battle damage clean-up techniques and chemical, biological, radiological, nuclear, and explosive (CBRNE) training will be required for MNPP operators, security force personnel, and chemical units. The Defense Threat Reduction Agency (DTRA) consequence management analysis recommended by the DSB report should inform and be a starting point for developing training requirements. While having an approved configuration/design of the MNPP and its fuel is a prerequisite to doing any detailed analysis and training plan development, the early knowledge and insights gleaned from a DTRA study would be useful in refining cost estimates[2] and influencing contracting language to yield an optimal prototype design.

During transport, countries will have concern about safety and security of devices crossing over, going through, or operating within their territories. Working with governments to resolve issues on this is essential. Leveraging the Navy’s Nuclear Reactors Program and NAVSEA 08’s experience in managing nuclear vessel port and canal transits may be an effective approach to address similar issues for land-based MNPPs. The transport of fully fueled reactors is possible under the existing nuclear agreements, but international legal issues will require clarification and further development to address when and how a reactor would become subject to international safety, security, and nuclear liability requirements during movement (IAEA 2013).

Work on this issue could leverage existing NNSA and international nuclear community work on licensing transportation of spent nuclear fuel by air. Since the U.S. nuclear industry and its regulators have not yet dealt with a mobile or transportable design, the Army will experience many unique first-time costs in laying the groundwork for regulatory and international approvals and acceptance. This work will be costly and time-consuming, and require much interagency coordination and support to accomplish. The Russians have overcome similar barriers, having constructed and begun movement of a 70-MWe floating power barge, the Akademik Lomonosov, to the port of Pevek Russia (Geobeats News 2018). This power barge will provide power to Pevek’s Arctic mining and maritime support community. Similarly, issues involving transport of a battle-damaged MNPP back to the United States for disposal must be studied. While design simplification and damage-resistant fuel choices help, detailed planning for cleanup and removal of battle-damaged reactors or reactor components will be expensive and

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[1] Environmental aspects of an MNPP go beyond radiological issues. Identifying a specific regulatory approach or path and identifying applicable requirements is needed. (See 42 USC 4321, 10 CFR 51, 40 CFR 1502, 32 CFR 651 etc.)

[2] Cost estimates here include the prototype device as well as addressing other costs such as battle damage cleanup and transport. Insights should also inform defense cooperative and implementing agreement development efforts and agreements.

pose some technical challenges to resolve. A combined technical and legal effort led by the General Counsels of DOD, DOE, and DOS is essential to examine the issues with returning damaged MNPPs and impacts in doing so on existing treaties, international agreements, and policies.

Improved reactor designs and encapsulated fuel (such as TRISO) are significant safety features that enable a reduction of the EPZ size. The EPZ is an area around a nuclear power plant to avoid or reduce radiation exposure from radioactive materials and facilitate development of pre-planned responses in an emergency. Current guidance creates two zones—the plume exposure pathway and ingestion exposure pathway—to avoid ingesting contaminated food or water. In large utility-scale power plants these zones encompass many square miles of area because of reactor design, and large amount of fuel on-site. MNPPs with newer vSMR designs, coupled with a smaller amount of encapsulated fuel can reduce, or altogether eliminate, the release of radioactive materials, enabling the EPZ to be reduced into a very small area. Reduction of EPZs is particularly important for basing, as most of the time, locations are not optimal, dictated by the enemy situation or host nation politics. Forward locations needing 5-10 MW of power tend to have substantial populations with more than 2,000 soldiers inside a relatively small footprint. Any supporting MNPP will be required to have a very small EPZ to be practical. Additionally, as MILCON is limited at forward or remote areas, an MNPP should not require complex construction for installation. Likewise, any reactor design must not require a complex emergency support response if damaged. MNPP designs should not require highly specialized training and equipment for forward area emergency response staff because these locations typically possess only simple emergency response equipment and limited emergency staff.

Environmental issues involving spent fuel disposal are a concern for system end-of-life-planning. Nuclear fuel is a DOE responsibility and issues such as recycling of nuclear fuel or long-term disposal are not DOD’s business. DOD should obtain and return fuel from DOE for operational purposes, allowing DOE to own and manage the nuclear fuel cycle from end to end. The Army can help DOE by having its development community work closely with DOE on preparing MNPP requirements and contracting documentation. The Army should ensure the design provides for affordable decommissioning and fuel-end-of-life cycle disposal costs.

5.6 Legal, Regulatory, and Licensing Assessment

Regulation and licensing pose unique problems for any new reactor design. Current regulatory schemes are focused on stationary power plants. The introduction of an MNPP, particularly one that would operate OCONUS, is precedent-setting and poses a number of challenges. Solving both will require interagency support. One option is to have ARO undertake the regulatory/licensing mission within Atomic Energy Act (AEA) authorities. A second option is to collaborate with the NRC to build a hybrid regulatory licensing arrangement between NRC and ARO.

Unlike the U.S. Navy whose ships remain under U.S. jurisdiction when outside U.S. territory, reactors on foreign soil are currently regulated by that individual nation.

DOS is working very similar issues with the International Atomic Energy Agency (IAEA) and nuclear community for larger transportable nuclear power plants, which move only once to their installation site, but have some similar deployment and operating scenarios.

Leased or contracted power/power purchase-type agreements (e.g., USACE World Wide Power Contract) exist today, but they do not employ nuclear power.

Deploying a land-based, air-transportable MNPP is a precedent-setting event, affecting a number of legal, regulatory, and licensing areas. Preparatory work at the national and international levels is necessary to address legal, nonproliferation, transportation, and host nation regulatory capability and authority issues. Unlike the U.S. Navy whose ships remain under U.S. jurisdiction when outside U.S. territory, reactors on foreign soil are currently regulated by that individual nation. Transport solutions to cross national boundaries and transit areas like the Suez Canal will require interagency efforts to resolve. Efforts at solving these types of issues should apply to unique military and commercial systems to facilitate eventual contractor-owned and-operated MNPPs that would be available to DOD when needed.

The concept and development of an MNPP challenge the existing regulatory framework governing the transport of nuclear materials. The existing body of work is centered around non-mobile, fixed facility-type nuclear power plants, and movements of fuel or small quantities of nuclear material (test samples, isotopes, etc.) internationally. While the International Atomic Energy Agency (IAEA) recognizes the need for adjusting standards and laws, examining and developing the necessary supporting legal protocols for mobile or transportable reactors has not been emphasized until quite recently. Existing regulatory controls of commercial or military reactors are focused on nation state development and control, which will not likely change.

Current international agreements focus on commercial transactions with a nation state view of ownership and regulatory responsibilities. Under these agreements, movement of an MNPP into another nation’s territory might be viewed as a transfer of authority between countries. Under this view, one state would be required to transfer the device and responsibility for regulating it, to a receiving state. Issues such as liability, safety, emergency notification, and disposal of waste are all potentially affected. OCONUS deployment of an MNPP will necessitate adjusting and shaping treaties, laws, and other agreements. The existing nuclear regime is based on the principle of sovereign responsibility for the peaceful use of nuclear energy. Changes to the regime may be needed, but before making this assumption, an interagency effort is needed to determine if an MNPP can be developed within it. The current view of the DOS is that it can[1].

Significant precursory work is required in a number of areas affecting military use of MNPPs. DOS will need to take the lead in examining most of these. Issues range from cross-border transport, safety and security issues, standards to host, supplier state regulatory responsibilities, reactor design, and contracting options. DOS is working very similar issues with the IAEA and nuclear community for larger transportable nuclear power plants, which move only once to their installation site, but have some similar deployment and operating scenarios. Leveraging existing IAEA work in this area, DOS will need to influence and shape the discussion for not only DOD

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[1] Burkart A. 2018. Comment resolution matrix from Dr. Alex R. Burkart, (Deputy Director Office of Nuclear Energy, Safety and Security, U.S. State Department) to Kerry McCabe (Engineer, Pacific Northwest National Laboratory), June 12, 2018, Ft. Belvoir, Virginia. Copy of email included in project files

and DOE, but also the U.S. domestic nuclear industry, which could sell MNPPs to firms providing remote location power, supporting the administration's goal of reinvigorating the domestic nuclear industry.

Resolving questions about what constitutes a transfer of the device or technology is essential to allow DOD to properly integrate nuclear power into DCAs and Implementation Agreements, as well as enable commercial industry to own and operate MNPPs in support of DOD through a contract vehicle such as power purchase agreement. This is particularly important in the case of a device being moved and operated under DOD control to produce electrical power for U.S. Contingency Bases or U.S. forces. Leased or contracted power/power purchase-type agreements (e.g., USACE World Wide Power Contract) exist today, but they do not employ nuclear power. While a solid case could be made that a DOD-owned reactor operating in support of deployed forces is U.S. government property and does not constitute a transfer to a host nation, the issue has less clarity once commercial contracts (in support of DOD) on foreign soil are involved.

This issue has impacts on international regulatory authorities and actions as well as potential impacts to nonproliferation agreements. Since the ability to contract for MNPP support (instead of owning it) will help DOD reduce its cost of power significantly (without incurring significant nuclear infrastructure costs and manning), an interagency and likely international review of the issue and any associated treaty or agreement amendments, are in order and would provide needed clarification on the issue for both DOD and the U.S. nuclear industry.

Existing, international transport rules and standards promulgated by international surface, air, and maritime bodies will require review and possible updating to identify potential limitations on timely movement of an MNPP internationally[1]. The U.S. Navy relies on international law and standards when operating its nuclear-powered warships, over which the United States retains jurisdiction when abroad; and on specific bilateral agreements to gain foreign port access for its nuclear-powered ships. Bilateral agreements are commonly used for transportation of nuclear material, however establishing these agreements can be difficult and time-consuming. In the Navy Reactor Office's case, convincing foreign nations to allow nuclear ships into ports required specific technical expertise and a superb operating safety record to assuage host nation fears. DOD will need to examine land-based nuclear power and develop agreements for future theater and country access. This will take time and must be done well in advance of any MNPP deployment.

In addition to bilateral agreements for transportation, DOD could pursue modifying/leveraging DCAs or Implementation Agreements to facilitate host nation approval for MNPP support. While the IAEA is examining transport issues for a fully fueled reactor, a deliberate effort is needed to address MNPP transportation and nonproliferation issues. Today, movement of nuclear materials requires bilateral agreements between two states that adhere to IAEA standards. Transport of nuclear items requires notification and approvals by any member state whose territory or airspace the reactor crosses during movement. The current approval process takes a significant amount of time to set up and develop the necessary bilateral agreements to enable transport. The emergence of a licensed and fueled reactor design will necessitate further IAEA discussion on the matter of transportable/mobile reactors.

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[1] Examples of relevant international bodies include the International Maritime Organization, International Civil Aviation Organization, International Air Transport Association, etc.

Domestic enrichment to support fuel production is another legal area of concern. URENCO-USA is the only commercial domestic enrichment facility operating in the United States today. Located in New Mexico, this plant produces LEU for the U.S. commercial nuclear utility market. Depending on future decisions, this facility could produce HA-LEU with relatively low cost through incremental upgrades. URENCO–USA is an arm of the URENCO Group, a nuclear fuel services company owned by the governments of the Netherlands, United Kingdom, and Germany. This company's enrichment technology and product sales are limited by treaty (Treaty of Almelo, Treaty of Washington [Korbmacher et al. 2014]) and it produces fuel for non-weapon, peaceful purposes only. Enriching HA-LEU for electrical production does not appear to be an issue, but formal discussions with URENCO-USA and their owning governments are needed to verify their willingness to support long–term HA-LEU enrichment.

While the treaty agreements make no mention of the use of fuel for military power purposes, both DOS and the NNSA have concerns about using technologies, materials, data/information, or components with possible peaceful use restrictions on them in any system used for military purposes. A domestic source for enrichment and fuel production greatly simplifies things and eliminates the need for clarification on what and how enriched material can or cannot be used.

One final area of legal concern is technology, specifically technology transfer and dual use technologies. The licensing and commercialization by the U.S. nuclear industry of an MNPP would greatly support DOD and should be facilitated at the interagency level. Any future MNPP program office should coordinate its Program Protection Plan closely with other agencies on issues such as dual-use technology and technology transfer. This work would need to be done in conjunction with DOS, DOE, Department of Commerce and its Bureau of Industry and Security, and potentially the NRC to ensure effective export control, treaty compliance, and coordinated regulatory/licensing activities, while promoting sustained industrial base capabilities and utility to worldwide DOD operations.

Regulation and licensing of a reactor design for an MNPP is another key area requiring senior leader attention. The authority for nuclear power regulation is found in the 1954 Atomic Energy Act (AEA) and amendments to it. Under the AEA, DOD has the ability to undertake develop, license, and regulate nuclear power[1]. The Army initially pursued this option in the 1950-1970 time frame, creating the Army nuclear power program. As mentioned earlier, the program operated a number of military test and operational reactors for a variety of purposes. Around 1974, Congress created the NRC as the nation's independent regulatory and licensing organization for civilian usage of radioactive materials in the U.S. government. The NRC licenses and regulates all reactors except DOE research reactors and certain defense reactors[2] licensed under Section 91 of the AEA for "Military Applications."

Under the AEA, the NRC regulates commercial nuclear power plants generating electricity. Pressurized water reactors and boiling water reactors are the only types of reactors in commercial operation in the United States. The NRC oversees 99 licensed nuclear power plants in the United States while formulating policies and regulations governing reactor and materials safety, managing licensees, and adjudicating legal matters to ensure safe operations. The NRC staff

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[1] Section 91b, and 110b, *Atomic Energy Act of 1954, as Amended*

[2] Defense utilization facilities authorized under Section 91.b. are specifically excluded from NRC licensure under Section 110.b. of the AEA of 1954. The Army currently regulates their 91.b. reactors under AR 50-7 and Army Reactor Permits.

numbers approximately 4,000 employees. Its annual budget is about $1 billion. Of this, 10 percent is congressionally appropriated and 90 percent is from collected fees for service (40 percent licensing and inspection and 60 percent generic regulatory expenses) from the nuclear industry. The NRCs organizational size (staffing) and budget are similar to that of the Naval Nuclear Reactors Office ($1.6 billion budget) but include multifunctional staff and R&D programs. The NRC's authority to regulate only applies to non-defense reactors within U.S. borders, possessions, and territories.

The Army created the ARO the early 1990s to serve as the regulator for Army-owned reactors. Since its inception, the ARO has primarily managed Army reactor decommissioning activities, with some regulation of test and medical reactor sites. Specific duties include establishing policies, assigning responsibilities, and prescribing procedures to ensure that Army reactors are designed, constructed, operated, maintained, and decommissioned in a safe, secure, and reliable manner, in compliance with laws, regulations and agreements, and consistent with sound practices. Key objectives include:

- Minimize the probability and severity of a reactor accident or incident.
- Maintain radiation exposures to levels within regulatory limits and as low as is reasonably achievable.
- Ensure adequate physical security of reactor facilities.
- Ensure regulatory compliance with environmental and transportation requirements.
- Ensure reactor facilities undergoing decommissioning meet unrestricted release conditions.

With the reduction of Army nuclear efforts, the Army Nuclear Power Program, and later the ARO, were downsized to two staff members and was nested within the USANCA, an Army G-3 FOA. Should the Army initiate a new MNPP program, ARO staffing and training will need to expand and Army regulatory changes to support worldwide MNPP operations will need to be established.[1] ARO's role and ability to reinvigorate its regulatory capability is necessary because any new MNPP effort will likely require legislative adjustments in authorities.

Regulation and licensing pose unique problems for any new reactor design. Current regulatory schemes are focused on stationary power plants. The introduction of an MNPP, particularly one that would operate OCONUS, is precedent-setting and poses a number of challenges. Solving both will require interagency support. One option is to have ARO undertake the regulatory/licensing mission within AEA authorities. A second option is to collaborate with the NRC to build a hybrid regulatory licensing arrangement between NRC and ARO. A third option would be to wait for the international community to develop and mature MNPP regulatory guidance on its own. As there is no plan for the international community to take up this issue anytime soon, this option will not be explored in this study.

Having ARO undertake the regulatory/licensing mission would allow the Army to manage these issues in-house. Such an effort could complicate commercialization of an MNPP design and would force Army/DOD to create new support infrastructure for training and operating its

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[1] The starting point for a staffing study would be the former (1954-77) Army Nuclear Power Program managed by the Nuclear Power Division of the Office of the Chief of Engineers. Army Regulation 50-7 Nuclear and chemical Weapons and Materiel: Army Reactor Program will likely require updating to clarify responsibilities supporting initiation and expansion of an MNPP program and deployed (OCONUS) operations.

MNPPs. Such a program could resemble a portion of the U.S. Navy Nuclear Propulsion Program. ARO authority would extend worldwide, much like the Navy's. However, unlike the Navy's ships which are under U.S. jurisdiction, the Army would likely require additional legal authorities (e.g., bilateral DCA and Implementation Agreements/Arrangements) to address concerns and meet host nation and international expectations. A drawback of this option is the necessary significant expansion of ARO's manpower staffing, budget, and the need for technical training and certifications.

The aforementioned August 1, 2016 final report from the Defense Science Board (DSF 2016) identified a number of recommendations to help DOD meet the challenge of providing reliable, abundant, and continuous energy. One recommendation was that the Secretary of Defense should designate the Army as the Executive Agent for all of the nuclear energy applications recommended in the report and provide adequate resources to accomplish the mission. A subsequent recommendation was for the Secretary of the Army to direct the appropriate entity within the Army to investigate and invest in vSMR technology maturation and develop a demonstration program for application to forward and remote operating bases and expeditionary forces. With assistance from DOE and NRC, cost-sharing opportunities and/or congressional support could be pursued. Furthermore, should a new reactor technology be licensed for the domestic market, it could give MNPPs commercial "legs," allowing commercial power vendors to own and operate MNPPs in support of DOD prime power contracts. This in turn would beneficially remove Army/DOD from the own/operate business model while reducing infrastructure costs and supporting solutions such as Power Purchase Agreements.

Controlling the cost of regulatory management of a new MNPP design is critical to managing FOAK costs. Recent experience by commercial industry entities with the NRC points to the need to develop a regulatory and licensing business plan that enables the NRC and licensee to coordinate and synchronize periodic review dates, requirements, and expectations. Such an approach is a good business practice that has proven successful in managing NRC licensing costs and cost escalation with minimal impact to program schedules. Developing and coordinating such a plan also allows the development and assignment of a set of core team members to shepherd the design through various reviews over time. Longevity of an NRC or ARO core licensing team membership ensures continuity in conducting reviews, an essential element in keeping cost and schedule disruptions to a minimum. Depending on reactor design, technology, and complexity, this approach and technique could enable significantly reduced NRC licensing times.

5.7 Dependencies and Barriers to Adoption

Nuclear power brings with it a unique set of complexities and interdependencies. While the concept of an MNPP has been around since the 1950s, and development work on MNPPs was done in the 1960s, the development and deployment of an actual MNPP is a precedent-setting event for DOD, the nation, and internationally. An intergovernmental approach is required to address the myriad of first-time issues generated by a mobile reactor capability that can be reliably transported by air, land and sea. Addressing these and shaping things for success is a challenge, but not an insurmountable one. The Army and DOD possess the type of skill sets and experience needed for detailed coordination. This fact, along with a strong capability to lead CFTs with the support of other Departments (e.g., DOE, DOS, and the U.S. Department of Transportation [DOT]), DOD, and interagency stakeholders are capable of addressing and solving anticipated FOAK issues. Establishing CFTs early in the process to work interdepartmental issues such as nonproliferation, safety, transportation, and fuel availability is essential to success. Knowledge generated from these early efforts should inform refinement of operational requirements affecting MNPP design and life cycle costs, as well as potential future follow-on opportunities (e.g., forward area water purification or fuel production).

Should Army senior leadership decide to adopt the MNPP concept, three major barriers must be overcome: current regulatory and licensing regime that focuses on large stationary nuclear power plants, the lack of internationally coordinated regulatory and licensing authority, and nuclear fuel availability. Reduction of these three barriers is a precondition for success, and thus efforts need to begin as early as possible. Interagency teaming with other departments, particularly DOS, DOE, NRC, and DHS is necessary to successfully address these barriers.

5.7.1 Current Regulatory and Licensing Regime Support Focuses on Stationary Nuclear Facilities Only

The existing nuclear regime, and its supporting treaties and other international agreements are fashioned to support large, stationary nuclear facilities, not small, mobile, MNPPs. The rules have not kept pace with progress. New technology and designs can support an air-transportable MNPP. Smaller, less capital-intensive power plants can be owned and operated worldwide, supporting commercial or DOD needs via contract (i.e., not government-owned operating under a power purchase agreement in support of DOD). These business transactions may or may not constitute a transfer of ownership and will complicate regime definitions, licensing, and regulatory actions until these issues are sorted out. New rules for transporting a fully fueled MNPP reactor to and from its factory and country of origin by land, sea, and air are needed. Integration and synchronization with 123 Agreements[1] and existing or future DCA and Implementation Agreements by the legal community are essential. Finally, additional international clarification and agreements on liability issues during transport, operation, and for potential battle damage should be examined. Resolving these will require DOS (lead agency) support and significant coordination.

5.7.2 Challenge and Opportunity in the Lack of Internationally Coordinated Regulatory and Licensing Authority

The lack of internationally coordinated regulatory and licensing authority complicates transport, operational planning, and execution. Some of this may be mitigated through DCAs and Implementation Agreements, or other bilateral agreements. The U.S. government has an opportunity for shaping nascent IAEA efforts at harmonizing international regulatory requirements to reduce or eliminate the need for multiple bilateral agreements. Success in this area would enable rapid deployment of MNPPs into a theater of operations in a crisis situation and open markets for U.S. power-producing firms operating internationally. The ability to leverage the NRC expertise gained through involvement and licensing an MNPP design may assist in reducing regulatory barriers with the IAEA and host nation regulatory agencies, particularly those less experienced in nuclear regulation. Leveraging NRC competencies and

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[1] Named after Section 123 of the United States Atomic Energy Act of 1954, as amended, these civil-nuclear cooperation agreements are generally required by U.S. law for significant exports of nuclear material and equipment.

processes (where appropriate) is a good business practice, but alternative DOD unique processes and timelines will need to be developed. Establishing a CFT to explore this issue and develop a memorandum of agreement between the NRC and Army/DOD is highly recommended. It could examine NRC capabilities, policies, processes, and regulations as well as ARO regulatory policies and authorities in detail. If a joint ARO/NRC regulatory/licensing solution is possible, authorities and other enabling actions and tasks could be pursued via legislative means and through interagency coordination. If regulatory and licensing hurdles cannot be overcome, Army/DOD could take action to license an MNPP design under existing AEA authorities. CFT work with the NRC should also inform Army decisions on ARO staffing and policy improvement options that are necessary to regulate a military-unique reactor design for its life cycle. In both cases, these efforts will inform and drive identification of “in-house” nuclear infrastructure requirements (e.g., training base/generating force) necessary for supporting the nuclear power regulatory and licensing mission.

5.7.3 Nuclear Fuel Availability

Nuclear fuel availability and cost control are critical to any MNPP effort. Significant preliminary work is needed in conjunction with DOE and commercial fuel manufacturers to determine if adequate amounts of HA-LEU fuel (TRISO or other) can be manufactured on schedule to meet DOD demand. Reconstituting a U.S. domestic nuclear fuel manufacturing capability will be costly and take time, but options to accelerate the schedule exist. It is critical that enrichment and fuel manufacturing both have appropriate volume demand to ensure a viable, long-term manufacturing capability.

6.0 Conclusions

Employment of a MNPP with vSMR technology addresses broader operational and strategic implications of energy delivery and management, a problem anticipated to increase significantly over the next several decades. Employment of mobile nuclear power is consistent with the new geopolitical landscape and priorities outlined in the U.S. National Security Strategy (NSS) and the 2018 National Defense Strategy focusing on China and Russia as the principal priorities for the DOD. MNPP can meet the anticipated power demands in both highly developed mature theaters, such as Europe, and immature theaters and lesser developed areas globally to meet future force demands including large-scale combat operations (LSCO) against near-peer adversaries.

MNPP is a classic example of disruptive innovation[1] and can provide a deployable, reliable, and sustainable option for reducing petroleum demand and focusing fuel forward to support Combatant Commander (CCDR) priorities and maneuver in multi-domain operations. Energy for power is a cross-cutting enabler and this study finds the MNPP can provide a continuous high-density power source, without the need for fuel resupply or other external power source(s), to meet future force demands. Multiple studies identify that air and ground delivery of liquid fuel comes at a significant cost in terms of lives and dollars (DSB 2016; AEPI 2009; Daehner et al. 2015). Approximately 18,700 casualties (or 52 percent) of the approximately 36,000 total U.S. casualties occurred from hostile attacks during land transport missions (Operation Iraqi Freedom and Operation Enduring Freedom [Daehner et al. 2015]). This observation lends substantial weight to DOD initiatives that evaluate and deploy alternatives to petroleum-based fuel systems (DSB 2016).

Mobile nuclear power is a viable option where:

- Fuel logistics and storage of Class III curtails Combatant Commander's (CCDR) options, increases complexity, and imposes substantial economic challenges.
- Infrastructure requires large-scale power (e.g., ports, airfields, rail, other transport supporting transport infrastructure, industry etc.).
- Mission Assurance is required or where "islanding," providing continuous power to a location even though energy from an electrical grid or external power source is no longer present, is desirable.
- Energy-intensive systems (e.g., forward radar site operations) require significant power.
- Power is desired to support Defense Support to Civil Authorities (DSCA).
- Remote bases where access to an established or stable electrical grid is unavailable or where the electrical grid requires reinforcement or reconstitution to support intermediate staging bases, logistics staging areas, and/or medium to large base camps.

This study concludes the timing for development of a MNPP is optimum. Energy dominance is a prominent highlight at the national level and priorities include revival and expansion of the nuclear energy sector, reducing barriers, and accelerating American energy innovation

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[1] In business, a disruptive innovation is an innovation that creates a new market and value network and eventually disrupts an existing market and value network, displacing established market-leading firms, products, and alliances.

(Executive Office of the President of the United States 2018, p. 7). At the cusp of this shift is the restoration of U.S. nuclear R&D capabilities to enable innovation in both the development and deployment of new reactors (Executive Office of the President of the United States 2018, p. 7). This change not only reduces dependence on foreign sources of energy but also portends a transformation in the American zeitgeist capable of ushering in a renaissance within the nuclear industry. The expansion of the U.S. nuclear energy sector has the potential to create a significant number of highly skilled jobs and can strengthen economic adjacencies within the utility, manufacturing, and mining industries—all key areas underpinning the defense industrial base. Unfortunately, energy dominance is not solely a U.S. objective, China and Russia's expansion of their nuclear reactor market influence globally is and will continue to challenge the United States. The United States is rethinking the policies of the past two decades, policies based on the assumption that engagement with rivals and their inclusion in international institutions and global commerce would turn them into benign actors and trustworthy partners. These policies have, for the most part, turned out to be false as reflected in the current NSS (2017) and 2018 National Defense Strategy (DOD 2018).

The introduction of an MNPP is precedent-setting but disruptive innovation is not without unique regulatory and licensing challenges within the current governance structure. The concept and development of an MNPP relies upon interagency support to navigate the existing regulatory framework applicable to new reactor design and the transport of nuclear materials. The existing regulatory body of work is centered on:

- Fixed facility-type nuclear power plants that are non-mobile and employ traditional (legacy) technology, and
- The movement of fuel or small quantities of nuclear material (e.g., test samples, isotopes, etc.) internationally.

These challenges are not insurmountable, given the national-level desire to expand the nuclear energy sector and reduce barriers to develop and deploy new reactors (Executive Office of the President of the United States 2018, p. 7). The Army and DOD possess the skill sets and experience necessary for detailed coordination across a broad array of stakeholders including the DOE, DOS, and DOT to resolve interdepartmental issues such as nonproliferation, safety, transportation, and fuel availability. A DOD-led interagency team approach offers the best chance of success for resolution of non-technical matters. The Army should develop MNPP requirements to enable the U.S. nuclear industry to design devices that meet the demanding future environment faced by the joint warfighter. Support for nuclear power exists, and U.S. political will to advance national nuclear industrial capabilities is strong. Shared funding opportunities with DOE are possible and should be explored to minimize impacts on Army modernization. Prototyping opportunities exist and can facilitate design, regulatory, and procurement activities in the near term. An MNPP capability supports current and projected power demands while reducing liquid fuel logistics burden. The MNPP concept is based on new, advanced, and safe technology currently available from the commercial and government sectors that should be further refined within the DOD and at the interagency level. Therefore, this study recommends the DCS G-4:

- Present the MNPP concept through the Commander, Army Futures Command (AFC) and the Vice Chief of Staff, Army (VCSA) to the Chief of Staff, Army for further consideration.

- Express Army support for a DOD prototyping effort by the Strategic Capabilities Office (SCO).
- Identify MNPP for future Joint Requirements Oversight Council (JROC)/Army Requirements Oversight Council (AROC) consideration.
- Continue to refine MNPP analysis using SCO prototyping efforts to:
  - Support joint operations
  - Leverage DOE laboratory support
  - Evaluate the scope and resource impacts to the Army.
- Advocate for MNPP acquisition through NDAA Section 804, Middle Tier Acquisition for Rapid Prototyping and Rapid Fielding or entry into the Joint Capabilities Integration and Development System (JCIDS) process and designation as an acquisition program of record.

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- H.R.590 - Advanced Nuclear Technology Development Act of 2017
- H.R.431 - Nuclear Energy Innovation Capabilities Act of 2017
- H.R.433 - Sensible Nuclear Waste Disposition Act
- H.R.1320 - Nuclear Utilization of Keynote Energy Act
- H.R.5260 - Advanced Nuclear Energy Technologies Act

- H.R.4378 - Nuclear Energy Research Infrastructure Act of 2018
- H.R.6140 - Advanced Nuclear Fuel Availability Act
- H.R.4891 - Dry Cask Storage Act of 2018
- H.R.589 - Department of Energy Research and Innovation Act
- H.R.5515 - John S. McCain National Defense Authorization Act for Fiscal Year 2019
- H.R.5895 - Energy and Water, Legislative Branch, and Military Construction and Veterans Affairs Appropriations Act, 2019
- H.Res.260 - Expressing the sense of the House of Representatives in support of the International Atomic Energy Agency's (IAEA) nuclear security role

Senate Legislation:

- S.512 - Nuclear Energy Innovation and Modernization Act
- S.97 - Nuclear Energy Innovation Capabilities Act of 2017
- S.3422 - Nuclear Energy Leadership Act
- S.2503 - Department of Energy Research and Innovation Act
- S.79 - Securing Energy Infrastructure Act
- S.1457 - Advanced Nuclear Energy Technologies Act
- S.1265 - Dry Cask Storage Act of 2018
- S.Amdt.3403 to H.R.589 - Department of Energy Research and Innovation Act

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Appendix A

List of Subject Matter Experts Interviewed

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Appendix A

List of Subject Matter Experts Interviewed

The authors consulted, interviewed, or corresponded with the following subject matter experts in the writing of this report.

U.S. Department of State

- Mr. Andrew Cartas
- Mr. Alex Burkart

U.S. Department of Energy

- Mr. Michael Worley, Associate Deputy Assistant Secretary, Nuclear Technology Demonstration and Deployment
- Mr. John Herczeg, Office of Nuclear Technology, Research and Development
- Mr. Ray Furstenau, Associate Principle Deputy Assistant Secretary, Office of Nuclear Energy
- Ms. Audrey Beldio, NA-192, Office of Domestic Uranium Enrichment
- Mr. Craig Welling
- Ms. Katy Strangis NA-24
- Ms. Joanna Sellen NA-24
- Mr. Kemal Pasamehmetoglu, Idaho National Laboratory
- Mr. Patrick McClure, Los Alamos National Laboratory

Department of Defense

- Mr. Andrew Plieninger, Office of the Under Secretary of Defense for Policy
- Mr. Robert Kolterman, Office of Nuclear Matters
- Mr. Grover Ford, Office of Nuclear Matters
- Mr. Dale Shirasago, Office of Nuclear Matters
- Ms. Gabby Perushek, Office of Nuclear Matters
- Mr. David Jones, Office of Nuclear Matters

U.S. Army

- Mr. Phil Shubert, G-3/5/7 Army Reactor Office
- Dr. Martin Moakler, G-3/5/7 Army Reactor Office
- Mr. Zachary Papa, World Wide Power Program, Philadelphia District, U.S. Army Corps of Engineers (USACE)

- Mr. Brian Hearty, Military Programs Environmental Division, USACE
- Mr. Frank Sage, ATEC
- COL Adrian Marsh, Project Manager Expeditionary Energy and Sustainment Systems (PM E2S2)
- Mr. Cory Goetz, PM E2S2
- Ms. Lisa Stone, PM E2S2

U.S. Navy

- Mr. Stephen Trautman, Deputy Director, Naval Reactors Program
- Mr. Matthew Napoli, Executive Director of Foreign & Public Affairs Naval Reactors

U.S. Nuclear Regulatory Commission

- Mr. John Segala
- Mr. Steven Lynch
- Mr. William Reckley

Industry

- Ms. Melissa Mann, URENCO-USA
- Mr. Paolo Venneri, Ultra Safe Nuclear Corporation (USNC)
- Mr. Dan Poneman, Centrus Energy Corp
- Mr. Larry Cutlip, Centrus Energy Corp
- Mr. Ron Faibish, General Atomics
- Mr. Robert Schleicher, General Atomics
- Mr. Scott Nagley, BWX Technologies
- Mr. Jacob DeWitte, OKLO
- Ms. Caroline Cochran, OKLO
- Dr. Claudio Filippone, Holos Generators

Others

- Mr. Larry Bramlette, COL USA (RET)

Appendix B

Nuclear Nonproliferation Regime

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Appendix B

Nuclear Nonproliferation Regime

The nuclear nonproliferation regime is a broad international framework of agreements and organizations aimed at preventing the spread of nuclear weapons and contributing to arms control and disarmament progress. The nuclear regime consists of a series of treaties, and other international agreements and organizations whose implementation of guidelines for nuclear material, technology, and equipment (dual-use) export and operations control availability and employment of nuclear facilities. The regime is geared toward preventing nuclear weapons proliferation while also supporting peaceful nuclear energy trade and use.

The Nuclear Non-Proliferation Treaty (NPT) is the core component of the global nonproliferation regime. It establishes a comprehensive, legally binding[1] prohibition on the spread of nuclear weapons and their technology, and also promotes the sharing of civilian nuclear technology and energy development for non-nuclear weapons states (NNWS). It establishes a requirement that nuclear material in such peaceful activity in NNWS be subject to safeguards administered by the International Atomic Energy Agency (IAEA). The IAEA monitors compliance with safeguard requirements, while assisting with development of civilian technology to expand nuclear energy.

Supporting the nuclear nonproliferation regime are U.S. bilateral civil nuclear cooperation agreements. Known as “123 Agreements” after Section 123 of the Atomic Energy Act of 1954, as amended, they provide a legal framework for U.S. exports of complete nuclear reactors, major components of nuclear reactors, associated equipment, nuclear material, and civil nuclear cooperation with other nations. These agreements both inform and affect any potential U.S. Department of Defense (DOD) mobile nuclear power plant (MNPP) program in a number of potential areas, including fuel, transportation, and potentially when providing power under Logistics Civil Augmentation Program (LOGCAP) or a DOD Power Purchase Agreement, that may be viewed as a potential transfer of an MNPP to NNWS. DOD must work closely with the U.S. Department of State (DOS) to address issues with potential NPT and 123 Agreement impacts.

DOD should undertake an examination of operator and owner liability in the event of a nuclear incident with the DOS and the U.S. Department of Energy (DOE) as early as possible to inform the MNPP requirements development effort. This preliminary work would apprise and enable the requirements process to design out many avoidable risks and hazards. The use of informed and appropriate design criteria and technologies such as factory-installed and encapsulated fuels that can prevent the emission of ionized radiation from nuclear fuel, should be leveraged to minimize potential human and environmental damage from a reactor. While DOD’s use of such a risk-informed approach is nothing new, it supports the reduction of potential liability claims and generates useful information for assuaging host nation concerns with MNPP operations.

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[1] Framework consists of a number of treaties and agreements supported by the United States Department of State. See U.S. Department of State, “Treaties and Agreements,” accessed July 20, 2018 at https://www.state.gov/t/isn/trty/index.htm

Development and deployment of an MNPP is a precedent-setting event. Existing NPT and 123 Agreements focus on controlling nuclear materials, technology, operations, processes, and regulation of a single-site purpose-built non-mobile fixed facility. Agreements on these generally fixed facilities are viewed from a national sovereign perspective with fuel (refueling) being the only component for transport after going operational. The introduction of a very small, factory-fueled, mobile, nuclear power plant that can easily be transported across national boundaries will necessitate updates to not only the nuclear regime, but for other related areas such as international transportation and customs (e.g., dual-use technology proliferation). DOS and DOE will need to engage the IAEA and others to modernize treaty and regulatory language and standards. Work on an international licensing approval process is being pursued by the Multinational Design Evaluation Program (MDEP). Leveraging this work is crucial in developing and adjusting agreements focusing on enabling commercial nuclear industry to support deployed U.S. forces.

Ideally a commercial vendor would own and operate an MNPP device for Army/DOD under a long-term power purchase agreement. Such a device could operate at a single site and potentially be relocated to other countries/locations within a combatant command (COCOM) theater/region. Some of these countries may or may not be parties to the NPT. Host nation countries may or may not have a qualified or functioning regulatory body required by current regime rules.

Other issues needing discussion and resolution involve the transfer of an MNPP. More specifically, does the movement of a DOD or commercially owned MNPP for Army use (and its return to the United States when the mission is complete) constitute an MNPP and nuclear material transfer to the host nation? Or, can the existing nuclear regime rules be adjusted to account for transient mobile reactors during their lifetimes, as long as they return to their country of origin for decommissioning and waste disposal?

If DOD were to embrace the MNPP concept and receive national and regime approval, the IAEA's position on the differentiation between reactor types will need to be shaped to enable commercial support to DOD missions. Existing nuclear regime regulations adequately cover fixed facilities, however regulations and guidance for MNPPs, which can be moved to multiple locations over an operating lifetime, are not developed. While the IAEA position on transportable nuclear power plants (TNPPs) and MNPPs appears to encourage future creativity and opportunity, a significant shaping effort will be required to support both DOD and the U.S. nuclear industry needs as well as those for future U.S. civil-military engagement.

It can be expected that solving the above issues will take some time. Making the needed adjustments to the nuclear regime rules in coordination with the IAEA could take five to seven years. Some of the key issues requiring immediate attention, should the DOD MNPP concept flourish, are international transport of a fueled reactor and the safety, liability, and nonproliferation challenges associated with it. As an interim fix, the DOS and DOD could pursue work on bilateral agreements with key allies and host nations. Such an effort focused on specific nations targeted for an initial MNPP capability rollout using bilateral agreements, may be possible within five years, following successful testing, certification, and licensing of an MNPP. Such an effort could accelerate capability deployment into operating environments.

Appendix C

Economics of the Holos Mobile Nuclear Power Plant Compared with Current Forward Operating Base and Remote Site Electricity Provision

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Appendix C

Economics of the Holos Mobile Nuclear Power Plant Compared with Current Forward Operating Base and Remote Site Electricity Provision

C.1 Introduction

Variable costs of generation based on a general distillate generator were compared with the costs of electricity for the Holos nuclear power generator. Current distillate prices were used to develop the variable costs for diesel generator sets. Lazard's 11th edition (2017) was used to estimate the fixed and variable operation and maintenance (O&M) costs for the diesel generators. Lastly, the nth-of-a-kind (NOAK) Holos costs (13 MWe) were compared with 12 Army, Navy, and Air Force sites' variable generation costs per kilowatt hour to determine which sites might be targets for Holos acquisition. Two of the 12 sites are served by utility companies, while the remaining sites' electricity is provided by diesel generation[1]. The latest utility prices were obtained for the two sites that obtain electricity off-site.

Risk analysis of the prices for both the sites' diesel and electricity prices and the Holos system costs were undertaken. Currently, the prices of fuel are low, compared with recent history. Whether distillate prices will remain low is in question. Determining a cost for tristructural isotropic (TRISO) fuel is complicated by the fact that it is currently out of production, domestically. Cost estimation risk for the Holos system is somewhat better. The design uses component parts tested at the laboratory level and above. Proven off-the-shelf components, coupled with Holos' development and use of a working sub-scale model[2] of its system, provide confidence in prototype design pricing, helping significantly in reducing some of the uncertainty on the price of the first-of-a-kind (FOAK) system.

C.2 Background

The Holos micro-nuclear power generator can fit in 20- and 40-foot International Organization for Standardization (ISO) containers; has a scalable capacity from 3,000 kW (20-foot ISO container) to 13,000 kW (40-foot ISO container); and can operate for 10 to 20 years (HolosGen™ 2018). The system varies in maturity level. The power conversion systems are commercial off-the-shelf (COTS) or derived from Holos Waste Heat Recovery Systems, which were developed and tested for applications on large diesel electric locomotives. According to Dr. Claudio Filippone, President and CEO of HolosGen LLC, the scalable turbo generators are at technology readiness level 8 (TRL-8). Pressure vessels are COTS. The graphite core is formed by fuel blocks developed to ease manufacturing with a miniature series of graphite fuel blocks manufactured to tolerance via computer numerical control (CNC) machines and tested to validate

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[1] Note – Guam has two separate sub-activities counted as a single site.

[2] This test assembly demonstrates a complete Holos system: closed-loop, direct-drive turbo-compressor and turbo-generator, hexagonal graphite fuel matrix with cooling sleeves and nuclear TRISO fuel compacts (simulated by electrical heaters), and Brayton heat rejection heat exchanger.

costing and thermal performance. As the fuel blocks cannot currently be loaded with TRISO fuel, they are considered TRL-6. The electrical and electronic controllers are COTs and have been tested at power. Full-scale testing without TRISO fuel is accomplished with a 6-MWt test rig developed to simulate operations and full–scale testing of a Holos subcritical module rated at 5.5 MWt.[1]

The fuel issue may be the availability of U.S.-sourced enriched uranium for military applications. Interpretations of "peaceful use" in the Washington Treaty may be required from U.S. Department of State (DOS) and U.S. Department of Energy (DOE) to determine whether the URENCO plant in New Mexico could enrich the fuel. In addition, based on background information, all MNPP designs examined require 10 percent to more than 20 percent enriched fuel. Currently the URENCO plant is only licensed to produce up to 4.95 percent enriched product. The authors understand that within three years the URENCO plant could be reconfigured and licensed to increase enrichment up to the low enriched uranium (LEU) limit of 20 percent[2]. Down blending of highly enriched uranium (HEU) might be a possibility, but needs to be investigated due to existing agreements with other entities.

C.3 Summary

The costs of traditional diesel generation were compared with the NOAK Holos nuclear generation system at various capacities and sizes of the Holos system (see Table C.1) using a levelized-cost-of-energy approach. The 13-MWe Holos system compares favorably at the estimated distillate costs at every level, depending on the fuel cost and capacity factor of the Holos system.

The Holos costs approximately 21 cents per kWh at a 25 percent capacity and ranges down to a cost of 7 cents per kWh at 97 percent capacity. At a more likely capacity factor of 75 percent capacity, the cost is just 8 cents per kWh, significantly better than the cost of distillate generation at 18.2 cents per kWh. The variable costs of the distillate generation, with JP-8 at $2.25 per gallon, range from 23 cents per kWh at 25 percent capacity to 19 cents per kWh at 100 percent of capacity. Costs were also estimated for JP-8 at $3.50 and $7.00 per gallon. The costs at $3.50 ranged from 35 cents per kWh at 25 percent capacity to 28 cents per kWh at 100 percent capacity. At $7.00 per gallon these costs ranged from 67 cents per kWh down to 55 cents per kWh at 100 percent. The distillate costs could be 3 to 5 cents per kWh higher than shown in Table C.1 as three bases with known O&M costs were 5 to 6 cents per kWh for operations and maintenance costs. Thus Holos could be cost-effective, compared with distillate generation. However, there is risk that Holos costs may be higher than forecasted.

The primary issue for this analysis is that no established U.S. nuclear vendor or recently formed start-up nuclear companies have built full-scale prototypes. However, for the Holos design, various components are off-the-shelf and the power generation system has been successfully tested, demonstrating the feasibility of a closed-loop Brayton cycle configuration. Three items

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[1] Weimar M. 2018. Email message to Mark Weimar (Economist, Pacific Northwest National Laboratory) from Claudio Filippone (President and CEO, HolosGen LLC). "Economic Questions for Holos System," March 28, 2018. Copy of email included in project files.

[2] McCabe K. 2018. Telephone discussion between Melissa Mann (President, URENCO USA Inc.) and Kerry McCabe (Engineer, Pacific Northwest National Laboratory), March 27, 2018, Ft. Belvoir, Virginia. Copy of conversation notes included in project files.

Table C.1. Electricity Costs of Traditional Distillate Generation Compared with Holos

Distillate System Costs				Holos System Costs				
	Fuel Case	**Fuel Case**	**Fuel Case**					
Fuel Cost $/gal	$2.25	$3.50	$7.00					
Rated Capacity (kW)	2,250	2,250	2,250					
Rental Cost	$30,000	$30,000	$30,000					
O&M Cost $/kW	$10	$10	$10		**NOAK**	**NOAK**	**FOAK**	**NOAK**
Total O&M	$22,500	$22,500	$22,500		**3.3 MWe**	**6.6 MWe**	**13 MWe**	
	25 percent Capacity Factor				**25 percent Capacity Factor**			
Rental Cost $/kWh	0.006	0.006	0.006	**Capital Costs**	0.555	0.296	0.305	0.178
O&M Cost $/kWh	0.015	0.015	0.015	**O&M Costs**	0.037	0.037	0.046	0.033
Fuel Cost $/kWh	0.209	0.326	0.651					
Total Cost/$kWh	**0.23**	**0.346**	**0.672**	**Total Costs**	**0.592**	**0.333**	**0.35**	**0.21**
	50 percent Capacity Factor				**50 percent Capacity Factor**			
Rental Cost $/kWh	0.003	0.003	0.003	**Capital Costs**	0.296	0.186	0.162	0.095
O&M Cost $/kWh	0.012	0.012	0.012	**O&M Costs**	0.019	0.019	0.023	0.016
Fuel Cost $/kWh	0.177	0.275	0.549					
Total Cost $/kWh	**0.192**	**0.29**	**0.564**	**Total Costs**	**0.315**	**0.205**	**0.185**	**0.111**
	75 percent Capacity Factor				**75 percent Capacity Factor**			
Rental Cost $/kWh	0.002	0.002	0.002	**Capital Costs**	0.22	0.155	0.121	0.071
O&M Cost $/kWh	0.012	0.012	0.012	**O&M Costs**	0.012	0.012	0.015	0.011
Fuel Cost $/kWh	0.169	0.263	0.525					
Total Cost $/kWh	**0.182**	**0.276**	**0.539**	**Total Costs**	**0.233**	**0.167**	**0.136**	**0.081**
	100 percent Capacity Factor				**100 percent Capacity Factor**			
Rental Cost/kWh	0.002	0.002	0.002	**Capital Costs**	0.192	0.145	0.105	0.061
O&M Cost/kWh	0.011	0.011	0.011	**O&M Costs**	0.01	0.01	0.012	0.008
Fuel Cost $/kWh	0.174	0.27	0.54					
Total Cost $/kWh	**0.186**	**0.283**	**0.553**	**Total Costs**	**0.202**	**0.154**	**0.117**	**0.07**

may drive costs upward: the core matrix, U.S. Nuclear Regulatory Commission (NRC) licensing, and the cost of the TRISO fuel. The fuel core cannot be tested because of a lack of U.S. TRISO fuel producers, and costs may change once fuel is acquired. The cost of licensing is also unknown as this is a FOAK for licensing. In addition, the acquisition of commercial fuel may be a problem. Interpretations of “peaceful use” in the Washington Treaty may be required from the DOS and DOE to determine whether the URENCO plant in New Mexico could enrich high-assay low enriched uranium (HA-LEU) fuel for a military MNPP. Currently the URENCO plant is only licensed to produce up to 5 percent enriched product. Down blending of HEU might be a possibility, but needs to be investigated due to existing agreements with other entities.

A FOAK cost estimate for the Holos 13-MWe system was evaluated to determine the comparability of the first Holos generator with diesel generation. The Holos 13-MWe generating system at 75 percent capacity is less than the cost of distillate generation at 14 cents per kWh with 18 cents per kWh for JP-8 generation at $2.25 per gallon. Higher fuels costs at $3.50 per gallon and $7.00 per gallon raise the cost of distillate generation to 28 cents per kWh and 54 cents per kWh, respectively—much more than even the FOAK Holos system.

Given the size of distillate generators used on military installations, a cost estimate was developed for smaller versions of the Holos at 3.3 MWe and 6.6 MWe. The costs of these smaller systems at 75 percent capacity are 17 cents per kWh and 23 cents per kWh for the 6.6-MWe and 3.3-MWe systems, respectively (Table C.1). In comparing these costs with the costs of the Holos 13-MWe system, it is clear that the larger Holos NOAK system is cost-competitive at every level with both the distillate systems and the smaller Holos systems. The costs in this analysis assume the Holos system is purchased rather than leased.

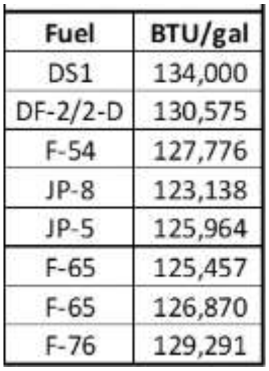
C.4 Distillate Generation

Generalized diesel costs were developed based on fuel consumption tables (Diesel Service & Supply 2018) for a 2,250 kW diesel generator set (Table C.2). The costs per kWh were adjusted to reflect the higher diesel BTU content for other distillate fuels based on Bowden et al. (1988) and Tosh et al. (1992). The BTU per gallon is shown in Table C.3.

Table C.2. Diesel Generator Fuel Consumption by Load

Generator Size (kW)	1/4 Load (gal/hr)	1/2 Load (gal/hr)	3/4 Load (gal/hr)	Full Load (gal/hr)
2250	48.1	81.1	116.4	159.6

Table C.3. BTU Content of Distillate Fuels



Fuel	BTU/gal
DS1	134,000
DF-2/2-D	130,575
F-54	127,776
JP-8	123,138
JP-5	125,964
F-65	125,457
F-65	126,870
F-76	129,291

For the generalized comparison, a $2.25 per gallon price was used along with $3.50 and $7.00 per gallon price. For the 12 sites evaluated, the costs were based on the Defense Logistics Agency (DLA) prices provided for each site. The highest BTU content distillate was used from each site when more than one distillate was provided.

For the generalized case, diesel O&M costs were based on Lazard's (2017) costs. Lazard's indicated diesel generators fixed O&M costs at $10 per kW and $0.01 per kWh. In addition, a $30,000 per generator cost was added to reflect that generators are usually leased rather than bought. Based on information from two sites, O&M costs can be from $0.05 to $0.06 per kWh due to the amount of redundancy that each site has. The generalized costs case is identified in Table C.4[1]. Costs were developed at 25 percent, 50 percent, 75 percent, and 100 percent of

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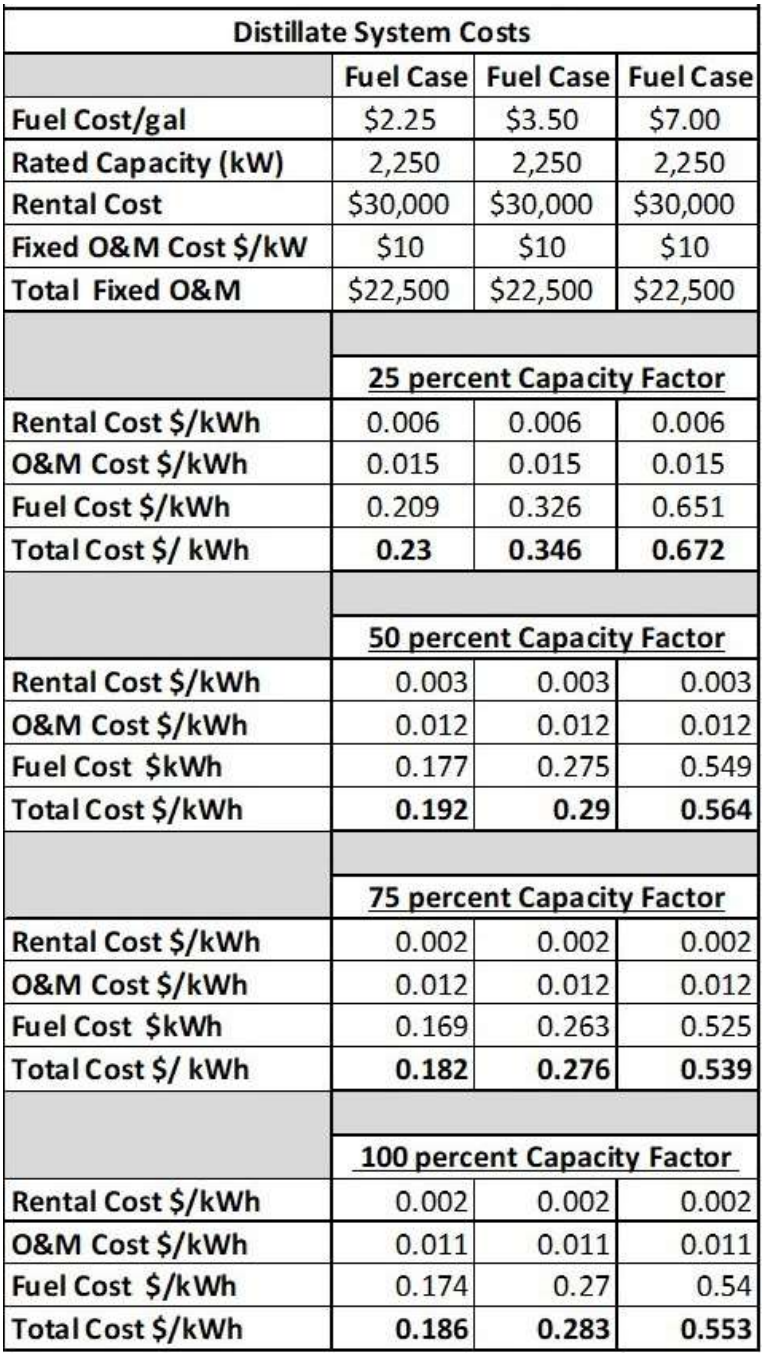
[1] MNPP study team used the DLA fuel cost of $2.15 per gallon for the economic assessment. This cost was an average for the FY 2016-2017 time frame. Current pricing is at $2.76 gallon (August 2018) and furthers the case for nuclear power.

capacity although diesel units would rarely, if ever, run at 100 percent of capacity. The authors assumed they would run at 75 percent of capacity for comparison purposes. Costs at 75 percent capacity for each of the prices were 18 cents per kWh, 28 cents per kWh, and 53 cents per kWh. For each price per gallon the range of costs for each capacity was fairly tight. At $2.25 gallons, the range was from 19 cents per kWh to 23 cents per kWh. At $3.50 per gallon the range was from 28 cents per kWh to 35 cents per kWh, and $7.00 per gallon.

Table C.4. General Distillate Generator Costs Using JP-8 Fuel



Distillate System Costs			
	Fuel Case	Fuel Case	Fuel Case
Fuel Cost/gal	$2.25	$3.50	$7.00
Rated Capacity (kW)	2,250	2,250	2,250
Rental Cost	$30,000	$30,000	$30,000
Fixed O&M Cost $/kW	$10	$10	$10
Total Fixed O&M	$22,500	$22,500	$22,500
	25 percent Capacity Factor		
Rental Cost $/kWh	0.006	0.006	0.006
O&M Cost $/kWh	0.015	0.015	0.015
Fuel Cost $/kWh	0.209	0.326	0.651
Total Cost $/ kWh	**0.23**	**0.346**	**0.672**
	50 percent Capacity Factor		
Rental Cost $/kWh	0.003	0.003	0.003
O&M Cost $/kWh	0.012	0.012	0.012
Fuel Cost $kWh	0.177	0.275	0.549
Total Cost $/kWh	**0.192**	**0.29**	**0.564**
	75 percent Capacity Factor		
Rental Cost $/kWh	0.002	0.002	0.002
O&M Cost $/kWh	0.012	0.012	0.012
Fuel Cost $kWh	0.169	0.263	0.525
Total Cost $/ kWh	**0.182**	**0.276**	**0.539**
	100 percent Capacity Factor		
Rental Cost $/kWh	0.002	0.002	0.002
O&M Cost $/kWh	0.011	0.011	0.011
Fuel Cost $/kWh	0.174	0.27	0.54
Total Cost $/kWh	**0.186**	**0.283**	**0.553**

C.5 Holos Costs

Holos costs were based HolosGen LLC costing data (HolosGen™ 2018)[1]. Those costs have been updated from time to time, thus costs modeled may not be exactly the ones published in 2018 by HolosGen, but are still close (Table C.5). The costs shown are for the 22-MWt/13-MWe generator. The costs represent 2017 best estimate of the costs. The overnight costs for the FOAK system is $9,488 per kWe. A 7 percent discount rate was used to levelize the capital costs (OMB 2018). The FOAK system costs (Table C.5) were used to estimate what the initial generator might cost per kWh. The overnight costs include the capital costs, initial fuel supply, and the decommissioning costs. The overnight costs include the time value of money for the individual components, and thus are somewhat different than the sum of the individual components divided by the capacity of the system.

Table C.5. Installation and Operations Costs for a 13-MWe Holos System

First of a Kind (FOAK)	Value		Nth of a Kind (NOAK)	Value
Cost Item			Cost Item	
Holos Quad (kWe)	13,266		Holos Quad	13,266
Integral Core	$26,607,866		Integral Core	$11,973,540
Power Conversion Unit	$16,129,126		Power Conversion Unit	$12,903,300
Additional Plant Equipment	$15,729,160		Additional Plant Equipment	$5,545,832
Licensing	$20,000,000		Licensing	$5,000,000
Engineering	$10,000,000		Engineering	$7,000,000
Capital Costs	$68,466,152		Capital Costs	$40,422,672
Initial Fuel Supply	$37,400,000		Initial Fuel Supply	$26,000,000
Overnight Cost ($/kWe)	$9,488		Overnight Cost ($/kWe)	$5,535
Operations & Maintenance	$14,049,595		Operations & Maintenance	$10,018,079
Decommissioning Costs	$7,993,024		Decommissioning Costs	$7,993,024
Total Investment	$139,208,770		Total Investment	$74,710,629

The kWh costs (Table C.6) were based on operating the 13-kWh Holos system for 20 years at 97 percent capacity factor and requiring a 7 percent rate of return. The number of years of operation at different capacities was adjusted based on fuel usage. For example, the 50 percent capacity was assumed to operate 40 years and at 25 percent, 80 years. Costs ranged from 7 cents per kWh at a 97 percent capacity factor up to a cost of 21 cents per kWh at a 25 percent capacity factor for the NOAK system. Note that the costs for the NOAK are lower than the costs of distillate generation at $2.25 per gallon at each capacity level. At a 25 percent capacity factor, they are very close to the cost of diesels. The range of capacity factor arose because some bases have significantly different peak demands during the year from the average demand of the installation. The diesel generators are assumed to operate at 75 percent capacity. For example, the authors found a base with a 22 percent capacity factor when sizing average demand to the 13-MWe peak Holos can provide. The costs per kWh for the FOAK 13-MWe system at a

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[1] McCabe, K. 2018. Email from Claudio Filippone (President and CEO, HolosGen LLC) to Kerry McCabe (Engineer, Pacific Northwest National Laboratory), "Presentation: Mobile HOLOS Generators for Expeditionary Power," January 2018. Ft. Belvoir, Virginia. Copy of email included in project files.

75 percent capacity factor were 14 cents per kWh, compared with the 18 cents per kWh for diesel generator, the normal assumed operating percentage. Thus, even the FOAK costs appear to be better than current operating costs for the diesel generator down to the 25 percent capacity factors, if costs are realized as estimated. At a 25 percent capacity factor, the FOAK system is more expensive than diesel. If fuel prices were to rise to $3.50 per gallon, the FOAK costs, if correct as estimated, would be competitive, even at the 25 percent capacity factor.

Table C.6. Costs for Holos System ($/kWh)

Holos System Costs				
	NOAK	**NOAK**	**FOAK**	**NOAK**
	3.3 MWe	**6.6 MWe**	**13 MWe**	
	25 percent Capacity Factor			
Capital Costs $/kWh	0.555	0.296	0.305	0.178
O&M Costs $/kWh	0.037	0.037	0.046	0.033
Total Costs $/kWh	**0.592**	**0.333**	**0.35**	**0.21**
	50 percent Capacity Factor			
Capital Costs $/kWh	0.296	0.186	0.162	0.095
O&M Costs $/kWh	0.019	0.019	0.023	0.016
Total Costs $/kWh	**0.315**	**0.205**	**0.185**	**0.111**
	75 percent Capacity Factor			
Capital Costs $/kWh	0.22	0.155	0.121	0.071
O&M Costs $/kWh	0.012	0.012	0.015	0.011
Total Costs $/kWh	**0.233**	**0.167**	**0.136**	**0.081**
	100 percent Capacity Factor			
Capital Costs $/kWh	0.192	0.145	0.105	0.061
O&M Costs $/kWh	0.01	0.01	0.012	0.008
Total Costs $/kWh	**0.202**	**0.154**	**0.117**	**0.07**

A smaller system was estimated based on the levels of demand found at the 12 sites. In four cases, the capacity of generation was less than 7 MW, an indicator that the 13-MWe system could be inefficient compared with a smaller system. Thus, a 6.6-MWe Holos system was estimated.[1] The NOAK capital costs for the 6.6-MWe system were estimated at $38 million with the initial fuel supply costing $57 million, decommissioning $2.3 million, and operating costs estimated at $5.7 million. The overnight capital costs were approximately $8,641 per kW. The costs for the 3.3-MWe system were the same as the 6.6-MWe variant, with the system rated at 3.3 MWe. The results of the analysis indicate that the costs per kWh are approximately 17 cents per kWh and 23 cents per kWh at 75 percent capacity for the 6.6-MWe and 3.3-MWe systems, respectively. At low capacity (25 percent), costs were 33 cents per kWh and 59 cents per kWh. The full range of costs can be found in Table C.6. The results indicate that even at 25 percent

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[1] McCabe K. 2018. Email from Claudio Filippone (President and CEO, HolosGen LLC) to Kerry McCabe (Engineer, Pacific Northwest National Laboratory), “Additional Data for Smaller HOLOS version,” April 4, 2018, Ft. Belvoir, Virginia. Copy of email included in project files.

capacity, the 13-MWe system is lower cost, which would approximate an average capacity of about 3,250 kW.

C.6 Risk Analysis of the Holos 13-MWe System

As identified in Section C.1, there is a risk that the costs of the Holos system will be higher than is currently forecasted; the primary reasons are the estimated costs associated with the core, the nuclear fuel and licensing. Evidence from studies indicate that the costs could on average grow by 250 percent (Merrow et al. 1979; Merrow et al. 1988). These cost growth cases were for energy process plants, the Barnwell Nuclear Fuel Plant, and nuclear power plants in general. These references are old and for large, monolithic plants. More recent cases exist for nuclear generating plants, but exact data could not be found. A closer examination of the costs for Holos provides a basis for the potential cost increases. To provide a potential range of Holos costs when operating at 75 percent, a 50 percent increase, and a 250 percent increase in costs were used. The costs estimated show that costs increase to just more than 12 cents per kWh with 50 percent increase, and to just less than 20 cents per kWh if the costs were 2.5 times the initial estimate.

C.6.1 Comparison of 12 Sites Variable Distillate Costs with Holos 13-MWe NOAK Costs ($/kWh)

Analysis was undertaken to determine whether a set of sites would be appropriate for deploying a NOAK version of the 13-MWe Holos system. Data were provided on the current capacity of electricity generation on the sites and the prices and types of fuel currently available at each site. The 12 sites are: Thule, Greenland; Kwajalein Atoll; Guantanamo Bay; Diego Garcia; Guam DFSP and Guam (AF), Anderson; Ascension Island; Antigua; Fort Buchanan; Bagram; Camp Buehring; Fort Greely; and Lajes Field.

Using the data from Tables C.2 and C.3, variable distillate costs for each site were developed. A 75 percent capacity factor was used for the distillate generation costs. Fuel costs per kWh were developed based on the prices provided for each site by fuel type. O&M costs were increased to 5.7 cents per kWh, based information from three bases indicating that O&M costs for those sites were higher than those provided by Lazard.[1] An additional cost may apply by site. For Bagram, the costs are for the main plant, which is not leased. However other diesel generators may be leased at $30,000 (Henry et al. 2013). The higher O&M costs occur because of the redundancy of systems, which must be maintained. Holos costs per kWh are shown in the Table C.7. The Holos system is less expensive for every site but Fort Buchanan, Camp Buehring[2], and Fort Greely, where the capacity factors are very low. Even then, if fuel costs rebound to former highs; or forward operating bases have higher effective costs of fuel, the Holos may be cost-effective if Holos costs are near forecasts. Table C.8 provides the effective variable costs for distillate generation at 50 percent higher fuel prices and at $7.00 kWh. The costs do not include the lease costs and are based on a 75 percent capacity factor. Lease costs would need to be added to the total variable costs if a base is leasing their generators rather than owning them.

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[1] The bases were Thule, Bagram, and Buehring. The costs in the table are from a spreadsheet on electricity costs for Buehring.

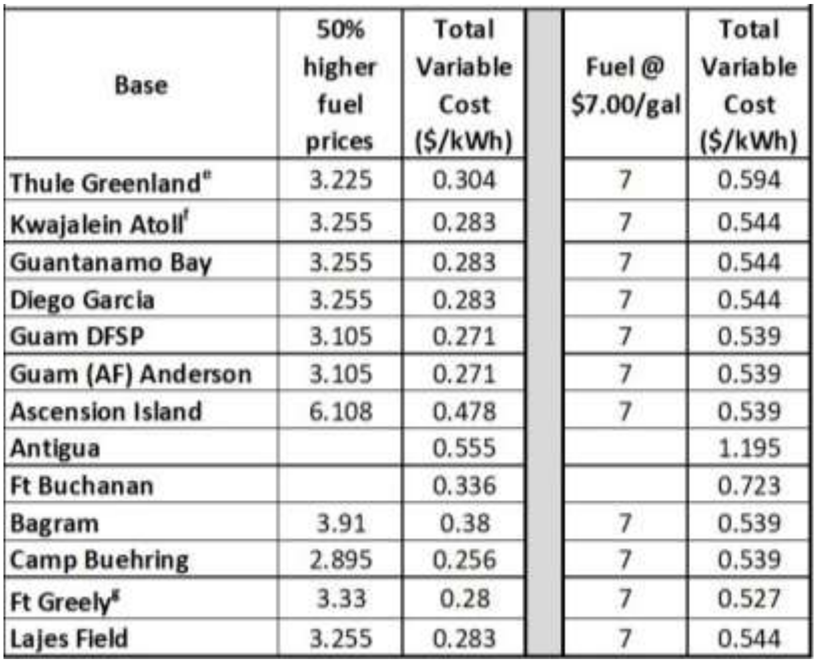
[2] Used Buehring Data from Idaho National Laboratory. Significantly higher than $0.01/kwh provided in Lazard (November 2017).

Table C.7. Comparison of Variable Distillate Costs for 12 Sites with Holos 13-MWe System

Base	Capacity (MW)	Fuel	Price ($/gal)	Fuel Cost $/kWh	Total Variable Cost ($/kWh)	Rental Cost ($/kWh)	Holos Average Capacity Factor	Holos Cost ($/kWh)
Thule Greenland[e]	35.5	JP8	$ 2.15	$ 0.165	$ 0.222	$ 0.003	44%	$ 0.125
Kwajalein Atoll[f]	33.8	F76	$ 2.17	$ 0.151	$ 0.208	$ 0.002	75%	$ 0.081
Guantanamo Bay	45.6	F76	$ 2.17	$ 0.151	$ 0.208	$ 0.002	84%	$ 0.075
Diego Garcia	22.3	F76	$ 2.17	$ 0.151	$ 0.208	$ 0.002	79%	$ 0.079
Guam DFSP	13.5	DS2	$ 2.07	$ 0.143	$ 0.199	$ 0.002	43%	$ 0.127
Guam (AF)	19.5	DS2	$ 2.07	$ 0.143	$ 0.199	$ 0.002	68%	$ 0.087
Ascension Island	6.7	UK fuel	$ 4.07	$ 0.281	$ 0.337	$ 0.002	43%	$ 0.127
Antigua	2.7	Utility			$ 0.370	$ 0.002	75%	$ 0.081
Ft Buchanan	4.1	Utility			$ 0.224	$ 0.006	25%	$ 0.212
Bagram	56	DF2	$ 1.93	$ 0.133	$ 0.190	$ 0.002	75%	$ 0.081
Camp Buehring	30	DF2	$ 1.93	$ 0.133	$ 0.190	$ 0.002	21%	$ 0.251
Ft Greely[g]	11.2	DS1	$ 2.22	$ 0.149	$ 0.206	$ 0.007	22%	$ 0.235
Lajes Field	4.1	F76	$ 2.17	$ 0.151	$ 0.208	$ 0.003	48%	$ 0.114

Notes: e. Actual Fuel Consumption per hour was obtained from Thule in 2015 for 2014. f. Kwajalein Atoll Garrison is a series of 11 islands each with separate grids. g. Notes from site visit indicate average demand at 1.5 MW and peak at 3.3 MW, far different that 11.2, noted that GVEA is providing a 10 MW capacity to the fort. From 2008 Wind Study.

Table C.8. Diesel Generator Electricity Costs at 50 Percent Higher Prices and $7.00 per Gallon



Base	50% higher fuel prices	Total Variable Cost ($/kWh)	Fuel @ $7.00/gal	Total Variable Cost ($/kWh)
Thule Greenland[e]	3.225	0.304	7	0.594
Kwajalein Atoll[f]	3.255	0.283	7	0.544
Guantanamo Bay	3.255	0.283	7	0.544
Diego Garcia	3.255	0.283	7	0.544
Guam DFSP	3.105	0.271	7	0.539
Guam (AF) Anderson	3.105	0.271	7	0.539
Ascension Island	6.108	0.478	7	0.539
Antigua		0.555		1.195
Ft Buchanan		0.336		0.723
Bagram	3.91	0.38	7	0.539
Camp Buehring	2.895	0.256	7	0.539
Ft Greely[g]	3.33	0.28	7	0.527
Lajes Field	3.255	0.283	7	0.544

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Appendix D

Nuclear Fuel

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Appendix D

Nuclear Fuel

Nuclear fuel and its availability are critical path issues for any Army/U.S. Department of Defense (DOD) mobile nuclear power plant (MNPP) development effort. Success in this area requires interdepartmental (DOD/U.S. Department of Energy [DOE]) support and cooperation as well as significant congressional, U.S. Nuclear Regulatory Commission (NRC) and commercial industry collaboration. Currently, the United States possesses a focused commercial national capability in the area of nuclear fuel production for test reactor and commercial power plant demand. The nuclear industry and DOD have not generated a sufficient demand signal to sustain long-term commercial production capacities. Current capabilities focus on the domestic fuel market and may prove insufficient for future DOD needs. An MNPP development and deployment could alter this situation, enabling and accelerating other capabilities supporting defense and other national needs.

Nuclear fuel has significant advantages over liquid fuels. It has the highest energy density of all fuel sources reducing bulk/volume and simplifying long-term power logistics and economics. Nuclear fuel’s high energy density would enable the Army to displace millions of gallons of liquid fuel (with the attendant handling, storage, and management issues) in the supply chain freeing up on-hand fuel stocks for battlefield use. Sustaining this advantage over long periods of time (before needing a refueling) is desirable and drives not only reactor design but also fuel enrichment decisions. Nuclear fuel can be classified into two enrichment types: highly enriched uranium (HEU) and low enriched uranium (LEU). The difference is driven by proliferation concerns. Generally, HEU has 20 percent or more uranium enrichment and is suitable for nuclear weapons use, while LEU has less than 20 percent uranium enrichment and is not suitable for nuclear weapons use. While HEU can be used for electrical power generation, it poses security and nuclear nonproliferation problems that the commercial nuclear industry seeks to avoid. Commercial nuclear power plants use LEU fuel enriched up to a 5 percent level. Higher enrichment of fuel provides some significant benefits and tradeoffs in design. Higher enrichment reduces the physical size of a reactor and its core, and also enables longer operating life between refueling periods. While commercial reactor fuel is enriched up to 5 percent, higher enrichment levels are possible. Enriched uranium above 5 percent and up to the 20 percent LEU maximum is known as high-assay low enriched uranium (HA-LEU). Few reactors use HA-LEU to date, the commercial availability of this fuel to support demand is limited and costly, due to low production volumes. No domestic commercial producers of HA-LEU enriching product in large volume exist.

Based on economic analysis and expert opinion, it is desirable for any Army/DOD MNPP to operate (unrefueled) for at least 10 years, perhaps as long as 20 years. This operation life can be accomplished with higher fuel enrichment levels. Establishing a national capability for HA-LEU is possible if a sustainable fuel demand volume can be achieved. Doing so is not only in DOD and the nuclear industry’s interests, but also supports other U.S. national obligations and needs such as supporting fuel for foreign research reactors (Korea/Japan/South America) and small reactors as well as the high performance research reactors located at a number of U.S. universities and DOE national laboratories (the Energy Policy Act of 2005, the Foreign Relations

Authorization Act, the Nuclear Non-proliferation Act of 1978, and 10 CFR 810). The aggregate demand for fuel from these reactors, along with a long-term DOD MNPP demand would sustain a long-term national commercial capability with significant benefits to DOD and the nation. Establishing such a capability would require commercial partners and NRC support for licensing facilities to enrich fuel up to the maximum HA-LEU levels.

A unique capability for an MNPP is use of encapsulated fuel. During nuclear fission, contaminants are generated. Because of a base camp's small physical footprint, contamination must be contained for safety purposes. DOE investments in encapsulation are ongoing, but have produced at least one solution, tristructural-isotropic (TRISO) fuel (Figure C.1). TRISO is a series of very small fuel pellets[1] packed into larger fuel assemblies for a reactor. Each TRISO fuel kernel is coated with layers of three isotropic materials that retain the fission products at high temperature while giving the TRISO particle significant structural integrity. The fuel is designed not to crack under stress from thermal expansion or fission gas pressure and can safely contain both volatile products and the fuel in case of an accident. This safety comes at a performance price. A great deal of the volume of a TRISO fuel assembly is not uranium but fuel coating and empty space within the packed volume. This poses an economic issue for commercial power plants, which can control the fuel and reactor conditions. While Chinese and other foreign vendors currently manufacture TRISO fuels, U.S. industry does not. Domestic capabilities to manufacture TRISO exist with multiple vendors, but actual production is dormant or nascent (Centrus 2018) due to a current lack of demand. Any business case to support domestic production would require a long-term demand for TRISO, in economical production volumes, to adequately capitalize a commercial facility for TRISO production. While TRISO manufacturing technology readiness is proven, recent DOE efforts to further improve it include a commercial pilot-scale effort by BWX Technologies to prove out manufacturing line processes that can be scaled up by simply adding multiple production lines (referred to as cascades) to achieve desired production volumes.

New enrichment is a necessity to support any Army MNPP development over the long term. Additionally, a short-term option for fuel production using HEU down-blending could be considered for up to four reactors if a sufficient quantity of HEU is available in U.S. government stockpiles. This down-blend approach could be used to reduce fuel wait time for initial testing and deployment reactor units, accelerating an MNPP programs schedule and availability, if desired.

New enrichment has two pathways to follow. First is to build a domestic commercial capability to enrich HA-LEU and potentially HEU in the future, to support other DOD or U.S. national needs. The need for a U.S. domestic capability to meet nuclear regime requirements for HEU would support weapons material production. Establishing this capability is anticipated to take five to seven years to commence production. A second, faster option is to leverage the existing enrichment market for Army power needs. URENCO-USA is a foreign-owned company[2] currently enriching material for the U.S. power market. URENCO-USA has the ability to increase production in an incremental fashion to meet Army needs at a relatively modest cost. While this solves the Army's needs, it may not support other DOE and DOD requirements as

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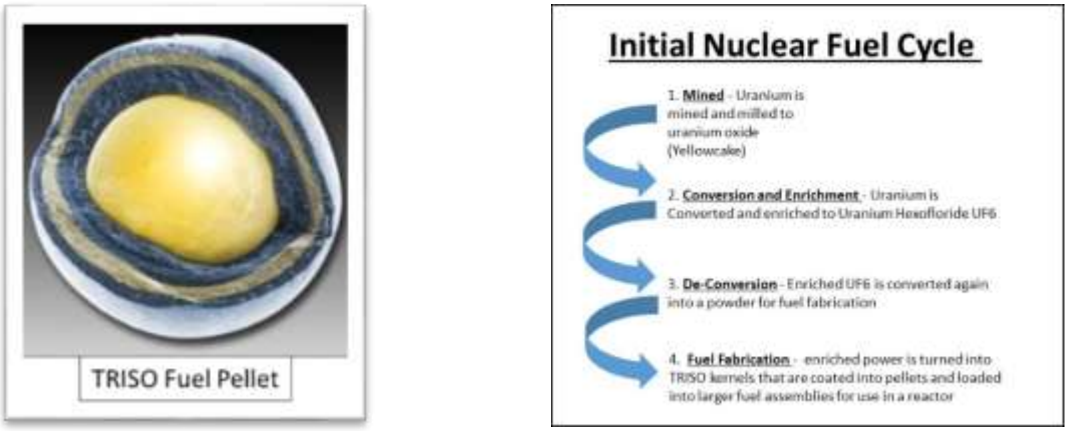
[1] A single TRISO fuel kernel is about 500 microns. A finished, completely coated TRISO pellet is approximately 1 mm in diameter.

[2] URENCO is owned by a consortium consisting of the governments of the Netherlands and the United Kingdom and Germany.



1. **Mined** - Uranium is mined and milled to uranium oxide (Yellowcake)
2. **Conversion and Enrichment** - Uranium is Converted and enriched to Uranium Hexofloride UF6
3. **De-Conversion** - Enriched UF6 is converted again into a powder for fuel fabrication
4. **Fuel Fabrication** - enriched power is turned into TRISO kernels that are coated into pellets and loaded into larger fuel assemblies for use in a reactor

Figure C.1. TRISO Fuel and the Initial Nuclear Fuel Cycle

URENCO is treaty-bound by a “peaceful use” agreement. It is possible however, that the firm’s owners could approve fuel enrichment to support military electrical power production. If approved, it would take about five years to make facility changes and obtain NRC licensing for HA-LEU production. The combined demands for HA-LEU from U.S. domestic, Army/DOD, and commercial sources would need to be examined, but is projected to make high-volume HA-LEU production economical. Upfront costs for this are estimated at $300 million to $500 million. Hurdles to this would be in the need for NRC-approved transport casks for both enriched material components and finished product HA-LEU fuel. Current transport casks are designed and rated for less than 5 percent enriched products and do not meet the safety requirements for higher enrichment level fuels. Overcoming this issue with industry and the NRC is anticipated to take five to seven years.

Another option is collocating fuel production facilities (enrichment, conversion, and TRISO fabrication) at the same site. This option depends on collaboration of the firms doing the fuel work, but is possible if sufficient long-term volume production capital costs can be spread over time using long-term contracts.

D.1 Fuel Procurement and Management

Additional thought needs to be put into the areas of fuel procurement and management. In discussions for this study, fuel chain vendors[1] all stressed that sustained production at some minimal level is essential for maintaining a viable HA-LEU nuclear fuel industry. Current volume of HA-LEU demand is insufficient to maintain an economical capability, but those combined with potential DOD demand may be able to sustain a long-term production capability. Fuel contracting is a DOE mission and should be leveraged. Vendors would like to work with DOE to create long-term contracts for fuel. Providing planning certainty enables industry to capitalize and add facilities and plant at the correct scale and cost to enable low-cost, long-term support. Lastly, DOE could possibly act as a fuel source and distributor for an Army or civilian MNPP, procuring, storing, issuing, and disposing of fuel modules for the life of the program. Using DOE to provide fuel to an Army MNPP program as government-furnished equipment (GFE), may simplify many program challenges and reduce costs.

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[1] URENCO, BWX Technologies, General Atomics and CENTRUS and X-energy.

D.2 References

22 USC 2651 et seq. 2002. *Foreign Relations Authorization Act, Fiscal Year 2003*. Public Law 107-228 as amended.

22 USC 3201 et seq. 1978. *Nuclear Non-Proliferation Act of 1978*. Public Law 95-242.

42 USC 15801 et seq. 2005. *Energy Policy Act of 2005*. Public Law 109-58 as amended.

10 CFR 810. 2015. Assistance to Foreign Atomic Energy Activities, Code of Federal Regulations, U.S. Department of Energy.

Centrus. 2018. "X-energy Contract with Centrus to Support Advanced Nuclear Fuel Fabrication Facility Work." March 28, 2018. Business Wire. Accessed July 20, 2018 at https://www.businesswire.com/news/home/20180328005516/en/X-energy-Contracts-Centrus-Support-Advanced-Nuclear-Fuel.

Appendix E

Funding Mobile Nuclear Power Plant Decommissioning and Spent Fuel Storage

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Appendix E

Funding Mobile Nuclear Power Plant Decommissioning and Spent Fuel Storage

All power plants have decommissioning costs involved with their removal and disposal. In most regards, decommissioning of commercial conventional and nuclear power plants differ only in the area of spent nuclear fuel storage. Both can have contamination cleanup issues, but unlike conventional fuels consumed during operation, nuclear fuel requires special handling, storage and disposal. Costs for decommissioning a nuclear facility, storing and moving its spent fuel into temporary or long-term storage, and eventually moving the spent fuel to a national long-term disposal site such as the deep geological repository storage facility at Yucca Mountain[1], must be factored into any nuclear power business case. Based on the discussion below, it is highly recommended that the Army examine the business practices employed by the U.S. Nuclear Regulatory Commission (NRC) and commercial industry as a potential approach to avoid the long-term costs incurred by legacy Army reactor fixed facilities.

The NRC requires all its reactor owners to maintain adequate funding for decommissioning as a pre-condition for licensing and operations. Before a nuclear power plant begins operations, the licensee must establish or obtain a financial mechanism, such as a trust fund or a guarantee from its parent company, to provide a reasonable assurance that sufficient funding will be available for decommissioning of the facility. Licensees may determine a site-specific estimate (provided that amount is greater than the generic decommissioning estimate) greater than the generic NRC formula[2]. Decommissioning funds are then accumulated over the operating life of the power plant in a number of ways: 1) upfront prepayment, 2) an external sinking fund, 3) a guarantee method using insurance or surety bond, and 4) for U.S. government federal licensees, a statement of intent that funds for decommissioning will be obtained when necessary. While the government can always provide a statement of intent, a periodic or ongoing setting aside of funds (in a segregated account) dedicated to decommissioning might make sense. The establishment of a revolving type fund for this could be investigated. Since the primary customer is a warfighter on a forward operating base, overseas contingency operations would likely provide the bulk of funding and it may be prudent to include funding from other sources (base funding) to accommodate remote site support.

To support this, appropriate formulas for a mobile nuclear power plant (MNPP) are needed. Development of optimized formulas for the reactor technology under consideration, designed at the appropriate reactor size and power generation scale enable accurate calculation of decommissioning costs. This information would assist the Army, U.S. Department of Defense (DOD), NRC, and nuclear industry in properly determining an upfront recoupment rate to charge

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[1] Yucca Mountain site license is under review, https://www.gao.gov/key_issues/disposal_of_highlevel_nuclear_waste/issue_summary

[2] The NRC employs two formulas to calculate the rough cost of decommissioning and cleanup. These are optimized for boiling and pressurized water reactor designs constructed as a large, fixed facility supporting long-term utility-scale power generation. See 10 CFR 50.75, Reporting and recordkeeping for decommissioning planning.

for electrical production in support of a reactor's eventual decommissioning and ultimate disposal.

A strong upfront design effort is needed to avoid complex, costly, and potentially hazardous decommissioning and disposal issues. Russia safely decommissioned one of its mobile nuclear power plants, the Pamir-630D[1]. Designed as a gas cooled reactor, it operated from 1985-87, was shut down and stored and then safely decommissioned and dismantled in a complex process that could have been minimized or avoided through pre-planning for disposal.

Planned upfront and actively managed, decommissioning and fuel storage costs can be minimized, reducing long-term Army, and commercial operator costs. Preplanning options such as having DOE manage reactor fuel purchase and issue, as well as spent fuel recovery and disposal, help reduce Army and DOD exposure to potential long-term costs. Proactive funding approaches such as the one employed by the NRC can ensure costs for reactor decommissioning and fuel disposal are planned and factored into an MNPP's total cost upfront, ensuring availability when needed for disposal.

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[1] Pahukhovich VM. *Safe Decommissioning of Mobile Nuclear Power Plant*, undated report, Department for Supervision of Industrial and Nuclear Safety, Minsk, Belarus. Copy of document included in project files.

Appendix F

Opportunity for Cost Reduction and Long-term Production: The Army Effort and Commercial Very Small Modular Reactor Market

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Appendix F

Opportunity for Cost Reduction and Long-term Production: The Army Effort and Commercial Very Small Modular Reactor Market

Facilitating commercial adoption of a very small modular reactor (vSMR)/mobile nuclear power plant (MNPP) is in the U.S. Army's best interest. While the commercial marketplace for electrical generation is large, small-scale power generation is not common due to economies of scale. The economics of commercial electrical production are driven by low production costs. Most consumers benefit from the current commercial electrical production, but it is not economical in remote locations without access to a power grid, or where extending the grid would be cost prohibitive. Small-scale power generation operations typically use diesel fuel generators and have higher power generation costs than utility-scale producers on the power grid. These higher prices are a cost of doing business in remote areas and are accepted as a market niche. This situation, where higher generation costs are acceptable, could be leveraged by Army to help reduce its MNPP acquisition costs.

Rather than designing and purchasing MNPPs for itself, the Army along with the U.S. nuclear industry, could examine and collaborate on approaches to meet both Army/U.S. Department of Defense (DOD) needs and international demand for remote location power with a single design or standardized family of vSMRs/MNPPs. This niche market could potentially be used to spread MNPP acquisition costs across a larger number of production units, reducing Army purchase costs over a device's 20-to-40-year life cycle. Commercial adoption could also lend itself to development of a long-term Power Purchase Agreement opportunity that DOD could ultimately leverage to avoid having to own and operate MNPPs.

The demand for remote site power is relatively small but substantial. This niche market includes mining locations and potentially hundreds of remote communities in Canada and Alaska and up to 52 small remote island states spanning the Caribbean, Atlantic, Indian, and Pacific oceans, and South China and Mediterranean seas. All these locations generally lack domestic fossil fuel reserves and cannot meet base electrical power demands with intermittent alternative energy options. For the Canadian mining market, an approximate cost of $0.30 per kWh[1] appears to be normal, which is similar to that of some U.S. forward operating bases (FOBs). The type of deployable MNPP produced for the Army/DOD could meet this commercial need, help reduce Army production costs, and support a U.S. nuclear industry capability resurgence and an overseas market for products. Available U.S. Energy Information Administration data[1] indicate that the island states alone produced more than 80 billion kilowatt-hours in 2010. This is equivalent to 9.1 GWe of annualized generating capacity, a large portion of which can be economically replaced by small nuclear reactors. If it can be assumed that 10 percent of this market can be served by nuclear power, this represents approximately 910 MWe of generating

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[1] Ontario Ministry of Energy. 2016. *SMR Deployment Feasibility Study: Feasibility of the Potential Deployment of Small Modular Reactors (SMRs) in Ontario*. H350381-00000-162-066-0001, Rev. 0, Hatch, Mississauga, Ontario. http://ontarioenergyreport.ca/pdfs/MOE%20-%20Feasibility%20Study_SMRs%20-%20June%202016.pdf, p. 78-79.

capacity[1]. Canadian mines alone represent a market of about 2.70 GWe of remote site generating capacity[1], which translates into about 270 production units (assuming a 10-MWe MNPP). The additive effect of commercial orders on production volume could enable establishment of a continuous production line whose additional surge capacity could support unforeseen emergency demand for DOD contingency needs, or commercial vendor power support for humanitarian assistance disaster relief operations.

Significant barriers to the development of a commercial MNPP market niche include fuel availability, first-of-a-kind costs, and statutes/rules governing international transport. Many nuclear industry vendors may lack some or all three key ingredients (capital, expertise, and political clout) to overcome these barriers, but it is important to note that all these barriers must be addressed for an Army/DOD solution to succeed. Resolving these issues would give the U.S. nuclear industry a “first-mover” advantage providing multiple benefits for U.S. interests and those of our trading partners and allies.

Appendix G

Small Nuclear Power Plant Designs with Mobile Nuclear Power Plant Potential

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Appendix G

Small Nuclear Power Plant Designs with Mobile Nuclear Power Plant Potential

This study examined five potential very small nuclear power plant designs that could meet, or potentially be modified to meet, a U.S. Department of Defense (DOD) mobile nuclear power plant (MNPP) concept. All the designs are still in the conceptual phase at varying levels of maturity. Obtaining specific detailed information on a design and its costs was complicated by the desire of designers to protect intellectual property in a competitive environment. Some idea of design maturity can be ascertained by a firms licensing activity. Applying for a commercial operating license requires detailed drawings and analysis to enable a regulator to approve a design for operation. Another method is to examine U.S. Department of Energy (DOE) studies and research employing the design or device components. Funding for this work is a sign of technical and component maturation somewhere around a technology readiness level (TRL) of 4 to 6. Lastly, the provision of detailed drawings provides additional information on manufacturability and manufacturing costs. Completed drawings around 70-80 percent can provide some reliable costing data for economic analysis.

The concepts shown in Figures G.1 through G.5 are examples of potential MNPP design possibilities. Additional designs are possible, depending on DOD requirements and interest from industry.

URENCO (U-Battery)	
System	Closed cycle Brayton, Helium
Power Output	4 MW electric
Fuel Type	TRISO enrichment 19.75%
Length	N/A
Weight	N/A
Fuel Life	Unknown
Cost	Unknown. Design is currently not configured for MNPP mission
Features:	• Cycle efficiency >40% when producing electricity with gas turbine-alternator.
Notes:	• Design is optimized for stationary power to support mining industry market with fixed facility. Modifications required to meet MNPP mission are unknown. • Demonstration by 2026 (mining application)

U-Battery –Image Not Available

Figure G.1. URENCO U-Battery

MegaPower	
System	Heat Pipe, closed cycle CO_2 Brayton
Power Output	Scalable - 2.25 to 17.5 MW
Fuel Type	300 –2600 kg of U-MO; average enrichment 12.5%
Length	10 meters
Weight	10.5 Tons (2.25 MW) to 11.5 Tons (17.5 MW)
Fuel Life	12 years
Cost	$11M to $39M depending on power required
Features:	• Designed for preventive maintenance - Power turbine components are replaceable with less than 3 hour personnel exposure. • Redundant power conversion loops enhance operational availability • Turbine room is accessible to personnel 3-days after shut down. • Radiation shield for separation to enhance personnel safety • Shield designed for unfettered access to reactor “package” seven days after shutdown. • Additional shielding may be necessary during operation to meet As Low as Reasonable Achievable (ALARA) Standards (additional analysis needed).
Notes:	• Reactor work under way. Further design maturation and integration of concept are required.

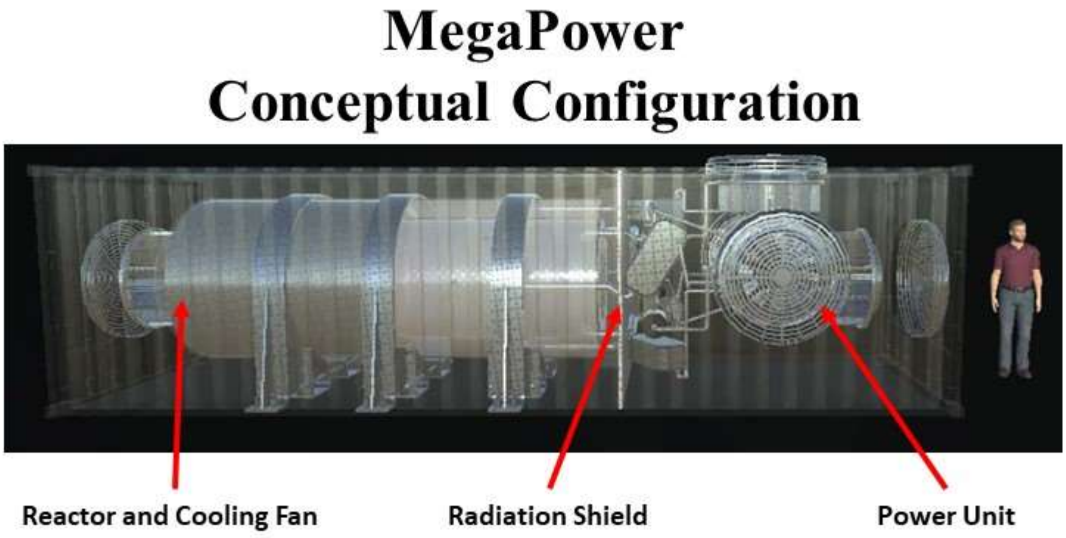

Figure G.2. MegaPower

eVinci	
System	Heat Pipe
Power Output	4-MW electric
Fuel Type	Unknown
Length	N/A – Currently optimized for mining market
Weight	N/A – Currently optimized for mining market
Fuel Life	5 to 10+ years
Cost	Unknown. Design is currently not configured for MNPP mission
Features:	• High reliability and minimal moving parts • Autonomous operation • Inherent load following capability
Notes:	• Program's technology development goal is to develop and demonstrate the eVinci micro reactor in less than six years. • System demonstration and qualification for commercial deployment by 2024. • Awarded $5 million funding from DOE (ARPA-E) for developing a self-regulating solid core block employing solid materials to inherently self-regulate reactor reaction rate.

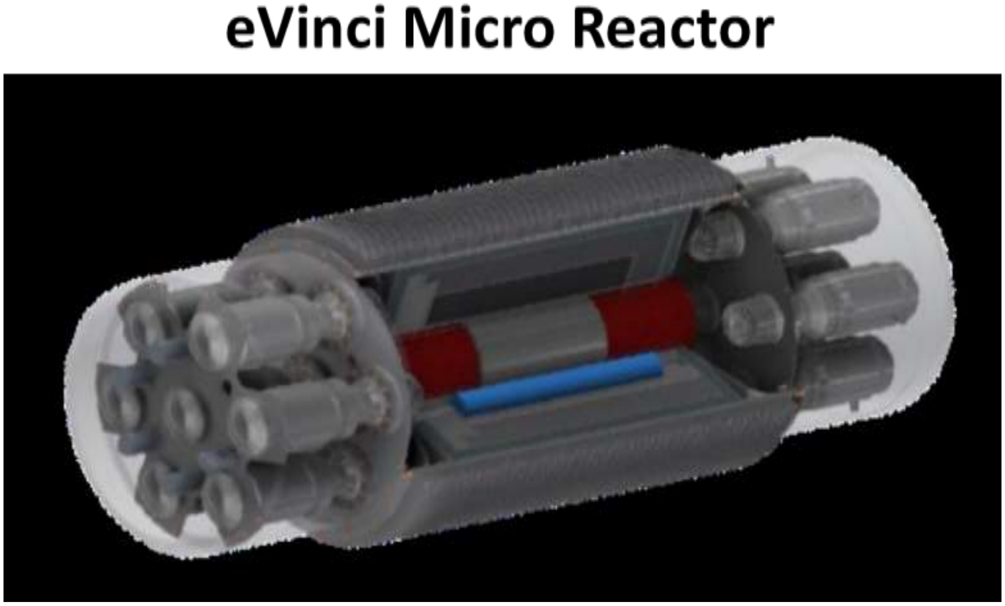

Figure G.3. eVinci Micro Reactor

StarCore	
System	High Temperature Gas Reactor, Helium
Power Output	Two 10-MW electric units
Fuel Type	TRISO
Length	N/A – Currently optimized for mining market
Weight	N/A – Currently optimized for mining market
Fuel Life	5 years
Cost	Unknown. Design is currently not configured for MNPP mission
Features:	• Fully automatic operation with operational data and keep-alive signals transmitted by satellite to a control center. • Load Following. • Redundant control systems
Notes:	• Design and scale are optimized for mining and remote village power – about 20 MWe

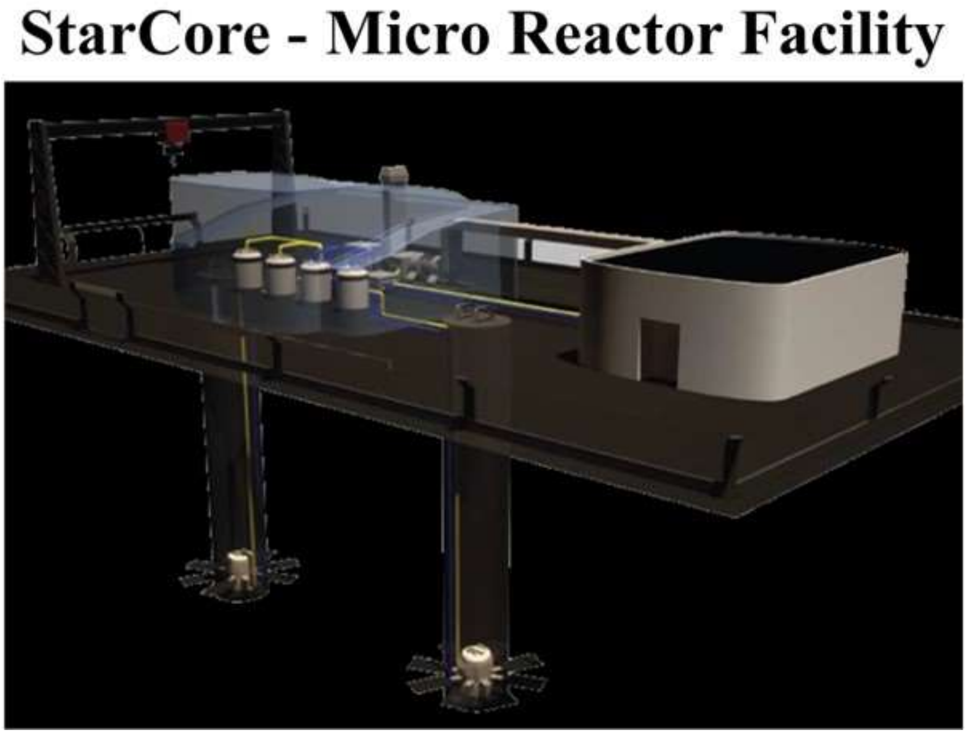
StarCore - Micro Reactor Facility

Figure G.4. StarCore Micro Reactor Facility

HOLOS	
System	Closed cycle Brayton, Helium
Power Output	13 MW electric (3MW and 6MW also available)
Fuel Type	TRISO
Length	40-ft ISO
Weight	N/A – Currently optimized for mining market
Fuel Life	10-20 years
Cost	Estimated at: $140M (FOAK) and $ 75M (NOAK)
Features:	• Mobile design • Fully automatic operation and load following. • Cyber and EMP hardened • Off-the-shelf turbo-machinery components • Enhanced reliability and safety (eliminates Balance of Plant) • Fuel cell is nuclear repository compliant, uses existing licensed dry casks • High component TRL
Notes:	• Component design drawings are computer-aided design and manufacturing quality with good manufacturability and cost data. • Component data collection from full-scale test rig. • Can be refueled - a 60-year total operational life.

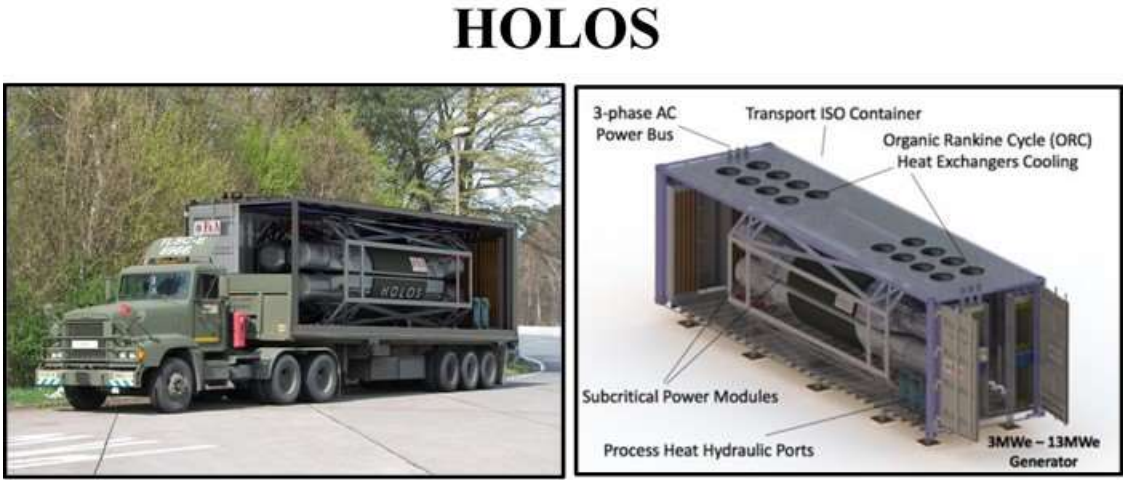

Figure G.5. Holos

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Appendix H

Future Study Requirements to Support Development

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Appendix H

Future Study Requirements to Support Development

The scope of this study is focused on a political, economic, social, technological, environmental and legal/regulatory (PESTEL) examination of a mobile nuclear power plant (MNPP). Detailed analysis of cost, safety, technical and operational issues were not pursued due to time and resource constraints. During the development of this study, the following areas were identified as topics for future recommended study to support further development of an MNPP concept with associated acquisition and regulatory planning. While not all-inclusive, or in priority order, these topic areas are provided to assist follow on efforts at continuing to build and refine the needed body of knowledge on the MNPP concept to support future decision-making.

1. Examine regulatory and licensing pathways and options:
    a. U.S. Nuclear Regulatory Commission (NRC) support:
        i. International connections and recognition supports deployments
        ii. Support for commercialization opportunities within the continental United States (CONUS) or outside the continental United States (OCONUS)
        iii. Development of best practices
        iv. Expertise with operations, environment, safety, and disposal
    b. Army Reactor Office (ARO) support:
        i. Regulating military systems OCONUS
        ii. Simplified permit to operate process
        iii. ARO staffing and impact on Army/U.S. Department of Defense (DOD) nuclear energy support infrastructure
        iv. Potential change to regulatory authorities and support processes for OCONUS deployments
        v. Limited existing infrastructure available through the Army Reactor Program, Army Reactor Council and Army safety office
    c. Hybrid regulatory and licensing (NRC/ARO) opportunities:
        i. Can regulation and licensing be jointly approached for MNPP specifically?
        ii. What areas and functions would remain unique to each organization and what shared capabilities/processes are possible?
        iii. How can such an arrangement be formalized by the U.S. government within existing statutes such as Sections 91b and 101b of the Atomic Energy Act?
        iv. What authorities would need to be changed?
    d. How is DOD/Army nuclear power infrastructure requirements affected by the regulatory decision? Can some of this burden be safely passed on to the commercial market through power contracting mechanisms?
    e. Which regulatory approached can support long-term DOD power purchase agreements from a commercial vendor/owner of an MNPP?
    f. Impact of regulatory/licensing approach on environmental and safety issues:
        i. Decommissioning and radiological cleanup/fuel storage
        ii. Environmental issues beyond radiological impacts
        iii. Multi-site monitoring (CONUS and OCONUS)
2. MNPP - Safety, Vulnerability Assessment and Consequence Management Issues:

    a. Human safety and battle damage/consequence management issues with encapsulated and non-encapsulated nuclear fuels
    b. All hazard threat assessment
    c. Mission assurance assessment
    d. Consequence management assessment (Defense Threat Reduction Agency [DTRA]) [1]
    e. Engineer field fortification options (revetment/dug in/overhead cover/etc.) for MNPP
3. Contingency facility design change impacts:
    a. DOD Unified Facilities Criteria (UFC) and Army Facilities Components System (AFCS)
4. Development of MNPP operational doctrine and device operating requirements. Recommend this be done using a combination of analysis, experimentation and testing.
    a. Operational employment within the Joint Force
        i. Mobility impact - System setup and shutdown time
        ii. Impacts on Operational Contract Support (OCS)
        iii. Optimal employment scenarios
            1. Large Scale Combat Operations (LSCO)
            2. Counterinsurgency Operations (COIN)
        iv. Improved understanding of functions and location power demand needs
    b. Operational employment in support of humanitarian assistance and disaster relief (HADR) operations
5. Manning and training issues:
    a. Manning requirements for support infrastructure
    b. Re-establishment of nuclear operator MOS series (52 H/J/K/L/M)
    c. Define key training issues:
        i. Operator training requirements and licensing
        ii. Device transport
    d. Contracting issues impacting OCS and power purchase agreements
6. Detailed cost review – reactor design and fuel
    a. Independent cost analysis
    b. Decommissioning and spent fuel storage/disposal costs
    c. Refined infrastructure needs and costs impacting:
        i. Physical security and storage
        ii. Training base
        iii. Operator certification testing
        iv. Transportation issues
        v. Consequence management options and impacts
        vi. Regulatory policy and management
7. Nuclear supply chain implications – nationally and globally
    a. Fuel availability at mass production levels
    b. Long term (10+ years) contracting options to support nuclear fuel purchases
8. Improved understanding of forward and remote site power requirements:
    a. Field data collection effort and follow-on study of forward and remote site electrical requirements

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[1] Section 7.9, page 45, of the 2016 DSB report recommends that DTRA and the Department of Energy (DOE) conduct a study to assess vSMR consequence management scenarios.

Appendix I

Political, Economic, Social, Technological, Environmental and Legal/Regulatory Framework and Tasks and Organizations Critical to Future Studies

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Appendix I

Political, Economic, Social, Technological, Environmental and Legal/Regulatory framework and Tasks and Organizations Critical to Future Studies

This study examines the feasibility of employing mobile nuclear power plants (MNPPs) using a political, economic, social, technological, environmental and legal/regulatory (PESTEL) framework. The purpose for the PESTEL analysis is to identify external forces affecting an organization—the U.S. Department of Defense (DOD) and more specifically the Army—from which the organization can analyze the external influences and attempt to gain a competitive advantage. For the purposes of this study, the PESTEL factors[1] are defined as:

Political Factors. These determine the extent to which government and government policy affect the task of DOD development and fielding of a future MNPP capability.

Economic Factors. These factors affect the economic issues of an Army/DOD decision for development and fielding on an MNPP capability. Effects on costs for operations as well as impacts to DOD and other supporting interagency (U.S. government) and industry partners are outlined.

Social Factors. These factors focus on the social environment and communication of key impacts of the introduction of an MNPP to the operating force, commercial industry, host nations and international community. Focus is on coordination and communication of key issues such as safety at individual an organizational levels.

Technological Factors. These factors consider the rate of technological innovation and development that affect any development or prototyping decision.

Environmental Factors. These factors relate to the influence occupational safety and regulatory oversight bring to the operating environment. This includes life cycle environmental issues.

Legal Factors. Understanding of the legal and regulatory environment DOD must operate within globally is vital. These factors identify treaty- and legislation-related issues and their impacts on the business decision and operations.

Table I.1 is not all-inclusive, but addresses some of the more prominent PESTEL opportunities and challenges for vSMR/MNPP success that are explored in this study.

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[1] Adapted from Oxford College of Marketing, *"What is a PESTEL analysis?"* accessed July 18, 2018 at https://blog.oxfordcollegeofmarketing.com/2016/06/30/pestel-analysis/

Table I.1. Analysis of PESTEL Elements for Very Small Modular Reactors and Mobile Nuclear Power Plants

PESTEL Elements	**Opportunities and Challenges**
Political	***Opportunities*** • Current environment is favorable for MNPP to support national security objectives, with strong support from the executive and legislative branches and industry. • DOD supports effort and possible prototyping. ***Challenges*** • Requires extensive interagency and host nation effort to identify, understand, and resolve the challenges arising in connection with fueled reactor movement (CONUS/OCONUS – e.g., cross-state, overflight, territorial waters), employment, regulatory responsibility, etc. • U.S. industrial base has a sole source for nuclear fuel enrichment and manufacturing. DOD demand for high-assay low enriched uranium (HA-LEU) fuel is significant.
Economic	***Opportunities*** • Example analysis predicts a 62% cost advantage over conventional liquid fuel power options. • Upfront nuclear fuel production capability (enrichment and fabrication) capitalization costs are estimated around $200 million. Sustained military demand would amortize investment over 10-20 years. • Possible cost-share opportunity with DOE, considering potential commercial nuclear power applications. • Estimated production volume may enable long-term economic production. ***Challenges*** • First-of-a-kind design and licensing reviews by NRC and DOE to manufacture and operate are costly. • MNPP/vSMR requires HA-LEU enriched fuel, which is not currently available on the commercial market or from DOE stockpiles due to low market demand. Emergent work on advanced reactors may alter and improve this situation. • Spent fuel and reactor disposal are potential economic liabilities if not pre-planned and managed throughout the life cycle.

Table I.1. (contd.)

PESTEL Elements	**Opportunities and Challenges**
Social	***Opportunities*** • Army Reactor Office teaming with NRC and industry. • Megawatt-level power enables future capabilities as outlined in Table 1 and Appendix E of the DSB report(a). • Perceived nuclear power benefits could support host nation emission/environmental goals. ***Challenges*** • Public "fear factor" is due in part to a general lack of nuclear education and understanding of new inherently safe reactor designs and operations. • Doctrine, policy, and processes will need to be modified to gain full advantage of a mobile, nuclear powered, prime-power system. • Army Reactor Office would need reconstitution.
Technological	***Opportunities*** • MNPP designs are adaptable to military needs. • Modern existing technologies and materials support near-term prototyping. ***Challenges*** • Commercial and government capabilities for fuel production provide options to meet prototyping and production within 5-7 years. • Few companies currently pursue MNPP remote power business market due to a low commercial market demand signal. • Availability of commercial designs (intellectual property) can be problematic.
Environmental	***Opportunities*** • Communications and nuclear health expertise and capabilities need emphasis and enhancement. • Reactor size and scale simplify analysis and solutions for emergency planning and consequence management. Techniques must be adapted to military application. ***Challenges*** • Consequence management techniques could be adapted to military application/environment. • Research and modeling are needed for determining device battle damage and area or personnel contamination if successfully attacked and damaged. • Disposal of spent fuel requires extensive coordination and prior planning. Army/DOD are dependent on the DOE efforts for fuel disposal.

Table I.1. (contd.)

PESTEL Elements	Opportunities and Challenges
Legal/Regulatory	***Opportunities*** • Any new reactor and associated testing could be implemented domestically in coordination with DOE and NRC within existing laws and regulations. • DOD or NRC can license reactor design for domestic use. NRC option allows commercialization of a device enabling DOD to contract for power rather than having to build/own and sustain supporting infrastructure. ***Challenges*** • Commercial U.S. licensing (NRC) jurisdiction and processes do not address military reactors operating overseas. • Military nuclear reactor authorities based upon Atomic Energy Act of 1954 legislation and amendments. A renewed Army program deploying mobile reactors on foreign soil may require some legislative update. • International law issues require research and coordination with the International Atomic Energy Agency. • Reactor transport and regulation OCONUS is a first for nuclear power and requires significant interagency coordination as well as transit and host state agreement review. • Commercial contracts through power purchase agreements on foreign soil may be problematic.
(a)Defense Science Board. 2016. *Task Force on Energy Systems for Forward/Remote Operating Bases*. U.S. Department of Defense, Washington, D.C. http://www.dtic.mil/dtic/tr/fulltext/u2/1022571.pdf. CONUS = continental United States; DOD = U.S. Department of Defense; DOE = U.S. Department of Energy; DSB = Defense Science Board HA-LEU = high assay – low enriched uranium; MNPP = mobile nuclear power plant; NRC = U.S. Nuclear Regulatory Commission; OCONUS = outside the continental United States; vSMR = very small modular reactor	

Due to the breadth and depth of the subject, U.S. government interagency coordination is a condition for a successful outcome. As such, early involvement by multiple agencies that are cognizant of and trained in understanding the PESTEL issues must convene and provide professional guidance and recommendations on a number of tasks deemed critical to a properly performed study. Table I.2 provides a listing of tasks and supporting stakeholder organizations. Offices of primary responsibility will need to be identified by DOD and coordinated at the interagency level (if applicable). Table I.2 is not all inclusive, and additional tasks and organizational support are likely. As an example, DOE with its nuclear expertise can provide significant support in nuclear fuel design, testing, storage, and disposal; reactor design; demonstration/prototyping; related safety and licensing; nuclear control; cyber systems; and all of the associated critical infrastructure in a DOE-protected secure environment. Nuclear operator training and related support, as well as general support to an Army MNPP program office would also be available as needed.

Table I.2 Tasks and Organizations Critical to Provide Input to Future Studies on Very Small Mobile Nuclear Power Plants for Ground Operations

Task	DOD	DOE[a]	DOS	NRC	Industry
Establish leadership governance and oversight mechanisms - Council of Colonels/General Officer Steering Committee (COC/GOSC)	X				
Identify needed changes in authorities and interagency interface/coordination permissions and mechanisms	X	X	X	X	
Identify and establish initial CFTs for: requirements development and potential AROC/JCIDS submission (including leads from DA Staff/TRADOC), technical issues, modeling and simulation, testing, prototyping, transportation, security, and liability/consequence management	X	X	X	X	
Develop initial MNPP requirements and acquisition/procurement objective quantity	X				
Estimate nuclear HA-LEU fuel requirements (initial)	X	X	X	X	X
Develop initial estimates: man-hours for reactor and fuel licensing	X	X		X	X
Identify possible fuel cost-sharing options	X	X			
Review nuclear and bilateral agreements, address legal issues on MNPP transport	X	X	X		
Develop fuel sourcing (enrichment and manufacturing) pathway options.	X	X	X	X	X
Examine disposal location options as well as costs and financial options for spent fuel and MNPP disposal	X	X		X	
Address options and legal issues related to the "transfer" of an MNPP and its regulation when deployed in support of DOD operations	X		X	X	
Establish CFT to examine NRC/Army Reactor Office (ARO) regulatory partnership and potential impacts on international nuclear regime and advancement of MNPP regulation	X	X	X	X	
Identify MNPP impact on, and adjustments to, existing and future Defense Cooperation Agreements (DCA)/Implementation Agreements (IA)	X	X	X		
Identify MNPP impact on, and adjustments to, existing and future defense-related international agreements and implementation arrangements	X		X		
Develop, construct, test, field, and operate prototype reactor	X	X	X	X	X

[a] National Nuclear Security Administration (NNSA) is part of DOE; CFT cross functional team; DOD = U.S. Department of Defense; DOE = U.S. Department of Energy; DOS = U.S. Department of State; HA-LEU high-assay, low enriched uranium; MNPP = mobile nuclear power plant

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Appendix J

Glossary

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Appendix J

Glossary

Accident forgiving - the ability of a material or component to withstand the extreme environments within a nuclear reactor that can occur during an accident event.

Additive manufacturing - another term for 3D printing. It is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.

Aerial port of debarkation (APOD) - an air terminal at which cargo or personnel are discharged.

Aerial port of embarkation (APOE) - an air terminal at which troops, units, military-sponsored personnel, unit equipment, and materiel board and are loaded.

Army Reactor Office (ARO) - an organizational element of U.S. Army Nuclear and Combating Weapons of Mass Destruction Agency (USANCA), under the leadership of the Army Reactor Program Manager (ARPM). The Deputy Chief of Staff, G–3/5/7 (DCS, G–3/5/7) is the proponent for the Army Reactor Program (ARP), and the USANCA is the focal point for the management of the ARP and the Army Reactor Office.

Balance of plant (BOP) - a term generally used in the context of power engineering to refer to all the supporting components and auxiliary systems of a power plant needed to deliver the energy, other than the generating unit itself.

Base load - the constant load in a power system that is not subject to variations due to seasons, temperature, or time of day. Generally, the system planner will acquire base load resources to match the base load (i.e., resources which run continuously except for maintenance and scheduled or unscheduled outages).

Brayton Cycle - a thermodynamic cycle named after George Brayton who described the workings of a constant-pressure heat engine. The original Brayton engines used a piston compressor and piston expander, but more modern gas turbine engines and air-breathing jet engines also follow the Brayton cycle.

Combatant Command (COCOM) - a unified or specified command with a broad continuing mission under a single commander established and so designated by the President, through the Secretary of Defense and with the advice and assistance of the Chairman of the Joint Chiefs of Staff.

Conditioned electrical power - the process of filtering the electrical current and voltage to meet power quality requirements. This includes reducing the fluctuations in the sinusoidal alternating current wave and the wave amplitude.

Council of Colonels (COC) - a working council of senior Army leaders composed of representatives from various organizations.

Defense Cooperation Agreement (DCA) - an agreement between the United States and another nation intended to bolster the U.S.-host nation alliance.

Defense Science Board (DSB) - a committee of civilian experts appointed to advise the U.S. Department of Defense on scientific and technical matters. The Board provides the Secretary of Defense; the Deputy Secretary of Defense; the Under Secretary of Defense for Acquisition, Technology and Logistics; the Chairman of the Joint Chiefs of Staff; and other Office of the Secretary of Defense Principal Staff Assistants, Secretaries of the Military Departments, and Commanders of the Combatant Commands, with independent advice and recommendations on scientific, technical, manufacturing, acquisition process, and other matters of special interest to the Department of Defense.

Directed energy - systems that focus a high-power laser on a precise aim point.

Down blending - surplus highly enriched uranium can be down blended to low enriched uranium to make fuel for a commercial nuclear reactor.

Electronic warfare - any action involving the use of the electromagnetic spectrum or directed energy to control the spectrum, attack of an enemy, or impede enemy assaults via the electronic spectrum.

First–of-a-kind (FOAK) - this term is used in engineering economics where the first item or generation of items using a new technology or design can cost significantly more than later items or generations, which are called NOAK, an acronym for “nth of a kind.”

Forward operating base (FOB) - any secured forward military position, commonly a military base that is used to support tactical operations. An FOB may or may not contain an airfield, hospital, or other facilities.

General Officer Steering Committee (GOSC) - reviews and provides endorsement decisions on prospectuses submitted as candidates for concept development.

Government-furnished equipment (GFE) - property in the possession of, or directly acquired by, the government and subsequently furnished to the contractor for performance of a contract. Government property includes material, equipment, special tooling, special test equipment, and real property.

High-assay-low enriched uranium (HA-LEU) - a form of low-enriched uranium with a concentration of ^{235}U between 5 and 20 percent. HA-LEU is commonly used in research reactors with enrichment levels in the 12 to 19.75 percent range.

High-temperature gas reactor (HTGR) - a class of gas-cooled reactors using either prismatic fuel blocks or pebble bed fuel configuration designs. Common features include: high pressure gas, relatively high temperature (for a reactor) at about 1000 °C, use of TRISO fuel, graphite as a moderator, and direct gas cycle (from reactor to Brayton cycle power conversion). The main safety feature of this design is the TRISO fuel that will not melt and release fission products. These design features were the focus of DOE’s Next Generation Nuclear Plant (NGNP) effort.

Highly enriched uranium (HEU) - contains 20 percent or higher concentration of ^{235}U.

Inherently safe (design) - a design that avoids hazards instead of controlling them. As perfect safety cannot be achieved, inherently safe designs simplify processes, reduce the amount of hazardous material and the number of hazardous operations in a device.

International Atomic Energy Agency (IAEA) - an international organization that seeks to promote the peaceful use of nuclear energy, and to inhibit its use for any military purpose, including nuclear weapons. The IAEA was established as an autonomous organization on July 29, 1957.

International Organization for Standardization (ISO) - an international standard-setting body composed of representatives from various national standards organizations. Founded on February 23, 1947, the organization promotes worldwide proprietary, industrial, and commercial standards.

JP-8 - Jet Propellant 8 is a jet fuel, specified and used widely by the U.S. military. It is specified by MIL-DTL-83133 and British Defense Standard 91-87, and is similar to commercial aviation's Jet A-1, but with the addition of corrosion inhibitor and anti-icing additives.

Load - the amount of electric power delivered or required at any specified point or points on a system. Load originates primarily at the power-consuming equipment of the customer. Synonyms are electricity demand or consumption.

Load factor - the ratio of average demand, in kilowatts, over a stated period of time to the maximum demand in kilowatts occurring in that same time period. Load factor is a measure of the variability of the load over a period of time, usually a day, a week, a month, or a year. A load factor of 1.0 corresponds to a load that is on 100 percent of the time. A load factor of 0.50 means that the load has an average demand equal to 50 percent of the maximum demand.

Load following - the process of decreasing/increasing the reactor power to meet electrical load demand. Load following capabilities can range from hour by hour to daily and weekly power variations depending on the electrical demand. The rate of the return to power is controlled by the secondary system heat removal requirements and fuel rod thermal/mechanical behavior.

Load forecasting - the procedures used to estimate future consumption of electricity. These estimates are used in planning for generation, transmission, and distribution facilities; calculating future revenue from the sales of electricity; determining cost allocations for the various rate classes; and assessing the impact on load of changes in policies or underlying conditions such as the level of employment in the region. Load forecasts are developed either to provide the most likely estimate of future load or to determine what load would be under a set of specific conditions (e.g., extremely cold weather, high rates of inflation, or changes in electricity prices). Forecasting procedures include trending (extrapolating past trends into the future) and econometrics (where statistical relationships are established between electricity use and causal variables such as price, population, income, and employment, and then used to forecast load based on projections of these causal variables).

Load growth - the increase in the consumption of electricity from one point in time to another expressed either in absolute or percentage terms. The growth in energy and power demand by a utility's customers.

Low enriched uranium (LEU) - has a concentration of less than 20 percent ^{235}U. Commercial light water reactors, the most prevalent power reactors in the world, use LEU enriched from 3 to 5 percent.

Megawatt electric (MWe) - electric output of a power plant in megawatts.

Micro-encapsulated fuel - a nuclear fuel form composed of a sphere of fissile material (e.g. uranium dioxide, uranium nitride and uranium carbide) encapsulated within graphite and silicon carbide layers to contain fission produces. The spheres, called TRISO fuel particles, range in size from 500 microns to 1000 microns in diameter. These spheres are typical dispersed within an inert matrix of graphite or silicon carbide to for larger fuel elements that make up a nuclear reactor.

Microgrid - a discrete energy system consisting of distributed energy sources (including demand management, storage, and generation) and loads capable of operating in parallel with, or independently from, the main power grid.

Micro-reactor - For this report, a micro-reactor is a system sub-component of a mobile nuclear power plant. The reactor is factory manufactured, small, lightweight (to support MNPP transport via truck, rail, or aircraft), and is designed to produce <20 MWe energy. It maintains neutronic simplicity (e.g., external controls) enabling safe semi-autonomous or autonomous operation.

Mobile nuclear power plant (MNPP) - a portable, complete power plant in the 2-20MW power range, consisting of a micro-reactor/very small modular reactor, coupled with its balance of plant equipment and controls, which is readily and rapidly relocatable by air, sea, or surface transport, as a single entity from one location to another.

Multinational Design Evaluation Program (MDEP) - established in 2006 as a multinational initiative to develop innovative approaches to leverage the resources and knowledge of the national regulatory authorities that are currently or will be tasked with the review of new nuclear power reactor designs.

Nuclear nonproliferation regime - a broad international framework of agreements and organizations aimed at preventing the spread of nuclear weapons and contributing to arms control and disarmament progress. Fears that the Cold War arms race was spiraling out of control led to the initial establishment of the regime, intended to promote stability and reduce the likelihood of nuclear weapons use. The nuclear nonproliferation regime consists of: international treaties, multilateral and bilateral agreements, voluntary (non-binding) agreements, international organizations, domestic agencies, laws, regulations, and policies of participating countries (necessary for regime compliance). The nuclear nonproliferation regime's components serve to: create legally binding nonproliferation obligations, strengthen international norms against the spread of nuclear weapons, control access to nuclear weapons-relevant materials and technologies, build trust between states by verifying compliance with treaty commitments, and enforce treaties in instances of non-compliance.

OCONUS - outside the contiguous United States (i.e., the states of Alaska and Hawaii, and all other countries).

Peak load - the maximum electrical load consumed or produced in a stated period of time. It may be the maximum instantaneous load or the average load within a designated interval of time.

Power purchase agreement (PPA) - or electricity power agreement, is a contract between two parties, one which generates electricity (the seller) and one which is looking to purchase electricity (the buyer).

Seaport of debarkation (SPOD) - the geographic seaport point at which cargo or personnel are discharged. For unit requirements; it may or may not coincide with the destination.

Seaport of embarkation (SPOE) - the geographic seaport in a routing scheme from which cargo or personnel depart. It is a port from which personnel and equipment flow to a port of debarkation; for unit and non-unit requirements, it may or may not coincide with the origin.

Small modular reactor (SMR) - an advanced reactor that produces equivalent electric power less than 300 MWe designed to be built in factories and shipped to utilities for installation as demand arises.

Transportable nuclear power plant (TNPP) - A factory-manufactured, transportable, and relocatable nuclear power plant which, when fueled, is capable of producing final energy products such as electricity, heat, and desalinated water. It includes the nuclear reactor (with or without fuel), the balance of the plant (e.g., turbine, generator) and fuel storage facilities, if necessary. The TNPP is physically transportable, but is not designed to either produce energy during transportation or provide energy for the transportation itself. The installed TNPP, land based or floating, is intended for use in the host State for different purposes such as electricity supply for remote areas, district heating, and desalination of seawater and hydrogen production, while preserving its capability for relocation if necessary. TNPPs are typically constructed and shipped as multiple assemblies from a factory. Upon arrival, these are assembled on-site and integrated into a facility to become a complete power plant. Other approaches such as the Russian power barge Akademik Lomonosov are assembled off-site and moved into position for connection to the power grid.

Tristructural-Isotropic (TRISO) - a type of micro-fuel particle consisting of a fuel kernel composed of UO_2 (sometimes UC or UCO) in the center, coated with four layers of three isotropic materials.

Turnkey Operation - a product or service concept that is complete, installed and ready to use upon delivery or installation.

U.S. Army Corps of Engineers (USACE) - provides oversight, safeguarding, maintenance, and ultimately decommissioning for three U.S. Army deactivated nuclear power plants.

U.S. Nuclear Regulatory Commission (NRC) - created as an independent agency by Congress in 1974 to ensure the safe use of radioactive materials for beneficial civilian purposes while protecting people and the environment. The NRC regulates commercial nuclear power plants and other uses of nuclear materials, such as in nuclear medicine, through licensing, inspection and enforcement of its requirements.

Very small modular reactor (vSMR) – for the purposes of this study, a vSMR is a class of micro-reactors or small modular reactors (SMRs) in the power range of 2-20MW, significantly smaller than commercial SMRs that could be transportable and deployable in forward areas, remote sites, and expeditionary force situations.

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Annex

Preliminary Analysis of Employment, Survivability and Force Protection of MNPP for Ground Operations

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Annex

Preliminary Analysis of Employment, Survivability and Force Protection of MNPP for Ground Operations

Contents

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1.0 Introduction

This Annex depicts mobile nuclear power's relationship to achieving a desired effect under specified standards and conditions through a combination of means and performance of tasks. The Universal Joint Task List (UJTL) is the common reference point throughout this document supporting capabilities-based planning across the range of military operations. Joint Capability Areas (JCAs), Concept of Operation (CONOP), Operational Mode Summary/Mission Profile (OMS/MP), etc., are discussed in relation to mobile nuclear power using relevant terminology to guide follow-on processes and documentation; this document is intended to inform vice replace the aforementioned artifacts.

2.0 Strategic Context

Long-term strategic competitions with China and Russia are the principal priorities for the U.S. Department of Defense (DOD), and require increased and sustained investment, because of the magnitude of the threats they pose to U.S. security and prosperity today, and the potential for those threats to increase in the future. Concurrently, the DOD is sustaining efforts to deter and counter rogue regimes such as North Korea and Iran, defeat terrorist threats to the United States, and consolidate gains in Iraq and Afghanistan while moving to a more resource-sustainable approach[1].

The 2018 National Defense Strategy aptly recognizes that our allies and partners are a critical component globally. Allies and partners provide access to critical regions, supporting a widespread basing and logistics system that underpins the DOD's global reach[2]. These mutually beneficial alliances and partnerships are crucial to the U.S. strategy, providing a durable, asymmetric strategic advantage that no competitor or rival can match[3].

3.0 Overview

The mobile nuclear power plant (MNPP) is a modular, rapidly deployable, and scalable power system providing reliable, utility-grade power to support multi-domain operations (MDO). The MNPP enables several JCAs yet most naturally aligns to JCA 4: Logistics. MNPP provides sufficient power for future directed energy/electronic warfare (DE/EW) systems, supports long-range precision fires, supplies constant and uninterrupted power to energy intensive Air and Missile Defense (AMD) capabilities (e.g., radars, etc.), supports deployment and redeployment (intermediate staging bases, logistics staging areas, medium to large base camps, etc.), can augment entry operations (bolster/supply power to reinforce and expand lodgment), and delivers the high-density power necessary to reinforce or reconstitute damaged infrastructure (e.g., ports, rail, and electrical grids).

The power plant and initial distribution system is transportable within a 40-foot International Organization for Standardization (ISO) container using military air (C-17/C-5), ship

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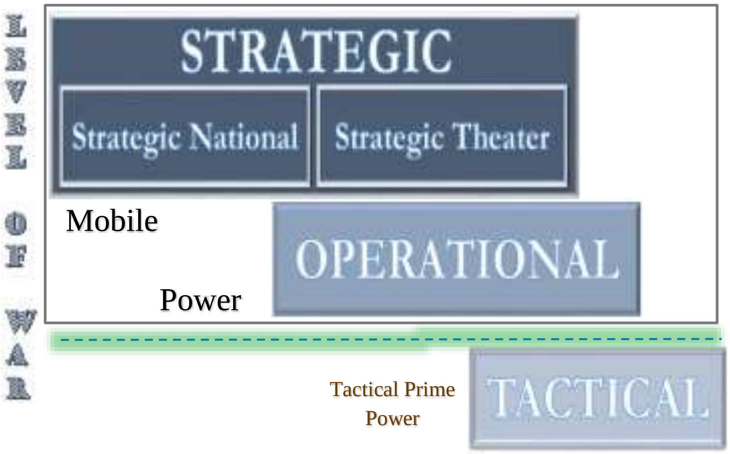
[1] Summary of the 2018 National Defense Strategy of the United States of America; https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

[2] https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf?mod=article_inline, p. 8

[3] ibid

(Navy/MSC/commercial), rail, or vehicle (commercial/military prime mover and trailer). The MNPP can be installed and operational within 72 hours to meet METT-TC mission requirements and is capable of providing 2-20 megawatts (MW) of power, 24/7 for 10 years or longer without resupply or interruption during equipment maintenance cycles.

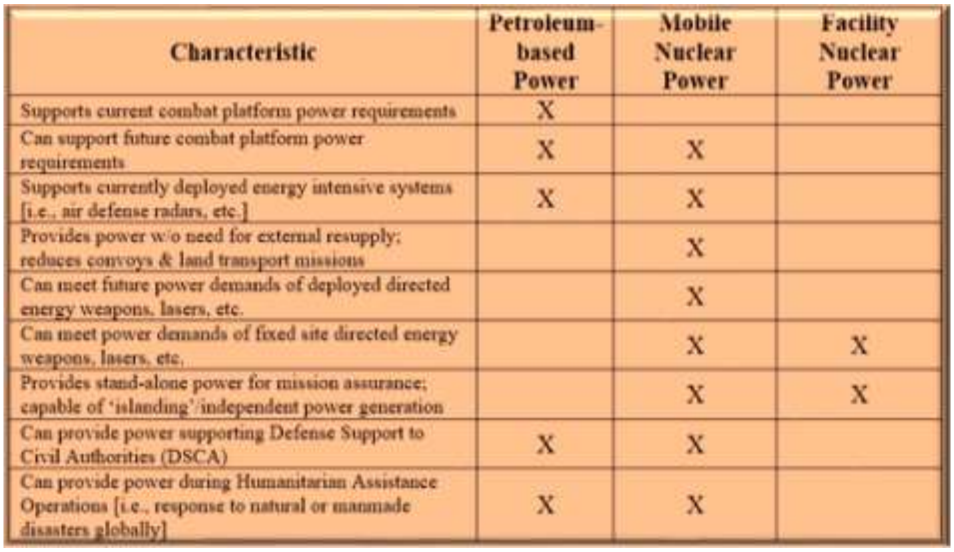
4.0 Employment



Mobile nuclear power directly supports key tasks across three of the four levels of war (LOW) identified in the common UJTL taxonomy, namely: Strategic National (SN); Strategic Theater (ST); and Operational (OP) level tasks. MNPP is designed to provide, bolster, or reconstitute primary power infrastructure supporting MDO and large scale combat operations (LSCO) against near-peer adversaries. MNPP is not specifically designed for the Tactical (TA) level of war or to supplant existing prime power systems employed on the "tactical edge" where battles and engagements are planned and executed to accomplish military objectives assigned to tactical units. Rather, mobile nuclear power provides a reliable, high-density power source enabling critical SN, ST, and OP LOW tasks ensuring both logistics and force flow support maneuver of combat elements to achieve objectives.

4.1 Mission Profile

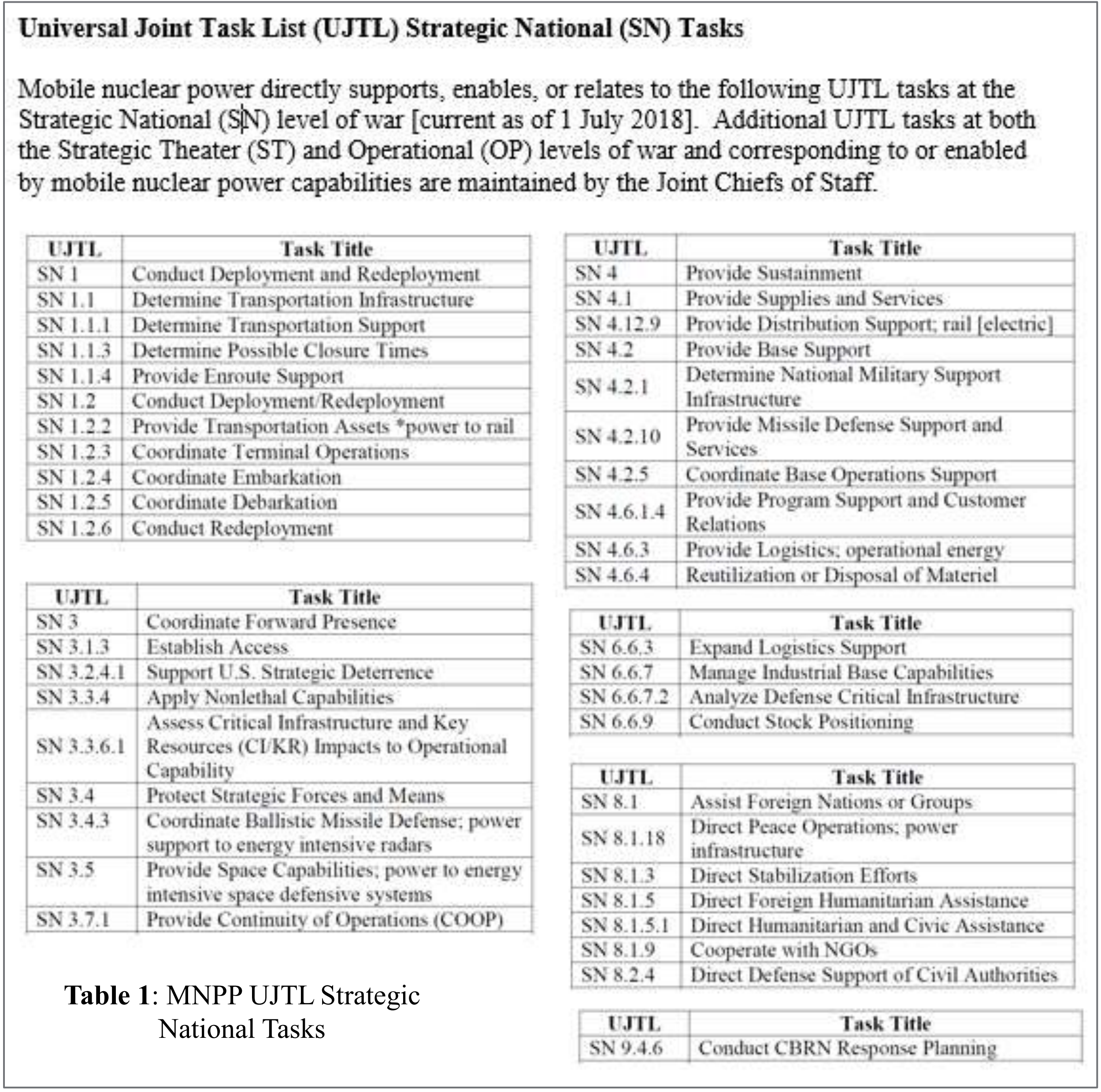
MNPP can support a wide array of functions and applications (see Figure 1) to meet operational energy demand across numerous enabling tasks. This document focuses on the most typical and demanding operations to capture a faithful combination of those activities, system states (modes), and complexities anticipated for the envisioned missions, roles, and operational environments. These areas, and their accompanying UJTL tasks, can be aggregated under the following headings:



Characteristic	Petroleum-based Power	Mobile Nuclear Power	Facility Nuclear Power
Supports current combat platform power requirements	X		
Can support future combat platform power requirements	X	X	
Supports currently deployed energy intensive systems [i.e., air defense radars, etc.]	X	X	
Provides power w/o need for external resupply; reduces convoys & land transport missions		X	
Can meet future power demands of deployed directed energy weapons, lasers, etc.		X	
Can meet power demands of fixed site directed energy weapons, lasers, etc.		X	X
Provides stand-alone power for mission assurance; capable of 'islanding'/independent power generation		X	X
Can provide power supporting Defense Support to Civil Authorities (DSCA)	X	X	
Can provide power during Humanitarian Assistance Operations [i.e., response to natural or manmade disasters globally]	X	X	

Figure 1: Mobile Nuclear Power

- Ports, Airfields, Remote Operations, and Contingency Bases
- Forward Base Mode (FBM) Radar Site Operations
- Defense Support to Civil Authorities (DSCA)/National Response Framework (NRF).



Universal Joint Task List (UJTL) Strategic National (SN) Tasks

Mobile nuclear power directly supports, enables, or relates to the following UJTL tasks at the Strategic National (SN) level of war [current as of 1 July 2018]. Additional UJTL tasks at both the Strategic Theater (ST) and Operational (OP) levels of war and corresponding to or enabled by mobile nuclear power capabilities are maintained by the Joint Chiefs of Staff.

UJTL	Task Title
SN 1	Conduct Deployment and Redeployment
SN 1.1	Determine Transportation Infrastructure
SN 1.1.1	Determine Transportation Support
SN 1.1.3	Determine Possible Closure Times
SN 1.1.4	Provide Enroute Support
SN 1.2	Conduct Deployment/Redeployment
SN 1.2.2	Provide Transportation Assets *power to rail
SN 1.2.3	Coordinate Terminal Operations
SN 1.2.4	Coordinate Embarkation
SN 1.2.5	Coordinate Debarkation
SN 1.2.6	Conduct Redeployment

UJTL	Task Title
SN 3	Coordinate Forward Presence
SN 3.1.3	Establish Access
SN 3.2.4.1	Support U.S. Strategic Deterrence
SN 3.3.4	Apply Nonlethal Capabilities
SN 3.3.6.1	Assess Critical Infrastructure and Key Resources (CI/KR) Impacts to Operational Capability
SN 3.4	Protect Strategic Forces and Means
SN 3.4.3	Coordinate Ballistic Missile Defense; power support to energy intensive radars
SN 3.5	Provide Space Capabilities; power to energy intensive space defensive systems
SN 3.7.1	Provide Continuity of Operations (COOP)

UJTL	Task Title
SN 4	Provide Sustainment
SN 4.1	Provide Supplies and Services
SN 4.12.9	Provide Distribution Support; rail [electric]
SN 4.2	Provide Base Support
SN 4.2.1	Determine National Military Support Infrastructure
SN 4.2.10	Provide Missile Defense Support and Services
SN 4.2.5	Coordinate Base Operations Support
SN 4.6.1.4	Provide Program Support and Customer Relations
SN 4.6.3	Provide Logistics; operational energy
SN 4.6.4	Reutilization or Disposal of Materiel

UJTL	Task Title
SN 6.6.3	Expand Logistics Support
SN 6.6.7	Manage Industrial Base Capabilities
SN 6.6.7.2	Analyze Defense Critical Infrastructure
SN 6.6.9	Conduct Stock Positioning

UJTL	Task Title
SN 8.1	Assist Foreign Nations or Groups
SN 8.1.18	Direct Peace Operations; power infrastructure
SN 8.1.3	Direct Stabilization Efforts
SN 8.1.5	Direct Foreign Humanitarian Assistance
SN 8.1.5.1	Direct Humanitarian and Civic Assistance
SN 8.1.9	Cooperate with NGOs
SN 8.2.4	Direct Defense Support of Civil Authorities

UJTL	Task Title
SN 9.4.6	Conduct CBRN Response Planning

Table 1: MNPP UJTL Strategic National Tasks

To clarify, employment of the MNPP in support of port, airfield, remote operations, and contingency bases within an operational environment consistent with large scale combat operations against a near-peer adversary is the most demanding operation. That said, any of the aforementioned operations (e.g., FBM Radar Sites, DSCA) along with their corresponding operational environments can serve as a practical base-mission profile within an OMS/MP estimate. FBM Radar and DSCA are presented below preceding a more elaborate discussion of the most typical operations: support to ports; airfields; remote operations; and contingency bases.

4.2 Forward Base Mode Radar Sites

The Forward Base Mode (FBM) radar sites utilize the Army Navy/Transportable Radar Surveillance (AN/TPY-2) radar, which complements the Terminal High Altitude Area Defense (THAAD) air defense/missile batteries. FBM sites are enduring, strategic locations that currently utilize the MEP-PU-810 (petroleum fueled) or similar to provide primary and backup power for 24/7/365 radar operations. Mobile nuclear power can easily meet the power demands of these energy intensive systems. Further, the MNPP can serve as primary and backup power supporting the operational area, thereby replacing commercial, host nation power where mission assurance and resilience is desirable. These sites may locate in remote areas where power system reliability, robustness, and service longevity are essential. MNPP provides resilient (capable of "islanding"[1]) and continuously available power, including no interruption during power system maintenance.

4.3 Defense Support to Civil Authorities (DSCA) / National Response Framework (NRF)

The MNPP may be rapidly deployed to a continental United States (CONUS) or outside continental United States (OCONUS) to Alaska, Hawaii, and U.S. territories in the event of a natural disaster to provide emergency power to key facilities responsible for life-saving, life-sustaining, public health, safety, and administrative facilities. DSCA mission support is typically coordinated through the Federal Emergency Management Agency (FEMA) and the United States Army Corps of Engineers (USACE) using the National Response Framework (NRF) as an architecture to guide disaster relief response. The MNPP will be installed to provide temporary power through an expedient distribution grid or it may be connected to existing substations or facilities. MNPP dramatically reduces logistics traffic and port/airfield congestion by providing significant, reliable, and independent power without the petroleum sustainment burden currently required.

Highly Developed Theater
Seaports of debarkation and aerial ports of debarkation may be available but require improvement.
Geospatial data may be available.
Real estate may be more available for acquisition.
Environmental baseline may be established.
Installations may be available for temporary use.
Road network is available.
Man-made obstacles predominate.
Complex or extensive infrastructure is present.

Figure 2: Highly Developed/Mature Theater

4.4 Ports, Airfields, Remote Operations, and Contingency Bases

From a macro perspective, mobile nuclear power supports operations in two general geographic categories, highly developed theaters and lesser developed theaters. The role of the MNPP in any theater can vary based upon Combatant Commander (CCDR) priorities; however, mobile nuclear power is configurable to enable key tasks across a broad spectrum. An example of a highly developed theater, along with associated characteristics (see Figure 2), is found within the United States European Command (USEUCOM) where infrastructure and power demands are ***significant***. Mobile nuclear power can bolster or reconstitute power at ports, airfields, and transportation infrastructure damaged

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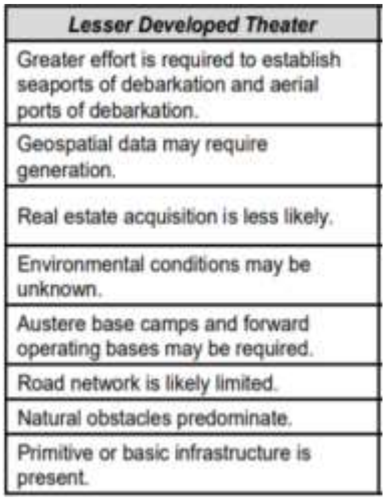
[1] Islanding is the condition in which a distributed generator (DG) continues to power a location even though electrical grid or external power is no longer present.

during previous phases of LSCO. MNPP directly supports or enables a variety of critical tasks (see Table 1). One example is SN 1.2.3: Coordinate Terminal Operations wherein MNPP provides a high-density, utility-grade power source supporting transit storage and marshaling of cargo; loading and unloading of ships or aircraft; and forwarding of cargo to destination.

Moreover, mobile nuclear power is able to restore and/or provide continuously reliable, large-scale, utility-grade power to other critical infrastructure. This includes European rail, a vital component for ensuring logistics and force flow within theater. Rail in Europe is mostly electrified and restoring electric power infrastructure is therefore critical to transport. This is especially true in large cities and ports where rail today runs almost exclusively on electricity. Regarding main lines, 60 percent of the European rail network is electrified and 80 percent of traffic runs on these lines[1]. Using prime power spot generation to reestablish this level of power is prohibitive, impractical, and redirects Class III (petroleum) away from combat platforms. Also of significance, MNPP meets the large scale power demands of intermediate staging bases, logistics staging areas, and medium to large base camps further enabling the focus on maneuver for the delivery of petroleum fuel.



Lesser Developed Theater
Greater effort is required to establish seaports of debarkation and aerial ports of debarkation.
Geospatial data may require generation.
Real estate acquisition is less likely.
Environmental conditions may be unknown.
Austere base camps and forward operating bases may be required.
Road network is likely limited.
Natural obstacles predominate.
Primitive or basic infrastructure is present.

Figure 3: Lesser Developed/Immature Theater

Examples of lesser developed theaters and their corresponding attributes (see Figure 3) include areas within United States Pacific Command (USPACOM) and United States Central Command (USCENTCOM). Some of these areas are characterized as having limited or less than the required infrastructure, at least initially, to meet desired levels. Lesser developed theaters require a greater effort to meet CCDR priorities across the entire SN 4: Provide Sustainment series of tasks. Maintaining those levels necessary to support the national and/or military strategy includes, by definition, those efforts to reduce the sustainment burden through improved operational energy performance and efficiency during sustainment operations. Mobile nuclear power not only meets this definition but greatly improves both efficiency and performance in lesser developed theaters. MNPP can be deployed within 72 hours to produce sustainable power at ports, airfields, contingency bases, and remote locations. Additionally, the expansion of contingency bases, historically powered by petroleum fuel, is recognized as less than optimum for a variety of reasons including:

- Significant quantities of fuel redirected away from maneuver to support contingency base operations (traditional base operations support [BOS] functions).
- Increased logistics requirements and supply lines to handle and transport Class III(B) introducing risk, particularly during land transport missions.
- Use of diesel generators in remote locations where little or no access to an established or stable electrical grid and/or where diesel fuel logistics and storage impose substantial economic challenges curtails options and/or increases complexity.

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[1] European Commission. 2017. *Electrification of the Transport System.* European Union, Brussels, Belgium. https://ec.europa.eu/programmes/horizon2020/en/news/electrification-transport-system-expert-group-report-0.

> **Example:** The Forward Operating Base (FOB) with the capacity of Bagram Airfield in Afghanistan represents a significant, recurring power demand [≈ 50+ MW] currently met with multiple diesel generators. Using an averaged $7/gallon [roughly twice the averaged CONUS retail price], the annual fuel cost approaches $256M and more importantly, requires the support for 286 annual refueling convoys. Mobile nuclear power is capable of replacing diesel generation, reducing petroleum fuel demand and associated transport risk, while providing stand-alone distributed generation without the risk of external power dependence ['Islanding'] or need for an existing electrical grid or fuel resupply of petroleum power generation.
>
> *'Islanding' is the condition in which a distributed generator continues to power a location even though electrical grid or external power is no longer present.*

- Ad-hoc approach and non-standard base camp designs lead to less than optimum power production, arbitrary configuration, and spot-generation (least desirable).

Redirecting Class III(B) away from combat platforms that are wholly reliant upon petroleum fuel for maneuver to support intermediate staging bases, logistics staging areas, and medium to large base camps introduces significant risk to effective execution of MDO. Concepts and emergent doctrine, including the Army Functional Concept for Movement and Maneuver, require Brigade Combat Teams (BCTs) to possess sustainment capabilities necessary to conduct cross-domain maneuver at extended supporting range and distance for up to seven days while achieving operational objectives. This requires an additional four days of supply for each BCT. The Army Sustainment Battle Lab (U.S. Army CASCOM) was directed during Unified Challenge 17 to plan for an Armored Brigade Combat Team (ABCT) to conduct semi-independent operations requiring a total of six days of supply (4 more than is currently available)[1]. The sustainment implications were significant (see Figure 4) including 500K gallons of Class III(B) in 5K tankers—the replenishment convoy for four days of supply of Class III(B) was estimated at 12 miles in length.

Predicated on the strategic context outlined within the 2018 National Defense Strategy, long-term strategic competitions with China and Russia as the principal priorities for the DOD, employment of the mobile nuclear power is consistent with the anticipated power demands and requisite tasks in both highly developed and lesser-developed theaters. Mobile nuclear power is a deployable, reliable, and sustainable option for reducing petroleum demand and focusing fuel forward to support the CCDR and maneuver.

Figure 4: Four Days of Supply for one ABCT

5.0 System Survivability

Consistent with the mission profile and employment described above, the most dangerous and likely threat to the MNPP system is near-peer adversary Theater

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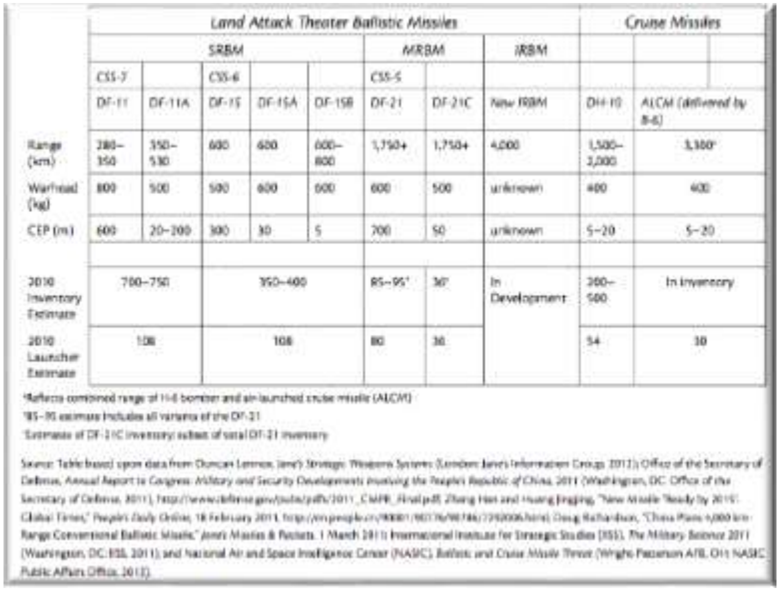
[1] *Sustainment Implications of the Semi-Independent Brigade Combat Team*, CASCOM, 27 February, 2017.

Missile (TM) and Ballistic Missile (BM) capabilities [see Table 2]. Theater Missile Defense (TMD) and Ballistic Missile Defense (BMD) are inherently a joint mission. Joint force components, supporting combatant commanders and multinational force BMD capabilities are required to be integrated[1]. They have the common objective of neutralizing or destroying the enemy's ballistic missile capability and are integrated to support the Joint Force Commander's (JFC's) overall concept of operations and major operational objectives.

Terminal High Altitude Area Defense (THAAD) and Patriot missile systems, possibly augmented by Aegis cruisers or destroyers, provide a two-tier defense for selected high-value assets[2], such as major ports. The two tiers provide a near impenetrable defense, deny the enemy a preferred attack option, and support the joint force. THAAD provides the upper-tier defense against medium- and short-range ballistic missiles, while Patriot and Aegis provide the lower-tier defense against short-range ballistic missiles, cruise missiles and air-to-surface missiles. (Patriot also has the capability to engage air breathing threats.)[3]

Table 2: Chinese conventional land-attack ballistic and cruise missiles



	Land Attack Theater Ballistic Missiles								*Cruise Missiles*	
	SRBM					MRBM		IRBM		
	CSS-7		CSS-6			CSS-5				
	DF-11	DF-11A	DF-15	DF-15A	DF-15B	DF-21	DF-21C	New IRBM	DH-10	ALCM (delivered by B-6)
Range (km)	280–350	350–530	600	600	600–800	1,750+	1,750+	4,000	1,500–2,000	3,300[a]
Warhead (kg)	800	500	500	600	600	600	500	unknown	400	400
CEP (m)	600	20–200	300	30	5	700	50	unknown	5–20	5–20
2010 Inventory Estimate	700–750		350–400			85–95[b]	30[c]	In Development	200–500	In inventory
2010 Launcher Estimate	108		108			80	30		54	30

[a] Reflects combined range of H-6 bomber and air-launched cruise missile (ALCM)

[b] 85–95 estimate includes all variants of the DF-21

[c] Estimate of DF-21C inventory; subset of total DF-21 inventory

Source: Table based upon data from Duncan Lennox, *Jane's Strategic Weapons Systems* (London: Jane's Information Group, 2012); Office of the Secretary of Defense, *Annual Report to Congress: Military and Security Developments Involving the People's Republic of China, 2011* (Washington, DC: Office of the Secretary of Defense, 2011), http://www.defense.gov/pubs/pdfs/2011_CMPR_Final.pdf; Zhang Han and Huang Jingjing, "New Missile 'Ready by 2015'," *Global Times, People's Daily Online*, 18 February 2011, http://en.people.cn/90001/90776/90786/7292006.html; Doug Richardson, "China Plans 4,000 km-Range Conventional Ballistic Missile," *Jane's Missiles & Rockets*, 1 March 2011; International Institute for Strategic Studies (IISS), *The Military Balance 2011* (Washington, DC: IISS, 2011); and National Air and Space Intelligence Center (NASIC), *Ballistic and Cruise Missile Threat* (Wright-Patterson AFB, OH: NASIC Public Affairs Office, 2013).

Enemy observation and specific targeting of the MNPP system housed within a 40-foot ISO container is estimated as problematic given the number of similar structures and heat signatures present. Terminal operations at the Port of Rotterdam alone handles over 11,500,000 similar sized containers annually without inclusion of intermodal traffic proximate to the port. It is anticipated that ports, airfields, remote sites, and contingency bases themselves constitute primary targets for enemy TM and BM threats and an MNPP system resides under CCDR allocated protection capabilities.

Figure 5: Port of Rotterdam

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[1] Army Techniques Publication (ATP) 3-01.7 *Air Defense Artillery Brigade Techniques*, March 2016

[2] ibid

[3] ibid

Concerns related to enemy targeting of a nuclear power source (i.e., second and third order effects) appear, on the surface, unfounded as Europe maintains well over 100 active nuclear power plants[1] employing traditional (legacy) nuclear technology and considerably larger in scale than the MNPP system. France alone derives ~75 about of its electricity from nuclear energy[2]. If damaged, these large-scale plants are capable of generating significant radioactive hazards including down-wind particulate (i.e., requiring plume modeling software analysis). In contrast, the MNPP employs advanced reactor and fuel technology with no/minimal anticipated down-wind hazard zone. MNPP system hazards are addressed in the Force Protection section of this document depicting the protection of personnel who may be adversely affected by the system or threats to the system.

Nuclear Power Plants in Operation in Europe, November 2016

The probability of adversary mission success using TM and BM will vary greatly depending upon several key factors including technology (precision factors). The formulas in Table 3 are used as the basis to provide the circular error probable 50 percent (CEP50), corresponding to any actual warhead (e.g., unitary or submissions), destructive power (kg), and the radius in which 50 percent of all missiles fired would land. Estimates can vary substantially based upon country of origin, with near-peer adversaries typically having more sophisticated precision guidance systems than regional actors (e.g., Iran, North Korea, etc.). For regional actors such as Iran with technology largely built upon previous Chinese versions, the CEP50 ranges between 100 and 700 meters depending upon missile design (see Figure 6). The Iranian estimate results in between a one-in-one hundred and one-in-one thousand chance to ensure destruction for a soft point target (example, exposed aircraft, unprotected personnel). For hardened targets (i.e., if MNPP is afforded a basic engineer constructed defensive position) the probability drops to as low as one-in-ten thousand to destroy with moderate confidence a single, fixed-point military target[3].

Table 3: Formulas

Probability of Hit given CEP and Target Size:

$P = 1 - exp\ (-0.6931 * [R^2/CEP^2]$

P=Probability of Hit
R=Radius of Target
CEP=Circular Error Probable of Weapon

Single Shot Survivability Probability (SSPS):

$SSPS = 0.5\ (LR/CEP)\ \text{^}2$

LR = Lethal Radius
CEP=Circular Error Probable of Weapon

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[1] Euronuclear.org, https://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-europe.htm.

[2] World-nuclear.org www.world-nuclear.org/information-library/country-profiles/countries-a.../france.aspx.

[3] *Iranian Missile Threat to US Air Bases: Distant Second to China's Conventional Deterrent – Analysis*, Eurasia Review, 9 September, 2015 https://www.eurasiareview.com/09092015-iranian-missile-threat-to-us-air-bases-distant-second-to-chinas-conventional-deterrent-analysis/.

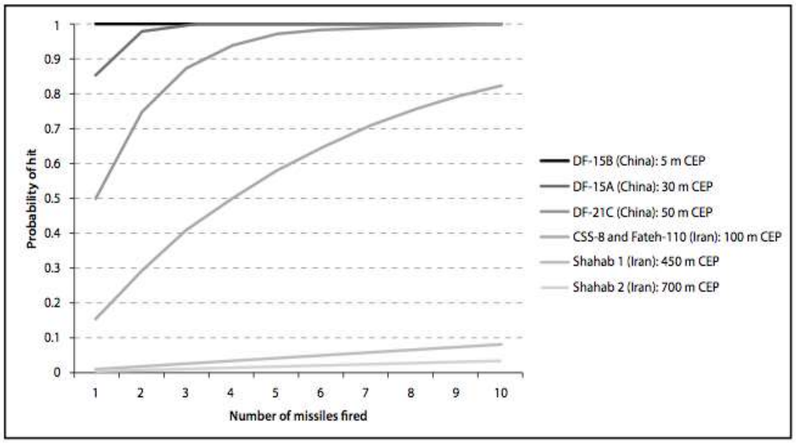

Figure 6: Hit Probability Comparison China and Iran

Near-peer competitors, such as China, employ more mature guidance technology resulting in increased precision and a lower CEP. The Chinese DF-21C with a 50-meter CEP was selected to serve as a basis for calculation to represent a near-peer adversary.

Given MNPP's approximate 42 sq/m ISO container footprint, in the open, and without improvement of any type (soft target) as a worst-case scenario, there is <1% probability of a hypocenter hit by a near-peer adversary TM or BM with a 50m CEP. Other factors with significant impact on system survivability include the warhead (unitary, submissions, etc.), detonation (i.e., delay, "quick," airburst, etc.) and destructive power [kg]. Similar to the vast majority of platforms, structures, and systems on the battlefield where TM or BM are anticipated as the most likely threats, the MNPP is not expected to survive a direct kinetic attack (see Figure 7 - Hypocenter, Ring 1: Complete Destruction, and Ring 2: Severe Damage). However, provided modestly improved position similar to constructed defensive fighting positions (e.g. dug in with overhead cover), the MNPP survivability is expected to increase substantially. Note, MNPP system shutdown and containment are addressed under Force Protection for the protection of personnel who may be adversely affected by the system or threats to the system.

Chemical, biological, radiological, and nuclear (CBRN) survivability is projected as a Key Performance Parameter (KPP) and it is anticipated the system shall be able to withstand the effects of CBRN contaminants and decontaminants, be able to be decontaminated to negligible risk levels, and be capable of being operated to successfully perform its mission in a CBRN environment. This includes operations wherein personnel are clothed in their appropriate individual Mission Oriented Protective Posture (MOPP) ensemble or personal protective equipment (PPE) for civilian applications. Accessibility and space shall be provided to store a portable decontamination apparatus proximate to the power plant. MNPP employment shall include the ability to install/operate an automatic chemical agent detector/alarm system (current inventory or emerging) with space provided for the storage of a chemical agent detector kit (T = O).

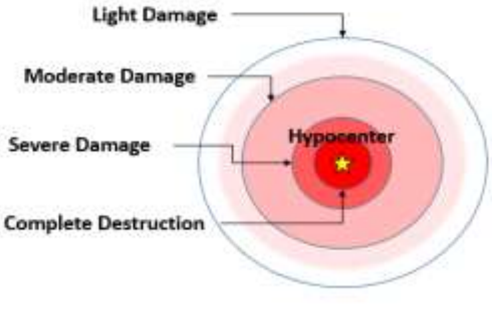

Figure 7: Disabling Probability Chart

6.0 Force Protection

This section addresses the protection of the system operator(s) or other personnel against kinetic and non-kinetic fires, CBRN, and environmental effects, rather than protection of the system itself and its capabilities.

6.1 Overview

The MNPP system is based upon redundant, diverse, and passive safety features achieved by leveraging new innovations in nuclear technology design to afford maximum protection to all personnel. These new designs incorporate lessons-learned from severe nuclear power plant accidents and operational-experience along with new technology employing modern, melt-resistant fuels. These fuels offer significant benefits in terms of sealing radioactive volatiles within the fuel itself under all operational and off-normal conditions. Some new designs seal the melt-resistant fuel within multi-layered and reinforced structures that are passively cooled by environmental air. Additionally, the MNPP will include engineered safety systems addressing design basis threat (DBT)/attack scenarios beyond those identified in the system survivability section to ensure the protection of users or other personnel who may be adversely affected by the system or threats to the system.

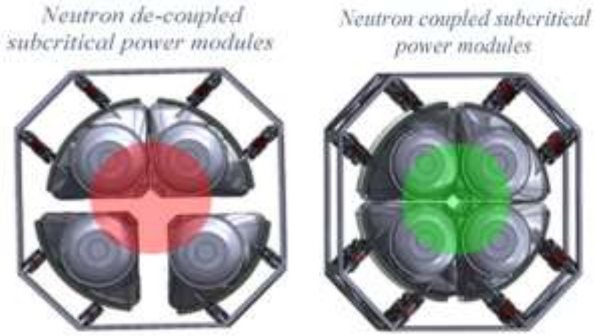

Figure 8: Independent Power Modules

6.2 System Safety

The MNPP system implements designs with multiple independent subcritical power modules[1]. Figure 8 represents an immediate shutdown capability and passive cooling. These independent modules enable omission of the conventional network of piping, tubing, fittings, valves, and electrical conduits coupling independent components, typically found in various reactor designs (small and large) and referred to as balance of plant (BoP). These are replaced by integrating the power conversion equipment with specially designed fuel cartridges. BoP elimination avoids risks associated with loss of coolant accidents (LOCAs) while decreasing the design vulnerability to design basis threats and beyond design basis accident scenarios. As each subcritical power module is sealed through multiple layers forming independent pressure boundaries, and the fuel cartridges are entirely segregating the fuel, the risks of radionuclide transports outside of the subcritical power modules is greatly reduced.

Computer fluid dynamic, mass and heat transfer analyses show that even under total loss of coolant the fuel cartridges temperatures remain significantly below safety thresholds with passive cooling. The melt-resistant fuel loaded within fuel cartridges were tested above safety

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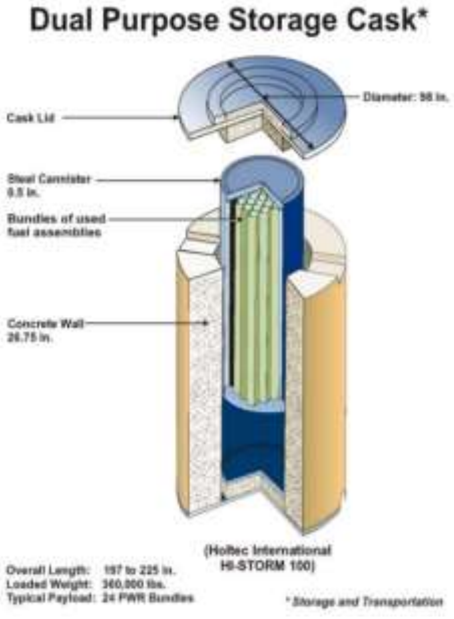
[1] Market research conducted on representative new technology; information obtained from HolosGen http://www.holosgen.com/.

temperature thresholds and demonstrated no release of volatile radionuclides up to extremely high temperatures (that cannot be reached via passive cooling)[1]. Each fuel cartridge segregates the melt-resistant fuel and provides mechanical and hydrostatic features that further minimizes migration of radionuclides. The small radioactive sources represented by a fractioned core and the diverse and redundant inherent passive and engineered safety features make fuel cartridges a substantially reinforced multi containment system.

Each subcritical power module rejects thermal energy as a result of the combined Brayton and Rankine power cycles operations. In these innovative designs, the unavoidable thermal rejection to the environmental air (Ultimate Heat Sink – UHS) occurs in two steps: the Brayton cycle components transfer the rejected thermal energy to a closed-loop Organic Rankine Cycle (ORC) integrated and thermally coupled with the subcritical power module reflectors and shield; the ORC condenser is then passively coupled to environmental air through heat exchangers thermally coupled to dedicated ISO container heat exchange surfaces. In this manner, the total amount of thermal energy rejected to the environment is reduced and the thermodynamic efficiency is increased (from 45 to 60 percent). The closed-loop integral ORC system captures a portion of the waste thermal energy rejected by the Brayton cycle and converts it into conditioned electricity. As the subcritical power module is positioned to execute a temporary or permanent shutdown, its fuel cartridge continues to naturally produce decay heat. The electrical power rate produced under shutdown is proportional to the power history prior to shut down and the time elapsed from shutdown. Passive natural convective air-cooling maintains adequate fuel cartridge cooling even under LOCA scenarios.

New innovations in nuclear fuels significantly improve safety. Encapsulated fuel technologies are notable in their ability to support operating and soldier safety. Examples include tristructural-isotropic (TRISO) which uses fuel particles consisting of a microsphere (i.e., kernel) of nuclear material encapsulated by multiple layers of pyrocarbon and a SiC (silicon carbide) layer. This multiple-coating-layer system is engineered to retain the fission products generated by fission of the nuclear material in the kernel during normal operation and all licensing basis events over the design lifetime of the fuel. Although operations depend on many factors, encapsulated fuels, such as TRISO, are particularly critical to safe reactor operation as the primary (but not the only) barrier to fission-product release.



6.3 Disposal

When the fuel cartridges are replaced at the end of their fuel cycle, power conversion components can be reconditioned and the generator can be re-licensed to resume operation for a total operational life of 60 years (two additional total fuel cartridges replacement per refueling after the first fuel cycle of 20 years). To substantially reduce decommissioning cost, system fuel cartridges and power conversion components can be

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[1] ibid

designed to fit within licensed canisters for temporary or long-term storage. As portions of the power components (mainly the electric motors representing the generator and recirculator) are removed from the subcritical power module, the fuel cartridges remain sealed within their reinforced structure during decommissioning activities and all the way to the welding of the storage cask lid. Depending on applications, the components continue to produce electricity at power rates proportional to the decay rate. As a portion of the decay heat energy is converted into electricity, fuel cartridges represent a lowered thermal loading for the dry cask and for underground, unventilated repositories with no active cooling. Fuel cartridge extraction, lifting and repositioning within licensed casks can be executed with conventional hydraulic lifting equipment (military or commercial) retrofitted with shields and remotely operated. Alternatively, the fuel cartridges can be lifted with cranes and positioning within dry casks follows procedures similar to those adopted for refueling and storage of conventional light water reactor fuel bundles (no extra shielding required).

6.4 Threat Risk and Consequence Management

The Defense Science Board (DSB) Task Force stated unequivocally that proliferation concerns associated with a vSMR reactors [MNPP is a type of vSMR] are likely no greater than that associated with commercial reactors. MNPP incorporates the recommendations of the latest DSB Final Report[1], including the use low-enriched uranium (LEU) [i.e., less than 20 percent enrichment] or other fuel types to decrease proliferation risk. Key System Attributes of the MNPP includes specifications for the reactor to pose no significant increase in threat consequence effects (e.g., unacceptable radiological consequences) and that the reactor will be capable of immediate shutdown and passive cooling—attributes that are currently available. The MNPP system is capable of immediate shutdown and uses passive cooling—current designs incorporate the latest threat risk and mitigation technology. The MNPP system will benefit from and be informed by independent consequence management scenario studies conducted by the Defense Threat Reduction Agency (DTRA) with the support of the Department of Energy (DOE) and in accordance with the DSB report.

6.5 Security

The employment concept for the MNPP system will include physical and technical security standards commensurate with nuclear material handling. In practice, this will follow established Physical Security program standards and safeguards in accordance with the governing authority. This generally aligns to physical boundary separation, patrol zones, and controlled access requirements similar to those found in Sensitive Compartmented Information Facilities (SCIFs); however, an MNPP system will not likely require the same levels of clearance/access as a SCIF (e.g., DOD Top Secret or DOE Q levels).

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[1] Defense Science Board *Task Force on Energy Systems for Forward/Remote Operating Bases, Final Report*, 1 August 2016.

6.6 Human System Integration (HSI)

Defense-in-depth is a safety philosophy in which multiple lines of defense and conservative design and evaluation methods are applied to ensure safety. The philosophy is also intended to deliver a design that is tolerant to uncertainties in knowledge of plant behavior, component reliability, or operator performance that might compromise safety. A comprehensive review of the regulatory foundation for defense-in-depth along with a definition of defense-in-depth appropriate for advanced reactor designs, specifically MNPP, will accompany the development process.

The assigned Program Manager for MNPP will address the applicable HSI domains (i.e., manpower, personnel, training, human factors engineering, environment, safety, occupational health, personnel survivability and habitability) IAW DOD 5000.2 to optimize total system performance, minimize total operational cost and ensure the system is built to accommodate the characteristics of the operational users that will operate, maintain, and support the system. The HSI design will incorporate as many cost and manpower savings features as possible to lessen the manpower impact on remote and mobile deployments.

6.7 Personnel Protection

MNPP system operations will follow HSI guidance for personnel safety; however, it is expected that normal plant operations will not require personal protective equipment (PPE). Personal safety in the event of an attack will follow evacuation planning guidance, and as necessary, use individual Mission Oriented Protective Posture (MOPP) or PPE at prescribed levels.

6.8 Evacuation Planning Zones

The small modular reactor design of the MNPP system (includes a much smaller amount of fuel), independent subcritical power modules, and sealed and reinforced fuel cartridges enable a substantial reduction of Evacuation Planning Zone (EPZ). Conventional (traditional) nuclear plants require EPZ’s measured in miles (see Figure 9). The MNPP system reduces the EPZ to hundreds of feet, a substantive leap forward in safety.

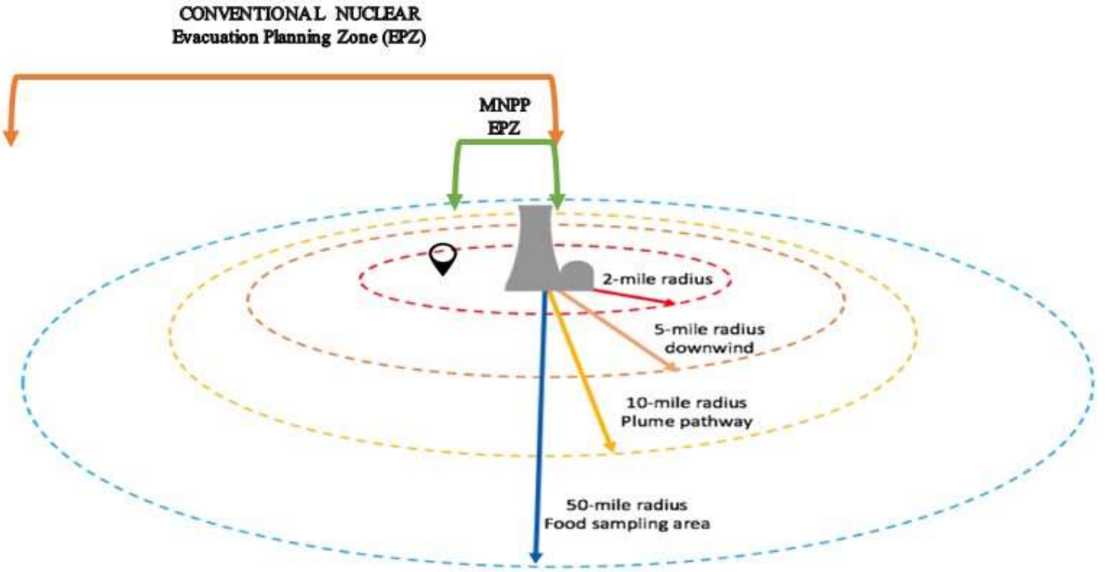

Figure 9: Conventional Nuclear Planning Zone (EPZ)

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UNITED STATES ARMY