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Purpose

This paper provides a high level overview of current nuclear power technology and the potential use of nuclear power at military bases. The size, power ranges, and applicability of nuclear power units for military base power are reviewed. Previous and current reactor projects are described to further define the potential for nuclear power for military power.

Introduction

Nuclear power was demonstrated and made practical so that it could support the military mission of powering ships and submarines. The critical mission benefits of almost unlimited air and fuel-independent power on submarines helped spur development of the nuclear power technology that still forms the basis for the modern nuclear power industry.[i] Potential production of large amounts of power with low-fuel volume inputs attracted military interest shortly after nuclear power was proven to be viable.[ii] The expected benefit of nuclear power plants at a forward operating base (FOB) is a significant reduction in the operational and transportation risks and cost required to power FOBs. The reduction in fuel and water volumes that need to be transported is viewed as particularly valuable during war time, when mission capability and reducing enemy exposure is considered much more important than cost.

Modern nuclear technology can develop a reactor that is inherently safe transportable and can be rapidly deployed to provide electrical power, heat, energy for purified water, and energy to manufacture liquid fuels for operations. This FOB local capability would greatly reduce the number of trucks or supply flights required to maintain the base capability. Fewer required trucks reduce the exposure of soldiers to attack while transporting fuel and water. This advanced capability would need to be met with a unique, small, advanced technology nuclear reactor.

Nuclear Reactor Technology

Nuclear reactors utilize a number of technologies in core design, fuel type, neutron moderator, coolants and power generation equipment to operate reliably and safely. Table 1 shows a few of the many combinations of nuclear properties utilized in successful reactor designs. There is large number of potential reactor technology combinations that have been demonstrated with test, research, and power reactors of various sizes. Commercial nuclear power plants can be as large as 1,700 MW electric[iii], using industrial steam turbines, down to space nuclear reactor systems[iv] that can operate at less than 5 kW, using thermoelectric converters.

The wide range in nuclear power generation is also reflected in a large range of physical sizes. Large commercial reactors vessels are some of the largest and heaviest components moved over a long distance. A large commercial PWR reactor cores are manufactured in only a few foundries around the world because of their size and shipped to build site. Individual components, reactor vessel, steam generator, and deaerator weigh several hundred tons and can be more than a hundred feet long.[v] The typical PWR vessel weights approximately 500 tons and is approximately 39 ft tall and 16 ft in diameter.[vi] The larger structures that make up primary containment are assembled on site and are significantly larger and heavier. Turbine and generators can also be very large and heavy. Transporting all these components is a significant challenge requiring mature infrastructure and unchallenged transport. Small Modular Reactors as the name suggests are much smaller and lighter. The NuScale reactor, 45 MWe, with all the primary components included is 76 ft long and 15 ft wide. This reactor was intended to be truck transportable using specialized heavy transport trailers.[vii] Even smaller reactors have been built and demonstrated that can be mounted fully or as components on a standard truck trailer. All the reactor concepts in Table 1 exist over a similar range of sizes and weights. The small sealed transportable autonomous 100 MWe reactor (SSTAR) is a lead cooled reactor design intended to approximate the goals of a large FOB reactor. The reactor and full primary system is 49 ft high and 10 feet in diameter and weighs approximately 500 tons. The reactor is designed to operate for 30 years. Smaller versions of the SSTAR reactor are also being designed.[viii]

The larger the reactor the more heat needs to be rejected; approximately twice the electric power is rejected as waste heat. Large commercial plants depend on very large cooling, towers, lakes or large rivers to reject heat. Heat discharge and the need for water is a major consideration in selecting a site for commercial reactor. When the much smaller reactors are designed there is the potential to use air cooling for heat discharge. Air cooling avoids the need for large quantities of water and makes site selection much easier. This technology would parallel at a larger scale that used by large diesel generators.

Reactor Type	Fuel	Coolant	Moderator	Power Cycle
Pressurized Water Reactor	UO_2	Water	Water	Primary or Primary/Secondary Steam Loops
High Temperature Gas Reactor	UO_2	High temperature CO_2 or He	Carbon	Gas/Secondary Steam loop, direct gas cycle, Brayton Cycle
Liquid Metal Fast Reactor	UO_2 or Metal or advanced fuels	Liquid metal, lead/bismuth, sodium, mercury	N/A	Metal/secondary steam loop, metal/gas loops, Brayton Cycle

Table 1: Example reactor type and properties

Nuclear reactors have complex design requirements imposed by the transport of neutrons that induce fission, limiting how small a practical reactor can be. A significant volume of shielding and ancillary equipment is also required to produce power and adequately protect operators and the environment. These requirements also limit the minimum practical size of a nuclear reactor.

Commercial nuclear reactors have been almost exclusively used to produce electrical power. Fission in the reactor core heats pressurized water, which is used to generate steam. The steam turns a turbine, which spins a generator producing electricity. This system is essentially the reactor design first developed for the nuclear navy. Some nuclear reactors use gas instead of water as the core coolant. In a few reactors, the heat (i.e., steam or gas) was used for industrial process heat applications purposes or heating. Test reactors are used for training, material testing, medical isotope production, and multiple scientific research activities.

The very high density of energy contained in nuclear fuel allows a reactor core to generate large amounts of power over a long time without refueling. A typical commercial reactor has one third of its core replaced every 18 to 24 months. This is several truck loads of fuel. This compares with a similarly sized coal plant using a train load of coal for each day of operation[ix]. Naval reactors can now power a ship for its entire lifespan. Reactors do not require air because no combustion is required to produce power. This is the feature that makes nuclear power so attractive for submarines and space applications. The primary benefit of a FOB deployed nuclear power plant is greatly reducing the logistical effort required to supply a forward base.. The high power density and longevity allows additional benefits at FOBs. Having easily available energy allows water to be desalinated and purified. The potential for liquid fuel or hydrogen production has been demonstrated in various tests. Easing the power, water, and fuel requirements greatly reduces the logistical requirements of a FOB.[x]

Nuclear Power Challenges

However, significant challenges are introduced when nuclear power is considered. Nuclear reactors present potential operating challenges because of the long-lived radioactive fission products that result from the fission process that generates power. Importing and operating a reactor designed to be transported is relatively straight forward, if sometimes difficult in remote locations. Transportable reactor technology has been demonstrated. A portable reactor would need to be very robust and safe to prevent events and accidents creating long-lived radioactive contamination. This risk is unique and separate from the risks of conventional power plants or munitions storage.

Designs exist that are container based truck transportable and weigh only a few tens of tons and would be assembled below grade to increase security. Drive-in covered or underground installations have been suggested to minimize the risk to direct attack while providing access. A reactor vessel, primary components and nuclear fuel packaged for shipping are very robust. They would be minimally at risk to light weapons especially if designed with extra temporary armor protection. The fuel could be damaged by shook effects damaging ceramic fuel or ductile cladding materials. The installed reactor secondary systems that generate power and cool the reactor would have operating risks similar to current diesel generators. The primary reactor system would be susceptible to direct aerial attack. Modern penetrating munitions would present a risk of damaging the primary reactor system allowing radioactive materials to be released. Various design choices, lead coolant or high temperature gas coolant for example could be selected to minimize the contamination effects if the reactor vessel is breached. Fully protecting the reactor from attack would have to be provided by the installation facility rather than by the intrinsic reactor system.

Peace time transport of nuclear reactor components and fresh fuel is an accomplished task that continues as a regular practice around the world. Operating commercial reactors are regularly upgraded by replacing some of their largest components including the steam generator and electrical generators. Currently the only major component that is not replaced is the reactor vessel. Used fuel is very radioactive and requires special shipping casks to safely transport. These casks are very robust and protected against accidental impacts. Peaceful shipments of used fuel have been on-going since the development of nuclear power.

Advanced coolants, liquid metals or high-temperature gases, portable shielding, and novel energy conversion systems can be used to address the required equipment and environmental requirements. Nuclear reactor designs would also demand specifically trained staff and unique maintenance activities. The operational challenges would be similar to that demanded for high-performance aircraft or the reactors used in nuclear ships.

A FOB reactor is also somewhat limited by nuclear enrichment limits. High enrichment or fuel with high fissile content in nuclear fuel allows for a smaller core to be designed which is desirable. High enrichment fuel does present a proliferation risk, because the fuel is more suited to fabrication of nuclear weapons. Enrichment and security would need to be balanced. In general, fuel with less than 20% U^{235} enrichment equivalent (i.e., commercial plants currently use <5% U^{235} enrichment) is accepted as low enrichment and a reduced proliferation risk.

Nuclear Options

The reactor system for FOBs will operate in a rugged environment separate from typical nuclear infrastructure. This will require that the reactor be very robust, simple, repairable, and straight forward to operate. A robust reactor will operate for long periods between required maintenance and be flexible in operations. Simple reactors would have simple modular components that are reliable, predictable, and potentially passive in operation. A repairable reactor will allow maintenance with local support and supplies. Simple-to-operate reactors conform to power production requirements quickly and easily. Long-term and expert input would not be required to keep the reactor safe and productive.

A major unique challenge for mobile or deployable reactors is nuclear shielding. The demand for small size to allow transportation and properly scale the power will greatly reduce the volume and distances between the reactor components compared to commercial nuclear reactors. The nuclear reactor on the NR-1 multipurpose, nuclear-powered submarine demonstrates how small a practical nuclear reactor system can be made.[xi] The NR-1 had an internal pressure hull that was 95 ft long and had a beam of 12.5 ft. Only a fraction of the hull length was be dedicated to nuclear reactor spaces and the reactor likely was less accessible than a more typical naval reactor. The size of this reactor is at least in the correct order of magnitude required for a FOB reactor. The size of the reactor can be affected by using advanced reactor concepts. Liquid metal reactors tend to be smaller than water or gas-cooled reactors. The shielding around an operating reactor can be shipped and installed separately from the reactor components if required. Placing the reactor underground may greatly reduce the need for shielding. Eventually, a disposal and removal plan needs to be established, where the core is removed from a forward site. The shield and core components can be broken down into small transportable components to match the maximum shielding required for transportation.

Failure of any components should be a repairable and manageable event. The reactor would need to be designed to avoid catastrophic damage or serious contamination of the site in any anticipated event. This is high standard that will demand both active and passive engineering features. The particulars of these engineered features will be unique to the reactor system and require development and extensive demonstration before application. The design and development process will be similar in scope and magnitude to the development of a new aircraft system.

Nuclear Applications

A nonmilitary application of small reactors has been to power space systems. Current space probes tend to use nuclear batteries that depend on the decay of radioactive elements to produce heat, which is used for electrical production. These nuclear batteries are relatively limited in power level compared to nuclear reactors. Both reactors and nuclear batteries are desirable in space applications because they can produce power without any atmosphere and have the potential to produce high powers for long periods of time. Space reactors have been and are being developed for high-power satellites. The reactors are specifically designed to be simple and highly reliable. The reactors tend to use simple power cycles, often Sterling cycle engines or thermionic converts. The operating mode for the reactors is also very simple where they to produce a steady level of power. The reactors are equipped with a minimum shadow shield totake advantage of the operating vacuum, which prevents radiation scattering around the shielding. These reactors demonstrate the smallest practical reactors that can be considered. Larger reactors can be used for space propulsion, but they are designed specifically and uniquely for propulsion.

Nuclear batteries are the simplest nuclear power source. They do not utilize fission; but captures the heat released as radioactive elements decay. The sources can be small and are robust since they have few or no moving parts. The heat is typically converted to electrical power using thermionic converters. Power sources above several hundred Watts utilize more conventional power conversion cycles. A Pu^{238}-based power source is used on the Mars rovers and Cassini space probe. The nuclear-decay based systems produce useful power and can be light and simple compared to a nuclear reactor. The largest space batteries currently produce a few hundred electrical Watts. Significantly larger systems are technically possible. The smallest systems being proposed can replace chemical batteries.[xii]

Currently synthetic conventional fuel (i.e., liquid or hydrogen) is reaching practical industrial applications. However, adding advancing synthetic fuel production for use at an operating military base remains a significant challenge. Combining the fuel production technology with nuclear power is potentially complex because of the unique operating characteristics of nuclear reactors including changing power levels, maintenance cycles, and safety requirements.

The Army started exploring nuclear power, the Army Nuclear Power Plant (ANPP) shortly after its application onboard a submarine was demonstrated. The mission requirement of the ANPP, to efficiently power remote and hostile bases, is the same as the current effort to power FOBs with nuclear power. The ability to greatly shorten the supply chain for power, fuel, and water was the focus of the program. Eight reactors were developed and operated between 1957 and 1977. The reactor description and applications are shown in Table 2. The program was run from Fort Belvoir as a joint activity between the Department of the Army and the Atomic Energy Commission.

The ML-1 reactor was intended to replace diesel generators. To minimize weight and volume a high temperature closed cycle gas reactor was developed. The reactor and turbine system introduced multiple new technologies. The reactor system would weigh 40 tons compared to contemporary 20-ton diesel generator. The reactor would be transportable on skids loaded on six military low bed semi-trailers. The skids would also be individually air transportable with 1960s era aircraft. The nuclear reactor would eliminate the need for 4 tons of diesel fuel each day, making on-going logistics significantly easier. The design was intended to be set up and ready to operate in 12 hours and ready to be removed in 6 hours. [ii] The ML-1 system testing proved problematic over 3 years of testing and operation due to repeated mechanical failures. The intended size and set up times of the ML-1 deployable reactor system were not demonstrated.

The Mobil Compact Reactor, (MCR), was proposed as the power source for a portable fuel production station at forward operating bases after the original concept of powering large transport trucks was rejected. The reactor was a liquid metal cooled and connected to an open cycle gas turbine power generator. The fuel production station would have greatly reduced the petroleum fuel supply chain. The intent was to make the entire reactor system fit on a single trailer including shielding. Heat-driven chemical reactions would have produced liquid fuels for vehicles or to recharge batteries. Significant technology development would have been required to further develop this concept. This system was never built or demonstrated.

The ANPP program demonstrated the potential for practical nuclear power to support military basing needs. Mobile prefabricated and operation of nuclear power plants in harsh environments was demonstrated. The work also demonstrated the current issues of technology maturity and specific mission need development. The ANPP faded as they answered their direct mission questions.

Reactor	First Criticality	Description	Application
SM-1	April 1957	2 MWe, located in Fort Belvoir	Multi-service training reactor; first reactor on an electrical grid
SL-1	January 1961	300 kWe, located at Idaho National Laboratory, test boiling water reactor for remote DEW radar station power	Prototype for remote DEW radar station power plant.
PM-2A	October 1960	2 MWe, located at Camp Century, Greenland,	Prefabricated component reactor moved to site, assembled, operated, and removed
ML-1	March 1961	300 to 500 kW, portable gas-cooled reactor	Truck, rail, or barge transportable
PM-1	February 1962	1.25 MWe, Sundance Air Force Station, pressurized water reactor	Provided power for radar station
PM-3A	March 1962	1.75 MWe, McMurdo Station, Antarctica	Portable reactor for heat, water, and power; disassembled and returned to the United States
SM-1A	March 1962	2 MWe, Fort Greely, Alaska	Development reactor
MH-1A	January 1967	10 MWe, Panama Canal, barge mounted	Power and water supply

Table 2 ANPP reactor descriptions

The smallest reactor actively being developed for commercial production in the U.S. is the NuScale reactor. This is a 45-MWe passive integral reactor[xiii]. Passive reactors depend on physical characteristics of the reactor rather than extensive active engineered systems. The cooling is based on natural circulation and safety cooling systems work passively as water boils off and air circulates. In an integral reactor, all the primary reactor components are contained in a single pressure vessel, preventing primary breakage and leaks. At 45 MWe, the reactor is approximately one twentieth the power level of typical commercial reactors. The reactors would typically be utilized in multiple units to match the local most economic power level. The basic small reactor concept started in 2000 as a national laboratory DOE funded project which was further developed by Oregon State University. The reactor concept was then transferred to NuScale in 2007[xiv]. The company started in delivering documents to the U.S. Nuclear Regulatory Commission (NRC) in 2008[xv]. The design certification package will be submitted to the NRC in 2016. The first operation of a NuScale reactor is planned for 2023[xvi].

A larger more conventional, but still advanced, passive reactor (i.e., the Westinghouse Electric Company AP600) had conceptual design start in 1986[xvii]. This reactor was developed and documents submitted to the NRC which eventually resulted in a design approval in 1998[xviii]. Multiple modifications and reviews resulted in the power up rated AP1000 being approved in 2011[xix]. Currently, four AP100 units are being built at two locations in the United States and four units are being built in China at two locations. The cost to develop the U.S. projects is in the billions of dollars. They are intended to start producing power in 2017 to 2019.

The smallest reactor to be documented with the NRC is the Toshiba 4s reactor[xx]. This small reactor uses an integral design and liquid sodium cooling and metal fuel. The reactor was based on previous Japanese research reactors and is designed to be as small as 10MWe. The reactor is intended to operate very safely for a long time, with the minimum operator and maintenance actions in remote locations. This reactor shares design features and operating requirements with various ANPP designs. The reactor was proposed for installation in Alaska in 2003 to reduce the dependence on imported diesel fuel in remote communities[xxi]. The NRC design review never advanced beyond initial discussions.

Experience with NRC reactor licensing indicates that 20-25 years are required for development and approval of new reactor designs. Although military applications may not utilize the full NRC approval process, a near equivalent process will be used, requiring similar development and approval times..

Summary

Various Army studies have also looked at supplying FOBs with advanced reactors similar to space reactors and high-temperature gas reactors. Low-power systems, based on radioactive decay similar to space batteries, have also been proposed.

The ANPP demonstrated the applicability of nuclear power to FOBs. Multiple nuclear plants were operated safely in remote and inhospitable locations. Previous ANPP demonstrations and designs show promise that a complete power generation system based on modern nuclear technology would weigh less than 40 tons, be transportable by an 18-wheel semi, and could be moved into position, installed and ready to generate power in 12 hours is possible. Such systems could provide several MW of quality power without the need of any support or fuels for years. Similarly, when redeployment is required, these systems could go from fully operational to ready for movement in less than 6 hours. Higher power less portable systems producing tens of MW intended for long term installation can be installed utilizing multiple trucks loads.

The ANPP was gradually scaled down as significant technical development needs were observed. The needed technical development was not considered worth performing due to high cost and risk and the acceptability of contemporary conventional power production, primarily diesel generators. The acceptance of reasonable costs and military risks of conventional FOB power production ultimately superseded the need to develop military-specific nuclear power plants. U.S. Department of Defense reviews are currently underway to evaluate technical solutions for specific FOB missions. The mission definition and requirements will greatly assist in selecting the most useful technology from many options to be developed. The defined nuclear power plant mission would need to justify the developmental work and the potential for significant investment in development of a unique reactor design and the required attendant technology. A reactor design intended to be appropriately sized and produce electricity and heat is a conventional development process. Adding design requirements for portability, air portability, extreme passive safety, liquid fuel production, and rapid removal create the need for additional development, technology, and cost. The use of advanced reactor technology is likely to be necessary for small portable reactor designs. The ideal reactor design, as demonstrated by ANPP, may be impracticably expensive.

Developing new reactors that are portable and scaled for military base applications is possible.. The design would need to be safe, secure and efficient when installed and capable of being practically removed. A method to manage radioactive material and used fuel would need to be developed. The ANPP demonstrated the potential for FOB reactors along with defining the technical challenges that remain to be solved.

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