ELECTRIC POWER RESEARCH INSTITUTE

EMERGING TECHNOLOGIES BRIEF

Full-Power Microreactor Demonstration Expands Horizons for Nuclear Energy

In May 2018, the U.S. National Aeronautics and Space Administration (NASA) revealed the successful full-power demonstration of a kilowatt-scale nuclear reactor suitable for supporting missions—including manned exploration of the Moon and Mars—with energy requirements beyond those that can be met by traditional options such as solar panels and radioisotope thermoelectric generators. The Kilopower demonstration represents a significant milestone, marking operation of the first novel reactor concept in the United States in 40 years and highlighting the potential for space and other microreactor applications.

Nuclear reactors ranging in capacity from kilowatts (kW) to tens of megawatts (MW) are not a new concept—for decades, small-scale reactors have powered satellites, submarines, aircraft carriers, icebreakers, and research reactors and have produced life-saving medical isotopes for diagnosis and treatment of illness. Russia's 2018 deployment of two 35-MWe pressurized water reactors (PWRs) is attracting attention largely because they are mounted on a barge, creating a floating nuclear power plant—the *Akademik Lomonosov.*

Prototype Kilopower microreactor (Credit: NASA)

What is exciting and new about NASA's milestone is that it demonstrates the ability to leverage advanced designs, fuels, materials, manufacturing methods, and power conversion and cooling technologies to create compact, rugged, portable, and safe nuclear energy systems. This brief introduces microreactor innovations and potential applications.

Power for Space Exploration

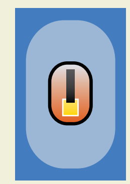
NASA reports that its new Kilopower microreactor was designed, built, and tested for less than $20 million (excluding fuel costs)—a bargain by nuclear research, development, and demonstration (RD&D) standards.[1] With a core smaller than a coffee can and overall size compact enough to fit inside a small closet, each reactor can produce up to 10 kWe—enough to power eight average U.S. homes—for a decade or more. Four units would be sufficient to supply the estimated 40 KWe needed to support an initial base of operations on the surface of Mars, with the option to add more units as demand increases.[2]

The ability to deliver high power for 10 years or more without refueling—in a package small and

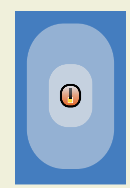
The Benefits of Very Small

The advantages of compact reactors are well established. In general, design and operational complexity diminish substantially with scale. Heat removal and safety systems are simplified, allowing for self-regulation and passive shutdown, and the radiological source term is reduced, improving siting flexibility and shielding options (including onsite burial) and reducing accident consequences. Small size also allows for key components, including the power conversion system, to be integrated into a single vessel, which facilitates factory fabrication, transportation, and modular construction and deployment. Substantially reduced scales and shorter construction durations should translate into large reductions in risk and capital requirements relative to the conventional nuclear plant paradigm.

Large reactors: *originally rated in the hundreds of megawatts and now generally 1000 MWe and above. Most new advanced light water reactors fall in this range.*



Small modular reactors (SMRs): *less than 300 MWe. These reactors rely on a high degree of factory fabrication and modularity for ease of transportation and construction. Smaller designs extend down to 50 MWe.*

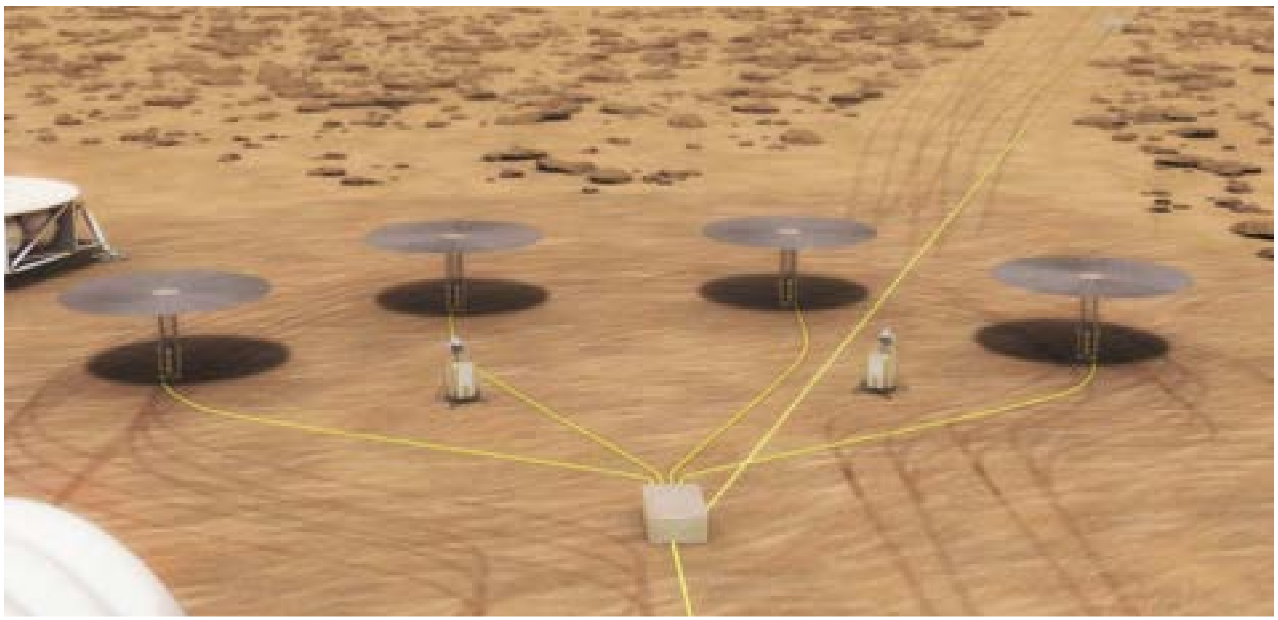


Microreactors, also known as very small modular reactors (vSMRs): *less than 50 MWe, down to kilowatt-scale technologies. These highly transportable reactors are designed for full factory fabrication and rapid deployment. Most terrestrial applications fall in the range of 1 to 10 MWe.*

light enough to be launched into space—derives from several key features and attributes of NASA's Kilopower technology:

- **Fission energy:** The unmatched power density of nuclear fission reactions yields over 1 million times the energy than can be released by chemical reactions such as combustion of fossil fuel. For space missions where added weight comes at a high premium, highly enriched uranium (HEU) is used.
- **Heat pipes:** Sealed metal tubes containing heat transfer fluid passively move heat from the reactor core to a heat sink, where it can be used to produce electricity. Substitution of multiple independent heat pipes for circulating fluids, pumps, and piping results in robust, fault-tolerant heat transfer and cooling systems.
- **Stirling convertor:** Proven and reliable heat engine technology converts heat to mechanical (rotational) energy and then electricity.

In addition, the simple physics of the small, compact reactor core results in a stable, self-regulating system that essentially seeks to operate at a constant temperature and power level but also is highly controllable: A reduction in power demand or heat removal (cooling) heats up the core, which expands, allows slightly more of the reaction-driving neutrons to leak out, and thereby throttles down reactivity and power output. Conversely, increasing power demand or heat removal leads to increased reaction rates and higher power output.



Conceptual drawing of four-unit Kilopower plant deployed on Mars (Credit: NASA)

Power for Terrestrial Niche Applications

The features of the Kilopower technology demonstrated by NASA for long-duration, remote, and independent operation in the harshest of environments suggest Earth-bound applications where reliability, robustness, dispatchability, and portability are critical requirements, worth buying at a premium. This includes many applications that today are served by diesel generators, which present important challenges in terms of fuel cost and supply, maintenance, reliability, and emissions. Potential microreactor applications fall into three general categories:

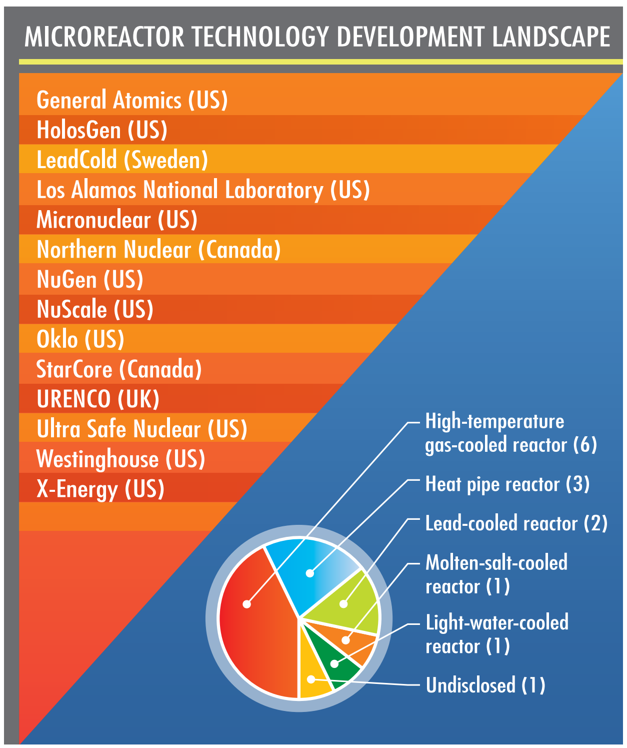
1. Power for remote off-grid communities, industrial sites, and defense installations, where reliable long-term operation—meeting requirements for reliability, safety, and security without the need for refueling for more than a decade—represents the primary benefit. Power demands could range from hundreds of kilowatts to dozens of megawatts.
2. Power for forward and remote military operations and bases and for civilian disaster response and recovery, where assured fuel supply security plus portability and modularity for rapid installation and decommissioning are key benefits. Power demands would generally fall under 10 MWe.
3. Power for grid-connected critical facilities and infrastructures that would benefit from the capability of uninterruptible supply and the ability to decouple from the grid for islanded operation if needed. Power demands for these distributed resource applications, which could support microgrids as well as utility grids, would vary widely.

Technology Pathways

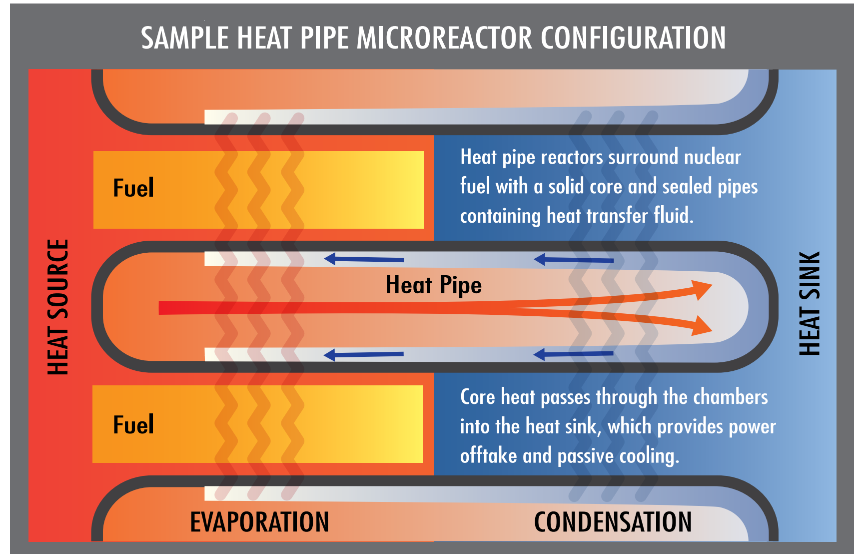
Over a dozen microreactor technologies are being pursued by private sector companies and research groups seeking to adapt advanced reactor designs for powering remote and/or critical facilities. Two general approaches have emerged in the current technology landscape:

1. Scaled-down versions of non-water-cooled reactors
2. Scaled-up versions of heat pipe reactors developed for kW-scale space applications

The first approach essentially reverses the historical trend that characterized initial commercialization of fission technology through size-based economies of scale. Most such designs maintain the traditional engineering paradigm pairing a nuclear island with a conventional power conversion system and employing pool and loop configurations for heat removal and power generation. One notable exception is the TRISO-fueled, gas-cooled HolosGen reactor, which essentially converts an existing nuclear jet engine design into a closed-cycle system for electricity generation.[3] The unique characteristics of this design provide for a portable, fully integrated heat production, transfer, and conversion system.



The second approach employs hermetically sealed heat pipes for core cooling and heat transfer in designs that share a common lineage with NASA's Kilopower technology described earlier. One example is Los Alamos National Laboratory's MegaPower reactor, a concept capable of providing 2 MW of electricity and 2 MW of thermal power continuously for 12 years.[4] The system is intended to be transportable by truck or plane, installed and operating within 72 hours of delivery, and removable from a site within 7 days of shutdown.



Conductive heat transfer to the heat pipe vaporizes the working fluid, which flows by convection toward the heat sink. Heat is released for power generation and cooling as the fluid condenses and travels back to the core along internal pipe surfaces.

Heat pipe technology is mature and ubiquitous, with uses ranging from efficient heat removal in confined spaces in consumer microelectronics (such as smart phones and tablets) to the cooling of oil pipeline supports in Arctic environments to prevent heat from friction of oil flow causing the foundation to sink in melting permafrost. Applications in nuclear energy systems bring some potentially game-changing benefits. Heat pipes offer near-universal compatibility with various reactor core, fuel, and power conversion options. Combinations of construction materials and heat transfer fluids can be tailored to meet a wide range of operating conditions and performance requirements, including temperatures above the melting point of steel.

Heat pipe reactors also are inherently simple. The switch to a solid-state core, with cooling provided in individual sealed channels, eliminates the need for pumps, valves, and other fault-susceptible components and systems. Heat transfer is largely independent of orientation unlike traditional fluid-cooled systems, providing ease and flexibility for transportation and installation. The use of multiple individually fabricated and tested heat pipes per fuel element makes for a redundant, fault-tolerant cooling and heat transfer system—providing for continuity of cooling even with one or more heat pipe failures.

Barriers and Challenges

From a technical perspective, nuclear fuel supply represents a potential roadblock to vSMR commercialization, a challenge facing most advanced reactor technologies. Many microreactor designs likely will need what is known as high-assay LEU—typically enriched in the isotope uranium-235 to between 15 and 20%. Down-blending weapons-grade uranium is one potential fuel source, as commercially produced light water reactor fuel currently is enriched only up to 5%. Achieving 15 to 20% enrichment is feasible using current technology. However, regulatory changes would be required, as would government assistance to help establish the market pull needed to overcome first-mover risks for fuel suppliers.

Paradigm shifts in transportation, portability, and control also pose commercialization challenges. Substantial buy-in by legal and regulatory authorities would be required in order to allow rapid deployment, periodic movement, and remote or autonomous operation of nuclear energy systems, especially since many applications may involve situations and locations that lie outside of the contemporary reactor siting, review, approval, and monitoring envelope.

Who Is The Customer?

Remote Villages. A number of microreactor developers are pursuing applications in remote, off-grid Arctic communities that rely on diesel generators. Long, harsh winters often render them inaccessible by road or boat for a significant portion of the year, necessitating airlifts to bring in fuel. According to a report by the University of Alaska Anchorage, rural Alaskan residents in the lowest income bracket spend 47% of annual earnings on home heating.[5] An affordable power source capable of cogeneration could significantly lower cost of living. A 2016 study commissioned by Ontario Ministry of Energy (OME) estimated potential levelized cost of energy (LCOE) savings of up to US$143/MWh on electricity alone could be achieved by replacing incumbent diesel energy sources in remote northern Ontario communities with vSMRs.[6]

Mining and Other Remote Industries. Like many communities in the Arctic, remote resource extraction sites often rely on diesel generators. According to the OME study, use of vSMRs at remote mines in northern Ontario could avoid an estimated 2.7 to 8.3 gigatonnes of CO_2-equivalent greenhouse gas emissions over a 20-year project span and could lead to potential energy cost savings of up to US $116/MWh.

Forward and Remote Military Bases. Many forward and remote military bases, including those located near or within combat zones, depend on onsite diesel generators to provide mission-critical energy. Fuel supply shipments create significant risk to both personnel and equipment, especially when routed through hostile territory. The U.S.

Market Opportunity: Displacing Diesel Generators

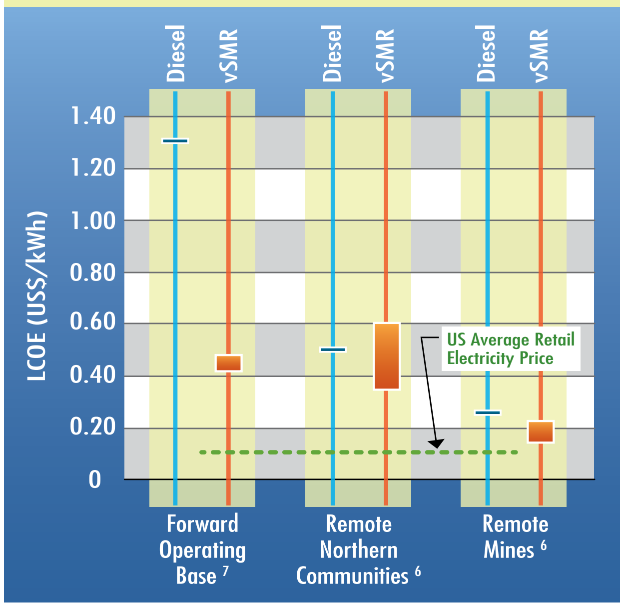
Power supply options for off-grid and remote communities, industrial sites, and facilities with relatively small electricity loads are highly limited. Diesel generators currently dominate the market for continuous generation capacity rated below 5 MWe. As a result, many isolated electricity markets are reliant on these combustion-driven systems, which demand large and steady fuel supplies that are vulnerable to disruptions and price volatility. A single 1-MWe generator running at full load consumes more than 100 gallons of fuel per hour.

Ensuring secure fuel delivery and providing bulk onsite fuel storage pose logistical challenges and create risks and cost premiums that can be extreme. Multiple levels of redundancy—standby backups resulting in oversizing of installed capacity relative to load—are standard. The maintenance intensity associated with these small systems further increases the price of power, relative to comparable grid-served markets. By providing around-the-clock power for extended periods, microreactors could potentially become cost-competitive sources of emission-free electricity (and heat) in markets that rely on diesel generation. Renewables, backed by storage, are already emerging as a viable competitor in these markets.

Department of Defense (DoD) has investigated advanced microreactors as mobile, uninterruptable, and sabotage-resistant power sources. Replacing 10 MWe of onsite diesel generation could eliminate the need for thousands of fuel shipments annually and reduce the cost of power by more than 70%, according to a 2016 report from DoD's Task Force on Energy Systems for Forward/Remote Operating Bases.[8]

Defense Installations and Security Infrastructure. Most domestic DoD installations rely on utility grids and maintain diesel generators to support critical loads during outages. Microgrids with onsite power generation are an increasingly attractive alternative for increasing resiliency and security, a tactical necessity. More than 90% of DoD installations demand less than 40 MWe and more than half less than 10 MWe, creating a potential opportunity for microreactors with island-mode capability. In August 2018, Congress directed the U.S. Department of Energy to outline a program involving deployment of a pilot microreactor to serve critical national security infrastructure before 2028.[9]

COMPARING COST ESTIMATES: DIESEL VS. MICROREACTORS



The LCOE of diesel generation is highly variable due to site-specific circumstances, and the economics of microreactors are highly uncertain. Based on limited comparative studies, the estimated cost range for microreactors suggests highly favorable or at least competitive LCOE for some niche applications.

Next-Gen Nuclear

EPRI's Next-Generation Nuclear program, funded by Technology Innovation, is creating a technical foundation to help inform public and private stakeholders on design, demonstration, and U.S. deployment of a commercial Generation IV reactor in the 2030s. This includes continuous scouting of developments relating to emerging reactor technologies that offer inherent safety, security, and flexibility advantages and the potential for novel applications. Further information about the developers and technologies covered in this brief can be found in the TechPortal, EPRI's database of energy innovations.

Disaster Response and Recovery. Natural disasters and physical and cyber attacks can disrupt or destroy conventional power generation and delivery infrastructure, potentially halting or degrading operation for extended periods. Special-purpose microreactors could be designed and held in reserve by governments and utilities to deliver black start and islanding capabilities when needed to help restore and maintain grid service and support broader recovery operations.

Distributed Energy Resource Applications. Technologies proven in niche markets can eventually find broad applications—think solar photovoltaic modules and battery energy storage systems. Innovative business models and capital cost reductions delivered through production economies could help serially fabricated microreactors make a case beyond the specialty markets described above. For example, mature technologies could support economic development and societal advancement on small island nations and in rural villages in developing countries. They could serve hospitals, data centers, and water treatment plants as microgrid-based solutions for continuing critical societal functions when grid power is lost. They also could provide load following and other ancillary service capabilities to support increased penetration of intermittent, variable solar and wind.

Implications

New applications, deployment opportunities, and operational missions can arise from microreactor innovations capable of supplying dispatchable and carbon-free electricity and heat reliably and safely over extended periods—years to decades—without the need for refueling. Commercial readiness for some designs could come as soon as 2025, pending successful demonstration and resolution of fuel supply, licensing, and other challenges.

Attributes such as compact size, factory assembly, portability, ease of deployment, ruggedness, and reliability could create early opportunities in niche applications typically served by diesel generators, where electricity and/or heat is supplied at a high premium due to fuel supply costs and risks. Examples include remote populations, industrial activities, and military and scientific installations, as well as forward operating bases. Mobile, continuous, and self-serving power for disaster response and recovery represents another possibility.

Longer-term application as a distributed energy resource and grid support option will be contingent on achieving production economies of scale, given current and anticipated high levels of competition among a variety of technologies.

For existing nuclear plant owner-operators, deployment of microreactors for niche applications and as distributed resources may create commercial opportunities either as contracted operators or via power purchase agreements. For others, the enhanced safety and reliability, lower capital cost, and potential for low operating costs afforded by autonomous or semi-autonomous reactors could lower the barrier of entry for nuclear ownership and operation.

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