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THE USE OF MICROREACTORS FOR OFF GRID APPLICTION IN THE NEAR FUTURE

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ABSTRACT: Nowadays, nuclear energy market suppliers are focused on reducing electric power generation, which is partially due to high costs and complicated licensing processes for new plants exceeding 5 GW. Following the Paris Agreement, there has been a shift in the country's economic opinion toward net-zero carbon targets. In particular, Georgia's Vogtle had an $18 billion overrun and Somerset's Hinkley Point C was delayed to 2031, incurring an additional $26 billion, prompting consideration of small modular reactor alternatives. Currently, microreactors are developed using coolants such as liquid metal, helium gas, or molten salt. Some use passive heat pipes for heat transfer whereas others use helium gas due to its high-temperature compatibility. To date, none of the operating reactors use these technologies for power generation. Hence, nuclear regulations are developing new safety criteria and licensing processes for microreactor design certification, construction, and operation. Microreactors are inexpensive, highly efficient, straightforward in construction, effectively transfer mass and heat, and they can produce power from less than 1 MW to 20 MW. Microreactors offer advantages such as flexibility, adaptability, mobility, and resilience, and they operate on a free power grid. Westinghouse has designed eVinci™, which uses a thermal spectrum to generate power ranging from 200 kW to 5 MW using a high-temperature heat pipe and sodium as the working fluid. Spatial microreactors operate at high temperatures, initially promising to reach a temperature of 650–700 °C. Innovative microreactor concepts have been introduced, involving enriched uranium fuel, heat pipes, passive cooling, and thermoelectric conversion.

Keywords: Microreactor, Small modular reactor, Heat pipe, Alkali metal, Stirling converter, Wick structure

Introduction

The future of nuclear energy development is focused on miniaturizing atomic reactor power. A promising nuclear energy system featuring a compact solid core with heat pipe cooling using alkali metals yields outstanding safety results. Nuclear reactors are becoming increasingly modular, autonomous systems (Fakhry et al., 2024). The benefits of nuclear reactors have enabled the use of nuclear power in a wide range of civilian and military applications. Autonomy and modularity have also brought nuclear power into the realm of centralized quality control. The next-generation heat pipe reactor designs, which are beginning to take shape, exemplify the next-generation modular, autonomous power systems. These reactors have been designed to operate autonomously for decades with passive safety, generating approximately 20 MW and targeting niche nuclear markets such as remote communities (Lin et al., 2024).

Nuclear microreactors (NMRs), also known as small reactors, enhance the concept of nuclear batteries and represent a flexible, cost-effective, decentralized, and portable means of ensuring global energy access. Within the small modular reactor (SMR) class are the microreactors that operate with plug-and-play technology, generating heat or electricity within a range of 1–50 MW.

Nuclear energy has the advantage of net-zero carbon emissions. Compared with solar and wind renewable sources, it is a suitable choice for various applications such as desalination and supplying power to remote sites. Consequently, microreactors are used in industrial manufacturing, water desalination, and hydrogen production.

Owing to their high mobility, transportable units with off-grid power solutions are more suitable for remote locations, military bases, disaster recovery operations, and space missions (Lane and Revankar, 2025). Conventional nuclear reactors, thermal power plants, and renewable sources are inadequate for rural, urban, and maritime areas. Microreactor challenges include mobile power solutions that enable greater adaptability to natural disaster interventions and infrastructure disruptions. Mobile and transportable solutions offer lower cost, more flexible module manufacturing, and ease of installation and deployment in remote regions.

The United States Department of Energy (DOE) manages the Advanced Reactor Demonstration Program (ARDP) to incentivize various projects exceeding 5.0 MW, such as those led by the National Aeronautics and Space Administration (NASA), who have revealed the outcomes of Kilopower reactor using Stirling technology (KRUSTY) (Gibson et al., 2017). The Kilopower reactor uses a heat pipe cooling system, where sodium is employed as the working fluid and uranium-molybdenum (UMo) is used as the fuel to generate 20 kW from a fast neutron spectrum (McClure et al., 2020). The MegaPower reactor is a microreactor and heat pipe-cooled nuclear reactor developed by the Los Alamos National Laboratory (LANL) for remote electricity generation.

The Special Purpose Reactor (SPR) initiative focuses on developing microreactors that are factory-manufacturable, easily transportable, and typically produce no more than 20 MW of thermal power. Many SPRs serve as prototypes for off-grid power solutions in military installations, emergency responses, and space missions. The heat pipe power system (HPS) for reactor cooling demonstrated a design-oriented Brayton cycle for deep space exploration. The LANL initiated the SPR project in 2017 with a compact reactor design capable of generating 5 MW of thermal power. In 2001, the Heat Pipe-Operated Mars Exploration Reactor (HOMER) was designed and developed as a compact fission power system for Mars surface missions (Poston, 2001). In 2017, LANL developed the MegaPower reactor, capable of delivering 5 MW of thermal power and it is a fast reactor designed for remote power applications. The MegaPower reactor uses passive heat pipe cooling, making it highly reliable and transportable. The MegaPower reactor is developed for portability and with its modular design, it provides a dependable, self-sufficient energy source for military bases or isolated civilian areas (Sterbentz et al., 2017). The core consists of a single-piece stainless steel design with heat pipes placed in the channels, employing a passive cooling approach that eliminates the need for pumps, valves, or intricate piping.

Microreactors generate between 1 and 20 MW and comprise a subclass of SMRs (Zohuri, 2020). The primary applications of microreactors are electricity production in remote locations, industrial applications, and space missions (Testoni et al., 2021). In 1961, the United States Navy initiated the Transit 4A, which was the first satellite to use an inaugural nuclear battery known as the radioisotope thermoelectric generator (RTG) (O'Brien et al., 2008). The RTG was a microreactor design that used heat from

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decaying radioactive isotopes, such as plutonium-238, with a half-life of 86.8 years, to produce electricity via the Seebeck effect. Owing to their availability and long half-lives, americium-241 and strontium-90 are potential options for plutonium-238.

Over the past five decades, NASA has used more than 45 RTGs for 26 space missions. From the 1960s to the 1970s, RTGs with a power ranging from 40 W to 50 W and an efficiency of 5.5% powered the Apollo, Pioneer, and Viking missions using general-purpose heat source (GPHS) modules (Bennett et al., 2006). After the 1980s, the efficiency of RTGs improved by ~6.5%, and the RTGs generated power ranging from 160 W to 300 W and were adopted in the Galileo, Ulysses, and Cassini missions. Since 2000, NASA has used a multimission radioisotope thermoelectric generator (MMRTG), which generates 110 W with an efficiency of ~7.5% and is used in Curiosity and Perseverance rovers for space and planetary environments. The MMRTG is a rugged power system capable of delivering 110 W of power at launch (Lewandowski et al., 2016). However, a new technology, that is, the radioisotope thermophotovoltaic (RTPV) system, can replace RTGs based on the photovoltaic effect, which transforms heat from radioactive decay into electrical energy (Wang et al., 2023).

Microreactors are cost-effective and can be readily installed at operational locations, thereby reducing construction delays because they are assembled from factory-built components. Microreactors operate under self-adjusting conditions and feature robust passive safety systems, thereby reducing the need for on-site personnel while maintaining the highest safety levels (Black et al., 2023). Microreactors have a small carbon footprint, allowing nuclear units to be transported by road, rail, sea, or air using standard 12-m containers (Shropshire et al., 2021).

Civilian nuclear power plants account for ~10% of the world's electricity and contribute to net-zero greenhouse gas emissions. In 2019, the Kilopower space reactor was developed with heat pipes as a viable cooling alternative to nuclear cooling systems. Heat pipe-cooled reactors (HPCRs) are a new trend in the research and development of nuclear energy generation systems. In addition, they offer benefits such as compactness, moderate costs, mobile features, and ease of operation, although their power output ranges from kilowatts to several tens of megawatts. Microreactor designs require minimal personnel and use heat pipes for passive cooling, thereby eliminating the need for pumps. A heat pipe is comprised of evaporator, condenser, and adiabatic segments, all of which operate within a sealed metallic vacuum envelope. Chemical alkalis, such as potassium, lithium, and sodium, serve as operating fluids that vaporize in the evaporator and condense via capillary action. In this paper, we review heat pipe reactors using Stirling converters and the fluid dynamics associated with multiphase flows.

Microreactor technologies

Microreactor technologies rely on thermodynamic cycles, such as the steam Rankine cycle, gas Brayton cycle, and, to some extent, the Stirling cycle. Based on passive heat transfer, heat pipes can transport thermal energy away from the reactor core, employ Brayton cycles, and deliver high heat transfer reliability with their compact design. However, heat pipes require

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extensive testing for long-term operations. Fission nuclear energy must be converted into electricity using a Stirling motor or chemical conversion such as those used in space missions. HPCRs can use HPS and molten salt as coolants or liquid fuel carriers, enabling high-temperature operation and demonstrating high efficiency, operating in either Brayton or Rankine cycles.

Thermoelectric converters

The first conversion method used in space exploration was the RTG, which operates with thermocouples to convert heat from radioactive decay into electricity, eliminating the need for moving parts, thereby permitting a long lifespan of the nuclear reactor. RTGs have limited power output and require radioactive fuels such as plutonium-238. The Stirling converter is based on a closed-cycle heat engine with a piston that converts thermal energy into electricity through precise engineering. However, alkali metal thermal-to-electric converters (AMTECs) directly convert heat into electricity using sodium ion transport, which degrades over time. In addition, the efficiency of AMTECs depends on the thickness of the electrode and temperature, where the efficiency increases with an increase in both of these parameters (Lodhi and Ahmad, 2015).

Robert Stirling invented an engine in 1816 that enabled the conversion of heat energy into electricity using various working fluids such as air and helium. The Stirling cycle involves compressing a cold fluid and expanding a hot fluid, thereby generating more work from expansion than that consumed during compression. Stirling engines are crankshaft mechanisms that convert the reciprocating motion of pistons into rotational energy using a rotating crankshaft. Stirling engines became popular after the 1930s due to low power; engine developments were for automotive use, while Stirling engines are more suited for stationary applications. They can be categorized into alpha, beta, and gamma types (Perozziello et al., 2021).

Alpha Stirling engines feature two pistons in separate cylinders linked via a regenerator, heater, and cooler. Beta Stirling engines have a piston and displacer in one cylinder, whereas gamma Stirling engines use separate cylinders. Beale created free-piston Stirling engines at Ohio University in the 1960s to minimize sealing and address lubrication challenges (Boucher et al., 2007). Unlike kinematic Stirling engines, they lack a mechanical link between the displacer and power pistons, which simplifies their design. Prior to the 1980s, Stirling engines were widely used in the industrial and automotive sectors. In the early 2000s, NASA's Glenn Research Center began testing Stirling converter prototypes for long-term use, offering a highly efficient system with more than 20% efficiency. NASA developed free-piston Stirling generators (FPSGs) and the space-based Kilopower project demonstrated the feasibility of FPSGs using heat pipes from nuclear reactors (Wang et al., 2025). Table 1 shows the primary characteristics of the energy conversion methods employed in space reactors.

Characteristic	Radioisotope thermoelectric generators (RTGs)	Stirling engines	Alkali metal thermal-to-electric converters (AMTECs)
Conversion type	Thermoelectric	Mechanical	Electrochemical
Fuel source	Plutonium-238	Heat, solar, nuclear fuel	Sodium
Efficiency (%)	5–7	20–30	15–40
Power (W)	100–300	50–150	50–500
Reliability	High	Low	Moderate
Temperature (°C)	–270–600	–200–800	600–1000
Lifespan (years)	Decades	5–15	10–15

Table 1. Main characteristics of energy conversion methods employed in space reactors.

AMTECs also use sodium, potassium, or lithium, which represents a distinct approach compared with RTGs, which require plutonium-238. NASA has considered AMTEC as a potential power conversion process alongside other technologies, such as the Brayton and Stirling cycles. The AMTEC technology was developed to convert heat directly into electricity through sodium ion conduction in a beta-alumina solid electrolyte. At least two NASA microreactors use AMTECs, including the Space Affordable Integrated Reactor Power System (SAIRS), with a power range of 10–100 kW (El-Genk and Tournier, 2004). The GAMA Space Heat Pipe (GAMA-SHP) is being developed as part of a strategic partnership between the United States of America and Indonesia, designed for a power output of 1.2 MWe (Harto et al., 2025). AMTECs operate at temperatures ranging from 127 °C to 427 °C and from 627 °C to 1027 °C. The Na-AMTEC achieved a power density of 55 W/kg, with efficiencies ranging from 15% to 20%. Over the years, microreactors using FPSGs and AMTECs have been developed for space missions. Since 1970, NASA has made advancements in RTGs that transform thermal energy into electrical energy. These generators are particularly notable because of their ability to operate under extreme conditions. Fig. 1 illustrates a free-piston Stirling engine, which operates without mechanical linkages, such as a crankshaft, connected to a heat pipe-cooled reactor.

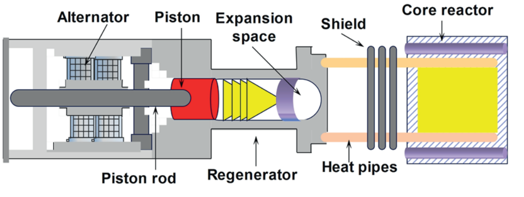

Fig. 1. Schematic illustration of the free-piston Stirling engine, which is a type of Stirling converter used in Kilopower reactors.

Heat pipe characteristics

The heat pipe consists of evaporator, adiabatic section, and condenser sections. The heat pipe has a metallic casing, which is an envelope partially filled with a working fluid such as water, acetone (C_3H_6O), or ammonia (NH_3), and an alkali metal such as sodium, potassium, or lithium. However, the internal wick structure of heat pipes provides capillary action, allowing the working fluid to return from the condenser to the evaporator (Tang et al., 2024) . The liquid inside the evaporator section vaporizes and is subjected to a heat source that increases its temperature and internal pressure. The vapor accelerates along the length of the heat pipe from the adiabatic section to the condenser section owing to the increased pressure. In the condenser section,

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the vapor encounters a cooler temperature, transferring the latent heat of vaporization to the condenser and transforming the vapor into a liquid as heat is lost to the integrated heat sink. After passing through the wick structure, the condensed liquid returns to the evaporator, creating a capillary force that ensures a continuous heat transfer cycle. The critical role of the wick structure is to distribute the working fluid and avoid dry-out effects. The wick structure must possess a suitable porosity and permeability. Common materials include sintered metals, meshes, and grooved structures. Fig. 2 shows a conventional heat pipe with the evaporator, adiabatic, and condenser sections.

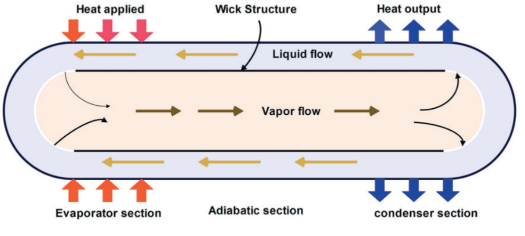

Fig. 2. Schematic illustration of a heat pipe, which consists of three sections. The concurrency of liquid and vapor flow represents a multiphase flow between the liquid and vapor phases.

HPSs have a higher thermal conductivity than solid metals, making it practical for isothermal operations. Conventional heat pipes exhibit effective thermal conductivities ranging from 1,500 W/(m·K) to 50,000 W/(m·K), compared with copper, with a thermal conductivity of 390–401 W/(m·K). Furthermore, HPSs may face extreme space conditions, such as in the lunar setting, where the external ambient temperature varies from –180 °C to 180 °C. Several heat pipe designs have been developed for various applications. Table 2 shows the comparison of several industrial heat pipes.

Type of heat pipe	Working principle	Applications
Conventional heat pipes	Capillary action	High efficiency, passive cooling
Thermosyphons	Wickless, gravity-driven	Power plants, geothermal systems
Loop heat pipes	Liquid and vapor	Spacecraft, high-power electronics
Pulsating heat pipes	Wickless, relies on oscillating fluid	Microelectronics
Variable conductance heat pipes	Thermal resistance based on temperature	Spacecraft, applications requiring precise control of temperature
Rotating heat pipes	Centrifugal force	Turbines, rotating equipment cooling

Table 2. Comparison of different types of heat pipes, along with their working principle and practical applications.

Heat pipe designs support multiple evaporator, condenser, and adiabatic sections. The key function of the working fluid is to facilitate heat transfer through capillary action in a wick structure; however, this can also be reversed using gravitational, centrifugal, electrostatic, and osmotic forces. Table 3 shows a brief description of the different wick structures used in heat pipes.

Feature	Sintered wick	Grooved wick	Meshed wick	Composite wick	Arterial wick
Capillarity	High	Low	Medium	Very high	High
Permeability	Medium	High	Medium	Medium-high	High
Conductivity	High	Low	Medium	High	High
Cost	High	Low	Low	Medium	High
Heat flux	High	Low-medium	Medium	High	Very high

Table 3. Main characteristics of different types of wick structures used in heat pipes.

Heat pipe enclosures are typically round cylinders, but can also be of various shapes, such as rectangular, conical, wavy, and nose cap. Another important concept is the wide variety of heat pipe types classified as conventional heat pipes, thermosyphons, loop heat pipes (LHPs), pulsating heat pipes (PHPs), rotating heat pipes (RHPs), variable conductance heat pipes (VCHPs), and micro-heat pipes. Thermosyphons are passive heat transfer devices used in a vertical orientation and applied over long distances, exhibiting high thermal efficiency (Mantelli, 2021). LHPs enable the transport of thermal energy over long distances through capillary action (Ling et al., 2024).

Heat pipe designs that are independent of capillary forces rely on centrifugal forces or oscillatory motion. PHPs use oscillatory motion. In contrast, RHPs depend on centrifugal forces. Therefore, RHPs and LHPs are distinct types of heat pipes, operating with heat loads ranging from 75 W to 300 W and heat fluxes between 6 and 22 W/cm². They comprise separate liquid and vapor flow paths, allowing for better thermal control and substantial heat capacity mobility. Wickless heat pipes, such as PHPs and RHPs, do not use capillary action; rather, they employ pulsating motion (Liou et al., 2019). In general, heat pipes exhibit a considerable effective thermal conductivity range of 4,000–100,000 W/(m·K), depending on their length and working fluid. A special type of heat pipe, known as VCHP, can alter its thermal conductance through a noncondensable gas (NCG). The VCHP is based on the NCG, which helps maintain temperature stability in satellites, space probes, and high-precision instruments. Fig. 3 shows the structures of heat pipes widely used for electronics cooling and in the aerospace industry.

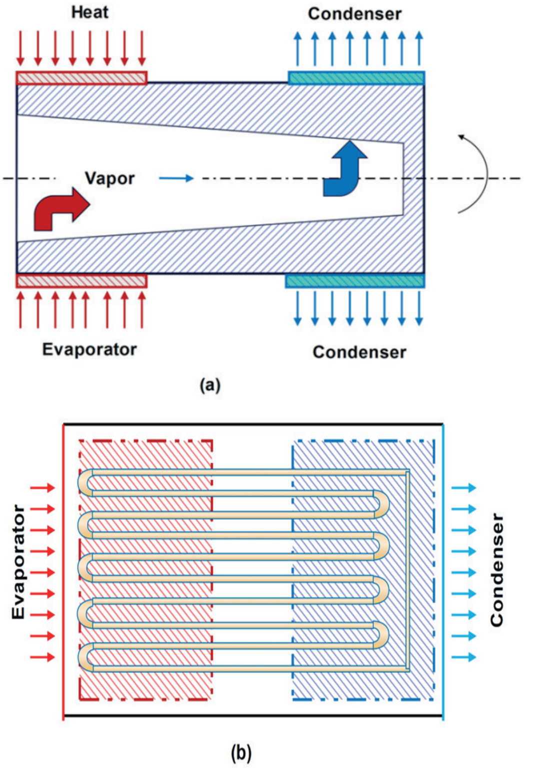

Fig. 3. (a) Structure of a rotating heat pipe (RHP) used for heat removal in rotating devices. (b) Structure of a loop heat pipe (LHP) widely used in spacecraft.

Heat pipe envelopes are manufactured using various metal alloys, including copper, aluminum, stainless steel, nickel, titanium, and molybdenum. The thermal performance depends on the choice of the working fluid, which must be compatible with the fluid properties and casing materials. An ideal fluid facilitates phase changes and resists corrosion (Jouhara et al., 2017). For electronics cooling, copper is suitable as a casing and water is used as the working fluid. Copper has high thermal conductivity and a boiling point that enables efficient heat transfer within a heat pipe, making it ideal for temperatures below 200 °C. Steel is chemically compatible with sodium, potassium, and mercury at elevated temperatures. However, stainless steel is not compa-

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tible with working fluids such as water or lithium. Nickel alloys are more suitable for operating with lithium as the working fluid at temperatures as high as ~860 °C, which is the limit for steels. Table 4 provides a concise summary of the heat pipe envelope materials based on their temperature and chemical compatibility.

Material	Typical temperature range (°C)	Maximum temperature (°C)	Common uses
Copper	–200–250	350	Electronics cooling
Aluminum	–200–150	200	Aerospace and aircraft
Stainless steel	–270–600	800	Industrial, space applications
Nickel alloys	–200–900	1000	Nuclear applications
Titanium	–250–500	600	Marine, aerospace
Tungsten/Molybdenum	500–2000	2500	Extremely high temperature applications

Table 4. Metallic materials used to manufacture heat pipe envelopes.

The material used in the wick structures must be highly chemically compatible with the working fluid. In general, wick structures used in heat pipes can be categorized as sintered, grooved, screened, meshed, and composite wicks. Electronics cooling systems use heat pipes with sintered, grooved, and meshed wick structures (Wong et al., 2022). The wick structure determines the type of heat pipe and measures the ability of fluid drawdown to the evaporator, depending on the pore size and wettability, which can be influenced by the operating temperature and presence of gravity.

An entrainment limit occurs due to the high gas velocity, which can shear liquid droplets from the wick, thereby reducing the efficiency. The viscous limit of the vapor pressure is too weak to drive fluid circulation effectively. Excessive heat input causes localized boiling in the wick, disrupts fluid flow, and compromises the boiling limit. The maximum heat transport capability of a heat pipe depends on the heat pipe limits.

More precise models and fluid properties have significantly improved the maximum heat transfer capabilities of heat pipes. These include the capillary, viscous, sonic, boiling, and entrainment limits. Capillary limits occur when the wick structure cannot transport a sufficient amount of liquid back to the evaporator. Table 5 lists the thermodynamic properties of the principal working fluids used in heat pipes.

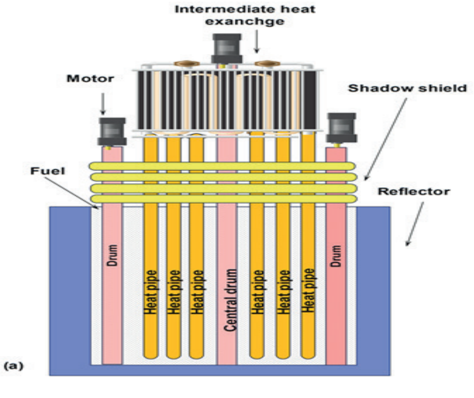
Analysis of heat pipe cooling reactors

In light water reactors, such as pressurized water reactors (PWRs), the saturated steam Rankine cycle is used due to restrictions of the coolant outlet temperature. To increase efficiency, the internal pressure in the reactor core must be increased. In the PWR core, the water coolant is maintained at a pressure of ~15 MPa and temperature of 290–330 °C to prevent boiling. In the secondary loop, pressurized steam from the primary loop is used to heat the water, driven by a steam generator that produces steam that expands in the turbine coupled with the generator, producing electricity. In nuclear units based on liquid metal operating in a fast neutron spectrum, the superheated Rankine cycle is more suitable to deliver a higher thermal efficiency, which involves

Thermodynamic property	Helium (He)	Ammonia (NH_3)	Water (H_2O)	Sodium (Na)	Potassium (K)	Lithium (LI)	Nitrogen (N)	Acetone (C_3H_6O)
Melting point (°C)	–272.0	–78.0	0.0	98.0	62.0	179.0	97.8	–95.0
Boiling point (°C)	–269	–33	100	892	774	1340	883	57
Latent heat of vaporization, H_{fg} (kJ/kg)	23.000	1180.000	2260.000	3600.000	1920.000	19.330	198.000	518.000
Specific heat capacity at constant pressure, c_p (kJ/Kg)	4.60	4.80	4.18	1.38	0.81	4.27	2.04	2.15
H_{fg}/c_p ratio	5	246	541	2680	2370	8393	97	241
Thermal conductivity W/(m·K)	0.151	0.507	0.609	141.000	102.400	84.800	0.026	0.180
Density (g/cm³)	0.00018	0.00077	1.00000	0.97100	0.86200	0.53400	0.00120	0.78400

Table 5. Thermodynamic properties of the principal working fluids used in heat pipes.

reheating and regeneration. Reheating and regeneration are also used to enhance the thermal efficiency of high-temperature gas reactors (HTGRs). Fig. 4 illustrates the core of the MegaPower reactor, which features drums and batteries. Fig. 4 also shows a schematic representation of the fuel assembly within the core.



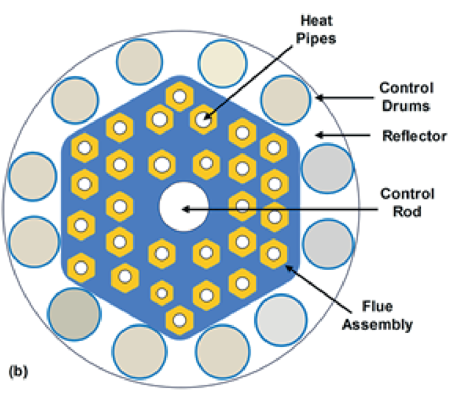


Fig. 4. (a) Schematic illustration of the microreactor heat pipe core with drums and a heat exchanger. (b) Schematic representation of the fuel assembly within the core.

Currently, power conversion systems are being considered for nuclear reactors, with opinions being divided between helium and supercritical carbon dioxide (sCO_2). The most commonly used thermodynamic cycles in microreactors operating with heat pipes are helium gas and sCO_2. In the former, superheated helium vapor is used whereas in the latter, supercritical CO_2 vapor is used. In addition, sCO_2 involves a direct cycle whereas superheated helium vapor involves an indirect cycle. From an economic perspective, the direct cycle of sCO_2 can reduce costs by up to 30% compared with the indirect cycle of helium (Wang et al., 2024).

An alternative approach to achieve maximum efficiency is to implement combined cycles that utilize both steam and gas such as the nuclear air–Brayton combined cycle (NACC). The NACC involves the use of a modified gas turbine that accepts heat from a nuclear reactor and co-fires with natural gas, resulting in a higher power output and flexibility. The NACC has been proposed for HTGRs. The second strategy is to employ gas mixtures such as helium-xenon (He-Xe) to improve the efficiency of energy conversion systems. NASA initially used a helium-xenon gas blend comprising 68% xenon and 37.32% helium, which resulted in a low density of 83.8 g.

The addition of xenon into sCO_2 can further enhance efficiency of the reactor. For sCO_2 Brayton cycles, a compressor stage can improve efficiency and mitigate irreversibility. Compression is typically divided into two stages. A heat pipe microreactor was originally used to explore its integration with the sCO_2 Brayton cycle in order to achieve higher efficiency and a power output of 1–5 MWe for remote and industrial applications. The Microreactor Applications Research Validation and Evaluation (MARVEL) comprises a sodium–potassium-cooled fast reactor that delivers electrical power less than 20 kW and thermal power of ~50 kW using a Brayton cycle. Currently, power conversion systems are the key factors in nuclear reactors, with opinions divided between helium and sCO_2. A technical review of the benefits and drawbacks of helium and sCO_2 Brayton cycles revealed both the advantages and disadvantages of these thermodynamic cycles. Physical differences were responsible for these results. CO_2 exhibits a critical temperature of 30.978 °C and critical pressure of 7.3773 MPa. Beyond this critical point, CO_2 becomes supercritical. At the critical point, CO_2 has a density of 0.467 g/cm^3, which is close to the boundary critical point of liquid CO_2, but it expands like a gas. A key benefit of large density of sCO_2 is it results in compact turbomachinery, which is suitable for portable systems. For the sCO_2 Brayton cycle, the best efficiency depends on reheating, which is a classical approach that can be implemented for any sCO_2 Brayton cycle layout.

Nuclear reactor cores operating with heat pipe cooling systems represent a new paradigm that is experiencing a rapid growth. To achieve a perfect thermal coupling, the fissile fuel must be optimally integrated with the evaporator section of the heat pipe. In some cases, the microreactor core is monolithic and is made of stainless steel, with fuel rods embedded in the steel block in the form of a matrix of fuel and heat pipes. The heat pipes must extend to an intermediate heat exchanger in the case of helium or sCO_2 Brayton cycles. Stirling converters are employed in microreactors operating at the kilowatt scale. Nuclear reactor cores with heat pipe cooling systems represent a new paradigm for microreactor design. The fuel element and cooling system, which consist of a heat pipe located in the same steel core matrix, form a single unit cell. Table 6 lists the main attributes of the Kilopower reactor built by NASA.

Property	NASA/LANL Kilopower reactor	USNC MMR
Power capacity	1–10 kWe	5–15 MWe
Core material/ fuel	Uranium-molybdenum (UMo), enriched with 93% of uranium-235 (also known as highly enriched uranium (HEU))	Uranium nitride (UN), enriched with 19.75% of uranium-235 (also known as low enriched uranium (LEU))
Moderator	$YH_{1.85}$ moderator	Graphite
Core temperature (°C)	800–1200	600–900
Heat pipe working fluid	Sodium	Potassium/ sodium
Heat pipe temperature (°C)	600–900	500–800

Table 6. Main attributes of the National Aeronautics and Space Administration (NASA) Kilopower reactor and Ultra Safe Nuclear Corporation (USNC) micro-modular reactor (MMR).

NASA formed a partnership with governmental institutions such as the LANL, DOE, and the National Nuclear Security Administration to develop the Kilopower reactor at the Glenn Research Center, located in Cleveland, Ohio. The Kilopower reactor was designed to provide power ranging from 1 kW to 10 kW to a spacecraft or lander. The development of the Kilopower reactor lasted for three years, starting in 2015, and tests were successfully conducted in 2018. The standard nuclear material used was uranium-molybdenum (U8Mo) enriched with 50% uranium-235. The core was formed from a solid-cast U8Mo alloy. The reflector was positioned axially above and below the core, and radially around the core. The neutron reflector was made of beryllium oxide (BeO), with a thickness ranging from 0.375 cm to 2.540 cm. A central scram control rod was used to quickly shut down the nuclear fission process in an emergency. The central scram control rod was made of boron carbide (B_4C) to control the fission process. Boron carbide exhibits a neutron cross section that controls the reactivity. The KRUSTY core was cylindrical, measuring 11 cm in diameter and ~25 cm in height. The cylindrical shape formed by U8Mo contained a central hole where the scram control rod was located. UMo fuel shows good structural stability coupled with high thermal conductivity, making it ideal for space power applications. The Kilopower reactor is a heat pipe-cooled reactor with a cooling system composed of eight sodium heat pipes with an outer diameter of 1.59 cm, inner diameter of 1.4 cm, and length of ~2 m, with each heat pipe weighing 4.3 kg.

The nuclear core design must have a lower conduction resistance from the fuel to the final heat sink to enable direct cooling of each component. Reactor cores are typically composed of uranium oxide or other fissile materials arranged as rods or assemblies within the core. Fuel rods generate heat through nuclear fission and thus, the heat pipe reactor core is a monolithic core block, which is a solid structure designed to house nuclear fuel and heat pipes for efficient heat transfer.

The Kilopower and MegaPower cores are monolithic core blocks and solid structures designed to house nuclear fuel and heat pipes for efficient heat transfer. In the Kilopower reactor, the core is a cylindrical form of UMo-sintered fuel. In the MegaPower reactor, the core is made of Haynes 216 stainless steel and drilled to accommodate the fuel rods and heat pipes. Microreactors use heat pipes manufactured from stainless steel or nickel alloys, such as Haynes 230, with a length of ~2 m and diameter of 2 cm.

NASA's Kilopower reactor features a simple cooling system composed of eight sodium heat pipes that transfer fission energy, represented by heat, from the uranium core to the Stirling engines. These heat pipes are made from Haynes 230 to support temperatures over 1149 °C, where sodium is used as the working fluid. The temperature in the fuel core ranges from 800 °C to 1200 °C. The evaporator on the core side operates at temperatures between 600 and 800 °C, while the condenser operates at temperatures between 500 and 700 °C. However, the heat pipes show poor performance at ~400 °C; however, the performance improves at ~600 °C, where the heat pipes begin to transfer significant amounts of heat. By the time the sodium heat pipes reach 800 °C, they are transferring more than double the thermal energy required to keep the Stirling engines operating smoothly. Fig. 5 illustrates a simplified Kilopower reactor core with only one central scram control rod made of boron carbide (B_4C), which is used to control the reactivity of the core formed by a cylindrical block of U8Mo enriched with 93% uranium-235 and featuring two sodium heat pipes.

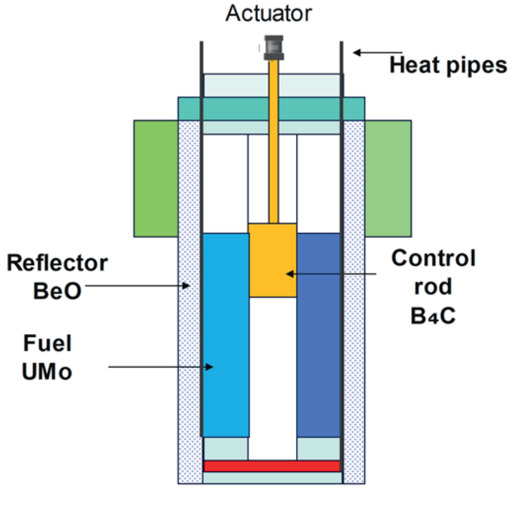


Fig. 5. Schematic illustration of the Kilopower reactor core containing UMo fuel as well as a scram control rod made of B4C to control reactivity.

Since the 1950s, the Brayton and Stirling cycles have been researched by space programs and American national laboratories. In the mid-1960s, NASA developed the Brayton Rotating Unit (BRU) to enhance the reliability and efficiency of the closed Brayton cycle for space power conversion. The BRU was implemented at the Glenn Research Center, designed to be 10 kW, and the 2-kW mini-BRU demonstrated technical feasibility and performance. NASA then introduced the SNAP-8 fission reactor using a helium-xenon gas blend. The 1970s oil crisis spurred the adoption of the Brayton cycle in solar energy. Currently, sCO_2 Brayton cycles are advancing carbon capture technology, supporting various demands on electrical grids. Fig. 6 illustrates a microreactor operating based on the Brayton cycle.

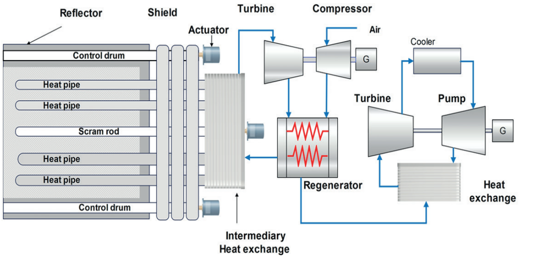


Fig. 6. Heat pipe-cooled reactor with a gas turbine, where the Brayton cycle is employed in the secondary loop.

The Southwest Research Institute, based in San Antonio, Texas, began working on a 10-MWe sCO_2 pilot power plant in 2020. At the same time, they developed a 10-MWe turbine that can function in dry cooling conditions at temperatures as high as 700 °C. AISI-316L and AISI-347 steels were used in the first test because high temperatures necessitate the use of corrosion-resistant alloys. Hence, efforts were made to study Inconel 800H, Haynes 230, and AFA-O6C. The Supercritical Transformational Electric Power (STEP) program encompasses several initiatives that cover every aspect and component of turbomachinery that adopts the sCO_2 Brayton cycle.

Conclusion

The existence of almost a hundred new reactor designs, ranging from 1 kWe to 300 MWe, has opened up a new energy market with lower investment requirements. Currently, nuclear reactors can be designed based on the SMR and microreactor concepts. Energy markets are undergoing a profound transformation, incorporating the desires of the human society and government perspectives on new technologies to reduce CO_2 emissions and mitigate global warming. The aspects of mobility and ease of transport have aroused strategic military interest in the desert and Arctic regions. Since 2018, experiments have been successfully carried out on the Kilopower reactor at the Nevada National Security Site. NASA has marked a historic milestone for nuclear reactors at the kilowatt scale. NASA's prototype introduced innovative engineering approaches, including the heat pipe cooling concept, which is popular for space missions. Heat pipes are necessary in the Kilopower reactor because of the space environment, which lacks an atmosphere and operates under microgravity. The reactor core is monolithic with a cylindrical fuel, featuring a scram control rod at its center and lacking moving parts. The code name KRUSTY refers to the use of Stirling converters for small power applications. Heat pipe reactors at the megawatt scale require further research because of the apparent differences from civil PWR-type reactors that have been in operation for over 50 years.

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Daniel de Souza Gomes: Conceptualization, Formal analysis, Methodology, Writing – original draft.

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Declaration of conflicts of interest

The author declares that there are no conflicts of interest that could have influenced the work reported in this paper.

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