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HEAT PIPE COOLED REACTOR USING BRAYTON CYCLE

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Abstract: Over the last seven decades, Los Alamos National Laboratory (LANL) has collaborated with the National Aeronautics and Space Administration (NASA) on several projects related to space exploration. NASA and LANL collaborated to develop the Kilopower reactor, a compact and lightweight device with an approximate power output of 10 kW. LANL developed the MegaPower concept project, which is a heat-pipe reactor fast-spectrum design intended to produce 5 MW of thermal energy. It is designed for remote locations to operate independently of the electrical grid. The MegaPower design differs significantly from Kilopower's. In addition to its power capacity, it does not use a Stirling converter; instead, it employs a Brayton cycle for power conversion. The reactor core was a 1 m-diameter, 1.5 m-high cylinder of stainless steel 316. It also features an advanced passive cooling system comprising 1,224 potassium heat pipes that operate between 650 and 1000 °C. The efficiency of MegaPower depends on the performance of heat pipes. The efficacy of MegaPower depends on the performance constraints exhibited by heat pipes, such as their boiling point and critical temperature. The optimization of heat pipes depends on proper wick structure, vapor cavity, and geometry of the evaporator and condenser to mitigate the risks associated with transients. In heat pipes, dry-out occurs when there is insufficient fluid to maintain the continuous circulation of vapor and liquid. The power conversion system utilizes an open Brayton cycle, which offers benefits over the steam **Rankine cycle.**

Keywords: Heat pipe cooled reactor, Brayton Cycle, capillary limit, sonic limit, Alkali metals

Introduction

Since the Paris Agreement, the objective has been to limit global warming to well below 2 °C as a result of the industrial revolution that began in the United Kingdom in the mid-18th century, with a further effort to limit it to 1.5 °C. Achieving net-zero carbon emissions by 2050 requires extensive behavioral changes across all sectors of human society. Simple implementation action plans that outline how countries will reduce greenhouse gas emissions and achieve their long-term climate goals, aiming to reach climate resilience, are long-term low-emission development strategies (LTLEDS), a roadmap for a more sustainable environment (Waisman et al., 2019). Nuclear energy produces lower carbon emissions than renewable sources such as solar and wind energy. Nuclear energy has emerged as a potential solution to avoid the catastrophic consequences of climate change (Dong et al., 2025).

Over the years, coal combustion has been preferred over electricity in the United States because of its abundance. The United States has 204 coal-fired power plants (CFPPs) in operation, which generate approximately 15% of the nation's electricity demand. However, nuclear energy stands in contrast to coal, oil, and natural gas, with reduced greenhouse gas emissions comparable to those from renewable sources (Williams et al., 2025). Today, the CFPPs exhibit significant carbon emissions, ranging from 515 to 1,265 gCO_2/kWh. Nuclear units produce reduced amounts of greenhouse gases, estimated to be approximately 12 gCO_2/kWh, accounting for approximately 2.5% of the total CO_2 emissions from coal-fired power plants (CFPPs) (Lee et al., 2017). However, Nuclear energy is a clean energy derived from mining methods used to extract uranium from the Earth.

Additionally, this includes other contributions as well as the transport, enrichment, and manufacturing of fuels. However, total emissions are lower than for wind energy and comparable to those of solar power, approximately one-third of solar power. Nuclear energy accounts for approximately 20% of global electric power generation and supplies approximately 10% of domestic demand in the United States (Black et al., 2023). Due to its low carbon footprint, nuclear energy will be a key factor in achieving net-zero emissions by 2050 (Yasir Mehboob et al., 2024).

The US government has incentivized plans to reduce the construction period and associated costs of nuclear plants. The growing global demand for electricity requires rapid, efficient power sources. A strategic plan to downsize nuclear units is an economic consequence of the high costs and delays associated with the construction of traditional atomic units. Over the past decade, many projects have exceeded their original economic budgets and schedules. There are examples worldwide, such as Olkiluoto (Finland), which faced several delays in the construction of a third reactor, Olkiluoto 3 (OL3). Flamanville-3, with a power output of 1,650 MWe (electrical), began construction in 2007 and was scheduled to enter service in 2013. However, Flamanville-3 faced numerous difficulties during its completion. Other identical cases, such as those at the Vogtle plant in Georgia in the southeastern United States, planned for 1,117 MW, and England at Hinkley Point (UK), with two reactors of 1,630 MW, also faced budget overruns and delays (Testoni et al., 2021). Critical cases include Flamanville-3, a European reactor, and the Vogtle plant with a Westinghouse design.

Civilian nuclear reactors have been built with power capacities exceeding 1000 MWe. The Westinghouse AP1000, planned for electricity generation, produces 1,000 MWe (electrical), and the European Pressurized Water Reactor (EPR) produces 1,650 MWe. These power units, operating at full capacity, can generate approximately 24 million kWh per day, equivalent to approximately 8.76 terawatt-hours (TWh) per year. The US Department of Energy (DOE) maintains Small Modular Reactor (SMR) programs under development that span a variety of sizes, technologies, capabilities, and deployment scenarios (International Atomic Energy Agency, 2024). The Tennessee Valley Authority, a federal corporation, formed a coalition to develop GE Vernova Hitachi BWRX-300, a PWR with a capacity of 300 megawatts of electricity (MWe). In the field of molten salt reactors (MSR), the DOE collaborates with Kairos Power, Terrestrial Energy, and Elysium (International Atomic Energy Agency, 2023). In Seversk, near Tomsk, Russian Rosatom developed a liquid metal small modular reactor (SMR), BREST-OD-300, with a capacity of 300 MWe. The reactor features nitride and lead coolants. The SMR limitation is a capacity of up to 300 MWe, which can be expanded by adding additional modules.

The US government offers various funding mechanisms, including grants, tax credits, and direct investments, to reactor suppliers such as Westinghouse, NuScale, X-energy, and Holtec. American companies are developing several concepts sponsored by the Inflation Reduction Act (IRA), including X-Energy and NuScale. Following

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a public strategy, they add funding from the Defense and Energy Security Initiatives, with financial backing from Holtec and Westinghouse. In other nations, this has been highlighted by a European task force, the European Industrial Alliance, which aims to accelerate SMRs. In France, Electricité de France (EDF) and its subsidiary NUWARD are developing the NUWARD SMR (Pioro, 2016). The NUWARD SMR is a collaborative project between the EDF and TechnicAtome Naval Group, a French company that builds two SMRs based on the PWR design, each with a capacity of 170 MWe. These units produced 340 MWe during the coupled operation.

A global push for small modular reactor technologies is underway, with more than 80 innovative designs from over 18 nations. Presently, it is necessary to enhance energy security and decarbonization to meet the demand in isolated regions. The US DOE initiatives have explored non-water-cooled reactors and promoted the use of liquid metals, molten salts, and gas-cooled reactors, which reduce fuel and water consumption. SMRs that do not rely on water are more specialized and use liquid metals, such as lead, alkali metals, such as sodium, and molten salts, such as chlorides and fluorides. Kairos Power plans to develop the Hermes demonstration reactor, a molten fluoride salt reactor scheduled for operation in 2027. A few High-Temperature Gas Reactor (HTGR) designs have been proposed to use tristructural (TRISO) fuel (Sato and Yan, 2025), including the MMR-5 developed by Ultra Safe Nuclear Corporation (USNC) and the Xe-100 built by X-Energy (Lane and Revankar, 2025).

Globally, several nations, including Canada, France, the United Kingdom, China, and Russia, are investing in SMR designs. Efforts have focused on next-generation reactors in Canada, with Moltex and Terrestrial Energy. China and Russia are currently deploying floating land-based units. On the European continent, in England, Rolls-Royce is developing an advanced Small Modular Reactor (SMR) with a power capacity of 470 MWe, targeting a domestic market and potential units for Sweden and Poland. China began its first SMR, the demonstration ACP-100, which delivered 125 MWe in 2019. Russia developed the KLT-40S, which has a thermal power of 150 MWth or 52 MWe.

It is a small modular pressurized water reactor that operates using uranium dioxide (UO_2) dispersed within an aluminum alloy matrix (Beliavskii et al., 2023). South Korea has developed a System-integrated Modular Advanced Reactor (SMART), which is a PWR designed for desalination with a capacity of 100 MWe (Böttcher and Sanches-Espinoza, 2023). However, regarding SMRs, the energy cost of generation exceeds the ideal level. SMRs exhibit a levelized cost of electricity (LCOE) of \$50 to \$100 per megawatt-hour (MW/h), while civilian PWRs have an LCOE of \$78 to \$97 per MW/h

TECHNOLOGICAL REVIEW

The microreactors generate 1-20 MWth (thermal) of energy and are constructed with modular components that enable easy transportation (Christensen et al., 2021). Several classes of microreactors have been developed, beginning with the heat-pipe space reactors. Furthermore,gas-cooled microreactors, which were initially developed from high-temperature gas reactors using natural uranium, were introduced in the 1950s. However, new fuel technologies have been developed for high-temperature applications. Westinghouse is developing a microreactor, eVinci™, with a thermal power of 15 MWth, utilizing TRISO fuel. The OKLO company is building the AURORA microreactor, with a thermal power of 1.5 MWth, designed to operate with high-assay, low-enriched uranium (HALEU) at enrichment levels between 5% and 20% (Skerjanc and Youinou, 2023).

The Defense Innovation Unit (DIU), also known as Unit X, operates within the US Department of Defense (DoD). The DIU's target is to accelerate the development of resilient power technologies, such as microreactors, for remote military bases. Microreactors are gaining attention because compact systems offer advantages such as mobility, portability, scalability, and resilience in remote locations. Microreactors are small and can be transported to remote regions by road, rail, ship, or air. Deployment in isolated areas: Microreactors operate either on the electric grid or off-grid. Mobility is enabled by the small dimensions of standard containers, which can be transported by road, rail, ship, or air to remote regions. Furthermore, microreactors can operate on the electric grid or off-grid.

The steam Rankine cycle is widely used for light water reactor (LWR) units; in contrast, open and closed Brayton cycles (CBC) are more suitable for MSR and HGTR units (Zhang et al., 2021). Brayton cycles operate with working fluids, such as air, helium, xenon, nitrogen, and CO_2 (Tian et al., 2025). Recently, Brayton cycles utilizing supercritical CO_2 (sCO_2) and gas mixtures, such as He-Xe, have become viable options.

Although the steam Rankine cycle in LWRs has many years of operational experience, it is often described as complex, less efficient, and requiring heavier turbomachinery than the Brayton cycle. However, few SMRs have adopted the Rankine cycle. The Gen4 Module (G4M), a liquid metal-cooled fast reactor that produces 25 MW of electrical power, operates with uranium nitride (UN). Numerous international initiatives have focused on small Light Water Reactors (LWRs). In the Russian Federation, a subsidiary of Rosatom, OKBM Afrinkantov, is developing the ABV-6, an Integral Pressurized Water Reactor (iPWR) that delivers 14 MW thermal and 8.6 MW electrical power, utilizing natural circulation. Simultaneously, OKBM Afrikantov is developing the RITM-200, classified as an iPWR with a capacity of 175 MWth or 50 MWe, for use in icebreakers as part of the marine propulsion initiative.

HEAT PIPE COOLED REACTOR DESIGNS

In 1958, American President Dwight D. Eisenhower signed the National Aeronautics and Space Act, marking the beginning of the space race and the United States' space propulsion programs. In the 1960s, the American space program began developing a heat-pipe-cooled reactor design to operate with a low-power radioisotope thermoelectric generator (RTG). Donald Grover introduced heat transfer devices, or heat pipes, while working at Los Alamos National Laboratory (LANL) in 1964. Moreover, they are basically intended for high-temperature applications, particularly space reactors. The advantages comprise that heat pipes can operate in a zero-gravity (space) environment and support a wide range of sizes, materials, temperatures, and internal

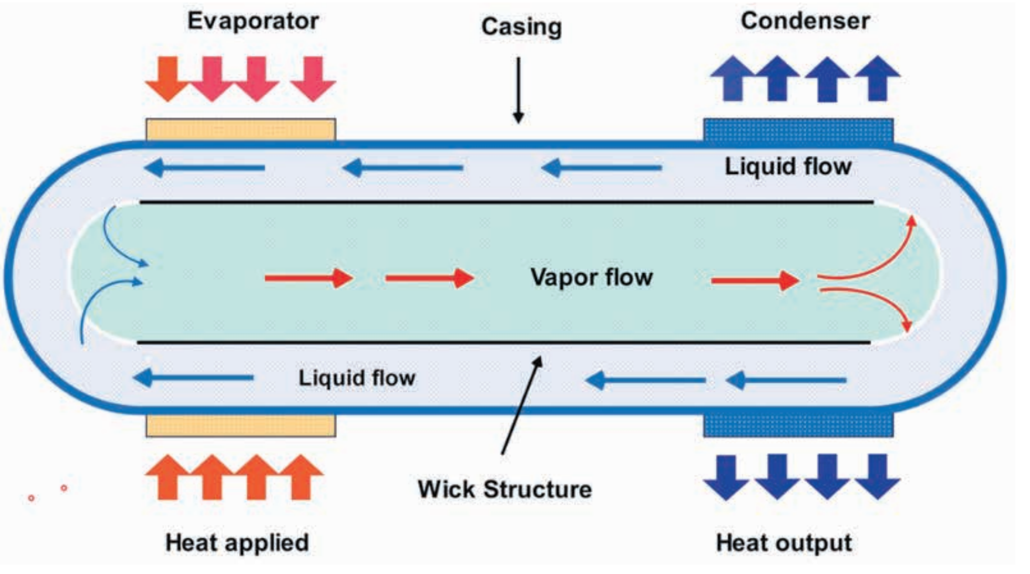

Figure 1. Conventional heat pipe and heat flux from the evaporator section are driven to the condenser section

and external configurations. Figure 1 shows the structure of a traditional heat pipe.

This year's solar-cell battery systems, or RTGs, and heat pipes were costly and presented technical difficulties (Lantz et al., 1974). Between 1970 and 1989, the Kurchatov Institute, with its pioneering spirit, led the Soviet Union in building the TOPAZ-II thermionic conversion reactor (Wu et al., 2023). To date, equally driven America has launched the Systems for Nuclear Auxiliary Power (SNAP) program, culminating in the development of the space reactor system SNAP-10A, the first nuclear reactor launched into space in 1965. Space reactors require efficient thermal management because there is no atmosphere for convective cooling, and they must operate in a gravity-free environment at the lowest possible temperature Microreactor designs use passive heat-pipe cooling, eliminating the need for pumps and valves and thereby reducing costs. Many heat-pipe-cooled reactors (HPCRs) have used sodium or potassium as the working fluid because core temperatures exceed 600 °C. Alkali metals exhibit suitable physical properties such as high thermal conductivity, low viscosity, and high surface tension. Within a temperature range of 600 to 1000 °C, alkali metals have melting and boiling points that are compatible with those of an ideal working fluid. This fluid evaporated near the heat source contact in the evaporator section, reached its boiling point, and flowed via capillary forces to the condenser section. In a heat pipe, natural fluid flow is driven by capillary forces, which are enhanced by an internal wick structure made of a porous metallic or ceramic material. However, a heat pipe requires a seamless integration of mechanical and chemical properties with the monolithic steel core of the nuclear reactor. In summary, alkali metals such as sodium, potassium, and lithium are more suitable at high temperatures because they remain liquid and superheat before evaporating (Dean et al., 1985).

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In HPCRs, sodium heat pipes operate at high temperatures, ranging from 600 to 800 °C, and are 1 to 2 m long, which is considered long compared to industrial heat pipes. A heat pipe requires perfect integration with the reactor core, which contains a fuel element that serves as a heat source and is powered by uranium fission. Each cooling system, comprising a heat pipe and fuel element, forms a single unit cell. To enable direct cooling of every component, our nuclear core design was meticulously crafted to reduce the conduction resistance from the fuel to the final heat sink. In the core reactor, uranium dioxide (UO_2) is arranged in rod or hexagonal assemblies. The cylindrical core of the reactor was coated with Haynes 230 steel, specifically designed for aerospace and turbine applications, owing to its high mechanical strength and resistance to high temperatures.

HPCRs enable direct heat extraction from the core reactor without pumps, valves, or extensive piping. While in the evaporator section of the heat pipe, which contains alkali metals such as sodium, potassium, and lithium, the adopted fluid evaporates near the nuclear fuel. Simultaneously, monolithic reactor cores made of stainless steel were drilled to accept heat pipes and fuel rods, after which the fluid flowed to the adiabatic section, transporting the vapor without heat exchange, driving it to the condenser section of the heat pipe, and transferring thermal energy from the reactor core to the Stirling engines for electricity conversion. The Kilopower reactor was designed by NASA and Los Alamos National Laboratory (LANL) to supply dependable power for expeditions to the Moon and Mars. Eight sodium heat pipes were used in the Kilopower project to transmit heat from the uranium core to Stirling engines. These heat pipes employ sodium as the working fluid and are constructed from Haynes 230 to withstand temperatures above 1149 °C. The temperature inside the fuel core rises to 800–1200 °C. (McClure et al., 2020).

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The partnership between NASA, LANL, and the private sector has enabled more affordable development of heat pipe microreactors, such as the Kilopower and Fission Surface Power Systems (FSPS). The FSPS was initiated in 2007. Table 1 illustrates a few heat pipe-cooled reactors in-built phases worldwide.

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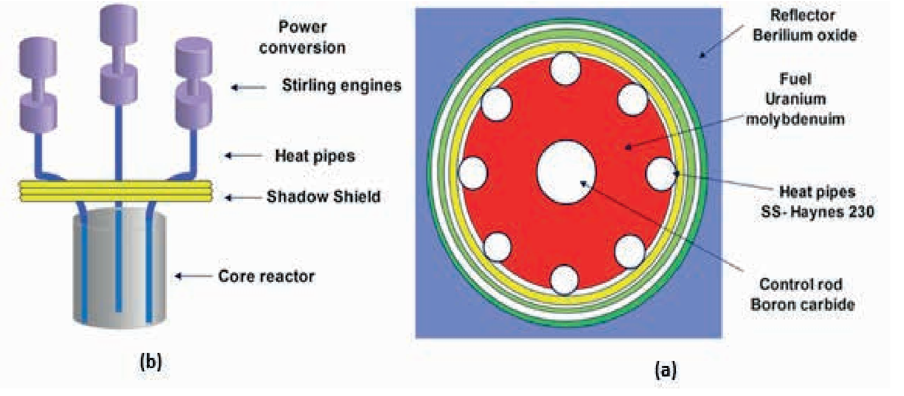

Figure 2. Kilopower core reactor schematic (a) and connection of core heat pipes with Stirling engines (b).

Reactor	Developer	Power	Working Fluid	Temperature (°C)
Kilopower	NASA	1-10 kWe	Sodium	800
Megapower	NASA/LANL	2 MWe	Sodium	1000
HOMER	LANL	5-10 kWe	Potassium	700
eVinci™	Westinghouse	200 kWe-5MWe	Sodium/Potassium	600-800
SAIRS	NASA	100 kWe	Sodium	900
LEU-HPT	LANL	1MWr	Sodium	800
Holos-Quad	HolosGen	3-13 MWe	Sodium	800

Table 1. Microreactors in development based on heat pipe cooling systems

Components	Pressure (MPa)	Temperature (°C)
Steam generator	6–7	275–300
Turbine High-Pressure stage inlet	6–7	275–300
Turbine Low-Pressure Stages outlet	0.005–0.001	40–50
Condenser	0.005–0.001	30–50
Feed Water Pump Inlet	0.005–0.001	30–50
Feed Water Pump Outlet	6–7	150–170

Table 2. Components parameters in the steam Rankine cycle used in light water reactors

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NASA has adopted sodium and potassium heat pipes for power outputs ranging from 1 to 10 kW. The Heat Pipe-Operated Mars Exploration Reactor (HOMER), initiated in 2001, is a conceptual space reactor designed for Martian surface missions. It integrates heat pipes with sodium working fluid to enable passive cooling. At the turn of the millennium, LANL developed a Heat Pipe Power System (HPS) featuring a compact and lightweight design that supplied power ranging from 1 to 20 kW; HOMER is a derivative of this system (Poston, 2001). HOMER is based on the HPS, a potential, near-term, low-cost power system. The first HOMER prototype, with a core composed of 97% enriched UO_2, featured 152 fuel pins clad with stainless steel (SS) owing to the Martian atmosphere. The initial core plan consisted of 57 sodium heat pipes with a steel casing, each containing 128 kg of UO_2. A Chinese proposal is for a lithium heat pipe-cooled space reactor known as the low-enriched uranium heat pipe reactor (LEU-HPT), which is based on heat pipe-segmented thermoelectric module converters (HP-STMCs) and includes moderators such as yttrium hydride (YH2) and 19.9%-enriched uranium nitride.

Alkali Metal Thermal-to-Electric Conversion (AMTEC) technology is integrated with a fast-spectrum neutron reactor cooled by sodium heat pipes in a Scalable AMTEC Integrated Reactor space (SAIRS) power system, which is a conceptual design for a high-efficiency space nuclear reactor. The SAIRS consists of a conceptual project to deliver 111 kW, with 60 sodium heat pipes reaching 927 °C. A core was formed from 60 modules using uranium nitride (UN) fuel pins and rhenium as cladding, brazed to a central sodium/molybdenum heat pipe. HolosGen, founded in 2017 and dedicated to developing mobile, scalable, and integral nuclear generators, is creating Holos-Quad; however, it is not yet operational. Holos-Quad is a helium-cooled gas reactor operating at 7 MPa that integrates a turbojet-type compressor and turbine and utilizes TRISO fuel implanted in hexagonal graphite blocks (Stauff et al., 2024). Holos is a compact reactor that fits into a commercial ISO container and is made possible by integrating a helium-cooled gas reactor with a compressor and turbojet-type turbine. The heat pipe length varies from 1 to 2 m for power below 10 kW; for MW power, over 60 heat pipes are required.

THERMODYNAMIC CYCLES

The Rankine Cycle was a cornerstone of power generation in the 20th century and played a crucial role across all industrial sectors. PWRs are widely used for PWRs owing to their suitability for vapor power plants, which comprise reversible processes. The Rankine cycle comprises four thermodynamic transformations that alternate between isentropic and isobaric conversions. The first step involved compression. The coolant water entered the pump as a saturated liquid and underwent isentropic compression. Heat is generated by the controlled nuclear fission of uranium in nuclear fuel rods. In a core reactor at high pressure, water coolant absorbs fission energy from U-235 fission while remaining in a liquid state at 15.5 MPa and 315°C. Subsequently, the heat energy is transferred from the primary loop to the secondary loop via a steam generator. In the secondary loop, water boils into steam at 6 to 7 MPa and 275 to 300 °C. Its principal role is in steam turbines, where isentropic expansion occurs. High-pressure steam dri-

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ves the turbine, converting thermal energy into mechanical work. In the condenser, the exhaust steam condenses back into liquid at a low pressure of ~0.005–0.01 MPa.

The energy conversion process in nuclear power plants, specifically in PWR designs, comprises six elements: a steam generator, a steam turbine, a condenser, a feedwater pump, a moisture separator, and a reheater (Fernández-Arias et al., 2020). The turbomachinery used in a PWR comprises pumps, turbines, and condensers. The steam generator consists of Inconel U-tubes operating at 6 MPa, measuring 21 m in height and weighing up to 800 tons. A steam turbine undergoes isentropic expansion of steam to generate mechanical work, producing power ranging from 600 to 1,500 MW. The exhaust turbine vapor is driven to the condenser, and the steam exhausted from the turbine must be condensed into a liquid. Feedwater heaters, on the other hand, heat the water pumped into the steam generator. In a pressurized water reactor, the heat produced by controlled fission in the primary loop is used to generate highly radioactive steam under high pressure. This heat is then transferred to the secondary loop via a steam generator that isolates it from radioactive effects, causing the water to boil and form steam. The Rankine parameters are listed in Table 2.

Thus, in the secondary loop, steam is not superheated. Boiling-water reactors (BWRs) operate simultaneously with superheated steam. The Rankine cycle operates as a direct flow in a BWR, eliminating the need for steam generators. The BWR allows the reactor core to convert water into steam, which directly drives the turbine. In contrast to PWRs, BWRs operate at 7 MPa and temperatures of 286–290 °C, forming a steam-water mixture with a steam quality of 10%–15%. Thus, PWRs are more efficient than BWRs because they operate at the boiling point of steam vapor-containing water droplets.

South Korea is developing a direct-cycle sCO_2-cooled micromodular reactor (MMR) called the KAIST, appropriating the same name as the MMR group. KAIST operates a supercritical CO_2 (sCO_2) Brayton cycle, coupled with natural circulation, for passive heat removal. Currently, reactor suppliers are witnessing a notable growth in sCO_2 Brayton cycles, which involve several SMR designs, including sodium fast reactors, gas-cooled fast reactors, and molten salt reactors. Several designs for Generation IV reactors have been proposed that leverage the benefits of sCO_2, owing to its high thermal efficiency at moderate temperatures. The main advantage of the sCO_2 cycle is its compact turbomachinery compared to steam cycles. In this cycle, sCO_2 is compressed near the critical point, where the fluid becomes nearly incompressible. Between 1995 and 2003, China faced a significant technological challenge in developing a strong capacity for Generation IV nuclear designs, with a focus on HTGRs (Zhang and Yu, 2002).

Additionally, the pebble bed reactor HTR-10, located at Tsinghua University in Beijing, utilizes TRISO fuel at approximately 725 °C with a power output of 10 MW. Numerous nations have announced projects involving Generation IV. The Chinese initiative is based on a helium-turbine HTR-10GT with a power of 10 MWe, and commercial deployments are expected by the 2030s (Geng and Wang, 2025). Figure 3 illustrates a heat pipe and sCO_2 Brayton

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cycle comprising a compressor, turbine, cooler, heat exchanger, and generator

China is developing at least five microreactor designs with power capacities ranging from 1 to 50 MWe. Echogen Power Systems in Akron, Ohio, focuses on optimizing sCO_2 by incorporating recuperation, precompression, and reheating, which are coupled with EPS100, an sCO_2 gas turbine proposed for waste-heat recovery (Wang et al., 2023).

HELIUM AND SUPERCRITICAL CO_2 CYCLES

Supercritical CO_2 turbines are being developed worldwide. Toshiba built an experimental 25 MWe turbine, and General Electric and Southwest Research Institute are developing a 10 MWe sCO_2 prototype turbine. At the same time, the Chinese Academy of Sciences is developing a 5 MWe turbine, and other corporations, such as Bechtel, have also declared research interest in sCO_2 turbines. Westinghouse is developing eVinci™, a microreactor based on sodium-cooled heat pipes, measuring 3.6 meters, reaching 800 °C, operating with TRISO fuel, and planned power output ranging from 5 MWe. The Swedish proposal is the Advanced Lead Reactor (ALR), also known as SEALER, which uses molten lead as a coolant and delivers 3-10 MWe (Wallenius et al., 2018).

In Denmark, the private company Copenhagen Atomics is creating a Seaborg compact molten salt reactor (CMSR) and a similar version (Cui et al., 2022). Seaborg is a Gen-IV design; however, it is not a microreactor with a power capacity of 250 MWth (approximately 100 MWe) and operates in a thermal spectrum using thorium fuel. Simultaneously, the Department of Defense (DoD), which was sponsoring a small, portable liquid-metal reactor, began a project on a Liquid Metal-cooled Ultra-compact Mobile Reactor. The prototypes are planned to operate in remote areas where weight and compactness are crucial considerations. Another significant factor is the viability of MSRs and HTGRs for steam cycling (Kindra et al., 2022). Generation IV reactors operate at high temperatures, ranging from 500 to 1000°C, to achieve high efficiency. Furthermore, HTGRs, compared to Generation IV reactors, operate at core outlet temperatures of around 850 °C and utilize helium as a coolant. Table 3 lists the primary attributes of the fluids used in the thermodynamic cycles in nuclear technologies.

In a cooling system, the heat generated in the core is directly transferred to the working fluid. Thus, the working fluid exhibits a set of thermal characteristics that can determine the cycle efficiency. Air serves as the working fluid in turbojet engines designed for aircraft propulsion. In this way, the gas's physical properties determine the gas turbine project parameters, even though nitrogen has lower thermal conductivity than air. Helium gas turbines achieve 40% efficiency when operating with weighted turbomachinery (Geng and Wang, 2024) . However, it improves heat transfer due to its lower molecular weight and higher thermal conductivity. Supercritical CO_2 operates at high pressures above 10 MPa, using compact turbomachinery that reduces compressor effort and increases efficiency. Table 4 shows fluid properties based on He, Xe, and CO_2 used in gas turbines in microreactors.

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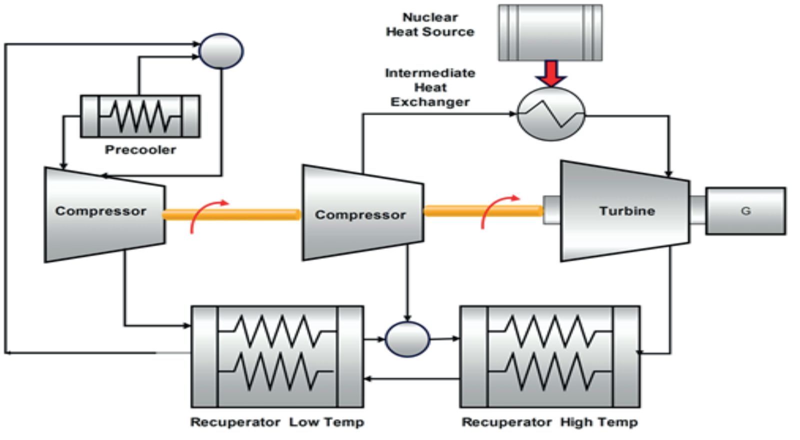

Figure 3. Heat pipe-cooled reactor connected to an sCO_2 Brayton cycle, comprising a compressor, turbine, regenerator, and generator.

Properties	He	Xe	CO_2	N_2	Water
Molar weight (g)	4.00256	131.293	44.01	28.014	18.11
K (mW/m·K) at 25°C	157.7	5.5	16.8	25.83	598
Cp (kJ/kg·K,) at 25°C	5.1926	0.158	0.846	1.04	4184
Cv (kJ/kg K) at 25°C	3.1156	0.095	0.652	0.743	4.184
Gamma (Cp/Cv)	1.67	1.67	1.29	1.44	1
Tc Critical temperature (°C)	-267.9547	16,583	31.05	126.2	374.14
Pc Critical pressure (MPa)	0.22746	5.8420	7.39	339,8	22.09
Critical molar volume (cm^3/mol)	57.3	118	94.0	89.5	56.0
Critical density ρc (kg/m^3)	69.6	1100	468	313	322
Zc Critical compressibility factor	0.301	0.286	0.274	0.290	0.230

Table 3. Physical properties of fluids He, Xe, CO_2, N_2, and H_2O used in Rankine and Brayton

Turbine parameters	Helium (He)	Xenon (Xe)	sCO_2
Inlet temperature (°C)	900–1200	800–1100	700–1000
Inlet pressure Pi (MPA)	2–8	7–20	7-20
Outlet pressure (MPa)	0.5–2	0.3–1.5	7–15
Thermal efficiency (%)	40–50	35–45	45–55
Mass flow rate (kg/s)	50–200	10–50	20–100
Rotational Speed (10^3 RPM)	10–25	5–12	15–40
Power Density	High	Moderate	Very High

Table 4. Properties of different gas turbines used in microreactors

To achieve the highest efficiency, combined cycles operating with both steam and gas, based on the nuclear air–Brayton combined cycle (NACC), have been proposed for High-Temperature Gas Reactors (HTGRs). Another approach is the Brayton cycle using gas mixtures such as helium-xenon (He-Xe), helium-neon (He-Ne), and sCO2, which significantly improve the efficiency of energy conversion systems. Earlier, NASA operated a helium-xenon gas mixture consisting of 68% Xe and 37.32% He with a low mass of 83.8 g. A set of desirable features, such as Prandtl numbers in the range of 0.18−0.7, coupled with thermal conductivity of the helium gas at 25 °C (0.153 W/m·K) and the incompressibility of xenon (Wang et al., 2023). The advantages of the He-Xe gas mixture are that it operates in compact system structures, exhibits exceptional compression performance and chemical stability, and optimizes the power/weight ratio. Figure 4 shows a transportable microreactor, such as the BWXT Mobile Microreactor or the Westinghouse eVinci™.

A few designs currently adopted supercritical carbon dioxide Brayton cycles, for which the INL, Westinghouse, and OKLO designs have been developed. Turbines use CO2 in its supercritical state as the working fluid, enabling higher turbine inlet temperatures and a simpler turbine design. X-Energy was founded in 2009 in Rockville, Maryland, USA. It has been developing a few HTGRs, including Xe-100, which uses TRISO fuel for safety and efficiency. Radiant Nuclear is headquartered in El Segundo, California, and was founded in 2019. Radiant Industries, based in Los Angeles, is developing microreactors for off-grid and remote power applications, focusing on compact, transportable designs that provide clean energy solutions (Jia et al., 2024).

Helium cycles are highly efficient because they recover heat more effectively. By contrast, for CO_2 Brayton cycles, the compressor stage can improve the efficiency and mitigate irreversibility. Compression is typically divided into two phases. The Brayton Cycle performance, similar to the closed Brayton cycle (CBC) (Liu et al., 2020), is predominantly determined by the selected working fluid; helium and supercritical carbon dioxide (sCO_2) are two of the most attractive choices for high-temperature applications.

Flibe (LiF-BeF_2) is a molten salt with excellent heat-transfer properties. Flibe Energy was developed to commercialize this technology. Kairos Power is developing Kairos Power Fluoride Salt-Cooled High-Temperature Reactors (KP-FHRs) using molten salt as the coolant. Kairos Power, based in Alameda, California, was established in 2016. The prototype KP-FHR is planned to be 140 MWth with lithium fluoride (LiF) and beryllium fluoride (BeF_2), also known as FLiBe, as coolants at atmospheric pressure. Low-pressure operation eliminates the need for thick-walled pipes and tanks, potentially reducing costs and enabling the use of TRISO fuel. In 2023, the US Nuclear Regulatory Commission (NRC) issued a construction permit for Tennessee's Hermes Kairos 35 MWth test reactor, which produces only heat.

MICROREACTOR THERMAL ANALYSIS

MegaPower is planned to generate 5 MWth of power for operations in remote regions. The initial targets offered reliable

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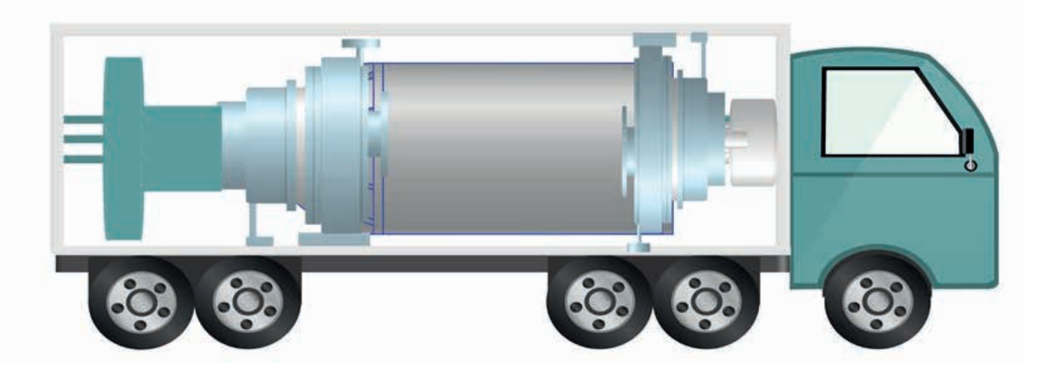

Figure 4. Transportable microreactor in a container with a length of 6 m, a width of 2.6 m, and a height of 2.66 m

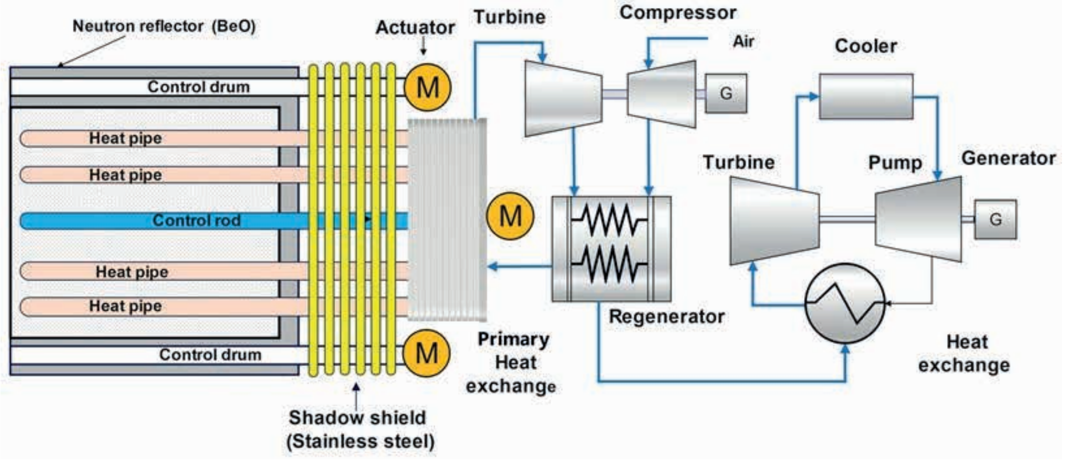

Figure 5. Core heat pipe reactor schematic: solid steel with fuel and control drums operating in the Brayton cycle

and resilient off-grid nuclear power. MegaPower, a fast-spectrum reactor developed by the Los Alamos National Laboratory, features a monolithic stainless-steel core with embedded heat pipes for passive cooling. MegaPower features solid-state cores constructed from monolithic 316 stainless steel, joined by passive heat transfer via alkali-metal heat pipes with potassium as the working fluid. The core structure consists of a solid steel block that embeds 352 unclad, 1.5 m-long fuel rods and 204 high-temperature potassium-metal heat pipes. Nuclear fuel consists of standard UO_2 and 19.75% enrichment, with a pellet diameter of 1.425 cm. The thermal model proposed by LANL assumes a constant-temperature boundary condition of 677°C for the monolith core and the upper reflector surfaces where the heat pipes are active.

In structural analysis, the mechanical model calculated the effects of temperatures ranging from 27 °C to 27 °C, reaching peak values, to determine stresses, heat fluxes, and thermal expansion. The thermal model assumes an initial temperature of 27°C. All resulting thermal stresses and expansions were determined based on the change in tempe-

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rature from the initial temperature. For the thermal expansion calculations, the lower surface of the model, corresponding to the bottom of the reactor gas plenum, was fixed. Axial expansions were measured from this fixed bottom surface, and radial expansions were measured outward from the inner reactor core surface. In steel, the core shows temperatures ranging from 676 to 696 °C, with a slight fluctuation of 20 °C. Under regular conditions, experiments show a relative thermal gradient of approximately 80 °C, varying from 676 to 756 °C, as a function of core position. The reactor in-core steel monolith can reach a maximum fuel temperature of 753 °C, or 76 °C above the isothermal boundary temperature of 677 °C under regular conditions. The maximum temperature of the monolithic core was 696 °C, 19 °C above the heat pipe isothermal operating temperature. The core mechanical response of stress also shows substantial variation, ranging from 0.28 to 37 MPa, with a peak of 37 MPa. Figure 5 illustrates the operation of MegaPower using the Brayton cycle.

CONCLUSION

Owing to overpricing and continued delays in the construction of nuclear power plants, reducing the power scale to SMRs or microreactors could help third-world countries with limited capital for the nuclear sector, also contributing to reduced CO2 emissions. Microreactors have a thermal limitation of 20 MW, resulting in a maximum electrical power of less than 10 MWe. Heat-pipe reactors were initially developed for space exploration, where they operate without gravity, necessitating heat pipes that can function in space. Thus, reactors in the kilowatt range are designed with energy converters such as Stirling or sodium converters, known as AMTECs. A key point is that reactors in the megawatt range use a Brayton- or Rankine-cycle configuration, featuring a monolithic core with fuel cells in a steel block. They used more than 60 heat pipes operating with sodium or potassium and achieved reactivity control using boron carbide (BC4) drums. In the secondary phase, they can operate using supercritical CO2, helium, or water for energy conversion. Megawatt reactors do not use Stirling converters because of their low power conversion efficiency. MRS and HTRGs have also emerged for terrestrial applications.

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Responsibility notice

The author is exclusively responsible for the printed material included in this paper.

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