Small Modular Reactors (SMRs)

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Abstract

This study presents a comprehensive technical and strategic analysis of Small Modular Reactors (SMRs) as a transformative solution for global sustainable energy. Utilizing a comparative research methodology, the research evaluates four primary SMR categories: Water-Cooled, Molten Salt, High-Temperature Gas-Cooled (HTGR), and Fast Neutron Reactors. Then, the study places specific emphasis on leading designs such as NuScale and HTR-PM. The analysis highlights the inherent safety advantages of SMRs, particularly passive cooling mechanisms. Furthermore, the paper addresses the manufacturing and operation stages, in addition to critical implementation barriers, regulatory frameworks, and spent fuel management strategies. The findings suggest that while SMRs significantly enhance grid flexibility and carbon reduction efforts, their commercial success remains contingent upon technological standardization and robust waste disposal solutions.

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Chapter 1

Introduction

The accelerating global demand for clean, secure, and reliable energy has renewed focus on nuclear power as a vital component of the low-carbon transition. With the growing population and industrial development, the world's electricity demand continues to rise. Renewable energy sources, while essential, remain intermittent and cannot alone provide stable baseload power. Consequently, nuclear energy is increasingly recognized as indispensable to achieving international climate goals.

However, conventional large-scale nuclear power plants (NPPs) face persistent challenges, including high capital costs, complex supply chains, extended construction timelines, and vulnerability to financial uncertainty. Cost overruns, regulatory complexity, and siting constraints have limited the deployment of new reactors in many countries. These limitations have motivated a global shift toward more flexible, cost-effective, and inherently safe nuclear technologies, among which Small Modular Reactors (SMRs) have emerged as a promising solution.

The concept of small nuclear reactors originated in the 1940s and 1950s during the development of compact reactors for the U.S. Navy's submarine program and the Aircraft Nuclear Propulsion project. In recent decades, however, the drawbacks of large plants—high initial investment, extended construction time, and inflexibility—have revived global interest in smaller, modular systems. The SMR concept represents a re-imagining of nuclear technology to deliver safer, more adaptable, and economically manageable reactors. Three key attributes define Small Modular Reactors(SMRs):

- Small: Each unit typically generates less than 300 MWe, enabling deployment in smaller grids and remote areas.

- Modular: Components are factory-fabricated, standardized, and transportable for on-site assembly, allowing scalable and repeatable construction.

- Reactor: Based on nuclear fission, they maintain the proven reliability of conventional reactors while integrating innovative safety and operational features.

This modular approach shifts the traditional "economy of scale" paradigm, as shown in Figure 1.1, to an "economy of multiples," allowing cost reduction through serial production, design standardization, and shortened construction schedules.

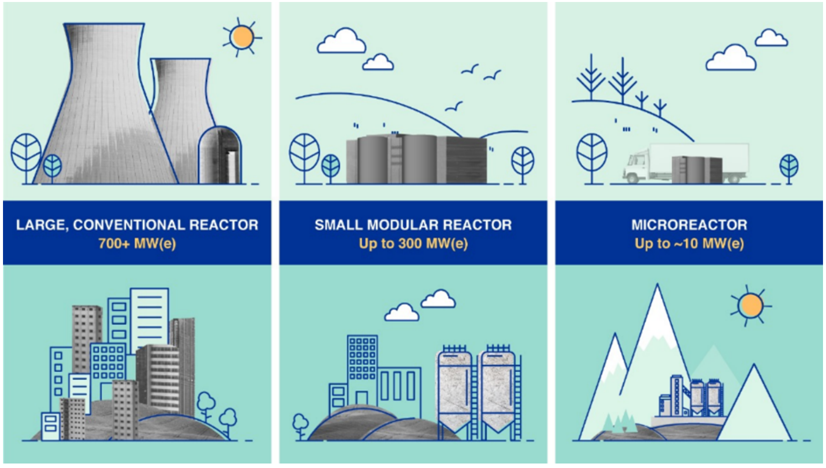


Figure 1.1: Indicate the Scale of the Different Types of Reactors. By International Atomic Energy Agency (IAEA), Advances in Small Modular Reactor Technology Developments, IAEA-TECDOC Series, Vienna

SMRs embody design integration and simplification by combining major components such as the reactor core, steam generator, and pressurizer—within a single pressure vessel. Many SMRs rely on natural circulation for cooling, which eliminates the need for active pumps and external power under normal and emergency conditions. The reduced power density enhances thermal margins and improves inherent safety.

Their compactness allows for underground or submerged sitting, providing additional protection against external hazards. Advanced control systems with digital instrumentation and automation improve reliability, cyber-security, and ease of operation. Fuel types range from Low-Enriched Uranium (LEU) to High-Assay Low-Enriched Uranium (HALEU) and TRISO particle fuel, offering flexibility across various reactor concepts. Typical refueling intervals range from 5 to 10 years, with some designs allowing sealed core operation for extended durations.

SMRs emphasize a defense-in-depth philosophy combining inherent, passive, and engineered safety mechanisms. Inherent safety is achieved through fundamental physical properties, negative temperature coefficients, natural convection, and gravity-driven cooling—ensuring automatic stabilization during abnormal events. Passive safety systems, such as gravity-fed cooling and containment heat removal by natural circulation, function without external power or operator action.

The smaller core size and integrated reactor vessel reduces the risk of coolant loss and minimize radiological consequences. Many designs also feature underground containment to mitigate external threats and reduce the emergency planning zone to the site boundary. These safety innovations represent a major step beyond Generation III reactors, enhancing public confidence and regulatory acceptance.

Unlike conventional gigawatt-scale reactors designed for steady baseload operation, SMRs offer high operational flexibility. They can perform load-following to complement intermittent renewables, stabilize electrical grids, and serve off-grid or remote regions. In addition to electricity generation, SMRs have multipurpose applications including district heating, seawater desalination, hydrogen production, and industrial process heat. This versatility allows integration into hybrid energy systems and supports broader decarbonization objectives. The diversity of SMR technologies reflects different design philosophies and coolant systems. The four main categories include:

1. Water-Cooled Reactors (WCRs) – Integral Pressurized Water Reactors (iPWRs) using proven light-water technology with advanced passive safety, as shown in Figure 1.2.

2. High-Temperature Gas-Cooled Reactors (HTGRs) – Utilizing helium coolant and TRISO fuel, providing very high outlet temperatures for industrial heat and hydrogen production.

3. Liquid-Metal-Cooled Reactors (LMRs) – Employing sodium, lead, or lead-bismuth eutectic coolants for efficient heat transfer and fast-spectrum operation.

4. Molten-Salt Reactor (MSRs) – Operating with liquid fuel mixtures that enable low-pressure, high-efficiency systems and potential for closed fuel cycles.

A major innovation of SMRs lies in their modular fabrication. Reactor modules and associated components are manufactured in centralized factories under controlled conditions, then transported to the site for installation. This process ensures higher quality, shorter construction schedules, and reduced financial risk compared to on-site assembly of large reactors. The approach also facilitates scalability—multiple modules can be added progressively to meet growing demand. Advanced manufacturing techniques such as additive manufacturing, non-destructive testing, and digital twin enhance production efficiency and component integrity.

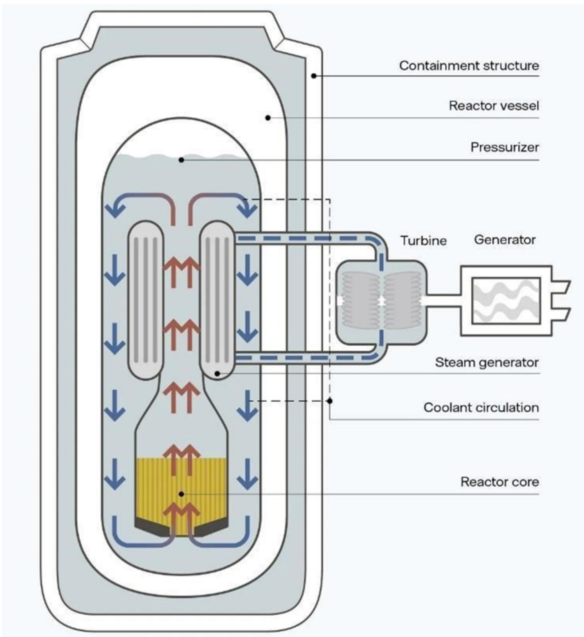


Figure 1.2: Illustration showing the compact design of a light-water small modular nuclear reactor. Used under Fair Use for academic commentary.

These capabilities support lifecycle management, maintenance optimization, and safe decommissioning.

Several countries have progressed from concept to deployment. The HTR-PM in China, the world's first commercial high-temperature gas-cooled SMR, achieved grid connection in 2021.

Russia's Akademik Lomonosov demonstrated a floating SMR platform supplying heat and power to remote Arctic regions. The CAREM 25 in Argentina, NuScale VOYGR in the United States, and SMART in South Korea represent milestones toward commercial viability. Such projects demonstrate the technological maturity of SMRs and their adaptability across various climates and infrastructures.

Despite strong potential, SMRs face several challenges. Regulatory frameworks remain fragmented and often tailored to large reactors, delaying design certification and site approval. Economic competitiveness depends on achieving mass production to lower unit costs. Fuel supply chains for advanced fuels such as HALEU are not yet fully established. Public acceptance and workforce training also remain essential factors for widespread adoption. Nevertheless, the modularity, passive safety, and flexible deployment of SMRs position them as a cornerstone of future nuclear innovation.

Their integration with renewables and applicability to remote or industrial areas could redefine nuclear energy's role in achieving global carbon neutrality.

The following chapters present a comprehensive examination of innovative Small Modular Reactor (SMR) technologies, with Chapter 2 focusing on their technical strengths and the most promising design concepts. Chapter 3 discusses key aspects of SMR manufacturing processes, while Chapter 4 addresses the fundamental operational principles of these reactor systems. An overview of the current development, licensing, and deployment status of leading SMR designs is provided in Chapter 5. Finally, the report concludes with detailed case studies in Chapters 6 and 7, which examine pioneering SMR models in depth, offering insight into their design philosophies, technological characteristics, and practical implementation.

Chapter 2

Small Modular Reactor Types

2.1 Water-Cooled SMRs

2.1.1 Technology

Coolant and Moderator

Water-cooled SMR-PWRs use light water as both coolant and moderator, maintaining the fundamental principles of PWR technology. Many designs rely on natural circulation driven by density differences in the heated coolant, eliminating the need for reactor coolant pumps. This improves reliability by removing pump failure modes and reduces parasitic power consumption. The coolant flows through the compact core and transfers heat to the internal steam generators, while the pressurizer maintains system pressure above saturation to prevent boiling and stabilize thermal-hydraulic transients. The integral reactor vessel houses all major primary-circuit components, reducing the need for large primary-loop piping, improving siting flexibility, and enabling passive heat removal during accident scenarios.

Fuel and Core Design

The reactor core of an SMR-PWR contains fuel assemblies based on standard LWR technology, typically using UO_2 pellets enriched to less than 5 % U-235. The core ensures sustained fission reactions while providing effective neutron moderation using light water.

Its compact geometry supports natural circulation of coolant and maintains strongly negative reactivity feedback coefficients, contributing to inherent safety during temperature excursions. SMR-PWRs incorporate an integral reactor pressure vessel that houses the core, internal steam generators, pressurizer region, and coolant pumps (if present). This integral configuration reduces external coolant inventory and enhances manufacturing quality through factory fabrication.

Heat transfer to the secondary side occurs through internal steam generators, often helical-coil or straight-tube types designed for compactness and efficiency. The pressurizer region, located at the upper part of the vessel, maintains system pressure above saturation to prevent boiling. Reactivity is controlled using control rods composed of strong neutron absorbers, limited soluble boron in some designs, and burnable absorbers inside fuel assemblies to maintain stable reactivity over the cycle. Some SMRs rely entirely on natural circulation, while others use small canned-motor pumps. The primary system is enclosed within a compact steel containment that provides confinement and enables passive heat removal during accident scenarios.

Safety Features

Water-cooled SMR-PWRs operate at high pressure to maintain the coolant in liquid form. Their thermal-hydraulic design supports natural circulation under both normal and shutdown conditions, reducing reliance on active components. Passive safety is a central design feature:

- Control rods insert into the core by gravity during shutdown.
- Passive heat exchangers remove decay heat to ultimate heat sinks.
- The elimination of large primary piping significantly reduces LOCA probability.

These features ensure safe shutdown and cooling without operator action or external power, enhancing resistance to station blackout events.

The modular design enables factory construction, reduces site work, shortens project schedules, and supports multi-module deployment with flexible output.

Refueling and Burnup

SMR-PWRs typically use conventional LWR fuel with <5 % U-235 enrichment. Refueling cycles range between 18–24 months, like modern large PWRs. They achieve discharge burnups exceeding 45 GWd/tHM, which improves fuel utilization and reduces waste per unit of energy.

About half the fuel assemblies are replaced during each outage to optimize burnup and economics. Because SMR fuel designs resemble those of existing LWRs, they benefit from established supply chains and regulatory familiarity.

Spent Fuel and Radioactive Waste

Spent fuel from SMR-PWRs is first transferred to on-site spent fuel pools for cooling and shielding, followed by long-term dry cask storage, commonly using systems such as MPC-37. These methods are well-established in current PWR operations.

Integral SMR designs reduce neutron leakage, which slows down vessel embrittlement and limits the activation of structural materials—an advantage during decommissioning. Some designs also incorporate dose-reduction measures to minimize worker exposure.

Although waste streams are like those of large PWRs, SMRs can achieve lower waste volume and reduced lifecycle radiation doses.

2.1.2 Advantages and Disadvantages

Advantages

- Enhanced Passive Safety: SMR-PWRs employ passive safety systems relying on natural circulation and gravity-driven control rod insertion, minimizing dependence on active pumps and external power, reducing the probability of LOCA, and enhancing core safety.
- Modular Construction and Scalability: Reactor modules are fabricated in controlled factory environments, enabling parallel construction and improving quality assurance.
- Scalable deployment: additional modules can be added to match energy demand.
- High-Pressure Operation: Operates at pressures around 15 MPa, maintaining coolant in the liquid phase, ensuring efficient heat transfer, stable thermal-hydraulic behavior, and operational reliability.
- Compact Core and Reduced Radioactive Inventory: Smaller cores result in lower radioactive inventory per module, simplify emergency planning and mitigate environmental impact in case of accidents.
- Flexible Deployment: Suitable for remote sites or small electrical grids, supports industrial heat applications such as cogeneration and desalination.
- Long Refueling Intervals: Refueling cycles can range from three to five years, reducing operational downtime and supporting high-capacity factors.

Disadvantages

- Higher Specific Capital Cost: Smaller reactors benefit less from economies of scale, resulting in higher $/MWe than conventional large PWRs.
- Limited Power Output: Typical module output ranges between 50–300 Mwe; large grids require multiple modules, introducing logistical and operational complexity.
- Neutronics and Thermal-Hydraulics Challenges: Compact cores lead to higher neutron leakage and elevated power density, requiring careful fuel and reflector design, which demands precise thermal-hydraulic control to ensure effective heat removal and reactivity management.

- Spent Fuel Management: Although smaller, modules still produce radioactive waste that requires conventional handling in spent fuel pools and long-term dry cask storage.
- Regulatory and Licensing Uncertainty: Novel designs face longer regulatory review periods, and Less historical operational experience compared to conventional large PWRs.
- Economic Competitiveness: Larger nuclear plants may have a lower levelized cost of electricity (LCOE) due to scale advantages.

2.1.3 Design Examples

Westinghouse Electric Company LLC, United States of America

The Westinghouse AP300 SMR, as shown in Figure 2.1, is a 330 MWe (990 MWth) Generation III+ single-loop light water Pressurized Water Reactor (PWR) based on licensed AP1000 technology, demonstrating industry-leading reliability. It is the only SMR using fully deployed and operating reactor technology. The plant integrates passive safety systems and simplified design to enhance construction, operation, and maintenance. Safety functions rely on natural forces like gravity, pressure, and natural circulation, eliminating the need for pumps, fans, or diesel generators and allowing operation without AC power, service water, or HVAC.

Figure 2.1: Westinghouse Electric Company LLC SMR Prototype Design. By Westinghouse Electric Company, official vendor documentation

Building on AP1000 experience, the AP300 offers. high delivery certainty through mature technology, proven licensing, modularization, optimized construction, and lessons learned. It employs Westinghouse 17×17 RFA fuel with excellent performance in over 50 plants and supports extended four-year operating cycles. Simplified architecture and optimized outage procedures enable short refueling outages, with availability exceeding 97% excluding planned outages.

The AP300 design suits a wide range of sites. In the unlikely event of a core melt, in-vessel retention of core debris ensures containment integrity, preventing severe ex-vessel accidents and minimizing environmental release. Overall, it combines proven PWR technology, passive safety, and robust fuel performance to deliver a reliable, deployment-ready SMR.

NuScale Power Module (NuScale Power, LLC, United States of America)

The NuScale Power Module™ (NPM), as shown in Figure 2.2, is a small, light-water-cooled, pressurized-water reactor (PWR) designed as a self-contained, factory-fabricated module. SMR plants with NuScale modules are scalable, with standard configurations of 4-NPM at 308 MW(e), 6NPM at 462 MW(e), and 12-NPM at 924 MW(e), the six-module layout being the reference for licensing. Each module operates independently but is managed from a single control room, approved by the U.S. NRC for three operators controlling up to twelve reactors. Key features include compact containment, natural circulation coolant flow, high-pressure vessels, and established light-water reactor technology validated through testing.

Figure 2.2: NuScale Power Module.By NuScale Power LLC, NuScale Power Module™ Design Overview, U.S. Nuclear Regulatory Commission (NRC) certified design documentation.

The NuScale design supports modular electricity production, flexible load-following, and non-electrical process heat applications, including cogeneration. Its philosophy emphasizes simplification, proven technology, modular nuclear steam supply systems, and passive safety, allowing unlimited cooling time after beyond-design-basis events without power, operator action, or makeup water. No design-basis accident exposes the core, and natural circulation provides efficient full-power operation, eliminating the need for reactor coolant pumps while ensuring inherently safe and reliable performance.

Rolls-Royce, United Kingdom

The Rolls-Royce SMR has been developed to provide an affordable, low-carbon energy generation solution that meets market needs. The design builds on optimized and enhanced use of proven technologies, offering class-leading safety performance and an attractive market proposition with minimal regulatory risk. Rapid, predictable, and repeatable construction is supported by site layout optimization, modular build, standardization, and commoditization, enabling efficient deployment. Primarily intended for base-load electricity generation at both coastal and inland sites, the Rolls-Royce SMR can also support heat-requiring or co-generation applications and serve as a primary, carbon-free power source for e-fuel production. The design philosophy focuses on optimizing the levelized cost of electricity with low capital investment while maximizing power output, maintaining robust economics for nuclear plant investment, and ensuring a plant size suitable for modularization and standardization across all units, Figure 2.3 shows a comprehensive representation of the reactor core system.

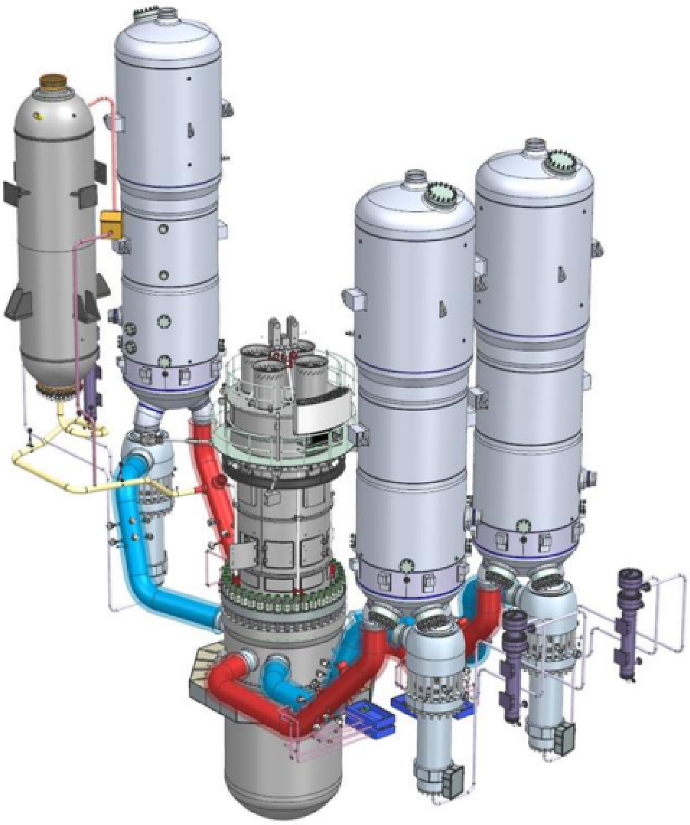


Figure 2.3: The Reactor Core and Cooling System of the Rolls-Royce SMR.

2.2 Molten Salt SMRs

2.2.1 Technology

Coolant and Moderator

Molten Salt Reactors (MSRs) employ molten fluoride, chloride, or mixed-halide salts as a primary coolant and, in some designs, as a fuel carrier. These salts operate effectively at high temperatures (600–900°C) while maintaining near-atmospheric pressure, thereby eliminating the high-pressure accident risks associated with conventional water-cooled systems. Their chemical and thermal stability enables efficient heat transfer and contributes to the system's inherent safety.

MSRs may use graphite as a moderator in thermal-spectrum configurations, while other designs operate in fast or mixed neutron spectra without moderation. The coolant's ability to remain liquid under extreme temperatures and its strong negative temperature feedback make it central to MSR-SMR safety and performance.

Fuel and Core Design

MSR designs can utilize either liquid or solid fuels. In liquid-fueled MSRs, fissile and fertile materials—such as uranium, thorium, or plutonium— are dissolved directly in molten salt, allowing fission to occur within the circulating fluid.As mentioned in Figure 2.4 heat is transferred through three physically separated loops. The primary loop contains molten salt that either serves as both fuel and coolant in liquid-fueled MSRs or acts solely as a coolant in solid-fueled designs; this loop directly removes heat from the reactor core while operating at high temperature and near-atmospheric pressure. Heat from the primary system is transferred to an intermediate loop containing a clean, non-radioactive molten salt, which provides an important isolation barrier between the radioactive primary salt and downstream systems. The tertiary (power conversion) loop uses conventional working fluid—such as helium, nitrogen, supercritical carbon dioxide, or steam—to convert thermal energy into electricity through Brayton or Rankine cycles.

In salt-cooled, solid-fuel MSRs (e.g., FHRs), the fuel remains in solid form—typically TRISO particles—while molten salt serves solely as the coolant. MSRs support online refueling, continuous removal of gaseous fission products, and adjustments to fuel composition during operation. These features maintain reactivity, suppress xenon poisoning effects, and enable long operational cycles. However, molten salts can be corrosive, require controlled chemistry, and must remain above their melting point to avoid freezing and flow blockage. Operational complexity may also increase in compact microreactor configurations.

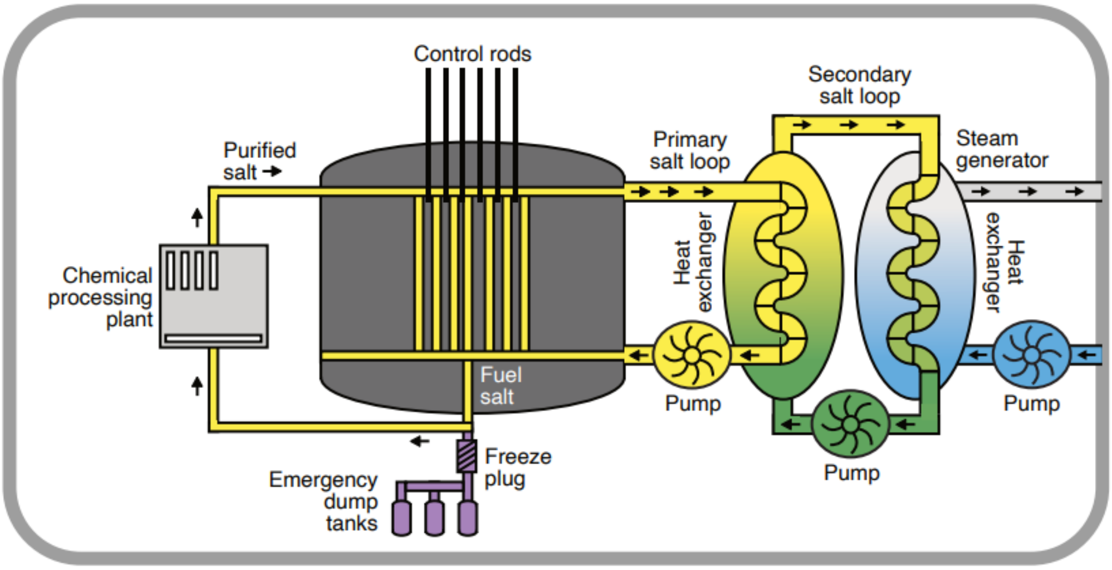


Figure 2.4: Elementary Design of the Circulation of Molten Salt Reactor.

Safety Features

- Strong negative temperature reactivity coefficient: As molten salt heats and expands, fissile material density decreases, automatically lowering the reaction rate and preventing power excursions.
- Low-pressure operation: Molten salts remain liquid at high temperatures while operating near atmospheric pressure, eliminating high-pressure accident risks common in water-cooled reactors.
- Passive drain-down shutdown: In abnormal conditions, molten fuel or coolant drains by gravity into subcritical tanks, where decay heat is removed through natural convection and radiative cooling without external power.

  The drain tanks are empty during normal operation and are kept heated so that the salt remains molten when transferred. During abnormal conditions (e.g., loss of power or overheating), a freezing plug (typically a section of salt kept solid by active cooling) melts. Once the plug melts, the molten salt drains by gravity into the drain tanks.
- Continuous fission-product removal: Circulating fuel allows xenon, krypton, and other gaseous fission products to be continuously stripped out, maintaining stable reactivity and preventing xenon poisoning.
- High thermal stability of salts: Molten salts tolerate high temperatures (600–900°C) without pressure buildup, providing wide thermal safety margins.

- Reduced mechanical stresses: Absence of high-pressure coolant systems lowers structural stress and minimizes the likelihood of mechanical failure.

- Stable response during transients: Self-regulating salt behavior and passive heat removal contribute to predictable, inherently safe responses to operational upsets.

2.2.2 Advantages and Disadvantages:

Advantages of MSRs:

From a safety point of view:

- Molten salts are chemically stable and non-flammable, so there is no risk of hydrogen explosions or sodium fires.

- Molten salts hold many fission products strongly, providing an extra barrier that limits radioactive release.

- Gaseous fission products can be removed during operation, preventing pressure buildup in the reactor core.

- Fuel in molten salt form does not suffer irradiation damage or mechanical failure.

- Molten salt as a heat sink: Molten salt absorbs decay heat after shutdown. Its high thermal inertia, especially in moderated designs, helps remove heat easily by circulating the liquid fuel through a heat exchanger.

- Excellent neutron economy: MSRs use neutrons more efficiently because the core lacks metal structures and other materials that absorb neutrons. Continuous removal of some fission products can further improve neutron economy.

- Flexible fuel cycle: Liquid fuel can include all actinides and allows for continuous recycling. It avoids fuel fabrication issues and is not vulnerable to mechanical or radiation damage like solid fuel. This flexibility supports breeding (using Th-232 or U-238) and recycling of TRU waste, reducing environmental and proliferation risks. On-site recycling also lowers transport risks.

From an economic point of view:

- High operating temperature: MSRs can run above 600°C, giving high efficiency (up to 50 %) with steam Rankine or CO_2 Brayton cycles, and enabling industrial heat applications that water-cooled reactors can't reach.

- Effective load following: The liquid fuel and strong negative temperature feedback allow MSRs to quickly adjust power output with minimal temperature changes, making them suitable for grids with variable renewable energy. They also avoid xenon poisoning issues common in solid-fuel reactors.

- High resource utilization: Many MSR designs can use and recycle all actinides, reducing waste. Continuous fission-product removal and stable salt chemistry allow higher burnup and lower initial enrichment compared to solid-fuel reactors.
- Simpler fuel qualification: Liquid fuel does not suffer radiation damage, so testing and qualification are much easier and faster than for solid fuel with cladding.
- Compact and modular design: Liquid fuel enables efficient use of core volume, supporting modular reactors and decentralized power production, which helps modern flexible energy grids.

Disadvantages of MSRs

- Structural materials can experience significant corrosion when exposed to high-temperature molten salts.
- Salt chemistry is difficult to control, and small changes in oxidation or impurities can affect reactor performance.
- Limited real-world operating experience reduces confidence and makes regulatory approval more challenging.
- MSR designs generate tritium, a radioactive gas that requires special containment systems. 5- Online fuel processing and fission-product removal systems are complex and not yet commercially proven.
- New infrastructure for fuel handling and processing is required, increasing initial costs.
- Long-term stability of certain molten salt mixtures is still uncertain.
- Standardized waste forms for long-term disposal of MSR fuel have not yet been fully developed.

2.2.3 Design Examples:

Copenhagen Atomics Waste Burner

The Copenhagen Atomics Waste Burner is a small 100 MW(t) nuclear reactor, the size of a 40-foot shipping container, using heavy water and fluoride salt fuel. It operates fully autonomously for 5 years without human intervention or maintenance, with passive decay heat removal. The reactor can burn transuranic waste and may transition to breeding after 3 years. All systems are contained within a leak-tight steel enclosure, protected by three safety barriers. The Copenhagen Atomics Waste Burner delivers heat, which can be coupled to a power conversion system. Its core uses lithium fluoride fuel and blanket salts with a heavy water moderator, allowing compact design and low neutron leakage. Bred uranium is transferred online, enabling potential self-sustained breeding. Reactivity is

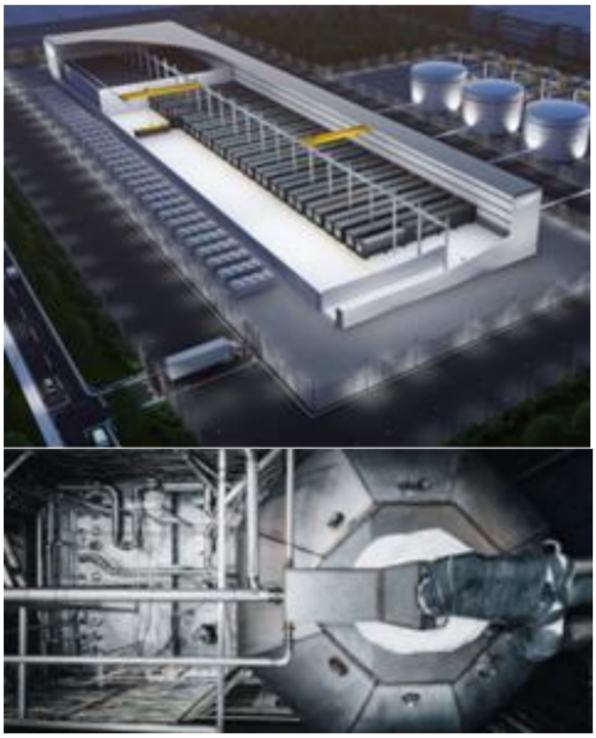


Figure 2.5: Copenhagen Atomics Waste Burner SMR Site.

controlled through adjustments to the heavy water level and negative temperature feedback. Fuel, blanket, and moderator are continuously circulated, and the reactor automatically shuts down if pumps fail or power is lost.

IMSR400

Terrestrial Energy's Integral Molten Salt Reactor (IMSR), as shown in Figure 2.6, is a Gen IV advanced reactor expected to be deployed in the early 2030s. It features a thermal-spectrum, graphite-moderated, near atmospheric pressure, self-contained, and integrated design. The dual IMSR facility operates at high temperature and low pressure, with a rated thermal capacity of 884 MW, providing 390 MWe net electrical power or 822 MWth net thermal power at 585°C, or a combination of both, over a 56-year plant life. The fuel salt is chosen for robust cooling and high radionuclide retention, using Standard-Assay Low-Enriched Uranium (SALEU) with less than 5 % U-235.

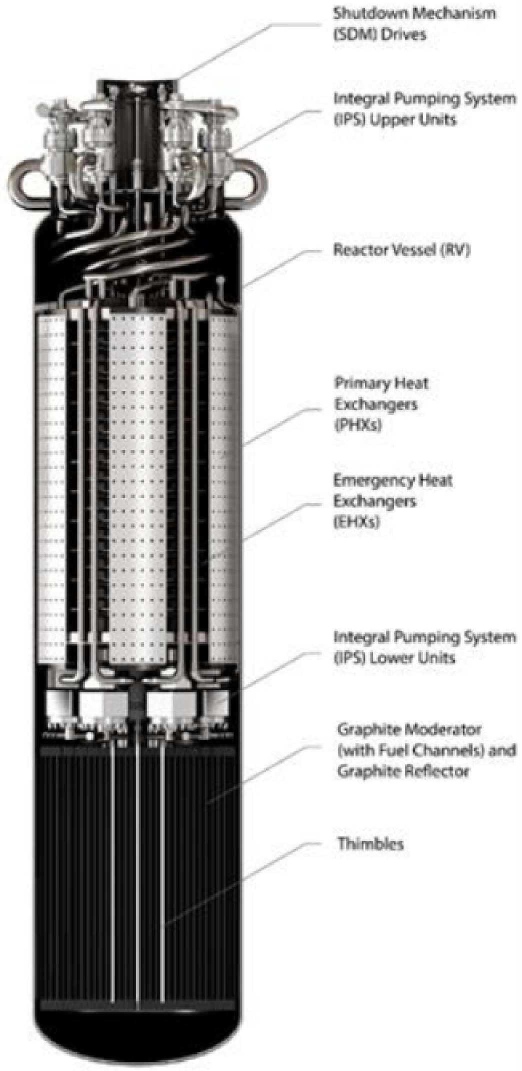


Figure 2.6: IMSR400 SMR Prototype Design.

The IMSR Nuclear Steam Supply System (NSSS) transfers heat from the reactor core to a steam generation system via two intermediary molten salt circuits in series, enhancing safety and operability. The primary circuit, entirely within the reactor vessel, includes parallel loops with pumps, piping, and primary heat exchangers (PHXs). The core uses molten fluoride fuel salt flowing through vertical graphite moderator channels, which act as both fuel and coolant. Heat from the fission reaction is deposited mainly in the graphite and fuel salt, then pumped through the PHXs and returned to the core. Reactivity control relies on a strong negative temperature coefficient, providing inherent self-regulation, along with a Shutdown Mechanism (SDM) for prompt independent reactor shutdown. The reactor vessel ensures core integrity by preventing damage from excessive temperatures.

Lithium Fluoride Thorium Reactor (Flibe Energy, United States of America)

The Lithium Fluoride Thorium Reactor (LFTR) proposed by Flibe Energy is a graphite-moderated, thermal-spectrum molten salt reactor that uses liquid fluoride salt mixtures containing both fissile and fertile materials. In this design, the molten salts—kept liquid at 500–700°C—serve as the medium in which fission occurs. Their ionic bonding prevents radiation damage and supports high-temperature, low-pressure operation, eliminating the high-pressure risks of conventional reactors. Heat from fission is transferred to a closed-cycle gas turbine system, with a supercritical CO_2 recompression cycle proposed to achieve thermal efficiencies of about 45 %.

The LFTR features a two-region core consisting of a central active zone and an outer thorium blanket, both filled with fluoride salt. In the blanket, $Th-232$ absorbs neutrons and breeds ^{233}U, which is chemically separated and returned to the core. This closed thorium fuel cycle enables highly efficient fuel utilization and extremely low fuel costs due to abundant thorium resources. Continuous chemical processing maintains fissile inventory and supports stable reactivity. LFTR's design philosophy emphasizes (i) inherent safety, with a no-meltdown and non-pressurized core; (ii) simplicity, to have an intrinsically stable and self-regulating design; (iii) fuel efficiency, and (iv) the potential to produce far less waste.

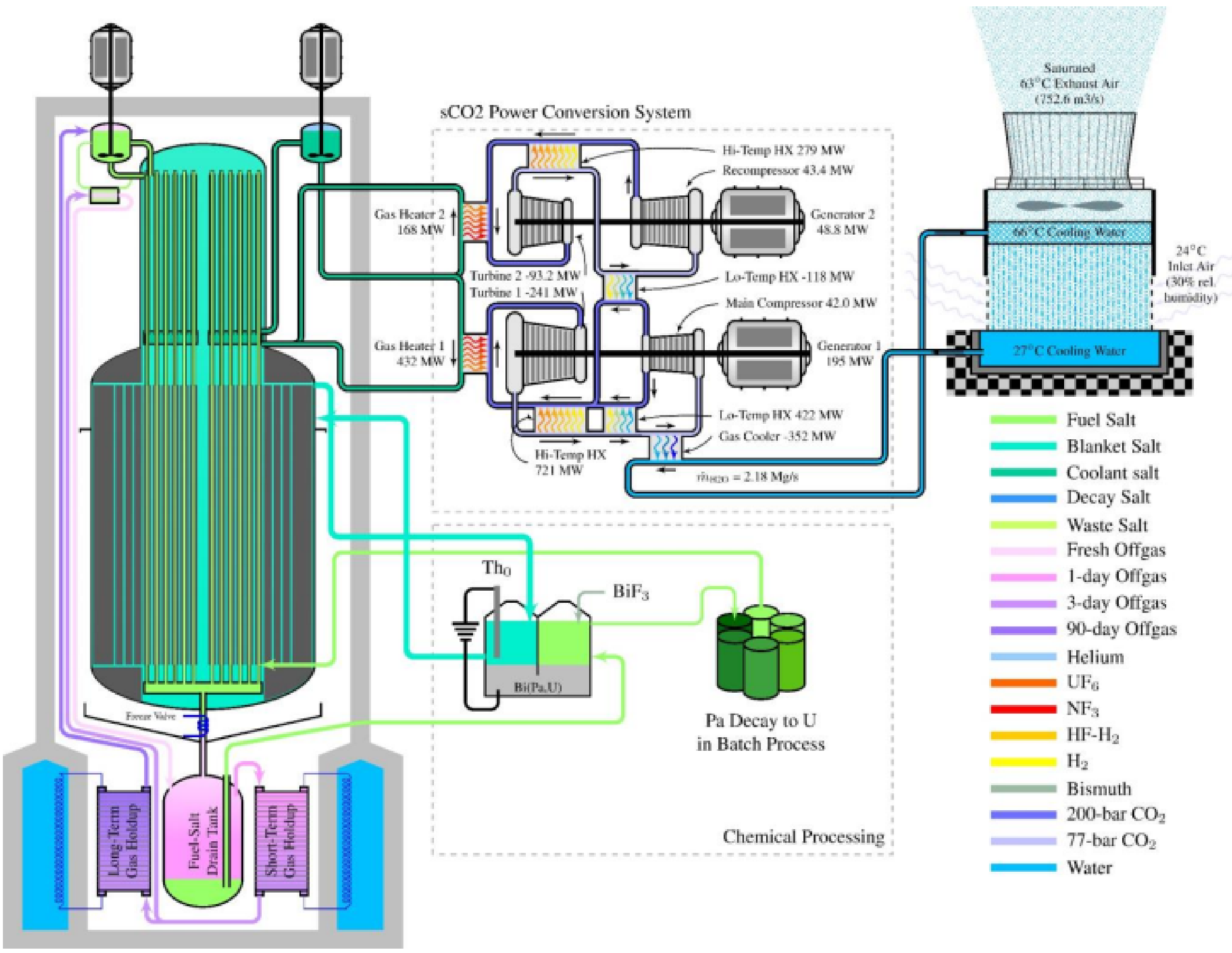


Figure 2.7: Elementary Design of Lithium Fluoride Thorium Reactor.

2.3 Liquid Metal-Cooled Fast SMRs

2.3.1 Technology

Coolant and Moderator

Liquid Metal Cooled Small Modular Reactors (LM-SMRs), as shown in Figure 2.8, employ liquid metals as the primary coolant to achieve high thermal efficiency and low-pressure operation. The most used liquid metals are sodium (Na), lead (Pb), and lead-bismuth eutectic (LBE). Each coolant has unique thermal, neutronic, and chemical characteristics that influence reactor design and safety.

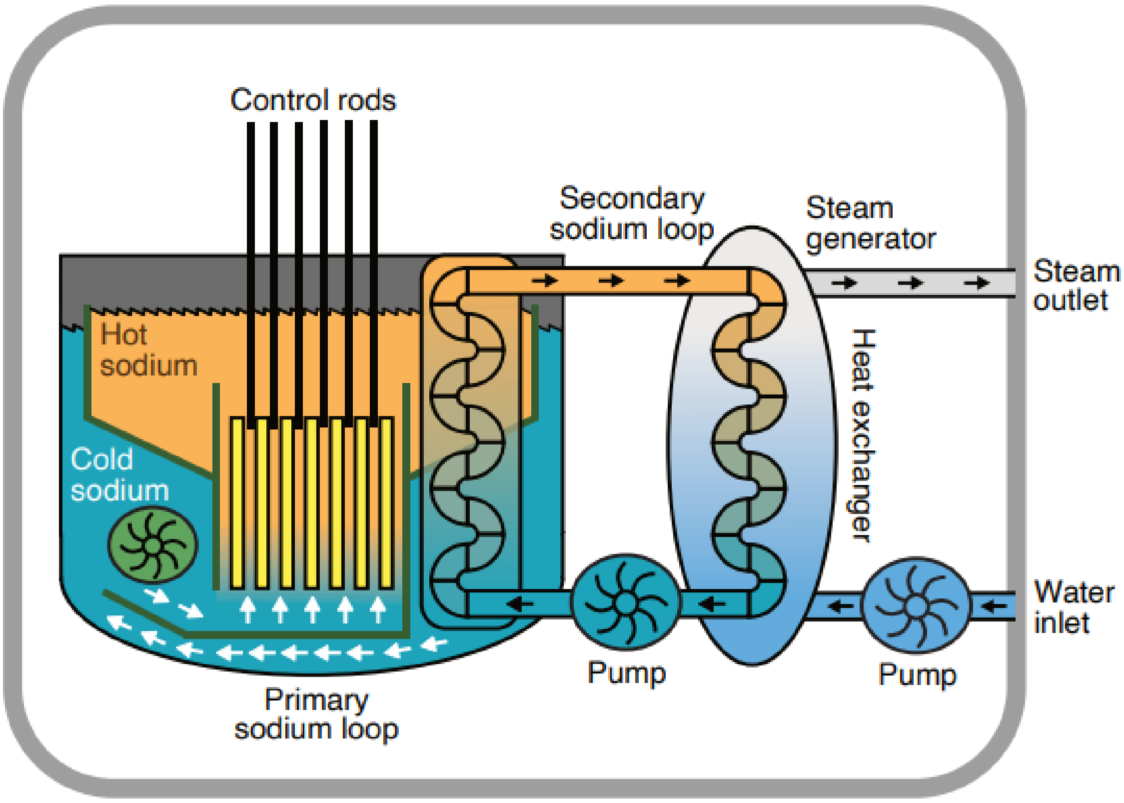


Figure 2.8: Elementary Design of Liquid Metal Cooled SMRs.

Table 2.1: Coolants Differentiation for Liquid Metal-Cooled Fast SMRs

Coolant	Sodium (Na)	Lead (Pb)	Lead-Bismuth Eutectic (LBE)
Melting Point (°C)	97.8	327.5	123.5
Boiling Point (°C)	883	1749	∼1670
Thermal Conductivity ($\mathbf{W/m \cdot K}$)	∼142 at 400°C	∼35–40 at 500°C	∼10–15 at 400°C
Specific Heat ($\mathbf{J/kg \cdot K}$)	1,300	∼150	∼150
Neutron Properties / Density	Low neutron absorption (∼0.53 barns)	High density (∼11 g/cm^3)	High density (∼10 g/cm^3)
Operating Pressure & Temperature	∼0.1–0.2 MPa at 400–550°C	Near-atmospheric pressure, 420–550°C	Near-atmospheric pressure, 420–550°C
Notes	Highly reactive with water/air; requires inert gas cover; widely used in SFRs (BN-600, BN-800)	Provides radiation shielding, low chemical reactivity, and potential corrosion of steel components	Suitable for startup due to lower melting point; chemically stable; compatible with compact heat exchangers

Liquid metals possess thermal conductivity that are orders of magnitude higher than water $\approx 0.7\ \mathrm{W/m \cdot K}$, enabling fast heat extraction and reducing thermal gradients in the core. Their high density and heat capacity allow compact reactor vessels and efficient heat transport. Passive safety is enhanced through natural circulation, which can remove residual decay heat even without pumps. Material compatibility is a critical design factor. Lead and LBE can corrode structural steels if oxygen concentration is not properly controlled, while sodium is chemically reactive with water and air, requiring inert cover gas systems and strict leak-prevention procedures.

Fuel and Core Design

LM-SMRs typically operate as fast neutron reactors without moderators, enabling a hard neutron spectrum and high fuel utilization. Core geometries are designed to maximize heat removal and neutron economy, with typical dimensions in the range of:

- Core diameter: 1.5–2.5 m
- Core height: 1.5–3 m
- Electrical output: 50–300 MW(e)

Fuel assemblies are arranged mainly in hexagonal lattices, which are standard for fast reactors to ensure stable coolant flow and uniform neutron flux. Several fuel types are used depending on the design:

- UO_2 enriched to 15–20 % U-235, higher than conventional LWR fuel.
- MOX fuel (UO_2–PuO_2) for plutonium recycling and improved fuel sustainability.
- Metallic fuels (U–Zr, U–Pu–Zr) offering superior thermal conductivity, high burnup capability, and breeding potential.

Fuel rods use corrosion-resistant cladding materials compatible with liquid metals, such as HT-9 ferritic–martensitic steel and advanced stainless-steel alloys. Reactivity is controlled using B_4C or hafnium control rods, with steel or lead reflectors to reduce neutron leakage. Fast-reactor cores rely on inherent negative reactivity feedback, mainly Doppler broadening and coolant-density effects, which improve passive safety during power changes. Typical operational parameters include:

- Fast neutron spectrum: 0.1–1 MeV
- Peak linear power density: 50–100 kW/m
- Fuel burnup: 80–100 GWd/t for metallic fuels (design-dependent)
- Coolant inlet/outlet temperatures:
  - Sodium: 400–550 °C
  - Lead/LBE: 420–550 °C

Safety Features

LM-SMRs incorporate multiple inherent and passive safety mechanisms derived from coolant properties and fast-reactor core design:

- Passive decay-heat removal: Natural circulation can remove up to ≈ 10 % of nominal power without active pumping.
- Low-pressure operation: Sodium and lead/LBE coolants operate near atmospheric pressure (≈ 0.1–0.2 MPa), minimizing mechanical stresses and reducing the risk of high-pressure failures.
- Reactivity control: Redundant shutdown systems, including control rods and absorber ball systems, ensure rapid and reliable SCRAM capability.
- Structural and chemical safety: Double-walled piping (for sodium systems), inert cover gas, and leak-prevention features reduce chemical-reaction hazards.
- Material durability: Corrosion-resistant cladding and structural alloys, along with oxygen-control strategies in Pb/LBE systems, mitigate long-term material degradation.
- Instrumentation and monitoring: Continuous assessment of coolant flow, temperature, and neutron flux enables early detection of operational anomalies.

Overall, LM-SMRs achieve a combination of high thermal efficiency, fast-spectrum fuel utilization, and passive safety features, enabling compact and robust reactor designs suitable for modular deployment.

2.3.2 Advantages and Disadvantages

Advantages

- High Power Density and Compact Footprint: Lead-cooled SMRs can achieve power densities up to 100 MW/m^3, enabling compact units suitable for transport and deployment in constrained locations.
- Fuel Flexibility and Sustainability: Fast-spectrum operation allows the use of MOX fuels, metallic fuels, and recycled plutonium, improving fuel efficiency and sustainability.
- Long Refueling Intervals: Extended refueling cycles of 3–5 years reduce operational interruptions, maintenance costs, and staffing requirements.
- Reduced Waste Generation and Breeding Potential: Some designs achieve a breeding ratio of ≈ 1.1–1.2, producing additional fissile material and reducing nuclear waste.

- Improved Load-Following Capability: Compact cores and high coolant heat capacity enable rapid adjustment of power output to match variable electricity demand.
- Economic and Deployment Advantages: Modular fabrication lowers construction costs and timelines. Multiple units can be installed on a single site, providing scalable and flexible power generation.

Disadvantages

- Corrosion / Materials Compatibility: Pb, LBE, and sodium can corrode structural materials via grain-boundary penetration, selective leaching, and oxygen-induced reactions. Mitigation includes coatings, oxygen control, and corrosion-resistant alloys.
- Radioactive Isotopes (Po-210 in LBE): Neutron irradiation of LBE produces highly toxic Polonium-210, requiring strict monitoring and radiological protection.
- High Coolant Density: Pb/LBE density increases reactor mass, structural loads, and seismic requirements.
- Maintenance Complexity: Heavy or toxic coolants require remote handling and modular designs for safe repair or replacement.
- Sodium Reactivity (SFRs): Sodium reacts violently with water/air, necessitating containment and specialized safety systems.
- Special Design Requirements: Pre-heating, oxygen control, and other liquid metal-specific operational needs add design complexity.
- Licensing & Regulatory Challenges: Modern SMR designs require updated licensing and operational documentation for approval.
- Proliferation Risks: Fast reactors could theoretically support fissile material breeding; safeguards and regulatory oversight are critical.

2.3.3 Design Examples

BREST-OD-300

The BREST-OD-300 is an innovative lead-cooled fast reactor developed as a pilot and demonstration small modular reactor (SMR) with a closed nuclear fuel cycle. It uses high-density uranium-plutonium nitride fuel [(U-Pu)N] and a two-circuit heat transport system to generate 300 MWe. Designed with inherent safety features, a pool-type integral layout, and high-performance lead coolant, the reactor aims to demonstrate complete fuel breeding, passive decay heat removal, and robust operational reliability for future commercial lead-cooled reactor facilities. Figure 2.9 represents a visualization of BREST-OD-300 SMR.

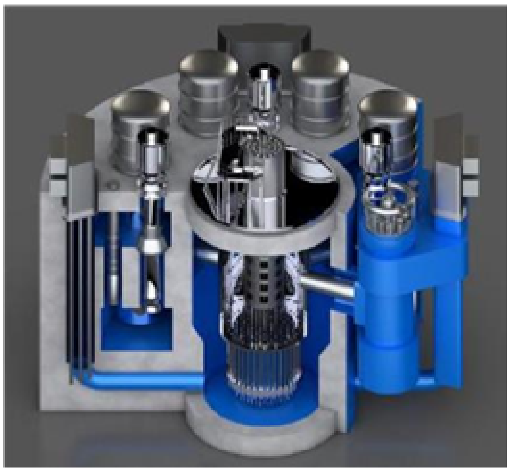


Figure 2.9: Copenhagen Atomics Waste Burner SMR Site.

ARC-100: sodium coolant

The ARC-100 is an advanced, sodium-cooled, fast-spectrum small modular reactor (SMR) with a 100 MW(e) capacity, as shown in Figure 2.10. Building on over 30 years of operational experience from the EBR-II reactor, the ARC-100 combines proven technologies with modern design improvements to offer a safe, efficient, and economically viable nuclear power solution. Its metallic uranium-zirconium fuel, long 20-year refueling cycle, and inherent safety features enable simplified operation, reduced proliferation risks, and the potential for fuel recycling. Designed for both grid-scale electricity generation and remote or off-grid applications, the ARC-100 addresses the key challenges of affordability, safety, flexibility, and waste management in next-generation nuclear energy.

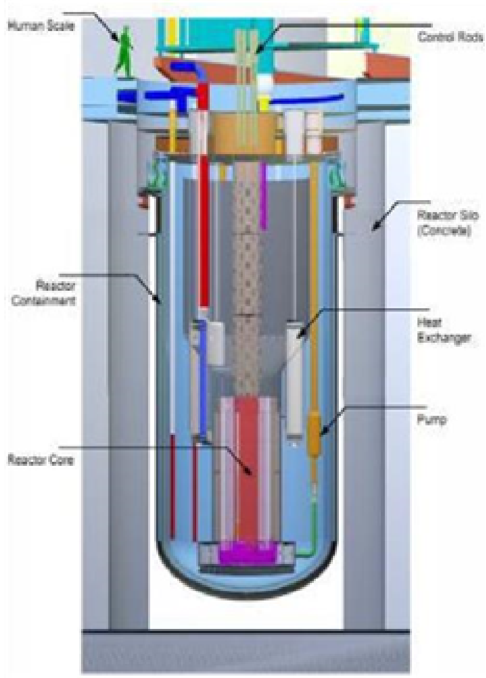


Figure 2.10: ARC 100 SMRs prototype design.

SVBR-100: Lead-Bismuth

The SVBR-100 is a 100 MW(e) multipurpose small modular reactor (SMR) cooled by lead-bismuth eutectic (LBE). Its design integrates decades of operational experience with LBE-cooled reactors, emphasizing inherent and passive safety, compact modular construction, and flexible fuel options. Capable of operating in both open and closed fuel cycles with refueling every 6–7 years, the SVBR-100 is suitable for electricity generation, district heating, desalination, hydrogen production, and minor actinide burning. Its Monoblock design, near-atmospheric pressure operation, and passive decay heat removal systems ensure robust safety, simplified maintenance, and enhanced operational reliability, Figure 2.11 shows a its initial design.

Figure 2.11: SVBR 100 SMR Prototype Design.

2.4 High Temperature Gas Cooled SMRs

Small Modular Gas-Cooled Reactors (SMR-GCRs) represent one of the most advanced categories of Generation IV and emerging commercial reactors. They combine modular construction with high-temperature gas cooling, typically using helium, to deliver safe, efficient, and flexible nuclear energy. Unlike large gas-cooled designs, SMR-GCRs are tailored for decentralized deployment, industrial heat supply, and improved passive safety. Their materials, fuel design, and thermal behavior allow operation at temperatures far beyond conventional light-water reactors, making them a strong candidate for future clean-energy systems, Figure 2.12 shows the circulation design of GCRs.

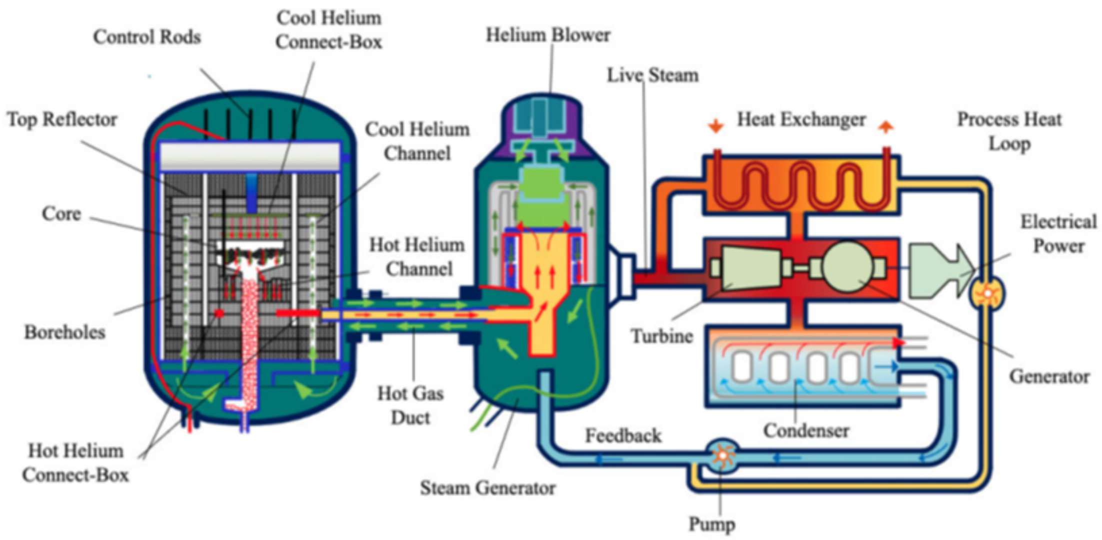


Figure 2.12: Elementary Circulation Design of High Temperature Gas Cooled SMRs

2.4.1 Technology

Coolant and Moderator

Coolant System

Helium gas is selected because it is chemically inert, transparent to neutrons, and remains single-phase at all operating temperatures. It enters the core around 250–350°C and exits at 700– 950°C, depending on the design. The coolant is circulated using electric blowers or compressors and directed toward the power conversion unit. Because helium does not react with fuel or graphite, it improves component lifetime and eliminates risks associated with coolant boiling or chemical corrosion.

Moderator and Reflector (Graphite)

Graphite blocks or pebbles act as the neutron moderator, slowing down fast neutrons to thermal energies through multiple scattering events. Surrounding axial and radial graphite reflectors return escaping neutrons to the core, improving fuel utilization and flattening power distribution. Graphite also enhances safety due to its high heat capacity (1.7 kJ/kg-K) and extreme temperature tolerance (sublimation point 3600 °C), providing passive thermal buffering during off-normal or accident conditions.

Fuel and Core Design

Reactor Core

The core contains the active fuel region built either from graphite prismatic blocks with embedded fuel compacts (e.g., Xe-100, GT-MHR) or mobile fuel pebbles (e.g., HTR-PM, PBMR). The combination of high-purity graphite and TRISO fuel allows the core to tolerate high temperatures while maintaining structural integrity and stable neutron moderation. The graphite matrix contributes to excellent heat capacity, extending response time in transient conditions, one of the reasons GCRs are considered inherently safe.

Fuel Elements

Most GCSMRs use low-enriched uranium (LEU, typically 8–15 %) in TRISO particle form. Each TRISO particle contains a UCO or UO_2 kernel surrounded by pyrolytic carbon and a SiC layer, creating a miniature containment capable of retaining fission products at temperatures above 1600 °C.

In pebble-bed reactors, thousands of TRISO particles are embedded in graphite pebbles that continuously or semi-continuously circulate through the core, enabling online refueling and achieving burnups around 80–120 GWd/tHM. In prismatic reactors, as shown in Figure 2.13, TRISO particles are pressed into cylindrical compacts inserted into channels within hexagonal graphite blocks, which remain stationary and are replaced only during scheduled refueling outages. Both designs rely on graphite's thermal conductivity and the strength of the SiC coating to ensure effective heat removal and high fission-product retention.

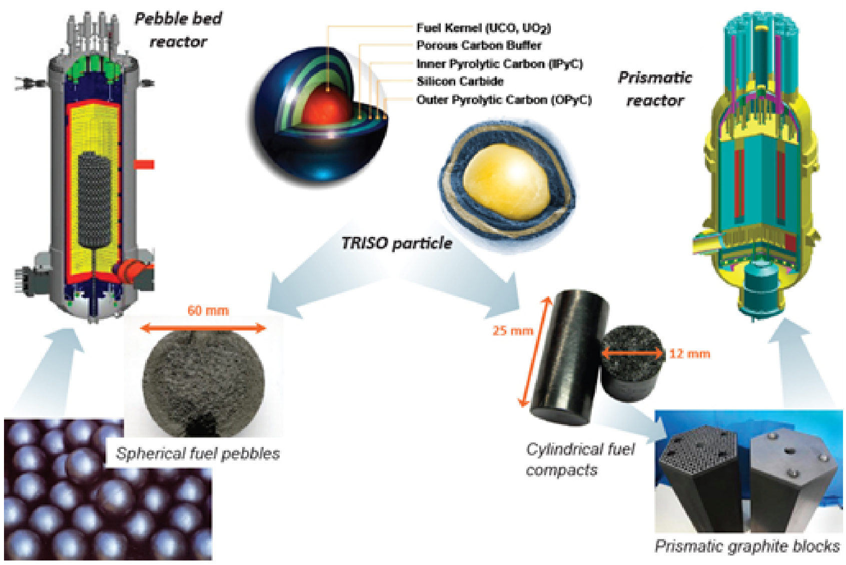


Figure 2.13: TRISO particle in a pebble and in a compact made from special grade graphite matrix

Fuel Cycle and Refueling Strategy

The fuel cycle of SMR-GCRs is primarily determined by the characteristics of TRISO-based fuel and the reactor configuration. Most designs employ a once-through fuel cycle using low-enriched uranium below 19.75 % U-235. The multilayer ceramic coating of TRISO fuel serves as the primary barrier against fission-product release, eliminating the need for conventional metal cladding used in light-water reactors. After irradiation, fuel is discharged and transferred directly to dry storage without the need for prolonged pool cooling. The high burnup capability and strong fuel encapsulation reduce both the volume and radiological hazard of spent fuel per unit of energy generated.

Refueling strategies vary by design. Pebble-bed reactors utilize online refueling, allowing fresh pebbles to be added and spent ones to be continuously removed, maintaining stable reactivity without reactor shutdown. Prismatic-block reactors follow a batch refueling approach at intervals of approximately 18–36 months. Some micro-modular reactor concepts adopt a sealed-core strategy, in which the entire core module is replaced every 7–10 years, significantly reducing operational complexity and on-site fuel handling.

High burnup and elevated thermal efficiency reaching up to approximately 47% result in improved fuel utilization and reduced uranium demand. While advanced fuel cycles involving thorium or higher-assay LEU are under investigation, they remain at the research stage.

Safety Features

Passive Decay Heat Removal

A major safety feature in GCSMRs is passive decay heat removal. After shutdown, decay heat is initially 6 % of full power and decreases over time. Thanks to the high-temperature tolerance of TRISO fuel and the thermal inertia of graphite, the core can dissipate this heat without active systems. Most designs use a Reactor Cavity Cooling System (RCCS), which removes heat from the vessel by natural convection and radiation, ensuring safe fuel temperatures even during total loss of power.

Inherent and Passive Safety Characteristics

SMR-GCRs depend on physics-based safety rather than engineered systems. The negative temperature coefficient ensures automatic reduction of reactor power during overheating. Large graphite heat capacity slows transient temperature rise, giving operators extended time for response. TRISO fuel maintains containment of fission products even in scenarios far beyond design-basis accidents.

2.4.2 Advantages and Disadvantages

Advantages

- High Thermal Efficiency: Outlet temperatures of 700–950 °C enable high electrical efficiency and support industrial heat applications such as hydrogen production.
- Strong Passive Safety: TRISO fuel maintains fission-product retention at very high temperatures, and helium coolant eliminates risks of boiling, chemical reactions, or hydrogen generation.
- Modular Deployment: Factory-built modules reduce construction time, enhance quality control, and allow flexible capacity addition.
- Industrial Heat Capability: High-grade heat makes GCSMRs suitable for combined heat and power and non-electric markets.
- Good Neutron Economy: Helium's negligible neutron absorption minimizes activation and improves neutron utilization.

Disadvantages

- Graphite Irradiation Effects: Long-term neutron exposure causes dimensional and thermal-property changes in graphite, requiring careful lifetime management.
- Complex TRISO Fuel Fabrication: Manufacturing demands tight quality control and remains expensive at an industrial scale.
- High-Pressure Helium Circuit: Operation at several MPa necessitates robust pressure boundaries and leak-tight designs due to helium's high diffusivity.
- Challenging Waste Management: Irradiated graphite and TRISO fuel complicate decommissioning and are not compatible with standard reprocessing methods.
- Economic Uncertainty: High capital cost for early units means competitiveness depends on serial production and design standardization.

2.4.3 Design Examples

HTR-PM (INET, China)

The HTR-PM in China is the first commercial modular high-temperature gas-cooled reactor, built using two pebble-bed cores that supply a single turbine. It uses TRISO fuel pebbles with 8–10 % enrichment and helium coolant to achieve high outlet temperatures and strong inherent safety. The reactor relies on passive safety mechanisms such as graphite thermal inertia and Doppler feedback to maintain stability during accidents. It reached criticality in 2021 and entered commercial operation in 2023, becoming the first full-scale Generation IV HTGR. The HTR-PM now serves as a reference design for future larger systems like the planned HTR-PM600.

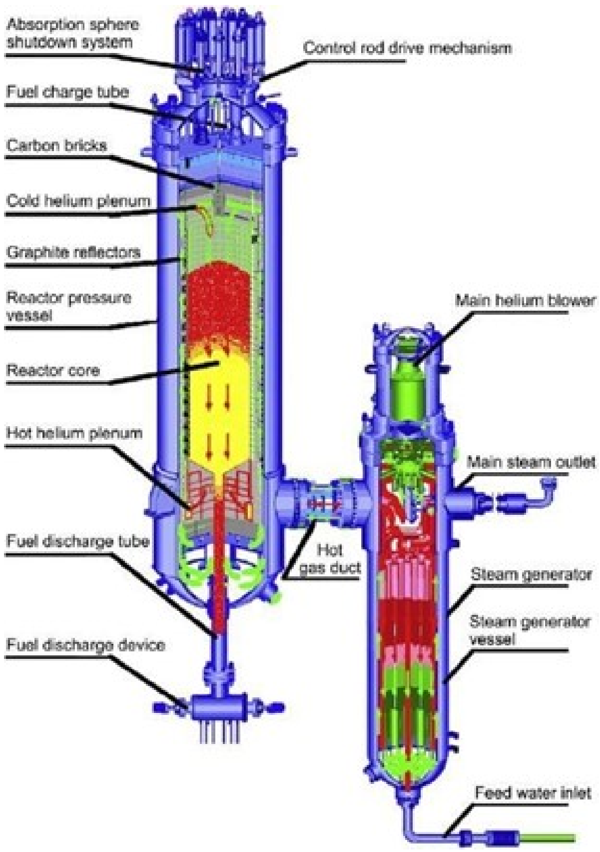


Figure 2.14: HTR-PM (INET, China) SMR Prototype Design.

EM² (General Atomics, USA)

The EM² is a helium-cooled fast-spectrum SMR producing 240–265 MWe using prismatic TRISO-fueled blocks. It operates at 850–900 °C, enabling direct Brayton-cycle conversion and high efficiency. The reactor uses a sealed, long-life core designed to operate for up to 30 years without refueling, relying on high burnup and internal breeding. EM² remains at the advanced conceptual stage but targets passive safety, reduced fuel handling, and suitability for high-temperature industrial applications.

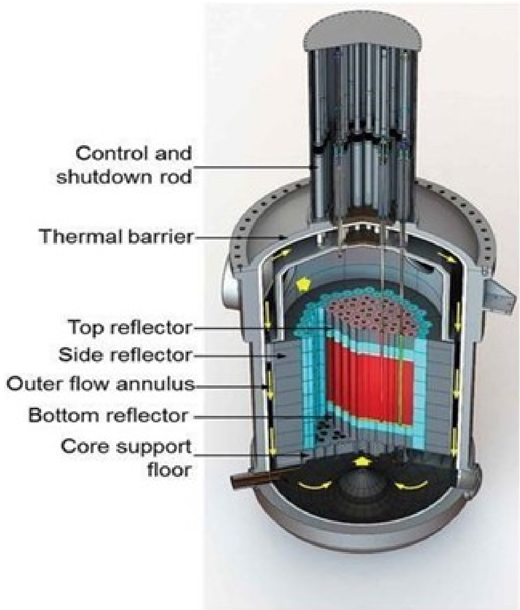


Figure 2.15: General Atomics, USA) SMR Prototype Design

Xe-100 (X-energy, USA)

The Xe-100 is an 80 MWe/200 MWt modular pebble-bed reactor intended for serial factory fabrication. It employs online refueling, helium coolant at 6–7 MPa, and outlet temperatures around 750–800 °C. The design supports coupling to industrial processes requiring high-grade heat. It is progressing through U.S. NRC licensing with multiple topical reports under review.

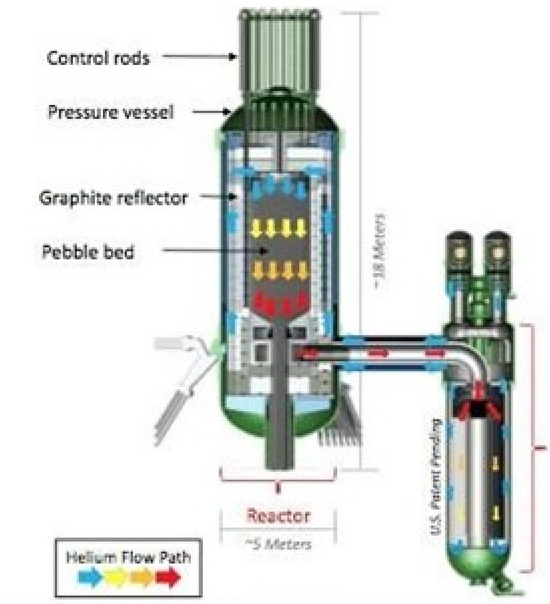


Figure 2.16: General Atomics, USA) SMR Prototype Design

Chapter 3

Manufacturing

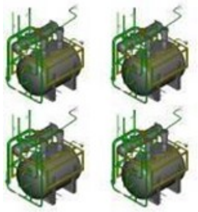
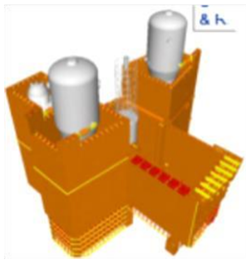
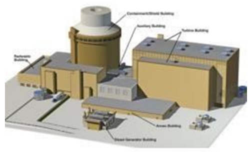
3.1 Rationale for Modular Manufacturing

The most important idea behind Small Modular Reactors (SMRs) is that they are no longer constructed mainly on-site like traditional large nuclear reactors. Instead, SMRs are treated as industrial products that are manufactured in factories, tested under controlled conditions, and then transported to the site for final installation. This fundamental shift is the key reason why SMRs are faster, safer, and more economical to deploy.

The transition toward modular manufacturing in SMRs is driven primarily by the limitations of traditional large-scale nuclear construction. Conventional nuclear power plants are typically built entirely on-site over extended periods ranging from seven to ten years to complete; however, China has demonstrated that SMR projects can be constructed in significantly shorter timeframes, with the HTR-PM reaching construction completion and grid connection in nearly five years, involving thousands of workers across civil, mechanical, and electrical disciplines. According to the International Atomic Energy Agency (IAEA), more than 70% of construction delays in recent nuclear projects were linked to on-site challenges such as adverse weather, logistical bottlenecks, and inconsistent quality control.

Modular manufacturing mitigates these risks by shifting fabrication and assembly activities to specialized factory facilities. Controlled factory environments regulate temperature, humidity, and cleanliness—facilitating high-integrity welding, precision machining, and comprehensive inspection. Automated and semi-automated manufacturing techniques reduce human error and increase repeatability. The IAEA notes that transferring work to factory settings enhances quality assurance and enables more predictable project timelines. Table 2 highlights the productivity and quality advantages of off-site factory environments. SMR modules benefit from advanced manufacturing capabilities, predictable schedules, and robust quality assurance, unlike traditional in-situ construction constrained by site conditions.

Table 3.1: Comparison of Nuclear Power Plant Construction Methods.

Aspect	Off-Site Factory (Supplier Facility)	On-Site Shop	In-Situ Construction
Final Product	 Modules, components, equipment	 Super-modules	 Full NPP (traditional build)
Productivity (Relative Time)	High (1 hour)	Moderate (3 hours)	Low (8 hours)
Transport Options	Road and/or rail; may require barge or ship for oversized loads	Derrick crane, barge	N/A
Manufacturing Capabilities	Many (Advanced fabrication, precision welding, NDE, module assembly)	Limited (Assembly-focused, not full fabrication)	N/A (Construction only; no manufacturing capability)

3.2 Factory Fabrication of SMR Components

3.2.1 Reactor Core and Nuclear Fuel

Fuel fabrication begins with uranium dioxide powder, which is pressed into pellets and sintered at high temperature. These pellets are then inserted into zirconium alloy cladding tubes to form sealed fuel rods using high-precision welding. The fuel rods are assembled into fuel bundles that are placed inside the reactor pressure vessel to form the reactor core. The core geometry must be designed with extreme accuracy to ensure proper heat removal, neutron moderation, and long-term safe operation. Any defect in this stage directly threatens reactor performance and safety.

Nuclear fuel manufacturing for SMRs varies depending on the reactor design: while some water-cooled SMRs use Low-Enriched Uranium (LEU) enriched up to 5% U-235, similar to conventional PWRs, many advanced SMRs require High-Assay Low-Enriched Uranium (HALEU), enriched between 5% and 19.75%, to enable higher burnup, compact cores, improved neutron economy, and refueling intervals of 8–15 years.

Fabrication of LEU and HALEU fuels involve converting uranium into UO_2 powder, pressing and sintering it into pellets, and loading them into cladding, though HALEU demands stricter criticality controls and specialized facility licensing. Other advanced SMRs, such as high-temperature gas-cooled reactors, employ TRISO fuel—spherical particles consisting of a uranium kernel coated with carbon and silicon carbide layers that provide exceptional containment of fission products even under extreme conditions. These TRISO particles are produced through chemical vapor deposition and undergo rigorous quality assurance, including X-ray inspection, thermal shock testing, and burnup analysis, making TRISO-based SMRs among the safest reactor concepts.

3.2.2 The Reactor Pressure Vessel (RPV)

The reactor pressure vessel is the structural backbone of the entire SMR. It is manufactured from high-strength low-alloy steel using advanced forging techniques. RPVs may require multiple forging steps, shown in the figure below, precision machining, and controlled heat treatment cycles to achieve the required metallurgical properties. Automated welding technologies such as robotic Tungsten Inert Gas (TIG) welding, Submerged Arc Welding (SAW), and orbital welding are used extensively to ensure consistent weld penetration and minimal defect rates.

Comprehensive non-destructive testing, such as ultrasonic and radiographic inspection, is performed to verify weld integrity. Finally, hydrostatic pressure testing is conducted to confirm that the vessel can safely withstand operating pressures. One major advantage of SMRs is the reduced vessel size, which simplifies manufacturing, transportation, and installation.

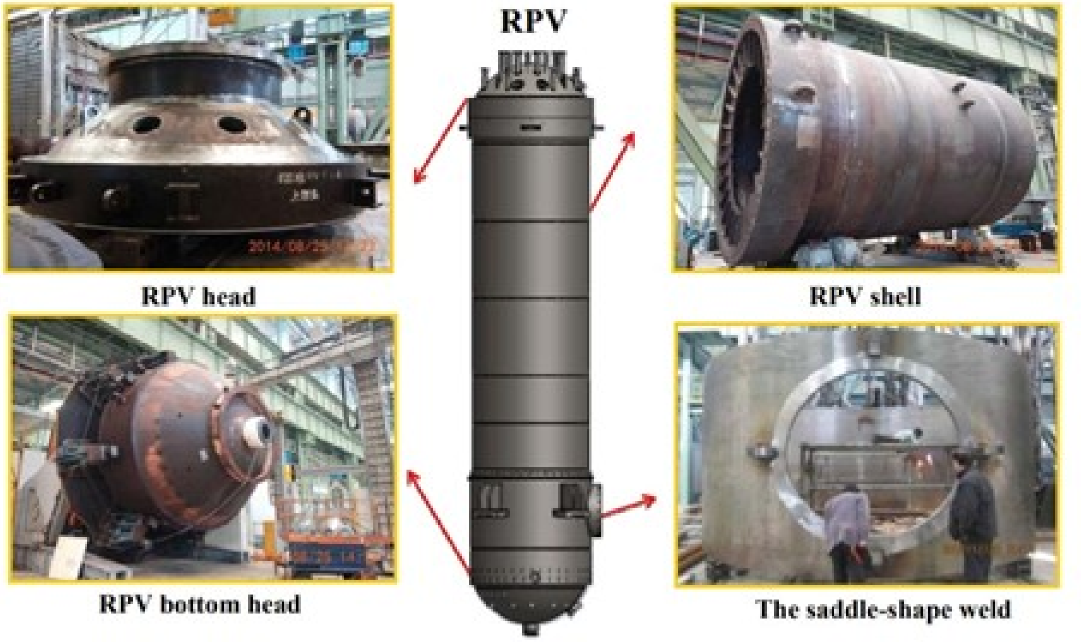


Figure 3.1: The RPV manufacturing progress

3.2.3 Control Rods

Control rods act as the braking system of the nuclear reactor, regulating power by absorbing neutrons. They are manufactured using absorber materials such as boron carbide, silver–indium–cadmium alloys, or hafnium. These absorber materials are sealed inside metallic cladding and subjected to mechanical, vibration, and thermal testing.

3.2.4 Steam Generators and Heat Exchangers

Steam generators serve as the thermal bridge between the nuclear system and the electrical power cycle. They are manufactured using thousands of high-alloy tubes assembled inside pressure shells. Automated welding, leak detection, and pressure testing ensure that heat transfer occurs safely without cross-contamination between the primary and secondary circuits.

3.2.5 Instrumentation and Control (I&C) Systems

The instrumentation and control systems are programmed, tested, and validated in the factory under thousands of faults and operating scenarios. Once approved, the software is locked and delivered as part of the control module. This represents a major technological shift from older analog-based nuclear control systems to fully digital safety-grade automation.

3.3 Module Assembly and Factory Acceptance Testing (FAT)

Following component fabrication, the factory transitions to module assembly. This stage involves integrating mechanical systems, electrical cabinets, control and instrumentation (I&C) panels, and thermal-hydraulic components into compact, transportable units.

Assembly areas inside factories are designed with heavy lifting equipment, laser alignment systems, and automated calibration tools to ensure perfect fit-up of components. Upon assembly completion, each module undergoes Factory Acceptance Testing (FAT). This testing phase includes hydrostatic pressure tests for piping systems, pneumatic leak testing, verification of electrical continuity, software validation for digital control systems, and functional checks for pumps, valves, and heat exchangers. Instruments are calibrated and tested under controlled conditions. The advantage of FAT is that most performance issues are identified and corrected before transportation, significantly reducing commissioning time at the installation site.

3.4 Transportation and On-Site Installation

Transporting SMR modules from the factory to the installation site involves significant engineering, logistical, and regulatory challenges, as modules must be moved using heavy-haul vehicles, rail, or marine vessels, depending on their size and destination. To ensure safe transit, modules are enclosed in protective steel frames to prevent mechanical damage, and vibration sensors are used to monitor dynamic loads throughout the journey. Upon arrival, high-capacity cranes lift the modules into place on pre-constructed civil foundations. Afterward, on-site work is limited to completing mechanical, electrical, hydraulic, and control system hook-ups, such as piping connections, cable routing, sensor integration, and system alignment.

This streamlined installation process is significantly simpler than conventional nuclear construction, as most components have already been assembled and tested in the factory. Site Acceptance Testing (SAT) then verifies that all connections and interfaces are properly completed, followed by cold and hot commissioning tests that evaluate system performance under progressively increasing operating conditions before regulatory approval for fuel loading is granted.

Chapter 4

Operation

4.1 Pre-Operation and Commissioning

4.1.1 Licensing

Licensing for SMRs is carried out by the national nuclear regulatory authority, which is responsible for evaluating the safety, design, and operational framework of the reactor. The process typically begins with a Design Certification, where the regulator reviews and approves the reactor's safety features and analytical models, followed by a Combined License (COL) that authorizes both construction and operation. The regulator ensures that SMR designs -especially those incorporating passive safety systems and modular factory fabrication- meet all nuclear-grade safety and quality requirements before the project can proceed.

4.1.2 Commissioning

The pre-operational tests focus heavily on validating the key passive systems. This includes verifying the performance of passive heat-removal pathways, simulation of loss-of-flow events, and confirming the functionality of gravity-driven emergency coolant injection systems. Commissioning also validates reactor protection logic and calibrates digital instrumentation and control (I&C) systems.

4.2 Startup and Power Ascension

Startup procedures in SMRs are generally simplified due to their inherent stability and standardized designs, beginning with fuel loading. The approach-to-criticality phase is carefully monitored through ex-core ionization chambers, in-core neutron detectors, and reactivity feedback measurements to ensure a controlled and predictable rise in neutron flux. Throughout power ascension, digital predictive control systems, particularly model-based predictive control (MPC), assist operators in managing the reactor's thermohydraulic and neutronic behavior.

4.3 Normal Operation and Thermal-Hydraulic Behavior

A key operational advantage of SMRs is their reliance on simplified, low-pressure thermal-hydraulic systems that use natural forces to maintain stable operation. Water-cooled SMRs such as NuScale and SMART employ passive recirculation, depending heavily on natural circulation for primary heat removal, which reduces mechanical complexity and lowers the number of active components. High-temperature gas-cooled reactors (HTGRs) operate at much higher outlet temperatures, enabling highly efficient Brayton-cycle power conversion. Reactivity is managed through conventional methods such as control-rod motion and coolant-flow adjustments, while inherent negative temperature coefficients, especially Doppler broadening and moderator density feedback, provide passive stabilization against power excursions. Advanced digital twins and sensor-rich monitoring systems further enhance performance by enabling continuous optimization of core behavior and supporting predictive maintenance.

4.4 Safety Systems: Passive and Digital

SMR safety is defined by its reliance on passive features that ensure cooling and shutdown without the need for active pumps or operator intervention. Passive safety features include natural-circulation cooling, gravity-driven emergency coolant injection, and decay-heat removal through air-cooled exchangers. The elimination of large-diameter primary piping substantially reduces the probability of a Loss-of-Coolant Accident (LOCA). Digital and cyber safety measures incorporate redundant fiber-optic sensors, automated trip logic, and AI-assisted anomaly detection, with architectures designed to be cyber-secure and compliant with rigorous international guidance.

4.5 Fuel Cycle

SMRs push for higher fuel utilization and longer in-core residence times, allowing them to extract more energy from each unit of fuel before replacement. Their fuel cycle varies by reactor type: LWR-based SMRs typically use enriched uranium or modern accident-tolerant fuels that improve performance and resilience under high temperatures; high-temperature gas-cooled reactors (HTGRs) rely on TRISO fuel, which contains multiple silicon-carbide and pyrolytic-carbon layers that can retain fission products even at extremely high temperatures; and molten-salt reactors (MSRs) dissolve uranium or thorium directly into fluoride salts, enabling continuous online fuel processing and very high burnup. From a sustainability perspective, advanced SMRs support high-burnup operation, the consumption of excess plutonium from spent fuel, and the use of abundant thorium resources, enhance fuel efficiency, and reduce long-lived waste.

4.6 Decommissioning and Module Removal

The end-of-life phase is simplified by modular, compact architecture, as several SMR designs permit full reactor modules to be removed and shipped to centralized waste management facilities, significantly reducing on-site handling complexity. Decommissioning timelines are shorter compared to conventional gigawatt-scale reactors, and the expected worker dose is substantially lower due to the reduced radioactive inventory and remote transport approach.

Chapter 5

Current Operating and Developing Status

This is an overview of various Small Modular Reactor (SMR) designs. It covers Water-Cooled, High Temperature Gas-Cooled, Molten Salt, and Liquid Metal-Cooled Fast SMRs, highlighting their design features, power output, developers, countries, and current development status. The aim is to summarize global advancements in SMR technology and compare different reactor types.

5.1 Water Cooled SMRs

Water-cooled SMRs are the most common type, primarily because they rely on established Pressurized Water Reactor (PWR) technology, which simplifies both development and regulatory approval. Decades of operational experience, along with existing supply chains, manufacturing infrastructure, and trained personnel, further support their practical implementation and faster deployment.

According to Table 5.1, most water-cooled SMR designs presented in the table are in advanced development or construction stages, demonstrating the relative maturity and near-term deployability of pressurized water reactor (PWR) technology compared to other SMR types. Several reactors—such as ACP100 (China), CAREM (Argentina), and RITM-200N (Russia)—are already under construction, marking tangible progress toward operational demonstration. Meanwhile, designs like NuScale Power Module have achieved regulatory design approval, positioning them for early commercial deployment. Others, including AP300, i-SMR, NUWARD, and SMR-300, remain in the detailed or basic design phase, indicating active engineering development and licensing preparation. Overall, this group reflects the most advanced and diverse class of SMRs worldwide, leveraging the proven safety, scalability, and reliability of water-cooled reactor technology.

Table 5.1: Status of Current Water Cooled SMRs

Design	Output Power (MWe)	Type	Developer	Country	Status
ACP 100	125	PWR	CNNC	China	Under construction
AP300	330	PWR	Westinghouse Electric Company, LLC	USA	Basic design
CAREM	30	PWR	CNEA	Argentina	Under construction
i-SMR	170	PWR	KHNP & KAERI	Republic of Korea	Detailed Design
NuScale Power Module	77	PWR	NuScale Power Inc.	USA	Design Approved
NUWARD	400	PWR	EDF, CEA, TA, Naval Group	France	Detailed Design
RITM-200N	55	PWR	JSC "Afrikantov OKBM"	Russian Federation	Under Construction
SMART	110	PWR	KAERI and K.A.CARE	Republic of Korea	Delayed Construction
Rolls-Royce SMR	470	PWR	Rolls-Royce	UK	Pending final approvals
SMR-300	320	PWR	Holtec International	USA	Detailed Design

5.2 Molten Salt SMRs

Table 5.2: Status of Current MSRs SMRs

Design	**Output Power (MWe)**	**Type**	**Developer**	**Country**	**Status**
CA Waste Burner	100 MW(t)	MSR	Copenhagen Atomics	Denmark	Detailed design
CMSR	110	MSR	Seaborg Technology	Denmark	Conceptual design
FUJI	200	MSR	International Thorium Molten-Salt Forum (ITMSF)	Japan	Conceptual design
IMSR 400	195	MSR	Terrestrial Energy Inc.	Canada	Detailed design
KP-FHR	140	Pebble-bed HTR Salt-Cooled Reactor	Kairos Power, LLC	USA	Under construction
LFTR*	250	MSR	Flibe Energy	USA	Conceptual design
Stellarium	110	MSR	Stellaria Energy	France	Conceptual design
ThorCon	250	MSR	ThorCon International	Indonesia / USA	Conceptual design
Thorizon	100	MSR	Thorizon BV	Netherlands / France	Conceptual design

Among the list of Molten Salt Reactors, Table 5.2, Kairos Power (KP-FHR / Hermes) is currently the most advanced project in terms of licensing and actual experimental construction. Terrestrial Energy – IMSR is also a serious and mature design that has achieved regulatory engagement and detailed design progress.

Most of the other projects on the list remain at the conceptual or feasibility stage, with no major recent updates showing they are close to implementation. The designs with clear regulatory activity or construction permits (like Kairos and Terrestrial Energy) have the highest likelihood of becoming real demonstration or commercial projects soon.

5.3 Liquid Metal-Cooled Fast SMRs

Table 5.3: Status of Current Liquid Metal-Cooled Fast SMRs

Design	Output Power (MWe)	Type	Developer	Country	Status
ARC-100	100	Sodium-cooled	ARC Nuclear Canada, Inc.	Canada	Conceptual design
Blue Capsule	50	Sodium-cooled	Blue Capsule Technology	France	Conceptual design
BREST-OD-300	300	Lead-cooled	NIKIET	Russian Federation	Under construction
HEXANA	150	Sodium-cooled	Hexana	France	Conceptual design
LFR-AS-200	200	Lead-cooled	NewCleo	Italy/France	Conceptual design
OTRERA 300	110	Sodium-cooled	Otrera Energy	France	Conceptual design
SEALER-55	55	Lead-cooled	BlyKalla	Sweden	Conceptual design
SVBR-100	100	Lead-Bismuth	JSC AKME Engineering	Russian Federation	Detailed design
Natrium	345	Sodium-cooled	TerraPower	USA	Conceptual design

Most fast-spectrum SMRs listed in Table 5.3 remain in the conceptual or detailed design stages, reflecting the ongoing transition of liquid-metal technologies from research to demonstration. The BREST-OD-300 in Russia is currently the only design under construction, representing a key milestone for lead-cooled reactor deployment. Other projects, such as ARC-100, Natrium, and SEALER-55, continue progressing through advanced design and licensing phases. The choice of liquid metals as a coolant —such as sodium, lead, and lead-bismuth—is driven by their high thermal conductivity, low operating pressure, and excellent heat removal capacity, which enhance both safety and efficiency. Overall, the table highlights growing international interest in fast-spectrum SMRs, though commercial deployment remains at an early stage.

5.4 High Temperature Gas Cooled SMRs

Table 5.4: Status of Current HTGR SMRs

Design	Output Power (Mwe)	Type	Developer	Country	Status
EM2	265	HTGR	General Atomics	USA	Detailed Design
GTHTR300	300	HTGR	JAEA	Japan	Basic Design
HTR-PM	210	HTGR	INET, Tsinghua University	China	In Operation
Xe-100	80	HTGR	X-Energy LLC	USA	Detailed Design

According to Table 5.4, High-Temperature Gas-Cooled Reactors (HTGRs) demonstrate a notable level of technological maturity within the advanced SMR categories, as shown by the HTR-PM in China already being in operation. This indicates that, despite its complex design requirements, HTGR technology has reached a stage of practical implementation.

Chapter 6

Case Study 1 - NuScale Power Module (NuScale Power, LLC, United States of America

6.1 Introduction

The NuScale Power Module™ (NPM) is a small pressurized-water reactor (PWR) cooled by light water, Figure 6.1 representing a module design. Small Modular Reactor (SMR) plants utilizing NuScale Power Modules (NPMs) are scalable and can be constructed with a variable number of modules to meet diverse customer energy requirements. Standard NuScale configurations include a 4-NPM plant producing 308 MW(e), a 6-NPM plant producing 462 MW(e), and a 12-NPM plant producing 924 MW(e). The six-module configuration is used as the reference plant size for Standard Plant Design Approval and related design and licensing activities. Plant configurations may include air-cooled and/or water-cooled condensers. Each NPM is a self-contained module that operates independently within a multi-module plant. All modules are operated from a single control room. The U.S. Nuclear Regulatory Commission (NRC) has approved control room operations allowing three operators to control up to twelve NuScale reactors. It has removed the requirement for a Shift Technical Advisor. Key plant design features include compact, factory-fabricated NPMs that integrate the containment, natural circulation coolant flow under all operating

Figure 6.1: NuScale Power Module Design.

conditions, a high-pressure containment vessel, the use of proven light-water reactor technology, and testing-based design development.

6.2 Target Application

The NuScale Power Module™ (NPM) is a small, modular, light-water-cooled pressurized-water reactor (PWR) designed for multiple applications:

Electricity Generation:

Each module delivers 77 MWe (gross), with plant configurations scalable to 308, 462, or 924 MWe using 4, 6, or 12 modules, respectively. Each module operates independently and is connected to a dedicated turbine-generator.

Flexible Grid Operation and Load Following:

The NPM allows flexible operation to respond to variable power demands. Individual modules can be refuelled without affecting other modules, enabling grid-support capabilities.

Non-Electrical Process Heat Applications:

The NPM can supply heat for industrial processes, cogeneration, desalination, hydrogen production, and district energy applications. Steam is produced via two once-through helical-coil steam generators integrated in the reactor pressure vessel.

Repowering of Coal-Fired Plants:

NuScale modules can replace retiring coal units on existing sites, utilizing portions of infrastructure such as cooling water systems, switchyards, and support buildings. This approach provides carbon-free energy while leveraging existing site advantages.

Independent Module Operation and Centralized Control:

All modules are managed from a single NRC-approved control room. Up to 12 modules can be controlled by three licensed operators, eliminating the need for a Shift Technical Advisor. Independent operation enhances flexibility and resilience.

6.3 Design Philosophy

NuScale SMR design emphasizes simplicity, modularity, proven technology, and passive safety:

Proven Light-Water Reactor Technology:

Uses established PWR technology with 17×17 UO_2 fuel assemblies enriched up to 4.95 %, 37 fuel assemblies per core, and 16 B_4C control rod assemblies. The design leverages decades of operational experience.

Design Simplification and Modularization:

The Nuclear Steam Supply System (NSSS) integrates the core, two helical-coil steam generators, and pressurizer within a single reactor pressure vessel (RPV), eliminating external primary coolant loop piping and reactor coolant pumps. Cooling relies on natural circulation.

Passive Safety Systems:

Safety systems operate without AC/DC power, operator intervention, or makeup water. Key systems include:

- **Decay Heat Removal System (DHRS):** Two-phase natural circulation system with passive condensers in the reactor pool.
- **Emergency Core Cooling System (ECCS):** Reactor vent and recirculation valves ensure core coverage and decay heat removal.
- **Containment and Reactor Pool:** Steel containment and below-grade pool provide a passive heat sink.

Enhanced Safety Margins:

Small core power, integral RPV, and passive systems reduce radioactive source terms and risk during design-basis and beyond-design-basis events.

Long-Term Operation:

A 60-year design life, nominal 18-month refueling cycles, and staggered module refueling maintain high availability and ease of maintenance.

6.4 Main Design Features

Nuclear Steam Supply System:

The nuclear steam supply system (NSSS) comprises the reactor core, helical-coil steam generators, and a pressurizer, all of which are housed within the reactor pressure vessel (RPV). The NSSS is enclosed within an approximately cylindrical containment vessel (CNV) located in the reactor pool structure. Each power module is connected to a dedicated turbine-generator unit and associated balance-of-plant systems.

Reactor Core:

The NPM core configuration includes 37 fuel assemblies and 16 control rod assemblies. The fuel assembly design is an approved, commercially available 17 × 17 PWR fuel assembly with 24 guide tube locations for control rod fingers and a central instrument tube.

Each assembly is approximately half the height of standard PWR fuel and is supported by five spacer grids. The fuel consists of UO_2 with Gd_2O_3 used as a burnable absorber, homogeneously mixed in selected fuel rods. The U-235 enrichment is up to the current U.S. manufacturer limit of 4.95 %.

Reactivity Control:

Reactivity control in each NPM is primarily achieved using soluble boron in the primary coolant and 16 control rod assemblies. The control rods are divided into two groups: a control group and a shutdown group. The control group includes four rods symmetrically positioned in the core and is used during normal operation to regulate reactivity. The shutdown group consists of 12 rods and is used during shutdown and scram conditions. The absorber material is B_4C, and the control rods are 2 m in length.

Reactor Pressure Vessel and Internals:

The reactor pressure vessel (RPV) is a cylindrical steel vessel with an internal diameter of 2.7 m and an overall height of approximately 17.7 m, designed for an operating pressure of 13.8 MPa. The upper and lower vessel heads are torispherical. A flange located just above the core region provides access for refuelling. The RPV upper head supports the control rod drive mechanisms, and nozzles on the upper head provide connections for reactor safety valves and reactor vent valves.

Reactor Coolant System and Steam Generator:

The reactor coolant system (RCS) circulates the primary coolant using natural circulation. As a result, reactor coolant pumps or external piping are not required to generate flow during power operation.

The RCS includes the reactor pressure vessel with the integral pressurizer, reactor internals, reactor safety valves, RCS piping inside the containment vessel, and associated components. Each NPM uses two inter-woven, once-through helical-coil steam generators for steam generation. The steam generators are located in the annular space between the hot-leg riser and the inner wall of the RPV. The steam generator consists of tubes connected to feedwater and steam plenums by tube sheets. Preheated feedwater enters the lower feed plenum through nozzles on the RPV. As the feedwater flows through the steam generator tubes, heat is transferred from the primary coolant. The secondary-side fluid is heated, boiled, and superheated to produce dry steam that is routed to the turbine-generator.

Pressurizer:

The internal pressurizer provides the primary means for controlling reactor coolant system pressure and is designed to maintain constant coolant pressure during operation. Reactor coolant pressure is increased by applying power to heaters installed above the pressurizer baffle plate, while pressure is reduced using spray systems supplied by the chemical and volume control system (CVCS).

6.5 Safety Features

The NuScale NPM incorporates engineered safety features designed to ensure reliable long-term core cooling under all conditions, including severe accident scenarios. These features include an integral primary system configuration, a containment vessel, passive heat removal systems, and severe accident mitigation features.

This fully passive safety design is demonstrated by the NuScale Triple Crown for Nuclear Plant Safety™, which ensures that the reactor can safely shut down and self-cool indefinitely without operator or computer action, AC or DC power, or the addition of water.

Engineered Safety Systems Overview:

Each NPM incorporates several simple, redundant, and independent safety features, as described below.

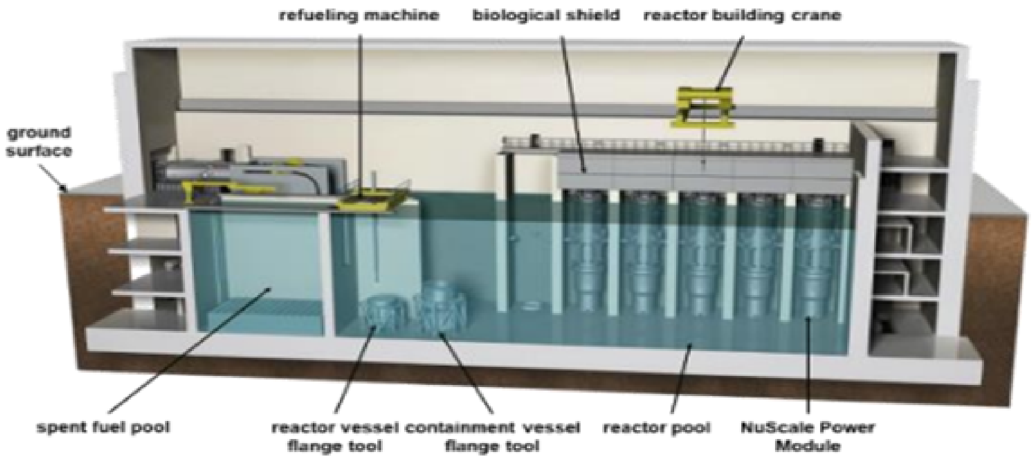


Figure 6.2: Cut-away view of SMR power plant with NuScale NPMs

Safety Systems for Design Basis Events (DBEs):

The decay heat removal system (DHRS) provides secondary-side cooling when normal feedwater is unavailable. The DHRS is a closed-loop, two-phase natural circulation cooling system. Two decay heat removal trains are provided, with one connected to each steam generator. Each train can remove 100% of the decay heat load and cool the primary coolant system. Each train includes a passive condenser immersed in the reactor pool. During normal operation, the DHRS condensers are maintained with sufficient water inventory to ensure stable operation.

Safety Systems for Design Extension Conditions (DECs):

The emergency core cooling system (ECCS) consists of two independent reactor vent valves (RVVs) and two independent reactor recirculation valves (RRVs). For loss-of-coolant accidents inside containment, the ECCS returns coolant from the CNV to the reactor vessel.

This action ensures that the core remains covered and decay heat is removed. The ECCS also provides decay heat removal in the unlikely event of a loss of feedwater combined with the loss of both DHRS trains. The ECCS removes heat and limits containment pressure through steam condensation and convective heat transfer to the inner surface of the CNV.

Containment System:

The functions of the containment vessel (CNV) are to contain radioactive releases following postulated accidents, protect the reactor pressure vessel from external hazards, and provide heat rejection to the reactor pool after ECCS actuation.

Each CNV is a steel cylindrical vessel with an external diameter of 4.5 m and an overall height of 23.1 m. The CNV houses the RPV, control rod drive mechanisms, and associated NSSS piping and components. The CNV is immersed in the reactor pool, which provides a passive heat sink for containment heat removal under LOCA conditions.

Spent Fuel Cooling Safety Approach:

The used fuel pool provides storage for up to 10 years of spent fuel, in addition to temporary storage for new fuel assemblies. The pool is connected to the ultimate heat sink and protected by the reactor building.

The pool water inventory provides approximately 150 days of passive cooling for spent fuel following a loss of all electrical power, without the need for additional water.

After removal from the reactor core, spent fuel assemblies are placed in dedicated storage racks in the below-grade used fuel pool. The pool is a stainless-steel-lined concrete structure adjacent to the reactor pool. A clean-up system limits the buildup of contaminants.

Within about five years, the decay heat of the used fuel is significantly reduced, allowing transfer to a secure dry storage area. The plant layout includes sufficient space for dry storage of all used fuel generated during the 60-year plant lifetime.

6.6 Instrumentation and Control System:

The NuScale design incorporates fully digital instrumentation and control architecture based on the Highly Integrated Protection System (HIPS), which utilizes Field Programmable Gate Array (FPGA) technology.

Highly Integrated Protection System (HIPS):

The HIPS platform is approved by the U.S. Nuclear Regulatory Commission and is developed according to the principles of:

- Independence
- Redundancy
- Predictability
- Repeatability
- Diversity
-

The system consists of four module types that can be interconnected to implement various safety system configurations.

FPGA-Based Control and Protection:

FPGA technology is used in the protection system to provide deterministic, hardware-based logic without reliance on microprocessors or operating systems. This design is inherently resistant to cyber-attacks and provides a highly reliable response to safety events.

Safety Control and Instrumentation System (SCIS)

SCIS provides automated safety responses to initiating events, including:

- Reactor trip
- Turbine trip
- Actuation of passive safety systems such as the DHRS, ECCS, containment heat removal, and shutdown accumulator system

Transients requiring decay heat removal are managed by the DHRS; loss of feedwater or a steam generator tube rupture is mitigated through isolation logic and activation of the appropriate passive systems.

Human-System Integration:

Full Human Factors Engineering (HFE) integration allows centralized operation of up to 12 modules from a single NRC-approved control room with three operators.

Instrumentation and Monitoring:

Continuous monitoring of reactor coolant parameters, steam generator performance, control rod positions, containment conditions, pool water inventory, and radiation levels. Instrumentation is integrated in the RPV and CNV to maintain system integrity.

6.7 Design and Licensing Status

- December 2016: NuScale submitted the Design Certification Application (DCA) to the NRC for a 160MWt (50MWe) design.
- September 2020: The NRC issued the Standard Design Approval for the NuScale DCA, making it the first ever SMR to receive NRC design approval.
- February 2023: The NRC issued its final rule fully certifying the design effective, making it the 7th reactor design certification the NRC has ever issued.
- October 2022: U.S. NRC approved NuScale's methodology for determining the appropriate size of the Emergency Planning Zone (EPZ) surrounding the power plant, allowing a wide range of potential plant sites to achieve a site boundary EPZ.

- December 2022: NuScale submitted a standard design approval (SDA) application for an uprated 6-module, 250MWt (77 MWe) per module plant design to be reviewed by the NRC.
- May 2025: NRC granted a Standard Design Approval (SDA) for the uprated 77 MWe module, completing the technical review ahead of schedule.

6.8 Fuel Cycle Approach

Fuel Type and Enrichment:

The NPM utilizes uranium dioxide (UO_2) fuel. The U-235 enrichment is below the U.S. manufacturer's limit of 4.95 percent enrichment.

Refueling:

Three-batch refueling is conducted on a nominal 18-month refueling cycle in an "in-out" shuffle scheme. During the refueling process, one-third of the fuel assemblies are removed from the NPM and placed in the spent fuel pool. Actual batch size, loading pattern, and cycle length will be established by customer-driven optimization requirements.

6.9 Waste Management and Disposal Plan

Spent Fuel Storage (Interim):

Spent fuel assemblies, after removal from the reactor core, are initially stored in the below-grade spent fuel pool (SFP) for initial cool-down. The SFP provides storage for up to 15 years of accumulated spent fuel assemblies.

Spent Fuel Storage (Long-Term):

After a period of initial cooling (around 5 years, when the thermal load is significantly reduced), the spent fuel assemblies are planned to be moved from the SFP to a secure on-site dry-cask storage area. The plant layout allocates space adequate for the dry storage of all spent fuel produced during the entire 60-year life of the plant.

Final Disposal:

Final disposal of spent fuel is expected to occur in a national fuel repository when available.

Radioactive Waste Building:

The radioactive waste building contains systems for processing gaseous, liquid, and solid radioactive waste and preparing it for off-site shipment. It includes equipment for compacting low-level waste to reduce volume and provides temporary waste storage. The building also houses HEPA(High Efficiency Particulate Air)-filtered HVAC (Heating, Ventilation, and Air Conditioning) systems and is designed to keep radiation exposure to workers as low as reasonably achievable.

Chapter 7

Case Study 2 - HTR-PM (Tsinghua University, China)

7.1 Introduction

In 1992, the Chinese central government authorized the construction of the 10 MW(t) pebble-bed High-Temperature Gas-Cooled Test Reactor (HTR-10) at the Institute of Nuclear and New Energy Technology (INET), Tsinghua University. The reactor achieved full-power operation in 2003. Following this milestone, INET carried out an extensive experimental program using HTR-10 to demonstrate the key inherent safety characteristics of modular high-temperature gas-cooled reactors. These experiments included scenarios such as loss of off-site power without reactor scram, shutdown of the main helium circulator without scram, control rod withdrawal without scram, and helium circulator trip without closure of the outlet isolation valve. Building on the successful operation and experimental validation of HTR-10, China initiated the second phase of its HTR development program in 2001 with the launch of the High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) project. Figure 7.1 visualizes the design of the Pebble bed core of the high-temperature gas-cooled HTR-PM.

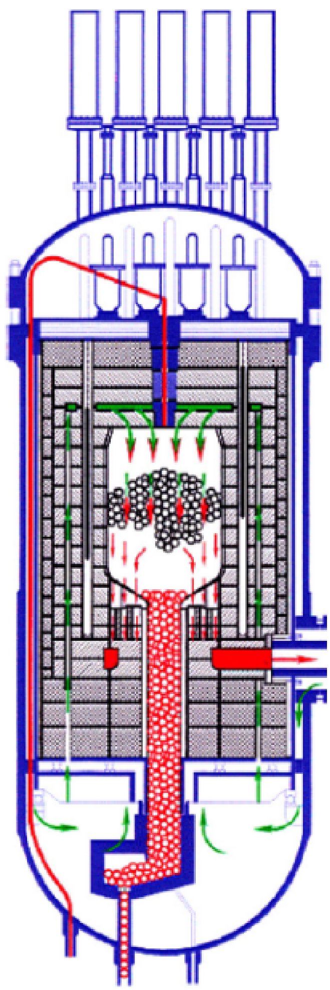


Figure 7.1: Pebble bed core of the high-temperature gas-cooled HTR-PM

7.2 Target Application

The High Temperature Gas-cooled Reactor Pebble-Modules (HTR-PM), developed by Tsinghua University based on the HTR-10 prototype, is primarily designed for safe and efficient electricity generation. The use of helium coolant and a high reactor outlet temperature enhances thermal efficiency and provides flexibility for cogeneration applications, such as district heating and industrial steam supply. In addition, the high-temperature characteristics of HTGR technology offer potential for future industrial applications, including hydrogen production through thermochemical processes.

7.3 Design Philosophy

The design philosophy of the HTR-PM focuses on achieving inherent and passive safety using high-quality TRISO fuel, a low-power-density pebble-bed core, and helium as an inert coolant. The reactor is engineered so that all significant safety functions can be maintained without the need for active systems or operator intervention, even under severe accident scenarios. Its modular configuration, two 250 MWth reactor units coupled to a single 210 MWe steam turbine, enhances design simplicity, operational flexibility, and economic scalability. The use of a graphite moderator and large thermal inertia ensures that, during any loss-of-cooling or loss-of-flow event, core temperatures remain below fuel failure limits, eliminating the need for off-site emergency response as envisioned in Gen-IV safety goals. Furthermore, the design emphasizes manufacturability and standardization, using repeatable reactor modules, helical-coil steam generators that can be tested at full scale, and electromagnetic-bearing helium blowers to reduce mechanical failure modes, as shown in Figure 7.2. Together, these principles define a robust design philosophy that prioritizes inherent safety, simplification, modularity, and industrial practicality.

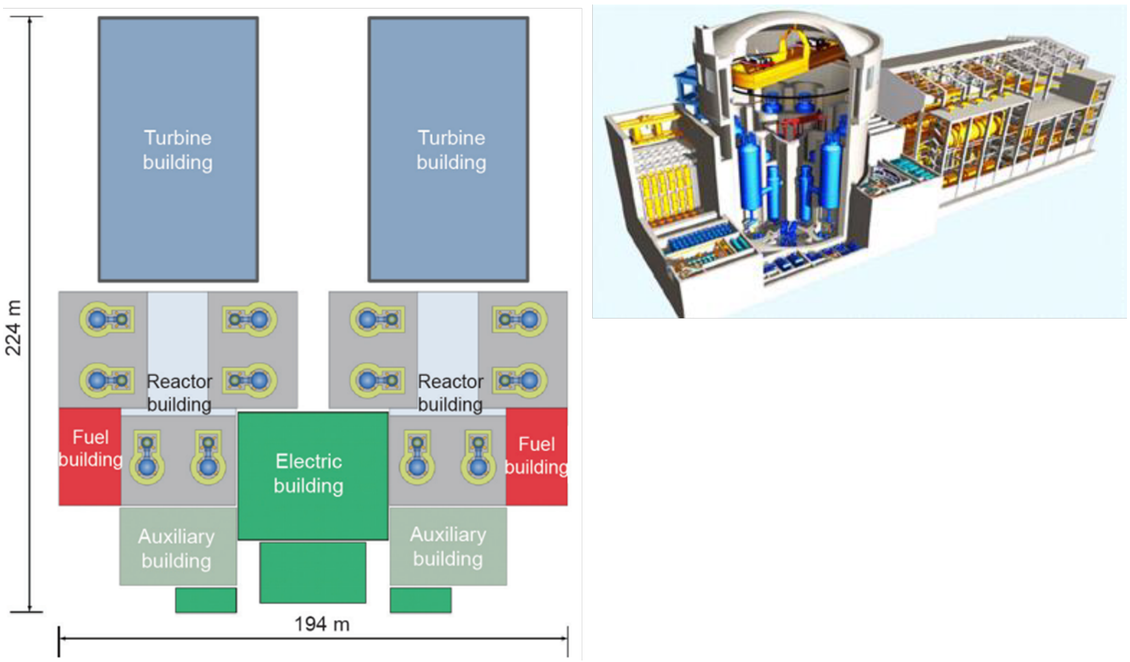


Figure 7.2: HTR-PM layout explanation. By World Nuclear Association, High Temperature Gas-Cooled Reactors, technical information publications.

7.4 Main Design Features

Reactor Core and Power Conversion Unit:

The HTR PM utilizes helium as the primary coolant, operating at a pressure of 7.0 MPa with a mass flow rate of 96kg/s. Helium enters the reactor at the bottom of the Reactor Pressure Vessel (RPV) with an inlet temperature of 250°C. The coolant rises through the side reflector channels to the top reflector, where the flow direction reverses, and helium moves downward through the pebble-bed core. Additional bypass flows are provided in the fuel discharge tubes to cool the fuel elements and in the control rod channels to cool the control rods. Within the active core, helium absorbs heat from the fuel and reaches an average outlet temperature of 750 °C, after which it flows to the steam generator for power conversion.

Fuel Characteristics:

The reactor uses spherical fuel elements, each containing 7 g of heavy metal, with an enrichment of 8.5 % U-235 for the equilibrium core. The uranium kernels (≈0.5 mm in diameter) are coated with three layers of pyrolytic carbon and one layer of silicon carbide (SiC). The coated particles are embedded in a graphite matrix 5 cm in diameter, which is further surrounded by a 5 mm thick graphite layer. This configuration ensures robust containment of fission products and contributes to the reactor's inherent safety.

Fuel Handling System:

The HTR PM employs a continuous fuel loading and unloading system. Fuel elements are loaded through a central fuel loading tube and discharged via a fuel extraction pipe at the bottom of the core. Each discharged fuel element passes through a burn-up measurement device. Fuel spheres that reach the target burnup are sent to the spent fuel storage tank, while those that have not reached the target are reinserted into the core for further irradiation.

Reactivity Control:

The reactor is equipped with two independent shutdown systems: a control rod system and a Small Absorber Sphere (SAS) system, both installed in the graphite side reflector. Reactivity is controlled using 24 control rod assemblies, with 6 SAS systems as a backup. Control rods are used for normal operation regulation and emergency shutdown, and stopping the helium circulator also triggers a reactor trip.

The drop of all control rods ensures long-term shutdown. SAS systems help reduce shutdown temperature, facilitating in-service inspections and maintenance. Both control rods and SAS spheres use B4C as an absorber material.

Reactor Pressure Vessel and Internals:

The primary pressure boundary consists of the Reactor Pressure Vessel (RPV), Steam Generator Pressure Vessel (SGPV), and Hot Gas Duct Pressure Vessel (HDPV), all enclosed within a concrete shielding cavity. The vessels are constructed from SA533-B steel plates and/or 508-3 steel forgings. Protection against high core temperatures is achieved through cold helium channels in the side reflector, which act as a thermal shielding layer.

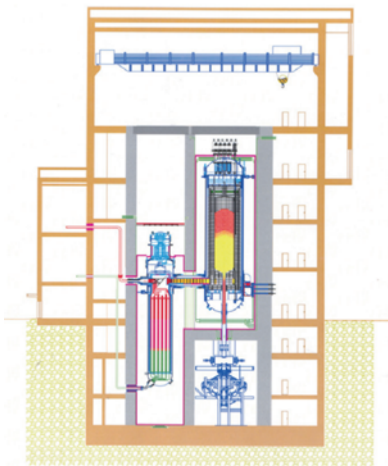


Figure 7.3: Cut-away view of HTR PM SMR

7.5 Safety Features

The High-Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM) is designed with a robust set of safety features that ensure reliable and inherently safe operation under both normal and accident conditions. The safety philosophy of the HTR-PM relies on passive mechanisms, inherent physical properties of the reactor design, and engineered safety systems.

Low Radioactive Inventory:

The HTR-PM maintains a very small radioactive inventory within its primary helium coolant under normal operating conditions. In the unlikely event of a release, this low inventory ensures that there is no immediate requirement for emergency actions, significantly reducing the potential impact on plant personnel and the environment.

Accident Tolerance:

In the case of reactivity accidents or loss-of-coolant scenarios, the rise in fuel element temperature does not lead to significant additional release of radioactive substances. The reactor design inherently limits the consequences of such accidents. Additionally, accidents involving water or air ingress are slow processes due to the reactor's structural and chemical characteristics, allowing sufficient time—ranging from several hours to days—for corrective measures to be applied. Air ingress accidents are considered design extension conditions, emphasizing their extremely low probability and manageable nature.

Inherent Safety Principles:

The HTR-PM integrates the inherent safety principles of modular high-temperature gas-cooled reactors (HTGRs). Key design features include:

- Low power density: Reduces thermal stress and peak fuel temperatures.
- High-quality TRISO-coated fuel particles: Ensure retention of fission products up to temperatures of 1620°C.
- Large negative temperature coefficient: Automatically reduces reactivity in response to temperature rises.
- On-line refueling: Maintains low excess reactivity throughout operation.
- Control rods: Provide precise control over reactivity and emergency shutdown capability.

Passive Decay Heat Removal:

Decay heat is passively removed from the reactor core through natural mechanisms such as conduction and radiation, without the need for active systems. Even in the absence of the main helium blower, the graphite structures and fuel elements' large heat capacity prevent fuel overheating. The Reactor Cavity Cooling System (RCCS) provides an additional passive heat removal path. In the unlikely event of RCCS failure, decay heat can still dissipate safely through the concrete reactor cavity, maintaining fuel temperatures within design limits.

Multi-barrier Containment:

HTR-PM employs multiple barriers to contain radioactive materials:

- First barrier: The TRISO-coated fuel particles themselves, which have demonstrated the ability to retain fission products at temperatures up to 1620°C.
- Second barrier: The primary pressure boundary formed by the reactor pressure vessel and associated components.
- Third barrier: The vented low-pressure containment (VLPC), designed using the ALARA (As Low As Reasonably Achievable) principle, including features such as sub-atmosphere ventilation, burst discs, and filters.

Chemical Control:

Ingress of water or steam is minimized by design features such as pipe sizing, positioning of the steam generator below the core, and dedicated dumping systems. Massive air ingress is practically eliminated due to small connection pipes and the absence of chimney effects. Procedures and systems are in place to remove moisture from the primary circuit in case of water pressure, preventing chemical reactions that could threaten safety.

7.6 Instrumentation and Control System

The instrumentation and control (I&C) system of the HTR-PM is designed like that of conventional pressurized water reactor (PWR) plants. It provides the necessary monitoring and control functions to ensure safe and stable operation of the reactor. The two reactor modules are operated under a coordinated control strategy, allowing the plant to meet different operational requirements while maintaining consistent performance of the coupled system.

Overall I&C Architecture:

The MT-HTR utilizes a digital instrumentation and control architecture designed for multi-module plant operation from a single control room. The system integrates module-specific and shared plant functions, supporting the modular nature of the reactor design while enabling centralized supervision and high automation levels.

Control and Protection Functions:

Reactor protection and safety actions are automatically initiated, with manual backup available. Key safety parameters and post-accident conditions are continuously monitored. Due to the inherent safety and passive heat removal characteristics of HTGR technology, the design minimizes the need for rapid operator intervention during abnormal events.

Distributed Control and Monitoring:

A distributed control system (DCS) is used for non-safety control and monitoring functions. Each reactor module is provided with an independent control interface, ensuring operational separation between modules and reducing the likelihood of operator error in a multi-unit environment.

Modular Human–Machine Interface (HMI) Design:

The control room adopts a modular HMI concept, with standardized and identical interfaces for each reactor module. Large overview displays provide continuous visualization of individual module status and overall plant conditions, enhancing operator situational awareness.

Staffing and Multi-Module Operation:

The I&C system is designed to support supervision of multiple reactor modules by a single operating crew, enabled by automation and standardized interfaces. Final staffing levels are subject to further verification and human-factors validation.

7.7 Design and Licensing Status

- 2008–2009: The Preliminary Safety Analysis Report (PSAR) of the HTR-PM demonstration plant was reviewed by the national licensing authorities, marking the initial regulatory assessment phase.
- December 2012: The Construction Permit was issued, authorizing the start of plant construction.
- July 2021: The Final Safety Analysis Report (FSAR) was approved, completing the comprehensive safety review required for operation.
- August 2021: The Operating License was granted following FSAR approval.
- Post-Licensing Phase: Fuel loading was conducted after licensing approval.
- Operational Milestones: The reactor achieved criticality first and subsequently entered power operation, confirming the successful transition from construction and licensing to operational status.

7.8 Fuel Cycle Approach

The HTR-PM employs a once-through fuel cycle based on spherical TRISO-coated fuel elements, as shown in Figure 7.4. Each pebble contains over 10,000 coated particles, with UO_2 kernels encapsulated in three layers of pyrolytic carbon and one SiC layer.

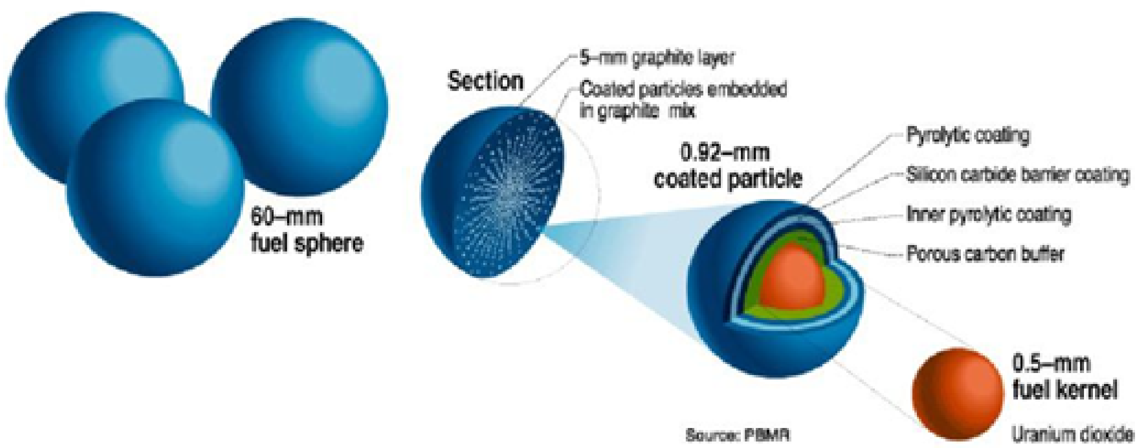


Figure 7.4: The structural diagram of HTR-PM fuel element. By Institute of Nuclear and New Energy Technology (INET), Tsinghua University, Fuel Handling and Storage Systems for HTR-PM, safety analysis documentation.

Fresh Fuel Handling and Storage:

Fresh fuel elements are transported in specialized transport-storage vessels shown in Figure 7.5, combining an external transport shell with an internal storage barrel. At the plant, the storage barrels are removed and placed in vertical storage racks with adequate spacing to maintain subcritical conditions. Pebbles are packaged in polyethylene strings to minimize impact damage and simplify handling. The fresh fuel facility includes a fresh fuel bank and a charging chamber, together holding up to 210,000 fuel elements, enough for six months of operation.

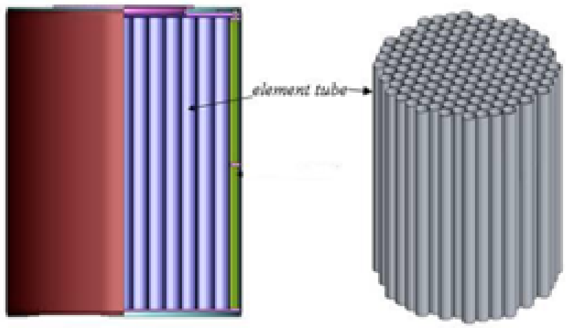


Figure 7.5: HTR-PM fresh-fuel storage vessel, By Institute of Nuclear and New Energy Technology (INET), Tsinghua University, Fuel Handling and Storage Systems for HTR-PM, safety analysis documentation.

On-Power Refueling Strategy and Core Evolution:

Unlike conventional PWRs, which perform refueling during shutdown periods, the HTR-PM uses continuous on-power refueling. Fresh pebbles are added from the top of the core, while spent or partially burnt ones are discharged through the bottom discharge pipe. Pebbles that have not reached their burnup limit are reintroduced into the core, enabling a stable power profile and minimizing shutdown-related losses. Continuous refueling is essential for pebble-bed reactors due to the slow downward movement of fuel during normal operation. Heating, measurement, and handling are entirely automated. Discharged pebbles pass through a burnup measurement system using a collimated HPGe detector to determine whether they should be discharged permanently or recycled. Equilibrium operation typically involves charging 400 fresh fuel elements per day and removing 400 spent elements, with nearly 6,000 elements circulating daily inside the reactor.

The refueling strategy, designed by INET, changes across operational stages:

- **Initial Charge:** A mixture of 4.2% enriched fuel elements and graphite pebbles, about 400,000 total, fills the core. Graphite pebbles are loaded first to reduce breakage risk, followed by mixed pebbles in controlled ratios.

- **Transition Cycle:** Graphite pebbles are gradually removed and replaced with low-enriched fuel. Later, low-enriched elements are replaced with 8.5% enriched pebbles until the core consists entirely of high-enrichment fuel.

- **Normal Power Operation:** The core contains only high-enriched pebbles. Fuel flows downward along defined paths into the discharge pipe, where measurement and sorting take place. Broken or out-of-specification pebbles are directed to dedicated storage tanks, while acceptable pebbles are either recycled or discharged, depending on burnup.

7.9 Waste Management and Disposal Plan

Discharging of Spent Fuel:

Fuel discharged from the core enters spent-fuel storage tanks housed in shielded steel structures. Once full, each tank is sealed and moved to dedicated dry-storage shafts. All handling is automated, with operators monitoring remotely.

Spent Fuel Storage Strategy:

HTR-PM adopts a long-term dry storage strategy without off-site transport during the plant's operational lifetime. Storage is divided into three areas: the buffer storage area, the first intermediate storage area, and the second intermediate storage area. Newly loaded spent fuel storage tanks are initially placed in the buffer storage shaft for several years to allow decay heat reduction, after which they are transferred to the first or second intermediate storage shafts for longer-term storage. Figure 7.6 shows a structural diagram of the spent fuel storage area. Each tank holds about 40,000 pebbles, which are not intended to be transported off-site during operational years. Cooling systems include closed forced ventilation, open forced ventilation, and open natural ventilation. Even under accident conditions when active systems are unavailable, natural ventilation alone can safely remove residual heat due to the low decay heat of TRISO fuel.

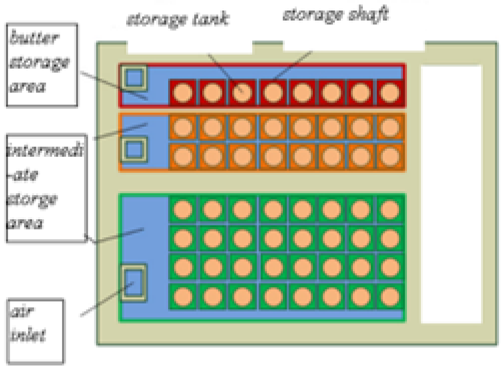


Figure 7.6: A structural diagram of spent fuel storage area. By International Atomic Energy Agency (IAEA), Spent Fuel Storage Technologies, IAEA Nuclear Energy Series.

Final Disposal and Waste Safety Philosophy:

Final disposal of spent fuel is planned via transfer to a national geological repository once available. Until then, all spent fuel remains securely stored on-site under dry conditions. The waste management philosophy emphasizes inherent fuel integrity, passive heat removal, minimal handling, and long-term containment, ensuring radiation protection and safety for workers and the public.

Chapter 8

Conclusion

Small Modular Reactors (SMRs) represent a significant advancement in nuclear energy technology, developed to address technical, economic, and safety limitations of conventional large nuclear power plants through modular construction, system integration, enhanced safety features, and flexible deployment. Rather than simple scaled-down versions of existing reactors, SMRs adopt a different design philosophy focused on simplification and adaptability. This report has shown that SMRs include a wide range of reactor concepts, such as water-cooled, molten salt, liquid metal-cooled fast reactors, and high-temperature gas-cooled reactors. Each category is defined by specific choices of coolant, fuel form, and neutron spectrum, leading to distinct operational and safety characteristics. Water-cooled SMRs build on established light-water reactor technology, while advanced concepts offer benefits such as low-pressure operation, improved fuel utilization, and high-temperature capability.

Comparative Comparison/Critique of SMR Technologies:

Each Small Modular Reactor (SMR) technology presents a distinct balance between safety, efficiency, technical maturity, and deployment readiness. No single design offers a universally optimal solution; instead, each reflects trade-offs shaped by engineering priorities and deployment goals.

Water-cooled SMRs benefit from the highest level of technological maturity and regulatory familiarity. Their reliance on proven light-water reactor technology reduces licensing risk and facilitates near-term deployment. However, their dependence on high-pressure systems, relatively lower thermal efficiency, and continued reliance on conventional fuel cycles limit their long-term innovation potential compared to advanced concepts.

Molten Salt Reactors (MSRs) offer exceptional safety characteristics and fuel flexibility, including the potential for online refueling and actinide recycling. Their low-pressure operation and strong negative temperature feedback provide inherent stability. However, unresolved challenges in materials corrosion, salt chemistry control, and fuel reprocessing infrastructure significantly hinder near-term commercialization.

Liquid Metal–Cooled Reactors (LMRs) achieve high power density and excellent neutron economy, enabling efficient fuel utilization and potential breeding capabilities. These advantages are offset by complex material compatibility issues, coolant chemical reactivity (especially for sodium), and increased engineering complexity associated with handling liquid metals under high-temperature conditions.

High-Temperature Gas-Cooled Reactors (HTGRs) offer exceptional thermal efficiency and robust fuel performance, particularly due to TRISO fuel's ability to retain fission products under extreme conditions. Their high outlet temperatures make them attractive for industrial heat applications. However, challenges related to graphite behavior under irradiation, fuel fabrication costs, and large reactor core volumes remain significant barriers.

Overall, the trade-off among SMR technologies lies between technological maturity and innovation. Water-cooled designs offer the shortest path to deployment, while advanced reactors promise superior efficiency, sustainability, and safety but require further demonstration and regulatory evolution. The optimal choice depends on national energy priorities, infrastructure readiness, and long-term decarbonization goals.

A key outcome of this study is that safety in SMR designs relies primarily on inherent and passive mechanisms. Natural circulation, negative temperature reactivity feedback, gravity-driven shutdown systems, and passive decay heat removal reduce dependence on active systems and operator intervention. The compact core size and integrated reactor vessel configuration further limit potential accident consequences and simplify emergency planning requirements.

From a construction and economic perspective, modular factory fabrication is a central advantage of SMRs. Manufacturing reactor modules in controlled factory environments improves quality assurance and reduces construction time and schedule uncertainty. This approach also supports phased capacity addition and lowers financial risk, although competitiveness depends on standardization and deployment scale.

Operationally, SMRs provide greater flexibility than traditional nuclear power plants. They can perform load-following, support grids with high shares of renewable energy, and supply non-electrical energy such as district heating, desalination, and hydrogen production, expanding the role of nuclear energy beyond baseload electricity generation.

The case studies presented in this report, including the NuScale Power Module and the HTR-PM, demonstrate that SMR technologies have progressed from conceptual designs toward practical implementation. These projects confirm the feasibility of modular construction and passive safety systems, while challenges remain in regulatory licensing, fuel supply, waste management, and early-stage economics.

In conclusion, Small Modular Reactors offer a credible pathway for the future development of nuclear energy by providing safer, more flexible, and more adaptable reactor systems. While not a standalone solution, SMRs can effectively complement renewable energy sources and support sustainable low-carbon energy strategies.

Chapter 9

Poster

This work provides an in-depth yet accessible overview of Small Modular Reactor (SMR) technology, synthesizing key technical concepts, design philosophies, and development trends. The objective is to present the significance of SMRs in a clear, informative manner that supports understanding by both specialists and non-specialists, highlighting their role, benefits, and potential impact in the future energy landscape, Poster 9.2.

In addition, an interactive website has been developed to present a concise summary of the work and the complete project, supporting our vision for a promising and sustainable future for this industry, QR 9.1.

Figure 9.1: Website QR Code

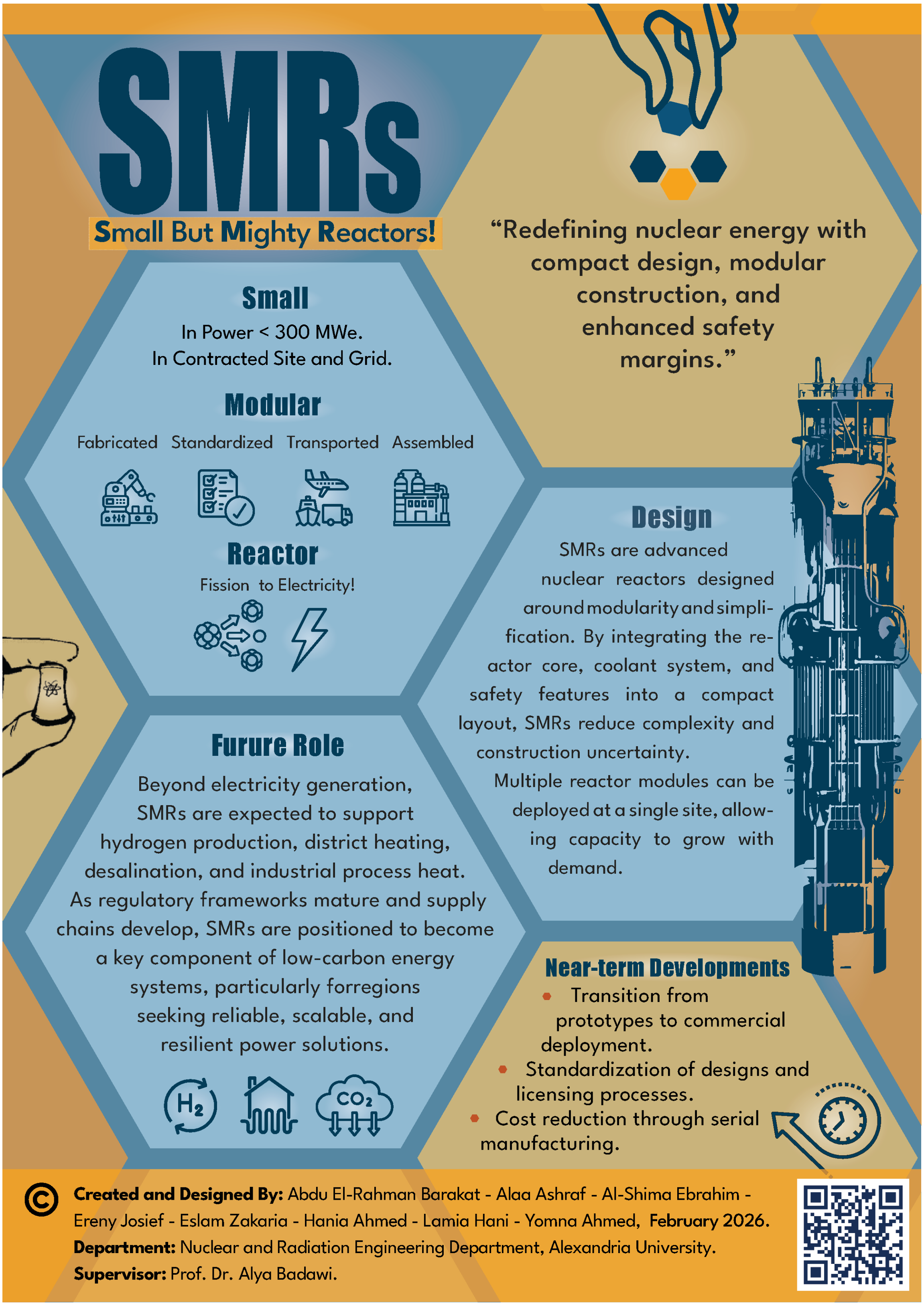


Figure 9.2: Poster

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Appendix A

Acronyms and Abbreviations

ALARA As Low As Reasonably Achievable

BWR Boiling Water Reactor

CNV Containment Vessel

COL Combined License

DCA Design Certification Application

DCS Distributed Control System

DHRS Decay Heat Removal System

ECCS Emergency Core Cooling System

EPZ Emergency Planning Zone

FAT Factory Acceptance Testing

FHR Fluoride Salt-Cooled High-Temperature Reactor

FPGA Field Programmable Gate Array

FSAR Final Safety Analysis Report

GCR Gas-Cooled Reactor

GWd/tHM Gigawatt-days per Metric Ton of Heavy Metal

HALEU High-Assay Low-Enriched Uranium

HDPV Hot Gas Duct Pressure Vessel

HEPA High Efficiency Particulate Air

HFE Human Factors Engineering

HIPS Highly Integrated Protection System

HMI Human–Machine Interface

HTGRs High-Temperature Gas-Cooled Reactors

HVAC Heating, Ventilation, and Air Conditioning

I&C Instrumentation and Control

INET Institute of Nuclear and New Energy Technology

iPWRs Integral Pressurized Water Reactors

LBE Lead-Bismuth Eutectic

LCOE Levelized Cost of Electricity

LEU Low-Enriched Uranium

LFTR Lithium Fluoride Thorium Reactor

LMRs Liquid-Metal-Cooled Reactors

LM-SMRs Liquid-Metal Small Modular Reactors

LOCA Loss-of-Coolant Accident

LWR Light Water Reactor

MMR Micro Modular Reactor

MOX Mixed Oxide (Fuel)

MPC Model Predictive Control

MSRs Molten Salt Reactors

NPM NuScale Power Module

NRC Nuclear Regulatory Commission

NSSS Nuclear Steam Supply System

PHXs Primary Heat Exchangers

PSAR Preliminary Safety Analysis Report

PWR Pressurized Water Reactor

RCCS Reactor Cavity Cooling System

RPV Reactor Pressure Vessel

RRVs Reactor Recirculation Valves

RVVs Reactor Vent Valves

SALEU Standard-Assay Low-Enriched Uranium

SAS Small Absorber Sphere

SAT Site Acceptance Testing

SAW Submerged Arc Welding

SCIS Safety Control and Instrumentation System

SDM Shutdown Mechanism

SFP Spent Fuel Pool

SFRs Sodium-Cooled Fast Reactors

SGPV Steam Generator Pressure Vessel

SMR-GCRs Small Modular Gas-Cooled Reactors

VLPC Vented Low-Pressure Containment

WCRs Water-Cooled Reactors