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A Review of Thorium-Fueled Molten Salt Reactors for Achieving India's Net-Zero 2070 Goal

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Abstract

With its growing energy needs and abundant thorium reserves, India is in a suitable position to implement emerging nuclear technologies. One such technology is the Molten Salt Reactor (MSR), which has proven theoretical advantages over Pressurized Heavy Water Reactors (PHWRs) across domains such as safety, efficiency, and waste management. With around 13% of the world's thorium reserves, the switch to MSRs provides India with a trade advantage as well, reducing its reliance on imported uranium. This review, using data from peer-reviewed literature, nuclear agencies, and government reports, provides a detailed comparative study between MSRs and PHWRs across five crucial domains: fuel use, reactor design and safety, waste management, engineering challenges, and economic viability. Results show that for the Indian context, MSRs have some major long-term advantages, including fuel burnup rates above 200 GWd/tHM and better use of local resources like thorium. However, major hurdles such as high capital costs, limited industrial and commercial readiness, and a lack of experience with new MSR technologies make the implementation of MSRs in India at this time exceedingly unfeasible. Therefore, the review considers Small Modular Reactors (SMRs), which are smaller, factory-built units that are quicker to build, easier to license, and fit well with India's manufacturing systems. While MSRs remain a promising long-term option, SMRs may be a more realistic and affordable way for India to move toward its clean energy and net-zero 2070 goals.

Keywords: thorium, sustainable energy, molten-salt reactors, small-modular reactors, India net-zero.

Introduction

Nuclear energy generation has been touted as one of the energy sources of the future ever since its inception in 1942, when the artificially built Chicago Pile-1 first sustained a nuclear reaction (International Atomic Energy Agency, 2019). However, it is yet to become extensively utilized due to the large construction and development costs involved in setting up a power plant (World Nuclear Association, 2021), ineffective methods of radioactive waste disposal and high waste generation, and long build times (World Nuclear Association, 2023c; OECD NEA, 2023). International disasters like Chernobyl and Fukushima further undermined the credibility of nuclear energy in the eyes of the general public (International Atomic Energy Agency, 2019). As a result of these factors, atomic energy has been limited to just 9 % of all energy production worldwide (World Nuclear Association, 2022), with only a select few countries like France using nuclear energy at a commercial scale (World Nuclear Association, 2023b). However, with the revival of old technologies such as Molten Salt Reactors (MSRs), the concept of Small Modular Reactors (SMRs) increasing in popularity, technological advancements, high energy density, minimal carbon emissions, and a minute geographical footprint, nuclear energy can be viewed as a genuine contender to power the world in the future (World Nuclear Association, 2021, 2023d).

One of the countries that could implement nuclear power to great effect is India, which first entered the forefront of nuclear energy in 1948, led by Dr Homi J. Bhabha (World Nuclear Association, 2023a). It holds approximately 13 % of the world's thorium reserves, most of which can be found on the beaches of India's coastal cities (World Nuclear Association, 2023a; International Atomic Energy Agency, 2020). To assess whether India should continue its reliance on PHWR, shift to MSRs, or perhaps even to the highly relevant Small Modular Reactors (SMRs), it is first essential to understand the broader energy landscape and policy objectives that drive its nuclear strategy (Department of Atomic Energy, India, 2020; Indian Express, 2023). While MSRs have garnered interest due to their theoretical advantages, SMRs, which are already being deployed commercially, provide a pathway more grounded in reality that is worth researching simultaneously (U.S. NRC, 2023; World Nuclear Association, 2023d).

Method

This literature review was conducted from January 2025 to August 2025. The methodology of the research is detailed below.

Source Selection Strategy

This review necessitated detailed searches across multiple academic databases. Peer-reviewed literature was accessed using Google Scholar, ScienceDirect, SpringerLink, and IEEE Xplore. The searches included the use of keywords from keyword families such as "thorium molten salt reactor", "pressurized heavy water reactor", "fuel cycles", "neutron economy", "small modular reactor India", "India sustainable energy", etc. (International Atomic Energy Agency, 2019; World Nuclear Association, 2021). Publications from 1990 to 2025 were prioritized with a filter to ensure use of the latest data and frameworks (OECD NEA, 2023). However, ORNL's MSRE was also included due to its historical significance and findings (Oak Ridge National Laboratory, 1972; Oak Ridge National Laboratory, 2016).

Government and Agency Sources

Official government and global agency reports were also accessed for this review. Specific organizations include the International Atomic Energy Agency (IAEA), the Bhabha Atomic Research Centre (BARC), the Nuclear Power Corporation of India Limited (NPCIL), and the Department of Atomic Energy (DAE), among others. These reports provided authentic and accurate data on different domains such as technical reactor specifications, government policies, thorium reserves, and government research, which are standard references in nuclear technology studies (International Atomic Energy Agency, 2020; Bhabha Atomic Research Centre, 2022; Department of Atomic Energy, India, 2020). Other policy documents specific to India, such as The Draft National Electricity Plan (NEP) and the NITI Aayog Net-Zero Roadmap, were also accessed and reviewed.

Inclusion/Exclusion Criteria

Peer-reviewed literature on relevant topics surrounding nuclear energy, MSRs, PHWRs, and SMRs was used, which is standard in such reviews (IAEA-TECDOC-1450, 2005; U.S. Nuclear Regulatory Commission, 2021). Government and agency reports with quantitative data about reactor metrics such as fuel burnup, thermal efficiency, waste reduction, and operating conditions were included (IAEA INPRO, 2019; World Nuclear Association, 2023b). Conference proceedings and technical briefs on innovations pertaining to MSRs and nuclear technologies were also included, specifically materials-science innovations (Oak Ridge National Laboratory, 1970; National Materials Advisory Board, 1982; Bhabha Atomic Research Centre, 2023). Non-technical media articles, speculative opinionated pieces, and any reports without sufficient quantitative analysis and evidence were excluded (U.S. Nuclear Regulatory Commission, 2021).

Data Extraction

Key metrics on reactor performance, such as fuel burnup, neutron economy, thermal efficiency, operating pressures, capital costs, and licensing readiness, were extracted from the literature and organized into a series of tables, placed in relevant sections of the review (International Atomic Energy Agency, 2005; Oak Ridge National Laboratory, 2016; International Atomic Energy Agency, 2019). This also shaped a comparison across 5 domains: Neutron economy and fuel utilization; Thermal efficiency and reactor design; Safety considerations and waste management; Economic and engineering viability; and The potential role of SMRs in India's nuclear strategy.

This methodology ensured a balanced and data-backed review of MSRs and other nuclear technologies in India.

The Future of Nuclear Power in India

India's energy landscape is at a crucial point. With one of the fastest-growing economies in the world and a population projected to exceed 1.5 billion by 2030, India's energy demand is expected to rise exponentially as the country develops further and transitions into secondary, tertiary, and quaternary sector production (World Nuclear Association, 2023a). Fossil fuels, currently India's largest energy source, are expected to pose serious problems in the future due to resource depletion and the nature of fossil fuels as an energy source, which increases global warming (World Nuclear Association, 2021).

Despite its current contribution of just 1.6 % to the nation's energy generation, nuclear power is recognized as a vital element for ensuring long-term energy security in India (World Nuclear Association, 2023a). Historically, India has relied on Pressurized Heavy Water Reactors (PHWRs) that burn uranium as fuel (Bhabha Atomic Research Centre, 2022; Department of Atomic Energy, India, n.d.). However, India possesses approximately 13 % of the world's thorium reserves (World Nuclear Association, 2023a; International Atomic Energy Agency, 2020). This has prompted significant interest in alternative thorium-based MSRs (IAEA-TECDOC-1450, 2005).

To arrive at an objective answer to the viability of MSRs in India, this review compares MSRs to conventional nuclear reactors in terms of safety, efficiency, economic viability, and policy alignment (International Atomic Energy Agency, 2019; OECD NEA, 2023). If India were to construct a nuclear reactor today, what would make the most sense: tried and tested PHWRs, theoretically superior MSRs, or the complete package of SMRs (World Nuclear Association, 2023b, 2023d; U.S. NRC, 2023)?

India's Energy Needs and the Role of Nuclear Power

India's electricity consumption has been growing at a rate of 4–6 % annually, with projections suggesting a doubling of energy demand by 2040 (World Nuclear Association, 2023a). While coal remains the dominant source (over 50 %) (World Nuclear Association, 2023a), concerns over carbon emissions, global warming, and an overdependence on oil imports have prompted the government to invest in clean energy (World Nuclear Association, 2021).

The Bhabha Atomic Research Centre (BARC) has developed a three-stage nuclear power programme aimed at effectively utilising India's thorium reserves. The three stages are:

1. Pressurised Heavy Water Reactors (PHWRs) using mined uranium;
2. Fast Breeder Reactors (FBRs), which are a means of producing fissile material;
3. Thorium-based reactors, such as Molten Salt Reactors (Indian Express, 2023; Department of Atomic Energy, India, 2020; Bhabha Atomic Research Centre, n.d.).

India is currently in Stage 2, with Stage 3 projected to come into effect between 2040 and 2070 (World Nuclear Association, 2023a; Bhabha Atomic Research Centre, n.d.). India's first FBR, known as the Prototype Fast Breeder Reactor (PFBR), was inaugurated on 4 March 2024 with the "Commencement of the Core Loading" by Prime Minister Narendra Modi (World Nuclear Association, 2023a; World Nuclear News, 2022). India has also developed a 500 MWe breeder reactor, situated in Kalpakkam, Tamil Nadu. It is designed to use uranium-238 to breed plutonium - uranium absorbs a neutron, decays to neptunium-239, and finally to fissile plutonium-239 (Department of Atomic Energy, India, n.d.; Bhabha Atomic Research

Centre, 2022). The surplus plutonium obtained can be used as fuel in more breeder reactors and expand India's nuclear capabilities (World Nuclear Association, 2023a).

While this three-stage programme provides a path forward, the choice of reactor technology used will depend on the technology's ability to meet India's long-term energy requirements efficiently and safely while taking into account the various environmental, economic, and technological factors that define India (OECD NEA, 2023; World Nuclear Association, 2021). To evaluate the viability of MSRs in India entirely, it is necessary to compare them to PHWRs on multiple levels: how effectively they utilise nuclear fuel, how they convert heat to electricity, how they manage neutrons, the overall performance of the reactors, and other aspects of nuclear physics involved in these reactions (IAEA-TECDOC-1450, 2005; U.S. NRC, 2021; Oak Ridge National Laboratory, 2016).

MSR Feasibility – Thorium Availability

Thorium is a fertile material rather than a fissile one, which means it can be converted into a fissile isotope ready for fission via the absorption of neutrons. This process is known as breeding, and in MSRs, it produces more fissile material than it consumes, eventually leading to increased power generation in the reactor itself (IAEA-TECDOC-1450, 2005). The process unfolds as follows:

1. Th-232 absorbs a neutron, transforming into Th-233.

2. Th-233 undergoes beta decay, releasing an electron, gaining a proton, and losing a neutron to form Pa-233 (protactinium)

3. Pa-233 undergoes beta decay over its half-life of 27 days to form fissile U-233, which is capable of sustaining a fission reaction and having positive energy output (IAEA-TECDOC-1450, 2005; International Atomic Energy Agency, 2020).

Thorium, however, is not capable of sustaining a reaction alone; the presence of fissile material such as isotopes of uranium and plutonium is necessary to set the reaction in motion (IAEA-TECDOC-1450, 2005). The amount of fissile material required is far less than in traditional PHWRs (Bhabha Atomic Research Centre, 2022).

The viability of thorium as a fuel in MSRs plays right into India's hands. India possesses one of the world's largest thorium reserves along its coasts in the form of monazite sand, a reddish-brown phosphate mineral containing rare earth metals, primarily thorium (World Nuclear Association, 2023a; BBC Future, 2018). Official figures suggest India has 846,000 tonnes of recoverable thorium, representing about 13.31 % of the world's thorium reserves (World Nuclear Association, 2023a). These reserves are found primarily on the beaches of India's eastern coastal states, including Tamil Nadu, Andhra Pradesh, and Odisha, with Andhra Pradesh containing 2.46 million tonnes of monazite (not thorium alone) (International Atomic Energy Agency, 2020; Bhabha Atomic Research Centre, n.d.). In contrast, India has only about 325,000 tonnes of recoverable uranium-roughly 4.02 % of the world's uranium reserves (World Nuclear Association, 2023a).

The relative abundance of thorium clearly suggests that MSRs are more optimal for India in this respect. As the world transitions towards sustainable and clean energy sources, MSRs can be a key component in making India fuel-independent and less reliant on importing raw materials from other countries (OECD NEA, 2023; World Nuclear Association, 2021). This strategic alignment between natural resources and reactor technology makes thorium-fueled MSRs an attractive prospect. The next step is to evaluate how these reactors compare in key technical domains such as neutron economy (IAEA-TECDOC-1450, 2005).

Technical Comparison – MSRs vs PHWRs

The following section is a comparison of MSRs and PHWRs across various important technical domains.

Neutron Economy/Fuel Efficiency

One of the most fundamental technical comparisons between reactor designs begins with their fuel utilization, neutron economy and conversion efficiency. Neutron economy is defined as how efficiently a reactor uses neutrons in a fission reaction. A higher neutron economy means a reactor uses neutrons more efficiently and conserves more neutrons, making it more fuel efficient and leading to increased energy output (IAEA-TECDOC-1450, 2005; International Atomic Energy Agency, 2019).

When a neutron is emitted from a heavy nucleus during fission, it typically possesses high amounts of kinetic energy. To increase the probability of a collision with another nucleus or atom, the neutrons must slow down. This process is known as neutron moderation. PHWRs use heavy water as a neutron moderator, hence the name. Heavy water is particularly effective in this regard as it does not absorb many neutrons, which allows the reactor to operate on naturally obtainable uranium-238 (Bhabha Atomic Research Centre, 2022; World Nuclear Association, 2023b).

MSRs can operate in two modes: thermal-spectrum and fast-spectrum MSRs. Thermal-spectrum reactors use moderators made of graphite. Slow-moving/thermal neutrons are ideal as they can be easily captured by thorium-232 and bred into fissile uranium-233 in the MSR itself (IAEA-TECDOC-1450, 2005; Oak Ridge National Laboratory, 2016). Fast-spectrum MSRs use no moderator to slow down neutrons and therefore have much higher energies (around 1 MeV) (International Atomic Energy Agency, 2019). These high-energy neutrons are less likely to be absorbed by the fuel, meaning more neutrons are available to support other fission reactions (International Atomic Energy Agency, 2019).

Fast-spectrum reactors also possess the capability of being able to burn nuclear waste and long-lived products like plutonium-239 (IAEA-TECDOC-1521, 2006). However, this technology is still in the experimental phase and is far from being commercially feasible. Moreover, due to the fast-moving neutrons, breeding of thorium-232 to fissile material does not occur as efficiently (International Atomic Energy Agency, 2019). Considering the abundance of thorium in Indian soil, thermal-spectrum MSRs are more suitable for the Indian context (IAEA-TECDOC-1450, 2005; Bhattacharjee, 2019).

In comparison to PHWRs, thermal-spectrum MSRs are more fuel efficient, as graphite, as a moderator, absorbs fewer neutrons, while in a PHWR, some neutrons are still absorbed by heavy water (Bhabha Atomic Research Centre, 2022; International Atomic Energy Agency, 2019).

The difference is clearly shown in Table 1.

Table 1

Neutron Economy and Fuel Efficiency - MSRs vs. PHWRs

Parameter	MSR	PHWR
Moderator	Graphite	Heavy Water (D_2O)
Fuel cycle	Continuous refueling	Batch refueling
Neutron Losses	Low	Moderate
Fuel efficiency	45%	28%

Note. Data adapted from (IAEA-TECDOC-1450, 2005; Bhattacharjee, 2019; Bhabha Atomic Research Centre, 2022; World Nuclear Association, 2023b)

Thermal Efficiency/Reactor Design

The thermal efficiency of a reactor refers to the “percentage of heat energy produced by the nuclear fission process within the reactor that is converted into usable electrical energy.” Essentially, it addresses how much thermal energy produced during the fission process is converted to usable electrical energy (International Atomic Energy Agency, 2019).

The efficiency of a nuclear reactor is affected by two parameters – operating temperatures and the type of coolant used. PHWRs and MSRs differ to a large extent in this aspect, primarily because MSRs operate at higher temperatures, and molten salts are used as coolants as well as fuel (Oak Ridge National Laboratory, 2016; U.S. Department of Energy, 2021). PHWRs and MSRs incorporate different thermodynamic cycles in their operation; PHWRs use Rankine cycles due to lower operating temperatures, and MSRs use Brayton cycles due to their higher operating temperatures (Idaho National Laboratory, 2021; Oak Ridge National Laboratory, 2016).

The Rankine cycle in a PHWR consists of four main stages. The fission process generates heat, which is transferred to a primary coolant loop containing heavy water operating at 300°C and 10 MPa. This transfers heat to a secondary loop containing water, which becomes steam and drives a turbine (Bhabha Atomic Research Centre, 2022). Despite being a widely popular and well-tested system, the Rankine cycle has a few inefficiencies – the phase transition of water from a liquid to a gas leads to latent heat loss, which is a process where a substance releases energy when changing state due to different amounts of energy required to make and break bonds (Oak Ridge National Laboratory, 2016). The use of steam at high pressure may also lead to material stress and corrosion, which may need frequent maintenance and care (Oak Ridge National Laboratory, 2016).

An MSR can avoid these inefficiencies by implementing a Brayton cycle rather than a Rankine cycle. It can do so due to higher operating temperatures over 700°C (U.S. Department of Energy, 2021; Idaho National Laboratory, 2021). The Brayton cycle utilizes gases such as helium or supercritical carbon dioxide instead of steam as the medium for heat transfer (Idaho National Laboratory, 2021).

Supercritical carbon dioxide is a state in which carbon dioxide exhibits the properties of both a gas and a liquid. Carbon dioxide is compressed beyond its critical point of 31.1°C and 73.8 bar using high-pressure compressors to convert it into a supercritical fluid (Idaho National Laboratory, 2021). It eliminates latent heat losses as there are no phase changes, making the MSR thermally efficient (Idaho National Laboratory, 2021). The comparatively higher density of supercritical carbon dioxide also aids in a more efficient thermal energy transfer (Idaho National Laboratory, 2021).

Helium, another alternative, is a noble gas known for its stability and unreactivity. This helps in reducing material degradation and maintenance costs (Oak Ridge National Laboratory, 2016). Furthermore, helium does not absorb neutrons and is also unaffected by radiation, making it an ideal medium for heat transfer in MSRs (Oak Ridge National Laboratory, 2016).

In a Brayton cycle, the gas undergoes a continuous compression-expansion process; it is compressed to a high pressure before heat addition, after which it expands through an electric turbine when the molten salt transfers heat from the fission reaction (Idaho National Laboratory, 2021).

Higher temperatures and Brayton cycles give MSRs much greater thermal efficiency than PHWRs, shown in Table 2 (U.S. Department of Energy, 2021; Idaho National Laboratory, 2021).

Table 2

Thermal Efficiency and Design Comparison - MSRs vs PHWRs

Parameter	MSR	PHWR

Cycle Type	Brayton (gas)	Rankine (steam)
Operating Temp	700-750°C	300°C
Working Fluid	Helium / Supercritical CO_2	Steam (via Heavy Water)
Thermal Efficiency	45%	28%
Maintenance	Lower	Higher

Note. Data adapted from (Oak Ridge National Laboratory, 2016; U.S. Department of Energy, 2021; Idaho National Laboratory, 2021)

Safety Considerations/Waste Management

A critical factor in choosing a reactor technology lies in safety and long-term waste disposal – especially in countries where public perception of nuclear energy remains cautious after incidents like Chernobyl and Fukushima (International Atomic Energy Agency, 2019).

MSRs incorporate a passive safety mechanism known as a freeze plug, which consists of frozen molten salt in piping separating the core from the sub-critical drain tank. When operating temperatures exceed the set point, the freeze plug melts, allowing fuel to drain into the tank where it cannot sustain a reaction (U.S. Nuclear Regulatory Commission, 2021; U.S. Department of Energy, 2021).

PHWRs rely on active-cooling mechanical systems that require a continuous power supply to circulate the coolant and maintain a safe operating temperature (Bhabha Atomic Research Centre, 2022). In a Loss-of-Coolant Accident (LOCA), coolant flow may stop, causing overheating and possible core meltdown (Bhabha Atomic Research Centre, 2022).

In terms of pressure, PHWRs operate above 10 MPa to keep water in a liquid state at higher temperatures. MSRs operate at atmospheric or near-atmospheric pressures of around 101,325 Pa (U.S. Department of Energy, 2021; Oak Ridge National Laboratory, 2016). The considerably less pressure in MSRs means they are less susceptible to high-pressure accidents such as steam explosions (caused by rapid depressurizations), reducing mechanical stress (U.S. Department of Energy, 2021).

The lower pressures can be attributed to the thermophysical properties of the molten fluoride and chloride. These molten salts have boiling points around 1400°C, in sharp contrast to water, which boils at 100°C (Oak Ridge National Laboratory, 2016; National Materials Advisory Board, 1982). High pressures are not required in MSRs due to the relatively higher boiling points of molten salts (Oak Ridge National Laboratory, 2016).

Another aspect of reactor safety is the management of nuclear waste. MSRs are designed in such a way that continuous fuel reprocessing is viable, which not only increases neutron economy but also removes some problematic and long-lived fission products, which is done using a variety of processes, including helium sparging and actinide burning (IAEA-TECDOC-1521, 2006; EPRI, 2020; Oak Ridge National Laboratory, 1974).

Fission products are byproducts of nuclear fission in a reactor, including isotopes of noble gases such as krypton and xenon as well as iodine-129 and plutonium-239 (Oak Ridge National Laboratory, 1974; World Nuclear Association, 2023c). Xenon-135 and isotopes of krypton are particularly damaging to the neutron economy and efficiency of a reactor as they are “neutron poisons” – that is, they readily absorb neutrons and slow down the chain reaction considerably (Oak Ridge National Laboratory, 1974).

These neutron poisons can be easily removed in an MSR by sparging the molten salt with helium, which captures these harmful gases and removes them from the system (Oak Ridge National Laboratory, 1974; EPRI, 2020).

Conventional PHWRs produce spent nuclear fuel rods that contain an array of long-lived fission products, primarily iodine-129 and neptunium-237. These fuel rods are replaced every 1–2 years, constantly producing long-lived waste that is challenging to store and manage (World Nuclear Association, 2023c; International Atomic Energy Agency, 2021).

Actinide burning is a process where non-fissile actinides absorb neutrons until they become fissile isotopes and are then burned for energy production (IAEA-TECDOC-1521, 2006). It occurs for transuranic elements and isotopes such as americium-241 and plutonium-239. Transuranic burning by MSRs in fast-spectrum configuration reduces the buildup of these isotopes and the amount of long-lived nuclear waste by around 80–90% (IAEA-TECDOC-1521, 2006; EPRI, 2020).

This is possible due to a higher neutron flux in MSRs (10^{15} n/cm²/s) compared to 10^{12}–10^{13} n/cm²/s in PHWRs, leading to a higher fuel-to-moderator ratio and increased neutron density in comparison to PHWRs (International Atomic Energy Agency, 2019; Oak Ridge National Laboratory, 2016).

Continuous refuelling, while a potent safety feature, is crucial in enabling MSR's high neutron flux year-round. A high neutron flux enables a higher fuel burnup, removes short-lived fission products, and facilitates transuranic burning. In PHWRs, only around 1% of fissile material (U-235) is used before the fuel rods are replaced. In MSRs, due to the fluid nature of the fuel, around 90% of fissile material is effectively fissioned (IAEA-TECDOC-1450, 2005; World Nuclear Association, 2023b). MSRs have more than 10× the fuel burnup of PHWRs, which can clearly be seen in Table 3 (World Nuclear Association, 2023b; IAEA-TECDOC-1450, 2005).

Table 3

Comparison of typical burnup rates between different reactors

Reactor Type	Typical Burnup (GWd/tHM)	Fuel Usage Efficiency
Light Water Reactor (LWR)	50–60 GWd/tHM	3-5% U-235 used
PHWR (India's IPHWR-700)	7–15 GWd/tHM	1% U-235 used
MSR	>200 GWd/tHM (targeted)	90% of fissile material
Fast Breeder Reactor	100–200+ GWd/tHM	High

Note. Data adapted from (World Nuclear Association, 2023b; IAEA-TECDOC-1450, 2005)

MSRs' continuous refuelling allows isotopes more time to become stable or short-lived by neutron irradiation. Table 4 provides a general overview and a summary of the safety comparison between MSRs and PHWRs (U.S. Nuclear Regulatory Commission, 2021; International Atomic Energy Agency, 2021).

Table 4

Safety and Waste Management – MSRs vs PHWRs

Safety/Waste Parameter	MSR	PHWR
Safety System	Passive, employing a freeze plug	Active, employing powered cooling systems
Operating Pressure	1 atm	10 MPa
Fuel Reprocessing	Continuous	None
Burnup Rate	>200 GWd/tHM	7–15 GWd/tHM
Waste volume/toxicity	90% reduction in long-lived waste	High; spent rods stored externally
Neutron Poison Removal	Possible (helium sparging, actinide burning)	Not possible

Note. Data adapted from (Atomic Energy Regulatory Board, 2020; Bhabha Atomic Research Centre, 2021; International Atomic Energy Agency, 2021; Indira Gandhi Centre for Atomic Research, 2022)

However, it is crucial to remember that while MSR technology looks very promising, the concept remains largely theoretical and has not been commercially deployed as of yet (U.S. Nuclear Regulatory Commission, 2024; U.S. Department of Energy, 2021).

Economic and Engineering Viability

The construction of molten salt reactors requires the use of specialized materials that are resistant to corrosion from molten fluoride or chloride salts. One such material is

Hastelloy-N, a nickel-based alloy developed in the 1950s at Oak Ridge National Laboratory (ORNL) (Oak Ridge National Laboratory, 1970; Oak Ridge National Laboratory, 1972). Hastelloy-N forms a protective nickel fluoride oxide layer, giving it self-healing properties and making it, to a large extent, unreactive; ORNL's MSRE reported corrosion rates as low as 25 micrometres/year in clean fluoride salts (Oak Ridge National Laboratory, 1970; Oak Ridge National Laboratory, 1972).

Hastelloy-N's compatibility with molten salt reactors extends beyond unreactivity; the alloy also can resist neutron embrittlement and helium bubble formation, two mechanisms that cause degradation in reactor materials (ORNL, 2019; HyperPhysics, n.d.). Neutron embrittlement is a loss of ductility due to neutron irradiation, and helium bubble formation occurs when insoluble helium bubbles accumulate and precipitate out in reactor materials. Both these mechanisms result in largely the same thing: a loss of purity and mechanical integrity, with the possibility of blistering, flaking, cracking, and swelling. All in all, these two phenomena severely reduce the lifespan of reactor materials, which is largely prevented when using Hastelloy-N (ORNL, 2019; National Materials Advisory Board, 1982).

India currently imports Hastelloy-N for experimental purposes from Europe and the U.S. However, Bhabha Atomic Research Centre (BARC) has indigenously developed a Ni-Cr-Mo-Ti alloy, which performed within 26% of imported Hastelloy-N in an experiment conducted by the Materials Group in the BARC (Bhabha Atomic Research Centre, 2023). MSRs also require precision manufacturing of heat exchangers and piping that can resist high temperatures, radiation, and salt creep (U.S. DOE, 2020; Indira Gandhi Centre for Atomic Research, 2020). Both the BARC and the Indira Gandhi Centre for Atomic Research

(IGCAR) have been actively exploring research that will aid in developing these techniques. BARC has studied the thermophysical properties of fluoride salts, developed redox control techniques, and examined properties such as viscosity and thermal conductivity. Research also explores alternative buffers such as Sm^{3+}/Sm^{2+} (Bagul, 2024). Most importantly, BARC has developed a dedicated facility known as MSCTF for testing the corrosion resistance of materials in molten fluoride salts like “FLiNaK” at elevated temperatures up to 1273 K under static conditions employing Be/BeF_2 buffers (Bhabha Atomic Research Centre, 2023). This was achieved by building a glove box-coupled, automated testing system that allowed for testing in a vacuum or in the presence of inert gases (Bhabha Atomic Research Centre, 2023). Rigorous testing at this facility has yielded results similar to other research conducted; nickel-based alloys like Hastelloy-N possess the best corrosion resistance and “are proposed for use as the structural materials in molten-salt systems”. However, as mentioned before, indigenous Ni-Cr-Mo-Ti are not far behind. BARC could also explore the use of Sm^{3+}/Sm^{2+} as a redox buffer in a $NaF–BeF_2$ molten salt mixture, which stabilizes the redox potential between –0.6 V and –1.0 V as demonstrated in a 2024 study done by Electrochemica Acta (Bagul, 2024). IGCAR has also initiated research that could be very helpful for the development of molten salts. For example, their work on pyrochemical and fluoride volatility-based methods to separate uranium, thorium, and other fission products from spent nuclear fuel could be very valuable (Indira Gandhi Centre for Atomic Research, 2022).

When it comes to economic viability, however, MSRs face serious hurdles. On paper, they offer many theoretical advantages, but there are no currently operational, commercially deployed MSRs. Without real-world experience, estimates of both capital and operating costs remain largely speculative and based on estimates (U.S. Nuclear Regulatory Commission, 2024; OECD NEA, 2023). As shown in Table 5, prototypes and potential commercial MSRs are projected to have higher capital costs than PHWRs. This is largely due to the need for entirely new supply chains, specialized reactor materials, and dedicated fuel-reprocessing infrastructure- none of which are currently established in the global nuclear industry, including in India (Energy Innovation Reform Project, 2017; OECD NEA, 2023). While India has had some success in developing corrosion-resistant alloys domestically, one has to ask whether resources would be better directed toward a more proven path, such as Small Modular Reactors. Another challenge is that of licensing; the liquid nature of MSR fuel means that no regulatory authority has developed a solid licensing framework. For example, the U.S. Nuclear Regulatory Commission has not fully approved a single MSR design (U.S. Nuclear Regulatory Commission, 2024). A summary of the economic and engineering viability comparison can be found in Table 5.

Table 5

Economic and Engineering Viability Comparison – MSRs vs PHWRs

Parameter	MSR	PHWR
Capital Costs	$7,000–10,000 (estimated)	$1,300–2,000/kWe
Fuel Import Dependency	Very Low (India has thorium)	High (Uranium mostly imported)
Materials (e.g., Hastelloy-N)	Not indigenously produced yet	Domestic supply chains exist

Infrastructure Requirements	Specialized	Well-established
Licensing Status	Immature	Mature

Note. Data adapted from (Energy Innovation Reform Project, 2017; OECD NEA, 2023; World Nuclear Association, 2021)

For a country like India that urgently needs to scale sustainable energy while managing financial risk, SMRs provide a viable way to proceed. Their compatibility with existing PHWR uranium cycles, lower capital intensity, and streamlined licensing pathways make them a highly feasible and workable solution to India's problems of green energy (World Nuclear Association, 2023d; U.S. NRC, 2023).

Evaluating Small Modular Reactors as a Feasible Alternative

As the drawbacks of MSRs become more and more apparent, Small Modular Reactors (SMRs) rise to prominence as a feasible solution for India's target of achieving net-zero by 2070. SMRs are classified as reactors under 300 MWe designed for modular, factory-based construction and commercial deployment (World Nuclear Association, 2023d). They are predominantly designed for power production but can also serve as heat generators and for desalination. Unlike MSRs, they build upon proven PHWR technology and India's well-established uranium fuel supply chains (Bhabha Atomic Research Centre, 2022; World Nuclear Association, 2023d). SMRs can be used to power anything from gated communities to factories (World Economic Forum, 2023).

Several SMR designs have already received official approval, such as the NuScale VOYGR (USA), with others like CAREM (Argentina) and SMART (South Korea) (U.S. NRC, 2023; NuScale Power, 2023; SMART Reactor / Korea Atomic Energy Research Institute, 2022; World Nuclear Association, 2023d). For India, SMRs offer specific benefits: they are much smaller than PHWRs, can be factory-assembled and transported to sites, and thus enable rural electrification with low-carbon energy (World Economic Forum, 2023; World Nuclear Association, 2023d). Microreactors, a subset of SMRs producing up to 10 MWe, are well-suited for gated communities and for smaller factories. The modular design also allows incremental deployment to match India's rising energy demand while reducing financial risk. Importantly, SMRs do not require location-specific customisation- unlike PHWRs or MSRs-thereby making them much cheaper, as shown in Table 6 (World Nuclear Association, 2023d; U.S. NRC, 2023; NuScale Power, 2023).

Table 6

General comparison between three reactor technologies

Parameter	**SMRs (NuScale VOYGR)**	**PHWRs (Indian 700 MWe)**	**MSRs**
Power Output	50–300 MWe per module	700 MWe	500–1000 MWe (conceptual)

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Fuel Type	Low-Enriched Uranium (LEU, 4.95% U-235)	Natural or slightly enriched Uranium	Thorium + U-233/U-235
Moderator	Light water/graphite/none	Heavy water (D_2O)	Graphite or none (depending on spectrum)
Coolant	Light water, helium,	Heavy water	Fluoride or chloride molten salt
Thermal Efficiency	30–37%	28%	45% (projected)
Refueling Cycle	24 months	1–2 years	Continuous online reprocessing
Passive Safety Features	Yes – gravity-fed cooling, underground siting	Limited; relies on engineered systems	Yes – freeze plug, passive salt drainage

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Waste Management	Known, compatible with existing systems	Long-lived waste; known management	Complex; fission products in salt and continuous reprocessing
Capital Cost (USD/MWe)	$5,900–7,700(NuScal)	$2,400–3,300(India-specific)	$7,000–10,000 (estimated)
Construction Timeline	3–5 years (modular, factory-built)	7–10 years	10–20 years (no commercial deployment, estimated)
Licensing Readiness	Multiple licenses (NuScale by US NRC in 2023)	Fully licensed	Not licensed anywhere yet
Manufacturing Feasibility	Factory-fabricated; domestic infrastructure compatible	Established in India	Requires exotic materials (e.g., Hastelloy-N)

Scalability	High (modular deployment)	Medium (large units only)	Low (first-of-a-kind risk)

Note. Data adapted from (World Nuclear Association, 2023d; U.S. NRC, 2023; NuScale Power, 2023; SMART Reactor / Korea Atomic Energy Research Institute, 2022; Bhabha Atomic Research Centre, 2022)

Conclusion

Molten Salt Reactors, on paper at least, have several technical advantages relative to most other reactor types, including PHWRs. They also align well with India's thorium strategy, with reserves estimated at 846,000 tonnes of recoverable thorium (World Nuclear Association, 2023a; International Atomic Energy Agency, 2020). This makes MSRs a strong option for reducing India’s reliance on imported uranium, which is especially important as the country seeks greener energy solutions (Bhabha Atomic Research Centre, n.d.; World Nuclear Association, 2023a). They offer some clear theoretical advantages, such as better operational safety, higher thermal efficiency, lower operational costs, and less long-lived radioactive waste (U.S. Nuclear Regulatory Commission, 2021; Oak Ridge National Laboratory, 2016; U.S. Department of Energy, 2021; World Nuclear Association, 2023c).

Ongoing work by Indian research institutions-including testing of advanced materials, redox control systems, and salt chemistries by BARC and IGCAR- means that MSRs could emerge as a viable option in the future (Bhabha Atomic Research Centre, 2023; Indira Gandhi Centre for Atomic Research, 2022; Bagul, 2024).

However, MSRs face significant challenges that cannot be overcome easily. They require specialized materials like Hastelloy-N and are projected to have comparatively higher capital costs. Most significantly, there is not a single fully-functioning commercially deployed MSR in the world right now (Oak Ridge National Laboratory, 1970; Energy Innovation Reform Project, 2017; U.S. Nuclear Regulatory Commission, 2024). Therefore, Small Modular Reactors (SMRs) offer a more realistic path for India's nuclear energy expansion today. SMRs are already licensed in several countries, can be built in factories, and use India's existing supply chains for uranium and infrastructure (U.S. NRC, 2023; World Nuclear Association, 2023d). Designs like the NuScale VOYGR are expected to cost less than full-scale MSRs and can be deployed faster with lower financial risk (NuScale Power, 2023; U.S. NRC, 2023; World Nuclear Association, 2021). SMRs can also provide high-density, low-carbon solutions for the energy needs of rural communities (World Economic Forum, 2023).

A dual strategy, which includes short-term SMR adoption and ongoing MSR research, might give India the most practical route to net-zero by 2070 (OECD NEA, 2023; World Nuclear Association, 2023d).

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