Thorium-Powered Abundance

Fuel for Bold Space Exploration, Sustainable Energy, Plentiful Freshwater, Thriving Agriculture

A Technology Companion for Chapter 10: Powering the Final Frontier: Thorium MSRs and the Architecture of Space Civilization

by Michael Lee Anderson

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Thorium-Powered Abundance: Fuel for Bold Space Exploration, Sustainable Energy, Plentiful Freshwater, Thriving Agriculture

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A Technology Companion for Chapter 10

Powering the Final Frontier: Thorium MSRs and the Architecture of Space Civilization

The Challenge

Space is both inviting and unwelcoming. A blank canvas of stars, silence, and starkness. In space, energy is survival. The farther we go, from the lunar poles to the Martian plains, from asteroids to exoplanets, the more critical energy becomes. Every habitat, rover, lab, drill, and printer rely on electricity. Unlike Earth, there are no backup power grids or fossil fuels available. While solar panels are effective in orbit, they fail in Martian dust storms. Batteries have limited capacity, and RTGs offer only a trickle of power, which is inadequate for sustaining a settlement.

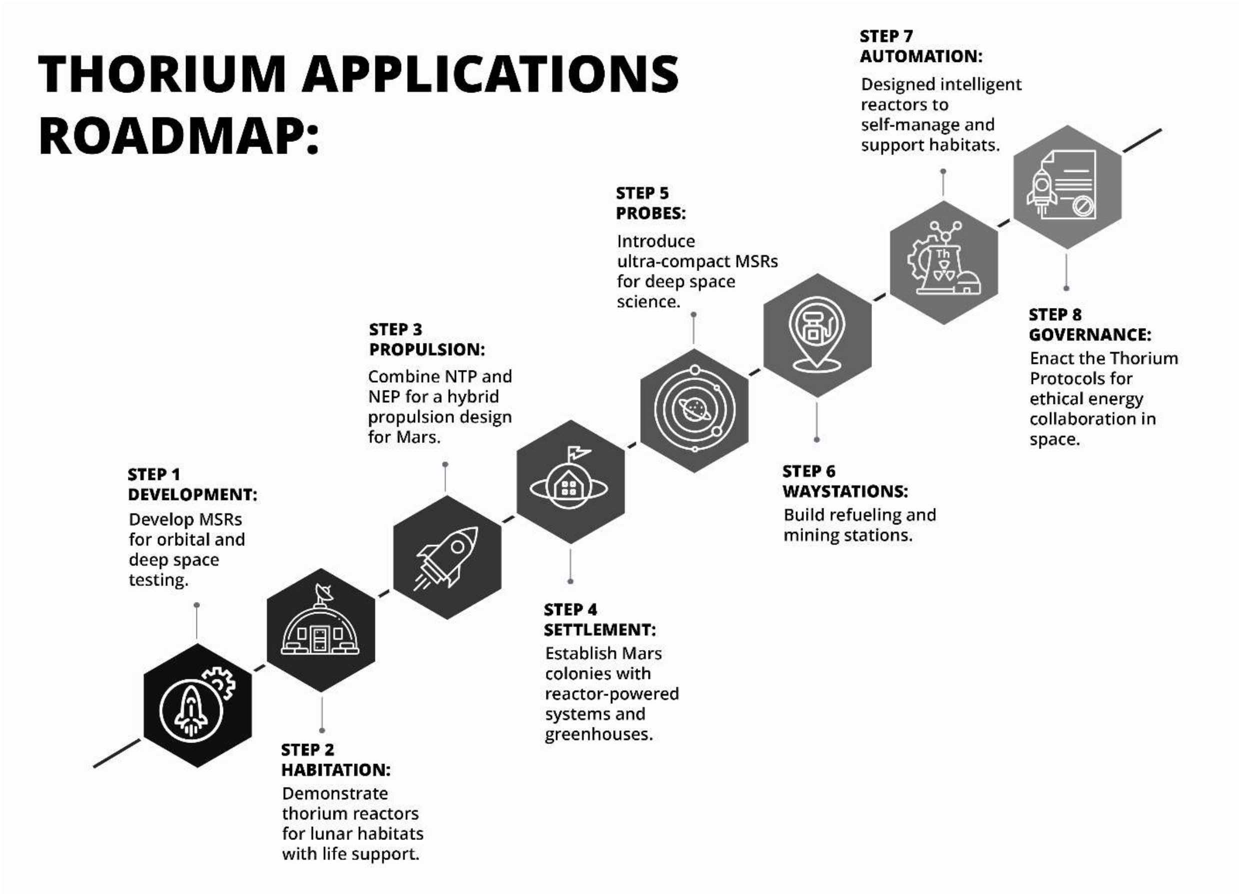
> *"Now, I spent 10 years working at NASA… and we had to think about how we would provide energy for this very unique community. There's no coal on the Moon. No petroleum. No atmosphere. Solar power fails for two weeks during the lunar night. Nuclear energy was really the only choice."*
> *— Kirk Sorensen TED Talk, Thorium, an alternative nuclear fuel*[1]

A scalable, continuous power source is imperative in space. Thorium molten salt reactors (MSRs) can fulfill this role. To venture outward means building from scratch in one of the most hostile environments imaginable. Yet within this vacuum lies humanity's greatest opportunity not just to explore, but to establish, endure, and thrive as a space-based community.

In 2025, the US Presidential Executive Order 13972 promoted the development and deployment of small modular reactors (SMRs) for space exploration.

But what would deploying reactors in space involve? Citing the known facts and applying some speculative imagination, let's envision a future that uses thorium SMRs for various missions, taking bold steps from launch operations to establishing lunar colonies, facilitating space travel to Mars, conducting mining, manufacturing for self-sufficiency, launching deep space probes and exploring beyond.

Space Thorium MSR Roadmap: Step by Step Development Framework



Step 1: Preparing for Launch: Engineering for the Void

The Vision

Space is an unforgiving realm. No air. No pressure. No gravity worth counting on. And most challenging for a power system: no atmosphere to convectively cool waste heat. These conditions necessitate a radical redesign of terrestrial energy systems before nuclear technologies, including MSRs, can safely and effectively operate beyond Earth.

Unlike pressurized water reactors (PWRs), which rely on high-pressure steam and heavy cooling systems, MSRs operate at atmospheric pressure and use a liquid fluoride salt mixture as both fuel carrier and coolant. This makes them an excellent candidate for space, provided several adaptations are made to account for the vacuum, radiation, and thermal dynamics of space.

The "Scalable Space MSR"

There are core technology enablers for optimizing thorium MSRs for space applications. To reduce repetition, we will refer to this as the "Scalable Space MSR," which supports modular scaling from 10 kW probe systems to multi-hundred-kW station hubs.

Here is the Scalable Space MSR reference architecture:

Fuel Composition: The reactor uses Thorium-232 with a U-233 starter load. It can start using a neutron source or cycles that are replenished with resources from in-situ utilization (ISRU).

Coolant: The coolant is FLiBe (a mixture of lithium fluoride and beryllium fluoride), which can operate steadily at about 700°C.

Containment Materials: We use Hastelloy-N or similar corrosion-resistant alloys. The system is designed to be unpressurized.

Moderator: We use either a graphite array or a salt-embedded moderation system, depending on the reactor's size.

Power Conversion: The reactor converts power using a Brayton cycle, which is preferred, or a Stirling engine in a closed-loop system.

Thermal Management: It features high-emissivity radiators with sodium heat pipes or liquid metal loops to manage heat.

Passive Safety: The reactor features a drain system with a freeze plug, designed to operate safely in zero or low gravity environments.

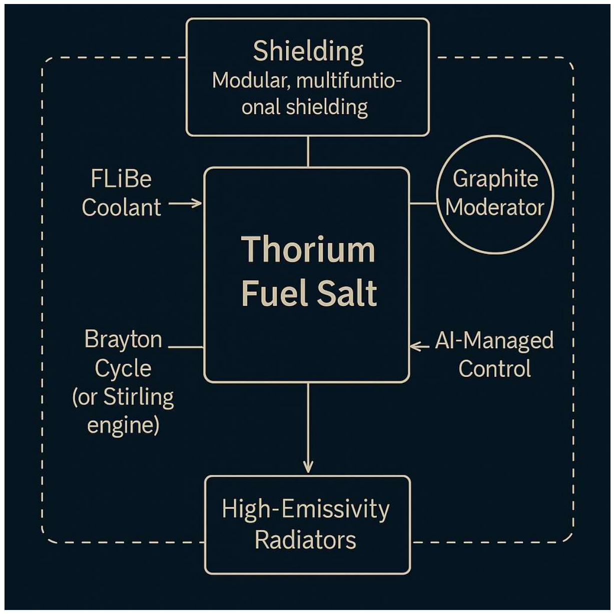
Autonomous Control: An AI system manages the operation of the reactor and provides predictive diagnostics.

Redundancy: There are dual coolant pumps and drain reservoirs that can be switched out while operating.

Shielding: The reactor uses modular shielding that can include water tanks or barriers made from regolith (the dust and broken rock on the Moon or Mars).

The graphite moderator helps to use neutrons more efficiently, allowing more efficient use of fuel and reducing the amount of fissile material required. FLiBe coolant has good thermal stability and low vapor pressure, which helps it transfer heat effectively in a vacuum. Together, these choices support compact, modular, and autonomous operation, ideal for space applications.

Scalable Space MSR Architecture



The "Space Tech Toolkit": Starting Points of Technology Applicable to Space

To support a space architecture powered by thorium and designed for multiple environments, here is a "Space Tech Toolkit" that categorizes key space technologies by their functions. This toolkit of enabling technologies will be helpful for the rest of this chapter.

1. Reactor and Fuel Systems

NASA Kilopower[2]: Demonstrated small-scale, autonomous uranium fission reactors (1–10 kWe) with Stirling engines and passive startup.

Copenhagen Atomic's molten salt reactors[3] are compact enough to fit inside a standard 40-foot shipping container, but powerful enough to produce around 100 megawatts of thermal energy at high temperatures and low pressure.

NASA Fission Surface Power (FSP)[4]: Producing scalable 40 kWe systems with commercial partners; adaptable to future thorium and molten salt designs.

CNSA (China)[5]: Early-stage development of 1 MWe class reactors with stated thorium MSR ambitions for planetary bases.

ESA Moon/Mars MSR Studies[6]: Emphasizing salt chemistry, high-temperature radiator integration, and transportability.

2. Heat Rejection and Thermal Management

Project Pele and Kilopower: Both incorporate passive thermal transport and radiator loop testing.

ESA Feasibility Studies: Focused on low-gravity radiator efficiency and modular heat loop design.

3. AI and Autonomous Control Systems

Kilopower Prototype: Demonstrated autonomous startup and shutdown sequences.

SpaceX Starship Avionics: Advanced real-time fault detection and machine-learning-based control algorithms.

NASA VIPER & DART Missions: Onboard navigation and obstacle avoidance via AI guidance.

4. Fuel Handling and Salt Chemistry

Los Alamos National Laboratory[7]: MSR corrosion studies and salt purification research inform ISRU-compatible designs.

Oak Ridge National Laboratory (historical)[8]: Original source of MSR fuel loop and reprocessing experimentation.

5. Robotics and Mobility Platforms

Anduril Industries[9]: A leading developer of autonomous defense and mobility systems, including AI-powered drones and sensor platforms with potential for planetary adaptation.

Palladyne AI (formerly Sarcos Robotics): Now focused on AI software to support intelligent robotic behaviors and perception in mobile platforms.

Boston Dynamics[10]: Produces adaptable terrestrial robots capable of dynamic movement and terrain navigation.

Tesla Optimus[11]: In March 2025, Elon Musk announced a plan to send a Tesla Optimus humanoid robot to Mars onboard a SpaceX Starship in 2026. Optimus is designed for multi-role automation and mobility in harsh environments.

VIPER Rovers[12] & NASA Artemis[13] : Lunar rovers designed for drilling, regolith handling, and volatile resource extraction.

6. In-Situ Manufacturing and Additive Fabrication

Relativity Space: Demonstrating launch-grade 3D printing of rocket structures; scalable to field-fabricated infrastructure.

NASA ISRU PROGRAMS: INCLUDING REGOLITH-BASED PRINTING, SINTERING, AND CLOSED-LOOP PARTS MANUFACTURING.

7. Power Conversion Systems

KILOPOWER: USES STIRLING ENGINES WITH PROVEN CONVERSION EFFICIENCIES.

PROJECT PELE: INTEGRATING CLOSED BRAYTON CYCLE TURBINES FOR MODULAR POWER SCALING.

8. Launch and Payload Integration

SPACEX & BLUE ORIGIN: DEVELOPING LARGE-VOLUME PAYLOAD PLATFORMS AND ROBOTIC DEPLOYMENT SERVICES FOR NUCLEAR PAYLOADS.

INTUITIVE MACHINES: SPECIALIZING IN LUNAR AND PLANETARY CARGO DELIVERY SYSTEMS.

This toolkit provides a structured reference for each step in the thorium MSR development roadmap. Technologies cited are real, demonstrated, or in active prototype development, and provide a tangible launchpad for space-rated reactor infrastructure.

Space Tech Toolkit Capability Readiness Matrix

Capability	Readiness Level
Reactor and fuel systems	Prototype stage
Heat rejection and thermal management	Prototype stage
AI and autonomous cotrols	Operational
Fuel handling and salt chemistry	Early pathinding
Power conversion systems	Prototype stage
Launch and payload integration	Speculative but plausible

The Mission

Demonstrate MSR operations in Earth orbit and deep space analogs. Develop power generation systems and life support modules that rely entirely on MSRs in zero-gravity, zero-atmosphere conditions.

Power Load Requirements

Scalable Space MSR: Scale 10-40 kWe demonstration units for orbital and cislunar testbeds.

Relevant Space Tech Toolkit Capability

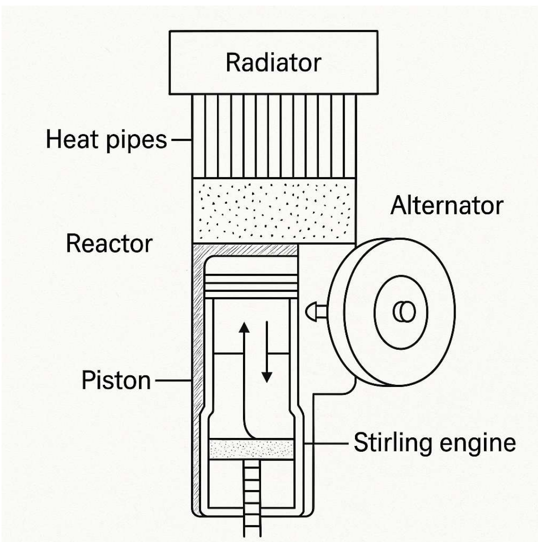
Reactor and Fuel Systems: NASA's Kilopower is in operation, while Copenhagen Atomic's reactors and NASA's FSP are still in the prototype stage.

Heat Rejection and Thermal Management: Project Pele's radiator testing reached prototype stage, and ESA is studying radiator concepts.

AI and Autonomous Controls: Kilopower's startup protocols and SpaceX's avionics are both operational.

Power Conversion Systems: The Kilopower Stirling engines are operational, while Pele's Brayton cycle turbines are in the prototype stage.

Stirling engine for NASA Kilopower



Launch & Integration: SpaceX and Blue Origin can handle payloads effectively, as they are both operational.

Innovation Needed

In a vacuum, heat can only be removed through radiation, which is heavily dependent on temperature. Modular MSRs, with outlet temperatures around 700°C, have a significant advantage over lower-temperature systems, such as pressurized water reactors (PWRs) or radioisotope thermoelectric generators (RTGs). Their higher operating temperature allows for more efficient radiative cooling. However, effective heat rejection still requires optimized radiator systems. Radiator fins or looped sodium heat pipes will need to be designed for weight, surface area, and dust resilience, especially on the Moon, where sharp regolith particles can degrade performance over time.

Let's compare the available power source options:

Space Power Sources: Solar vs RTG vs. Thorium MSR

Power Source	Efficiency	Output	Mass/Volume	Maintenance	Notes
Solar	Variable (5–25%)	Limited by insolation	Large surface area	Needs dust removal, battery storage	Ineffective during lunar night or Mars dust storms
RTGs	~6%	Low (100–500 W)	Compact	Fixed output, no moving parts	Best for deep space; insufficient for habitats
MSRs (Thorium)	~40–45%	Scalable (kW to MW)	Compact/modular	Passive safety, autonomous	Operates during lunar night; adaptable to all environments

A Reactor for the Final Frontier: Designing a Space-Rated MSR

Picture this: a molten salt reactor, humming quietly on the surface of the Moon. Or orbiting silently above Mars, powering life support systems and scientific instruments in the vacuum of space. But here's the catch: we can't just take a reactor designed for Earth and launch it into orbit. Space is a hostile, unforgiving place. No atmosphere. No gravity. No second chances. That's why space-rated molten salt reactors need a fundamental redesign from their Earth-bound cousins.

There are six key adaptations needed to make a molten salt reactor function in space.

First, there's the challenge of containment. On Earth, reactors are built to handle pressure. In space, we flip the script. These reactors must operate at atmospheric pressure, using an advanced alloy called Hastelloy-N. Why? Because it resists corrosion from the reactor's molten fluoride salts, even after years of high heat and radiation.

Second, we need fuel flexibility. A space MSR will use thorium-232 as the primary fuel, but to get things started, it carries a small charge of uranium-233. To ensure reliable startup in microgravity, optional neutron sources may be added as well.

Third, there's thermal management. On Earth, we get rid of waste heat through air and water. But in space? There's no air. So we rely entirely on radiation: literally radiating heat away into the black void. This means building massive radiator arrays using heat pipes filled with sodium or other liquid metals. These radiators have to be efficient, dust-resistant, and built to last.

Fourth, coolant circulation. Gravity-fed systems won't work in zero-g. So, we turn to mechanical or electromagnetic pumps to keep the coolant flowing and the core stable.

Fifth, we need to design for passive safety, even in microgravity. On Earth, molten salt reactors rely on a freeze plug, essentially a solid stopper that melts if the reactor overheats, allowing the fuel to safely drain. In space, that mechanism must work without gravity. That means engineering a zero-g-compatible freeze plug that functions reliably in all orientations.

And finally, we come to autonomy. There are no maintenance teams floating outside Jupiter. These reactors must run themselves. That means AI-driven control systems, predictive maintenance software, and remote diagnostics, all hardened against space radiation.

Without these six adaptations, even the best-designed MSR would be doomed in space. Our Scalable Space SMR design addresses every one of these challenges, including those in the reactor's secondary systems. Because adapting the core is only part of the job. The rest of the system needs a makeover, too.

Take heat rejection, for instance. On Earth, we rely on convection and conduction. In space, it's radiation or nothing. That's why our radiator panels are enormous, highly emissive, and designed to repel dust and micrometeoroids.

Power conversion? Forget steam turbines. In space, we favor Brayton or Stirling cycle engines: sealed, high-efficiency systems that work well in microgravity and don't rely on boiling water.

Materials and handling? There's no oxygen in space, so components must resist vacuum outgassing, that is when materials slowly shed molecules in a vacuum. Everything must stay structurally sound across extreme hot and cold cycles.

And then there's radiation shielding. It can't be static. It must be modular, maybe even dual-purpose. For example, we can design water tanks that provide shielding for the crew while also supplying the life support system.

All of this is more than just engineering. It's reimagining how we power civilization beyond Earth, one reactor at a time.

Adapting the Reactor's Unsung Heroes: The Secondary Systems

Designing the reactor core is only half the story. What often gets overlooked, but is just as critical, are the secondary systems. These are the support components that make the entire system work: the radiator panels, power converters, materials, and shielding. On Earth, they're built to work in a gravity field, surrounded by atmosphere. In space? Everything changes.

We will start with heat rejection, the most important and the most difficult challenge. On Earth, we get rid of heat through air and water, through convection. But in the vacuum of space, there is no air to carry heat away. There's only radiation. That means we need enormous radiator panels to shed the reactor's thermal energy. These panels must be lightweight but durable, highly emissive, and dust-resistant, especially if they're destined for the lunar surface or Mars, where fine regolith clings to everything. And because there's no wind or weather, their cooling performance must be entirely passive: no airflow, no fans, just pure infrared glow into the blackness.

Next, we come to power conversion. On Earth, we often use steam turbines in a Rankine cycle, turning boiling water into power. That won't work in space. Instead, we favor Brayton or Stirling cycles: closed-loop systems that run without water, without atmospheric pressure, and without gravity. They use compressible working fluids like helium or supercritical CO_2, cycling through expansion and compression chambers to spin a generator. These systems are sealed, silent, and capable of operating in low-gravity environments for years at a time.

Then there's the matter of materials and handling. On Earth, we take atmospheric oxygen for granted - it keeps most materials stable. In space, there is none. Materials outgas in vacuum, shedding molecules that can foul sensors or coat optics. Thermal expansion and contraction are more extreme, especially on the Moon, where surface temperatures can swing hundreds of degrees. So every gasket, pipe, and panel must resist corrosion, outgassing, and structural fatigue. Materials must be space-rated: designed to survive a wide thermal envelope, intense radiation, and years of wear in silence.

And finally, there's radiation shielding. In space, radiation doesn't come from just one direction. It comes from the Sun. From cosmic rays. From the reactor itself. So, shielding must be modular, directional, and multifunctional. What's a smart solution we can borrow from submarines? Water tanks that surround the reactor serve a dual purpose, acting as both life support and protection. Water is a phenomenal radiation absorber. So, while the crew uses it to drink and recycle, it can also block neutrons and gamma rays from the reactor. This type of dual-use engineering is essential in space, where every gram counts and every system must serve multiple purposes.

These adaptations are vital. Without them, even the best-designed reactor won't survive the rigors of launch, orbit, or off-world operation. But with them, we enable crew to live, work, and thrive beyond Earth.

Towards a Space Energy Architecture

Molten salt reactors are crucial for creating self-sustaining outposts and enabling advanced activities such as in-situ resource utilization (ISRU), manufacturing in space, and deep-space missions. To move forward, we need to establish testing platforms for MSRs in orbit, integrate these habitats autonomously, and develop systems that share fuel and heat effectively with other technologies. It's also essential to create multinational regulations to oversee these efforts. By investing early in space-rated thorium MSRs, companies and agencies can position themselves at the forefront of a future energy economy that spans multiple planets.

Now that we've identified a technology baseline, we are ready for launch.

Step 2: The Moon Colony

The Vision

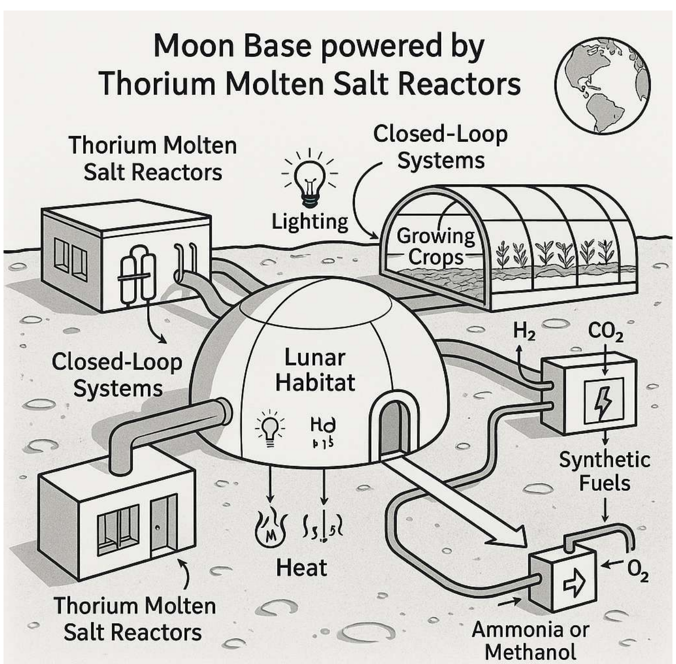
Imagine the Moon - silent, desolate, but not lifeless. In a crater near the lunar south pole, a steady light glows from a self-sustaining habitat. Beneath a meter of regolith shielding, a thorium MSR hums quietly, supplying warmth, light, and life. A nearby rover returns from an in-situ thorium deposit, soon to be processed into reactor fuel.

This vision echoes what Kirk Sorensen once described:

> *"Thorium is also common on the Moon and easy to find. Thorium has an electromagnetic signature that makes it easy to find, even from a spacecraft. With the energy generated from a liquid fluoride thorium reactor, we could recycle all of the air, water, and waste products within the lunar community. Doing so would be an absolute requirement for success. We could grow the crops needed to feed the members of the community even during the two-week lunar night, using light and power from the reactor. It seemed like the liquid fluoride thorium reactor, or LFTR, could be the power source that could make a self-sustainable lunar colony a reality." —Kirk Sorensen, TED Talk*[1]

Inside the habitat, the crew wakes up to warm, filtered air and purified water. Greenhouse crops thrive under LED arrays warmed by low-grade reactor waste heat. Closed-loop systems manage CO_2 levels and recycle air and water to sustain a carbon-neutral biosphere. During the two-week lunar night, when temperatures plummet and sunlight vanishes, the reactor ensures the lights stay on and life endures. Outside, robots 3D-print new structures from sintered regolith while the AI-guided MSR manages neutron flux, thermal gradients, and system diagnostics.

Moon Base Powered by Thorium Molten Salt Reactors



The Mission

Deploy thorium MSRs on the Moon to power long-duration lunar habitats. Demonstrate sustainable life support, in-situ fuel potential, and closed-loop environmental controls under continuous reactor operation.

Power Load Requirements

Lunar habitats require at least 40 kWe to maintain operations during the lunar night, including:

- Lighting, air circulation, heating, and fluid systems for habitability
- Greenhouse systems for crop production
- Electrolysis units for oxygen generation and water reclamation
- Communications arrays for Earth transmission
- Robotic systems and 3D printers
- Reactor control and monitoring systems
- Scalable Space MSR: Scale to 40–100 kWe for long-duration lunar base operations.

Prefueled with thorium-232 and seeded with U-233, this compact reactor would deliver continuous heat and electricity. The system would be autonomous, radiation-hardened, and optimized for low-maintenance operation.

Relevant Space Tech Toolkit Capability

Reactor and Fuel Systems: Kilopower is active and provides 1 to 10 kilowatts. Copenhagen Atomic's reactors and NASA's FSP are still prototypes.

Heat Management: Project Pele's high-temperature loops reached prototype stage.

AI and Controls: SpaceX's avionics and NASA's DART AI are currently active.

Power Systems: Kilopower Stirling is active, while the Brayton cycle is still a prototype.

Launch and Integration: SpaceX Starship cargo systems are active.

NASA is actively developing compact fission surface power systems to deliver baseline energy for lunar operations. The initial focus is on HALEU-fueled systems, but molten salt and thorium fuel cycles are gaining attention.

India's Chandrayaan-1 mission confirmed thorium-rich regolith, making in-situ thorium utilization (ISRU) a future possibility.

The European Space Agency's Moon Village concept and a 2021 ESA-funded feasibility study have also examined molten salt thorium reactors for lunar deployment, highlighting thorium's thermal efficiency and abundance.

International consortia and private ventures are exploring high-temperature molten salt microreactors for space applications. NASA's Kilopower project, in partnership with the Department of Energy and Los Alamos National Laboratory, successfully demonstrated the viability of small fission reactors for space. Although current designs use uranium-235, the modular molten salt architecture offers a foundation for future thorium variants.

The Artemis program's[13] long-term vision includes the Artemis Base Camp, as outlined in NASA's 2020 "Plan for Sustained Lunar Exploration and Development" and the 2022 "Moon to Mars Objectives." The plan calls for:

A crew habitat at the lunar south pole
40 kWe-class fission power systems
Pressurized and unpressurized rovers
Systems to extract water ice and generate oxygen
Integrated communications and scientific payloads
A dependable fission power system is critical for surviving the 14-day lunar night, when solar arrays are nonfunctional and batteries are insufficient.

Our concept design for a Scalable Space MSR would meet the Artemis Base Camp requirements. The next challenging step is to adapt the Scalable Space MSR into a propulsion system.

Step 3: The Journey to Mars: Advanced Nuclear Propulsion

The Vision

To bridge the vast and unforgiving distance between Earth and Mars, propulsion systems must advance beyond traditional chemical rockets. Two promising technologies are leading this new era.

Nuclear Thermal Propulsion (NTP) heats hydrogen propellant to over 2,500°C, allowing for high-thrust maneuvers with three times the efficiency of conventional rockets. Meanwhile, Nuclear Electric Propulsion (NEP), powered by a thorium MSR, generates continuous electricity for ion engines, enabling sustained acceleration over months with unparalleled fuel efficiency.

This spacecraft functions as a self-sustaining habitat. A rotating ring simulates Mars's gravity (0.38 g) and supports closed-loop life support systems, including electrolysis, CO_2

scrubbing, and water reclamation. At the ship's core lies the MSR, which channels heat through molten salt loops to radiator wings that glow as they dissipate thermal energy into space.

Lessons learned from lunar missions have equipped us to manage heat rejection, radiation shielding, and autonomous system control, capabilities that are now integrated into this craft designed for deep space exploration.

The Mission

Deploy a dual-mode, MSR-powered deep-space transport that combines NTP for high-thrust burns and NEP for continuous ion drive, aiming to complete Mars transit in under 150 days. The same reactor must power habitat life support, scientific labs, and communications while sustaining propulsion through varying mission phases.

Power Load Requirements

Subsystem Power Draw	**(kWe)**
Life Support, Habitat Ops	25–30
Artificial Gravity, Guidance	5
AI, Navigation, Data Systems	8–10
Science & Experimentation Labs	10
Communications (Laser + RF)	5–8
Ion Propulsion (NEP)	150–250
Thermal Pumps, Heat Transfer	3–5
Total Continuous Load	210–320

Scalable Space MSR: Scale to 250 kWe hybrid for NTP and NEP propulsion stack.

During NEP cruise, propulsion dominates the load. For rapid maneuvers or orbit insertion, NTP pulses are used independently, requiring short-term thermal management via reactor bypass systems.

Relevant Space Tech Toolkit Capability

Reactor and Fuel Systems: Kilopower is operational and provides 1 to 10 kilowatts of power. Copenhagen Atomic’s reactor is in the prototype stage, and NASA's FSP is also in the prototype stage.

Heat Rejection and Thermal Management: Project Pele's high-temperature loops reached the prototype stage.

AI and Autonomous Controls: SpaceX's avionics and NASA's DART AI systems are operational.

Power Conversion Systems: The Kilopower Stirling system is operational, while the Brayton cycle is still in the prototype stage.

Launch and Integration: SpaceX Starship cargo systems are operational.

Notably, Russia's Zeus (Transport and Energy Module), under development by Roscosmos, aims to use a fission reactor to power Hall-effect thrusters for interplanetary missions[14]. Though still in the concept stage, Zeus has received funding and could evolve toward molten salt or hybrid designs[15]. In the U.S., NASA and DOE's Kilopower and Fission Surface Power projects are advancing compact fission reactors in the 1–40 kWe range. DARPA's DRACO program[16], led by BWXT[17] and Lockheed Martin[18], focused on NTP systems for cislunar operations, with potential extension to Mars-class missions.

Innovation Needed

To make the Scalable Space SMR design work for space travel, it must use a hybrid propulsion approach that combines two types of nuclear power: nuclear thermal propulsion and nuclear electric propulsion. NTP utilizes a fission reactor to heat hydrogen, providing high-thrust burns, while NEP uses the same reactor to generate electricity for ion engines during prolonged space missions.

The thorium-fueled MSR creates fissile uranium-233, which produces heat for the Brayton cycle. This provides the electricity needed to power onboard systems, including ion thrusters. In the NTP process, hydrogen is heated in the reactor core and then expelled through a nozzle to generate thrust. This hybrid system supports NTP thrust bursts using heated hydrogen and NEP through ion thrusters, combining the rapid maneuverability of thermal propulsion with the endurance of electric drive.

To realize this hybrid platform, six major advancements are required:

1. **Multi-Mode Reactor Throttling** – Enable reactors to switch between steady-state electric generation and pulsed high-thrust operations.
2. **Microgravity Brayton Cycle** – Turbines with magnetic bearings, non-lubricated seals, and low-gravity vibration damping must be validated in space.
3. **Radiation-Hardened Autonomy** – AI systems must manage all spacecraft operations with minimal Earth input, including power arbitration and failure prediction.
4. **Scalable Ion Propulsion** – Ion thrusters must evolve to megawatt-class power levels (vs. current 2–7 kWe) to utilize the full potential of MSRs.
5. **Thorium Fuel Logistics in Space** – Reactor salt chemistry and waste isolation must be adapted for microgravity, with robotic maintenance capability.

6. **Multifunctional Shielding** – Use mission-critical components (e.g., water tanks, food storage) as part of radiation shielding to reduce mass.

This NEP-NTP hybrid modification of the Scalable Space SMR is entirely fission-based.

Looking Ahead: Fission-Fusion Upgrade

A far-future propulsion alternative merges the strengths of fission and fusion into a single integrated system, offering the potential for deep space travel at unprecedented speeds and efficiencies. In this hybrid design, a compact thorium-based fission reactor provides continuous electrical power for life support, navigation, and fusion reactor ignition, while a fusion drive, such as a deuterium-tritium or deuterium-helium-3 system, delivers bursts of ultra-high specific impulse for fast interplanetary or even interstellar transit. The fusion stage provides the propulsion muscle, producing thrust through the controlled reaction of light nuclei, while the fission stage ensures steady baseline power and eliminates the need for massive solar arrays or chemical fuel reserves. Benefits include vastly reduced transit times to Mars and beyond, superior fuel efficiency, reduced radiation shielding needs (through smart directional exhaust), and a scalable architecture for robotic or crewed missions. This system, currently speculative, could redefine mission profiles across the solar system, enabling rapid return flights, dynamic rerouting, and the possibility of true off-world expansion.

Step 4: Mars: The Forge of New Worlds

The Vision

Mars is distinctly different from the Moon. It has an atmosphere composed of carbon dioxide, and although it receives sunlight, it also experiences dust storms that can last for weeks, obscuring solar energy.

Wind whips across the surface, scattering dust that clings to the solar panels, but the nuclear reactor operates without interruption. On Earth, a power outage is merely an inconvenience; on Mars, it can be a matter of life or death.

The energy demands here are substantial: 30 kW for life support, 60 kW for industry, and 20 kW for agriculture. At the heart of the settlement, two MSRs glow within basalt casings. One reactor powers an oxygen extraction facility, water systems, and a greenhouse dome, while the other operates a sintering furnace that transforms Martian dust into load-bearing bricks and tiles for roads and shelters.

Beneath a dome, spinach grows in CO_2-enriched air warmed by reactor waste heat. Outside, autonomous rovers 3D-print spare parts from locally sourced materials. This is not just about survival; it represents the farthest outpost of human existence.

The Mission

Establish dual-reactor hubs to support agriculture, regolith processing, and oxygen extraction on Mars. Validate the startup procedures of autonomous reactors and develop long-term safety protocols to ensure they function effectively under Martian conditions. Enhance manufacturing and self-sufficiency by utilizing thorium MSRs to power on-site production of spare parts, infrastructure, and radiation shielding. Integrate 3D printing, sintering, and in-situ resource utilization-fed fabrication lines for use on Mars and beyond.

The Power Load Requirements

Here, power demands are higher to include more industrial support. Establish a 120–150 kWe thorium MSR system to support a full-scale Martian outpost. This includes:

30 kWe for habitation systems
60 kWe for ISRU and regolith processing
20 kWe for greenhouses and hydroponics
Additional capacity for rovers, sensors, and comms

Scalable Space MSR: Scale to 120–150 kWe distributed across two 80 kWe units. The two 80 kWe MSRs provide built-in redundancy, ensuring the colony remains operational even during equipment servicing or unexpected events.

Relevant Space Tech Toolkit Capability

Reactor and Fuel Systems: CNSA 1 MWe initiative (Concept Design), ESA MSR studies (Concept Design), NASA FSP (Prototype stage).

Heat Rejection and Thermal Management: ESA heat transfer concepts (Concept Design).

AI and Autonomous Controls: NASA DART & SpaceX avionics (Operational).

Robotics: Boston Dynamics/Palladyne AI for mobility and handling (Operational).

In-Situ Manufacturing: NASA ISRU additive fabrication and sintering (Prototype stage).

Fuel Handling: Los Alamos salt chemistry research (Prototype stage).

China's CNSA has announced plans to develop a 1 MWe-class nuclear power system for lunar and Martian bases. This includes thorium MSRs in early-stage designs and aligns with the Chinese Academy of Sciences' focus on long-term, self-sustaining habitats.

The European Space Agency (ESA) has evaluated MSR concepts in its Moon and Mars initiatives, emphasizing modularity, transportability, and safety in radiation-rich, low-gravity environments.

Private firms, such as Oklo[19] and Ultra Safe Nuclear Corporation (USNC)[20], are advancing microreactor platforms originally designed for terrestrial deployment. These designs, while currently based on HALEU fuel, are being explored for Martian adaptation and may incorporate molten salt thorium variants in future iterations.

Innovation Needed

To realize a thorium-powered Martian settlement, we must bridge critical engineering gaps across multiple domains: reactor design, materials science, heat management, autonomous systems, and resource integration. The following innovations are essential to adapt MSR technology for the harsh, isolated, and resource-limited conditions of the Red Planet.

Reactor Miniaturization and Autonomy: MSRs must be compact enough for transport aboard vehicles like SpaceX's Starship and capable of autonomous startup and operation. This includes AI-managed systems, thermal regulation, and passive safety engineered for Martian conditions like CO_2 frost and abrasive dust.

Molten Salt Chemistry in Martian Conditions: Molten salt flow in 0.38g gravity remains untested. Engineers must model and validate flow dynamics, thermal expansion, and salt chemistry in reduced gravity. Materials like Hastelloy-N must resist both thermal cycling and Martian environmental wear. If thorium is to be sourced locally, ISRU-based extraction and processing systems must be autonomous and dust-resilient.

Compact Heat Rejection: Radiative cooling is the only viable method on Mars. Radiator panels must be high-emissivity, foldable, and self-cleaning to shed dust. Future systems may use electrostatic or phase-change tech to optimize heat dissipation in space.

Shielding and Habitat Design: With no protective magnetosphere, Mars requires robust radiation shielding. Sintered regolith bricks, underground reactor placement, and multipurpose shielding (like water tanks) must all be designed for robotic assembly prior to crew arrival.

MSR–ISRU Integration: The synergy between reactor waste heat and ISRU systems is critical. Thermal energy can power regolith-based oxygen extraction, brick manufacturing, and water electrolysis. Standardized interfaces are needed to couple reactors with these components in modular, serviceable architectures.

Building with Local Resources

Thorium-powered systems offer not only energy but infrastructure. With access to Martian CO_2, regolith, and ice, MSRs could power reactors that extract oxygen, metals, and water for use in construction, life support, and even synthetic fuel production. Structures, tools, spare parts, and shielding could be manufactured on-site, reducing launch mass and supporting a self-sufficient colony.

Synthetic Fuel Production

Using CO_2 from the Martian atmosphere and hydrogen from buried ice, reactors could enable local synthesis of fuels such as methane, ammonia, or methanol. These would power rovers, heat greenhouses, and even provide propellant for return flights, supporting full-cycle energy independence.

A Future Hybrid Fission-Fusion Solution?

Looking further ahead, a base could adopt a hybrid system: thorium MSRs providing a steady energy baseline, supplemented by compact fusion reactors for peak loads, such as intensive regolith processing, industrial-scale 3D printing, or expanded habitation during crew rotations. Both systems could share a common FLiBe loop for tritium breeding and thermal integration, enhancing redundancy and operational resilience. This hybridization would represent a major step toward energy self-sufficiency on Mars and beyond.

A Springboard to Deep Space

Mars is unforgiving of errors, leaving no margin for improvisation. This characteristic establishes it as the ultimate testing ground for innovation. The implementation of thorium MSRs on Mars represents not only an engineering challenge but also a bold declaration of our intent: to survive, adapt, and flourish as a base that nurtures new technologies while serving as a launching pad for further space exploration.

Step 5: Deep Space Reach: Miniature Reactors for Outer Planet Probes

The Vision

As humanity's ambitions extend beyond the inner solar system, our power systems must evolve accordingly. The Voyager probes ventured into the depths of space relying on diminishing plutonium heat. However, the next generation of deep space missions will require significantly more: greater power, more extended longevity, and enhanced capabilities. Miniature thorium MSRs, approximately the size of a barrel, can provide power to these probes for 30 to 50 years. This would enable them to support instruments capable of mapping subsurface oceans on Europa, analyzing hydrocarbons on Titan, or scanning exoplanet atmospheres from the far reaches of the Kuiper Belt. These probes will act as self-sustained outposts of intelligence, silent scouts that continuously stream scientific data and fill in the edges of our exploration map.

The Mission

Develop ultra-compact thorium MSRs and deployable heat rejection systems for long-duration scientific probes beyond Jupiter's orbit. Enable high-data-rate communications, sustained onboard science, and electric propulsion in regions where solar power is no longer viable.

The Power Requirement

Beyond the asteroid belt, solar irradiance drops below practical thresholds. Meanwhile, plutonium-238, used in RTGs, is rare and expensive. Miniaturized thorium MSRs offer a scalable, abundant alternative capable of providing 10–20 kWe continuously. This output could support:

- Long-range ion propulsion for station-keeping or orbital insertion
- Ground-penetrating radar for icy moon exploration
- Spectroscopy payloads for biosignature and exoplanet detection
- Quantum-encrypted communications or high-gain optical relays
- Radiothermal heating to protect systems in deep cold
- Scalable Space MSR: Scale to 10–20 kWe ultra-miniaturized probe MSRs.

This steady, autonomous energy supply could extend scientific operations for decades, making possible multi-target missions that were previously unthinkable.

Relevant Space Tech Toolkit Capability

Reactor and Fuel Systems: The Kilopower[2] Stirling cycle is currently operational, demonstrating effective power generation. Additionally, design studies for fission microreactors are underway as part of early pathfinding efforts in advanced nuclear technology.

Heat Rejection: Compact radiator concepts that focus on efficient heat dissipation, currently at the concept design stage to optimize performance for future systems.

Power Conversion Systems: Stirling systems are operational and effectively converting thermal energy into electrical power, showcasing reliable technology for space and terrestrial applications.

AI and Autonomy: AI diagnostics specifically tailored for Earth-based fission platforms are presently in the prototype stage, aiming to enhance safety and operational efficiency.

Most current deep space probes use radioisotope thermoelectric generators (RTGs), which generate less than 300 watts of electricity and operate at low efficiency (~6%). NASA's Next-Generation RTG (NGRTG)[2] program aims to improve performance, but output remains limited.

The Kilopower project has demonstrated 1–10 kWe reactors with Stirling conversion, but not yet at the miniaturized scale needed for interplanetary probes. Concepts for fission reactors below 100 kg total system mass remain unproven.

Russia's Zeus TEM project envisions higher-power space reactors but targets crewed transport rather than microprobe power systems. No current mission has yet flown a molten salt reactor in space, although laboratory research into compact fuel salts and microgravity-compatible containment is underway.

Innovation Needed

To realize thorium MSR-powered interplanetary probes, key innovations must be achieved:

Reactor Miniaturization: Shrink reactor mass to under 200 kg including shielding, radiators, and power conversion. Innovations in salt composition, shielding geometry, and compact Brayton or Stirling cycles will be critical.

Autonomous Start-up and Self-Regulation: Design reactors that can self-initiate and operate without human intervention for decades. AI-driven fault detection, fuel burnup tracking, and self-repair systems are essential.

Microgravity-Compatible Radiators: Deploy lightweight, high-emissivity radiator fins that work in deep space. Must handle freeze-thaw cycles, dust impacts, and radiation exposure over decades.

Dust-Hardened Electronics and Shielding: Probes must shield against galactic cosmic rays, solar flares, and micrometeoroids, while minimizing mass. Consider layered shielding using structural materials, regolith-inspired composites, or multifunctional insulation.

Long-Term Propellant Compatibility: Match reactor output with ion or Hall-effect engines capable of operating for years. Require ultra-long-life thrusters, xenon or alternative propellant storage, and thermal management integration with reactor systems.

Probes will Map the Waystations

Future deep space probes will be unmanned and powered by thorium energy. Equipped with miniature MSRs, these intelligent machines will quietly and tirelessly explore the cosmos, mapping resources that can be mined as waystations for deeper space exploration.

Thorium’s potential extends beyond reactors and resource resilience - it’s now being explored for cutting-edge quantum technology. In 2025, DARPA launched the SUNSPOT program (Sources for Ultraviolet Nuclear Spectroscopy of Thorium) to develop a next-generation nuclear clock based on a unique property of the thorium-229 isotope. Unlike atomic clocks, which rely on electron transitions, this clock would harness transitions within the nucleus itself, enabling precision timing that is more stable, less sensitive to environmental noise, and resilient enough for deep-space navigation or secure communications. Thorium’s nuclear structure is so well-suited to this purpose that researchers have focused specifically on its ultraviolet resonance near 148 nanometers; an elusive transition only now becoming accessible with advances in vacuum-ultraviolet laser technology. If successful, thorium could anchor an entirely new class of ultra-compact, radiation-hardened quantum timing systems. If researchers can tune a laser to this faint signal, they could create a tiny nuclear clock that stays accurate for decades, ideal for space probes, secure communications, and even GPS systems on the Moon or Mars. It’s one more way thorium could quietly shape the future of space exploration, not just by powering our journey, but by keeping it perfectly on time.

Step 6: The Working Frontier: Mining and Refueling Waystations

The Vision

On a carbon-rich asteroid in the Main Belt, a drill hums under the low gravity. Nearby, a chemical reactor splits carbon dioxide (CO_2) and hydrogen into methane fuel. Ice is harvested and then electrolyzed to produce oxygen and hydrogen. Metals are smelted from regolith. The power source for all this? A thorium molten salt reactor.

These facilities serve as the logistical backbone of interplanetary exploration. With thorium's stable and long-lasting energy output, these autonomous stations can operate as ISRU hubs, fuel depots, and resource factories. They provide propellant, oxygen, and raw materials to vessels traveling to Mars, the outer planets, or beyond.

Thorium decentralizes energy access, allowing each station or colony to function independently of Earth. This promotes international collaboration rather than competition. In a domain where no nation can lay claim to territory according to the principle established in the Outer Space Treaty of 1967, thorium-powered infrastructure levels the playing field, ensuring that all stakeholders have access to energy and resources.

From the shadow of Ceres to the orbit of Vesta, autonomous mining stations powered by compact MSRs will extract water, break down hydrocarbons, and refine metals. These modular installations will grow incrementally, enabled not only by thorium power but also by artificial intelligence, robotics, and additive manufacturing. Some will be crewed, while most will operate autonomously, powered by thorium cores and functioning with near-complete independence.

Today's robotic platforms, such as those developed by SpaceX or Boston Dynamics for use on Earth, could be adapted for microgravity excavation and ISRU tasks. What currently mows lawns and inspects launch pads may soon mine regolith and construct fuel tanks in space.

The Mission

Demonstrate thorium MSR-powered in-space mining operations and establish ISRU-driven refueling depots on asteroids and small planetary bodies. Prove the viability of autonomous, energy-independent infrastructure for fuel synthesis, metal extraction, and life support resupply.

The Power Requirement

Mining stations and ISRU platforms will require modular power systems scaled from 20 to 200 kWe, depending on activity:

20–40 kWe for basic robotic excavation, lighting, and communication relays
40–80 kWe for water electrolysis, CO_2 cracking, and cryogenic fuel storage
100–200 kWe for integrated operations with metal refining, additive manufacturing, and docking services for visiting spacecraft

Scalable Space MSR: Scale to 20–200 kWe scalable modular systems.

Each thorium MSR module must be compact, durable, and scalable, delivering uninterrupted power in harsh thermal and radiation environments.

Relevant Space Tech Toolkit Capability

Reactor and Fuel Systems: Copenhagen Atomic's containerized concepts are in the prototype stage.

Heat Rejection and Thermal Management: ESA is designing modular loops as a concept.

AI and Autonomous Controls: SpaceX and DART avionics are currently in operation.

Robotics and ISRU: Boston Dynamics and NASA are working on the VIPER project, which is in the prototype stage.

In-Situ Manufacturing: NASA is using additive fabrication, currently in the prototype stage.

Fuel Handling: Los Alamos is conducting chemistry research at the prototype stage.

Enabling Advancements Applicable for Space Mining

Many of today's technologies will mature and enable future space mining missions.

NASA's Lunar ISRU and VIPER Rover: Testing regolith mining and volatile extraction on the Moon

ESA's PROSPECT program: Volatile prospecting tools designed for autonomous drilling

SpaceX, Boston Dynamics, Anduril, and Palladyne AI Robotics: Terrestrial platforms with AI and mobility features that can be repurposed for remote space environments

Kilopower (NASA/DOE) and Copenhagen Atomics (commercial): Compact fission systems in development that serve as templates for scalable, thorium-capable systems

No mission to date has demonstrated ISRU at scale or integrated fission energy with mining operations in space, but the component technologies are converging.

Innovation Needed

Modular, Low-Mass MSRs: Thorium MSRs must be miniaturized for launch and surface deployment. Target reactor mass: under 500 kg, with integrated shielding and autonomous startup capabilities.

Fully Autonomous ISRU Systems: Mining and fuel synthesis must be AI-managed with limited human intervention. Autonomous robotics, error correction algorithms, and machine learning systems must coordinate excavation, processing, and maintenance.

Dust- and Radiation-Hardened Hardware: Asteroid environments are abrasive, cold, and irradiated. Power systems, pumps, seals, and electronics must be ruggedized for decades of operation without crewed service.

Energy-Integrated Chemical Reactors: CO_2 cracking, water electrolysis, and methane synthesis units must be thermally integrated with reactor waste heat for optimal efficiency. This requires standardized heat interfaces and real-time thermal balancing.

On-Site Additive Manufacturing: To achieve full logistical independence, ISRU systems must produce spare parts, tools, and replacement components via robotic 3D printing. This closes the supply chain loop and supports long-term mission sustainability.

Fueling the Exploration

The space economy will depend on logistics fueled by thorium. These mining and refueling outposts will enable humanity to expand throughout the solar system by harvesting, processing, and refueling with reactors. In this new frontier, thorium will serve as a key resource, supporting independence and powering waystations for our next big leap.

Step 7: Becoming Autonomous: New Tools for a New Era

The Vision

To move beyond Earth's orbit and stay there, our systems must become not just sustainable but intelligent. Autonomy is the key to permanence. In the harsh, remote environments of the Moon, Mars, asteroids, and deep space, the margin for error is razor thin. Real-time communication with Earth becomes infeasible due to delays. Crewed maintenance is limited by mass, cost, and survival constraints.

To meet these demands, we must equip reactors and support infrastructure with AI-driven autonomy, predictive diagnostics, and self-repair capabilities. Picture an MSR that senses microfractures forming in its containment wall, diverts flow, initiates robotic patchwork, and notifies Earth only when it's already resolved. Imagine a robotic 3D printing arms using sintered regolith to fabricate new shielding panels, drone swarms maintaining radiator arrays, and machine learning systems optimizing reactor output in real-time to match fluctuating loads.

Thorium MSRs will serve as more than power plants. Their high-grade heat can distill water, split molecules, produce breathable oxygen, and sterilize medical equipment. With the right systems in place, they could melt Martian ice, support atmospheric processing, and potentially aid in cryogenic stasis systems for crew preservation on interstellar journeys.

Autonomy extends to communications as well. Future data relays, especially laser-based optical links, will require 10-20 kW per node to maintain high-bandwidth connections across millions of kilometers. Only reactors can sustain the continuous, high-output energy that these systems demand.

The Mission

Design and deploy fully autonomous reactor control and maintenance systems that enable distant outposts to operate for years or decades without direct human oversight. These tools will serve as the operational backbone for AI-managed, self-repairing habitats and robotic scientific stations.

The Power Requirement

Autonomous systems require a continuous power supply across three tiers:

- Reactor Core Operation: 20–50 kWe for AI controls, cooling pumps, diagnostics, and reactivity control
- Peripheral Robotics: 10–30 kWe for 3D printers, manipulators, drones, and repair arms

Communications & Data Systems: 10–20 kWe for laser relays, satellite links, and onboard computing
Scalable Space MSR: Scale to 50–100 kWe per autonomous hub.

Scalable Space MSR: A single thorium MSR delivering 50–100 kWe can support an entire autonomous node with margin for redundancy and expansion.

Relevant Space Tech Toolkit Capabilities

AI and Autonomous Controls: Kilopower startup protocols (Operational), SpaceX Starship AI, (Operational)

Robotics: Boston Dynamics, Palladyne AI, ETH Zurich mobility platforms (Operational), Tesla Optimus mars announcement (2025) (Prototype).

In-Situ Manufacturing: NASA Regolith 3D Printing and Sintering (Prototype Stage).

Power Conversion: Kilopower (Operational), Brayton turbines (Prototype stage).

Communications Systems: High-Energy Laser Relays (Early Pathfinding).

Enabling Advancements Applicable for Autonomy

The technology enablers for autonomy can be found across industries. Here are some noteworthy developments:

NASA's VIPER and DART AI navigation systems: Demonstrate autonomous terrain navigation and obstacle avoidance

SpaceX Starship avionics: Built on real-time fault recovery and deep learning models

Boston Dynamics, Palladyne AI, and ETH Zurich robotics: Provide advanced manipulators and AI-guided mobility platforms

Kilopower and Fission Surface Power (FSP): Demonstrate modular, unattended reactor startup and shutdown protocols

These elements provide a robust foundation for building intelligent reactor systems that can detect, adapt, and recover from failure.

Innovation Needed

AI-Driven Reactor Control: Machine learning models must manage reactivity, temperature gradients, and neutron flux in real time. Algorithms need to process massive sensor datasets with zero-latency local decision-making.

Predictive Diagnostics: Systems must forecast failures before they happen, tracking corrosion, thermal fatigue, radiation damage, and coolant composition with high fidelity.

Robotic Self-Maintenance: Onboard tools should include robotic arms, microdrones, and modular repair kits. These systems must remove, print, and replace components on the fly without human assistance.

Autonomous Fabrication: Advanced 3D printing with local materials (e.g., regolith) will support part replacement, shielding upgrades, and thermal component replication, backed by AI-validated design libraries.

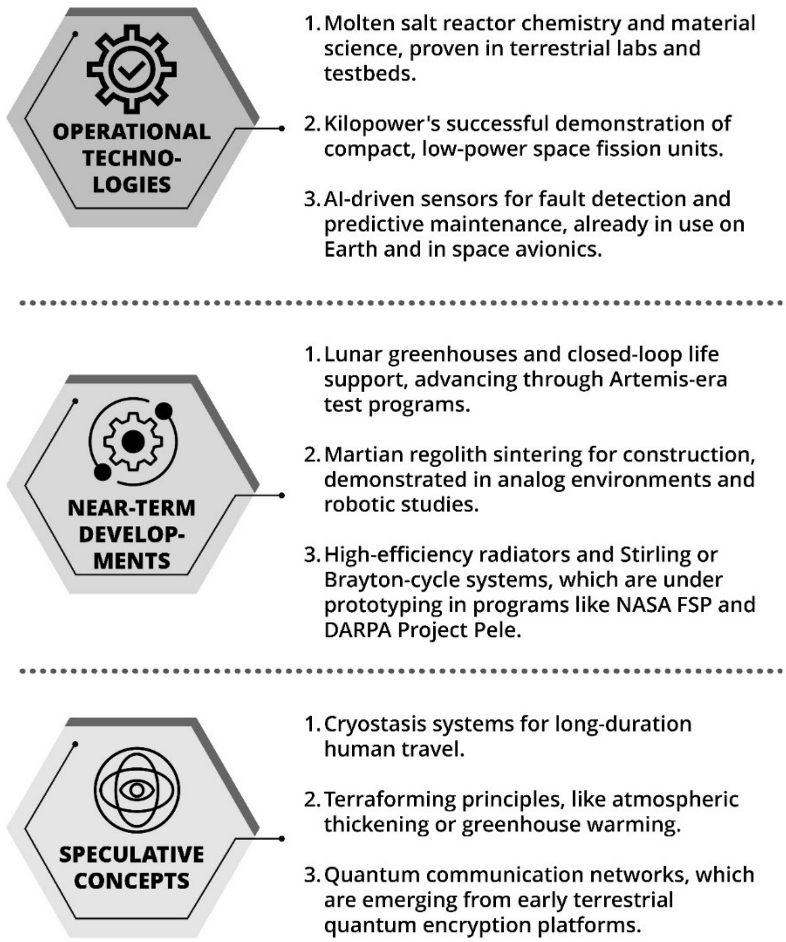
Secure and Resilient Communication: Autonomous nodes must use encrypted, fault-tolerant protocols to relay data, updates, and alerts to mission control across vast distances, even when Earth is temporarily out of reach.

Programmable Power: Imagine a future where nuclear materials can be turned up or down like a dimmer switch: decaying when we need energy, and quiet when we don't. That's the vision behind DARPA's Decay on Demand program. Announced in 2024, this research effort explores whether it's possible to speed up or control radioactive decay using precisely tuned beams of X-rays or other energy inputs. If successful, this could transform how reactors manage fuel and waste, especially in space. Instead of carrying large, passive isotope batteries, future missions could use compact fuel sources that release energy only when triggered. It could even allow reactors to reshape waste into safer or more useful forms on the fly. This level of control, deciding when and how fast a radioactive material decays, would be a game-changer, giving advanced thorium systems a new layer of intelligence. It means a system could not only generate power but adjust its fuel behavior based on mission demands, emergencies, or even habitat conditions. In the future, energy in space won't just be powerful; it could be programmable.

Autonomy for a Multiplanetary Future

Autonomy is vital for long term settlement in space. We require fully autonomous reactor control and maintenance systems capable of operating for years without human intervention. These systems will support AI-managed habitats and robotic stations. As humanity ventures beyond Earth, thorium-powered machines will not only function effectively but also adapt and self-repair, becoming essential for a multiplanetary civilization.

Technology Maturity Assessment



Step 8: Peace Through Power: Thorium as a Catalyst for Collaboration in Space

The Vision

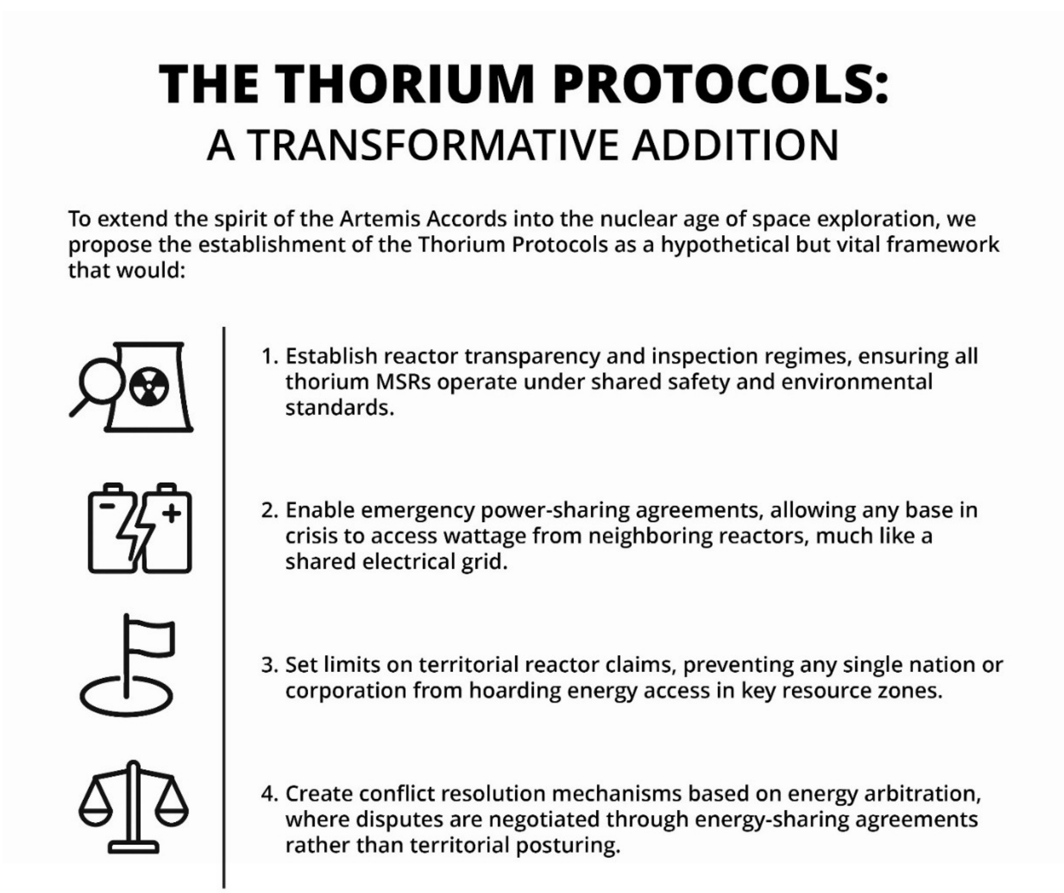
Throughout history, wherever scarcity has taken root, conflict has often followed. In the harsh frontiers of space, where life depends on continuous access to air, water, food, and power, the risks of resource-driven tension escalate. Yet, thorium molten salt reactors offer a unique opportunity to invert that dynamic. By decentralizing energy production, thorium enables every base, outpost, or vessel to operate independently, no longer reliant on Earth-bound fuel deliveries or vulnerable to energy monopolies.

Imagine colonies where energy abundance fosters diplomacy. Where settlements are not strategic vulnerabilities but resilient, autonomous communities. This vision requires more than technology; it demands policy.

The Artemis Accords: The Foundation

In the real world, the Artemis Accords[13], initiated by NASA in 2020, form a set of multilateral agreements that guide peaceful exploration and use of outer space. Signed by more than 30 countries, the accords promote principles such as transparency, interoperability, the sharing of scientific data, peaceful conflict resolution, and the responsible use of space resources. Critically, they emphasize cooperation over territorial control.

The Artemis Accords lay the groundwork for international collaboration, focusing primarily on surface activities, scientific exploration, and broad norms of behavior. What they do not yet address in detail is the governance of shared nuclear infrastructure, particularly the management, safety, and ethical use of high-power systems, such as MSRs.



From Scarcity to Solidarity

By removing the competition for fuel and solar access, thorium MSRs foster a new ethical paradigm, one where cooperation replaces conquest. Independent power generation no longer means isolation; it becomes the foundation of mutual resilience. In this world, energy is not a weapon. It is a guarantee of peace.

In the same way the Antarctic Treaty demilitarized the South Pole, the Thorium Protocols could de-weaponize energy in space. By promoting open access, reciprocal agreements, and cross-national oversight, these protocols could ensure that power systems become symbols of shared purpose, not domination.

The Mission

Foster international collaboration by sharing thorium energy systems. Turn power into diplomacy, ensuring that energy independence enables a cooperative, multinational human presence in space.

Power Load Requirements

Scalable Space MSR: 40–100 kWe shared infrastructure units per base.

Relevant Space Tech Toolkit Capability

GOVERNANCE FRAMEWORKS: THE ARTEMIS ACCORDS ARE CURRENTLY IN USE, WHILE THE THORIUM PROTOCOLS ARE A NEW AND PLAUSIBLE INTRODUCTION, BUT NOT YET IMPLEMENTED.

REACTOR AND FUEL SYSTEMS: KILOPOWER IS A WORKING SYSTEMS, WHILE COPENHAGEN ATOMIC'S REACTOR AND THE FSP IS IN THE PROTOTYPE STAGE.

AI AUTONOMY: KILOPOWER, DART, AND SPACEX HAVE OPERATIONAL AI SYSTEMS.

FUEL HANDLING & SAFETY OVERSIGHT: ORNL STANDARDS AND RESEARCH FROM LOS ` ARE IN THE PROTOTYPE STAGE.

INTEROPERABILITY ARCHITECTURE: THE SHARED LOGISTICS PROTOCOLS USED IN ARTEMIS-ERA PLANNING ARE IN THE PROTOTYPE STAGE.

Shaping a Collaborative Power Dynamic

Power has always shaped geopolitics. In space, it will shape civilization. With thorium as a steady flame and the Thorium Protocols as its guiding law, we can ensure that energy becomes the great equalizer, not the next great conflict.

International Partnerships in Nuclear Space Energy Development

Country / Region	Lead Agencies / Companies	Key Projects / Collaborations	Relevance to MSRs / Thorium
United States	NASA, DOE, DARPA, Westinghouse	Kilopower Project, Fission Surface Power, DARPA DRACO, Project Pele	Potential for small MSRs for lunar outposts and spacecraft propulsion
European Union (ESA)	ESA, CEA (France), Rolls-Royce (UK), Tractebel (Belgium)	Lunar power feasibility studies, nuclear microreactor design for ESA missions	Evaluating molten salt and solid-fuel space reactor options
China	CNSA, China Academy of Space Technology (CAST), SINAP	Space reactor roadmap, lunar base planning, 2030s nuclear space tug	Prototype MSR (TMSR-LF1) could be adapted for orbital power
Russia	Roscosmos, Rosatom	TEM "Zeus" space tug using nuclear electric propulsion	Fast reactors tested; thorium-compatible R&D in place
India	ISRO, BARC, Department of Atomic Energy	Moon and Mars missions with nuclear auxiliary power in concept stage	Long-term thorium expertise via AHWR may transfer to space platforms
Japan	JAXA, Mitsubishi Heavy Industries	Feasibility studies on nuclear thermal propulsion, space microreactors	Focus on compact and safe reactor design integration
South Korea	KARI, KAERI	Collaborating with US on SMRs and nuclear R&D for space	Thorium MSRs considered under long-range lunar power scenarios
Canada	Canadian Nuclear Labs, NB Power, Moltex	Regulatory leadership in SMRs; exploring off-grid deployment models	Salt reactor R&D relevant to off-planet systems
United Arab Emirates	ENEC, space partnerships via MBRSC	Potential for nuclear-enabled desalination + lunar interest through Artemis Accords	UAE's nuclear experience provides regulatory precedent

Peace through power is a system design, and a collaborative approach for how we build a future worth living in, together.

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