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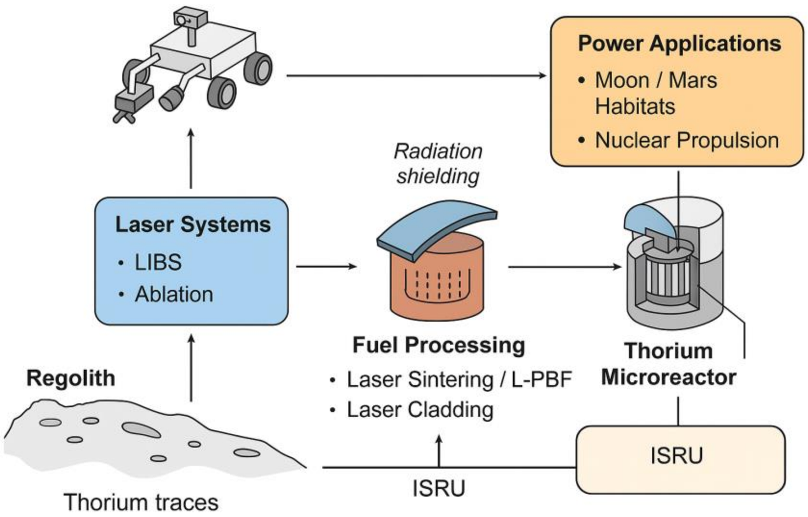
Laser-Based Thorium Processing and Utilization for In-Situ Nuclear Power Generation in Space Exploration: A Comprehensive Review

Aswin Karkadakattil*

Independent Researcher, India.

Abstract: The growing need for long-duration, high-density energy systems in space has revitalized interest in nuclear fission for extraterrestrial missions. Thorium (Th-232), with its favourable nuclear characteristics, long half-life, and planetary abundance, offers a promising alternative to uranium for compact, low-maintenance power systems on the Moon and Mars. Simultaneously, laser-based materials processing has emerged as a key enabler for precision manufacturing, in-situ resource utilization (ISRU), and real-time elemental analysis in space-like conditions. This review explores the integration of laser-based techniques in the extraction, fabrication, and application of thorium-bearing materials for space nuclear systems. It covers laser ablation and laser-induced breakdown spectroscopy (LIBS) for thorium detection in regolith, laser sintering and melting for fuel preparation, and additive manufacturing approaches for producing radiation-tolerant components. Advances in simulation and thermal modelling of laser–material interactions are reviewed, alongside key challenges such as radioactive handling, microgravity effects, and material degradation. Current experimental gaps and technology readiness limitations are identified, and a development roadmap is proposed. The findings highlight the potential of laser-assisted thorium processing as a critical enabler of sustainable, deployable space nuclear power systems.



Laser-Enabled Thorium ISRU System for Space Nuclear Power

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*Independent Researcher, India. **Corresponding Author:** 132302004@smail.iitpkd.ac.in.
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1. Introduction

Future space exploration missions, particularly those involving long-duration stays on the Moon, Mars, or deep-space transit, require power systems that are compact, reliable, and capable of operating independently of solar availability. Critical functions such as life support, scientific instrumentation, mobility, thermal regulation, and in-situ resource utilization (ISRU) demand continuous and scalable energy supply. While photovoltaic systems and radioisotope thermoelectric generators (RTGs) have historically served this purpose, they exhibit notable limitations solar panels suffer from reduced efficiency due to dust accumulation and prolonged darkness in polar regions, while RTGs offer limited power output and depend on scarce isotopes like Pu-238. In contrast, nuclear fission systems offer high energy density, continuous power output, and long operational life, making them particularly attractive for extra-terrestrial applications. Among nuclear fuels, thorium (Th-232) is increasingly being considered as an alternative to uranium due to its superior safety profile, lower proliferation risk, and potential abundance in lunar and Martian regolith. Thorium's fertile nature allows it to be bred into fissile uranium-233 in situ, enabling potential use in compact space-based reactors. Laser-based materials processing offers an enabling technological pathway for thorium utilization in space. Its non-contact nature, adaptability to vacuum and microgravity, and compatibility with miniaturized, robotic platforms make it ideal for both ISRU-based extraction and precision fabrication of reactor components. Techniques such as laser ablation and laser-induced breakdown spectroscopy (LIBS) have demonstrated capabilities in resource mapping and in-situ analysis, while laser sintering and additive manufacturing have proven effective for building complex structures from metallic and ceramic feedstocks.

	SOLAR	RTG	URANIUM	THORIUM
POWER DENSITY	MODERATE	LOW ~100~500 W	HIGH	HIGH
RELIABILITY	INTERMITTENT	HIGH	HIGH	HIGH
ISRU POTENTIAL	HIGH (MOON/MARS)	NONE	NONE	POTENTIAL (Th IN REGOLITH)
COMPLEXITY	LOW	MODERATE	HIGH	HIGH

Figure 1: Comparative overview of potential space power systems

Each power source is evaluated based on power density, operational reliability, compatibility with in-situ resource utilization (ISRU), and system complexity. Thorium offers high energy density, long-term reliability, and potential ISRU advantages for future lunar and Martian missions, making it a strong candidate for compact nuclear power generation in space. A comparative analysis of major space-compatible power systems is illustrated in Figure 1, highlighting the trade-offs among solar photovoltaic systems, radioisotope thermoelectric generators (RTGs), and nuclear fission-based approaches using uranium and thorium. While solar power remains attractive due to its simplicity and ISRU compatibility, its intermittent nature and reduced performance in dust-prone or shadowed environments limit its utility for long-duration missions. RTGs, though reliable, provide limited power output and are constrained by the scarcity of isotopes like Pu-238. Uranium reactors offer high energy density and reliability but present proliferation and waste management concerns. Thorium, on the other hand, stands out for its favourable neutron economy, relatively benign waste profile, and potential accessibility from extraterrestrial regolith. As shown in the figure, thorium systems may offer a unique balance of high-power density, operational reliability, and long-term sustainability for space applications, particularly when paired with in-situ laser-based processing techniques. This review aims to systematically explore the role of laser-based techniques in the thorium fuel cycle with specific focus on space exploration. The scope includes methods for thorium extraction and analysis using lasers, laser-driven manufacturing of reactor fuels and components, integration into compact fission systems, and current limitations. The review also identifies existing knowledge gaps, outlines potential experimental directions, and proposes a roadmap for future research on laser-enabled thorium power systems for lunar, Martian, and deep space missions.

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Table 1: Comparative Properties of Thorium, Uranium, and Plutonium for Space Nuclear Applications

Property	Thorium (Th-232)	Uranium (U-235 / U-238)	Plutonium (Pu-238 / Pu-239)
Natural Abundance	Abundant (monoisotopic Th-232)	U-238 abundant, U-235 rare (~0.7%)	Not found in nature; synthetic
Energy Density	High (when converted to U-233)	High (especially U-235)	Very high (Pu-238: ~0.5 kW/kg)
Fissile/ Fertile Nature	Fertile (breeds U-233)	U-235: Fissile, U-238: Fertile	Pu-239: Fissile, Pu-238: RTG source
Proliferation Risk	Low (U-233 harder to weaponize)	Moderate to High (U-235, Pu-239 usable in weapons)	High (Pu-239); Pu-238 non-weapons-grade
Radiotoxicity	Lower than U/Pu	Moderate (esp. U-238 waste)	High (long-lived isotopes)
Decay Heat	Low	Moderate	Very High (especially Pu-238)
Reactor Suitability	Thermal breeders (molten salt, solid fuels)	Widely used (solid fuel reactors)	RTGs (Pu-238), reactors (Pu-239)
ISRU Potential	Possible (traces on Moon/Mars regolith)	Rare (enrichment needed)	Unlikely (complex synthesis)
Waste Management	Less long-lived waste	Moderate (actinides present)	Complex (high radiotoxicity)

2. Thorium as a Nuclear Fuel in Space Context

The thorium fuel cycle, cantered on Thorium-232 (Th-232), presents a unique and potentially game-changing approach for nuclear power systems in space exploration. When bombarded with neutrons, Th-232 transmutes into Uranium-233 (U-233), a fissile material capable of sustaining a controlled chain reaction. The key reaction sequence

$$^{232}\boldsymbol{Th} \rightarrow [\boldsymbol{n},\boldsymbol{\gamma}]\ ^{233}\boldsymbol{Th} \rightarrow [\boldsymbol{\beta}^{-}]\ ^{233}\boldsymbol{Pa} \rightarrow [\boldsymbol{\beta}^{-}]\ ^{233}\boldsymbol{U}$$

U-233, while fissile, emits high-energy gamma radiation due to U-232 contamination, which increases radiation shielding requirements but also reduces the risk of weaponization an important consideration for extraterrestrial use by civilian space agencies.

2.1 Decay Chain and Reactor Breeding Cycle

The thorium decay chain is relatively simple compared to uranium and plutonium, with a long half-life (~14 billion years) for Th-232 and minimal generation of long-lived transuranic waste. This enables efficient use in molten salt reactors (MSRs) or compact fast-spectrum designs suited for deep-space or lunar bases. Figure 2 illustrates the Th–U breeding cycle, highlighting the neutron absorption, beta decay, and final fission of U-233 in a self-sustaining loop, potentially supplemented by laser-induced neutron sources or compact fusion-neutron systems.

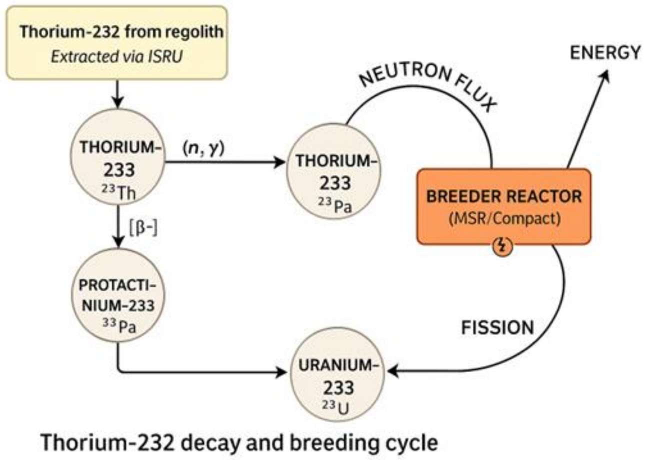

Figure 2: Conceptual Schematic diagram illustrating the thorium-232 nuclear fuel cycle relevant to space applications.

The process begins with thorium-232 (Th-232), which undergoes neutron capture (n,γ) to form thorium-233 (Th-233). This isotope beta decays to protactinium-233 (Pa-233), which further decays to uranium-233 (U-233) a fissile material usable in compact breeder reactors. In a space context, Th-232 can be extracted in-situ from lunar or Martian regolith using ISRU (In-Situ Resource Utilization) techniques. The cycle is particularly suited for molten salt reactors (MSRs) and other closed-loop nuclear systems optimized for long-duration space missions. The thorium fuel cycle offers a unique pathway to generate nuclear energy in extraterrestrial environments. As shown in Figure 2, the fertile isotope 232Th undergoes neutron activation, leading to the formation of the fissile 233U through an intermediate beta decay chain. This process is favourable for space-based reactors due to the relatively low proliferation risk, high thermal efficiency, and potential for compact system design. Moreover, the presence of thorium in lunar and Martian regolith, as identified by missions such as NASA's Lunar Prospector and ISRO's Chandrayaan-2, opens avenues for ISRU-enabled fuel generation, minimizing

2.2 Natural Availability and ISRU Potential

Recent spectral and radiometric data from NASA's Lunar Reconnaissance Orbiter (LRO) and ISRO's Chandrayaan missions confirm thorium concentrations in specific lunar regions, particularly the Procellarum KREEP Terrane (PKT). On Mars, thorium presence is more diffuse, but trace amounts have been inferred via gamma-ray spectrometry. Extraction of thorium from regolith is technically feasible through laser-induced vaporization, microwave sintering, or electrochemical methods making in-situ resource utilization (ISRU) a viable strategy for long-duration missions or off-Earth reactor fuel provisioning. Table 2 summarizes estimated thorium content from available lunar and Martian survey data.

Table 2: Thorium Concentrations in Lunar and Martian Regolith

Celestial Body	Region / Location	Thorium Content (ppm)	Source / Instrument
Moon	Procellarum KREEP Terrane (PKT)	~4–6 ppm	Lunar Prospector Gamma Ray Spectrometer (LP-GRS)
Moon	Mare Imbrium / Oceanus Procellarum Basin	~5–8 ppm	Lunar Prospector regional data
Moon	Compton–Belkovich volcanic complex	14–26 ppm (localized peak)	Lunar Prospector + higher-resolution analysis
Moon	General highland regions	~1–3 ppm	Global lunar composition maps

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Mars	Average global surface (mid-latitudes)	~0.7 ppm (range ~0.2–1.1)	Mars Odyssey Gamma Ray Spectrometer (GRS)
Mars	Higher Th locales (e.g. Acidalia Planitia)	~0.8–1.0 ppm	Mars Odyssey GRS regional variation reports

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- IAEA (2015). Thorium Fuel Cycle – Potential Benefits and Challenges. IAEA TECDOC-1450.
- Lawrence et al., (2003). "Thorium abundances on the lunar surface." Journal of Geophysical Research.
- Boynton et al., (2007). "Global Martian elemental maps from Mars Odyssey." Science.

3. Laser-Based Thorium Extraction Techniques

Thorium extraction on planetary surfaces requires precise, energy-efficient methods adaptable to extreme environments. Laser-based systems especially laser ablation and LIBS offer promising solutions for both extraction and in-situ analysis of thorium-bearing materials.

3.1 Laser Ablation Fundamentals

Laser ablation is a process in which high-intensity laser pulses irradiate a solid surface, resulting in localized melting, vaporization, and ionization. This leads to the formation of a plasma plume containing atomic and ionic species.

The ablation rate m˙\dot{m}m˙ and energy density (fluence) FFF are calculated using:

Ablation rate and energy density (fluence) equations:

$$\dot{m} = (\boldsymbol{\alpha} \times \boldsymbol{F}) / \boldsymbol{Lv}$$

$$\boldsymbol{F} = \boldsymbol{Ep} / \boldsymbol{A}$$

Where:

- **α** = material absorptivity
- **F** = laser fluence (J/m^2)
- **Lv** = latent heat of vaporization (J/kg)
- **Ep** = pulse energy (J)
- **A** = laser spot area (m^2)

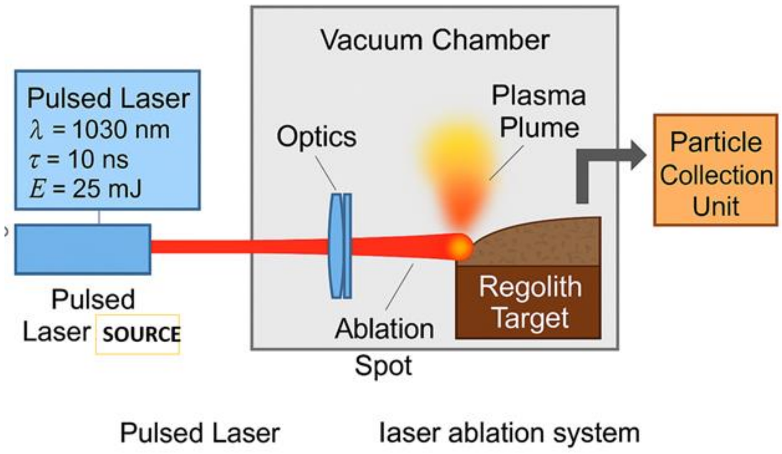

Figure 3: Conceptual Schematic diagram of a pulsed laser ablation system designed for in-situ extraction of thorium from planetary regolith under vacuum conditions

The setup includes a pulsed laser source ($\lambda = 1030\,nm, \tau = 10\,ns, E = 25\,mJ$), beam focusing optics, and a regolith target positioned within a vacuum chamber. Upon irradiation, a plasma plume forms at the ablation spot, and the resulting vaporized material is directed into a particle collection unit for downstream analysis or separation. This image illustrates the functional layout of a laser ablation system configured for planetary regolith processing, particularly targeting thorium recovery. The pulsed laser generates high-intensity pulses that are focused via optical lenses onto the surface of the regolith target inside a vacuum chamber. The interaction creates a plasma plume, signifying material ablation, which is subsequently transported to a particle collection unit. This schematic supports feasibility analysis for resource extraction on the Moon or Mars using compact, non-contact laser-based methods.

3.2 LIBS for In-Situ Element Detection

Laser-Induced Breakdown Spectroscopy (LIBS) is a diagnostic tool used to identify elements by analysing the optical emission spectrum of the laser-induced plasma. In space exploration, LIBS has been integrated into instruments like ChemCam (Mars Science Laboratory) and SuperCam (Perseverance Rover). For thorium, emission lines such as 401.9 nm, 764.6 nm, and others are significant and detectable under low-pressure conditions.

3.3 Laser Separation and Partitioning

Laser techniques can not only detect but also aid in separating thorium from silicates and other oxide complexes. Minerals like monazite or thorite can be preferentially ablated due to their distinct absorption and thermal properties. By tailoring pulse duration (e.g., nanosecond vs femtosecond), wavelength (e.g., 532 nm, 1064 nm), and laser fluence, selective ablation of thorium-containing phases is achievable. This could enable localized extraction and pre-concentration before reactor use.

3.4 Pulsed vs Continuous Wave Lasers

Pulsed lasers (e.g., nanosecond or femtosecond) deliver energy in bursts, leading to localized high temperatures and pressures. This results in efficient material removal and reduces thermal diffusion. Continuous wave (CW) lasers, in contrast, maintain steady irradiation. They are useful for slow, bulk heating and deep melting, but are less effective for selective material removal. Comparison Between Pulsed and Continuous Wave (CW) Laser Modes is shown in Table 3.

Table 3: Comparison Between Pulsed and Continuous Wave (CW) Laser Modes

Laser Mode	Typical Use	Advantages	Limitations
Pulsed	LIBS, fine ablation	High precision, localized heating	Plasma shielding, optics degradation
CW	Broad melting, welding	Stable operation, simple setup	Less selective, heat-affected zones

3.5 Environmental Challenges on Moon/Mars

Deploying lasers on planetary surfaces involves addressing challenges such as:

- **Vacuum conditions**: Affect plume expansion and plasma formation.
- **Dust and regolith**: Can scatter or absorb laser light, degrading efficiency.
- **Extreme temperature variations**: Affect electronics, optics, and alignment.

Future laser systems must be ruggedized, temperature-tolerant, and include self-cleaning optics or protective enclosures to withstand extraterrestrial environments. Typical Laser Ablation Parameters for Planetary Regolith Studies is shown in Table 4

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Table 4: Typical Laser Ablation Parameters for Planetary Regolith Studies

Parameter	Range	Source/Application
Wavelength	266 – 1064 nm	Nd: YAG, Ti: Sapphire
Pulse Duration	10 ns – 100 fs	LIBS, ultrafast ablation
Fluence	1 – 20 J/cm²	Regolith analogs
Repetition Rate	10 Hz – 10 kHz	LIBS spectroscopy
Spot Diameter	50 – 500 µm	Precision ablation
Pressure	10^{-5} – 10^{-2} atm	Lunar/Martian simulation

4. Integration with Space Nuclear Systems

The deployment of compact fission reactors for long-duration space missions whether on the lunar surface, Mars, or deep space has gained momentum due to their ability to provide stable, high-density power. Thorium-based microreactors present a promising avenue, particularly when integrated with advanced laser manufacturing methods. Laser-assisted fabrication techniques enable the creation of high-precision components critical to the reactor's performance and safety. These include fuel cladding structures, micro-channelled heat exchangers, and nozzles for thermal propulsion systems. The superior thermal resistance, microstructural uniformity, and dimensional control offered by laser processing make it ideal for manufacturing in space or pre-launch fabrication.

Power conversion technologies such as the Brayton cycle, thermoelectric generators, and Stirling engines are commonly coupled with these reactors. These systems convert nuclear heat into usable electrical energy for propulsion and habitat systems. Importantly, such microreactors can serve dual purposes providing propulsion thrust during transit and powering surface habitats or ISRU operations post-landing.

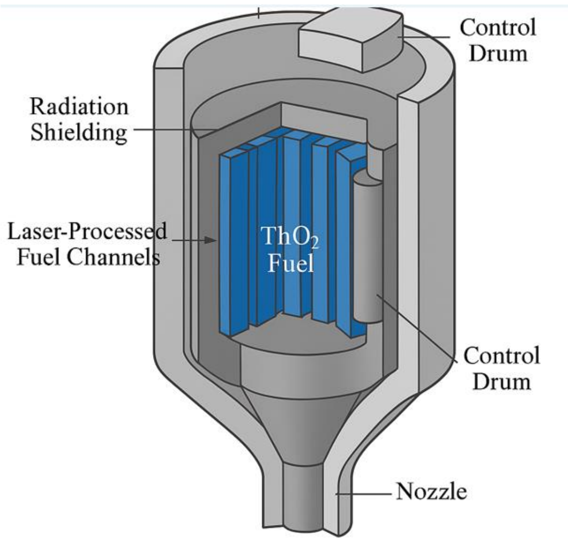

Figure 7. Conceptual cutaway schematic of a compact thorium-based microreactor featuring laser-processed ThO_2 fuel channels.

The central reactor core is enclosed within multilayer radiation shielding and regulated by dual control drums. A nozzle at the base allows for potential thermal propulsion or passive heat rejection. Laser-based manufacturing techniques enable high-precision fabrication of fuel elements and structural components, supporting the deployment of reliable nuclear power systems for long-duration extraterrestrial missions.

Figure 7 illustrates the conceptual architecture of a compact thorium microreactor designed for in-situ space deployment. At its core lies an array of laser processed ThO_2 fuel channels arranged in a high-density configuration to optimize neutron economy and heat transfer. These channels are fabricated using precision laser sintering or additive manufacturing techniques, ensuring microstructural uniformity and dimensional accuracy. Surrounding the reactor core is a robust radiation shielding layer, engineered to mitigate gamma and neutron flux, thereby protecting adjacent electronic and habitat systems. The dual control drums facilitate neutron flux regulation, while the base-mounted nozzle serves as a multifunctional outlet for thermal propulsion or passive radiative cooling. The schematic emphasizes the integration of advanced laser-based manufacturing to meet the stringent demands of microgravity operation, remote deployment, and modular construction in extraterrestrial environments.

Table 5. Comparison: Traditional vs Laser-Assisted Fabrication Routes for Reactor Components

Parameter	Traditional Fabrication Methods	Laser-Assisted Fabrication Methods
Manufacturing Techniques	Casting, forging, extrusion, welding, machining	Laser Powder Bed Fusion (L-PBF), Directed Energy Deposition (DED), laser cladding
Material Wastage	High (subtractive processes, ~30–60% material loss)	Low (additive, near-net shape, ~5–10% material loss)
Geometric Complexity	Limited by tooling; poor for internal features	Excellent; allows lattice, micro-channels, conformal cooling paths
Processing Time	Long (multiple steps, preforms, post-processing)	Short (layer-by-layer, reduced assembly steps)
Dimensional Precision	~±0.1–0.3 mm (machining dependent)	~±0.01–0.05 mm with in-situ monitoring
Microstructure Control	Limited; anisotropy, large grains common	High; rapid solidification, fine-grained, tailored via scan strategies
Mechanical Performance	Variable: weld seams can be weak, stress concentration points	High strength; customizable density, directional solidification
Customization and Iteration	Costly and time-consuming for each variant	Rapid prototyping; software-driven flexibility
ISRU Compatibility	Not feasible with raw regolith or oxides	Potential for regolith-derived powder feeds (under research)
Space-Readiness	Requires Earth-based heavy tools, gravity	Portable systems; compatible with robotic ISRU setups in vacuum/micro-g
Energy Efficiency	High energy input for bulk processes	Localized heating; less energy-intensive overall

- AEA TECDOC-1938: "Additive Manufacturing for Nuclear Applications"
- NASA Langley Additive Manufacturing Reports (2023)
- Oak Ridge National Lab (ORNL): AM of reactor parts (e.g., MCFR projects)
- ESA AMIS Database (Additive Manufacturing in Space)
- Journals: Additive Manufacturing, Journal of Nuclear Materials, Materials & Design

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5. Simulation and Modelling Approaches

The advancement of laser-based thorium processing for space applications critically depends on robust Multiphysics simulations that can predict material behaviour under extreme conditions. While experimental data remains limited due to radiological constraints and environmental challenges, simulation frameworks offer a valuable surrogate for design and optimization.

5.1 Laser–Thorium Interaction Modelling

Numerical models such as finite element methods (FEM) and heat transfer solvers have been applied to simulate the laser sintering of metallic and ceramic materials. For thorium oxide (ThO_2), modelling efforts must account for high melting points (~3300 K), phase transformations, and localized vaporization under high-fluence laser irradiation. These models can guide parameter optimization (e.g., spot size, scan speed, pulse duration) to ensure uniform energy deposition and avoid cracking or void formation.

5.2 Microgravity-Specific Melt Pool Dynamics

Laser processing in microgravity introduces unique challenges due to altered convection and surface tension effects. Computational fluid dynamics (CFD) models adapted for low-gravity regimes are essential to simulate melt pool behaviour, Marangoni flow, and re-solidification in the absence of buoyancy. Existing studies on Inconel or Al alloys under parabolic flight conditions offer transferable insights for Th-based systems.

5.3 Radiation Shielding Simulations

Incorporating laser-processed thorium composites into habitat walls or equipment casings requires radiation transport modelling. Monte Carlo codes such as MCNP or GEANT4 can simulate neutron and gamma attenuation, helping to design multifunctional shielding structures. These models can quantify dose reduction efficiency when using thorium-doped laser claddings or layered composites.

5.4 Multiphysics Modelling of Fuel Fabrication

Advanced simulation tools such as ANSYS, COMSOL Multiphysics, or OpenFOAM allow the integration of thermal, structural, and fluidic phenomena during additive manufacturing. These tools are essential for optimizing the sintering of ThO_2 pellets, thermal gradients in DED-processed components, and stress distributions during laser-induced melting.

Table 6. Summary of Modelling Tools and Their Applications in Thorium–Laser Research

Tool / Software	Primary Modelling Domain	Relevance to Thorium–Laser Systems
COMSOL Multiphysics	Heat transfer, phase change, thermal stress	Simulates thermal gradients, melting-solidification behaviour, and stress buildup in ThO_2 laser sintering
ANSYS Fluent (CFD)	Fluid flow, melt pool dynamics, convection	Models melt pool behaviour under microgravity and evaluate scan speed, pulse duration, and Marangoni effects
MCNP / GEANT4	Radiation transport (neutron/gamma shielding)	Simulates attenuation properties of laser-processed Th composites in habitat walls or reactor shields
Open FOAM	Multiphase flow, plasma-regolith interaction	Useful for simulating ablation plume evolution in Th regolith laser extraction under low-pressure vacuum
MATLAB / Python FEM	Custom modelling of localized thermomechanical effects	Models' temperature distribution and residual stresses during laser processing of Th-based materials

Note:

COMSOL Multiphysics and ANSYS Fluent are widely adopted in academic and industrial research for simulating laser sintering, thermal gradients, and melt pool behaviour, and have been validated in numerous peer-reviewed studies. MCNP and GEANT4 are standard Monte Carlo-based tools extensively used for radiation shielding analysis in terrestrial and space-based nuclear systems. OpenFOAM, an open-source Multiphysics solver, has been applied in NASA-supported microgravity CFD studies and plume evolution modeming. Simu fact Additive and Autodesk Netfabb are increasingly used in metal additive manufacturing simulations, offering predictive capabilities for distortion, residual stress, and thermal history in layer-by-layer builds.

6. Challenges, Risks, and Research Gaps

Despite the promising synergy between thorium-based nuclear fuel and laser-assisted processing techniques, several critical challenges remain that must be addressed before practical deployment in extraterrestrial environments.

6.1 Lack of Experimental Validation in Space-Like Conditions

A major limitation is the scarcity of experimental data under vacuum, low-gravity, and extreme temperature conditions representative of the Moon or Mars. Most laser–material interaction studies are conducted under Earth-bound laboratory environments, which do not fully capture the altered thermal conduction, melt dynamics, and plasma plume expansion that occur in space. There is an urgent need for microgravity-compatible testbeds aboard platforms like the ISS, lunar landers, or suborbital flights.

6.2 Radiological Safety and Handling in Microgravity

Thorium, while less hazardous than plutonium, remains a radioactive material requiring careful containment and shielding. The handling of thorium feedstock, fuel debris, and activated structural materials under microgravity introduces new operational hazards. Particle resuspension, radiogenic dust dispersion, and difficulty in mechanical manipulation complicate automation and robotic processing strategies.

6.3 Oxidation and Atmospheric Sensitivity

Thorium is highly reactive in the presence of oxygen and moisture, leading to surface oxidation that can affect laser absorption, sintering behaviour, and long-term material integrity. Processing chambers in space must maintain controlled atmospheres, likely requiring inert gas environments (e.g., argon or helium) or sealed vacuum systems, both of which add mass, complexity, and power requirements to ISRU systems.

6.4 Regulatory and Ethical Considerations

The deployment of fissionable material beyond Earth is tightly regulated by international frameworks such as the Outer Space Treaty (1967) and guidelines from the IAEA and national space agencies. Launch safety, containment during transit, and planetary protection protocols introduce procedural and ethical hurdles. There is also growing scrutiny over the militarization or weaponization potential of space-based nuclear assets, even if designed for civilian use.

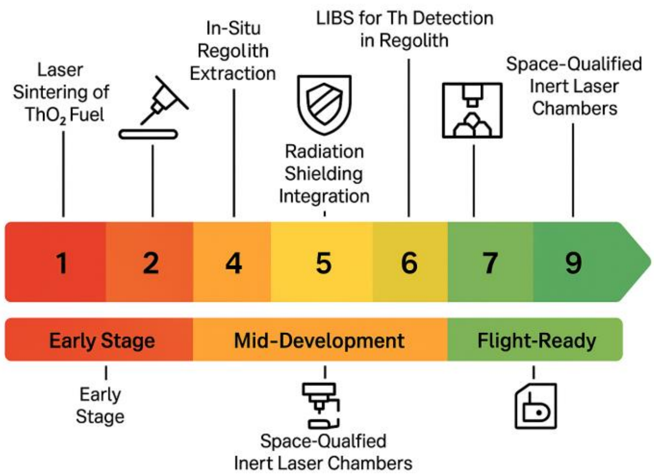

Figure 9. Technology Readiness Levels (TRLs) for subsystems enabling laser-based thorium utilization in space applications.

The chart highlights the current maturity levels of critical technologies, including laser sintering of ThO_2 fuel, in-situ regolith extraction, LIBS-based elemental detection, additive manufacturing of reactor parts, radiation shielding integration, and space-qualified inert laser chambers. Most subsystems remain in early-to-mid

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development stages (TRL 2–6), underscoring the need for coordinated research, experimental validation in space-like conditions, and regulatory alignment for future deployment in extraterrestrial environments.

To contextualize the development status of enabling technologies, Figure 9 presents a technology readiness level (TRL) assessment of subsystems integral to the realization of laser-assisted thorium power systems in space. The mapping reveals that while laser-induced breakdown spectroscopy (LIBS) for elemental detection and radiation shielding composites have reached mid-TRLs (5–6), other essential components such as in-situ regolith extraction and ThO_2 laser sintering remain in early experimental phases (TRL 2–3). Additive manufacturing techniques for fuel and reactor components, although demonstrated terrestrially, require space-qualified adaptation and environmental validation. This TRL snapshot reinforces the multidimensional challenge posed by deploying nuclear systems in space not only from a materials engineering perspective, but also from the standpoint of autonomy, radiological containment, and system-level integration under microgravity. Accelerating these technologies toward flight readiness will require high-fidelity simulation, microgravity experimentation, and sustained policy support.

7. Future Outlook and Roadmap

The convergence of laser-based manufacturing, thorium nuclear fuel cycles, and space infrastructure development represents a paradigm shift in the realization of autonomous, long-duration power systems for extraterrestrial missions. The next two decades are poised to witness accelerated progress, driven by cross-disciplinary advances in robotics, AI, additive manufacturing, and nuclear materials science. This section outlines the projected technological trajectory and strategic roadmap for the maturation and deployment of laser-enabled thorium systems in space.

7.1 Integration with Robotic Mining and ISRU Systems

Future lunar and Martian exploration will increasingly depend on robotic autonomy for in-situ resource utilization (ISRU). Laser-based thorium extraction aligns naturally with ISRU platforms due to its non-contact, vacuum-compatible nature. Robotic rovers equipped with LIBS and pulsed laser ablation systems could autonomously scan, identify, and extract thorium-rich phases from regolith. Integration with AI-driven sample discrimination and automated feedstock handling systems will be crucial for closed-loop fuel production cycles.

7.2 AI-Augmented Process Optimization

The complexity of laser–material interactions, especially under space-relevant constraints (e.g., reduced convection, radiative cooling), necessitates AI-enhanced control strategies. Machine learning algorithms can be trained on simulation and terrestrial experimental data to optimize laser parameters in real-time, adjusting fluence, scan speed, and spot size for maximal material efficiency and microstructural quality. These intelligent systems will also monitor process health using in-situ diagnostics such as thermal imaging and melt pool sensors, enabling predictive maintenance and autonomous recovery.

7.3 Mission-Driven Applications: Moon, Mars, and Beyond

Laser-fabricated thorium microreactors can serve dual purposes: (i) thermal and electrical power supply for habitats, and (ii) nuclear thermal propulsion systems for interplanetary transit. On the Moon, deployment of modular Th-based microreactors will overcome the limitations of solar power during 14-day lunar nights. On Mars, the reactor's compact form factor and long operational life can support habitat power, rover recharging, and atmospheric processing units. Beyond Mars, laser-enabled thorium systems may provide sustainable power for asteroid bases or deep-space observatories operating beyond the heliopause.

7.4 Decentralized Energy Grids and Habitat Scalability

In contrast to centralized power stations, laser-fabricated thorium microreactors offer scalable, modular energy solutions. Clusters of microreactors can be distributed across habitat modules or mission zones, linked via decentralized microgrids. This improves redundancy, reduces single-point failure risks, and allows power scaling according to mission phase (e.g., landing, expansion, long-term habitation). Reactor components manufactured and repaired on-site using laser additive manufacturing will significantly reduce Earth-dependence and resupply constraints.

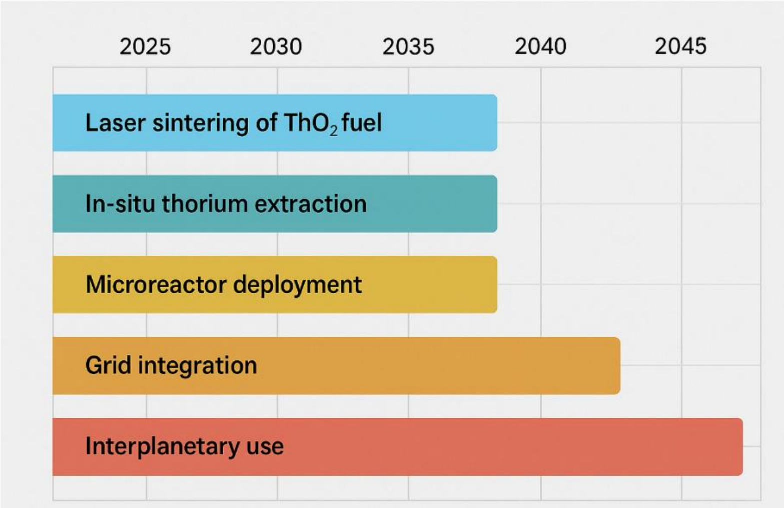

Figure 10. (Conceptual) Projected timeline for the adoption of laser-based thorium systems in space (2025–2045).

The roadmap illustrates key developmental phases, beginning with laser sintering of ThO_2 fuel and in-situ thorium extraction, followed by microreactor deployment and grid integration for lunar and Martian habitats. The timeline culminates in interplanetary utilization, indicating long-term prospects for deep-space power and propulsion applications.

The roadmap presented in Figure 10 outlines a staged development path for laser-enabled thorium technologies, aligned with anticipated milestones in space exploration. In the near term (2025–2035), emphasis will be on terrestrial validation and simulation-guided optimization of laser sintering and extraction processes. By the mid-2030s, functional demonstration of thorium microreactors and component-level testing under lunar gravity conditions is expected to bridge the gap to TRL 6–7.

In the long term (post-2037), integration into decentralized surface energy grids and eventual adaptation for deep-space missions will become viable. The roadmap reflects not only the engineering challenges, but also the regulatory, logistical, and AI-control requirements that must be concurrently addressed to realize the vision of in-situ nuclear power generation for sustained extraterrestrial presence.

Table 7. Proposed Research Roadmap: Short, Medium, and Long-Term Milestones

Time Horizon	Milestones	Key Objectives
Short-Term (2025–2030)	Terrestrial validation of laser sintering for ThO_2 fuel pellets- Calibration of LIBS for thorium detection in regolith simulants- FEM and CFD modelling of laser–material interactions under space-like conditions- Radiation shielding simulation using Th-based composites	Establish process fundamentals, verify modelling accuracy, and benchmark hardware performance
Medium-Term (2030–2037)	Demonstration of in-situ thorium extraction from lunar/Martian regolith analogs- Development of space-compatible inert laser processing chambers- Additive manufacturing of reactor-grade components under simulated lunar gravity- TRL advancement of microreactor subsystems to TRL 6–7	Integrate core subsystems, validate component-level operation under space constraints
Long-Term (2037–2045)	Deployment of laser-fabricated thorium microreactors on the lunar surface- Integration with autonomous AI-driven ISRU platforms- Implementation of microgrid-based energy networks across Moon/Mars habitats- Demonstration of deep-space nuclear propulsion using Th fuel	Achieve operational deployment, grid integration, and multi-use functionality for interplanetary missions

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8. Conclusion

The integration of thorium-based nuclear fuels with laser-assisted processing technologies and in-situ resource utilization (ISRU) represents a promising strategy for addressing the long-term power demands of lunar, Martian, and deep-space missions. Thorium's favourable nuclear characteristics such as high availability, reduced proliferation risk, and compatibility with closed fuel cycles make it an attractive candidate for compact space reactors. Simultaneously, laser-based techniques offer the precision, flexibility, and environmental compatibility needed for both fuel fabrication and in-situ extraction under extraterrestrial conditions. This review has examined the current state of laser-Thorium systems, covering materials processing methods, additive manufacturing, diagnostic techniques, simulation frameworks, and integration within space nuclear architectures. The analysis indicates that while several subsystems such as LIBS-based detection and radiation shielding have reached moderate technology readiness, others like ThO_2 sintering and regolith extraction remain at early experimental stages. Addressing the technical and logistical challenges outlined in this review will require advances in laser-material interaction modelling, autonomous control systems, and the development of robust, space-qualified hardware. Regulatory, safety, and ethical frameworks will also need to evolve alongside technological progress to ensure responsible deployment. Realizing the full potential of laser-enabled thorium systems in space will depend on sustained, cross-disciplinary collaboration across nuclear engineering, materials science, robotics, artificial intelligence, and space mission planning.

9. Policy, Safety, and Ethical Considerations

The prospective deployment of laser-assisted thorium reactors in space introduces a range of policy, safety, and ethical challenges that must be addressed alongside technological development. Unlike terrestrial nuclear power systems, space-based fission reactors operate in highly constrained environments, where risk tolerance is extremely low, and regulatory frameworks are still evolving.

9.1 Safety Protocols for Orbital and Planetary Operations

Thorium, while less proliferative than plutonium or enriched uranium, remains a radioactive material and must be handled with stringent containment and shielding protocols. During launch, the reactor core must be subcritical and encapsulated in impact-resistant enclosures to mitigate the risk of dispersal in the event of launch failure. Once deployed, operational safety is further complicated by microgravity-induced dust mobility, regolith contamination, and the absence of real-time human intervention. Autonomous safety interlocks, thermal regulation systems, and radiation shielding using in-situ materials (e.g., regolith or boron-carbide composites) are essential to mitigate these risks.

9.2 Regulatory Landscape and International Compliance

The deployment of nuclear systems beyond Earth is currently governed by a patchwork of treaties and national regulations. The Outer Space Treaty (1967) prohibits the placement of nuclear weapons in orbit or on celestial bodies but permits peaceful nuclear applications under strict liability and environmental protection clauses. Agencies such as the IAEA, along with space-faring nations under the Artemis Accords, are actively exploring cooperative frameworks for nuclear safety, launch authorization, and post-mission decommissioning. However, no standardized global protocol currently exists for fission reactor deployment on the Moon or Mars, creating a policy vacuum that must be addressed through multilateral dialogue.

9.3 Ethical and Planetary Protection Concerns

The autonomous nature of in-situ nuclear fabrication and energy generation raises questions of accountability, especially in missions where human oversight is delayed or absent. Ethical considerations include the potential contamination of extraterrestrial environments, unintended ecological consequences, and dual-use concerns—where civilian technologies may be repurposed for military or strategic advantage. Furthermore, under the Planetary Protection Guidelines of COSPAR, any deployment of biologically or radiologically active systems must demonstrate non-contamination of scientifically valuable regions, particularly on Mars and icy moons.

9.4 Recommendations for Governance Integration

To ensure the responsible deployment of thorium-based nuclear systems, it is imperative to establish an international regulatory framework that includes:

- Technology-neutral launch and safety certification
- Guidelines for autonomous nuclear operations and AI governance
- Emergency response protocols for orbital or surface malfunctions

- Transparent disclosure of dual-use capabilities and mission intentions

As space missions become longer in duration and more reliant on autonomous power systems, the alignment of technological innovation with robust governance will be critical to maintaining international trust, mission security, and ethical stewardship of off-Earth environments.

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