Hephaestus: Lunar Surface Nuclear Reactor Conceptual Designs and CONOPS

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Background and Objective

Establishing a permanent human presence on the Moon offers significant scientific and economic benefits, including access to valuable resources like silicon, titanium, and helium-3. A reliable energy source is essential for lunar settlement, especially near the Moon's south pole, where water can support life and fuel production. While solar power and hydrogen fuel cells are possible options, nuclear energy is emerging as the most promising solution due to its consistency, sustainability, and suitability for lunar operations. This project focuses on developing a concept of operations for nuclear power on the moon to sustain lunar habitation and resource utilization.

Reactor Selection and Designs

- Based off the Mission Basic Requirements identified by the team, the chosen reactor for this project is the Rolls-Royce (RR) Nuclear Microreactor. The reactor can generate between 1MW to 10MW of power with each megawatt able to support up to 150 astronauts. To convert the reactor heat into electricity, a Brayton Cycle or Stirling Engine is used as Brayton Cycle turbines have a higher conversion efficiency.
- The fuel utilized by the reactor is Tri-Structural Isotropic (TriSO) fuel which consists of tiny, robust particles containing a uranium-based fuel kernel coated in multiple layers of carbon and ceramic materials. These layers enhance safety and significantly reduce the risk of fuel failure and reactor meltdown. TriSO fuel's robust nature, with its high resistance to neutron irradiation, corrosion, and oxidation, extends fuel life and reduces the frequency of refueling.

Below are some designs of the reactor and the fuel used:

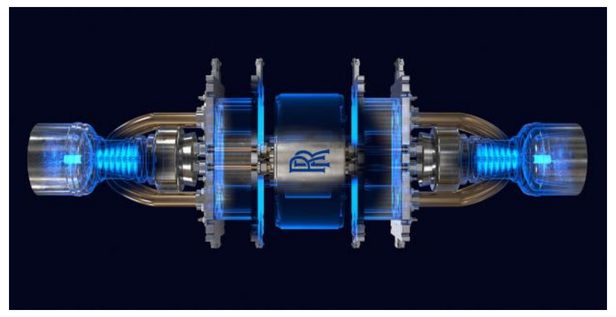

Figure 1: RR Microreactor Design

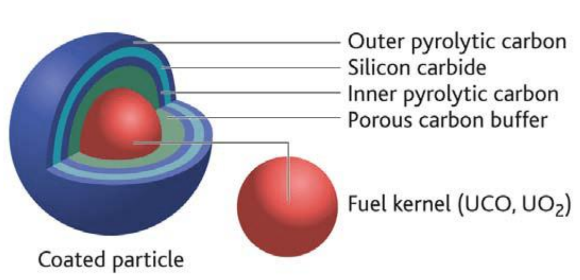

Figure 2: TriSO fuel Model

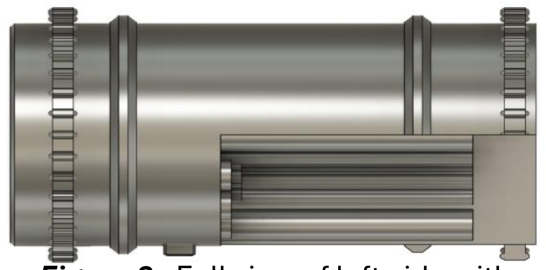

Figure 3: Full view of left side with Cross-Sectional View

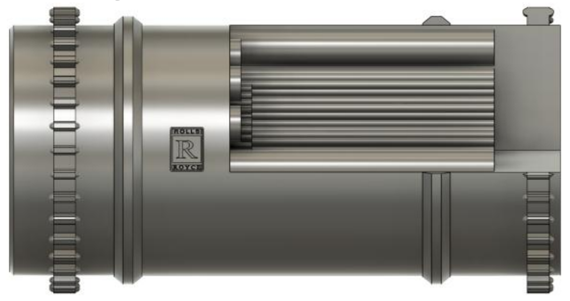

Figure 4: Front view of left side

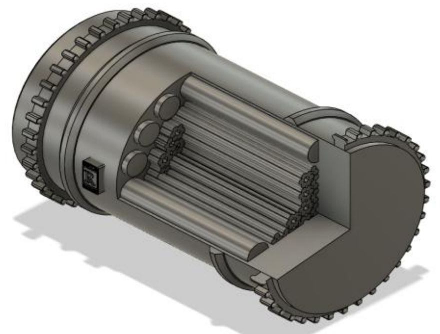

Figure 5: Isometric view of left side

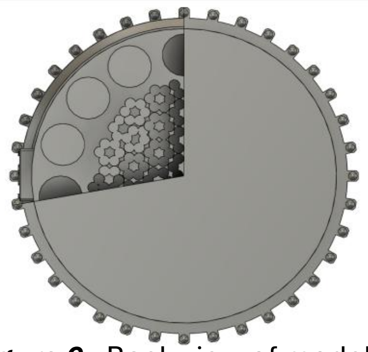

Figure 6: Back view of model

Lunar Establishment and Integration

- The chosen spacecraft for the mission will be the SpaceX Starship due to its ability to withstand heavy loads. The reactor will be placed in the payload bay of the spacecraft and shall be kept a safe distance from the crew and sensitive cargo.
- The lunar south pole's PSRs holds 1.3 trillion pounds of water ice, essential for life support, cooling, and fuel production. Due to long lunar nights, the RR Microreactor will provide reliable power, supporting missions like NASA's Artemis mission. Strategically positioned on a crater's edge, the reactor avoids ice contamination, prevents dust settling inside, and ensures easier access and maintenance.
- Communication with the reactor will be done using LunaNet infrastructure and maintenance will be performed through automated sequences for simple tasks and with robots and humans for formidable ones.

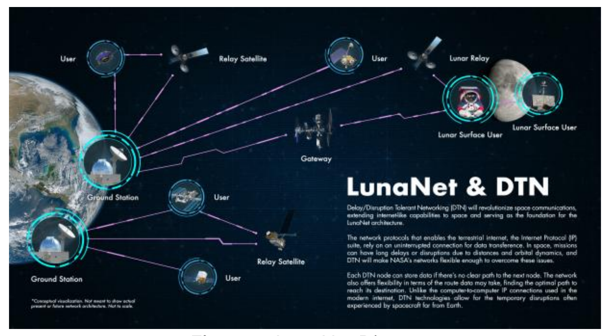

Figure 7: LunaNet Diagram

Power Distribution

- Establishing a sustainable lunar presence requires a robust power infrastructure. The RR Microreactor will generate electricity using Brayton or Stirling systems for use in life support, ISRU, LTVs, and scientific equipment. Power will be transmitted primarily through High-Voltage Direct Current (HVDC), which offers greater efficiency, reduced energy loss, and lighter infrastructure compared to AC. HVDC also performs better in a vacuum and doesn't require frequency synchronization, making it ideal for a multi-source lunar grid.
- Radiation-hardened cables will be used to withstand extreme lunar temperatures and radiation. In Permanently Shadowed Regions (PSRs), superconducting power lines could offer high transmission, though maintaining cryogenic temperatures presents challenges.
- Power distribution will rely on a network of nodes: primary nodes near the reactor will stabilize output, while secondary nodes near habitats and facilities will step down voltage. Wireless Power Transmission (WPT), microwaves or lasers, may supplement mobile or temporary systems. While effective in the Moon's atmosphere-free environment, WPT is best suited for short-term or mobile applications due to energy loss.

Figure 8: Power Production and Transmission CAD Model

		Reactor Selections			
Selection Aspects	Weight	Lunar Regulation Batteries	Flywheel Storage	Fuel Cells	Super Capacitors
Energy Density	0.25	2	3	4	1
Power Density	0.2	1	3	2	4
Cycle Life	0.15	1	4	2	3
Temperature Sensitivity	0.1	1	4	2	3
ISRU Potential	0.15	4	1	2	3
Space Heritage	0.15	1	3	4	2
	Total Score	1.7	2.95	2.8	2.55

Figure 9: Backup Storage Pugh Decision Matrix

Risk Mitigation and Evacuation Protocols

With safety being the utmost priority for NASA in any mission, it is imperative that risk mitigation strategies and evacuation protocols must be created and implemented.

Risk ID	Risk Description	Likelihood (1-5)	Impact (1-5)	Risk Score	Mitigation Strategy
1	Launch failure during reactor transportation	2	5	10	Implement rigorous launch protocols and redundant safety systems.
2	Reactor damage during lunar landing	2	5	10	Utilize shock-absorbing landing systems and conduct thorough landing simulations.
3	Exposure to cosmic radiation during transit	3	4	12	Equip spacecraft with enhanced radiation shielding and monitor radiation levels.
4	Micrometeorite impact on reactor during transit	2	4	8	Design protective shielding and implement early detection systems for micrometeorites.
5	Failure in reactor deployment mechanisms on the Moon	2	5	10	Conduct extensive pre-deployment testing and have contingency plans in place.
6	Reactor malfunction post-deployment	2	5	10	Implement redundant reactor systems and continuous monitoring protocols.
7	Inadequate heat dissipation leading to overheating	3	4	12	Design efficient heat dissipation systems and conduct thermal analysis.
8	Radiation leakage from reactor	1	5	5	Ensure robust reactor shielding and regular radiation monitoring.
9	Structural failure of habitat due to lunar seismic activity	1	4	4	Design habitat structures to withstand lunar seismic events.
10	Insufficient shielding against cosmic radiation	3	4	12	Incorporate advanced shielding materials into habitat design.
11	Micrometeorite impact on habitat	2	4	8	Utilize reinforced materials and implement early detection systems.
12	Habitat airlock failure	2	5	10	Design redundant airlock systems and conduct regular maintenance checks.
13	Life support system malfunction	2	5	10	Implement redundant life support systems and regular system checks.
14	Water extraction system failure	3	4	12	Develop reliable in-situ resource utilization (ISRU) technologies.
15	Food production system failure	3	4	12	Establish robust food production systems with backup supplies.
16	Psychological effects of isolation on crew	3	3	9	Provide mental health support and design habitats to promote social interaction.
17	Communication system failure with Earth	2	5	10	Implement redundant communication systems and autonomous operational protocols.
18	Power distribution failure within habitat	2	5	10	Design redundant power distribution networks and conduct regular maintenance.
19	Lunar dust infiltration into habitat	4	3	12	Implement advanced dust mitigation strategies and air filtration systems.
20	Failure in waste management systems	2	4	8	Develop reliable waste management protocols and backup systems.

Figure 10: Shortened Risk Matrix

Conclusions

- The Rolls-Royce Microreactor is the most reliable and scalable reactor for the success of this project.
- TriSO fuel is the most optimal fuel option due to its efficiency and safety compared to other fuel types.
- SpaceX Starship will transport the reactor to the lunar south pole and LunaNet will be used to establish communication with the reactor.
- Power generation through Brayton systems and transmission through HVDC will be crucial for development and life support on the Moon.
- For the safety of the crew and cargo, eventual habitants in the colony, and other lunar operations, risk mitigation and evacuation protocols must be put in place.
- The success of this project will ensure the continued survival of humans as the world will begin to face a freshwater shortage by 2040 and eventually the world will become fully uninhabitable.

Future Work

- Planning for the colony's power supply must prioritize long-term feasibility. Rather than relying on a system designed to fail after a certain amount of time, the energy infrastructure must be adaptable and scalable to support future growth and rising power demands, such as powering mining operations.
- The RR Microreactor was chosen for its modular design, allowing additional units to be easily added as needed. This ensures reliable energy for expanding habitats, industry, and research.
- Each reactor operates independently, simplifying maintenance and reducing the risk of total failure. This decentralized approach enhances sustainability and lays the foundation for a robust energy system to support lunar expansion and future deep space missions.

References

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Acknowledgements

We would like to thank Mr. Robert Nuckols, our NASA mentor, for his guidance and support during this project.