Lunar Surface Nuclear Reactor Conceptual Designs & CONOPS

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Xe-100

BACKGROUND

NASA launched the Fission Surface Power Project as an ambitious initiative aimed at developing a compact, long-lasting nuclear fission reactor to generate electricity on the Moon. The Artemis III mission (planned for 2025) intends to return human presence to the moon to establish long-term lunar operations; requiring a supply of reliable power to lunar habitat(s), life support systems, thermal management systems, communication systems, mobile units, research equipment, mining and resource processing, back-up emergency systems, and Lunar Gateway support (Kaldon & Presby, 2024). The reactor must have an operating-life of 10 years (1 year with human intervention and 9 years autonomously) and be capable of providing 40 kWe of continuous power. NASA seeks to foster creative solutions and innovations by keeping the specifications for a small modular reactor (SMR) to a minimum.

LOCATION & CLIMATE

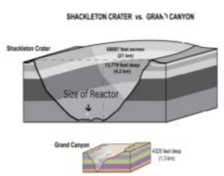


Figure 1: Shackleton Crater vs. Grand Canyon comparison

Spanning 21 kilometers in diameter, with depths of over 4.2 kilometers, the Shackleton Crater is located in the south pole of the moon. Fittingly, the crater was named after Ernest Shackleton, who survived 2 years (with a crew of 27) trapped in ice on an expedition to Antartica. The Shackleton Crater is the most promising location on the lunar surface, by bolometric stability, size and proximity to the south pole of the moon.

The physical environment on the Moon is extremely harsh and differs significantly from the Earth's surface, creating unique challenges for any technology deployed on the lunar surface. In particular, the Xe-100 reactor must operate under extreme temperature fluctuations, heightened radiation, exposure to lunar dust, and in the vacuum of space. These factors will directly influence the reactor's design, materials, thermal systems, and operational strategy.

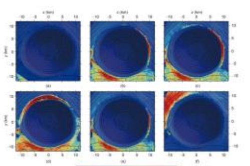
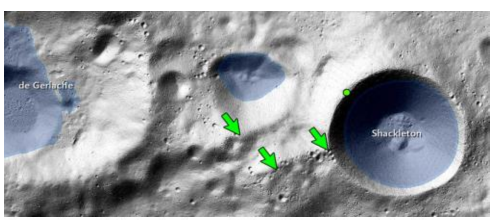


Figure 2: Surface temperature of Shackleton at various times.



The picture shows possible landing points. The green dot indicates the location of the south pole and the green arrows show illuminated terrain. The areas with permanent shadow are marked in blue. Shackleton crater is 21 kilometers in diameter is over 4 kilometers deep. (Photo: NASA/GSFC/Arizona State University).


Figure 3: Model of Xe-100 Reactor with Steam Generator

The Xe-100 Nuclear Reactor, developed by X-Energy (shown to the left) is a high-temperature gas-cooled reactor (HTGR). In order to operate at temperatures above 750° C, the Xe-100 utilizes helium gas as a method to extract heat away from the reactor core and moderate operating temperatures. Helium gas does not react with the TRISO-fuel, and absorbs heat as it cycles throughout the core. This heated helium gas is then used to power a steam generator, which produces electricity. In the event of a loss of power or lack of coolant provided to the reactor, the helium gas acts as a passive safeguard, continuing the natural circulation of helium gas throughout the core--cooling it down.

One of the main appeals the Xe-100 reactor is its dominance in efficiency over other nuclear reactors our team researched, with an efficiency rate of 45%.Thus, 45% of the thermal energy produced by the reactor gets converted into electrical energy for use, which is around 10% more efficient than other nuclear reactors (Expanded on below).


Figure 6: 3d printed Xe-100

The efficiency of the Xe-100 reactor is above any other reactor the team researched. Reaching an efficiency rate of 45%. Efficiency is calculated by using the formula for thermal efficiency (η): $\eta = Electrical\ Output\ Energy / Thermal\ Output\ Energy\ x$ 100. This implies that 45% of the thermal energy produced by the reactor is converted into electrical energy. Therefore, the thermal output is approximately 200 MWt (megawatts thermal) and 80 MWe (megawatts electric) and is dependent on the efficiency of the steam cycle (to the left and right are a 3d printed model of the Xe-100 and the size/design in AutoCAD, respectively).

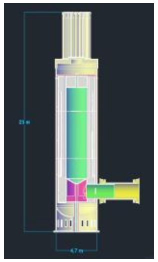


Figure 4: AutoCAD model of Xe-100 Reactor

FUEL

Our Xe-100 Reactor is powered using TRISO (tri-structural isotropic) fuel. TRISO fuel is small, spherical pebbles of uranium oxide coated in three layers of carbon to contain the fission processes within the pebble. Due to these extra layers of carbon coating, the TRISO fuel is much more stable at higher temperatures exceeding 750° C and releases minimal radioactive waste in comparison to other uranium-based fuel sources.

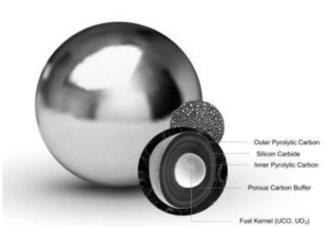


Figure 5: Visual model of the TRISO fuel pellet

SAFETY & EVACUATION PLAN

Thermal insulation and active heat management are essential to regulate extreme temperatures. The reactor's insulation and heat management systems absorb heat during the day and provide adequate warmth during the night.

Thermal Energy Storage:

Implementing thermal energy storage systems, such as phase-change materials (PCMs), help store excess heat during the lunar day. These materials change from solid to liquid at a specific temperature, absorbing heat, and then release it slowly during the night when temperatures plummet.

Active Heating System:

Active heating, such as using resistive heaters or heat pipes, could be employed to maintain critical components, particularly the reactor core, at operational temperatures. These systems could be integrated into the reactor's internal design, keeping it warm during lunar nights.

Evacuation Plan:

In the event of critical reactor failure, astronauts will board a Lunar Terrain Vehicle (LTV) and travel to a safe location until radiation levels return to a safe level. In the event of imminent danger, reaching the Human Landing System (HLS) and returning to the Lunar Gateway would ensure crew returns home safely.

POWER DISTRIBUTION MAPPING

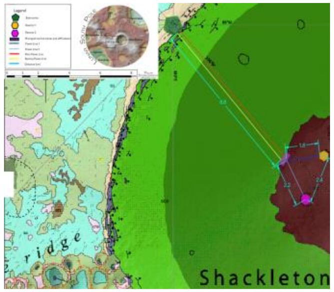


Figure 7: Power Distribution Map

With an output of 80 MWe, Xe-100 will support all energy needs for the Artemis III mission. The provided power system utilizes two reactors with different power lines to increase reliability. The power will be connected to the microgrid control room and the undisrupted power supply (UPS) station to utilize the excess energy and use it as a backup in potential emergency situations. The UPS will also help provide a more stable and consistent power output. In short, the distribution plan contains two power lines to meet the mission's needs, the two-power line solution is utilized to ensure redundancy and power safety of the habitat.