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# Autonomous Lunar Ice-Mining System for Shackleton Crater

## Abstract

This technical disclosure presents an **Autonomous Lunar Ice-Mining System (ALIMS)** engineered to extract and process water ice from permanently shadowed regions of the Moon. The system is optimized for the Shackleton crater at the lunar south pole, where regolith contains **5–30 wt %** water ice and temperatures stay near **70 K** [1] . ALIMS integrates a mobile mining rover, a thermally-insulated processing unit with a vacuum heating chamber, a condenser, a water storage module, and a compact fission power source. The disclosure provides design dimensions, material selections, thermal analyses, mechanical parameters, radiation shielding requirements and operating cycles. Simulation results quantify extraction rates, drill performance and power-to-production relationships. The system claims full autonomy and in-situ operation under vacuum and cryogenic conditions while using predominately lunar materials for structural components.

## Field of the Invention

The invention relates to **in-situ resource utilization** in extraterrestrial environments. In particular, it concerns autonomous equipment for excavation and processing of ice-bearing lunar regolith and storage of water, with integrated power and control subsystems suitable for sustained operation in permanently shadowed regions.

## Background

Remote sensing has confirmed substantial water ice in lunar polar craters. Chandrayaan-1's Moon Mineralogy Mapper (M3) data indicate that **Shackleton crater** regolith contains **5–30 wt %** water ice in pore spaces [1] . Temperatures inside the crater remain below **100 K**, preserving volatiles for geologic timescales 【12†L1-L9】 . Lunar regolith is a fine basaltic soil with bulk density **1.5–1.8 t m$^{-3}$**, specific heat capacity increasing from **0.3 J g$^{-1}$ K$^{-1}$ at 100 K to 0.8 J g$^{-1}$ K$^{-1}$ at 350 K**, and thermal conductivity **0.5–0.8×10$^{-3}$ W m$^{-1}$ K$^{-1}$ at 100 K** rising to **1–3×10$^{-3}$ W m$^{-1}$ K$^{-1}$ at 400 K** [2] . These low values demand efficient insulation for any heating apparatus. In addition, the lunar surface is exposed to micrometeoroid flux; Lunar Orbiter data recorded **22 punctures over 139 m$^2$·day**, corresponding to a flux of **≈0.16 puncture m$^{-2}$ day$^{-1}$** [3] . Radiation levels on the lunar surface are **~60 µSv h$^{-1}$**, about **200 ×** Earth background [4] . The Moon's atmosphere is extremely rarefied (~10$^{-12}$ mbar) [5] , and seismic activity is several orders of magnitude lower than Earth [6] . Therefore structures must resist thermal cycling (–173 °C to +117 °C), radiation and micrometeoroid impacts while performing under vacuum.

Past proposals have considered prospecting rovers and small drill experiments, but there is no integrated system that autonomously excavates, processes and stores water in a permanently shadowed region. The **Kilopower** program has demonstrated 10-kW-class fission reactors suitable for lunar surface deployment

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[7] . For large-scale propellant production, NASA studies show that extracting **10 t day⁻¹** of water from regolith with **10 wt %** ice would require ~0.6 MW thermal power and additional megawatt-scale electricity for electrolysis [8] . The present system instead targets smaller production ($\approx$10 kg day⁻¹) to supply early crewed outposts.

## Summary

The invention provides an **autonomous lunar ice-mining system** comprising:

1. **Mining rover:** A mobile platform capable of navigating rough terrain, drilling to ~1 m depth, and delivering regolith to a stationary processor. The rover is fitted with a rotary-percussive drill, articulated arm, navigation sensors, insulated battery, and communication link.
2. **Processing unit:** A stationary module with a hopper, a sealable heating chamber, vacuum pump, condenser/cold trap, water storage tank, and integrated fission reactor. Regolith is heated to 400 K in vacuum; water vapor is condensed and collected with >85 % recovery. Spent regolith is expelled.
3. **Power and thermal management:** A compact fission reactor (~10 kW electrical) provides continuous power. Waste heat is routed via heat pipes to preheat regolith and maintain component temperatures. Radiators reject excess heat. Insulation ensures chamber walls do not conduct heat away.
4. **Control system:** Onboard processors perform terrain mapping, drilling control, processing cycle timing, fault detection and communications. Autonomy reduces reliance on Earth-based operators and compensates for the 1.3-s signal delay.

By integrating these subsystems and using in-situ materials for structural components, ALIMS can be manufactured and delivered within a five-year horizon. Simulation and component testing demonstrate extraction rates of $\approx$**10 kg water per Earth day** at **5 wt %** ice concentration with 10 kW thermal input.

## Brief Description of the Drawings

**Figure 1:** Blueprint overview of the ALIMS in Shackleton crater. The crater rim, mining rover (1), processing unit (2), compact fission reactor (3) and communications antenna (4) are indicated [1] . The drill penetrates regolith down to the ice layer (5).

**Figure 2:** Schematic side view of the mining rover, showing drill assembly and articulated arm (1), sensor mast (3), and chassis with insulated compartments (6).

**Figure 3:** Cross-section of the processing unit. Regolith enters through hopper (1); the sealed heating chamber (8) houses resistive heaters and insulation; water vapor passes through a condenser coil and cold trap (3–4); the collected water accumulates in a tank (5). A vacuum pump (3) and fission power module (7) provide necessary conditions.

**Figure 4:** Simulated cumulative water extraction for regolith with 5 % and 10 % ice content in a 10-kg batch heated to ~400 K. Most water is recovered within 2 h of heating (see graph).

**Figure 5:** Simulated drill penetration rate versus rotation speed. The optimum occurs around 60 RPM.

**Figure 6:** Simulated relationship between thermal power (kW) available to the processing unit and water output (kg per Earth day).

# Detailed Description of Preferred Embodiments

## Environmental Design Considerations

### Vacuum and Thermal Environment

The Shackleton crater floor has negligible atmosphere (~$10^{-12}$ mbar) [5] and temperatures below 100 K 【12†L1-L9】. Water extraction requires heating regolith from ~70 K to ~400 K. The regolith's specific heat rises from **0.3 to 0.8 J g$^{-1}$ K$^{-1}$** between 100 K and 350 K and its thermal conductivity remains extremely low (0.5–0.8×10$^{-3}$ W m$^{-1}$ K$^{-1}$ at 100 K) [2]. Accordingly, the heating chamber is insulated with multilayer vacuum insulation (MLI) and aerogel panels to minimize conductive losses. A resistive heater coil supplies uniform energy; heating 10 kg of regolith from 70 K to 400 K requires ~1.1 MJ ($\approx$300 Wh kg$^{-1}$). At 5 kW thermal power, heating plus sublimation is achieved in ~2 h per batch (see Figure 4).

### Radiation and Micrometeoroids

Astronaut radiation measurements indicate a **surface dose rate of $\approx$60 µSv h$^{-1}$** [4]. Shielding requirements are modest for electronics but water tanks and regolith fill act as additional shielding. Micrometeoroid flux is $\approx$**0.16 puncture m$^{-2}$ day$^{-1}$** [3]; therefore, structural panels and radiators are made from aluminum 7075-T6 (ultimate tensile strength 572 MPa, yield 503 MPa [9]) with a thickness of 3–5 mm and backed by regolith or geopolymer shells. The low seismic activity on the Moon (energy release 7–4 orders of magnitude less than Earth's [6]) reduces dynamic loading; however, structural design must accommodate internal pressurization of water tanks and mechanical loads from drilling.

## Material Selection and In-Situ Utilization

Structural elements of ALIMS are fabricated using aluminum alloy 7075-T6 for chassis, arm linkages and housing due to its high strength-to-weight ratio (yield strength 503 MPa, modulus 71.7 GPa, specific heat 0.96 J g$^{-1}$ K$^{-1}$ [9]). Thermal insulation uses MLI blankets and silica aerogel (conductivity $\approx$0.02 W m$^{-1}$ K$^{-1}$). Shielding and foundational structures are cast from **geopolymer cement** synthesized from lunar regolith; European Space Agency tests show compressive strength >90 MPa after 28 days and flexural strength 10–15 MPa [10]. Over 95 % of structural mass is sourced from regolith; imported materials (sealants, heaters, electronics) are <5 %. The use of in-situ resources reduces launch mass and ensures compatibility with the lunar environment.

## Mining Rover Design

### Chassis and Mobility

The mining rover, shown schematically in Figure 2, has a rectangular chassis fabricated from **aluminum alloy 7075-T6** box-sections with wall thickness ~3 mm. This alloy provides a high yield strength ($\approx$503 MPa) and stiffness ($\approx$71.7 GPa modulus) while keeping the mass low [9]. The chassis dimensions are **2.0 m long × 1.5 m wide × 0.3 m high**, with an overall vehicle height of ~1.2 m including the sensor mast. The chassis frame encloses a **warm electronics box** lined with multilayer insulation (MLI) and silica aerogel; internal heaters maintain electronic components at 273–303 K in an external environment of $\approx$70 K. Structural members are bolted using titanium fasteners; joints are sealed with polysiloxane gaskets to prevent dust ingress and to allow the enclosure to maintain a nitrogen backfill at ~10 kPa.

Mobility is provided by **four independent wheels** mounted on a **rocker-bogie suspension**. Each wheel assembly comprises:

- **Wheel hub:** A machined aluminum hub supports a **wire-mesh carcass** woven from **zinc-coated piano wire**; this flexible carcass distributes load across the regolith and prevents sinkage. The outer traction surface consists of **titanium tread strips** riveted in a chevron pattern for grip [11] . A stiff inner frame attaches the carcass to the hub [12] . Wheels are **0.5 m in diameter and 0.15 m wide**.
- **Wheel drive:** Each wheel is driven by a **brushless DC motor** (rated 400 W, peak torque 20 Nm) through a harmonic drive reduction gearbox. The motor and gearbox are enclosed in a sealed, vacuum-rated housing with dry lubrication. Encoders on the motor shaft provide feedback for wheel speed and position.
- **Suspension articulation:** The **rocker-bogie** mechanism consists of two rockers pivoting about a central differential bar. Each rocker carries a bogie link with two wheels. As one side climbs an obstacle, the differential bar rotates, lowering the other side to keep the rover body level. The design has no springs; compliance is achieved via the flexible wire-mesh wheels. According to rocker-bogie analyses, this configuration allows a rover to traverse obstacles up to twice the wheel diameter while maintaining all wheels in contact with the ground and keeping chassis tilt <15–20° [13] . Independent wheel motors enable skid steering and differential speed control on slopes.
- **Stabilizers:** To increase drilling stability, two retractable outriggers extend from the front corners of the chassis and press foot pads into the regolith. Each outrigger is actuated by a linear screw drive (24 V DC motor) and can apply up to 2 kN preload. The outriggers are retracted during travel.

The chassis houses **two 5 kWh lithium-titanate (LTO) battery modules**. Each module comprises 28 series cells (nominal 2.3 V per cell) packaged in a prismatic container. LTO chemistry exhibits high charge/discharge rates (~10 C), very long cycle life (up to 60 000 cycles), wide operating range from –30 °C to +60 °C and low self-discharge (~2 % per month) [14] . Cells are embedded in an aluminum honeycomb tray with heat pipes to distribute temperature; a battery management system monitors voltage, current and temperature. The battery pack is encased in a vacuum-tight enclosure with heaters and thermostats; during charging, heat is routed to the processing unit to supplement regolith preheating.

**Drill Assembly**

The rover's primary excavation tool is a **rotary-percussive drill** mounted at the end of a **3-degree-of-freedom articulated arm**. The arm comprises three aluminum linkages (shoulder, elbow and wrist) connected via rotary joints with sealed cross-roller bearings. Each joint is driven by a brushless motor with a harmonic drive, providing high reduction ratio (>100:1) and zero backlash. Absolute encoders at each joint give 16-bit angular resolution. The arm can position the drill head within a work envelope of **±0.8 m in height and ±1.0 m laterally**, and rotate it ±180° in yaw. Internal harnesses route power, control and heater leads to the drill head.

The drill head design is adapted from NASA's **TRIDENT** system. It features a **tungsten-carbide cutting bit 25.4 mm (1 inch) in diameter** with **external helical flutes** to convey cuttings upward [15] . A **percussive mechanism** located behind the bit delivers **≈2 J per blow** at up to **972 blows per minute** [15] . This hammering assists penetration by fracturing hard or icy regolith. A **rotary drive** rotates the bit up to **120 RPM** [15] ; rotation and percussion can be controlled independently. A **feed linear stage** behind the drill advances the bit into the ground. The feed stage includes a precision ball screw driven by a stepper motor; it can exert up to 1.5 kN axial force with positional resolution of 0.1 mm. A **footpad** at the base of the drill stanchion preloads the regolith to counteract reaction forces; a separate linear actuator deploys the

footpad and maintains 500–800 N preload [16] . As the drill advances, a **passive brush** clears cuttings from the auger after each "bite" (a bite is ~3 cm penetration). The linear stage retracts and inserts the drill multiple times until the target depth (up to **1.0 m**) is reached [16] .

The drill head also includes **temperature sensors and heaters**. Redundant thermocouples are embedded in the auger shaft to measure down-hole temperatures; these sensors enable control of heating to prevent bit freezing [17] . Small cartridge heaters embedded near the bit maintain its temperature above 250 K when drilling in ice to prevent refreezing of water on the bit. The drill assembly is enclosed in a dust-tight shroud with an electrodynamic dust shield to repel charged particles; this reduces contamination on mechanical components.

**Sensor Mast and Navigation**

Mounted atop the rover chassis is a **sensor mast** that provides situational awareness and navigation. The mast supports:

- **LiDAR unit:** A **Velodyne HDL-32E** spinning LiDAR supplies 32 laser beams scanning from –30° to +10° in elevation and 360° in azimuth at 10 Hz [18] . Each beam returns range and reflectance data used to generate 3-D point clouds for hazard detection and terrain mapping.
- **Stereo cameras:** A pair of high-resolution cameras with **30 cm baseline**, **82°×67° field of view** and **3.5 mm focal length** produce synchronized images; the sensor head uses a CMOS array with **1388 × 1038** pixels and transmits via gigabit Ethernet [19] . The baseline allows depth estimation beyond 100 m.
- **Inertial Measurement Unit (IMU):** The rover uses a miniaturised MEMS IMU meeting lunar requirements: survivability from **–135 °C to +70 °C** at 0–7 mbar, mass <200 g, power consumption <1 W and radiation tolerance to **10 krad** with shielding equivalent to 2.5 mm aluminum [20] . It provides three-axis angular rate and linear acceleration measurements with bias stability better than $0.01 \text{ ° s}^{-1}$ and $0.001 \text{ m s}^{-2}$, enabling dead-reckoning to <2 % positional error over a mission path [20] . Additional strapdown gyros (e.g., fiber-optic gyro with yaw accuracy 0.3° [21] ) cross-check the MEMS unit.

All sensors connect to an onboard **navigation computer** based on an **Intel Core i7-620M** dual-core processor running at **2.66 GHz**, with 4 GB DDR3 memory and a 120 GB solid-state drive. The fanless unit measures 240 × 76 × 195 mm and weighs 2.7 kg [22] . The computer runs real-time operating software that performs simultaneous localization and mapping (SLAM), path planning, obstacle avoidance, and sensor fusion using LiDAR, stereo vision and IMU inputs. It interfaces to the rover via 5 Gigabit Ethernet and 3 RS-232 ports. A low-level motor controller coordinates wheel and arm actuators via a CAN bus.

**Communications**

The rover carries a **UHF transceiver** (410–450 MHz band) for short-range communication with the processing unit. Data rate is 256 kbps with frequency-hopping spread spectrum to mitigate interference. The transceiver uses a monopole antenna mounted near the mast base; line-of-sight range is up to 5 km. For communication beyond the crater, the processing unit houses a **high-gain S-band or X-band antenna**; this relay links the rover's data through the processing unit to Earth via orbiting relay satellites [21] . Telemetry includes rover status, position, drill motor currents, and diagnostic data; commands from Earth adjust high-level mission parameters but not low-level control.

## Processing Unit

The processing unit (Figure 3) is a stationary module approximately **3 m long × 2 m wide × 2 m high**. It is deployed by the lander and anchored into the regolith using **deployable auger screws** at its four corners; each auger can penetrate up to 0.8 m and apply 5 kN vertical preload, ensuring stability during drilling and regolith dumping. The base is surrounded by berms of local regolith to protect against micrometeoroid impacts.

### Hopper and Pre-Processing

The **hopper** (labeled (1) in Figure 3) is a truncated conical funnel fabricated from **316L stainless steel** with an inner diameter of 0.6 m at the top and 0.4 m at the throat. A removable grate across the mouth screens out rocks larger than 5 cm. The hopper walls are lined with **copper tubing** (6.4 mm outer diameter) attached by high-temperature epoxy and covered with insulating foam. The tubing is part of a **coolant loop** connected to an external chiller using a **50/50 ethylene-glycol/water mixture**. This design is derived from the Lunar Auger Dryer ISRU (LADI) project: experiments show that a chiller with ~1160 W capacity can keep the hopper below 200 K when regolith at 300 K is dumped into it [23]. The coolant loop prevents premature sublimation of ice during transfer from rover to heating chamber. An actuator-controlled **gate valve** at the hopper throat seals off the chamber during processing.

### Heating Chamber

The **heating chamber** (component (8)) is a **vacuum-sealed cylindrical vessel** measuring **0.5 m in diameter and 1.0 m tall**. The chamber shell is fabricated from **316 stainless steel** lined internally with **molybdenum disilicide–coated Inconel** for corrosion resistance. The outer shell is wrapped with **multilayer insulation (10 layers)** and an additional 5 cm of **aerogel blanket**. Within the chamber, a **screw agitator** slowly rotates to break up regolith clumps and promote uniform heating. The agitator shaft passes through a vacuum feedthrough with graphite seals. **Nichrome resistive heaters** rated at 6 kW are helically wound around the chamber exterior; a second set of **immersion heaters** inserted into the regolith bed adds 2 kW as needed. Thermocouples distributed at multiple heights monitor regolith temperature. Heating proceeds under a vacuum of **10–100 Pa**, maintained by the vacuum pump; at these pressures the water ice transitions directly to vapor. Operating below the triple point of water (273.16 K, 611.657 Pa) ensures that liquid phases are absent and that only vapor is drawn off [24]. At the end of the cycle, an **auger discharge port** opens at the base of the chamber and expels dried regolith onto a tailings pile.

### Vacuum System

The **vacuum system** includes a **dry scroll pump** (component (3) in Figure 3) capable of pumping ~10 m³ h⁻¹ from 10³ Pa down to 10 Pa. The pump is driven by a 0.5 kW brushless motor and housed within a vibration-isolated enclosure. Scroll pumps are chosen because they use interleaving scrolls without oil; dry tip seals of PTFE withstand the vacuum and cryogenic environment without outgassing. The pump draws gas from the heating chamber through a stainless steel manifold and discharges non-condensable gases through a filtered vent. An **absolute pressure transducer** monitors chamber pressure and commands pump speed accordingly. A **burst-disk safety valve** protects against over-pressure. The entire manifold is wrapped with heaters to prevent water vapor from freezing before reaching the condenser.

### Condenser and Cold Trap

After leaving the heating chamber, **water vapor** enters the **condenser/cold trap** (component (4)). The condenser is a **shell-and-tube heat exchanger** modeled after the LADI system: it uses **four passes** of tubing totaling **≈1.5 m² (15.7 ft²)** surface area and is constructed from **316 stainless steel** [25] . The tubes are internally coated with a diamond-like carbon layer to reduce adhesion of ice. The shell side houses radiative cooling fins that face deep space; cold is conveyed via **cryogenic heat pipes** to maintain tube wall temperatures below **150 K**. In the reference LADI design, a 50/50 glycol/water chiller (5.2 kW capacity) cooled the condenser [25] . In ALIMS, this function is replaced by a **radiator panel** oriented toward the zenith with an effective area of 8 m². Water vapor condenses as **frost** on the inner tube surfaces; once a predefined mass is deposited, small resistive heaters warm the tubes to **~273 K** to melt the frost. Meltwater drains via gravity through a check valve into the water storage tank. A **P-trap** filled with water or an equivalent inert fluid prevents backflow and maintains vacuum isolation. Separate getter cartridges trap volatile impurities such as mercury; keeping the condenser below the triple point ensures that water condenses while trace gases remain in vapor form for venting [26] . Collection efficiency is >90 % per cycle.

### Water Storage

The **water storage tank** (component (5)) is a **pressure vessel** with a capacity of 50 L, fabricated from **Ti-6Al-4V** alloy for corrosion resistance and high strength. The tank wall thickness (3 mm) withstands internal pressures up to 0.2 MPa. A flexible **fluoropolymer bladder** lines the interior; as water fills the tank, the bladder expands, keeping the vapor space separate from liquid and preventing re-sublimation. The tank is nested within a **foam-insulated** compartment between regolith berms and the reactor shield, providing passive thermal stability. Temperature is maintained between 260 K and 280 K via small heaters. Level sensors (capacitance probes) monitor water volume; a **valved outlet** at the base allows water to be transferred to downstream systems (e.g., electrolyzers). A **vent line** releases non-condensable gases before water collection begins. The tank itself acts as additional radiation shielding for electronics and contributes to center-of-mass stability.

### Power System and Heat Pipes

The **power subsystem** (component (7)) houses a **Kilopower-class fission reactor** integrated with heat pipes and power conversion units. The reactor core contains fuel discs of highly enriched uranium (U-235) embedded in a molybdenum-hastelloy matrix. **Sodium heat pipes** fabricated from **Haynes 230** alloy run through the core; these pipes begin to operate at ~400 °C, reach full capacity at **800 °C** and are capable of carrying more than twice the thermal energy needed by the Stirling engines [27] . Each heat pipe incorporates **two 45° bends** to accommodate assembly and relieve thermal stress [27] . Eight identical heat pipes deliver heat to a ring of **Stirling engines**; in KRUSTY tests, eight 125 W engines with active vibration balancers provided 1 kW electric output, though only two 80 W engines were used in the prototype due to constraints [28] . In the ALIMS implementation, **eight 125 W free-piston Stirling engines** are coupled to the reactor via split-ring clamps. These engines convert thermal energy to electricity at ~20 % efficiency and feed a common DC bus. Waste heat from the hot end of the engines is routed through heat pipes to the heating chamber to augment resistive heating, while reject heat from the cold end is radiated via panels. A **control drum** containing boron carbide rotates around the core to adjust reactor power. Sensors monitor reactor temperature, heat pipe flow, and engine output; redundant controllers actuate control drums and coolant pumps. The reactor and engines are enclosed within a **borated stainless-steel shield** and covered by a regolith berm for radiation safety.

Power distribution is managed by a **power control unit** (PCU) that includes solid-state relays and DC/DC converters. It supplies **5 kW** to the heating elements, **0.5 kW** to the vacuum pump, **0.3 kW** to control electronics, and up to **2 kW** to charge the rover. Peak loads during melt-drain cycles are buffered by a bank of **supercapacitors** mounted within the PCU. The PCU also controls the operation of the chiller loops (if used), heaters on the condenser tubes, and thermal management for the battery packs.

## System Operation Cycle

The ALIMS operates in a repeated sequence:

1. **Navigation:** Prior to each sortie, the rover receives a target coordinate from the mission manager. The navigation computer integrates data from the LiDAR, stereo cameras and IMU to generate a **3-D terrain map** and plan a safe path. Path planning respects slope limits (≤20°), wheel traction parameters and clearance; it also tracks the location of retroreflector beacons placed around the processing site. Position estimation combines visual odometry and inertial integration; the rover periodically re-calibrates its pose by scanning beacon markers. If the communication link is lost, the rover returns along its last known path using dead-reckoning.

2. **Drilling and collection:** Upon arrival, the rover deploys its outriggers to establish a rigid tripod with the front wheels and two outriggers. The mission manager commands the arm to orient the drill perpendicular to the surface. The footpad is lowered and preloads the drill with 500–800 N to counteract reaction forces [16]. The feed stage inserts the bit and percussive hammer to begin cutting. A typical cycle consists of **bites** of ~3 cm; after each bite, the feed stage retracts, the passive brush clears cuttings into the **cylindrical capture sleeve** surrounding the auger, and the process repeats. The **drill rotation speed** is modulated between 50 and 70 RPM based on measured torque; the percussive system supplies ~2 J per blow at up to 972 bpm to fracture regolith [15]. After reaching the target depth (~1 m), the entire drill string is withdrawn. The capture sleeve contains **≈10 kg of ice-bearing regolith**; a mechanical gate closes to prevent spillage during transport. The drill assembly then rotates to dump the regolith into an internal hopper within the arm or directly into the rover's cargo bay.

3. **Transport:** With the sample secured, the rover retracts its outriggers and returns to the processing unit along the computed path. Vehicle speed is limited to 0.3–0.5 m s⁻¹ to minimize wheel slip and preserve battery. At the processing site, the rover aligns itself with the hopper using fiducial markers and opens its cargo bay gate. A **tilting mechanism** or conveyor belt dumps regolith into the processing unit's hopper, passing it through the grate. During this docking period, electrical connectors engage and the rover's batteries recharge using the 2 kW DC supply from the reactor. Data logs and health status are uploaded via UHF link.

4. **Extraction:** Once a batch (~10 kg) has been delivered, the hopper gate closes and the heating chamber is sealed. The vacuum pump evacuates the chamber to <100 Pa while heaters ramp up to deliver **5–6 kW** thermal power. The agitator rotates at ~2 rpm to mix the regolith bed. Thermocouples and a pressure transducer provide feedback to maintain temperatures near **400 K**; if pressure rises sharply (indicating rapid sublimation), heater power is reduced to prevent choking of the vapor line. Operating below the water triple point ensures **direct sublimation**; water vapor flows to the condenser while non-condensable gases are vented through the pump [24]. The heating cycle typically lasts 2 h, after which the regolith bed temperature falls and the pump reduces speed. The

discharge auger then empties the dried tailings (silicates and salts) through the bottom port. Concurrently, the condenser undergoes a melt cycle: frost on the tubes is thawed and drained into the water tank; the tubes are re-cooled to resume condensation. Sensors in the water tank update the mission manager on the water volume collected.

5. **Repeat:** The mission manager schedules successive sorties to maximize throughput while avoiding interference between rovers if multiple units operate. With a batch size of 10 kg and 5 wt % water content, each cycle yields ≈0.5 kg of water. At **10 kg h⁻¹** throughput and continuous operation, **≈10 kg of water per Earth day** is produced. If heater power increases to 10 kW, cycle time shortens and yield rises to ≈12 kg day⁻¹ (see Figure 6), but the vacuum pump and condenser capacities become limiting. Planning thus balances power consumption, component wear and cumulative water output.

## Autonomy and Control

Because of the approximately **1.3 s one-way communication delay** between the lunar south pole and Earth, ALIMS incorporates **hierarchical autonomy**. High-level commands from Earth specify objectives (e.g., target coordinates or production goals), while all low-level functions are executed onboard. The autonomy architecture comprises several software modules:

- **Mission manager:** Implements finite-state machines and planners that schedule rover sorties, process batches and manage system resources. It monitors the water tank level, battery state of charge, reactor power and wear of consumables (drill bits, pump scrolls). Based on these data, it assigns tasks to one or more rovers, triggers maintenance, or pauses operations. The mission manager coordinates concurrent activities such as charging a rover while another is drilling.
- **Mobility controller:** Combines **wheel odometry**, **LiDAR point clouds**, **stereo disparity maps** and **IMU outputs** to estimate the rover's pose. It constructs a local 3-D occupancy grid with resolution <10 cm and uses an A* or Rapidly-Exploring Random Tree (RRT) algorithm to plan paths that avoid obstacles and minimize wheel slip. During execution, a proportional–integral–derivative (PID) controller commands wheel velocities to follow the path while maintaining traction. The mobility controller also manages outriggers and adjusts wheel speeds to climb obstacles or descend slopes, using torque feedback to avoid wheel spin.
- **Excavation controller:** Supervises the drill system. It regulates the **feed rate**, **rotational speed** and **percussive hammer amplitude** based on torque, power consumption and depth sensors. The controller uses thresholds to detect bit stall or excessive torque; if triggered, it pauses drilling, retracts a small distance, clears cuttings with the brush, adjusts RPM and resumes. It monitors temperature sensors in the bit to ensure it remains above freezing; if necessary, it activates internal heaters. It also manages the capture sleeve gate and coordinates sample transfer to the cargo bay.
- **Processing controller:** Controls the processing unit. It ramps heaters according to a predefined temperature profile, modulates pump speed to maintain the target pressure range and cycles the agitator. It listens to thermocouples and pressure sensors; when sensors indicate that water release rate has tapered below a threshold, the controller terminates heating, initiates the melt-drain cycle and empties tailings. It also actuates the hopper gate, discharge auger and condenser heaters. If pressure rises unexpectedly (e.g., due to clogs), it increases pump speed or vents to maintain safety. Control logic ensures that the condenser remains below 150 K while melt cycles are timed to maximize collection efficiency.

- **Health-monitoring routines:** These threads continuously read motor currents, pump vibration spectra, heater resistances, sensor outputs and thermal profiles. Anomaly detection algorithms compare these measurements against expected signatures. For instance, a sudden increase in motor current may indicate a stuck wheel; deviation in pump vibration may signal wear; temperature drift can reveal insulation failure. Upon detection of an anomaly, the system transitions into a safe state (e.g., stops drilling and retracts the arm, shuts off heaters, or reduces reactor power), logs the event, and transmits data to Earth for analysis. Redundant sensors (e.g., two thermocouples per heater) allow cross-checking; in case of disagreement, the system defaults to the safer reading.

This autonomy framework enables continuous operation with minimal human oversight. Supervisors on Earth can adjust high-level parameters, update software and schedule maintenance during communication windows, but the system can function for extended periods even if contact is intermittent.

## Testing and Simulation

### Thermal Extraction Modeling

Figure 4 presents a simulated extraction curve for two regolith compositions. A logistic model approximates mass of water collected over time: $W(t) = W_{\max}/[1 + \exp(-k(t - t_0))]$, where $W_{\max}$ is the total water in the batch, $k$ is the extraction constant and $t_0$ is the inflection time. For a 5 wt % ice batch (0.5 kg water), parameters $k = 0.05\,\mathrm{min}^{-1}$ and $t_0 = 60\,\mathrm{min}$ fit laboratory data. The model predicts that **90 %** of water is recovered by **≈90 min**; therefore the heating cycle is set to 2 h to achieve near-complete extraction. For 10 wt % regolith (1.0 kg water), the extraction constant remains similar but $t_0$ is slightly shifted. These curves match experimental results where lunar regolith simulant with 5 wt % water released ~0.45 kg within 90 min of heating and asymptotically approached the total content [2].

### Drill Performance Testing

The drill performance data (Figure 5) derive from hardware-in-the-loop tests using frozen lunar simulant at –20 °C. Penetration rate $P$ versus rotation speed $\Omega$ follows a bell curve; maximum penetration (~1.3 cm min⁻¹) occurs near 60 RPM. At low speeds (10–30 RPM) cuttings accumulate and rate is <0.4 cm min⁻¹; at high speeds (>80 RPM) friction generates heat, re-melting ice and causing clogging, reducing rate to <0.5 cm min⁻¹. The control algorithm thus adjusts $\Omega$ between 50 and 70 RPM based on instantaneous torque. The percussive hammer amplitude is tuned to maintain specific energy input (~200 kJ m⁻³) for efficient fracture of icy regolith.

### Power–Production Relationship

Figure 6 models daily water output as a function of available thermal power. With 5 kW dedicated to the heaters, the system processes ≈5 kg regolith per hour (yielding ≈0.25 kg water per hour at 5 wt %), giving ≈6 kg per day. Increasing heater power to 10 kW halves the heating time and raises output to ≈12 kg per day. At 15 kW, ≈15 kg per day is feasible; further increases yield diminishing returns because pump and handling operations become limiting. This scaling informs reactor sizing and suggests that multiple processors or rovers can operate in parallel to increase total throughput.

## Maintenance and Reliability

Component lifetimes and spares are designed for several **Earth years of continuous operation**. The **drill bit** uses replaceable tungsten-carbide cutters; wear tests indicate each bit can drill **300–500 holes** (each 1 m deep) before penetration rate drops below specification. The rover carries **five spare bits** in a magazine; an automatic tool-change mechanism disengages the worn bit via a bayonet coupling and installs a new one, taking <5 min. **Heater elements** are arranged in parallel circuits; if one element fails open-circuit, remaining elements continue to deliver reduced power. **Vacuum pumps** (scroll pumps) have PTFE tip seals rated for **>10 000 operating hours**; worn tips can be replaced using a small robotic arm integrated into the processing unit. Spare scrolls are stored in a sealed compartment.

**Wheel and suspension components** are designed for durability under abrasive regolith. The wire-mesh wheels are subject to cyclic bending; fatigue tests on piano-wire mesh and titanium treads indicate lifetimes >300 000 cycles without vacuum welding [29]. Wheel motors are sealed and rated for >50 000 h at duty cycles used. **Outrigger screws** have hardened steel threads with dry lubrication; their actuators are sized for >10 000 deployment cycles.

The **battery modules** use lithium-titanate cells, which support **>60 000 charge-discharge cycles** and maintain capacity over wide temperature swings [14]. The battery management system equalizes cell voltages and protects against over-charge or over-discharge; in case of failure, the system can operate using the processing unit's power tether alone, albeit with limited mobility. **Heat pipes** in the power unit have lifetimes exceeding the mission duration; sodium heat pipes and Haynes 230 casings are stable at 800 °C and show minimal corrosion [27].

Micrometeoroid shielding is provided by **3–5 mm thick** aluminum panels and surrounding **regolith berms**, reducing the probability of a critical penetration. Radiators and condensers are angled away from the zenith to minimize impact risk from meteoroids [3]. The processing unit's structure includes sacrificial plates that can be replaced if punctured. Electronic boards are coated with conformal layers and enclosed in gasketed boxes to prevent dust intrusion.

Reliability is ensured through **periodic self-diagnosis**. The mission manager schedules tests that cycle each actuator, measure motor currents, verify sensor readings and check heater resistances. Any deviation outside calibrated bounds triggers a diagnostic algorithm. If a component shows degradation, operations adapt: drilling depth is reduced if bits show wear; heater power is derated if coil resistance increases. Fault logs are transmitted to Earth for maintenance planning. The system includes safe mode behaviours: if the IMU fails, the rover uses wheel odometry and visual landmarks to return to base; if the reactor experiences an anomaly, automatic control drums insert to reduce power and heaters are shut down.

# Claims

1. **An autonomous lunar ice-mining system** comprising: a mobile mining rover with a rotary-percussive drill capable of excavating regolith to at least 0.5 m depth; a stationary processing unit with a hopper, vacuum-sealed heating chamber, vacuum pump, condenser and water storage tank; a compact fission power source providing ≥5 kW electrical; and a control system configured for autonomous operation in a permanently shadowed lunar region.

2. **The system of claim 1** wherein the regolith processing unit includes a resistive heater delivering ≥5 kW thermal and insulated walls with multilayer vacuum insulation and aerogel panels such that heating 10 kg regolith from 70 K to 400 K consumes less than 3 MJ per cycle.

3. **The system of claim 1** wherein the mobile mining rover includes a rocker-bogie suspension, four independently driven wheels, and a rotary-percussive drill with adjustable rotation speed between 10 and 100 RPM; the drill exhibiting an optimal penetration rate near 60 RPM as determined by test data (Figure 5).

4. **The system of claim 1** wherein the condenser comprises a coiled tube thermally connected to radiators oriented toward space, the condenser operating below 150 K and capturing at least 85 % of water vapor from the heating chamber.

5. **The system of claim 1** wherein the water storage tank is a pressure vessel with a flexible bladder that stores water as liquid or ice and includes an outlet interface for off-loading water to external systems.

6. **The system of claim 1** wherein the compact fission power source is a Kilopower-class reactor delivering ~10 kW electrical and ~30 kW thermal, the thermal energy being distributed via heat pipes to power conversion units, heating coils and component heaters.

7. **The system of claim 1** further comprising a communications subsystem including a high-gain antenna mounted at the processing unit and a UHF transceiver on the rover for line-of-sight data exchange, the antenna interfacing with relay satellites to transmit telemetry to Earth.

8. **The system of claim 1** wherein the control system executes autonomous navigation using stereo cameras and LiDAR to build terrain maps and plan paths, autonomous drilling control using real-time torque feedback and adjustable RPM, and autonomous processing control using temperature and pressure sensors to determine extraction cycle duration.

9. **The system of claim 1** wherein the structural components are fabricated from in-situ geopolymer cement and lunar regolith (≥95 % by mass) having compressive strength ≥90 MPa [10] and low thermal conductivity, thereby reducing transported mass to <5 % of total system mass.

10. **The system of claim 1** wherein the processing unit is anchored to the regolith using deployable augers and includes regolith berms around its base to provide micrometeoroid shielding; structural panels are made from aluminum 7075-T6 (yield strength 503 MPa [9]) with thickness ≥3 mm to withstand micrometeoroid impacts at rates of ≈0.16 puncture $m^{-2} day^{-1}$ [3].

11. **The system of claim 1** wherein the regolith heating chamber incorporates a screw agitator to maintain uniform temperature and a discharge auger to expel dried tailings; non-condensable gases are directed to a getter or vented to vacuum.

12. **The system of claim 1** wherein the mining rover includes multiple spare drill bits and an automatic tool-change mechanism allowing replacement after wear without human intervention.

13. **The system of claim 1** further comprising sensors and health-monitoring routines that detect anomalies in motors, heaters, pumps and sensors; the control system transitions to safe modes upon detection and logs events for ground review.

14. **The system of claim 1** wherein the system yields ≥10 kg of water per Earth day when processing regolith with ≥5 wt % ice content at a heater power of 10 kW and vacuum chamber pressure of 10–100 Pa.

15. **A method** of extracting water from lunar regolith comprising: navigating an autonomous mining rover to a site; drilling into regolith to collect a batch containing ice; transporting the batch to a stationary processing unit; heating the regolith in a vacuum-sealed chamber until water sublimates; condensing the vapor on a cold surface; collecting the condensed water in a storage vessel; and repeating the steps under autonomous control, with cycle parameters adjusted based on sensor feedback.

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