

## ON THE EXTRACTION OF VOLATILES FROM LUNAR REGOLITH USING SOLAR POWER.

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**Introduction:** Lunar Crater Observation and Sensing Satellite (LCROSS) and Lunar Reconnaissance Orbiter (LRO) missions have confirmed that in polar regions of the Moon, craters can act as cold storage, capable of accumulating and preserving volatile materials like water ice [1]. The concentration of water in the regolith at the LCROSS impact site is estimated to be  $5.6 \pm 2.9$  wt. % [2]. Other volatiles such as mercury, sodium, sulfur dioxide, carbon dioxide, formaldehyde, ammonia and methanol have been identified [3].

Extraction of water and other useful volatiles from lunar regolith promises great opportunities for the future exploration missions. The present paper investigates methods for the extraction of volatiles from regolith within the shadowed craters of the Moon using solar power.

The concept involves transfer of beamed solar power from concentrators, located either onboard orbiters (Fig. 1) or on the top of the crater walls, to the volatile extraction and processing system, located in the shadowed area. A preliminary design for the extraction system includes an oven heated by solar power that is transferred by the fiber optics from the solar concentrator (Fig. 2). Note that the feasibility of transferring concentrated solar energy by the fiber optics has been demonstrated in successful tests of the optical waveguide solar thermal power system for ISRU applications [4]. The regolith is heated to the temperatures that exceed the boiling points of the contained volatiles at the atmospheric pressure of the Moon. As each volatile reaches its liquefaction point and condenses out of the gas mixture, it is pumped into a separate storage tank.

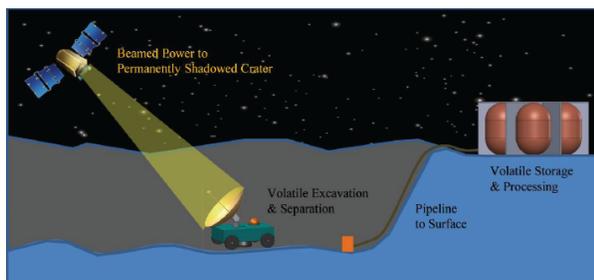


Fig. 1. Lunar volatile extraction architecture.

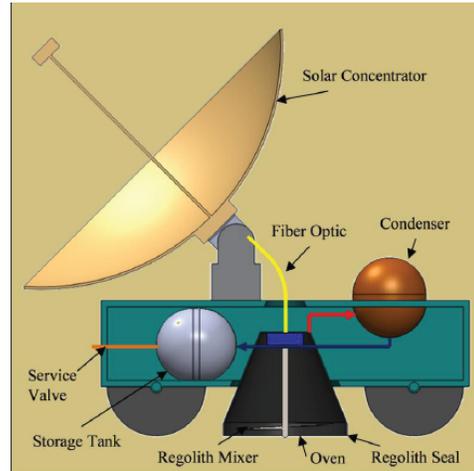


Fig. 2. Volatile extraction and processing system.

To develop the extraction equipment, it is necessary to determine the amount of power that is required for the sublimation of frozen volatiles, located in the lunar regolith. Temperature and atmospheric pressure in the craters of the Moon are 40 K and  $10^{-7}$  Pa, respectively. Note that at 40 K, ice sublimates if pressure is lower than  $10^{-54}$  Pa [5], which explains the existence of ice in lunar craters. To extract volatiles on the Moon, the regolith should be heated to the boiling point at  $10^{-7}$  Pa. For example, the boiling point of water at this pressure is 134 K.

The present paper focuses on the analysis of heat transfer from the top surface of regolith, irradiated by the light beam, down to the underlying layers. This analysis is needed for the determination of required solar power.

**Results and Discussion:** A two-dimensional steady model for heat transfer in the surface layer of lunar soil irradiated by a vertical light beam was developed using GAMBIT software. The radiation from the regolith surface to the space was neglected. A square of specified size was considered in the vertical plane of the regolith. All four sides of the squares were defined as walls at 40 K and the inside area was defined as the lunar regolith. After the GAMBIT model was created, it was imported into ANSYS FLUENT software, where boundary conditions were assigned to the simulation. The density, specific heat, and thermal conductivity of regolith were taken from [6, 7].

Different values of the heat flux transferred by the light beam were tested.

Figure 3 shows the obtained temperature field in the top part of the selected square area 1 m x 1 m (mesh size 2 mm) at the heat flux of 1000 W/m<sup>2</sup>, while Figure 4 shows the calculated temperature along a vertical axis that aligns with the direction of the beam. It is seen that the temperature exceeds the boiling point of water (134 K at 10<sup>-7</sup> Pa) in a layer as deep as 6 cm.

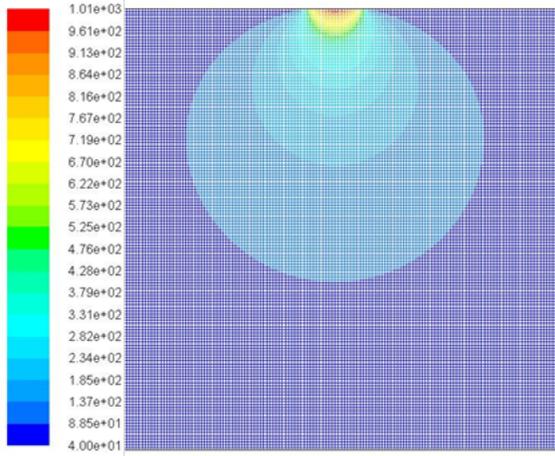


Fig. 3. Temperature field in the surface layer of the Moon heated by the light beam with energy flux of 1000 W/m<sup>2</sup>.

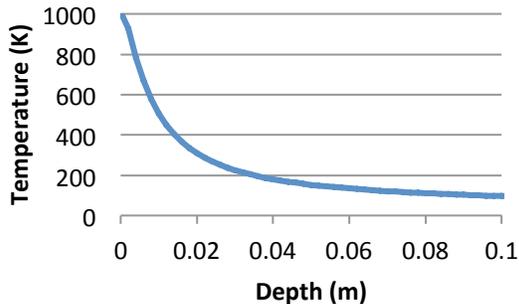


Fig. 4. The regolith temperature as a function of depth calculated for the light beam with energy flux of 1000 W/m<sup>2</sup>.

For accurate calculations, the size of the selected area should be sufficiently large, so that the mesh size does not affect the results. Figure 5 shows that at the mesh size 1-5 mm, the “boiling” depth is almost insensitive to the size of the selected area if this size is larger than 0.5 m.

Finally, Figure 6 demonstrates that with increasing the heat flux, the “boiling” depth increases.

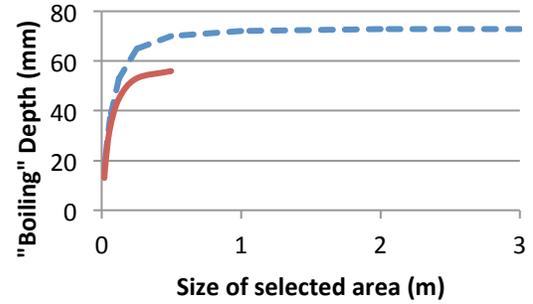


Fig. 5. The “boiling” depth as a function of the size of the selected area; heat flux: 1000 W/m<sup>2</sup>; mesh size: 1 mm (solid curve) and 5 mm (dashed curve).

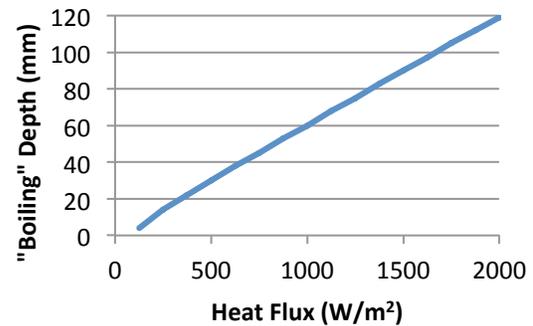


Fig. 6. The “boiling” depth vs. the heat flux in the light beam (the area: 1 m x 1 m, mesh size: 2 mm).

**Conclusions:** A two-dimensional steady model has been developed for heat transfer in lunar regolith irradiated by a beam of concentrated solar power. The model allows one to calculate the depth that can be heated to the boiling point of water or any other volatile at the atmospheric pressure of the Moon.

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**References:** [1] Gladstone R. et al. (2010) *Science*, 330, 472-476. [2] Colaprete A. et al. (2010) *Science*, 330, 463-468. [3] Paige D. et al. (2010) *Science* 330, 479-482 [4] Nakamura T. and Smith B. (2011) 49<sup>th</sup> AIAA Aerospace Sciences Meeting, 4-7 Jan. 2011, Orlando, FL, AIAA 2011-433. [5] Feistel R. and Wagner W. (2007) *Geochimica et Cosmochimica Acta*, 71, 36-45. [6] Balasubramaniam R. et al. (2009) 47<sup>th</sup> AIAA Aerospace Science Meeting, 5-8 Jan. 2009, Orlando, FL, AIAA 2009-1339. [7] Sibille L. et al. (2006) *Lunar Regolith Simulant Materials: Recommendations for Standardization, Production and Usage*, NASA/TP—2006-214605.