ICE MINING IN LUNAR PERMANENTLY SHADOWED REGIONS.

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Introduction

The Colorado School of Mines has developed a system architecture for a lunar permanently shaded region (PSR) mining operation to extract and process water ice to LOX/H2 propellant. A key component of the architecture is an ice extraction method called thermal mining. In thermal mining ice is sublimated by applying heat directly to the surface of the PSR and the near subsurface, then directing vapor to cold traps where it freezes for transport to a processing system. The overall CSM PSR ice mining architecture is shown in Fig. 1, while Fig. 2 shows a schematic of the thermal mining capture tent and cold trap subsystem.

Motivation

Methods for extraction of PSR ice can be grouped into two classes: extraction based on bulk physical removal of icy regolith as solid material from the ground and extraction based on in situ sublimation of ice that allows regolith to remain in place. Excavation-based methods are typified by bulk excavation of the surface using rovers equipped with shovels, bucket ladders, or bucket wheels. Excavation methods require transport and handling of large volumes of regolith, which drives up mass and power requirements of PSR ice collection. Extraction methods based on sublimation of ice directly from the surface using directed energy methods, such as sunlight, microwaves, or radiant heaters avoid many of the drawbacks of excavation methods. Sublimation of ice in the ground is followed by vapor transport to a collector that hauls only the ice to a processor.

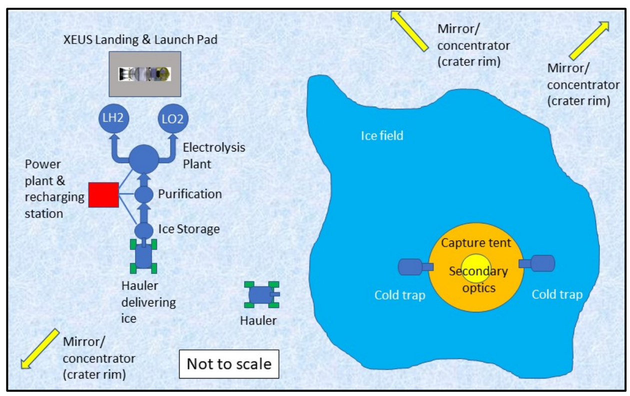

***Figure 1**. System architecture. Plan view.*

Thermal Mining

In thermal mining heat is applied either directly on the surface via concentrated sunlight, subsurface via conducting rods or heaters placed in boreholes, or both depending on the local conditions. The heat sublimates ice into vapor, which escapes from the surface. Vapor is captured by a dome-shaped tent covering the heated surface. Vapor in the tent is vented through openings into cold traps outside the tent where it refreezes. Once the cold traps are full of refrozen ice, they are removed and replaced with empty cold traps. The ice-filled cold traps are transported to a central processing plant for refinement into purified water, oxygen, or

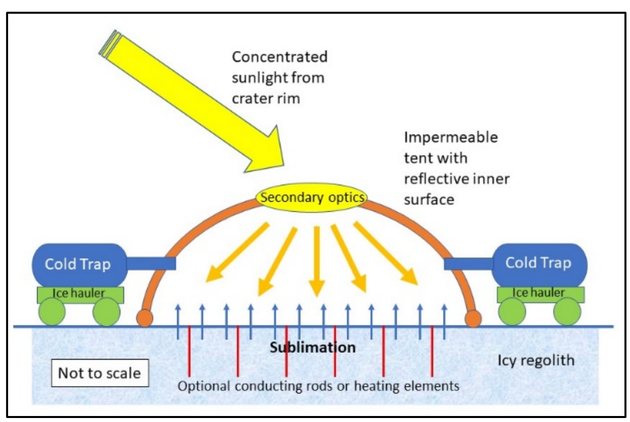

***Figure 2**. Thermal Mining concept.*

liquid hydrogen (LH2)-liquid oxygen (LO2) propellants. The entire operation can be tele-operated from Earth. Critical functional steps of thermal mining are:

1. Sublimation of ice and transport of water vapor through the subsurface
2. Equalization of the vapor production rate to sum of cold trapping and vapor loss rates
3. Reduction of vapor loss rate to a low level
4. Power delivery and passive cooling of the cold traps

Sublimation and Vapor Transport

In thermal mining the surface of the PSR is heated to sublimate ice and transport vapor through the surface. The goal is to cause a sufficient rate of water vapor transport out of the surface to meet overall system production rates. The process is governed by heat transfer through the surface, vapor generation via sublimation, and vapor transport through the surface. An adequate rate of vapor transport out of the PSR surface can be generated due to several factors: (1) the heat transfer rate of icy regolith is significantly greater than dry regolith, (2) sublimation of water increases to high rates above 200K, and (3) LCROSS mission data suggest the surfaces in the PSRs are porous, thus vapor can diffuse through the subsurface.

Balancing the rates

Figure 3 shows a schematic of the Thermal Mining ice extraction process that focuses on the movement of gas through the tent and cold trap. The process can be described by a differential equation:

$$\frac{dm}{dt} = \dot{m}_{sublimation} - \dot{m}_{deposition} - \dot{m}_{loss}$$

where m is the mass of water vapor in the tent at any time, $\dot{m}_{sublimation}$ is the mass flow rate of water vapor emerging from the PSR surface via sublimation, $\dot{m}_{deposition}$ is the mass flow rate at which water is frozen in the cold trap, and $\dot{m}_{loss}$ is the rate water vapor is lost through leaks in the tent, which is primarily due to the imperfect gap between the tent and the PSR surface. We assume that $\dot{m}_{loss}$ can be kept to <10% of $\dot{m}_{sublimation}$, which requires that the surface area of the tent-to-surface gap be <10% of the cold trap entrance area. In this analysis we assume the cold trap has sufficient internal surface area to capture ice and sufficient heat dissipation via radiation to the environment to freeze ice at $\dot{m}_{deposition}$.

Freezing ice within the cold trap is an effusion process.

$$\dot{m}_{deposition} = pA_{coldtrap}\sqrt{\frac{M_{H_2O}}{2\pi RT}}$$

where p is the pressure in the tent, $A_{coldtrap}$ is the entrance area of the cold trap, and T is the temperature of a water molecule. A similar effusion equation can be written for $\dot{m}_{loss}$ by replacing the cold trap entrance area with the area of the gap between the tent and PSR surface. Using the ideal gas law, the mass of water vapor under the tent, m, can be written in terms of the pressure, volume, and temperature of gas under tent. The differential equation then becomes a first order ODE for pressure as a function of time.

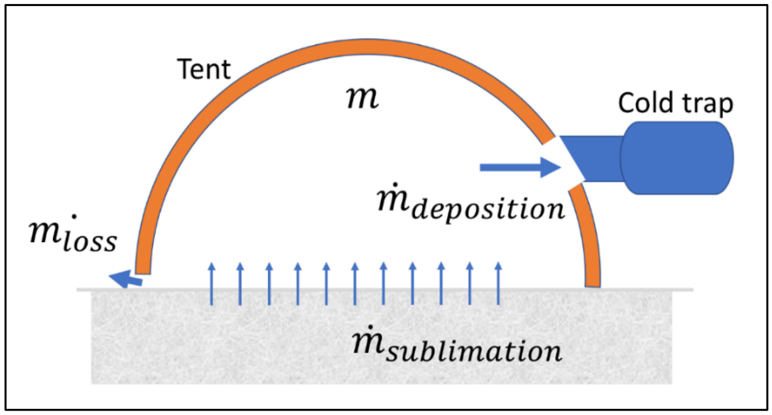

Figure 3. *Thermal Mining ice extraction process.*

The surface must be heated to a temperature such that sublimation proceeds at a rate sufficient to meet production goals. Kossacki (Kossacki and Leliwa-Kopystynski, 2014) show that the sublimation rate increases rapidly above 200 K and Andreas (Icarus, 2007) shows that 100 µm diameter ice grains lose mass rapidly above 170 K. Surface temperature for sublimation was set at 220 K. At this temperature, the system quickly goes to steady state in minutes, and the tent pressure will equilibrate at 10 to 30 Pa for a cold trap entrance area of 1 m^2. Quick approach to steady state means that the tent transfer dynamics will essentially be in steady state throughout operation and the transients in the overall system are governed by heat transfer, sublimation, and vapor transport through the surface. Low operating pressure is important for several reasons: (1) if the pressure rises too high the tent can lift off the surface, and (2) the mean free path is less than the characteristic dimensions of the system (<1 m), which ensures that the analysis and modeling methods are in the correct flow regime.

Power Delivery

Critical components of thermal mining are power delivery for sublimation of ice from the PSR surface and power to freeze the vapor into the cold traps. Figure 4 shows the power needed to extract ice by sublimation from the PSRs. Power is sensitive to ice content below 2wt% ice because it is dominated by the power needed to heat regolith; whereas, above 5wt% the power becomes relatively insensitive to ice content. Extracting the ice is a two-step process: heating the icy regolith mixture from 40 K to 220 K followed by sublimation.

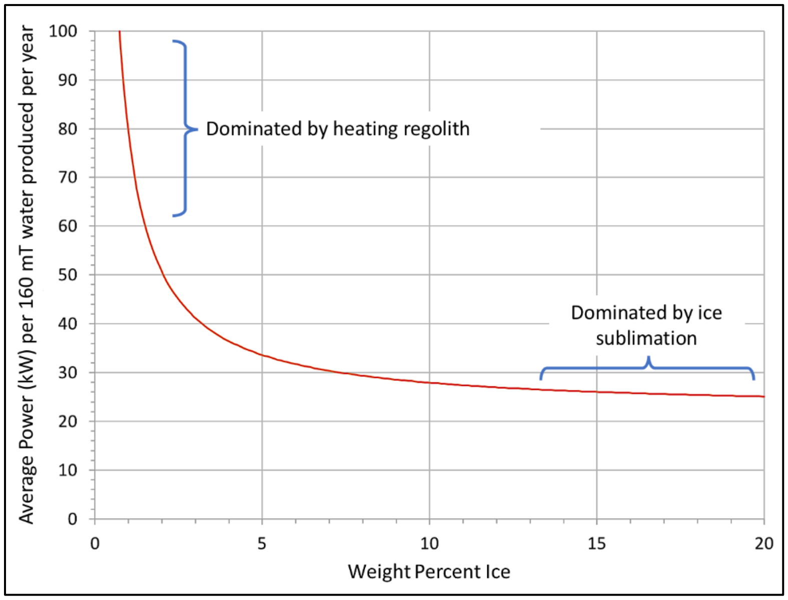

Figure 4. *Power to extract 160 mT of water ice per year with 70% solar availability as a function of water weight.*

The best estimate of lunar PSR water ice content comes from the LCROSS mission at 5.5wt% ice, while other estimates put the ice content at 10wt% and the most pessimistic estimates put it at 1wt%. This suggests that the thermal mining process should be situated at a location with more than 4wt% ice.

Thermal mining employs a cold trap that is passively cooled by radiation to the ambient PSR environment. The surface of the PSRs are as low as 40K, while space is 2.7K. The cold trap must provide sufficient cooling capacity to dissipate the heat of deposition (equal to the heat of sublimation). This can be provided by the thermal mass of the cold trap and sufficient radiative surface area on the cold trap. The cold trap temperature will drop to near the ambient environment during transport between the tent(s) and gas processing system. Ice collection in the cold trap will proceed until the cold trap surface temperature is equal to the ice vapor temperature. A combination of thermal mass, radiative surface area on the cold trap, and con-ops of cold trap haulers will provide sufficient cold trap passive cooling.

Thermal Mining Sizing

A thermal mining sizing solution for water extraction of 1600mT per year is shown in Table 1. Thermal mining can be scaled to meet any water extraction goal, larger or smaller by scaling the tent or adding more tents, cold traps, and other thermal mining system elements. Extractable ice per surface area is estimated to be 16 kg/m^2. The solution includes tents of 29 m diameter. A single tent would need to be placed 243 times per year. Additional tents would provide additional margin. The number of ice haulers depends on the density of ice in the cold trap, volume of cold trap, ice hauler traverse speed, distance between ice field and processing station, and transfer time at the processing station.

Table 1. *Baseline Thermal Mining design.*

Requirement	Value
Area mined (m^2 / year)	100,000
Yield per m^2 (kg)	16
Ice sublimated per m^2 (kg)	18
Dwell time (hour)	44
Move time (hour)	12
Power (kW)	500
Tent diameter (m)	29
Tent plan area (m^2)	641
Exit area to cold traps (m^2)	2
Leak area (m^2)	0.2

Conclusions

Thermal mining is an efficient, scalable, sustainable method of ice mining at the lunar poles. This method works best in any ice type as long as there is space for vapor transport. The method benefits from direct solar energy transfer while using variable heating to control production rate. With lower weight and fewer moving parts, thermal mining provides a feasible alternative to traditional excavation concepts.

References

Andreas, E.L., 2007. New estimates for the sublimation rate for ice on the Moon. *Icarus*, 186(1), pp.24-30.

Kossacki, K.J. and Leliwa-Kopystynski, J., 2014. Temperature dependence of the sublimation rate of water ice: Influence of impurities. *Icarus*, 233, pp.101-105.