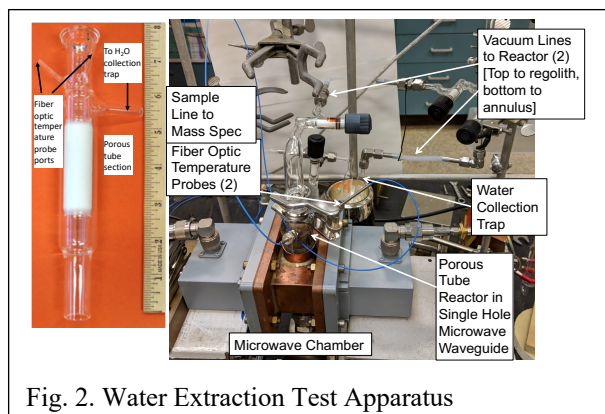
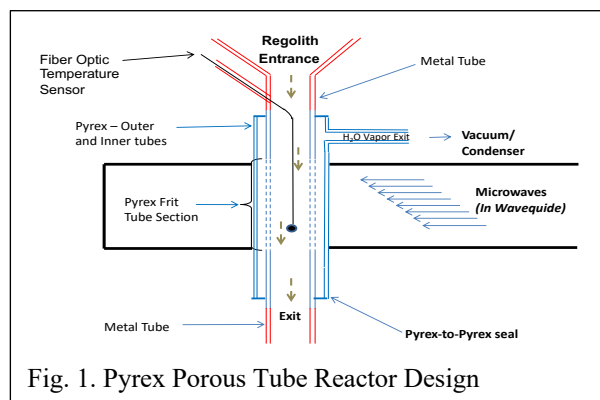


**APPROACHES FOR EXTRACTING VOLATILES FROM REGOLITH USING ELECTROMAGNETIC RADIATION.** G. Voecks<sup>1</sup>, M. Barmatz<sup>1</sup>, J. Lux<sup>1</sup>, G. Gavalas<sup>2</sup>, D. Hoppe<sup>1</sup>, D. Steinfeld<sup>1</sup>, J. Batres<sup>1</sup>, and O. Igbinosun<sup>1</sup>, <sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, M/S 125-109, 4800 Oak Grove Drive, Pasadena, CA 91109, E-mail: [Gerald.E.Voecks@jpl.nasa.gov](mailto:Gerald.E.Voecks@jpl.nasa.gov), <sup>2</sup> California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125.

**Introduction:** NASA is planning astronaut missions to the moon and Mars. Water will be essential for the success of these missions. We have evaluated various electromagnetic radiation methods to extract water from ice contained in lunar regolith material. These methods do not depend on heat transfer to heat the material because, with uniformly applied radiation, the material can uniformly absorb the energy. This can result in a more uniform temperature profile as the ice sublimates into vapor. In designing an efficient reactor, to sublime ice, there are four parameters to consider that impact the energy and extraction efficiency with respect to time: (1) the energy absorption by the regolith, (2) the rate of applying the absorbed energy, (3) the temperature increase throughout the heated volume of material caused by the energy absorption, and (4) the water vapor pressure differential generated within the volume of regolith material created by the transfer of heat energy to sublime the entrapped ice. The interaction of the four parameters sets the boundaries for the energy/time/quantity of water collected.

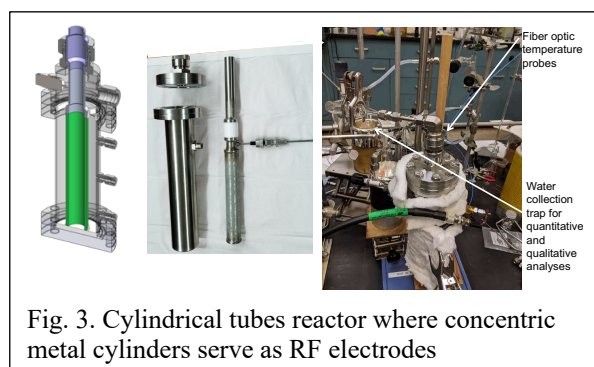
**Approaches:** Our initial studies used a resonant microwave system [1,2] coupled to a volatile condensation unit to efficiently extract water from Mars simulants containing hydrated minerals. For this process, we designed a porous tube reactor shown in Fig. 1 that has been used with 2.45 GHz microwave for both Mars and lunar regolith simulant studies. In this design, water vapor will transfer through the porous Pyrex frit wall into an evacuated annulus through which it will transfer to a condensing unit for collection. Figure 2 shows a picture of the test apparatus. Tests with this apparatus have included ambient (Mars) and -20°C (lunar) conditions. These studies have been performed



with batch samples to validate this concept approach.

**30 MHz RF Reactors:** We have also been investigating the application of RF for water extraction. The concept is to apply an RF field across two metal electrodes. Two experimental RF reactor designs have been evaluated for extracting water from lunar regolith simulants containing ice. One design incorporates a porous metal cylinder tube inside a metal cylinder while the other utilizes a parallel plates approach. The advantages of applying RF are (1) porous metal rather than porous glass can be employed and (2) the efficiency of the electronics is higher at this RF frequency compared to 2.45 GHz. Figure 3 illustrates a cylindrical tube reactor design. Water vapor sublimated during heating of the regolith located in the annulus between the two cylinders is transferred through the evacuated central porous cylinder for collection in a cold trap. This approach may have significant advantages in a drilling system where the outside cylinder serves as a coring drill.

An alternative 30 MHz RF reactor approach



consists of two parallel metal plates with the regolith situated between the plates. In this design, one of the plates is porous for extracting the sublimed water vapor. This reactor design can be easily scaled-up for extracting large amounts of water

One example of a scaled-up reactor for space applications is shown in Fig. 4. The belt in this device can be moved at a rate commensurate with the amount of water released and the power applied while monitoring the temperature of the regolith as it passes from inlet to exit. One operating option would vary the RF field from the inlet section to the exit section, as a function of the ice content and temperature. The area of the 'bed' within the RF field can be chosen to match the thickness of material passing between the plates.

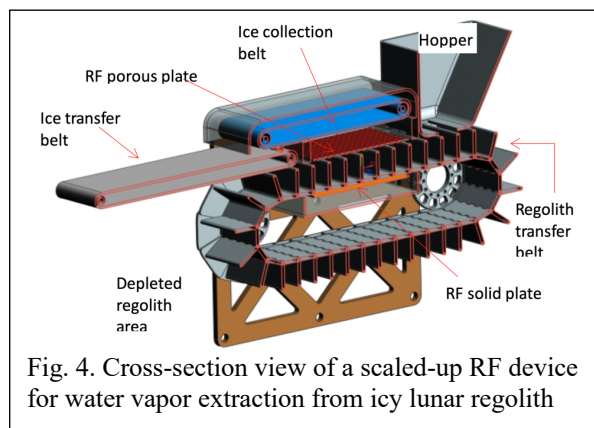


Fig. 4. Cross-section view of a scaled-up RF device for water vapor extraction from icy lunar regolith

We have developed a sublimation model that can be used to predict the expected water extraction under various operating conditions. An example of these predictions for a RF parallel plates reactor is shown in Fig. 5. For this case, 2500W was supplied to a 1-meter by 1-meter cross-section RF parallel plates reactor with a 6 cm thick sample (85.4 kg) containing 5% ice crystals. The top plate had 100  $\mu$  pores (40% porosity).

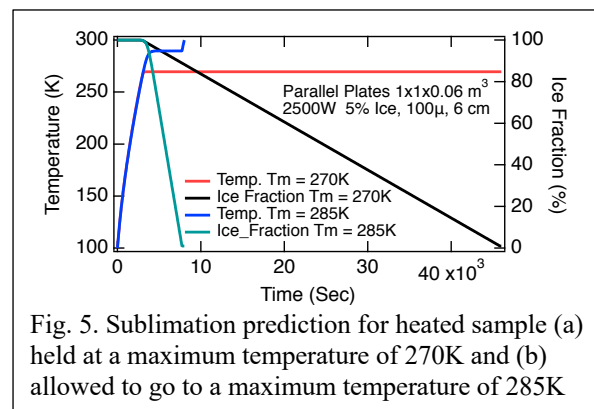


Fig. 5. Sublimation prediction for heated sample (a) held at a maximum temperature of 270K and (b) allowed to go to a maximum temperature of 285K

For the 270K case where the heated sample is held just below the ice melting temperature, it would take ~12.7 hours to extract all the ice. However, if the sample

temperature was allowed to go to its maximum temperature of 285K, it would only take ~2.15 hours to vaporize all the ice. With continuous batch processing, ~51.5 kg of water could be extracted per day.

**Important considerations:** As ice is heated by the radiation energy absorbed throughout the regolith material, it will vaporize and migrate towards regions of lower temperature and pressure. This affects the success in achieving a meaningful collection process. The rate of heat applied should not be in excess of the combined rate of ice sublimation and water vapor transmission within the regolith. An imbalance in water vapor generation and transmission rate through the regolith to the point of collection could result in diffusion of the vapor away from the collection point area because of diffusion transport resistance within the material [3].

**Results:** In support of the recent lunar exploration objectives, a 2.45 GHz porous tube reactor was used to evaluate water extraction from JSC-1A simulant containing 5% water ice. Two heating runs were performed in which the JPL cold room was held at -20°C and the simulant temperature, monitored via two fiber optic sensors, was increased to an elevated temperature while collecting the released water. One run applied 2W with a 20.5 gm sample and the other applied 5W with a 14.5 gm sample. In each case water was individually collected during the time the regolith was below 0°C and separately from the time above 0°C. The amount of water collected was about equal in both traps. The 2W run extracted ~100% while the 5W run extracted ~78% of the initial water ice mass.

The parallel cylindrical tubes reactor has also been evaluated with RF for extracting water from the same icy lunar simulant material. This reactor holds a ~250 gm sample in a 1 cm annulus. The initial heating also starts with the reactor at -20°C and fiber optic sensors are employed in the simulant and externally. Observations have shown that the internal cylinder wall temperature increases while the external cylinder wall may not increase above 0°C. In this case some water vapor appears to transfer to the colder outer wall rather than to and through the inner porous tube. This effect was not observed when both walls are heated above 0°C. An imbalance between water vapor removal and heat transfer may be responsible for this phenomenon.

**References:** [1] Barmatz, M., Steinfeld, D., Begley, S.B., Winterhalter, D., and Allen, C., (2011) *LPS XXXXII*, Abstract #1041. [2] Barmatz, M., Voecks, G., Steinfeld, D., Heinz, N. and Hoppe, D. (2016) *Space Resources Roundtable and the Planetary & Terrestrial Mining Sciences Symposium*. [3] Reiss, P., Grill, L., and Barber, S.J. (2019) *Planetary and Space Science* 175, 41–51.