CONCENTRATED SOLAR DRIVEN *IN-SITU* RESOURCE UTILIZATION ON THE MOON

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Introduction

Solar Resources on the Moon

Lunar conditions ideal for solar utilization:

- Solar irradiation
  - Moon: ~1365 $\frac{W}{m^2}$ (A.M. = 0)
  - Earth: ~1000 $\frac{W}{m^2}$ at peak (A.M. = 1.5)
- Declination
  - Moon: 1.5°
  - Earth: 23°
  - Very little seasonal variation in solar irradiation during the year
- 1 lunar day is ~14 earth days
- No atmosphere: No attenuation
- No clouds: No sun blocking

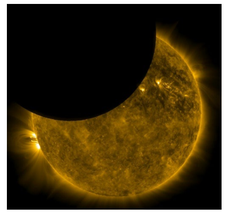
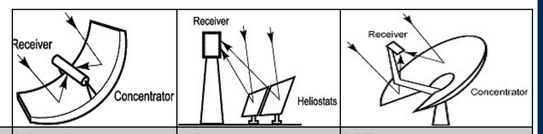


Image Credit: NASA

Concentrating Technologies

Concentration ratio:

- Ratio of incident solar irradiation upon the concentrator to solar irradiation received by the receiver measured in "suns"
- Performance metric for solar concentrating infrastructure



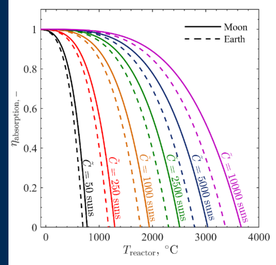
Technology[1]	Trough system	Tower system	Dish system
Concentration Ratio	30-100 Suns	500-5000 Suns	1000 to 10000 Suns
Solar Tracking Capability	One-axis tracking	Two-axis tracking	Two-axis tracking

Efficiency of Thermal/Thermochemical Processes

- Theoretical solar receiver/reactor[1]
  - Blackbody
  - Cavity receiver

$$\eta_{absorption} = \frac{Q_{net}}{Q_{solar}} = 1 - \frac{\sigma T_{reactor}^4}{G_{DN}\tilde{C}}$$

- Theoretical metric of performance:
  - $\eta_{absorption}$ is the solar energy absorption efficiency
  - σ is the Stefan-Boltzmann constant
  - $T_{reactor}$ is the reactor temperature
  - G_{DN} is the direct-normal solar irradiation
  - $\tilde{C}$ is the mean flux solar concentration ratio
- Assumes only radiative losses to the environment



In-situ resource utilization (ISRU)

- Artemis: return to the Moon
- Launching cost is exorbitant
- ISRU: transforming regolith into resources
  - Construction/ Additive Manufacturing:
    - Tools
    - Habitats
    - Radiation shielding
  - Thermal/ Thermochemical Processing:
    - Oxygen
    - Water
    - Metals
- Example: ISRU production of mirrors for concentration technologies[2]
- These processes should utilize concentrated solar

Lower temperature processes	Trough	$\tilde{C}$ =50 suns	$\eta_{absorption}$ = 0.5	$T_{reactor}$ = 610 °C
Higher temperature processes	Tower	$\tilde{C}$ =2500 suns	$\eta_{absorption}$ = 0.5	$T_{reactor}$ = 2070 °C
	Dish	$\tilde{C}$ =10,000 suns	$\eta_{absorption}$ = 0.5	$T_{reactor}$ =3040 °C

Equilibrium Modeling

Chemical equilibrium analysis

- Determined chemical equilibrium compositions for each type of regolith: Highlands (HL), High-Titanium Mare (HTM), and Low-Titanium Mare (LTM)
- Used an in-depth database of macroscopic thermodynamic properties in HSC
- Gibb's free energy minimization performed to determine equilibrium compositions
- Engineering assumptions:
  - Isobaric process
  - Pressure on the surface of the moon ($3 \cdot 10^{-15}$ bar)
- Inputs: Proportional amounts of oxides contained in lunar regolith
- Output: Forecast compositions as a function of temperature at Lunar pressure, normalized to mass of regolith processed

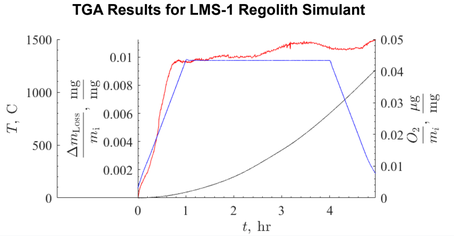
Oxide[3]	HL (wt%)	HTM (wt%)	LTM (wt%)
Al_2O_3	25.1	12.4	13.2
CaO	14.9	11.4	10.8
Cr_2O_3	0.1	0.4	0.4
FeO	6.3	16.6	17.2
K_2O	0.1	0.1	0.2
MgO	7.6	8.9	10.0
MnO	0.1	0.2	0.2
Na_2O	0.4	0.4	0.4
P_2O_5	0.1	0.1	0.2
SiO_2	45.0	41.0	45.4
TiO_2	0.5	8.5	2.9

Results: Thermochemical Processing of Regolith

Thermogravimetric Analysis (TGA)

- Sample was run with the following program
- Starting from 100° C
- Heated at a heating rate of 20 K/min to 1300° C
- Kept at 1300° C for 3 hours
- Cooled at a cooling rate 20 K/min to 150° C
- Allowed to cool to room temperature
- LMS-1
- 0.4 µg of O_2 were release per mg of sample

TGA Results for LMS-1 Regolith Simulant

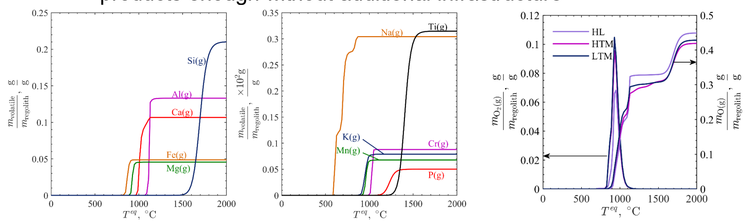


Oxygen

- O_2 vital for human exploration missions
- O_2 thermodynamically favorable between 900° to1050°C
- Ideal temperature for O_2(g) production with concentrated solar irradiation: 950°C

Raw Materials

- Raw materials will reoxidize quickly, necessitating a rapid separation
  - Rapid cooling prevents the recombination of oxides
  - The lunar surface temperature is sometimes low enough to cool the products enough without additional infrastructure



Chemical equilibrium compositions as a function of temperature at 3×10^{-15} bar for left: raw material and right: oxygen

Results: Thermal Extraction of Volatiles

Water

- H_2O vital for human exploration missions
- Regolith at the poles contains ~ 1 wt% $H_2O(s)$[5]
- Heating the regolith could extract this water

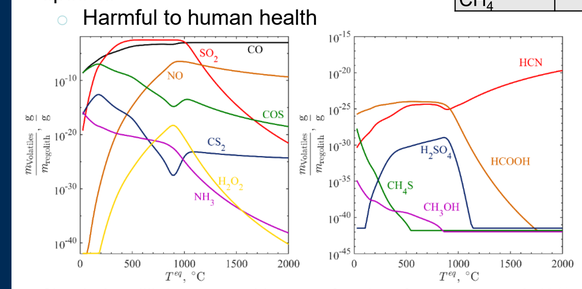
Volatiles

- LCROSS data showed presence of other volatiles
- Heating the regolith will also produce toxic species
  - Harmful to human health

Volatile	Molecular Abundance relative to H_2O According to LCROSS Data[4]
H_2O	100.00%
H_2S	16.75%
NH_3	6.03%
SO_2	3.19%
C_2H_4	3.12%
CO_2	2.17%
CH_3OH	1.5%
CH_4	0.65%

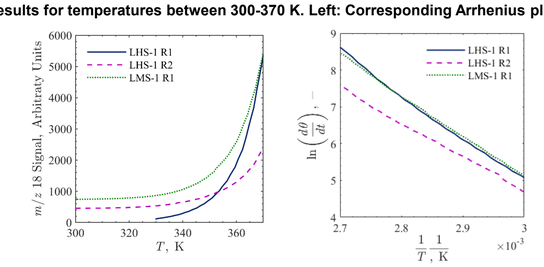
Temperature Programmed Desorption

- Regolith Simulants LHS-1 and LMS-1
- Heated to 800 K
- Leading Edge Analysis
- Energy of desorption:
  - 0.999 eV for LHS-1 R1
  - 0.807 eV for LHS-1 R2
  - 0.949 eV for LMS-1 R1



Chemical equilibrium compositions as a function of temperature at 3×10^{-15} bar for toxic species

Right: TPD results for temperatures between 300-370 K. Left: Corresponding Arrhenius plot



Ongoing and Future Work

Ongoing Work

- Correlate ISRU processing of lunar regolith for specific resources to an ideal locations for thermal/thermochemical processing
- Conduct thermogravimetric analysis on LHS-1 and LMS-1 heated to temperatures
- Compare results with the theoretical equilibrium

Future Work

- Design a solar thermochemical reactor that uses concentrated solar power for ISRU
- Experiment using the Solar Fuels and Technologies Laboratories' High Flux Solar Simulator

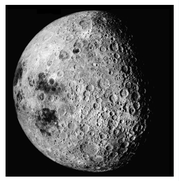


Image Credit: NASA

Left: Solar Fuels and Technologies Laboratory's High-Flux Solar Simulator

Conclusions

- The solar conditions on the moon are ideal for using high-quality solar irradiation for ISRU.
- Equilibrium composition predictions were made for oxygen, water, and metal/metalloid favorability as a function of temperature and pressure for lunar regolith processed by thermal/thermochemical techniques.
- Extracting water is complicated by other potentially dangerous volatiles at the south pole.

References

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- [5]Hayne, P. O. *et al.*, "Evidence for exposed water ice in the Moon's south polar regions from Lunar Reconnaissance Orbiter ultraviolet albedo and temperature measurements." *Icarus* 255 (2015) 58–69.

This work was carried out as part of REVEALS which was directly supported by the NASA Solar System Exploration Research Virtual Institute cooperative, agreement number NNA17BF68A.