National Aeronautics and Space Administration

Ionic Liquid and In Situ Resource Utilization

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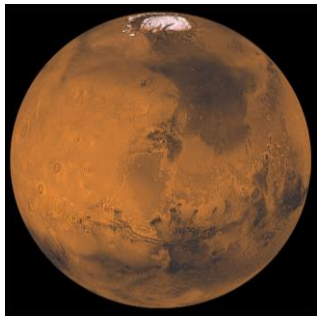
How Do We Supply In Space Construction?

- Sending materials to the Moon or Mars is extremely expensive
  - Over $10k/lb to the Moon or about $20k/lb to Mars
- Concrete is very dense (2 tons/cubic yard)
- Even a small habitat or structure would cost tens or hundreds of million dollars
- Launching raw materials from Earth won't work, but there is a solution to this problem…

In Situ Resource Utilization

In situ resource utilization is “living off the land”

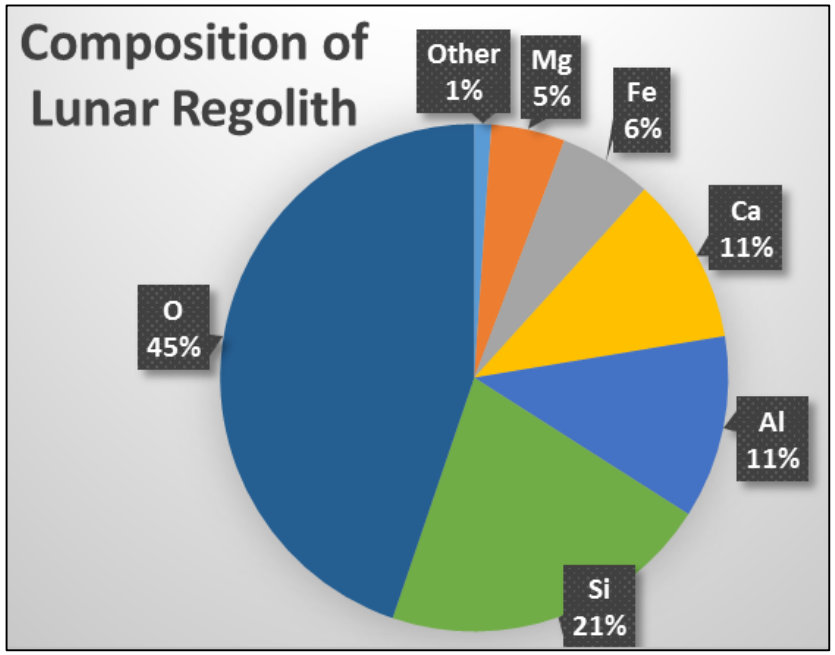


Mars
- Regolith (metals, oxygen, construction materials)
- Ice caps (water)
- Atmosphere (CO_2)

Moon
- Regolith (metals, oxygen, construction materials)
- Hydrates (water)
- Cold volatiles (NH_3, CO, H_2O, and many more)

Other
- Waste
- Obsolete or broken hardware
- Asteroids (metals, volatiles)

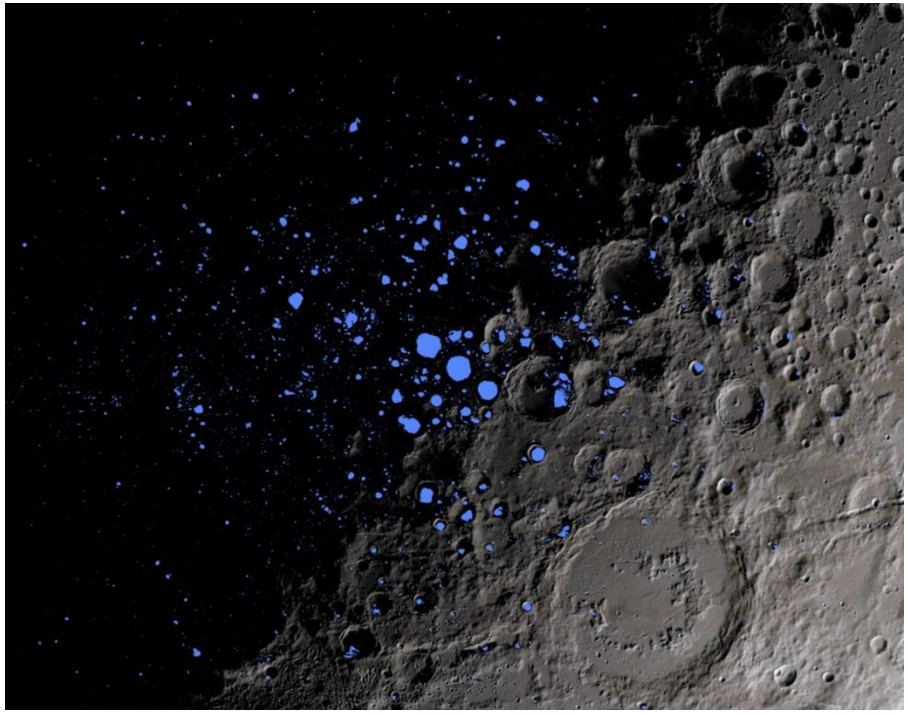
Lunar Regolith

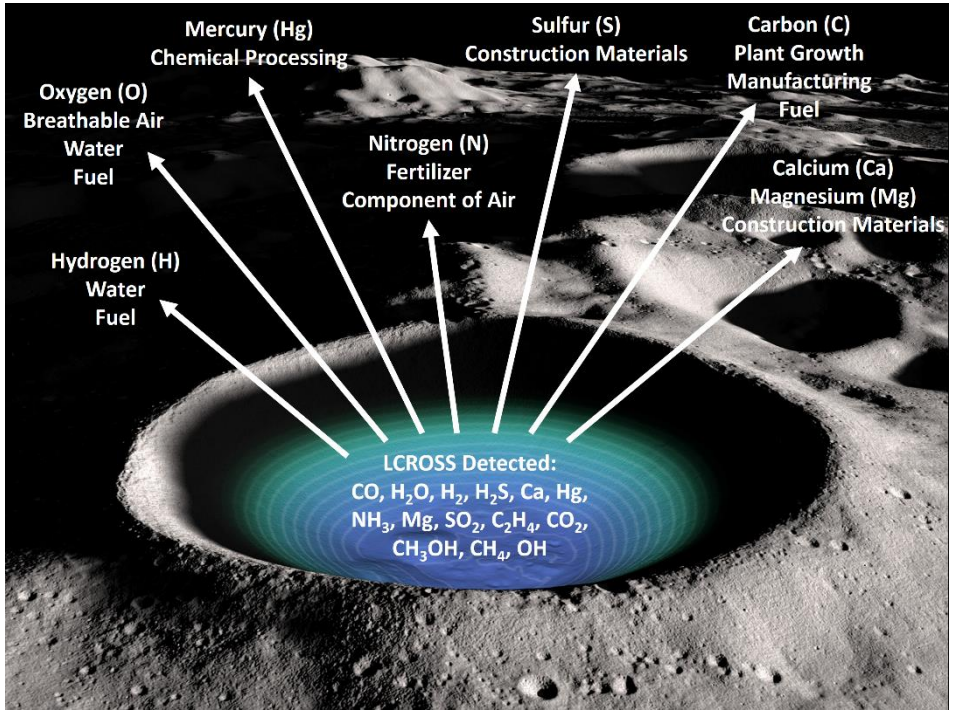


- Martian and lunar regolith contain valuable elements
  - Cement (Mg, Ca, Si, O)
  - Additive Manufacturing (Mg, Fe, Al)
  - Solar Cells (Si)
  - Life support and propulsion (O)

Permanently Shadowed Regions

- Permanently shadowed regions (PSR) are craters near the Moon's poles which have never seen sunlight
- Extremely cold as a result, which has led to normally volatile compounds freezing
- LCROSS missions confirmed that many potentially useful volatiles are present in significant quantities





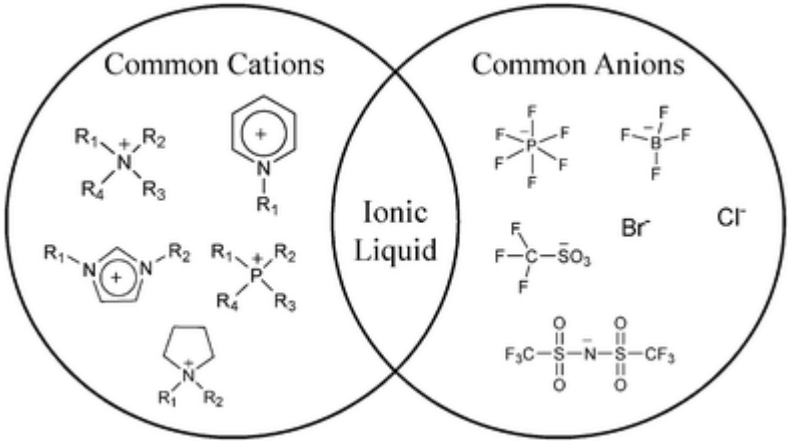
Raw Materials to Feedstocks

- The in situ resources are found in states that are not suitable for use as feedstocks
  - Metals oxides rather than metal
  - Mixed composition rather than single elements
- Terrestrial technologies for processing ores to recover metals are not suitable for in space use
  - Both mass and health/safety concerns
- Requires the development of new technologies
- One promising candidate uses a new class of materials know as ionic liquids

What are Ionic Liquids?

- Ionic liquids (IL) are organic salts which are molten at or near room temperature.
- Being entirely composed of ions, ILs have a number of properties that make them attractive for in-space use, including high electrochemical and thermal stability, low vapor pressure, and high ionic conductivity.
- The chemical structure of ILs can be readily modified through simple chemical processes, which allows for the preparation of task specific ILs, or ILs with properties tuned for a given application.
- Select ILs have been shown to chemical digest many metal oxides.

Table salt (left) and an IL (right).



M.D. Joshi and J. L. Anderson RSC Adv., 2, 5470–5484 (2012).

What are Ionic Liquids?

IL Research at NASA Centers

	ARC	GRC	JSC	JPL	KSC	LaRC	MSFC	GSFC
Solvents and Cleaning Agents			X				X	
Lubricants			X					
Oxygen and Metal Extraction							X	
Electroplating							X	
CO_2 Reduction							X	
Gas Capture, Purification, and Concentration							X	
Structural Components and Coatings			X				X	
Liquid Telescopes	X							
Green Propellants		X				X	X	
Batteries and Solar Cells	X	X	X		X		X	X
Biological Uses	X					X	X	

Ionic Liquid-Based Regolith Processing

- A three step process that uses ILs to digest regolith and recover high purity metals has been demonstrated.
- First, an acidic IL is used to digest the metal oxide producing a solution of dissolved metal in depleted IL and water as a byproduct.

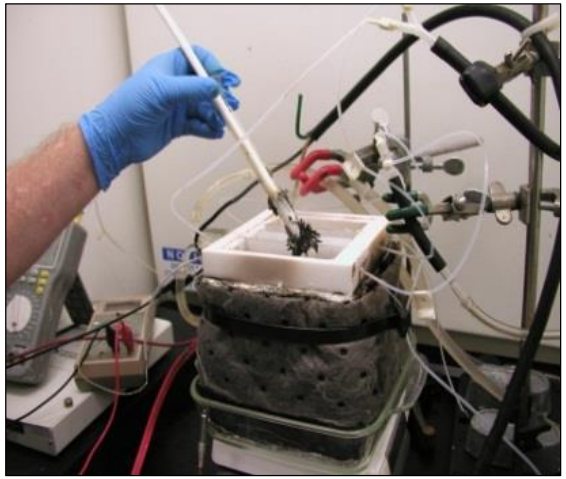
$$2HSO_4^- + MO \rightarrow 2SO_4^{2-} + M^{2+} + H_2O$$

- The water produced in the first step is electrolyzed and the H_2 produced is stored for use in the third step.
- The dissolved metals are electrochemically plated out of solution while the depleted IL is regenerated to its acidic state.

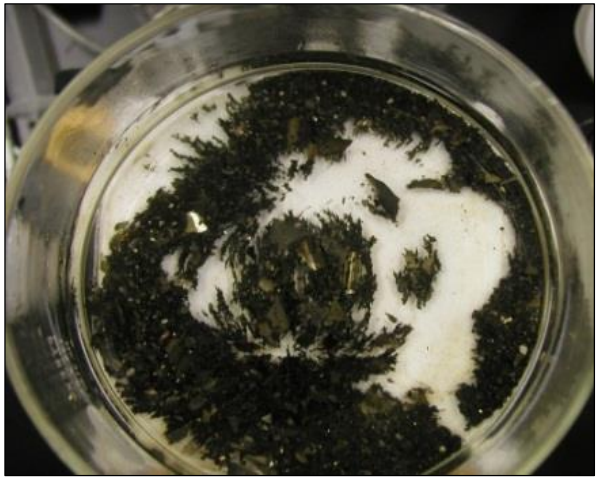
$$M^{2+} + 2e^- \rightarrow M \;||\; 2SO_4^{2-} + H_2 \rightarrow 2HSO_4^- + 2e^-$$

- The IL is then ready for reuse to digest additional regolith.

Campo del Cielo IAB meteorite

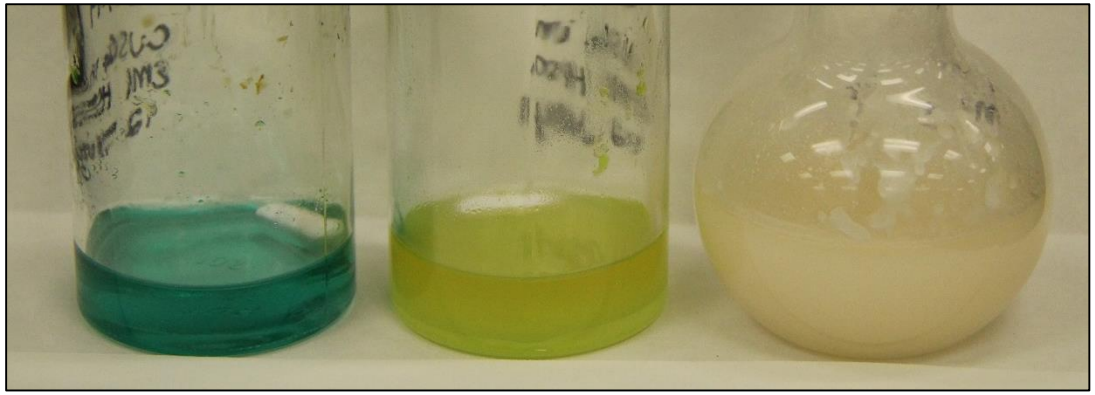


Meteorite material is dissolved in IL and metals are electroplated



Metal is recovered and ready for use.

Ionic Liquid-Based Regolith Processing



Solution of EMI HSO_4 and 0.1 M copper (left), nickel (middle), and magnesium.

Water recovered from IL after digestion of Asteroid Vesta material.

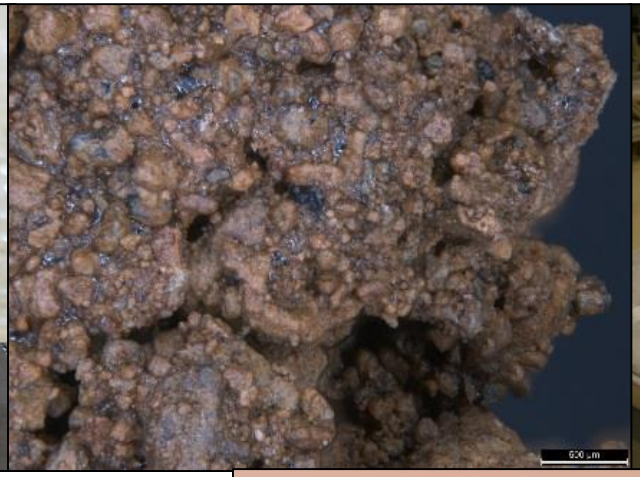
Table of Standard Electrochemical Potentials for Regolith Processing

Increasing Electropositivity ↓

Oxidant		Reductant	E^o(V) vs. SHE
$Ni^{2+} + 2e^-$	↔	Ni	-0.25
$Fe^{2+} + 2e^-$	↔	Fe	-0.44
$Ti^{2+} + 2e^-$	↔	Ti	-1.63
$Al^{3+} + 3e^-$	↔	Al	-1.662
$Mg^{2+} + 2e^-$	↔	Mg	-2.372
$Ca^{2+} + 2e^-$	↔	Ca	-2.868

← Limit of aqueous solutions

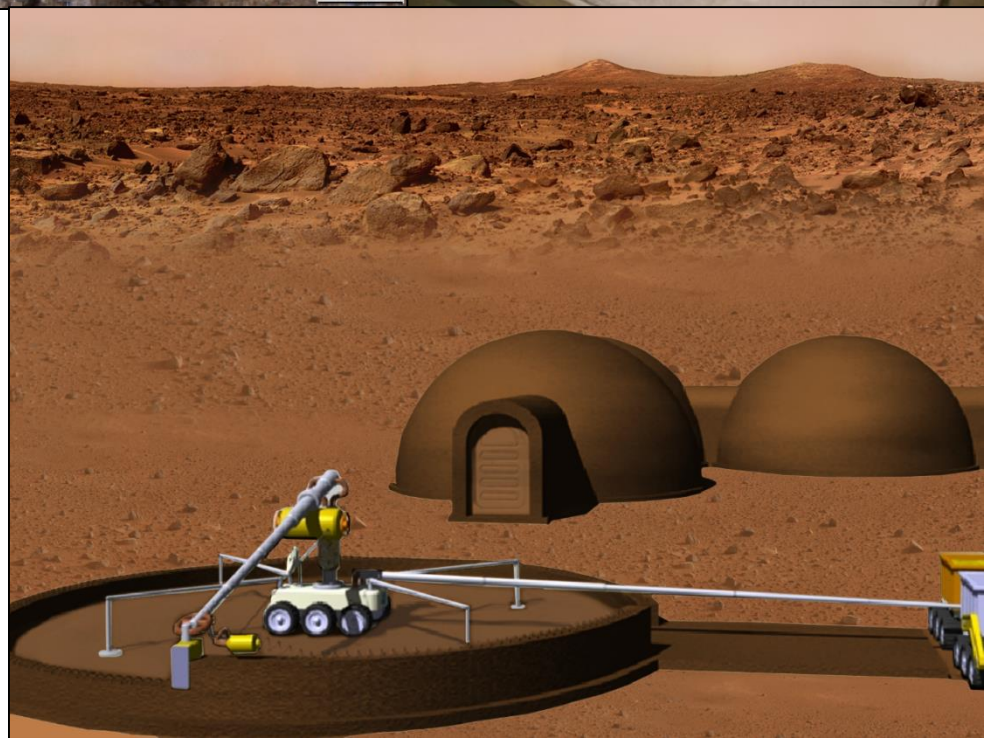
Cements Derived From ISRU



IL-based process to produce construction materials from regolith

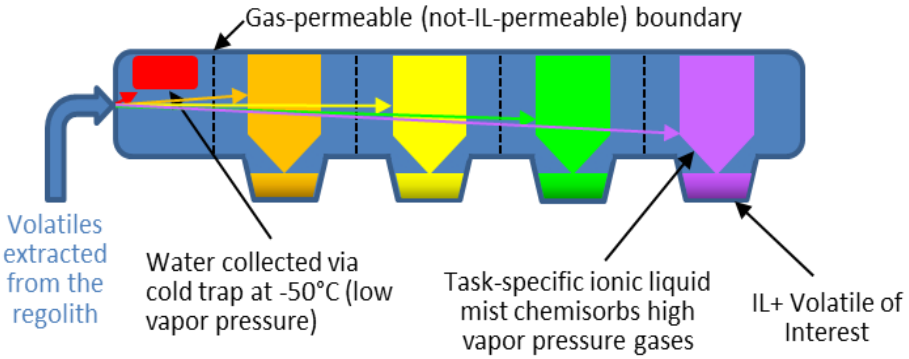
1. Extract sodium from silicate materials using IL
2. Electrolyze sodium in IL to produce sodium hydroxide
3. Combine sodium hydroxide with silica to produce sodium silicate
4. Sodium silicate is added to regolith

The resulting materials can be suited for 3D printing to allow for the additive construction of buildings.



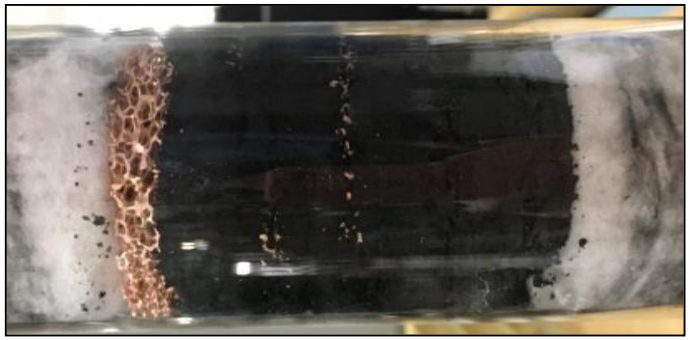
Other ISRU and IL Applications

Gas Capture & Purification



Recovery of Oxygen from CO_2

$$CO_2 + 2H_2 \rightarrow C + 2H_2O$$



Production of Methane from CO_2

Advanced Composite Materials for Cryogenic Vessels and Structures

Advanced Propulsion for CubeSats

UTSI's μSTAMP electrospray thruster

Summary

- In Situ Resource Utilization is vitally important to reduce the cost of future long duration, deep space, human exploration missions.
- Ionic liquids are a promising new class of materials that are allowing the development of new ISRU technologies, as well as technologies that benefit NASA's exploration needs in many other areas.