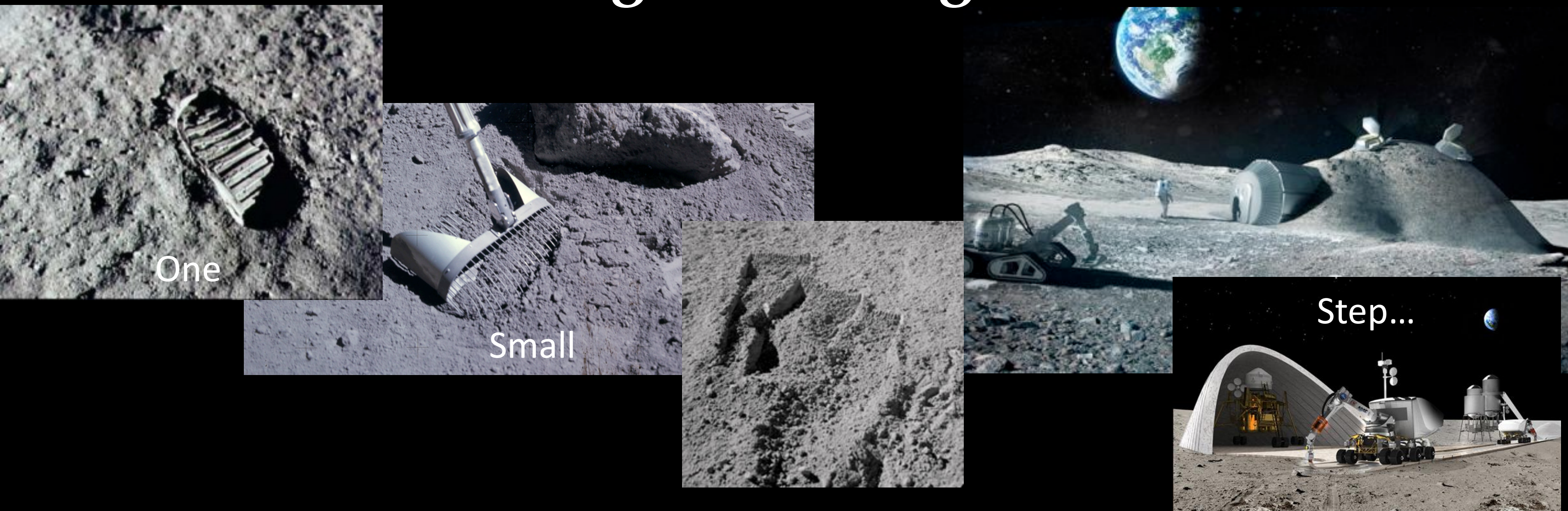
Additive Manufacturing and Resource Extraction Using Lunar Regolith



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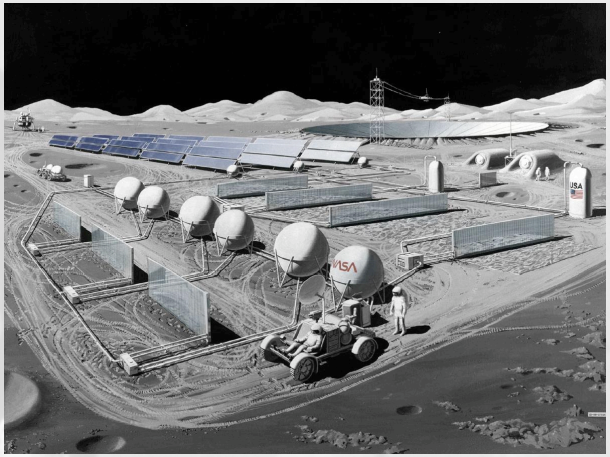
Outline

Presentation Overview

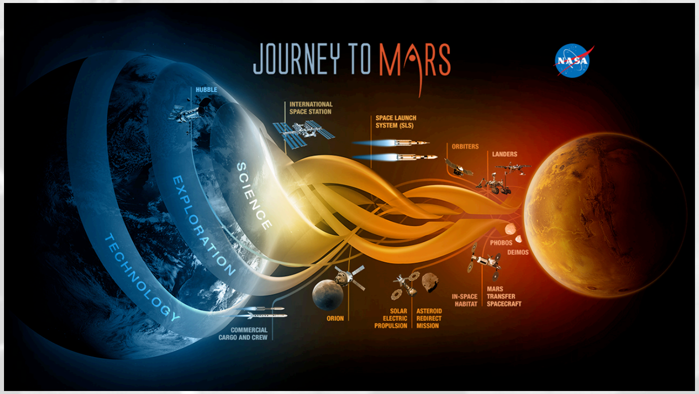
- **1. Setting the Stage**
- **2. Magnetic Induction Heating**
- **3. Heat, Print, Release, and Capture Experiment**
- **4. Current and Future Work**

Expanding into the Solar System

- To enable outposts, space operations, and eventual colonies, we need to develop the key technologies necessary now

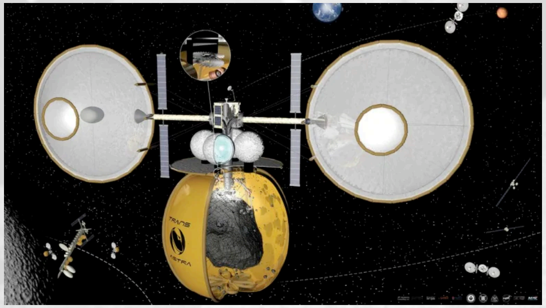


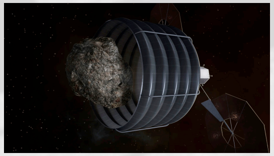
- Current NASA roadmap includes returning the Moon (to stay) on the way to Mars

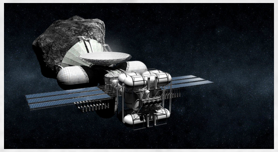


- Asteroid resources can be utilized to provide fuels and raw materials

- **Moon as a testbed critical if we want to expand beyond the Earth!**

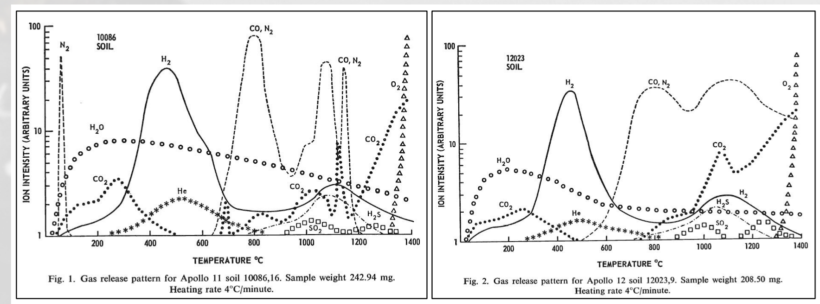






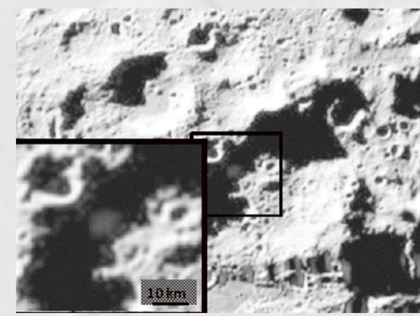
Lunar Resources

- Lunar surface materials can provide numerous resources if properly excavated and utilized
- Apollo samples showed lunar regolith contains usable volatiles such as OH, H_2O, H_2S, CO_2, NH_3, SO_2, and CO, which are released by heating to 1200°C



(Gibson and Johnson, 1971)

- Water detected in LCROSS impact plume in Cabeus crater *(Colaprete et al., 2010; 2012; Gladstone et al., 2010; Hurley et al., 2012)*

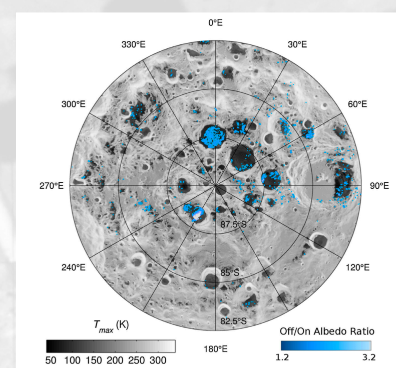


LCROSS impact site

- Also over much of the lunar surface at levels of hundreds of ppm *(Pieters et al., 2009; Sunshine et al., 2009; Hendrix et al., 2012)*

- Fe and Ti-bearing silicates highly valuable as a construction material for habitats, roads, berms, walls *(Handbook of Lunar Soils – Morris et al., 1983)*

So the resources are there…



Hayne et al 2015

Additive Manufacturing On The Moon

- The use of lunar regolith in additive manufacturing (AM) has been an active area of research for many years

- Current efforts include: laser or solar heating and sintering, polymer binders, resistive heating, and microwave sintering *(Vaniman et al., 1986; Taylor & Meek, 2005; Balla et al., 2012; Montes et al., 2015; Davis et al., 2017; Jakus et al., 2017; Chen et al., 2018)*

- Each method has drawbacks – Brittle products, high power draw, thermally fragile, etc

- **Does Magnetic Induction (MI) heating have the potential to address some of these shortfalls?**

ESA/Foster+Partners

KICT

AI Space Factory

Oregon State

NASA

Magnetic Induction Heating

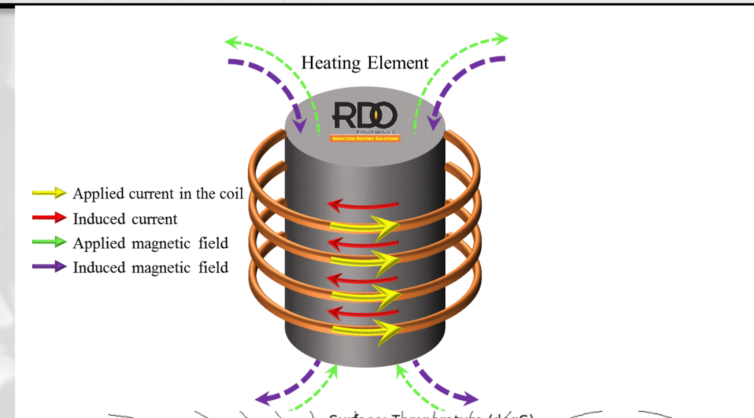
- **MI heating** and sintering works by applying an alternating current (AC) through loops of copper coils
- The oscillating magnetic field from the coils (solenoid) induces a magnetic field in the workpiece (a ferrous metal crucible)

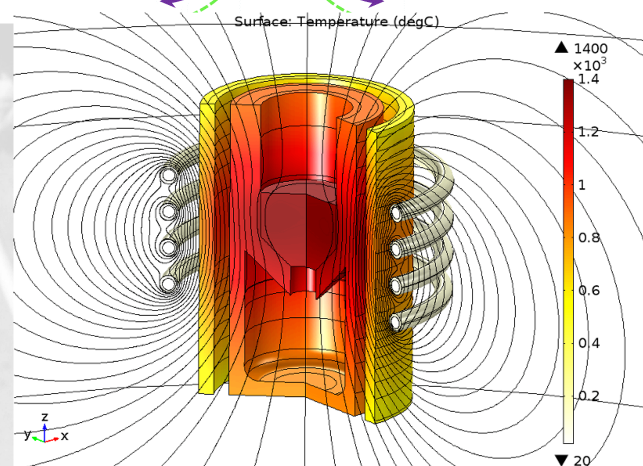
$$\Delta B_z = \frac{\mu_0}{4\pi}\frac{2\pi R^2 I}{\left(R^2+(d-z)^2\right)^{3/2}}\frac{N}{L}\Delta z$$

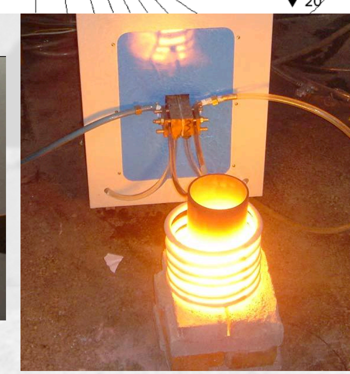
Magnetic field inside coil

- Based on Lenz's law (E = $-N\partial\Phi B/\partial t$), produces a force in the opposite direction resisting each subsequent change in the applied field, **producing eddy-currents in the metal**
- This current-induced "friction" rapidly heats the metal, and the lunar regolith that will be placed inside to ~1200°C

Reliable industrial method…







MI AM Experiment

This project aims to advance the MI for ISRU concept by addressing unanswered questions about the operation, engineering, and efficiency of this application to off-world problems

- ✓ Fast
- ✓ Simple
- ✓ Function in a vacuum
- ✓ Relatively low-cost

But – leaves some unanswered questions

- ❖ Do the power requirements prohibit such a method?
- ❖ Can a battery be used in the circuit to reduce input power (solar array)?
- ❖ Does the printed product have construction material strengths?
- ❖ Can the crucible be pressure sealed to capture released gases?

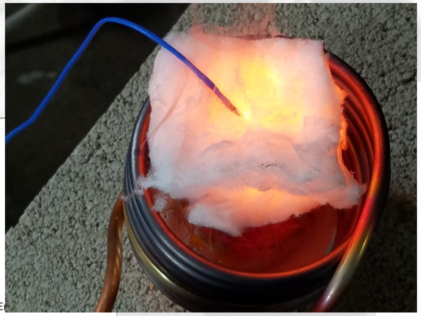
MI 3D-Printing

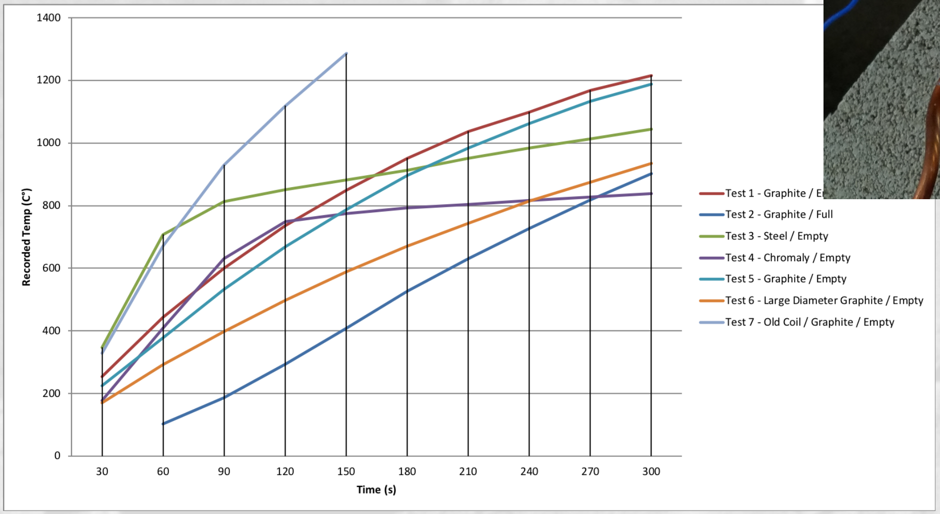
Testing Validity of MI Printing

- By producing cylinders and bricks with various levels of sintering we can determine baseline power req's coupled with resulting product physical properties

- **Keys: Functional req's for lunar case and comparisons to other methods**

Examples of microwave and polymer products



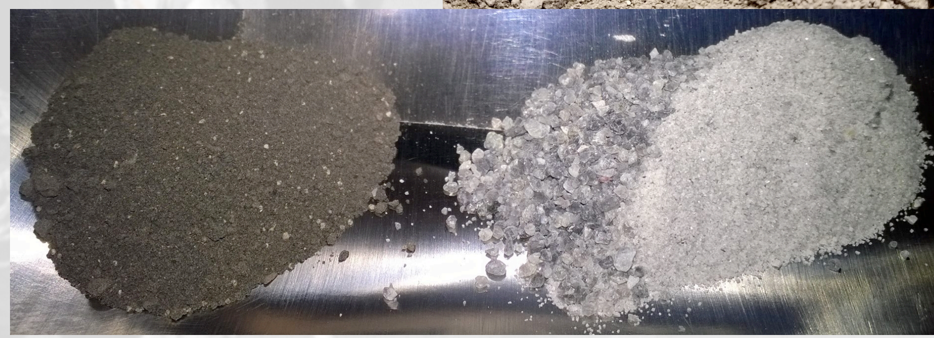


RedWorks' coil, heating data, and MI printed cylinders

Materials

<u>Using Currently Developed Planetary Simulants</u>

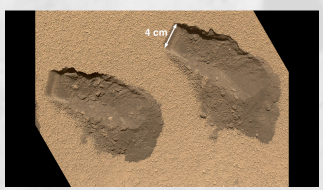
- High-fidelity mineralogical lunar simulants from *Off Planet Research* and *CLASS Exolith* Labs

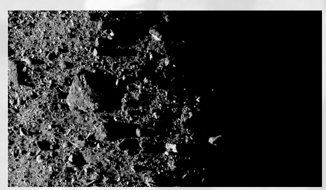


OPRL2N, OPRH2N

- Highlands and Mare

- As well as some Mars and asteroid simulants





LHS-1 Lunar Highlands

- Particle size distributions based on Apollo samples

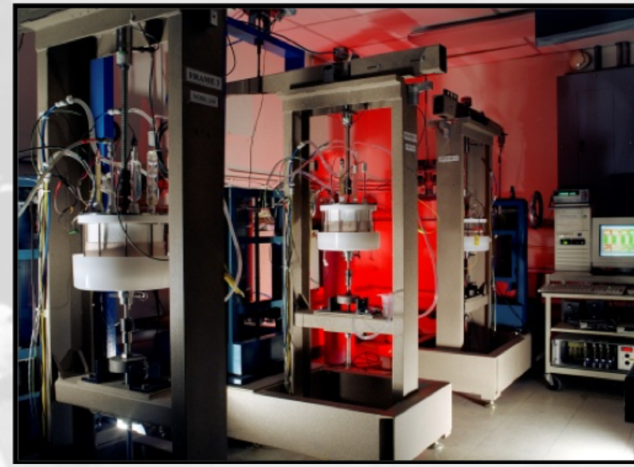
LMS-1 Lunar Mare

Printed Product Physical Strengths

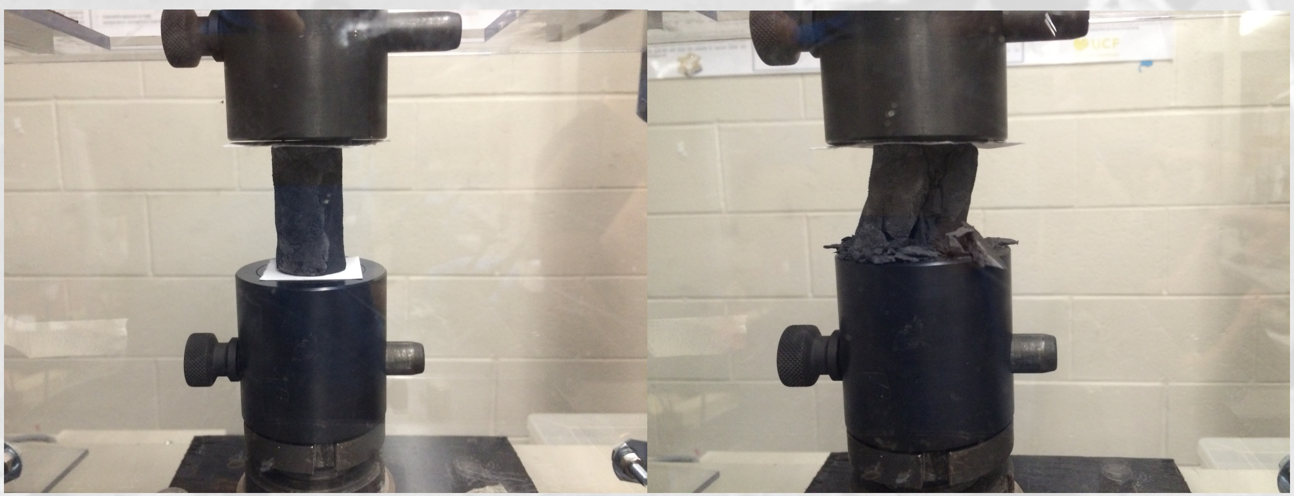
Making a case for lunar construction

Measuring…

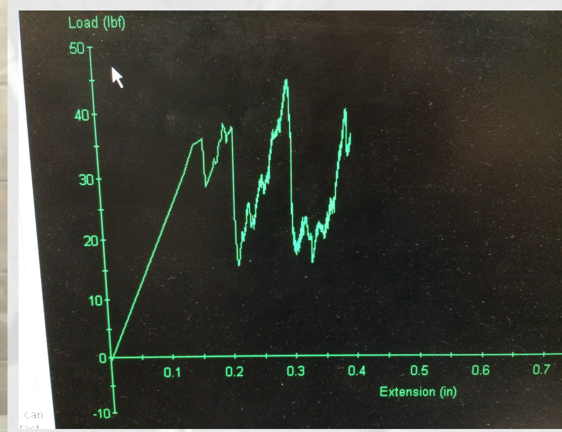
- Unconfined compressive strength $\sigma = \frac{F}{A}$
- Shear strength $\tau = \frac{\sigma_1 - \sigma_3}{2},$
- Porosity/density $\phi = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{particle}}}$



“Instron Jungle” at SwRI



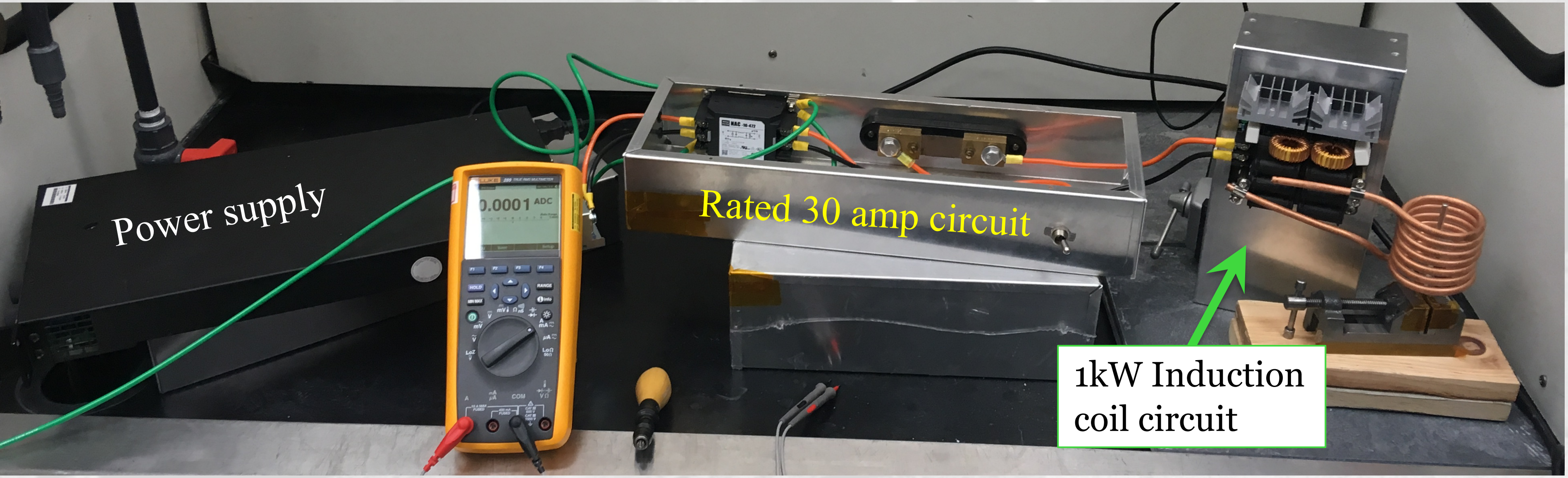
Example of compressive testing in a load cell



Current Progress

- Proof of concept testing will lead to rapid prototyping
- Initial tests at 15A, 300W = < 300 °C temps in workpiece…next is **<u>21A 1kW</u>**
- **Initial takeaways:** Coil design is critical and is frequency of circuit

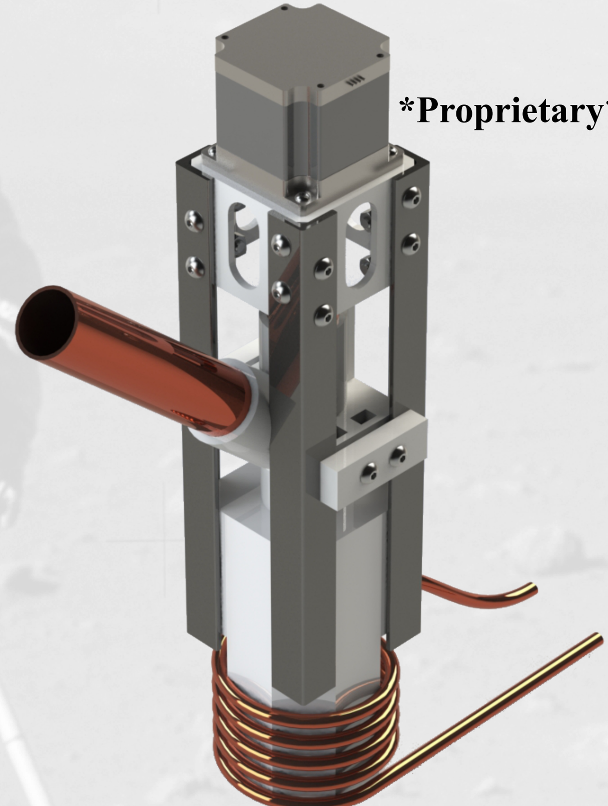
Temperature readings (200-300°C)



Future Work

Magnetic Induction 3D Print Head Prototype

Proprietary



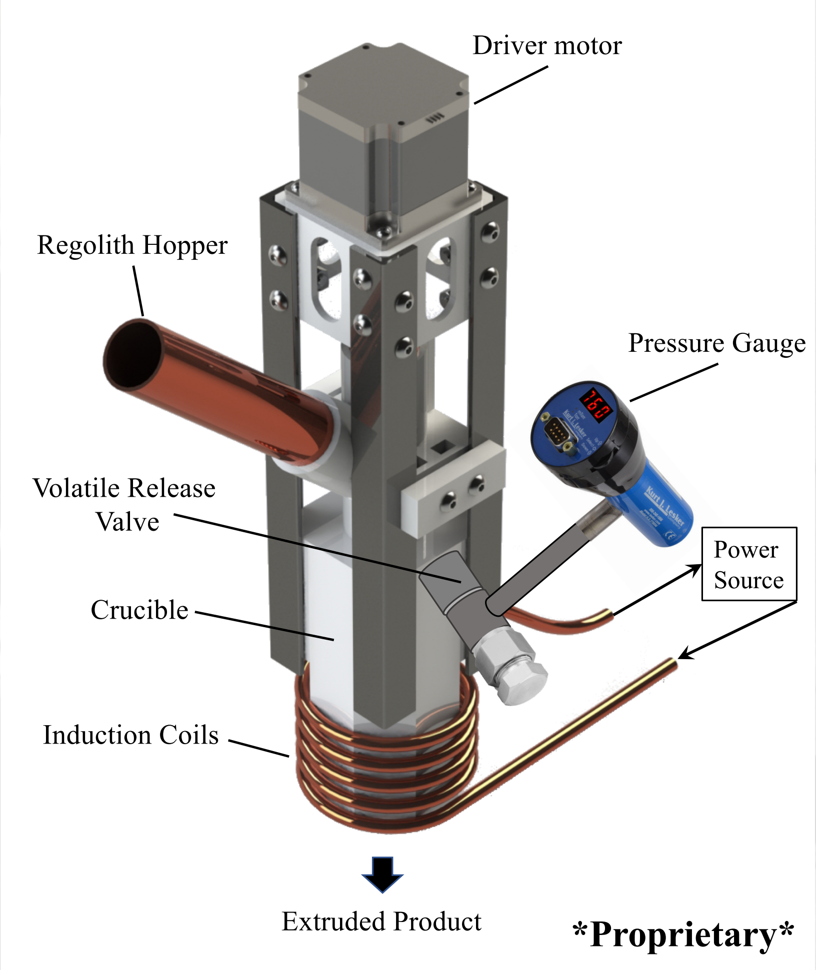
Extruded Product

Tasks:

- Print head machining - build out of driver unit and integrated coil/crucible
- Begin initial testing of completed unit
- Print cylinders for mechanical properties testing

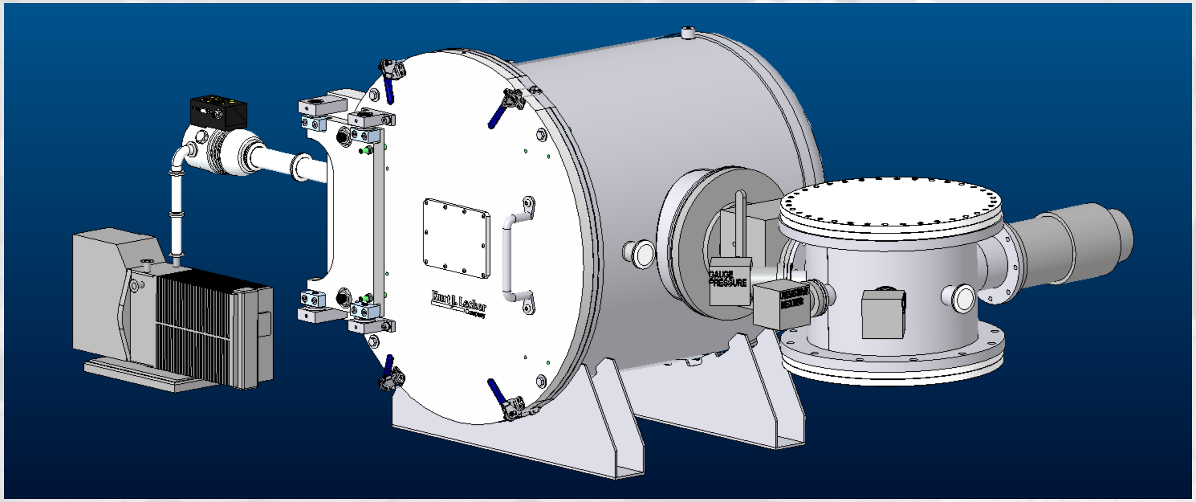
Future Work

- The MI print head will be modified to form the HPRC device.
- Vacuum valves to isolate internal pressures due to volatile release will be added
- The integration of pressure valves on the print head will be tested using a pressure gauge
- Leading to a brass-board level cold trap and gas feedline attached to the MI print head enclosed in a cryo-cooled high-vacuum chamber at SwRI



Future Work

- Heat Print Release Capture chamber construction
- Environmental testing, printing in similar environment
- Cryo-cooler cold plate to trap volatiles
- The integration of pressure valves on the print head will be tested in the chamber
- Considerations will be made with regard to valve seal temperature rating, the flow of regolith through a seal, the potential corrosive nature of H_2S gas, and the range of expected pressures

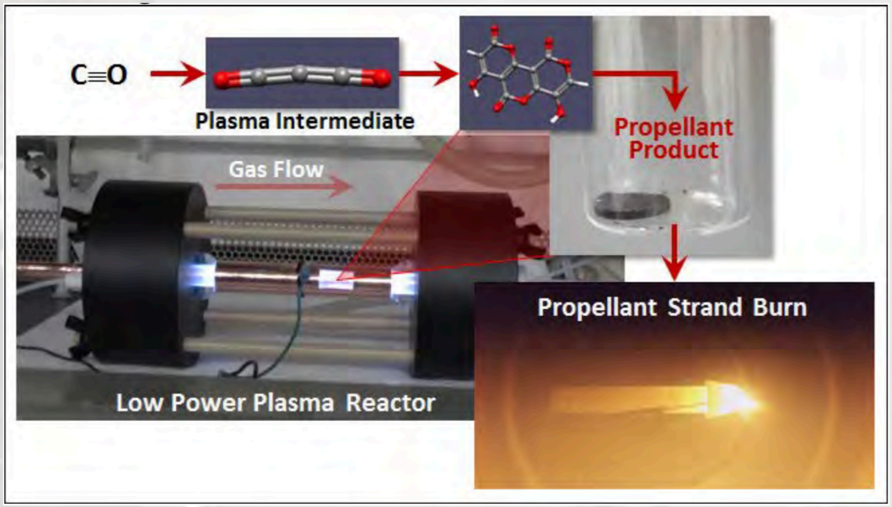


Preliminary design of cryo-cooled test chamber for vacuum printing

Future Work

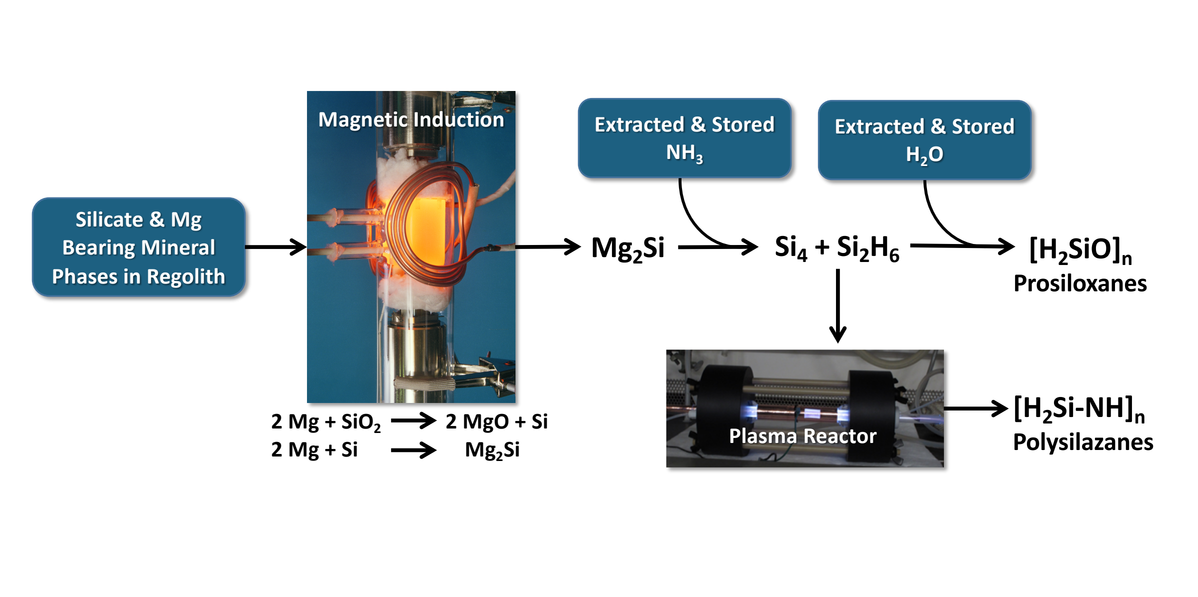
Feed forward of captured volatiles

- Will partner with SwRI sorption lab where they are already working on ISRU processing, membrane filtration, and storage of captured products to be produced in our prototype system



- Solid propellants being created by plasma reactor from CO feedstocks

- New possible area of research involving silanes and other silica-based reactive products



Thank you Space Resources Roundtable!

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and onward we go