Moon to Mars Oxygen and Steel Technology (MMOST)

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ISRU – Metals and Oxygen
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Moon to Mars Oxygen and Steel Technology (MMOST)

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September 15, 2020 – September 14, 2022

Pioneer Astronautics

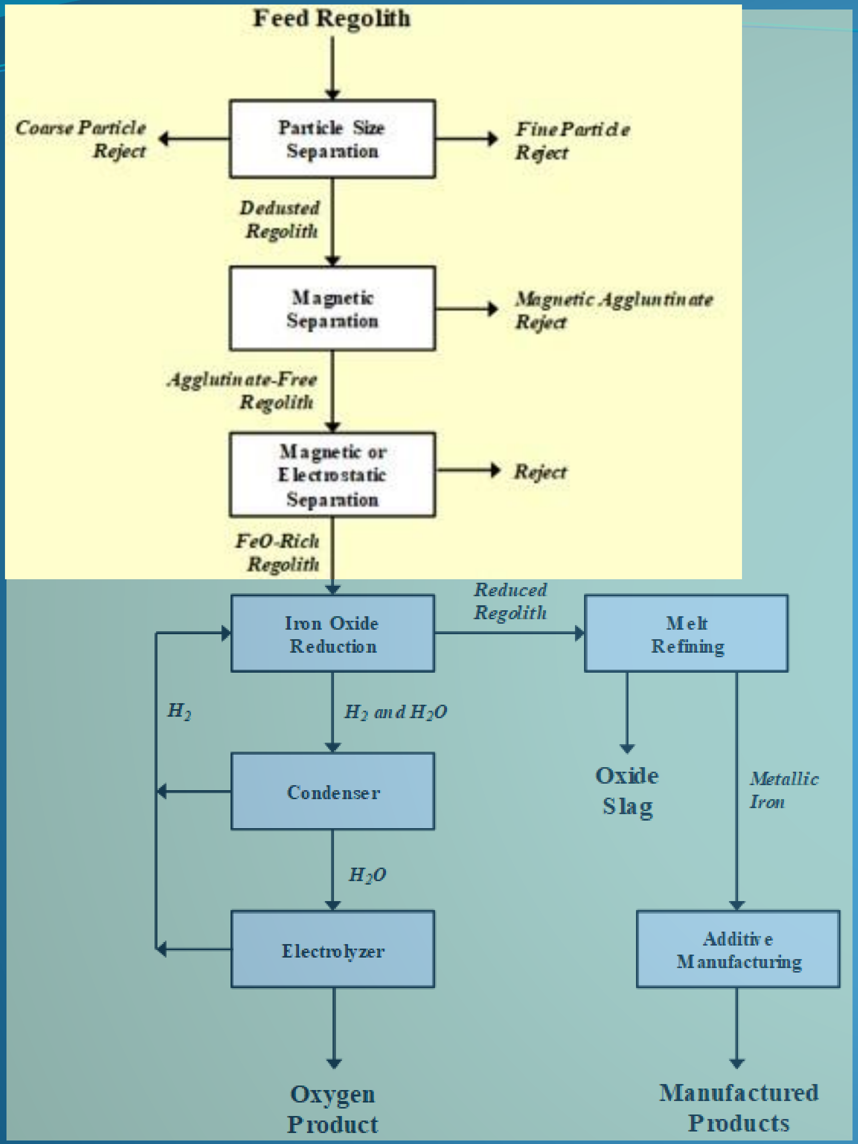
Colorado School of Mines

Honeybee Robotics

Moon to Mars Oxygen and Steel Technology

Description:

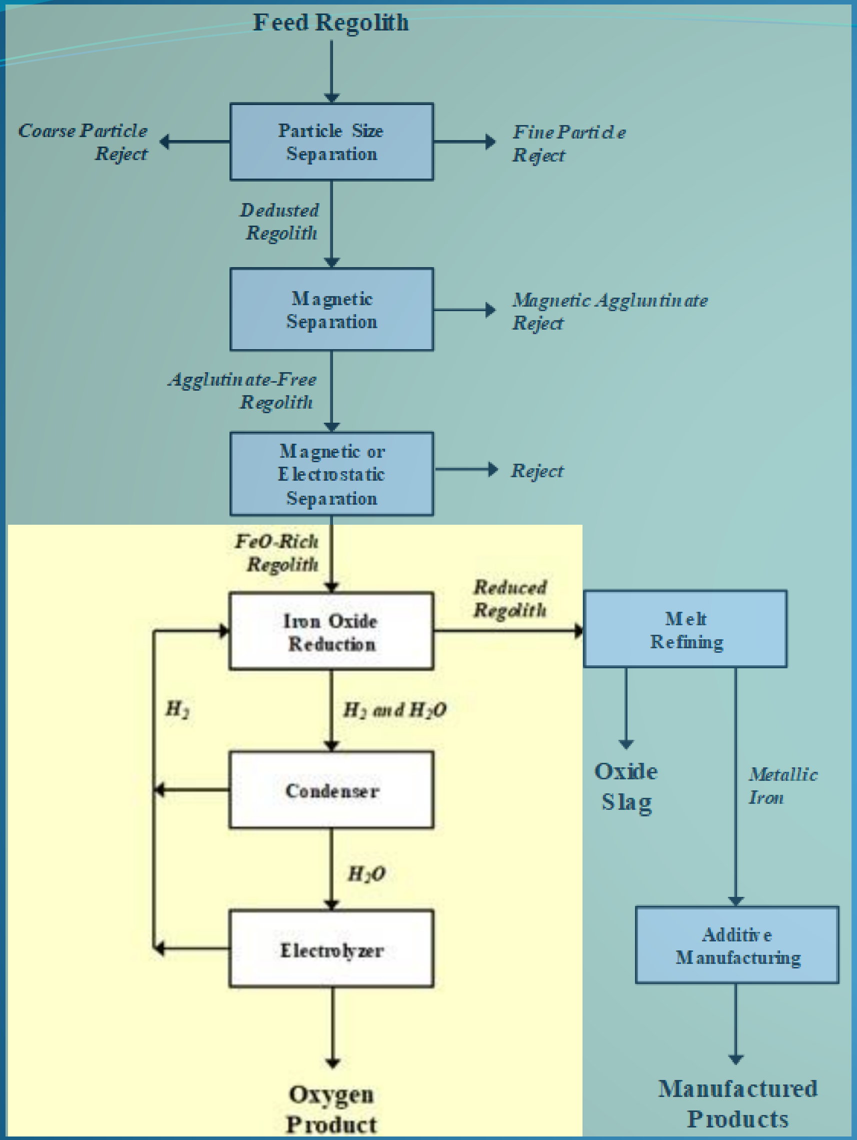
- Two-year design/build/test/demonstrate program
- Integrated system to produce metallic iron/steel and oxygen from beneficiated lunar regolith
- Process employs particle size sorting/dedusting, magnetic-electrostatic beneficiation, iron oxide reduction, electrolysis, melt-refining, materials handling, and process automation
- Iron product to be alloyed as required for demonstration of additive manufacturing, machining, and casting applications
- MMOST effort targets 3.5 kg/day Fe and 1 kg/day O_2
- Final MMOST design targets 35 kg/day Fe and 10 kg/day O_2
- Lunar OXygen In-situ Experiment (LOXIE) targets 0.5 kg/day O_2 prototype representing an oxygen production flight experiment (beneficiation/reduction/electrolysis)



MMOST Block Flow Diagram

MMOST Beneficiation Module:

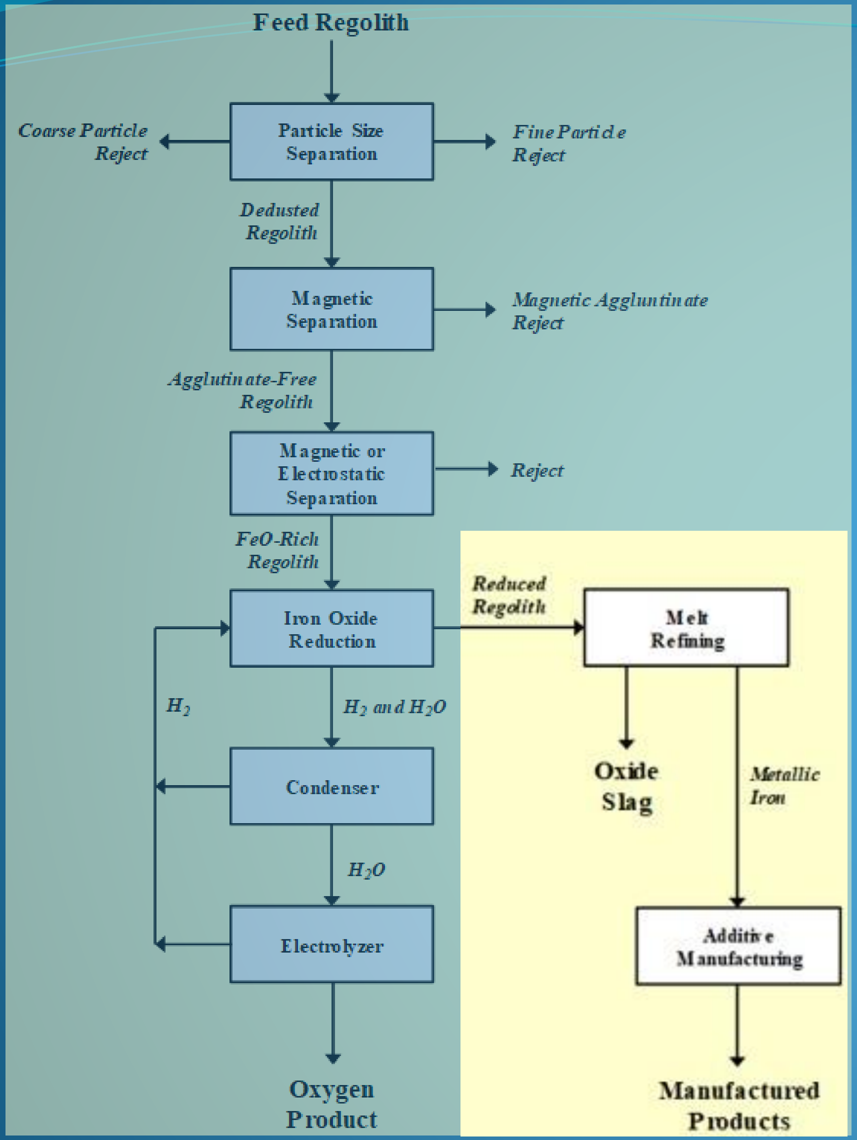
- Reject coarsest and finest particles
- Remove agglutinates
- Upgrade FeO concentration via magnetic and/or electrostatic separations
- Produce FeO-rich feed to hydrogen reduction



MMOST Block Flow Diagram

MMOST Iron Oxide Reduction Module:

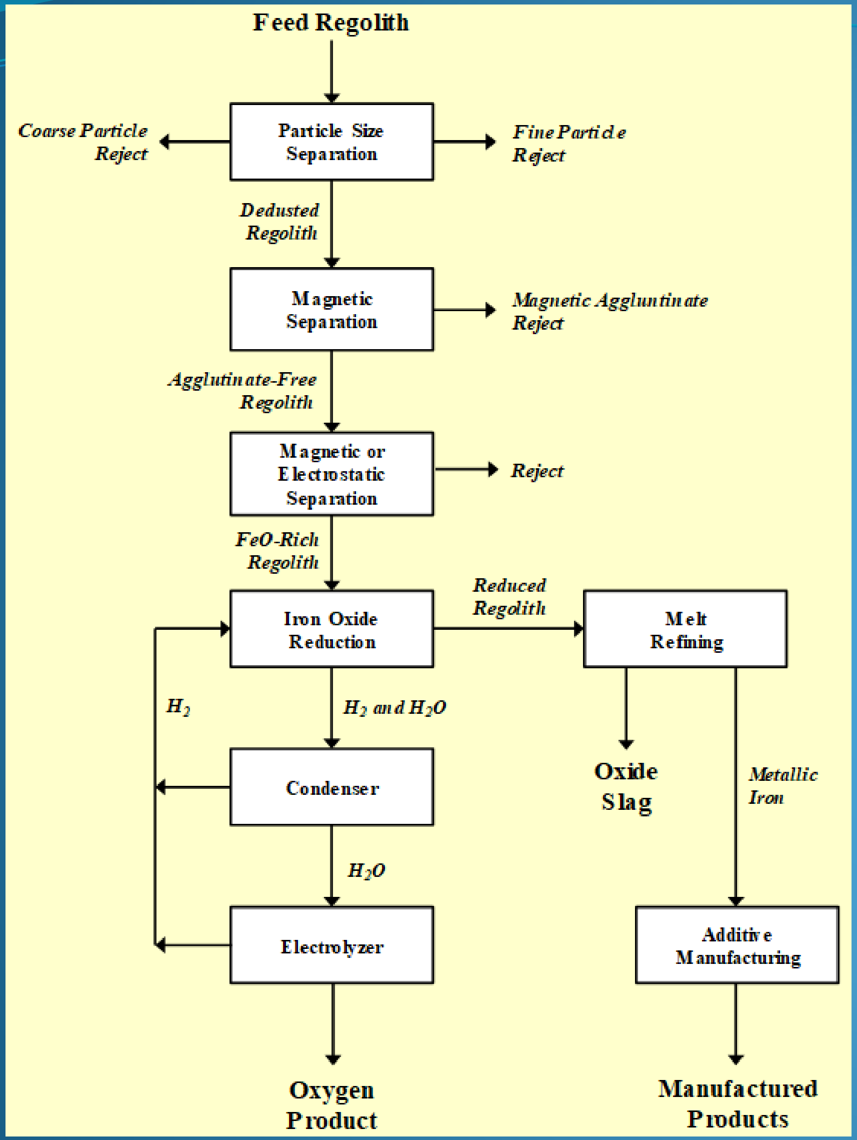
- Back-pulsed fixed-bed reactor for reduction of iron oxides
- Condenser to recovery water
- Electrolysis integrated with iron oxide reduction
- Reduced regolith fed to melt refining



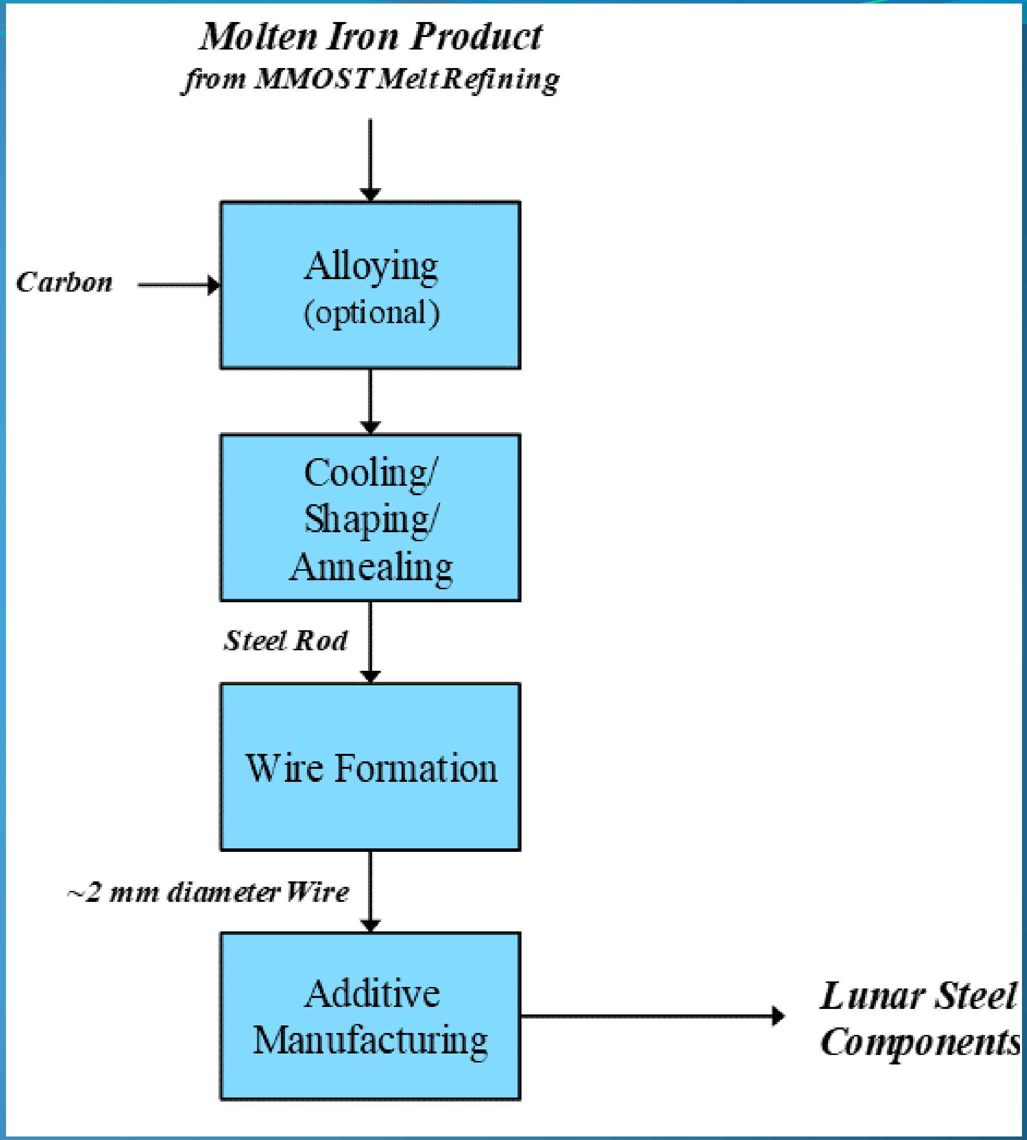
MMOST Block Flow Diagram

MMOST Melt Refining Module:

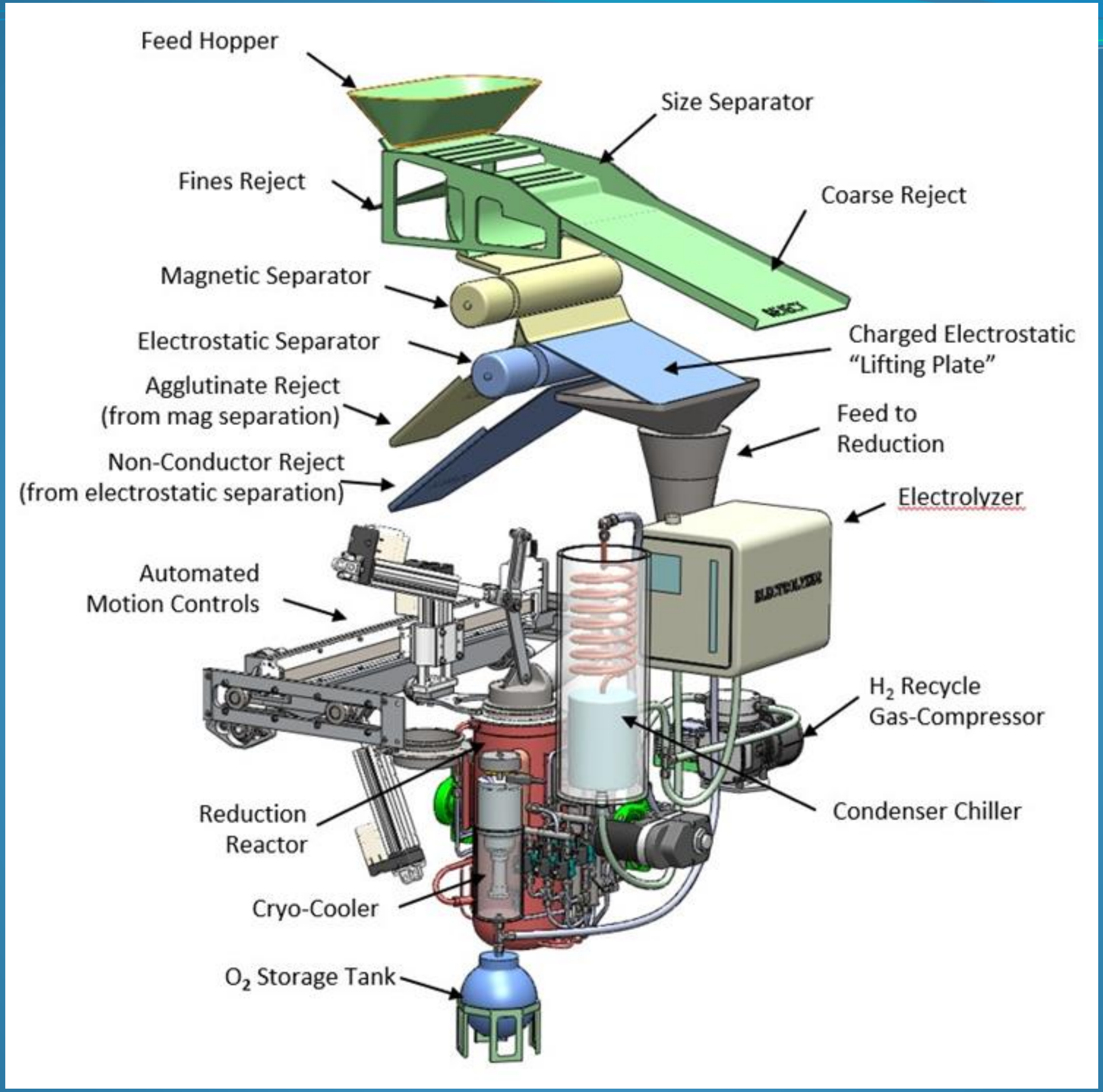
- Heat hydrogen reduction residue to melt metal and oxide phases
- Coalesce metallic iron
- Separate metallic iron from oxides
- Generate feed to additive manufacturing



MMOST Block Flow Diagram



MMOST Metal Production Steps



LOXIE O_2 Production Prototype

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Flow Sheet Development

High Ilmenite Case:

Liberated ilmenite grains were identified in samples returned from Apollo and were successfully beneficiated by electrostatic/magnetic separations during small-scale experiments (Agosto, Taylor)

Demonstrated fundamental feasibility; Achieved upgrading to 60-70 percent ilmenite

High FeO Case:

“Anomalous” high FeO in high latitude regions (i.e. near the South Pole) are not as well understood as lower latitude mare regions from which samples have been returned; however:

Potential FeO concentrations up to ~20% near S Pole from spectral analyses (Kring and Durda)

Low Ca pyroxene minerals with up to up to 10-15% FeO near crater rims; also areas in the SPA with FeO abundance of greater than 16 percent (Ohtake)

Potential hematite (Fe_2O_3) at up to 11% abundance at high latitudes on the Moon (Li)

Ilmenite present but at much lower abundance than high-Ti mare (~2% ilmenite vs 8% or more)

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Flow Sheet Development

Lunar Mare – High Ilmenite ($FeO \cdot TiO_2$) Case:

- Target is to produce beneficiated regolith containing 70% ilmenite (37% total FeO)
- O_2 yield of about 8 percent; Iron yield of about 29 percent

High FeO Case:

Directed toward anomalous mare-type regions, particularly near the South Pole (Artemis)

For regolith containing relatively high FeO content

Target is to produce beneficiated regolith containing 30% total FeO

O_2 yield of about 7 percent; Iron yield of about 23 percent

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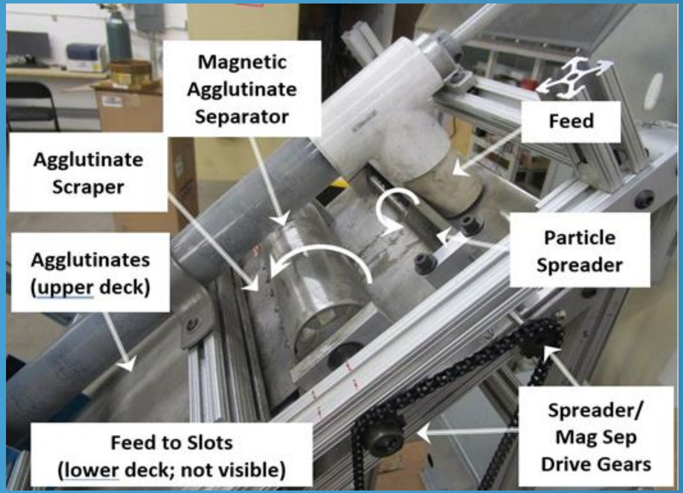
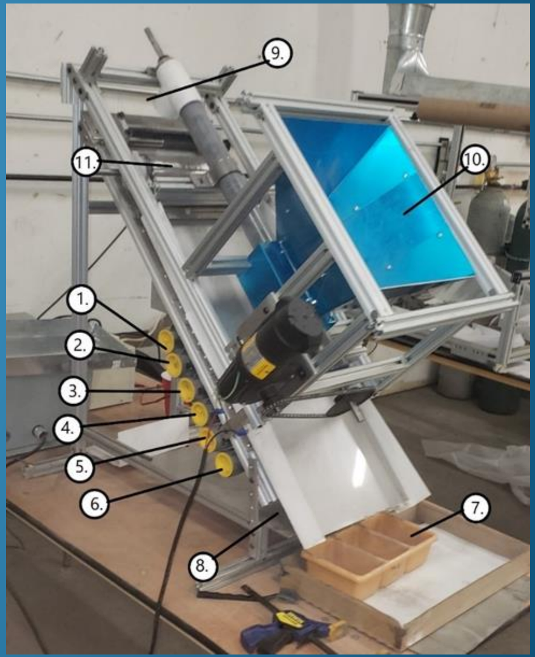
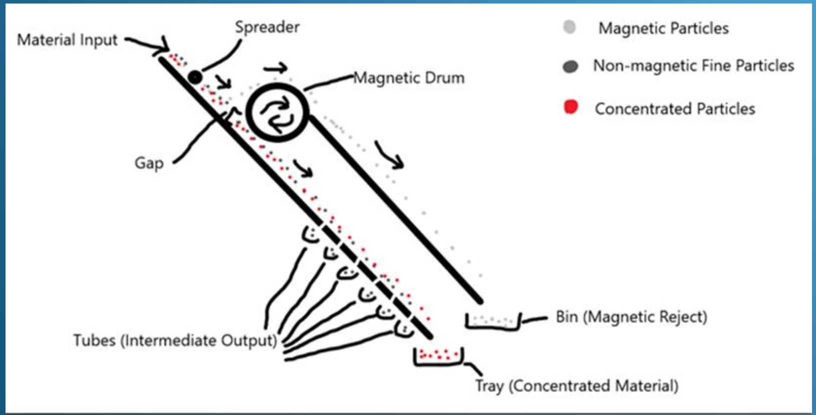
Activities in Progress:

- Beneficiation Module
  - Slotted Ramp Separator
    - No screen blinding; minimal moving parts
    - Remove coarsest, least reactive particles
    - Remove dust
    - Integrated agglutinate extractor



Slotted-Ramp Particle Size Separator





US Standard Mesh	Particle Size Distribution, Weight Percent Retained	
	All Slots	Tray
>50	5.5	37.4
50-100	12.8	42.5
100-200	38.9	17.4
< 200	42.8	2.7

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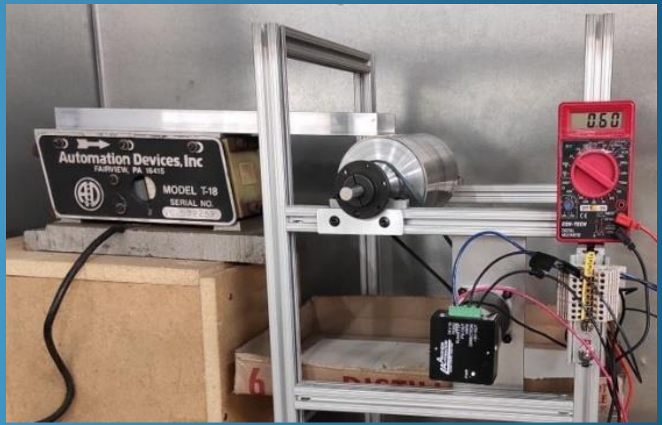
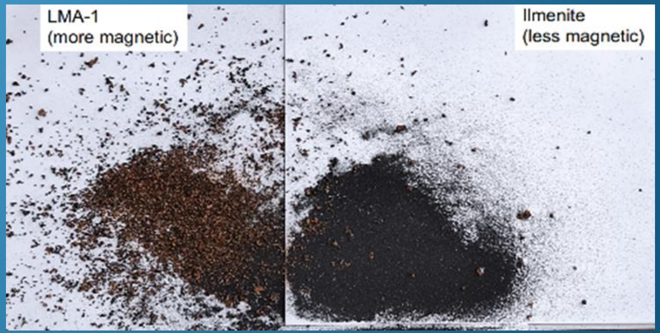
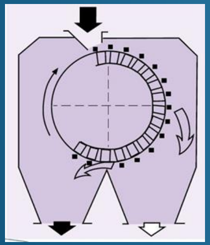
Activities in Progress:

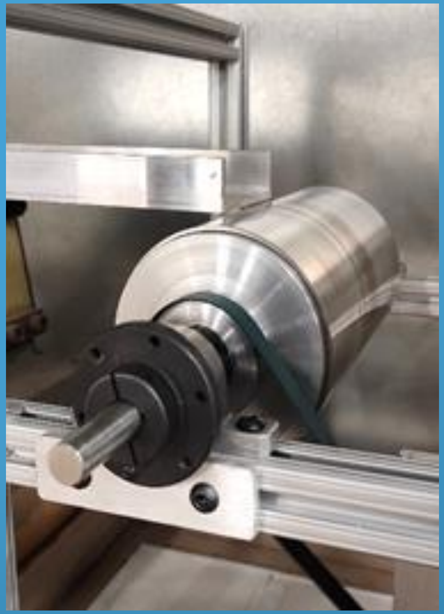
- Beneficiation Module
  - Magnetic separator
    - Permanent magnet drum separator
    - Adjustable operating parameters to optimize separations

Permanent Magnet Drum Separator









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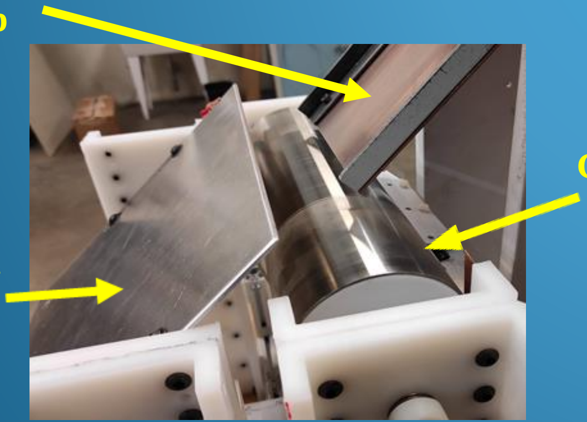
Activities in Progress:

- Beneficiation Module
  - Electrostatic separator
    - >10 kV; low current
    - Grounded drum/charged “lifting plate”

Electrostatic Separator



Ilmenite/Anorthosite

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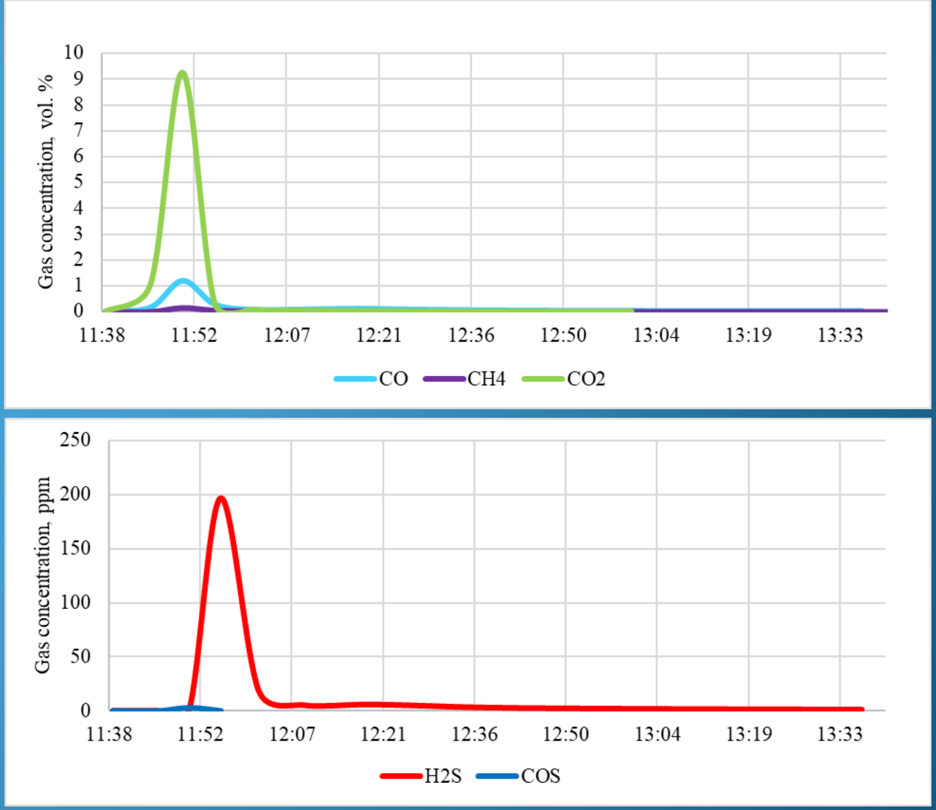
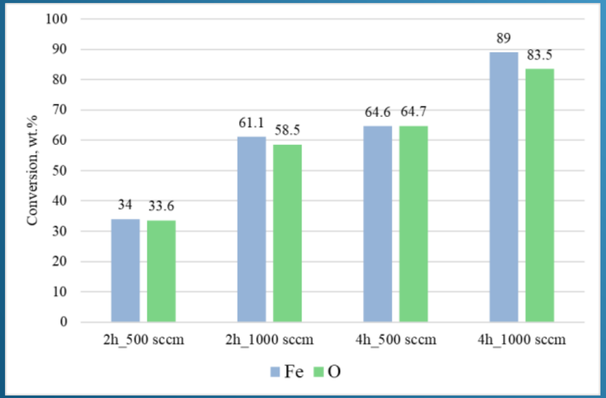
Activities in Progress (continued):

- Lab iron oxide reduction experiments
  - Identify range of operating conditions using various feed compositions
  - Produce samples for melt refining tests and evaluation of metal for manufacturing
  - Identified electromechanical automation/motion control requirements (linear sliders, rotary actuators, grippers, clamps)



Contaminant Release



Effect of Process Conditions on Oxygen and Iron Yield

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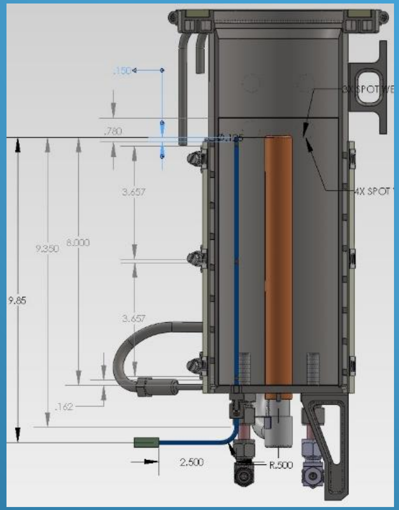
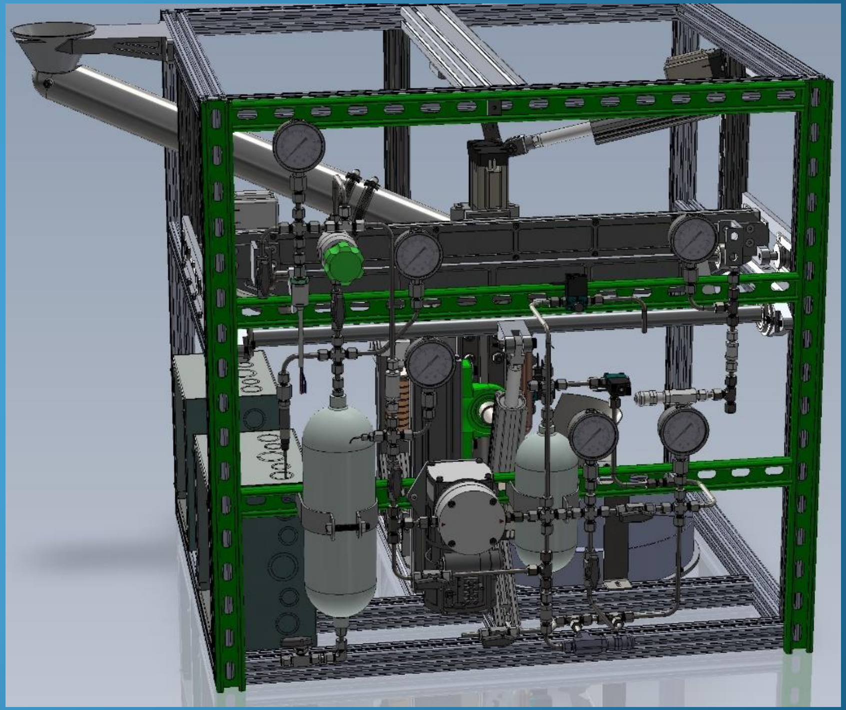
Activities in Progress (continued):

- Iron oxide reduction hardware
  - Validate reduction performance and motion controls
  - Demonstrate operation in vacuum
  - Refine scale-up parameters





MMOST Iron Oxide Reduction System
(configured to fit in a one cubic meter vacuum chamber)

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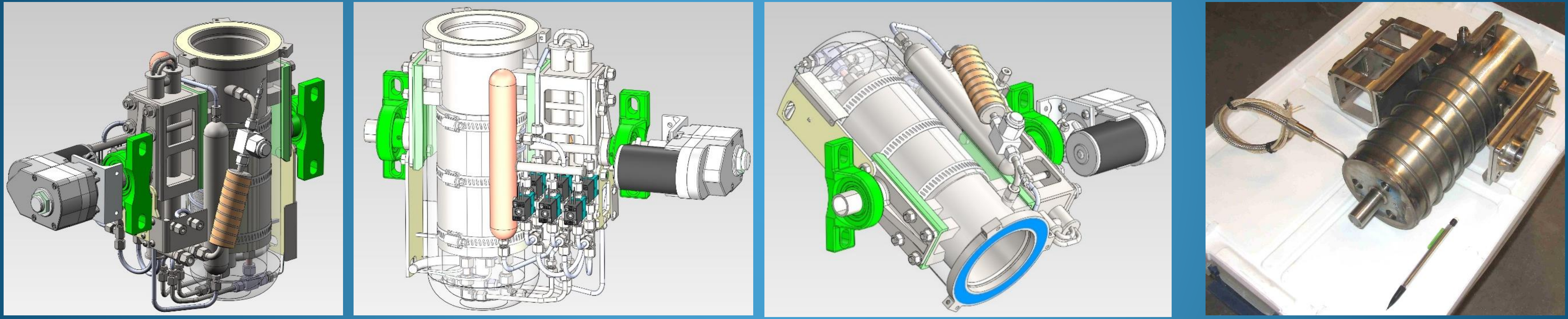

MMOST Iron Oxide Reduction Reactor Subassembly

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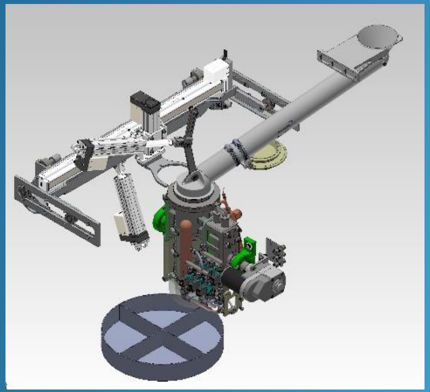
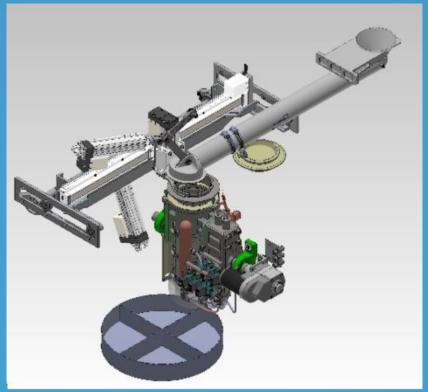
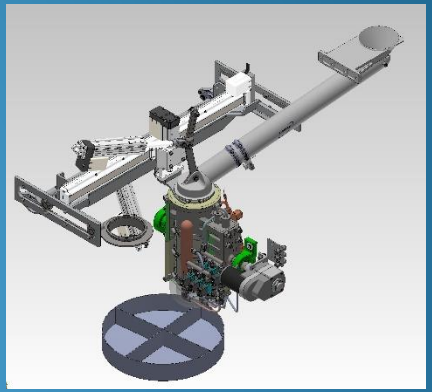


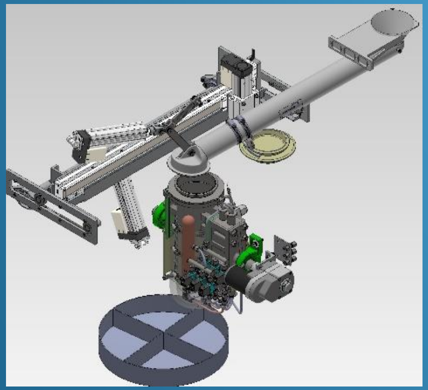
Load Regolith



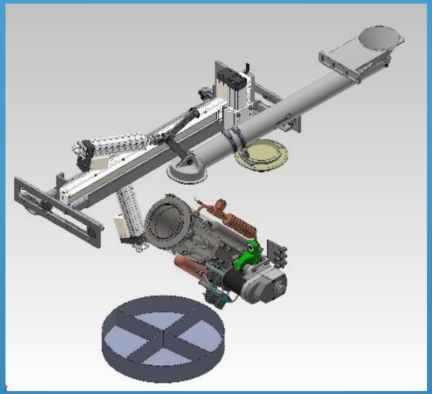
Remove Protection Sleeve/Install Lid



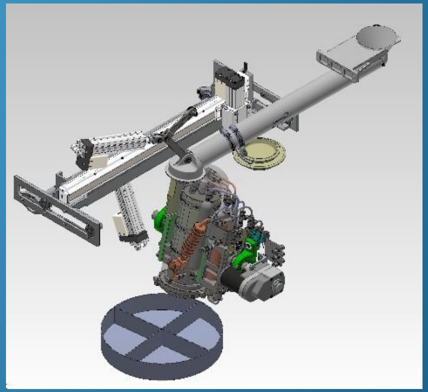
Reduction



Sleeve Installed/Ready to Discharge



Partial Inversion



Full Inversion

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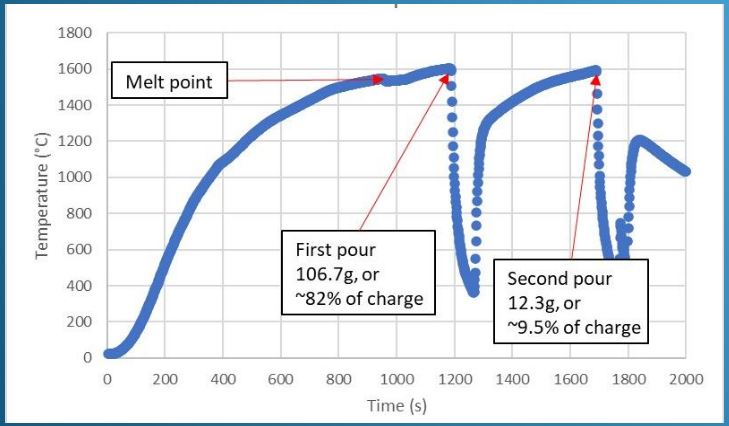
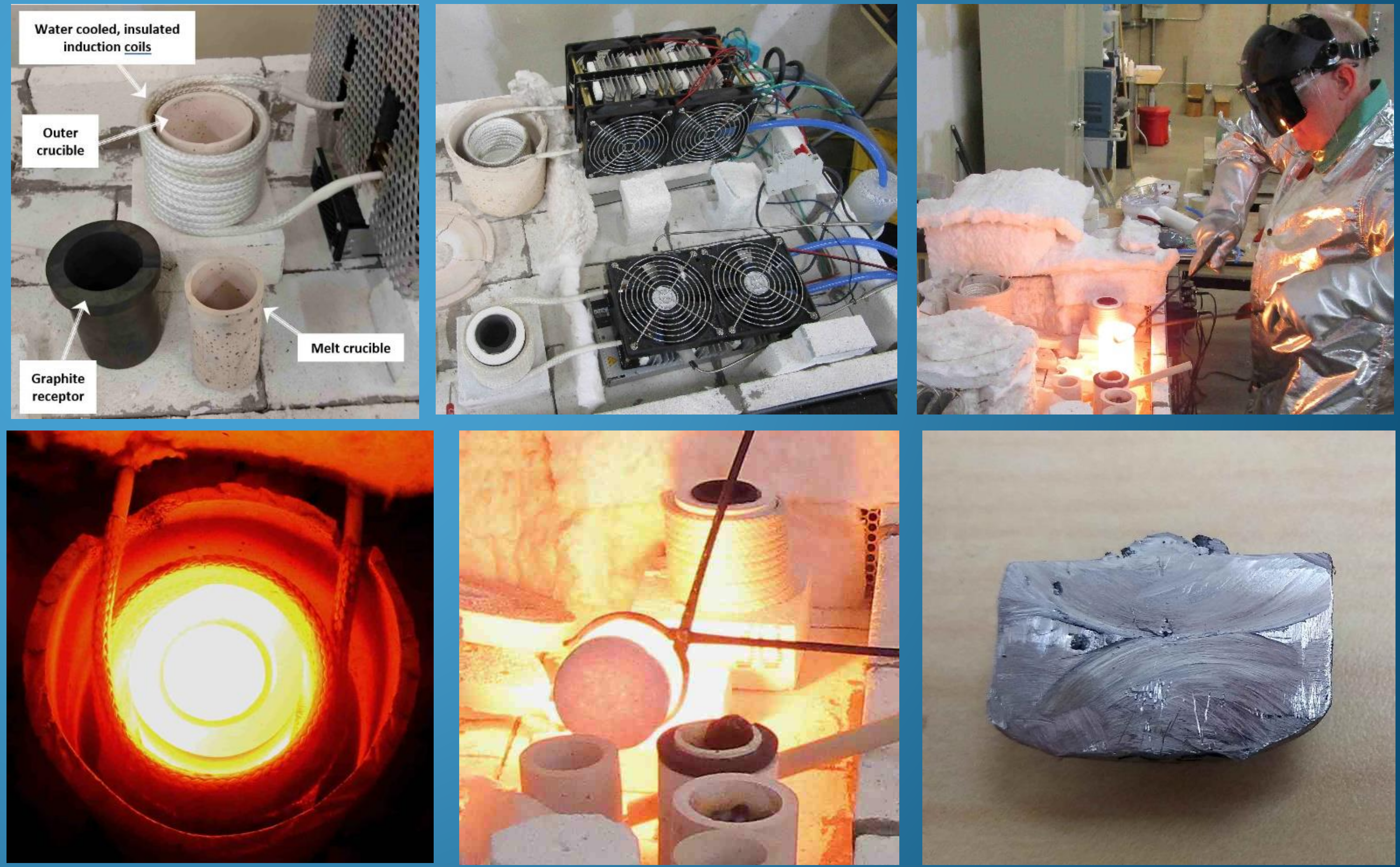
Activities in Progress (continued):

- Melt refining of reduced regolith
  - Induction Heating
    - No electrodes
    - Need to couple induction coils to reduced regolith



Induction Furnace Heating Rate

Induction Furnace Experiment



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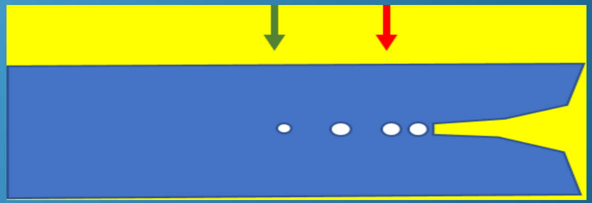
Activities in Progress (continued):

- Melt refining of reduced regolith
  - Induction Heating

Initial Fe Coalescence (from high TiO2 slag)

Iron Bead (from full melting in boron nitride crucible)

3/8" Diameter Iron Rod (in ceramic mold)



Preliminary Pour ("piping" upon cooling)

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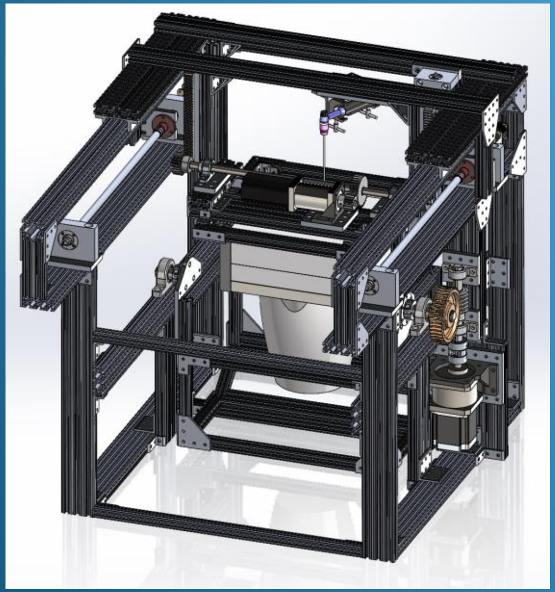
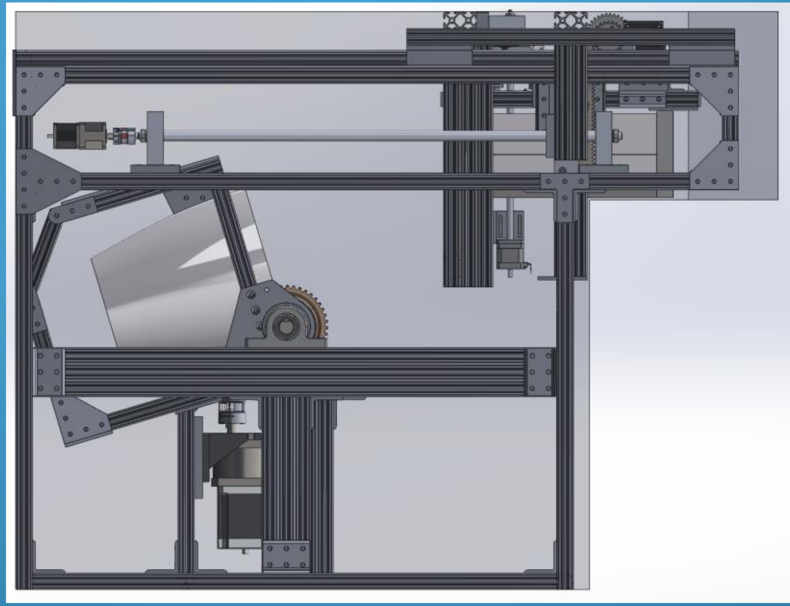
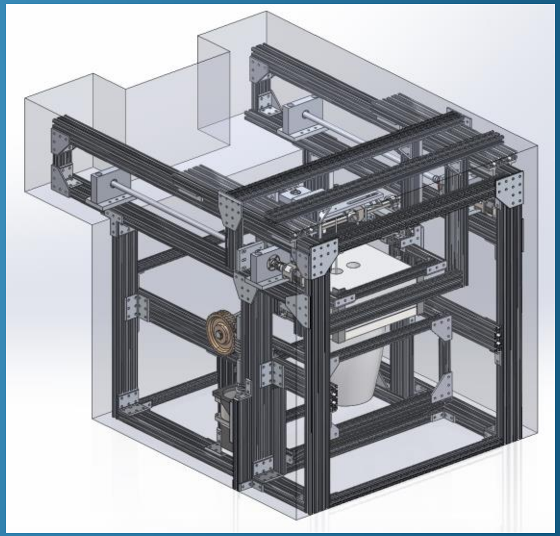
Activities in Progress (continued):

- Melt refining of reduced regolith







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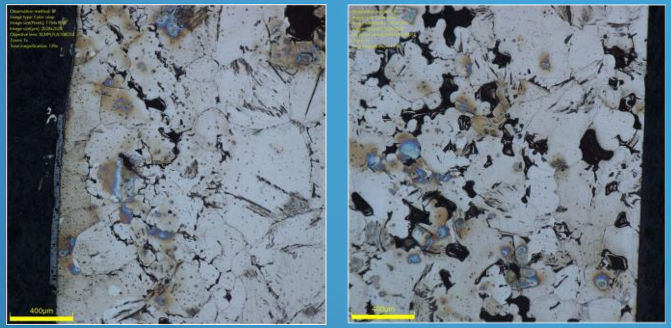
Activities in Progress (continued):

- Colorado School of Mines Materials Characterizations

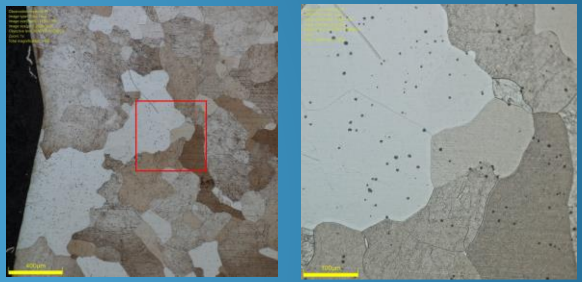

Ground Basalt

Percentile	Size(um)
10	6.06
20	14.86
30	26.61
40	40.69
50	59.61
60	85.44
70	115.1
80	165.6
90	306.1
95	533

Simulant Particle Size Distribution



Electric Arc Melted Iron Porosity (edge and center regions)



Induction Melted Iron Inclusions

MMOST Induction Melted Iron Grain Texture

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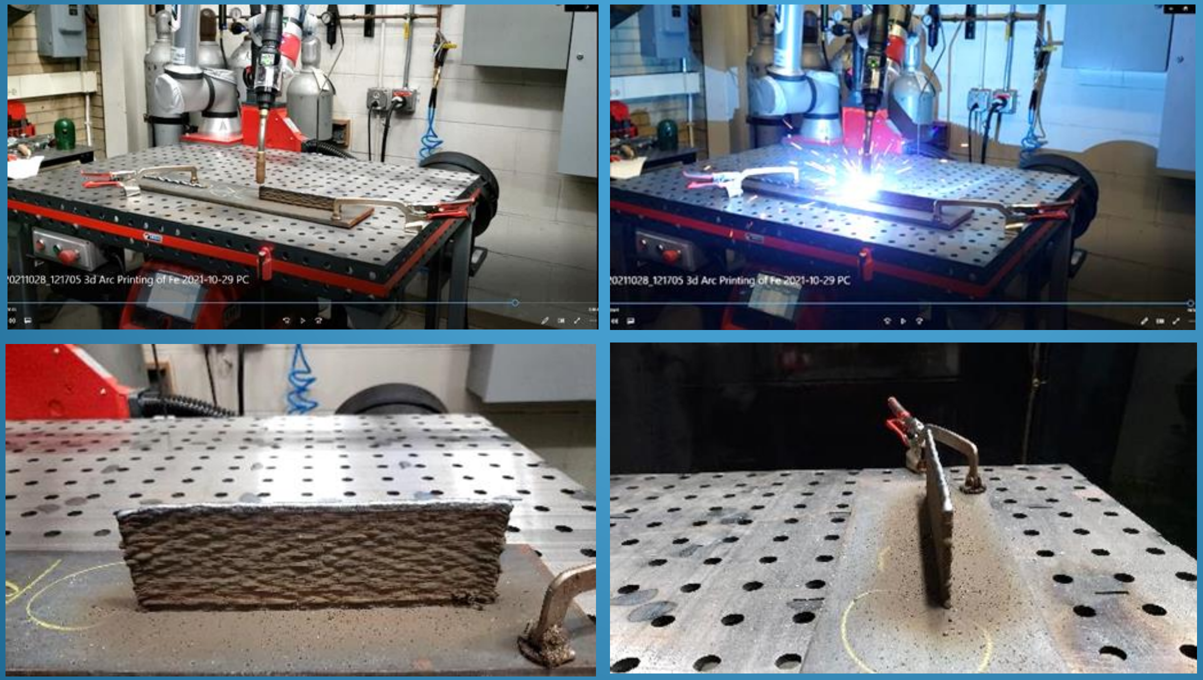
Colorado School of Mines – Additive Manufacturing Evaluation:



Wire-fed arc deposition of metallic iron

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Forward Plans:

- Continue operation and refinement of each MMOST process module
- Integrate unit operations using protocols that minimize peak power demand
- Demonstrate LOXIE in vacuum
- Establish mass, volume, power estimates for a scaled-up system
- Define path toward mission infusion

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Potential Follow-on Activities/Mission Infusion:

- LOXIE lunar flight experiment
  - Robotic sub-scale system
  - Delivered to the Moon on a CLPS lander
- Pilot unit operation
  - Crewed Artemis mission
  - Demonstrate operations and manufacturing in the lunar environment
- MMOST commercial system
  - Support lunar base operations
  - Develop a cis-lunar economy

NASA

PIONEER ASTRONAUTICS

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