Extraterrestrial Metals Processing

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Extraterrestrial Metals Processing (EMP)

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David Eisenman (Technical Monitor)

Extraterrestrial Metals Processing (EMP)

Project Description:

- Identify and validate metal production technologies applicable to ISRU on Mars or the Moon
- Demonstrate end-to-end iron production via conversion of Mars or lunar analog materials to fabricated components
- Design a light metals production unit via lab-scale experiments and small-scale light metal preparation

Extraterrestrial Metals Processing (EMP)

- Mars baseline:
  - Significant deposits rich in iron, magnesium, and silicon-bearing minerals
  - Water available for production of H_2 and O_2
  - Atmospheric CO_2 available for production of CO and C reducing agents
- Also applicable to the Moon:
  - Possibly requires feed enrichment
  - Requires greater process recycle to minimize consumables

Extraterrestrial Metals Processing (EMP)

Primary Constituents of Target Metals, Oxides, and Reducing Agents:

- Iron, Magnesium, Carbon, Silicon, Oxygen, Hydrogen

Primary ISRU Feed Stocks to Support EMP:

- Water, Carbon Dioxide, Iron Oxides, Silicon Oxides, Magnesium Sulfate, Ilmenite

Primary ISRU Processes to Support EMP:

- Thermochemical Reactions, Electrolysis, RWGS

Primary and Secondary Products:

- Iron/Steel, Light Metals, Silicon/SiO_2, Carbides, Silicides, Refractory Oxides

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Extraterrestrial Metals Processing (EMP)

- Iron Production:
  - Reduction by hydrogen or carbon monoxide to produce metallic iron
    - Reduction with CO chosen
      - $Fe_2O_3 + 3\ CO = 2\ Fe + 3\ CO_2$
      - Provides ability to generate carbon steels
      - Leverages Earth knowledge base for reducing/refining/heat treating
      - Amenable to closed-loop Reduction-RWGS-Electrolysis process
    - RWGS to Regenerate CO from CO_2
      - $CO_2 + H_2 = CO + H_2O$
    - Electrolysis to Produce H_2 to Support RWGS (and make O_2 byproduct)
      - $H_2O = H_2 + 0.5\ O_2$

Extraterrestrial Metals Processing (EMP)

- Iron Production (continued):
  - Purification/Refining
    - Physical beneficiation
    - Melting, with slag/fluxes
    - Possible direct use without further impurity removal
  - Manufacturing
    - Casting
    - Sintering
    - Extrusion
    - Additive manufacturing (3D printing)

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- Iron Production (continued):
  - Example Feed Stocks
    - Martian "blueberries"
      - Occur as spherules of a few millimeters diameter
      - Rich in hematite (Fe_2O_3) at 70% or more
      - Little or no beneficiation required
    - Undifferentiated soil
      - Still relatively rich in iron oxide (order of 20% on Mars)
      - Can be upgraded via aqueous processing prior to reduction

Pelletizer/Blueberry Simulant

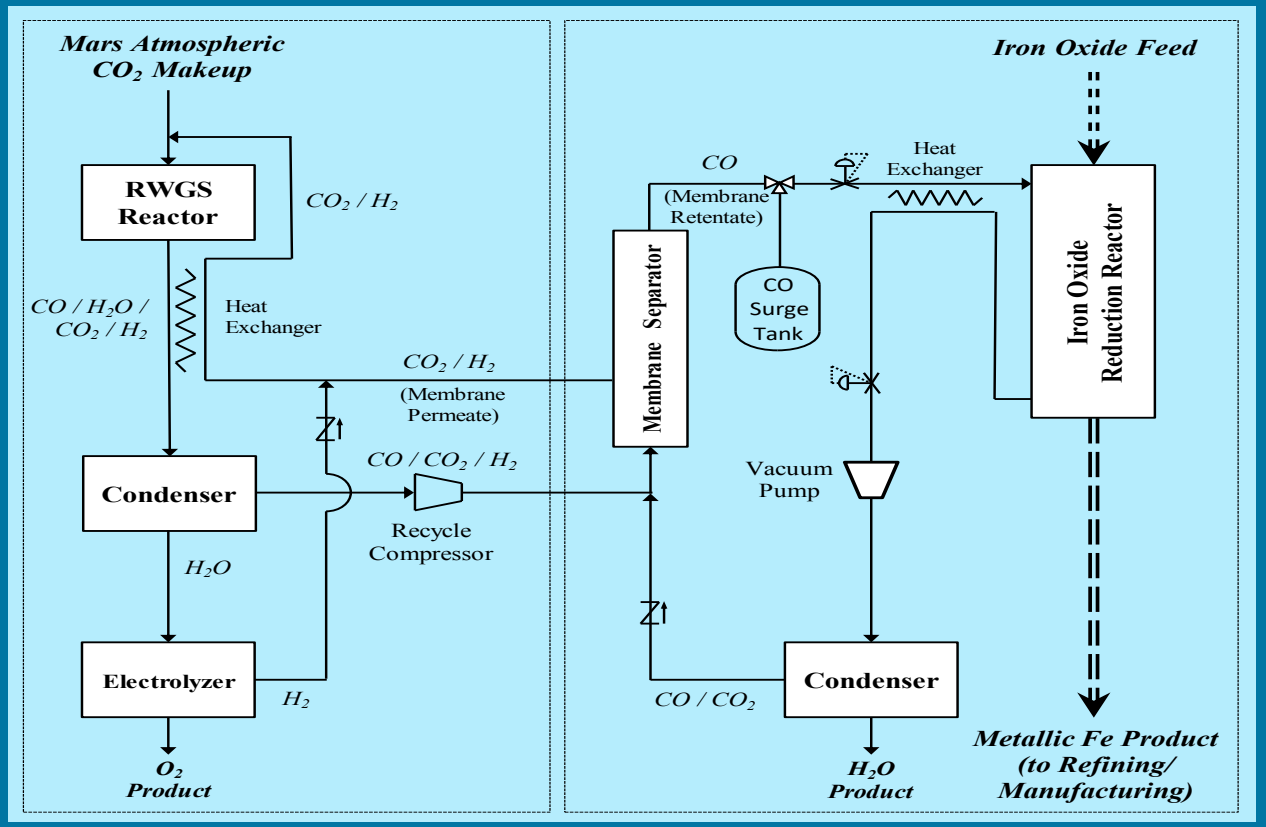
Mars-1 Simulant and Residue;
Fe, Mg, Al, Ca Oxide Concentrates
from Aqueous Processing

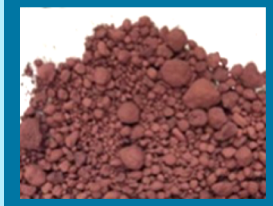
Extraterrestrial Metals Processing (EMP)

- Iron Production (continued):
  - Process design
    - 1 kg/day metallic iron production rate
    - Batch solids reactor/continuous gas flow
    - Generate free-flowing or lightly agglomerated product
    - 750 – 900°C
    - 0.5 - >2 bar absolute pressure
      - Lower pressure → little or no carbon/carbides
      - Higher pressure → more carbon/carbides
    - Excess CO flow
      - Drives reaction to completion faster (~60 minutes)
      - Excess CO is separated/recycled in closed loop process

Extraterrestrial Metals Processing (EMP)

- Iron Production (continued):





Extraterrestrial Metals Processing (EMP)

- Light Metals Production:
  - Magnesium is the preferred target
    - Rich magnesium sulfate salts on Mars
      - Thermally decompose to MgO, SO_2, O_2
    - Mg metal has higher strength-to-weight ratio than aluminum
    - Compatible with low pressure/CO_2 Mars atmosphere
    - High Mg vapor pressure enables alternative to molten salt electrolysis
      - $CO_2 + H_2 = CO + H_2O$ (RWGS)
      - $2\ CO = C + CO_2$ (Boudouard)
      - $SiO_2 + 2\ C = Si + 2\ CO$
      - $2\ MgO + Si = 2\ Mg_{(vapor)} + SiO_2$

        "Pidgeon Process" (~1200°C)

High purity Mg produced by silicothermic reduction

Extraterrestrial Metals Processing (EMP)

- Light Metals Production:
  - Silicothermic Reduction of MgO
    - Silicothermic reduction of MgO is not thermodynamically favorable
    - However, high Mg vapor pressure allows Mg product to be removed as vapor – reaction continues when operating at low pressures
  - Carbothermal Reduction of MgO
    - Simpler process (eliminates Si production step)
    - $MgO + C = Mg_{(vapor)} + CO$ (at >1200°C; low pressure)
    - Requires fast separation of Mg vapors from CO to prevent back reaction
    - Novel carbothermal reduction/product separation method is being investigated

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Extraterrestrial Metals Processing (EMP)

- Manufacturing:
  - Casting/Machining

Metallic iron from Mars-1 simulant Fe_2O_3 concentrate

  - Sintering

Sintered/machined iron from JSC-1 lunar simulant

  - Additive Manufacturing

Extraterrestrial Metals Processing (EMP)

- Additive Manufacturing Candidates:
  - Powder-based technologies offer opportunity for manufacturing using minimally refined feeds:
    - Powder Injection Technology
      - Laser Metal Deposition (LMD)
    - Powder Bed Technologies
      - Selective Laser Sintering (SLS)
      - Selective Laser Melting (SLM)
      - Electron Beam Melting (EBM)
  - Selection will be based on trades against hardware mass and power

Extraterrestrial Metals Processing (EMP)

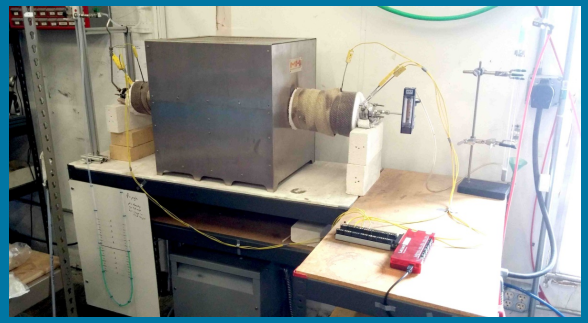
Summary:

- Many ISRU resources are available to support human space exploration
- ISRU process techniques can generate materials of sufficient quality for manufacturing
- Potential manufacturing methods, especially additive manufacturing, continue to evolve and improve

Extraterrestrial Metals Processing (EMP)

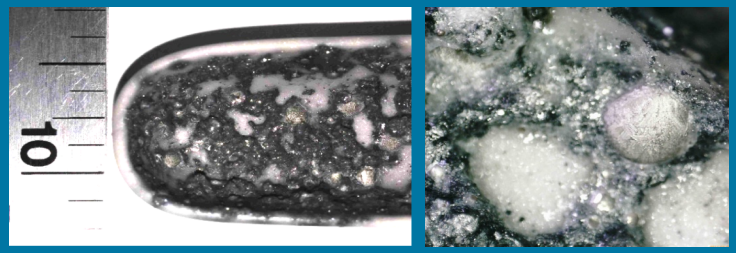
Extraterrestrial Metals Processing (EMP)

Carbothermal Reduction Experiments (Soil Simulants)



High-Temperature
Laboratory Furnace

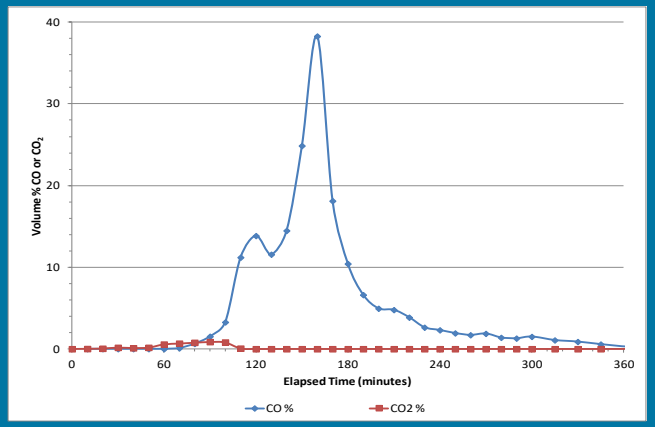
Feed (left) and Residue (right)
(JSC Mars-1 Simulant)



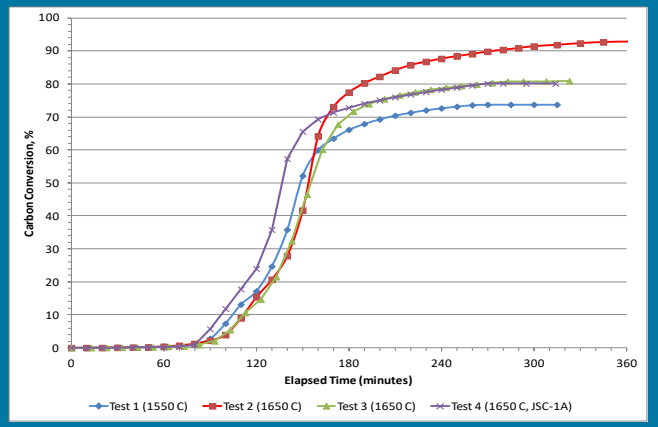
Residue Close-Up Images
(Ca/Al rich glassy oxide slag and
ferrosilicon beads)

Extraterrestrial Metals Processing (EMP)

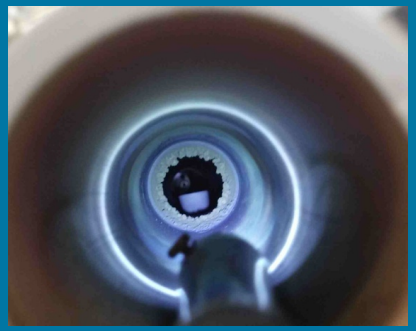
Carbothermal Reduction Experiments (Soil Simulants)



CO and CO_2 Release Profile (CT-02)



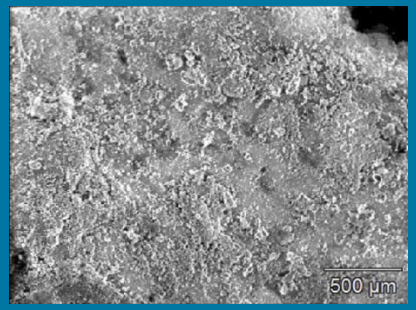
Carbon Conversion; CT-01 to CT-04
(CT-02 = 1650°C at ~240 minutes)



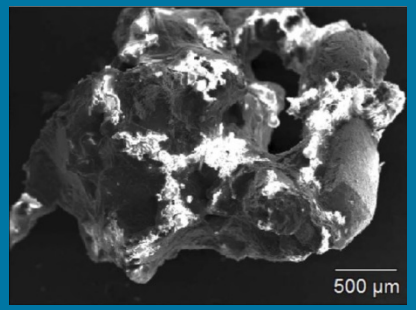
Fumed SiO Condensed
on Furnace Tube Walls

Extraterrestrial Metals Processing (EMP)

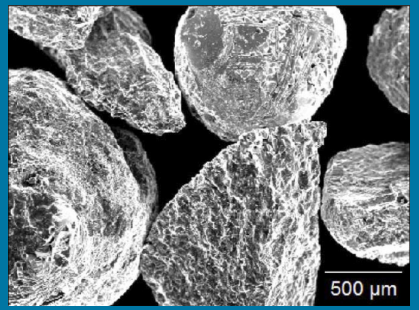
Carbothermal Reduction Experiments (Soil Simulants)



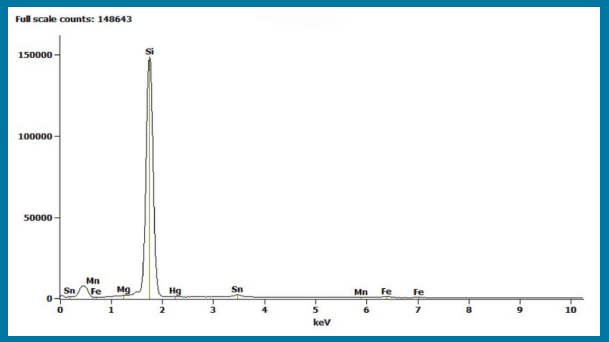
Condensed SiO

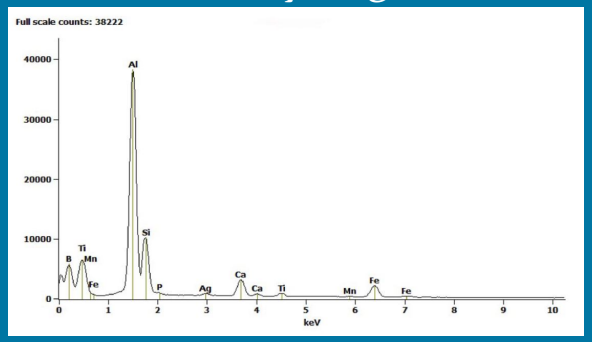


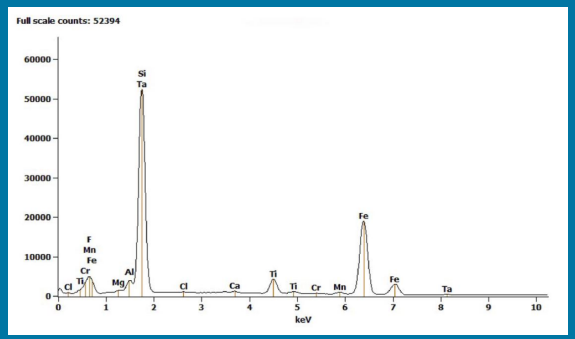
Glassy Slag



Ferrosilicon Beads



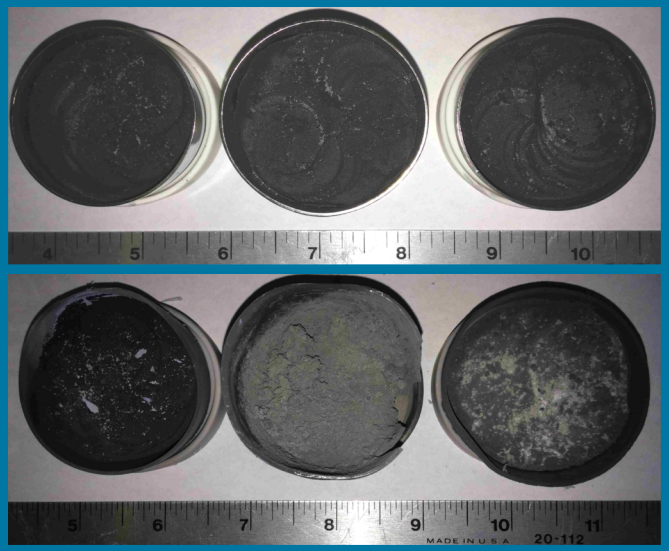




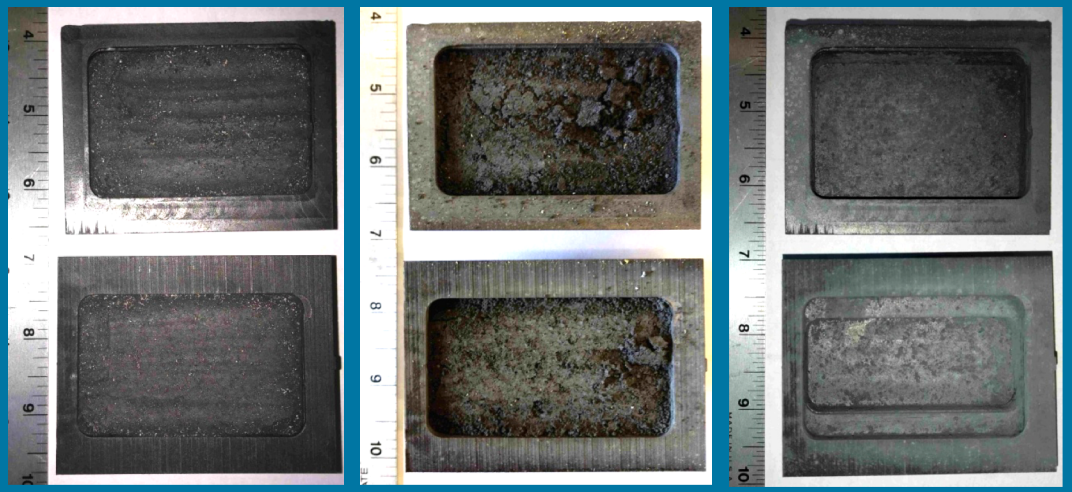
Energy Dispersive X-Ray Spectra (EDS) from
Scanning Electron Microscope (SEM)

Extraterrestrial Metals Processing (EMP)

Carbothermal Reduction Experiments (Si-Rich Feeds)



Silica Sand/Carbon in Zr Crucibles
(top: before testing;
bottom: after reduction)



Si-Rich Mars-1 Simulant/Carbon in High-Density Graphite
(left: before testing; center: after reduction;
right: after removing residue)

Extraterrestrial Metals Processing (EMP)

Silicothermic Reduction Experiments (Magnesia Feed)

Magnesium Product Resulting from 1250°C at ~1 mbar Pressure
(left: Mg on collection mesh and reactor walls;
center: Mg on upstream edges of collection mesh;
right: Mg crown peeled from cold zone reactor surfaces)

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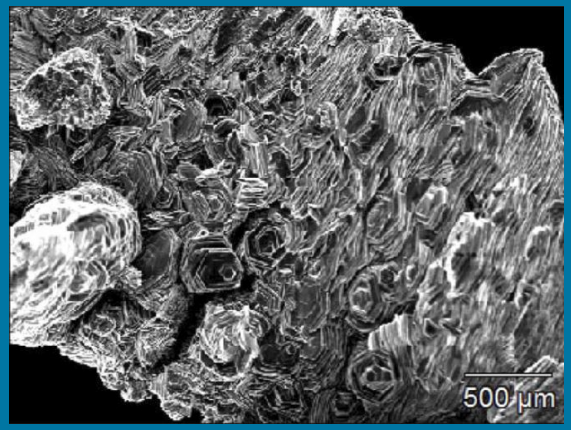
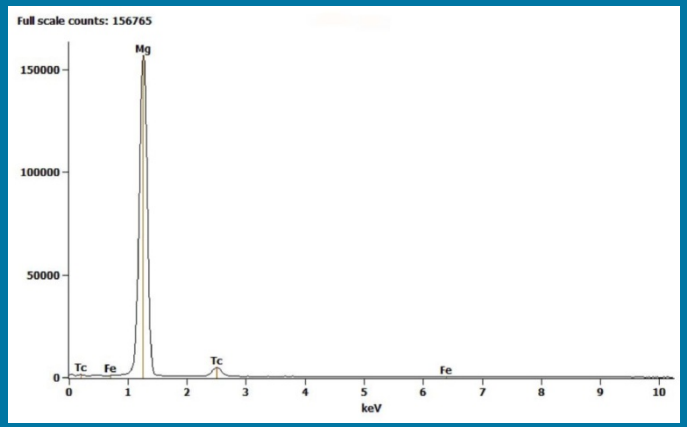
Extraterrestrial Metals Processing (EMP)

Silicothermic Reduction Experiments (Magnesia Feed)





Magnesium Crown Product

Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray Spectra (EDS)

Acknowledgements

- NASA Jet Propulsion Laboratory / SBIR Program
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