Production of Steel from Lunar Regolith through Carbonyl Iron Refining (CIR)

POWDER METALLURGY RESEARCH LAB

THE UNIVERSITY OF UTAH

NASA BIG IDEA CHALLENGE

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Motivation

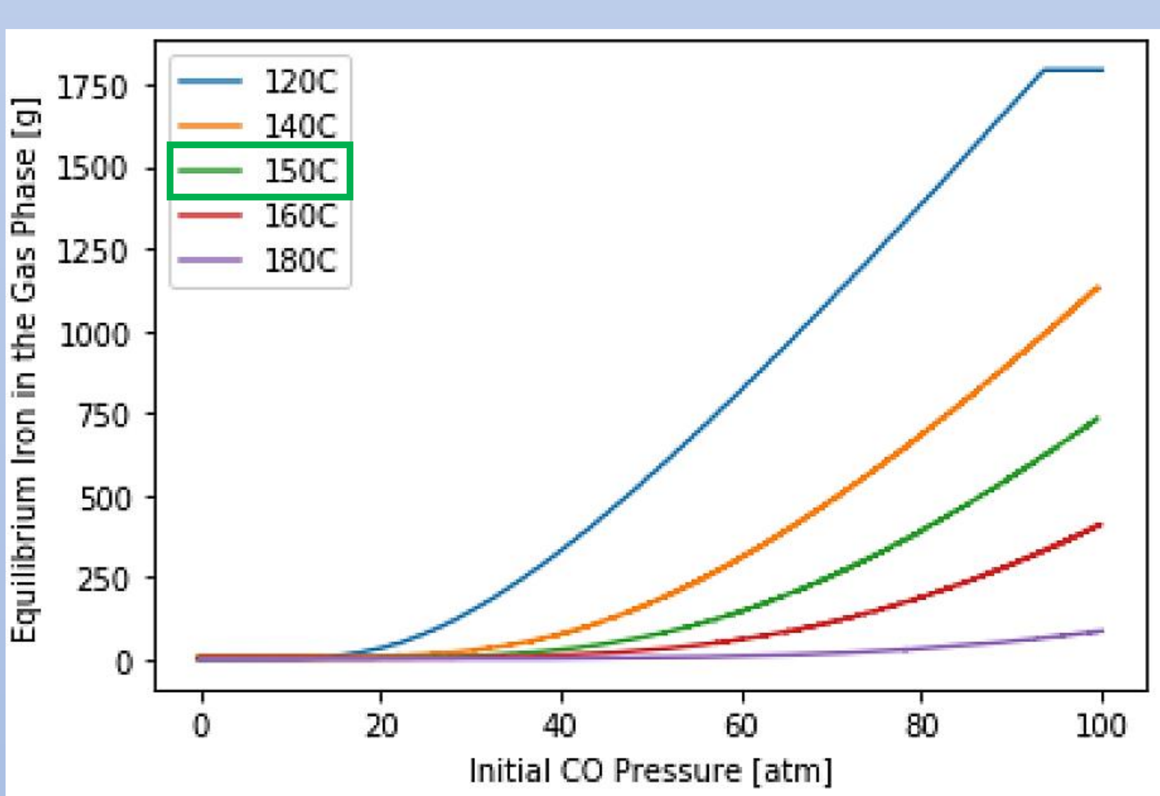
Transporting equipment to the moon is extremely cost-prohibitive, and competition is fierce over a limited cargo volume. Freight impediments are circumvented if the required material can be harvested, processed, and shaped at the destination. The hostile and remote environment constrains candidate technologies to establish a production pipeline with minimal equipment volume and a low dependence on consumables.

Approach

Carbonyl Iron Refining (CIR) has attributes especially conducive to these constraints. Our proposed CIR concept tailors existing iron refining technology into lunar-optimized apparatus. CIR uses a reactive gas phase to concentrate disparate iron particles into a high-purity (>98%) powder product with properties favorable for additive manufacturing. The process does not consume the reactive gas, making the apparatus nearly closed-loop.

Feasibility Calculations

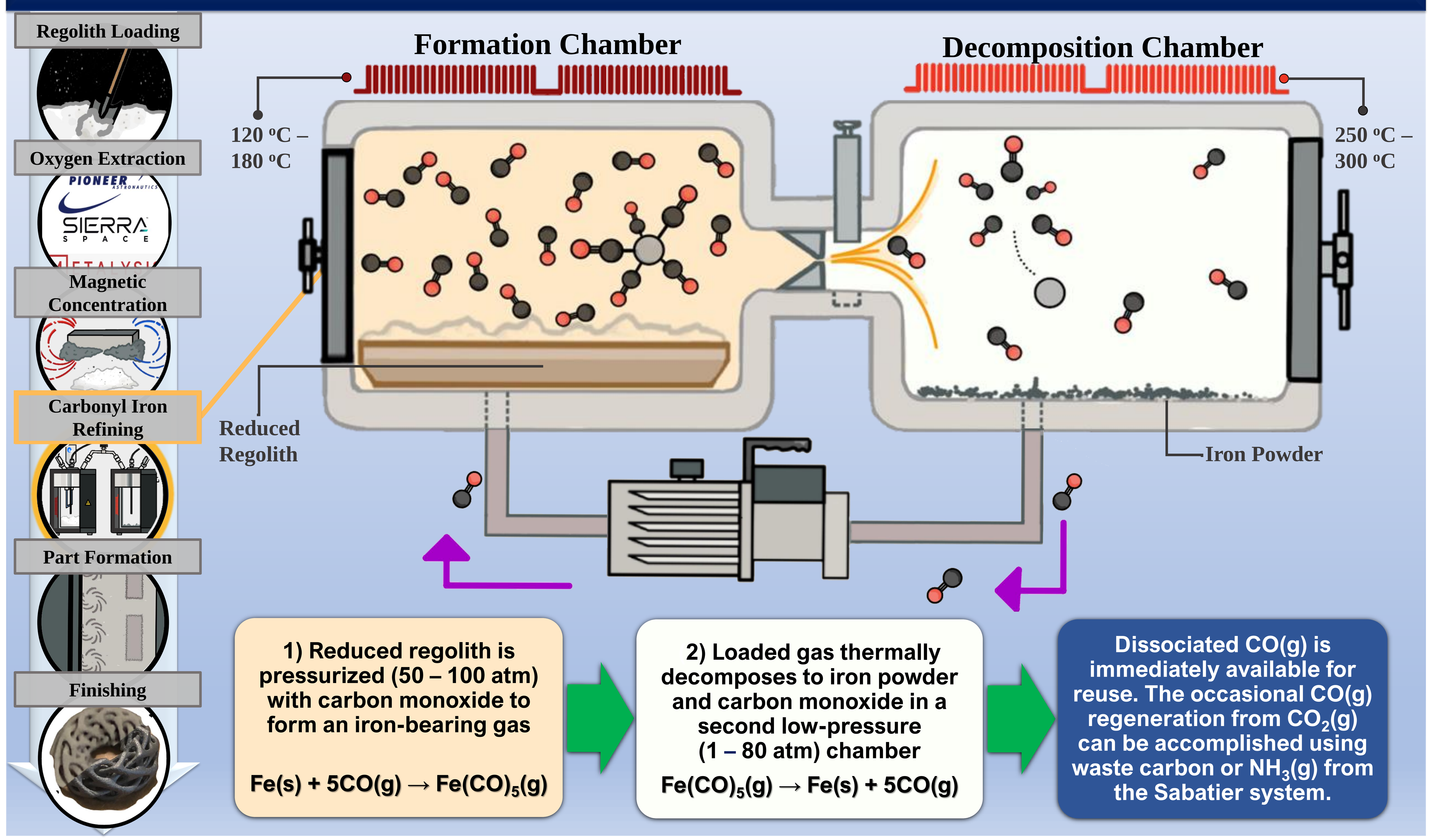
- Iron pentacarbonyl ($Fe(CO)_5(g)$) formation is favored at low temperatures and high pressure. However, operating at a low *T* introduces a kinetic limitation.
- Carbonylation is commercially done at high *P* (>200 atm) to maximize per-batch iron yield over the course of ~48 hours. Production at lower pressures has received relatively little research.
- Operating at lower pressures appears ideal for the lunar environment, where a curtailed throughput may be an acceptable tradeoff for a lighter vessel.
- Thermodynamic calculations suggest the feasibility of low-pressure equilibrium iron yield.



Pressure [atm]	Iron Yield per Cycle [g]	Cycles to Break Even
20	3.74	43,829
40	29	5,653
60	145	1,131
80	389	422
100	732	224

Temperature: 150 °C; Apparatus mass: 164 kg; Composition: 10 wt% Fe; Volume loading: 10%; Volume Reactor: 100 L

Proposed CIR Production on Moon: Two-chamber design



Carbonylation and Decomposition Verification Testing

Lab-scale carbonylation system

- Built for verification testing under specific conditions of *T* and *P* for $Fe(CO)_5(g)$ formation and decomposition into iron.
- Formation chamber was a 0.6-liter titanium pressure vessel connected to a 19-liter stainless steel decomposition chamber.

Experimental conditions

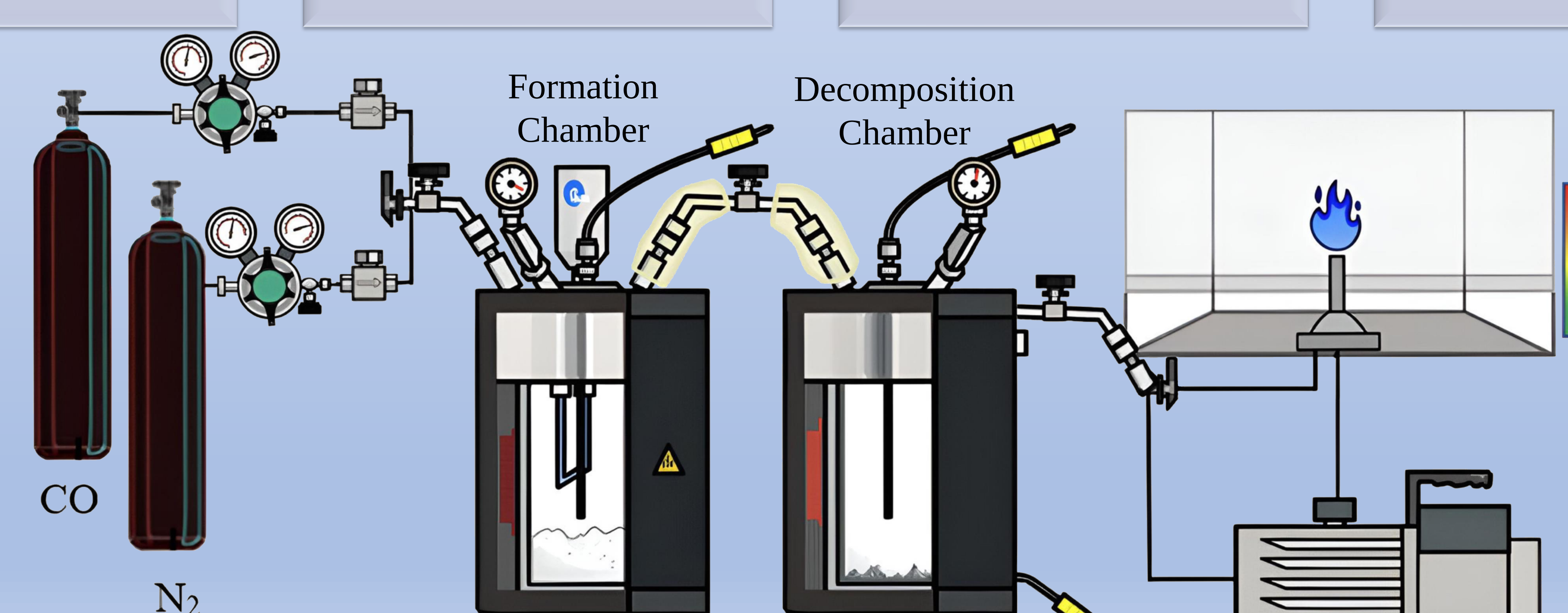
- *T* (120 – 150 °C) and *P* (50 – 55 atm) combinations were tested to find the optimal yield of $Fe(CO)_5(g)$ formation.
- The pressure was maintained between 180 to 410 minutes.

Verification testing

- Performed on 11 samples with different loading materials:
  - 6 with iron puriss
  - 4 simulant regolith from Pioneer Astronautics,
  - 1 simulant regolith reduced in-house.
- 7 of the 11 experiments produced a small quantity of powder product.

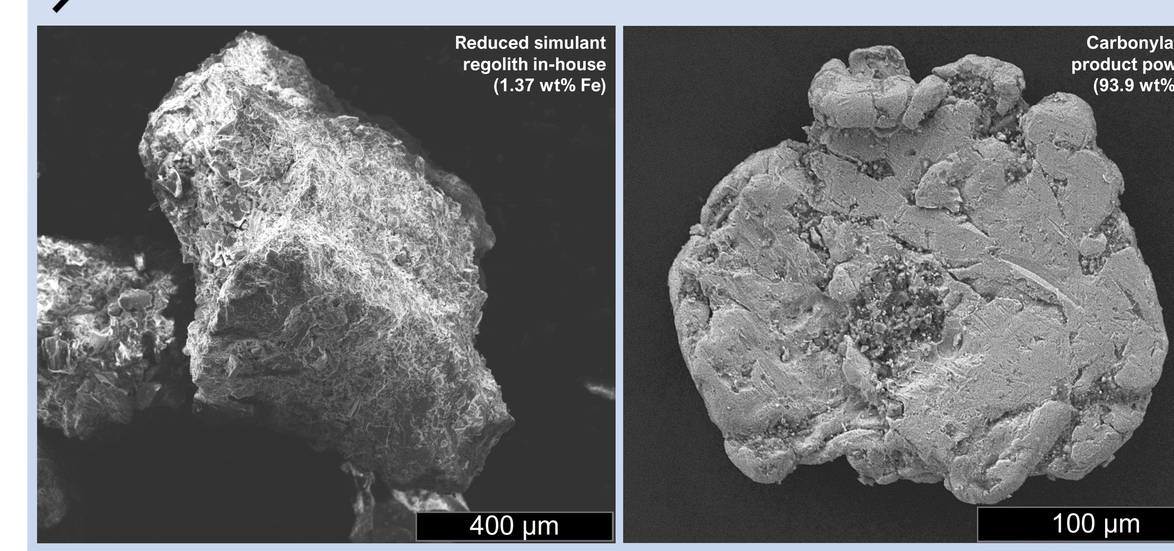
Further Experiments

- Two additional experiments with CO(g) were performed using a High-Pressure wire-mesh TGA up to 180°C and 80 bar to verify the $Fe(CO)_5(g)$ formation.
- A decrease in mass up to 0.9% mass decrease was observed for a 3 h 39 min experiment.

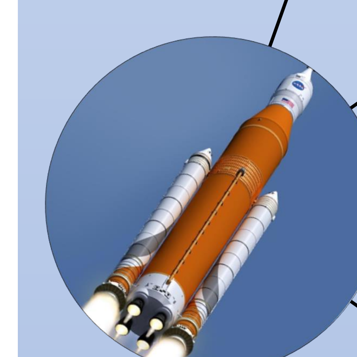


Results and Conclusions

1. Products were found to be >91 wt% iron, with balance oxygen (E3, E8, E11 contained ~99, 6.4, 1.37 wt% Fe in starting material).
2. XRD verification on E8 assuaged iron powder entrainment concerns, confirming the absence of Ti and Si peaks.
3. Carbonylation product was large in diameter (mean~200 μm) and of low density (~3.2 g/cm³) compared to puriss powder.
4. Feasibility of extracting and concentrating iron into a product powder from a reduced simulant regolith was demonstrated.



Future Research



1. Modify decomposition chamber variables to densify and shrink the product particles to meet the constraints of additive manufacturing.
2. Refine a kinetic model by maintaining formation conditions >8 hours to inform ultimate lunar viability.
3. Consider testing production at an intermediate pressure (80-120 atm).
4. Address yet unanswered questions pertinent to a closed-loop carbonylation system, such as monitoring and maintaining an effective CO/CO_2 ratio.
5. Test the merits of magnetically concentrating free iron directly from the lunar surface to remove the need for a prior reduction step.

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