# Pneumatic Planetary Regolith Feed System for In-situ Resource Utilization

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- Introduction
- Pneumatic Regolith Feed System
    - Description
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        - Laboratory and Reduced Gravity Flight Testing
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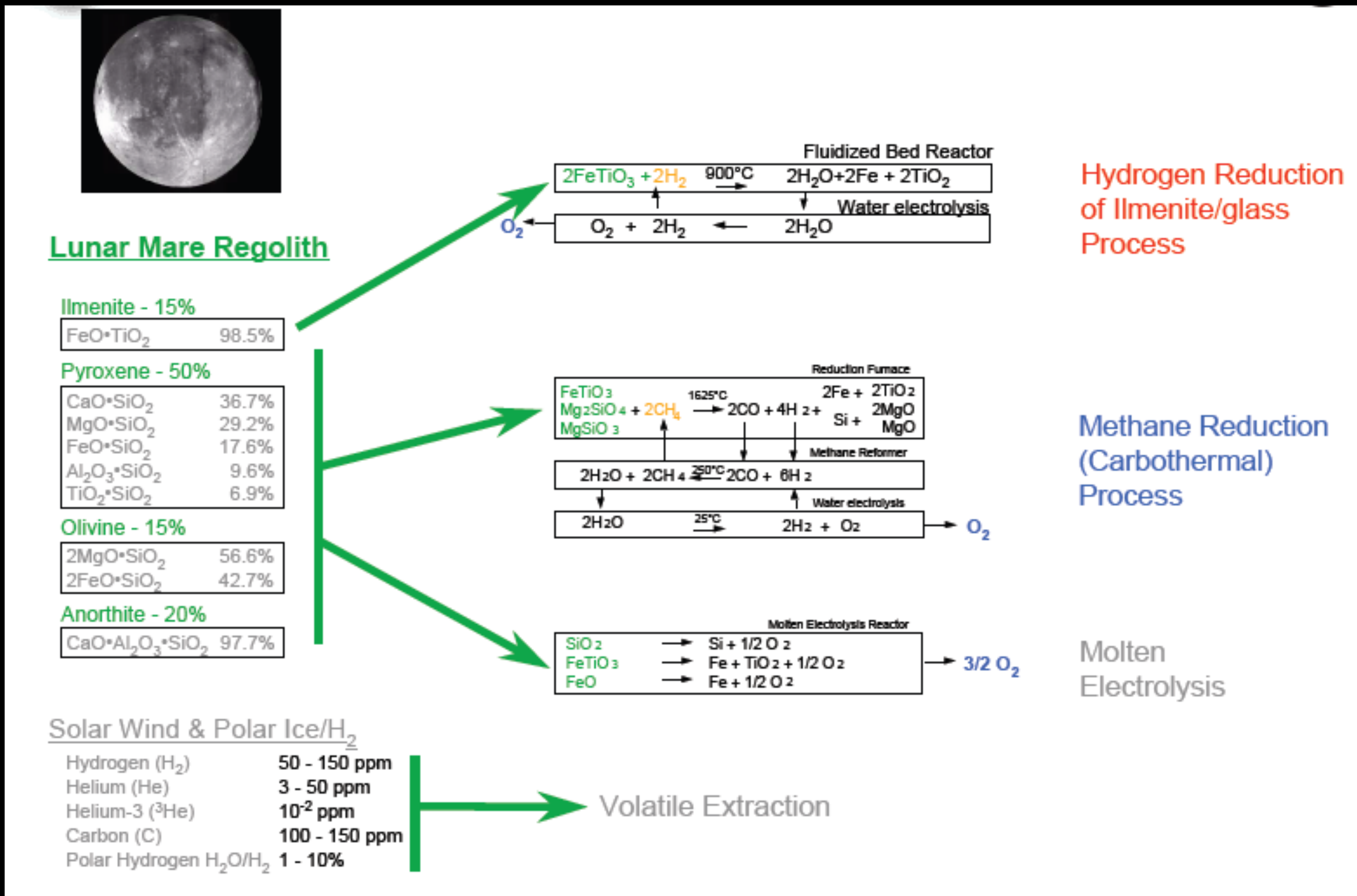
- Conclusions
- Acknowledgments

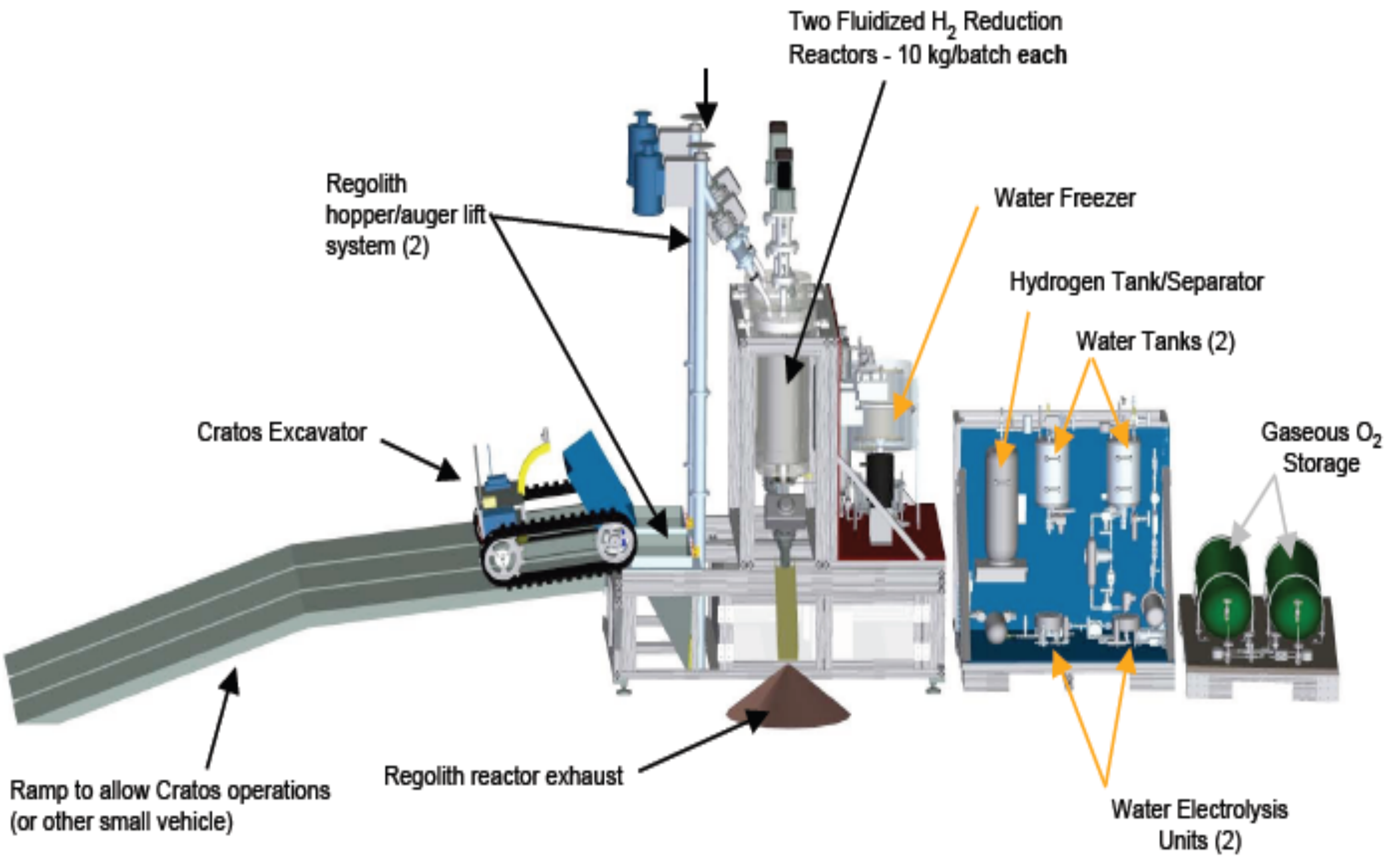
# In-Situ Resource Utilization
# "Living Off the Land"

Oxygen is one commodity that can be produced from Regolith

# Some Methods of Lunar Oxygen Production



# Configuration of the 2008 ROxygen I Hydrogen Reduction System




NASA ROxygen $H_2$ Reduction System

# Testing of a Regolith Hopper Design as a Reduced Gravity Flight Experiment through the NASA IPP/FAST Program

(http://www.nasa.gov/offices/ipp/innovation_incubator/FAST/index.html)

TEST RESULTS

Time to Empty JSC-1A
•2g – 12 Seconds
•1g – 15 Seconds
•1/3g – 35 Seconds
•1/6g – 90 Seconds

Time to Empty NU-LHT
•2G – 25 Seconds
•1g – Stall
•1/3g – Stall
•1/6g - Stall


Flight experiment in May 2008 to test the flow of regolith simulant inside a hopper under reduced gravity conditions

# Hot Regolith Ejection from the ROxygen I $O_2$ Reactor

Gemco Valve

Figure: Valves are needed that are compatible with the flow of granular materials. Spherical Disc Valve from Gemco, Inc is shown above.

Video: Gemco valve attached to a hopper during a valve qualification test.

# Hot Regolith Ejection from the ROxygen I $O_2$ Reactor

Gemco Valve

Figure: Spherical Disc Valve from Gemco, Inc is shown above.

Video of hot spent Tephra (@1000°C) flowing out of a Gemco valve attached to bottom of the ROxygen I Reactor.

# Lessons Learned

•Testing in reduced gravity environments is important to ensure correct operation of the system. Regolith does not flow at 1/6$^{th}$ G – it needs dynamic assistance

•Augers must be inclined at least 10 degrees in any gravity condition to work effectively

•Pre-size sorting of regolith is required to prevent jamming by rocks & pebbles

•Lead times for regolith tolerant high temperature valves were a challenging aspect of this design : 6-8 months. High temperature regolith valves are highly specialized and few vendors were capable or willing to tackle this challenge.

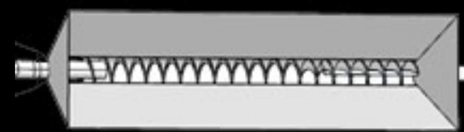
•It is difficult to hold vendors to pre-negotiated schedules. This can cause the overall project schedule to slip.

•The motors on top of the auger tubes gave the system a high center of gravity and increased the volumetric envelope of the system. A new design concept has evolved which can eliminate these motors on top of the tubes.

•Modularize each subsystem such that it can easily be disassembled from the system, shipped, then easily reassembled

•Difficult to talk an excavator owner into accepting the regolith directly from the reactor instead of picking it up from the ground after it has cooled

# Pneumatic Regolith Transfer and ISRU Processing Steps



Excavator Delivers Regolith to Trough

→

Regolith is Transferred to the Pneumatic Transfer System's Supply Bin

→

Regolith is Conveyed Pneumatically to an ISRU Reactor

↓

Regolith is Chemically Reacted to Yield Useful Products Like Oxygen and Metals such as Titanium

E.g., Carbothermal, Hydrogen Reduction, Molten Oxide Electrolysis

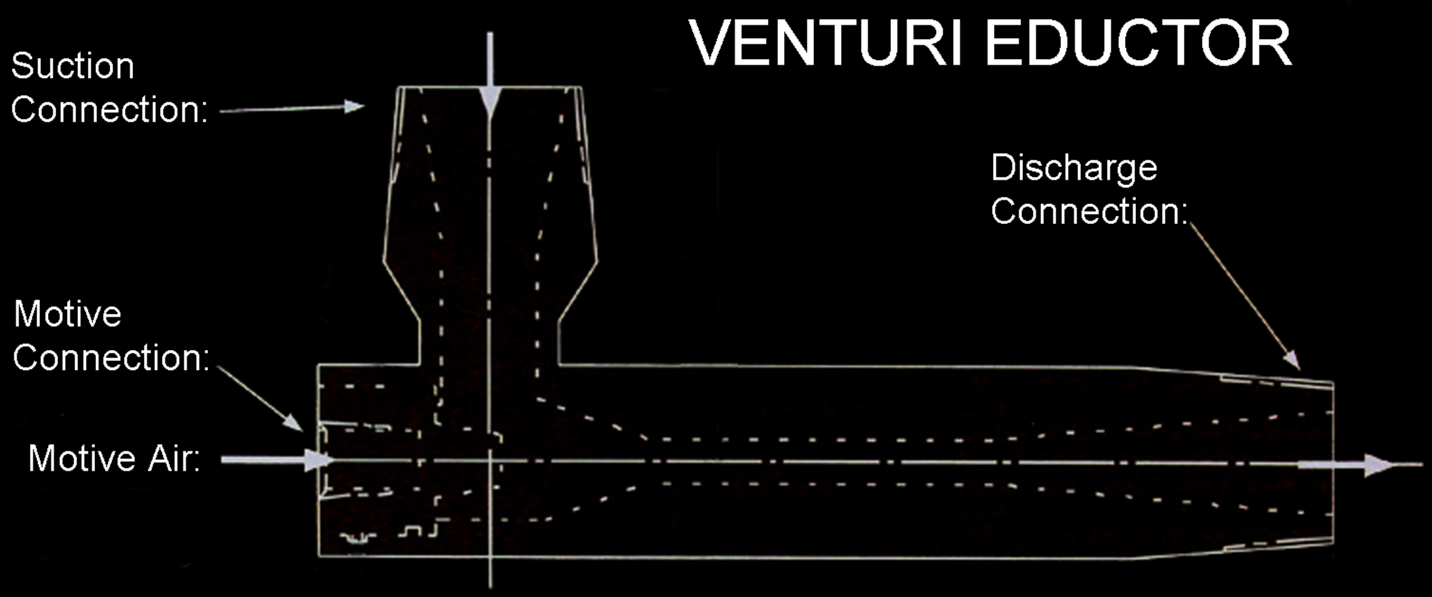
←

Regolith is Conveyed Pneumatically Within the ISRU Reactor

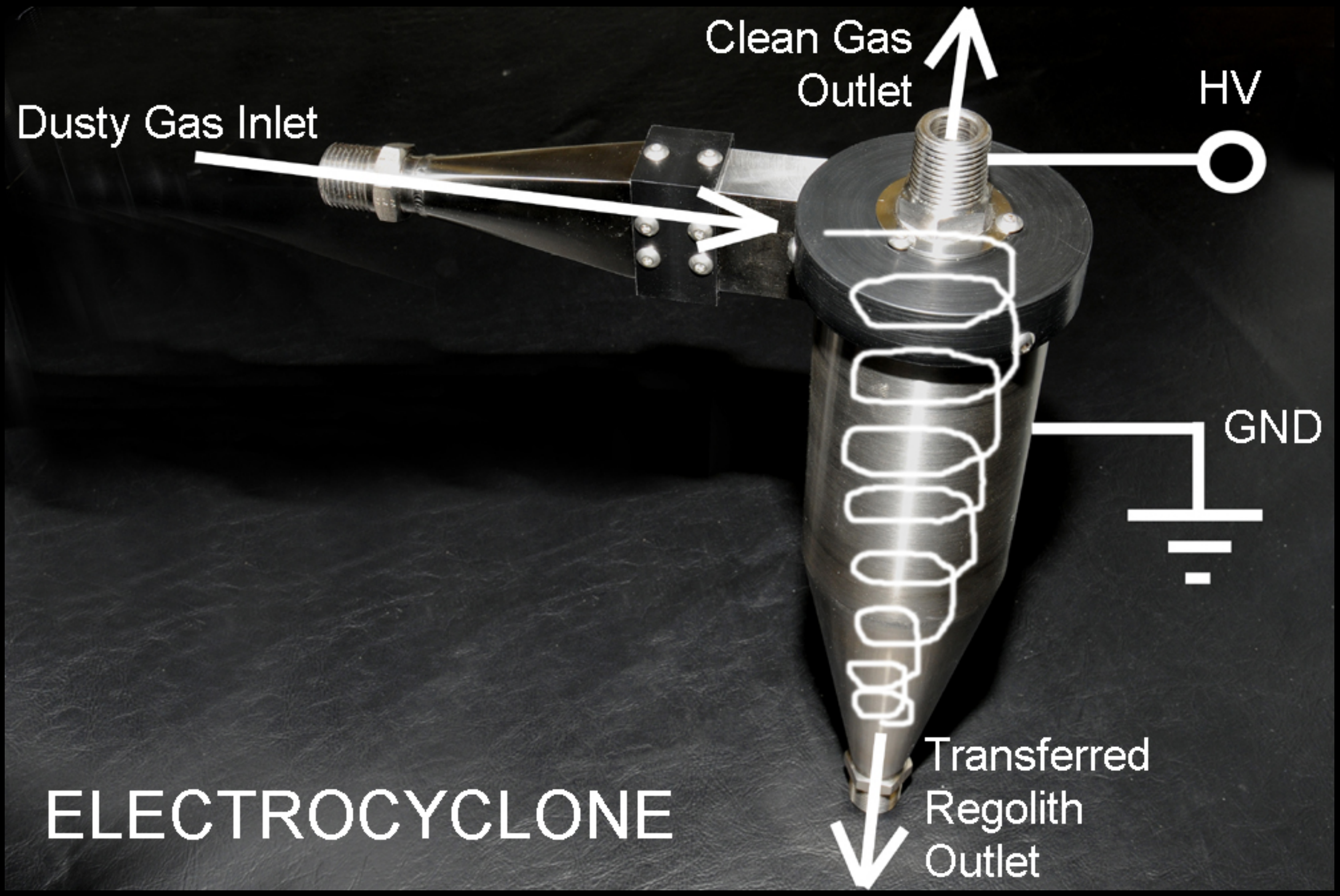
←

Spent Regolith is Pneumatically Conveyed Out of the ISRU Reactor

# Venturi Eductor



# Electrocyclone Separator



# Pneumatic Regolith Transfer System Designed for 1 g and 1/6 g

HEPA Filters for Exhaust Air from Electrocyclone

Cyclone/Electrocyclone Gas-Particle Separator

Secondary Containment Enclosure w/Hinged Door (Total Weight: 195 kg)

**Regolith Supply Partially Hidden in Back (17kg of NU-LHT-2M)**

Receiving Bin (Empty) Serving as an ISRU Reactor Mockup

High Voltage DC Power Supply for Electrocyclone

Venturi Eductor (hidden) attached to Supply Bin for Gas-Solids Mixing

Gas Supply (from Reg. Compressed Air Bottle)

# Reduced Gravity Testing Pneumatic Regolith Transfer System


perience
CMP 40s
CLARK
NNJ04JA83C-4319

# Pneumatic Feed System Testing in Reduced Gravity

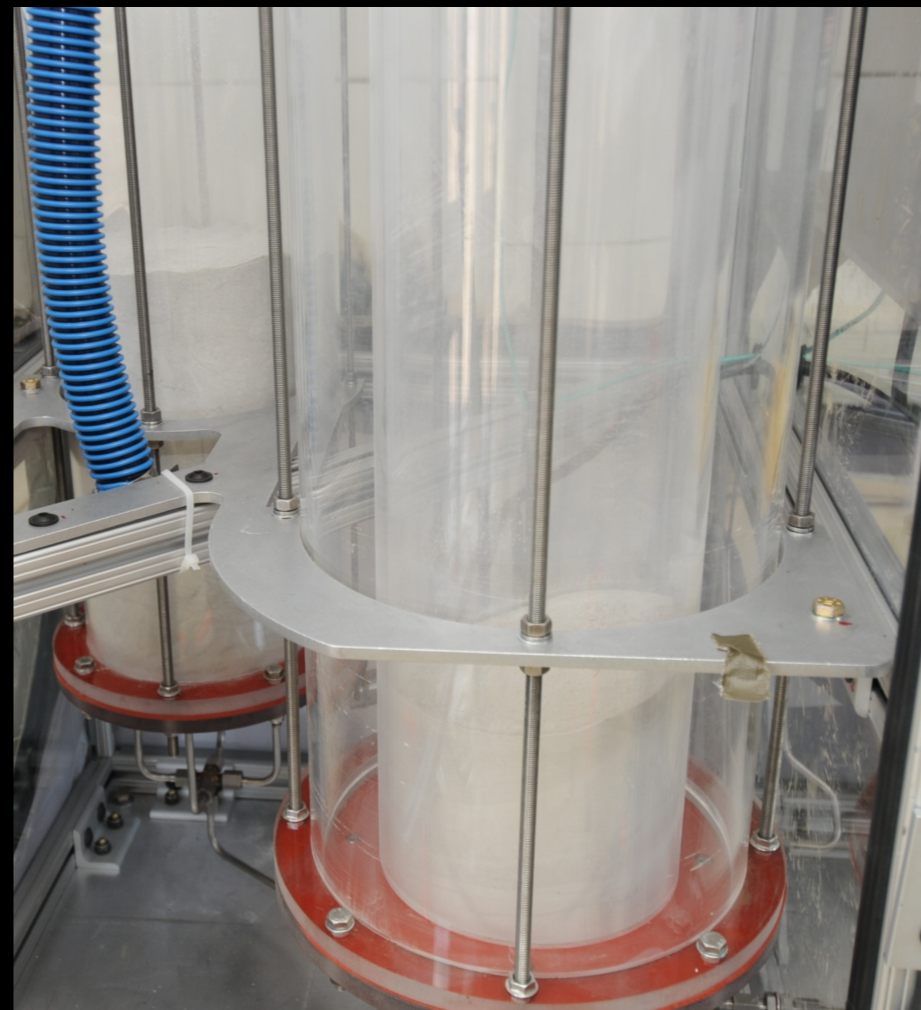
## TEST RESULTS

- Tephra (16.5kg) transferred well in 1 g
- Tephra (16.5kg) transferred better in 1/6 g

- NU-LHT-2M transferred well in 1 g. Sieved (1.4 mm) 12.5 kg was transferred in ~3 min in 1g.
- NU-LHT-2M (8.8kg) transferred better in 1/6 g (rocks in unsieved sample plugged the eductor that halted regolith transfer)

- Fluidization was evident
- Eductor formed a hole that collapsed as a result of fluidization

- Cyclones were overwhelmed by simulant flow (electrocyclone needs a dilute flow)
- Cyclones were re-designed for dense flow



1 g and 1/6 g Testing of Pneumatically Conveyed Lunar Regolith Simulants

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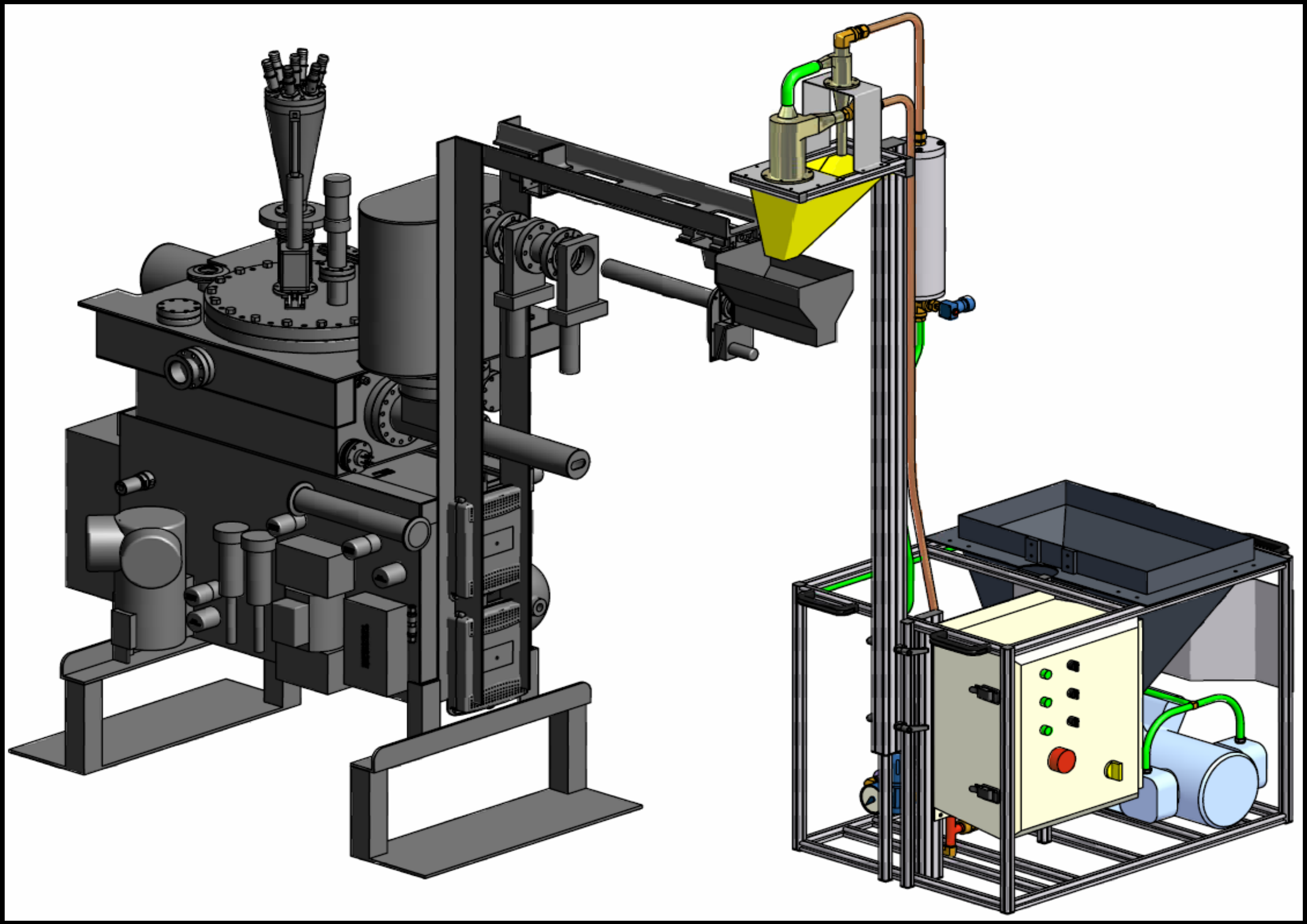
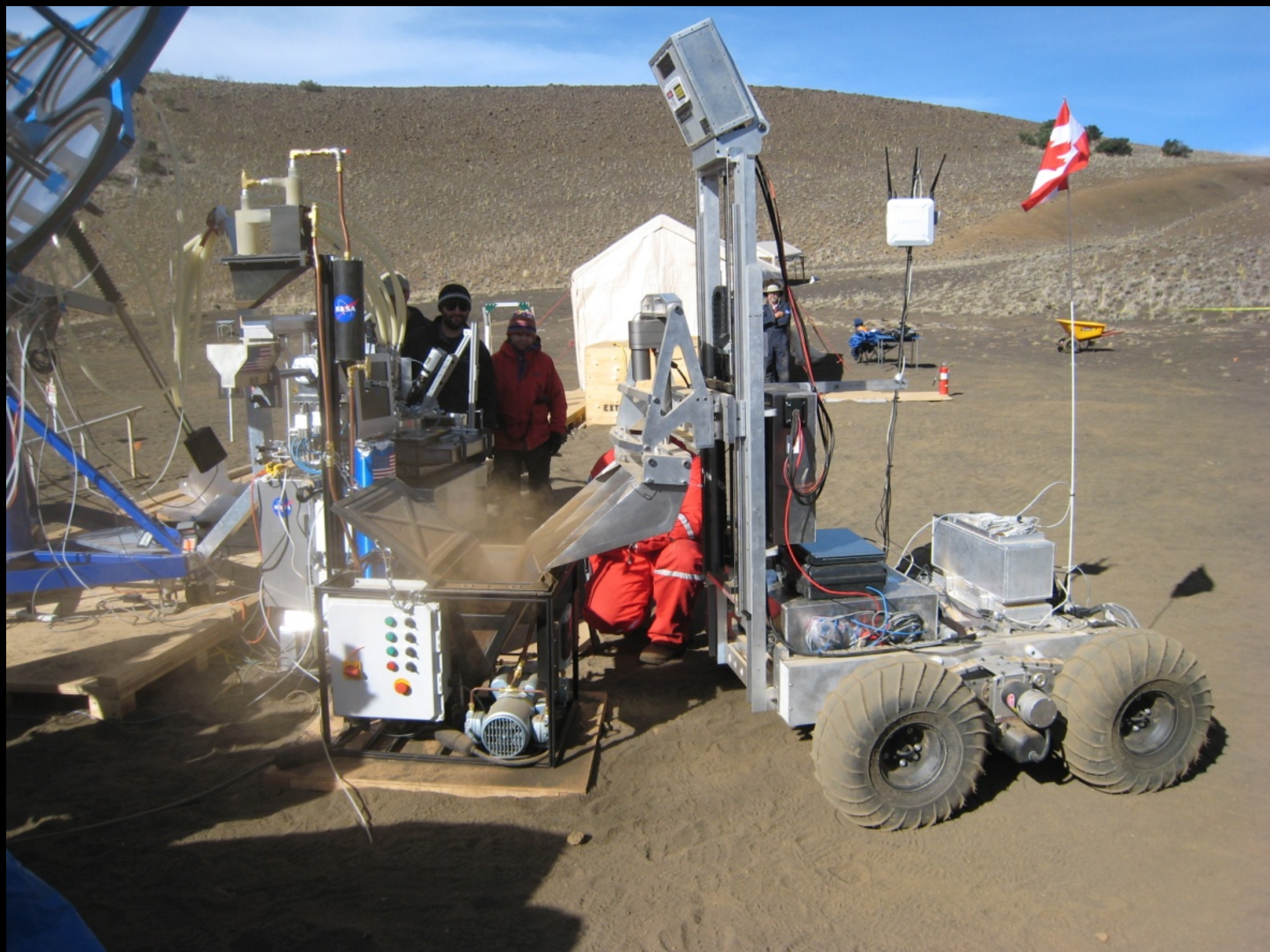
# *From Dust To Thrust:*
# Field Test at Mauna Kea, Hawai'i in February 2010

## Carbothermal $O_2$ Production



- Carbothermal $O_2$ System with Auger Feed into Reactor – Orbitec, Inc
- Pneumatic Vertical Lift Feed System – Honeybee Robotics/NASA KSC

Pneumatic Regolith Feed System
for the Carbothermal $O_2$ reactor
at the Mauna Kea field test in February 2010



# Design Challenges

- Closed loop system using recycled gas is difficult to achieve

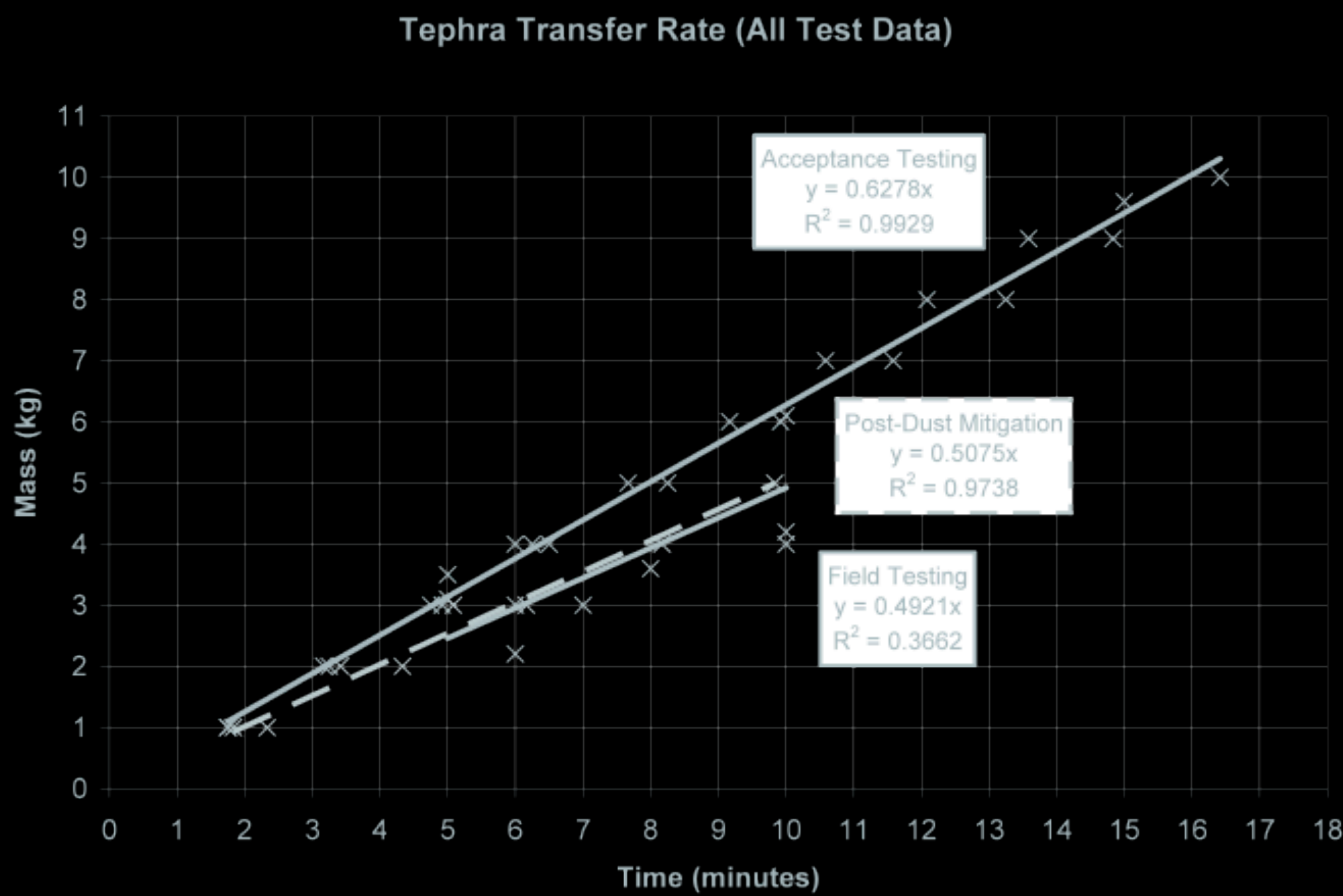
- Must separate regolith from gas efficiently

- Must move hot gas using a compressor without overheating the compressor but without removing excessive heat from the gas

- Must not clog

Video: The Pneumatic Regolith Feed System at the Mauna Kea field test in February 2010 filling the hopper of the Carbothermal $O_2$ reactor

# Carbothermal Results Mauna Kea




Mass of regolith transferred per unit of time was linear showing that a known amount of Tephra could be predicted using this curve

# Lessons Learned

• Testing in reduced gravity environments is important to ensure correct operation of the system

• Quick "Proof of Concept" prototypes can help to sell new methods

• Steps must be taken to ensure no oversized particles enter the feed system that could cause a flow stoppage

• The feed system must be protected from potential damage from the regolith delivery excavator

• Optically transparent feed system components can provide valuable test data through visual observation of granular flow inside the system that may not be achievable analytically

# Possible Regolith Feed Systems Trade-Offs

## Pneumatic Transport

**Pros**

+ Compact
+ Good Packaging
+ Versatile - easily reconfigurable to fit other systems
+ Low temperature valves
+ Improved performance in 1/6 g
+ System commonality – reuse of ISRU fluidization components

**Cons**

– Complexity
– Additional Cooling
– Sandblasting of tubing and fittings
– Size Sorting
– Compressor required if not already available
– Possible filter service

## Inclined Auger

**Pros**

+ Simple
+ Robust
+ Handles flow issues well

**Cons**

– Does not package well
– Heavy
– Can jam if particles are too large
– Does not accommodate multiple delivery locations well
– Does not re-configure well

# Conclusions

- Auger based feed systems are simple and perform well, but do not package as well as a pneumatic regolith feed system
- Auger based feed systems are not as adaptable as other concepts
- Pneumatic regolith transfer was successfully demonstrated at 1 g and at 1/6 g
- It is possible at 1/6 g to pneumatically convey a dense flow of the lunar regolith simulants NU-LHT-2M and Tephra to a vertical height of 1.52 meters (limited by the aircraft)

# Conclusions

- Turning off the flow of dusty gas between parabolas resulted in inefficient cyclone performance, and likely contributed to the cyclones being overwhelmed by the dust flow during the RGF experiment

- Very efficient cyclone separators are essential to a closed-loop pneumatic regolith transfer system in which the gas must be reused

- Reduced gravity flight experiments and ground tests demonstrated that lunar regolith simulant is very easily conveyed pneumatically into a simulated ISRU oxygen production plant reactor

- Existing solutions from terrestrial industries can be used but must be adapted to a space environment and proven in integrated system testing

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for In-situ Resource Utilization

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