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Evolution of Regolith Feed Systems for Lunar ISRU O2 Production Plants

Robert P. Mueller[1]
National Aeronautics & Space Administration (NASA) Kennedy Space Center, KSC, Florida 32899, USA

Ivan I. Townsend, III[2]
Arctic Slope Regional Corporation (ASRC) Aerospace, Kennedy Space Center, KSC, FL 32899, USA

James G. Mantovani[3]
National Aeronautics & Space Administration (NASA) Kennedy Space Center, KSC, Florida 32899, USA

Philip T. Metzger[4]
National Aeronautics & Space Administration (NASA) Kennedy Space Center, KSC, Florida 32899, USA

The In-Situ Resource Utilization (ISRU) project of the NASA Constellation Program, Exploration Technology Development Program (ETDP) has been engaged in the design and testing of various Lunar ISRU O_2 production plant prototypes that can extract chemically bound oxygen from the minerals in the lunar regolith. This work demands that lunar regolith (or simulants) shall be introduced into the O_2 production plant from a holding bin or hopper and subsequently expelled from the ISRU O_2 production plant for disposal. This sub-system is called the Regolith Feed System (RFS) which exists in a variety of configurations depending on the O_2 production plant oxygen being used (e.g. Hydrogen Reduction, Carbothermal, Molten Oxide Electrolysis). Each configuration may use a different technology and in addition it is desirable to have heat recuperation from the spent hot regolith as an integral part of the RFS. This paper addresses the various RFS and heat recuperation technologies and system configurations that have been developed under the NASA ISRU project since 2007. In addition current design solutions and lessons learned from reduced gravity flight testing will be discussed.

Nomenclature

CxP = Constellation Program
ETDP = Exploration Technology Development Program
ISRU = In-Situ Resource Utilization
MOE = Molten Oxide Electrolysis
NASA = National Aeronautics & Space Administration
PILOT = Precursor ISRU Lunar Oxygen Testbed
PISCES = Pacific International Space Center for Exploration Studies
RFS = Regolith Feed System
TRL = Technology Readiness Level

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[1] Chief, Surface Systems Office, NE-S, KSC, FL 32899, PH (321) 867-2557, Email: Rob.Mueller@nasa.gov, AIAA Senior Member.

[2] Lead Systems Design Engineer, Arctic Slope Regional Corporation (ASRC) Aerospace, Mail Stop: ASRC-9, Kennedy Space Center, FL 32899, USA PH (321) 867-9442; Email: Ivan.I.Townsend@nasa.gov

[3] Physicist, Granular Mechanics & Regolith Operations Lab, NE-S, KSC, FL 32899, PH (321) 867-1870, Email: James.G.Mantovani@nasa.gov

[4] Lead; Physicist, Granular Mechanics & Regolith Operations Lab, Mail Stop: NE-S, Kennedy Space Center, FL 32899, USA PH (321) 867-6052; Email: Philip.T.Metzger@nasa.gov

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I. Introduction

In- Situ Resource Utilization (ISRU) is a promising method for increasing sustainable operations in Space. By using local resources such as energy from sunlight, oxygen from the regolith and possibly water from ice deposits on the Moon and Mars it will be possible to supplement consumables such as life support oxygen, potable water, buffer gases, fuel cell replenishment and propellants for transportation spacecraft. The implications of using ISRU are profound and will affect future space exploration architectures and strategies. By "living off the land" it will be possible to reduce the amount of logistics re-supply consumables that will be lifted out of Earth's gravity well and transported into space for delivery to human settlements at locations such as the Moon, Mars, Lagrange points and other orbital Solar System locations.

Current NASA efforts regarding ISRU are focused on producing oxygen and water on the Moon and Mars. On Mars the oxygen may be extracted from the predominantly carbon dioxide atmosphere or electrolyzed from the frozen water which has been discovered beneath the Martian regolith by the Phoenix lander mission in 2008 (Smith et al, 2009). On the Moon, the lunar regolith contains minerals such as ilmenite, that can be reacted and O_2 can be extracted. NASA is currently considering three oxygen extraction processes: hydrogen reduction, carbothermal and molten oxide electrolysis. Each process is successively more efficient but also more technologically immature. Therefore hydrogen reduction, with a projected yield of 1% O_2 (by mass) from the lunar regolith, is the least risky technology while the Carbothermal process can produce yields of 12% but has not been demonstrated to the same degree as hydrogen reduction has. Molten Oxide Electrolysis (MOE) has potential for very high yields of 28% or more, but has a low Technology Readiness Level (TRL).

These three processes are being developed by designing and building prototypes and then demonstrating them in the laboratory and in analog site field tests. The hydrogen reduction process has been demonstrated in a NASA project called "ROxygen". The ROxygen phase I prototype was deployed and demonstrated oxygen production from volcanic ash called tephra, at the Pacific International Space Center for Exploration Studies (PISCES) analog field test site on Mauna Kea in November 2008. The Precursor ISRU Lunar Oxygen Testbed (PILOT) was developed by Lockheed Martin, Denver, using the hydrogen reduction process and was also demonstrated at PISCES, Mauna Kea in November 2008. Currently the experiences and lessons learned from these two prototype systems are being incorporated into the ROxygen phase II prototype which is in the design phase at this time.

Meanwhile the NASA Carbothermal oxygen production plant prototype has been designed and fabricated by Orbital Technologies Corporation, Madison, Wisconsin. This prototype will be field tested at PISCES in February 2010. The Molten Oxide Electrolysis processes are being developed by a NASA led team which includes the Massachusetts Institute of Technology and is currently in the lab bench top testing phase.

All of these prototypes require a RFS. In the case of the ROxygen and Carbothermal prototypes, there has been a steady evolution from auger based devices and systems to closed loop pneumatic conveying systems. In some cases, a combination of auger mechanisms and pneumatic transfer lines have been used, but in general the pneumatic conveying RFS allow for better packaging and integration with the reactor sub-systems. In the case of MOE, the RFS may be substantially different and is currently in the TRL 2 stage, which means that the technology concept and/or application is being formulated.

II. ROxygen Phase I

This regolith transfer system consists primarily of slightly inclined augers, auger motor/gear reductions, excavator ramps, valves, tubing, a control system, and a 4 sided hopper tapered inward towards the bottom. This hopper is the interface that accepts regolith from an excavation vehicle and delivers it to the auger feed inlet. The regolith flows to the bottom of the hopper then is transferred to the hydrogen reduction reactors using augers rotating inside a tube. The regolith then gravity feeds into the reactors through isolation valves where the reduction reaction occurs. Once the reduction has taken place, the regolith is removed from the system by opening isolation valves at the bottom of the reactors and is gravity feed down a chute such that an excavator can remove the spent material.

Figure 1. ROxygen I Oxygen Production Plant with an Inclined Auger RFS being Field Tested on Mauna Kea Volcano in Hawaii

III. ROxygen Phase II

This regolith feed system uses a horizontal trough to accept regolith from a lunar excavator then moves the regolith to an airlock hopper using a horizontal/inclined auger. The regolith is then pneumatically conveyed to 3 regolith reduction reactors where Oxygen is extracted from the regolith. The feed system will fluidize the regolith during the reaction using pressurized gas nozzles, transfer heat from the hot regolith from the previous reaction to the regolith intended for the next reaction, then transfer the regolith within the reactor as required. The spent regolith will be moved from the reactor to an outlet airlock then transferred to a horizontally rotating arm and delivered to an excavator for removal.

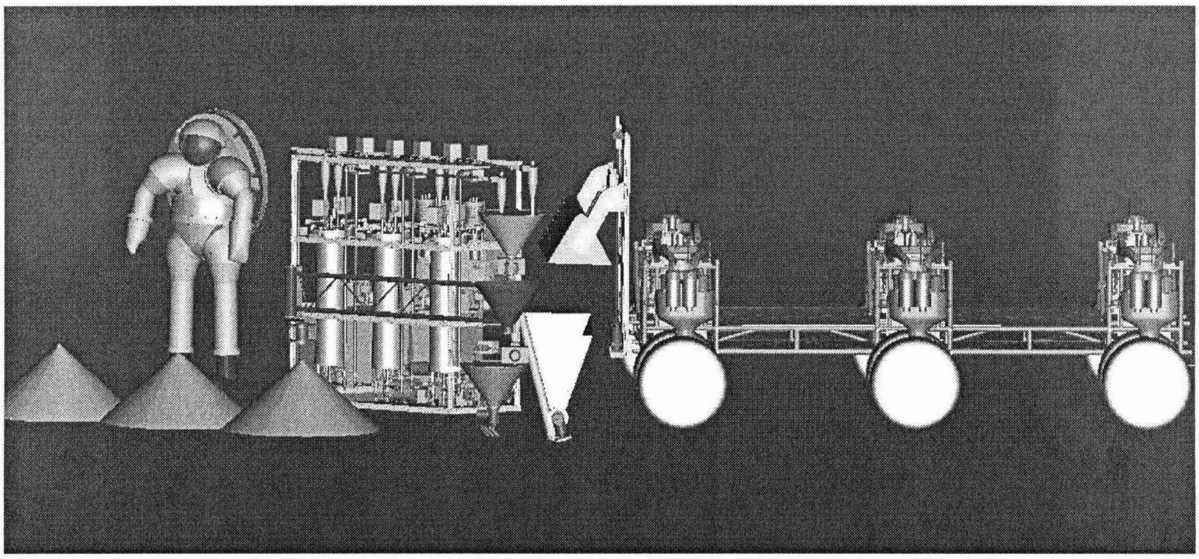
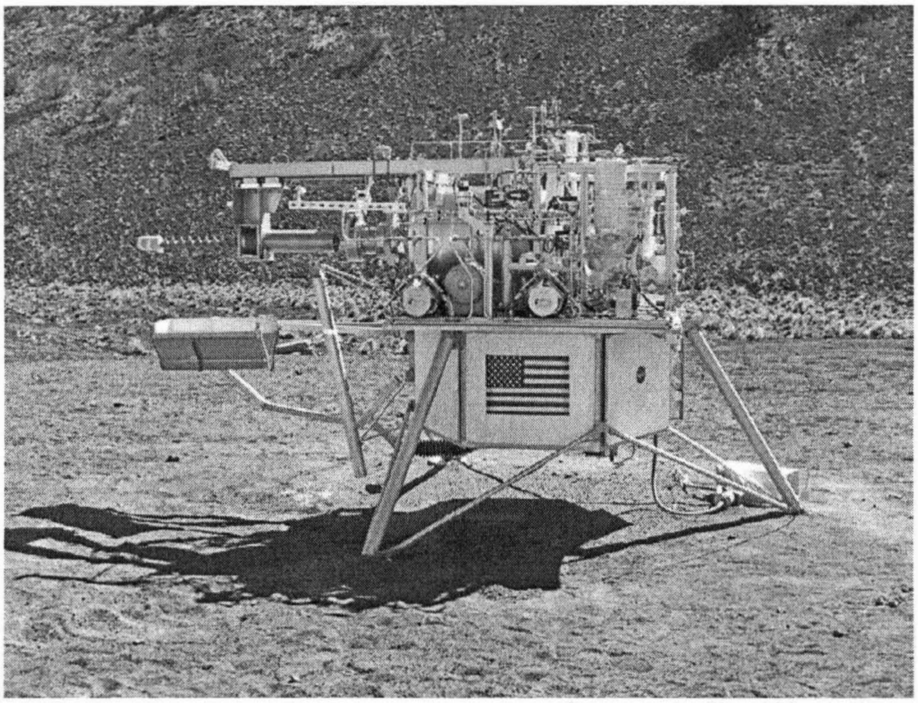


Figure 2. ROxygen II Oxygen Production System 3D Computer Model with a Closed Loop Pneumatic Regolith Feed System

In addition, the ROxygen II system uses a pneumatic regolith transfer in order to enable an innovative heat recuperation system. An annular cylindrical reactor vessel contains the virgin regolith which is pre-heated by the heat leak from the main reactor chamber. Subsequently after the spent regolith is ejected, the virgin pre-heated regolith is transferred into the main reactor with pneumatic transfer lines to achieve a net energy savings for the ROxygen II system.

IV. PILOT

This transfer system uses a v-shaped bin to accept regolith from an excavator then mechanically raises the regolith bin to contact a horizontal auger using a 4 link arm structure and a single motor\gear reduction. The auger is then rotated using a motor\gear reduction to pull the regolith from the bin into the reactor. When the reactor is filled with regolith, the auger rotation direction is reversed allowing the auger to remove itself from the reactor inlet. This allows an isolation valve to be closed and the reaction to occur.



Courtesy: Lockheed Martin Corp.

Figure 3. PILOT Oxygen Production System being Field Tested on Mauna Kea Volcano in Hawaii

V. Auger Based Feed Systems

The auger based feed systems worked well to move regolith vertically from a receiving hopper to the hydrogen reduction reactors. They were non-complicated, easily controlled and very robust. The auger feed systems tested here moved regolith approximately 7 feet vertically throughout the entire demonstration without requiring maintenance. The system supplied a constant flow of regolith as a function of auger speed/time such that any desired quantity of regolith could be reliably deposited into the reactors without requiring regolith mass feedback from the reactors. Some undesirable characteristics of the auger feed system is that the augers required large heavy motor/gear reductions and the system may not package as well as some other regolith feed system types.

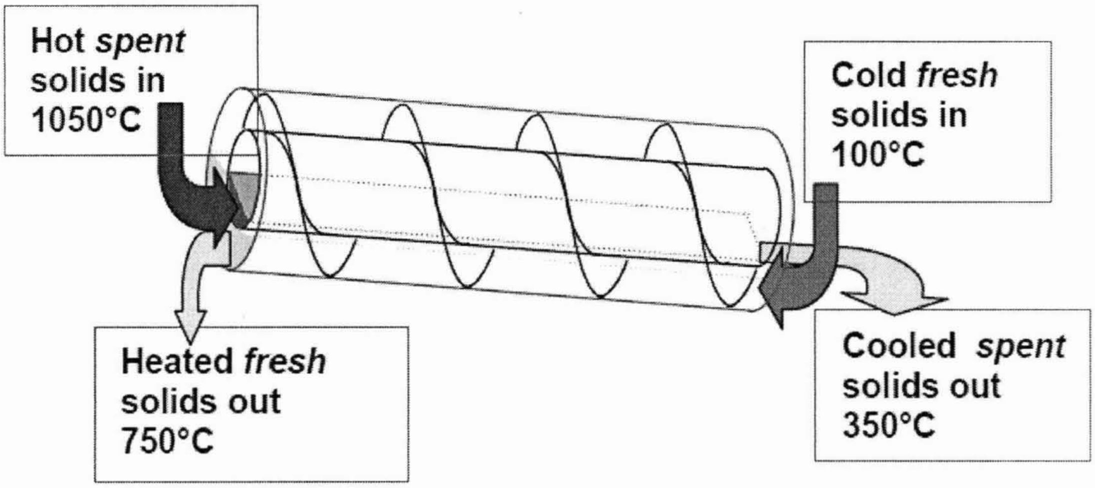
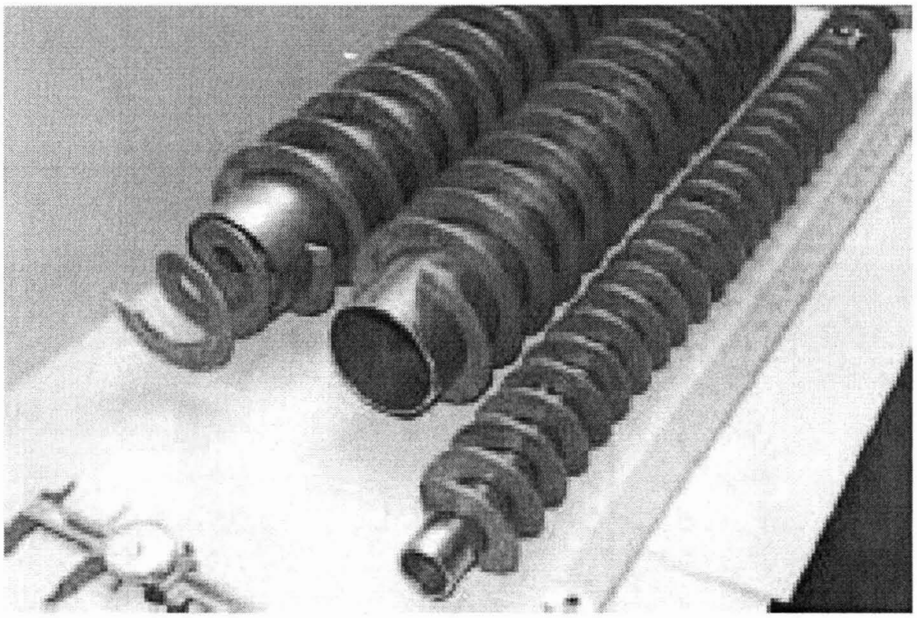


Figure 4. Counter-Flow Auger Solid – Solid Granular Materials Heat Exchanger

Counter-flow auger systems have been investigated in order to combine regolith transfer with heat recuperation in a simultaneous operation. The results were promising since it was possible to accurately control and measure the regolith flow and heat transfer. The work showed that the counter-flow auger systems repeatedly effectively transferred more than 50% of the heat in the hot exit stream to the incoming cool regolith stream . When tested, a counter flowing solid with gas mixture, achieving heat transfer of 62%. Using the counter -flow auger system, it is possible to reduce the heating requirement of a lunar ISRU system by 80%, reducing the total power consumption by a factor of two. (Zubrin, 2009)

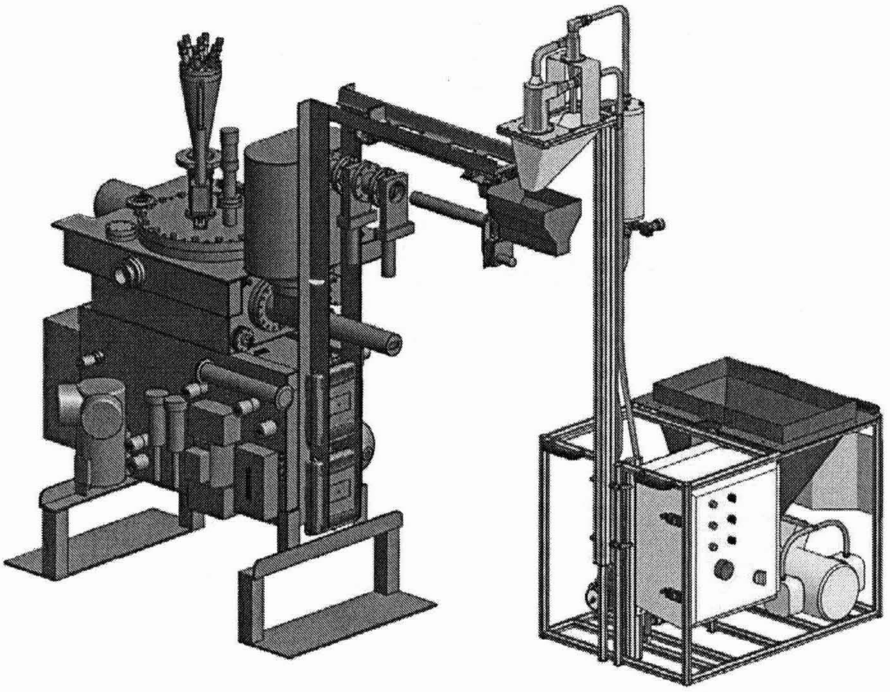


Courtesy: Grainflow Dynamics inc.

Figure 5. Counter-Flow Auger Heat Exchanger Prototypes for Laboratory Testing

VI. Carbothermal

This Carbothermal O2 reactor regolith transfer system consists primarily of an air compressor, two cyclone air/particulate separators, valves, tubing, control system, and a 4 sided hopper tapered inward towards the bottom. This hopper is the interface that accepts regolith from an excavation vehicle and delivers it to the pneumatic feed inlet. The regolith flows to the bottom of the hopper then is transferred using an eductor to two cyclones that separate the regolith from the transfer gas. The regolith drops through the bottom of the cyclone and into the Carbothermal receiving bin and allows the Carbothermal reduction process to begin. The transfer gas is filtered by the cyclones then recycled throughout the transfer process such that all gas is recovered and is feed to the inlet of the air compressor so that it can be compressed and run through the system again. The Carbothermal receiving bin has its own auger drive system that transfers the regolith into an internal hopper system which is isolated by a gate valve system through which the auger is horizontally translated for regolith transfer. Once the internal hopper is full, the auger retracts and the valves are closed.



Courtesy: Honeybee Robotic SMC

Figure 6. Pneumatic Feed System Attachment to Carbothermal Oxygen Production Plant

VII. Pneumatic Conveying Feed Systems

This section discusses our recent efforts to develop and demonstrate pneumatic conveying methods for achieving the transfer of lunar regolith simulant as a dense-flow under both earth gravity (1-g) conditions and simulated lunar gravity (1/6-g) conditions (Mueller 2010). A mechanical conveying system is normally the simplest method for transferring regolith from one location to another, although there is a chance of mechanical failure due to exposure to abrasive lunar regolith particles that can cause the jamming of moving parts. The method of pneumatically conveying lunar regolith becomes a viable option in the case of ISRU oxygen production since a gas exchange/circulation system is already required for the ISRU chemical reactors being considered for oxygen production on the moon. In addition, pneumatic conveyors involve no moving parts during the transfer of regolith particles thus reducing the risk associated with mechanical breakdown.

A basic pneumatic conveyor system (Mills 2004, Dhodapkar 2006) consists of four elements: (1) a source of compressed gas, (2) a device for feeding granular material into the gas flow, (3) a conduit for the dusty gas flow, and (4) a gas-solids separation device at the receiving end of the pipeline. Pneumatic conveyor systems that are developed for lunar applications must be closed-loop systems in order to reuse the gas, which represents a scarce and valuable resource on the moon. The effect of the gravitational environment must also be taken into account when developing a lunar regolith pneumatic conveyor system (Liu 1988, Sullivan 1992, Sullivan 1994, Schrunk 1999, Crosby 2008).

Experiments had been performed in earth's gravity at NASA Kennedy Space Center, but results were not known for the lunar gravity environment. A reduced gravity flight (RGF) experiment was led by researchers from NASA KSC and was based on the previous terrestrial experiments, but reconfigured to a portable design. The RGF experiment was conducted over two flight days (13-14 August, 2009) onboard a Zero-G Corporation aircraft that was configured for reduced gravity testing and was prepared for the flight test at the NASA JSC Reduced Gravity Office's facility located at Ellington Field in Houston, Texas.

Crosby and Agui (Crosby 2008) recently studied the cyclonic filtration of a dilute flow of lunar regolith simulant particles (JSC-1AF) in reduced gravity as a possible means of filtering air inside a habitat. Our study differs from this previous work by focusing on the pneumatic transport of a very dense flow of lunar regolith simulant, and the use of a series array of cyclones to separate the dense dusty gas flow.

In the 1-g environment of earth, pneumatic conveying utilizes a small amount of compressed gas to transport a large quantity of granular material. A carefully designed cyclone separator can mechanically separate the mixture of gas and granular material in a highly efficient manner, including micron-sized particles. When the solid particulates in the dusty gas flow collide with each other and with container walls, they can become charged triboelectrically. This effect can be utilized to enhance the particle removal efficiency by applying an electric field to the dusty gas flow inside the cyclone to guide the charged particles towards the wall of the cyclone where they slow down and agglomerate, which makes it easier to collect the particles at the solids outlet port located at the bottom of the cyclone (Dietz 1982). This type of cyclone is called an electrocyclone.

A reduced gravity experiment was performed by JSC researchers in 1992 involving the pneumatic transport of 150□m diameter glass beads using a venturi eductor to feed the glass beads into an air flow. They found that choking velocity measurements for vertical particle flow against gravity was noticeably lower at 1/6-g as compared to 1-g (Sullivan 1992, 1994). A lower choking velocity may result in less internal pipe erosion caused by abrasive lunar dust if the dust can be conveyed at a lower velocity. However, the disadvantage with lowering the gas flow rate is that since cyclone separators are designed to operate at a specific input flow rate, a lower flow rate can reduce the gas-solids separation efficiency. Another aspect of our study was to investigate the use of an electrocyclone as a means of maintaining a level of high efficiency for particle removal even if the dusty gas flow velocity is lowered. A high particle removal efficiency at the receiving end of the pneumatic transfer process is necessary in order to be able to recycle the convey gas for repeated use.

The main objectives of our terrestrial and reduced gravity flight (RGF) experiments were (1) to demonstrate the feasibility of pneumatically transferring lunar regolith as a dense, dusty gas to an ISRU reactor, (2) to measure our system's typical mass transfer rate for a given lunar regolith simulant that is conveyed pneumatically against gravity as a dusty gas to a fixed vertical height under local gravity conditions (1-g and 1/6-g), and (3) to determine the efficiency of our series cyclone filtration system in removing particles from the exhaust gas flow, including the potential use of an electrocyclone to enhance particle removal efficiency.

Figure 8 shows the experimental test rig that was used to demonstrate dense pneumatic conveying of lunar regolith simulants under terrestrial (1-g) conditions as well as under reduced gravity (1/6-g) conditions.

Figure 7. Photo of the RGF experiment showing Tephra that fell from cyclone A into the Regolith Discharge Container.

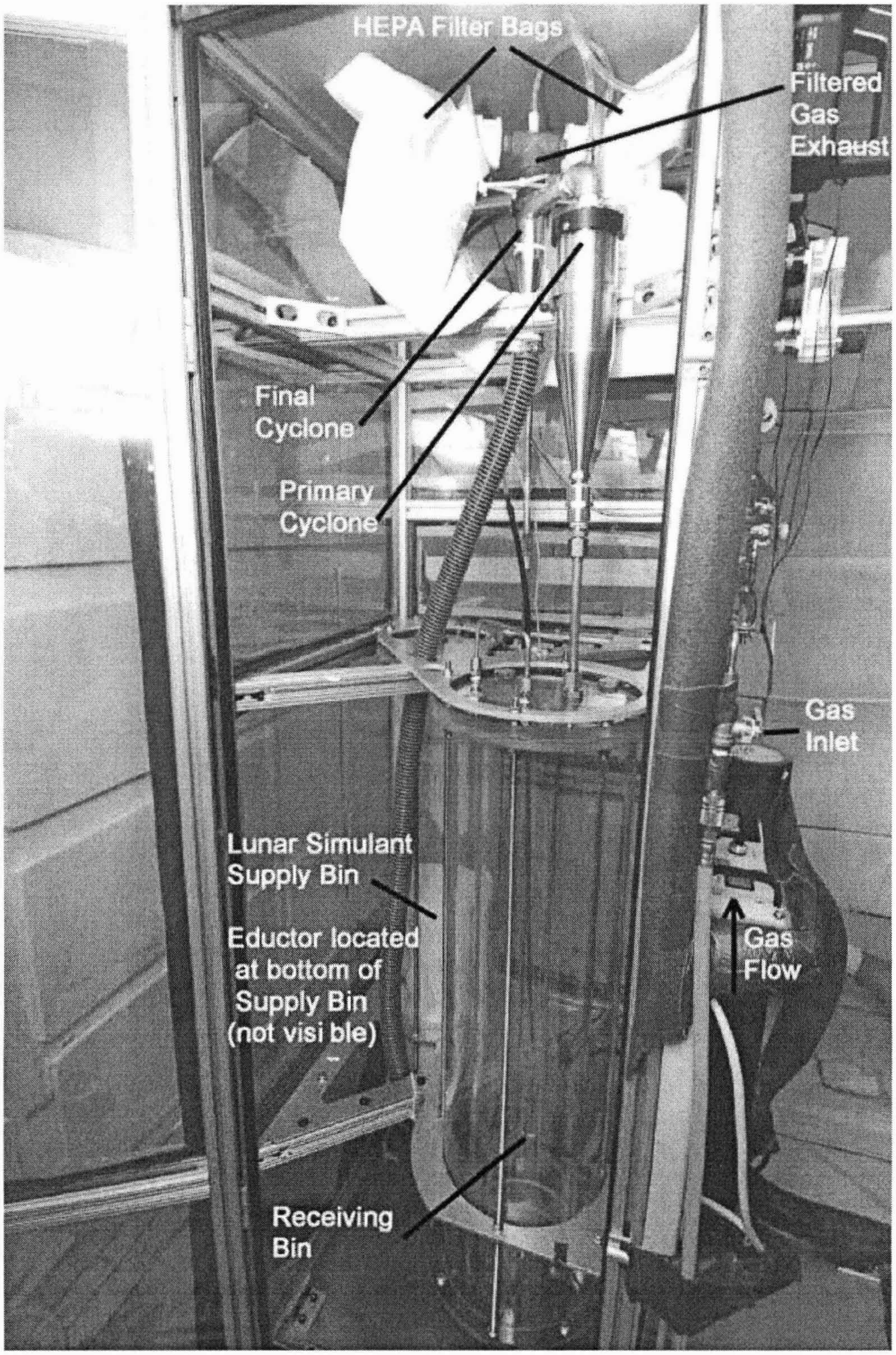


Figure 8. General setup for the Pneumatic Conveying Of Lunar Regolith Simulant With Gas-Solids Separation By Cyclonic Filtering.

(The system is contained within a polycarbonate enclosure which serves to define a controlled area for the shown test setup.)

Figure 7 shows the actual testing of the pneumatic transfer hardware during the reduced gravity flight as Tephra was transferred pneumatically into the Regolith Discharge Container, which served as an ISRU reactor mockup. Although nearly all of the Tephra was transferred during the reduced gravity flight, dust adherence to the walls of the acrylic container prevented an exact determination of the total time needed to complete the pneumatic transfer of Tephra into the discharge container. The same hardware setup was used to conduct the terrestrial testing.

The Tephra flowed vertically upward along a convey pipe from the eductor located at the bottom of the Supply Container (not visible in photo). The convey pipe had a vertical-to-horizontal transition which connected it to the inlet of cyclone A. The gas exhaust from cyclone A became the input for the smaller cyclone B, which discharged dust into the blue hose shown in the picture. The exhaust from cyclone B passed through HEPA filter bags before exiting into the transparent containment box, which had a secondary HEPA filter that allowed the filtered air to enter into the aircraft cabin.

As a result of terrestrial and reduced gravity experiments, we have been able to show that the dense-flow pneumatic transfer method is able to successfully convey lunar regolith simulants such as NU-LHT-2M and Tephra to a vertical height of five feet, which is not an absolute physical limit but simply a limitation that was imposed by the available vertical space in the reduced gravity aircraft. Although we have shown that it is possible to transfer lunar regolith simulants pneumatically as a dense flow of dusty gas in a simulated lunar gravity environment, it is also important to realize that the reduced gravity aircraft also undergoes periods of increased gravity as high as 1.8 g, which may cause the granular regolith simulant material to become compacted. The degree to which this effect might influence the pneumatic regolith transfer process can be lessened by keeping the simulant in a semi-fluidized state throughout the parabolic flight.

A cyclone separator is an important component of a pneumatic regolith transfer system since it delivers the regolith to a desired location, and filters the convey gas sufficiently so that the gas can be reused. It may be possible to design a single cyclone to perform gas-solids separation provided that a moderate dense flow of dusty gas is able to yield a sufficient mass transfer rate by metering the regolith feed at the eductor. The exhaust gas from any cyclone separator will contain fine particles that may be detrimental to the mechanical operation of a compressor intended for reusing the gas. In that case, a second cyclone, known as an electrocyclone, may be designed to remove particles that are even smaller than those removed by an ordinary cyclone of the same size.

Overall, the reduced gravity flight experiment proved that lunar regolith simulant can be effectively conveyed pneumatically in an ISRU oxygen production plant in order to introduce regolith simulant into the reactor; fluidize it within the reactor and hopper feed systems; transfer it from outer reactor annulus zones to an inner reactor cylinder vessel; and subsequently expel it from the reactor for disposal or use in subsequent resource processing (silica, aluminum, titanium, iron, etc.). The results of this experiment were used to influence the design of the ROxygen second generation oxygen production system being developed by the NASA ISRU project, in order to show that it is indeed possible to produce a minimum rate of one metric ton of oxygen per year (of lunar operation) from lunar regolith simulants in a reliable, long life and low maintenance system. (Mueller, 2010)

VIII. Gravity Feed Systems, Percussive Vibration and Magnetic Pumping

Discharge from a gravity-feed hopper can subject to jamming even in a terrestrial environment, but in the lunar environment with reduced gravity it is extremely difficult to ensure reliable flow. It can be enhanced through the use of augers, vibrators, or magnetic fields. Recent simulations with augers located near the throat have identified the rotation rate of the auger as a critical parameter, because the lunar soil accelerates down toward the auger blades very slowly in lunar gravity. In the simulations, the augers tended to slap the soil back into the hopper rather than pull it out. Low frequency, high amplitude vibration has been used successfully in reduced gravity (flying in parabolic trajectories in an aircraft). One concern about percussive vibration methods is that it may produce long-term wear on the machinery, especially operating in the presence of highly-abrasive lunar dust. It may be desirable to use non-moving methods to un-jam the soil, and this is what motivated our study of magnetic pumping. Lunar soil is magnetic primarily through the presence of nano-phase iron particles embedded within the soil grains' glass patinas (deposited on their surfaces from the vapor of micrometeroid impacts). The nano-phase iron particles are sufficiently small that they behave super-paramagnetically. Thus, in the presence of an externally-applied non-uniform magnetic field, they magnetize and produce a force that draws the soil grains into the gradient of the field. The force is proportional to the magnitude of the external field multiplied by its gradient. Lunar soil simulant JSC-1A is also magnetic due to the presence of hematite. We measured its apparent magnetic susceptibility to be 46% less than the susceptibility of an Apollo 14 lunar soil sample. Lunar highlands simulants NU-LHT-2M, OB-1, and

CHENOBI, are not significantly magnetizable, so we have modified them by adding nanophase iron particles through both wet and dry mixing procedures. We have performed experiments with these simulants to demonstration magnetic pumping of soil by placing field coils at the throat of a hopper, which was sufficiently small that the lunar soil would ordinarily jam in the throat rather than discharging by gravity. Each pulse of electrical current in the coils successfully produced a short jet of soil exiting the hopper. In many cases, after a finite number of pulses the hopper un-jammed and the bulk of the soil exited freely. Experiments in reduced gravity (flying parabolic trajectories in an aircraft) have not been as successful to-date, primarily due to deficiencies in the test apparatus, but pumping in reduced gravity has been observed.

Acknowledgments

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The reduced gravity experiment was supported by the NASA IPP under a 2009 program known as Facilitated Access to the Space Environment for Technology Development and Training (FAST). NASA IPP also supported the Pacific International Space Center for Exploration Studies PISCES) analog field tests on Mauna Kea Hawaii in November 2008, as well as the Carbothermal pneumatic feed system attachment that will be tested in January 2010 at the PISCES test site, Mauna Kea, Hawaii.

Outstanding assistance from the Reduced Gravity Office at NASA Johnson Space Center ensured that the experiment would fly safely. The NASA KSC Prototype Development Laboratory contributed substantial manufacturing expertise and effort in order to produce this experimental payload under tight schedule constraints. Ground-based tests at NASA Kennedy Space Center were supported through funding from the NASA KSC CDDF program and from the ROxygen ISRU project under NASA ETDP. Finally, the management of the NASA KSC Surface Systems Office and KSC Engineering and Technology Directorates were very supportive of this advanced technology development effort.

In addition all of our industrial partners mentioned in the paper above, as well as component suppliers that have often provided invaluable advice and support. Most of all the team of dedicated engineers and technicians must be thanked for their commitment and hard work in order to design, fabricate and test these ISRU systems, often in harsh and demanding field test analog site locations with dust storms, extreme temperatures and long test days.

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Robert P. Mueller, James G. Mantovani Ph.D., Philip T. Metzger Ph.D.
National Aeronautics & Space Administration (NASA) Kennedy Space Center, KSC, Florida 32899, USA

Ivan I. Townsend III
Arctic Slope Regional Corporation (ASRC) Aerospace, Kennedy Space Center, KSC Florida 32899, USA

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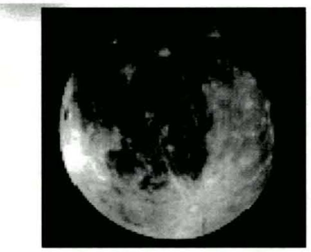
Agenda

- Introduction – Review of Feed System Concepts
- Roxygen Phase I (Hydrogen Reduction)
- Roxygen Phase II (Hydrogen Reduction)
- PILOT (Hydrogen Reduction)
- Carbothermal
- Auger Based Feed Systems
- Pneumatic Feed Systems
- Gravity Feed Systems, Percussive and Magnetic Pumping
- Conclusion

Robert P. Mueller: rob.mueller@nasa.gov

Methods of Lunar Oxygen Production under Consideration



Lunar Mare Regolith

Ilmenite - 15%	
$FeO \cdot TiO_2$	98.5%

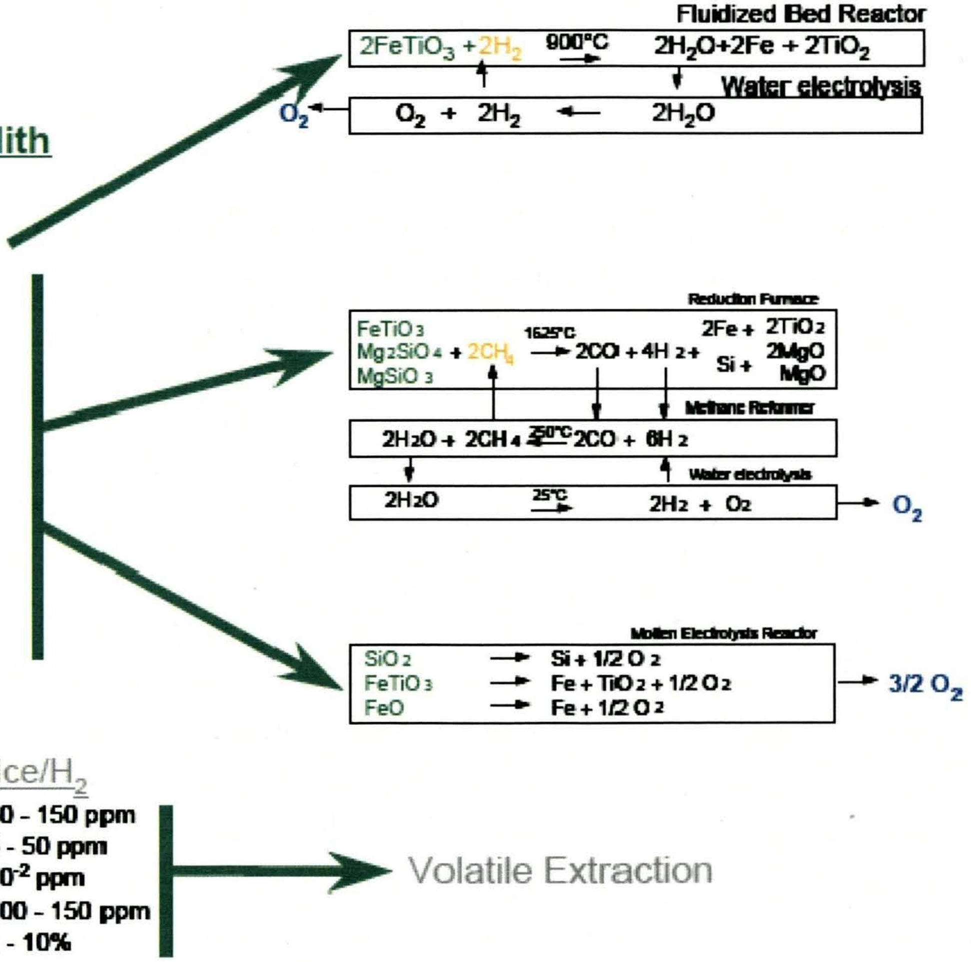
Pyroxene - 50%	
$CaO \cdot SiO_2$	36.7%
$MgO \cdot SiO_2$	29.2%
$FeO \cdot SiO_2$	17.6%
$Al_2O_3 \cdot SiO_2$	9.6%
$TiO_2 \cdot SiO_2$	6.9%

Olivine - 15%	
$2MgO \cdot SiO_2$	56.6%
$2FeO \cdot SiO_2$	42.7%

Anorthite - 20%	
$CaO \cdot Al_2O_3 \cdot SiO_2$	97.7%

Solar Wind & Polar Ice/H_2

Hydrogen (H_2)	**50 - 150 ppm**
Helium (He)	**3 - 50 ppm**
Helium-3 (^3He)	**10^{-2} ppm**
Carbon (C)	**100 - 150 ppm**
Polar Hydrogen H_2O/H_2	**1 - 10%**



Fluidized Bed Reactor

$2FeTiO_3 + 2H_2 \xrightarrow{900^\circ C} 2H_2O + 2Fe + 2TiO_2$

Water electrolysis

$O_2 \leftarrow O_2 + 2H_2 \leftarrow 2H_2O$

Hydrogen Reduction of Ilmenite/glass Process

Reduction Furnace

$FeTiO_3$, Mg_2SiO_4, $MgSiO_3$ $+ 2CH_4 \xrightarrow{1625^\circ C} 2CO + 4H_2 +$ $2Fe + 2TiO_2$, $Si + 2MgO$, MgO

Methane Reformer

$2H_2O + 2CH_4 \xleftarrow{250^\circ C} 2CO + 6H_2$

Water electrolysis

$2H_2O \xrightarrow{25^\circ C} 2H_2 + O_2 \rightarrow O_2$

Methane Reduction (Carbothermal) Process

Molten Electrolysis Reactor

$SiO_2 \rightarrow Si + 1/2\,O_2$

$FeTiO_3 \rightarrow Fe + TiO_2 + 1/2\,O_2$

$FeO \rightarrow Fe + 1/2\,O_2$

$\rightarrow 3/2\,O_2$

Molten Electrolysis

Volatile Extraction

Robert P. Mueller: rob.mueller@nasa.gov

Roxygen Regolith Feed System: Design Criteria

- Deliver regolith simulant from the ground level to the inlet of the Roxygen reactor cylinder

- The Reactor was constrained to being in a vertical configuration to enable a gravity feed of regolith simulant into and out of the reactor cylinder.

- Channel the spent regolith from the outlet tube of the reactor to a regolith disposal location on the ground for eventual pickup by a disposal hauler machine.

- The feed system had to be simple, lightweight, reliable, safe and capable of transportation and field assembly.

- The packaging of the feed system into the overall Roxygen prototype envelope was a major driver in the generation and selection of various concepts.

- In order to maintain pressure inside the reactor, the regolith feed system had to be capable of isolating the reactor at the inlet and outlet tubes.

- Regolith tolerant valves were researched and developed, which had seals that are capable of maintaining a desired pressure even after cold and hot regolith had passed through them.

Robert P. Mueller: rob.mueller@nasa.gov

Regolith Feed System Concepts

Over twenty system concepts were generated and evaluated. The basic elements of the system and related methods were:

◆ **Reactor Chamber Shape:**

- V-Shaped Bottom
- Cylindrical
- Angled-X
- Conical (Distributor Plate)
- Rectangular

Regolith Feed Methods:

Gravity Feed
Screw Conveyor Feed
Pneumatic Feed/Pulse Flow
Vibration
Rotary Feed
Fluidization / Prevent Sintering
Centrifugal Flow
Circulatory Flow
Mechanical Vibration
Mixers/ Fins

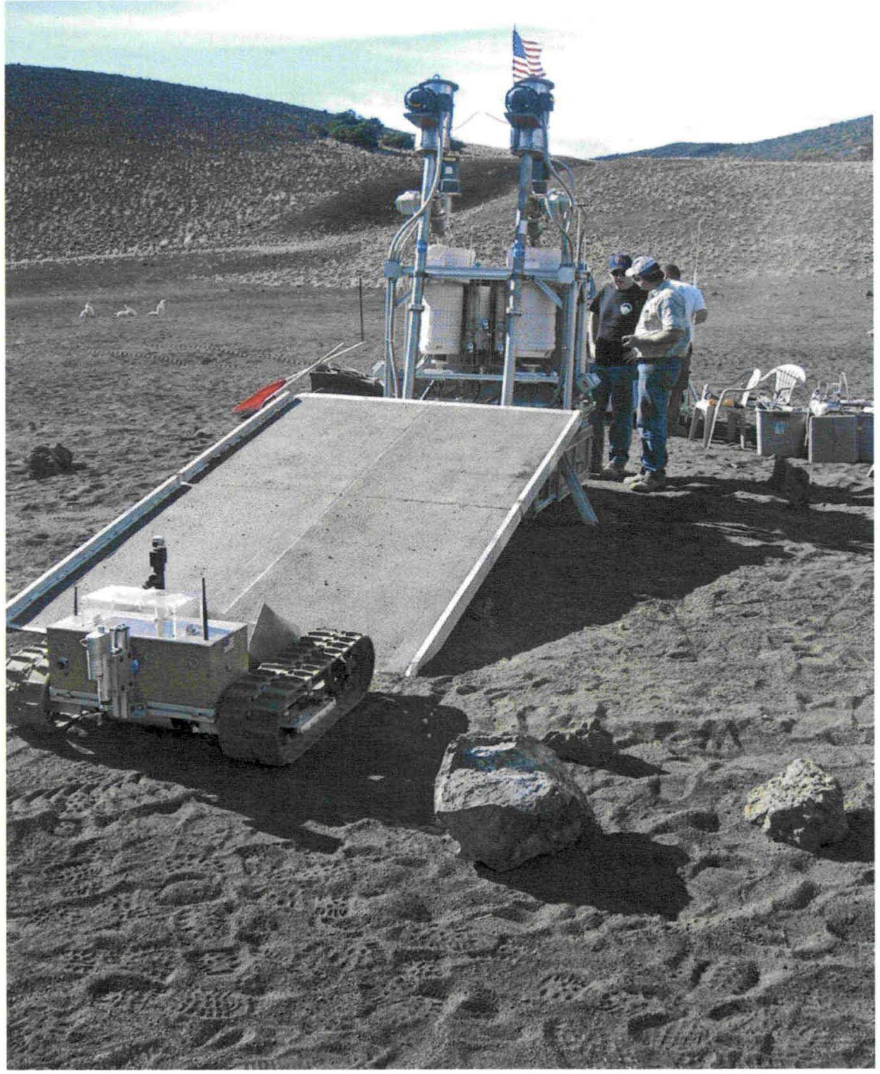
Regolith Feed System Concepts

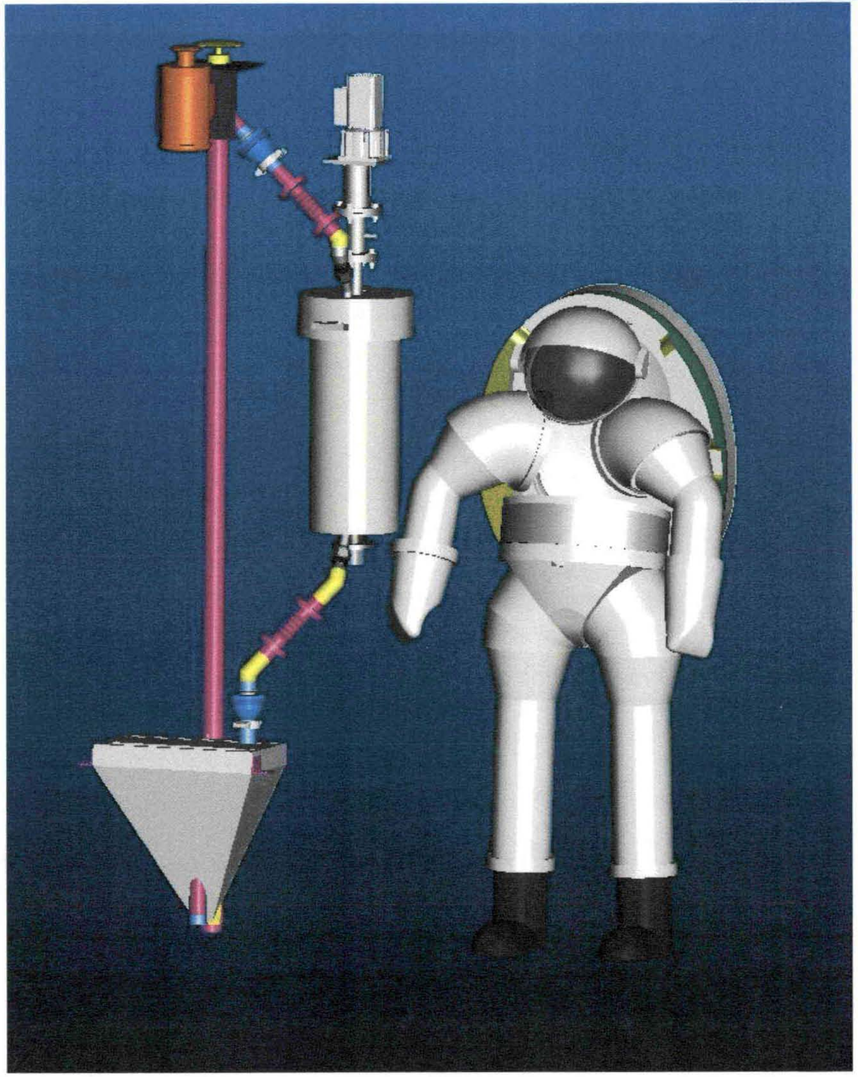
- **Processing:**
  - Batch processing
  - Continuous Processing

- **Heat Recuperation:**
  - Solid-Solid Heat Transfer
  - Solid-Gas Heat Transfer
  - Heat Pipes

- **Regolith Withdrawal:**
  - Gravity Withdrawal
  - Screw Withdrawal/Conveyor
  - Gas withdrawal / Pulse Flow
  - Vibration
  - Rotary Feed

Roxygen Phase I (Hydrogen Reduction)





Inclined Auger Feed System

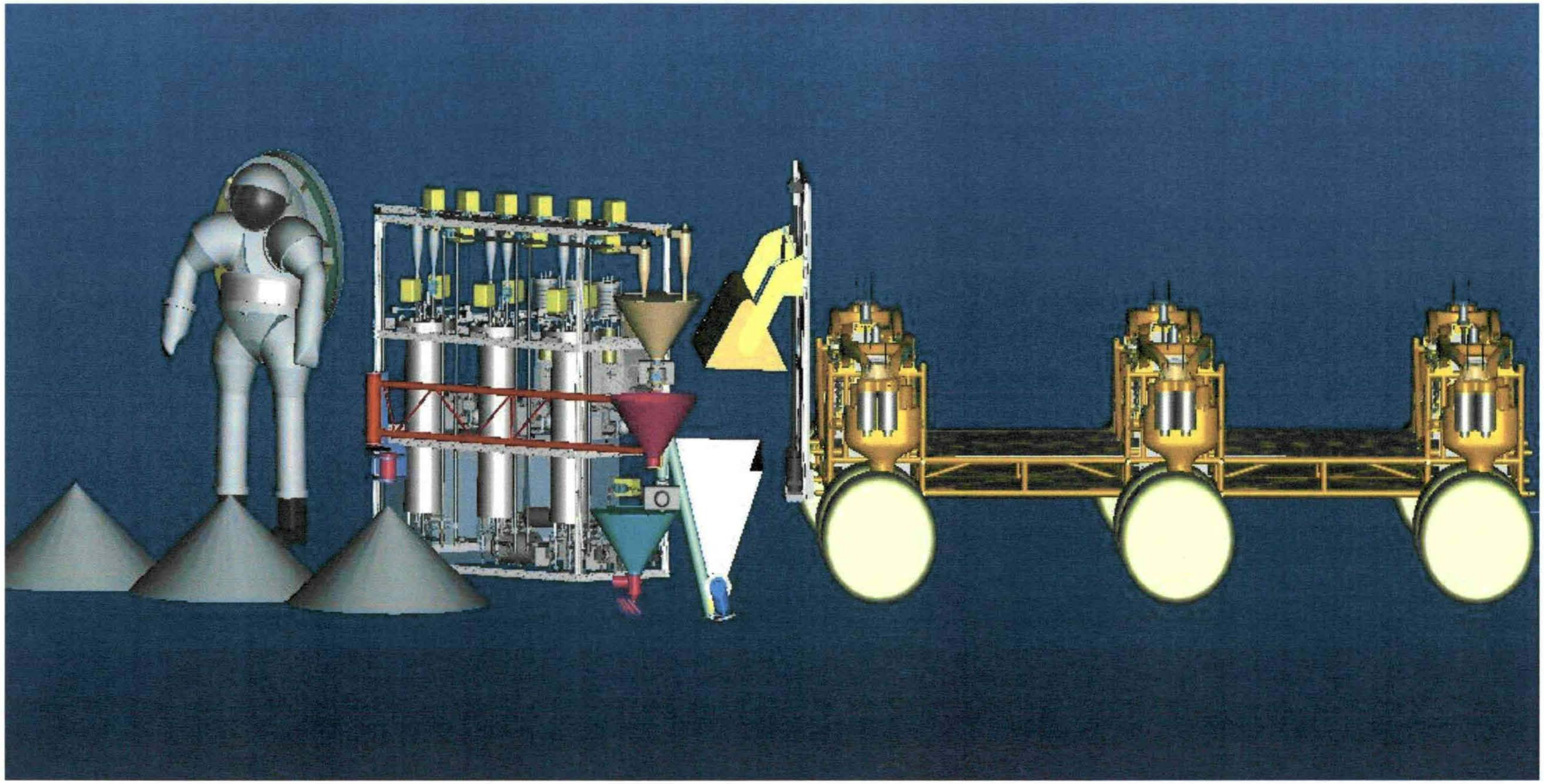
Robert P. Mueller: rob.mueller@nasa.gov

Roxygen Phase I (Hydrogen Reduction)

Gravity Feed Ejection System

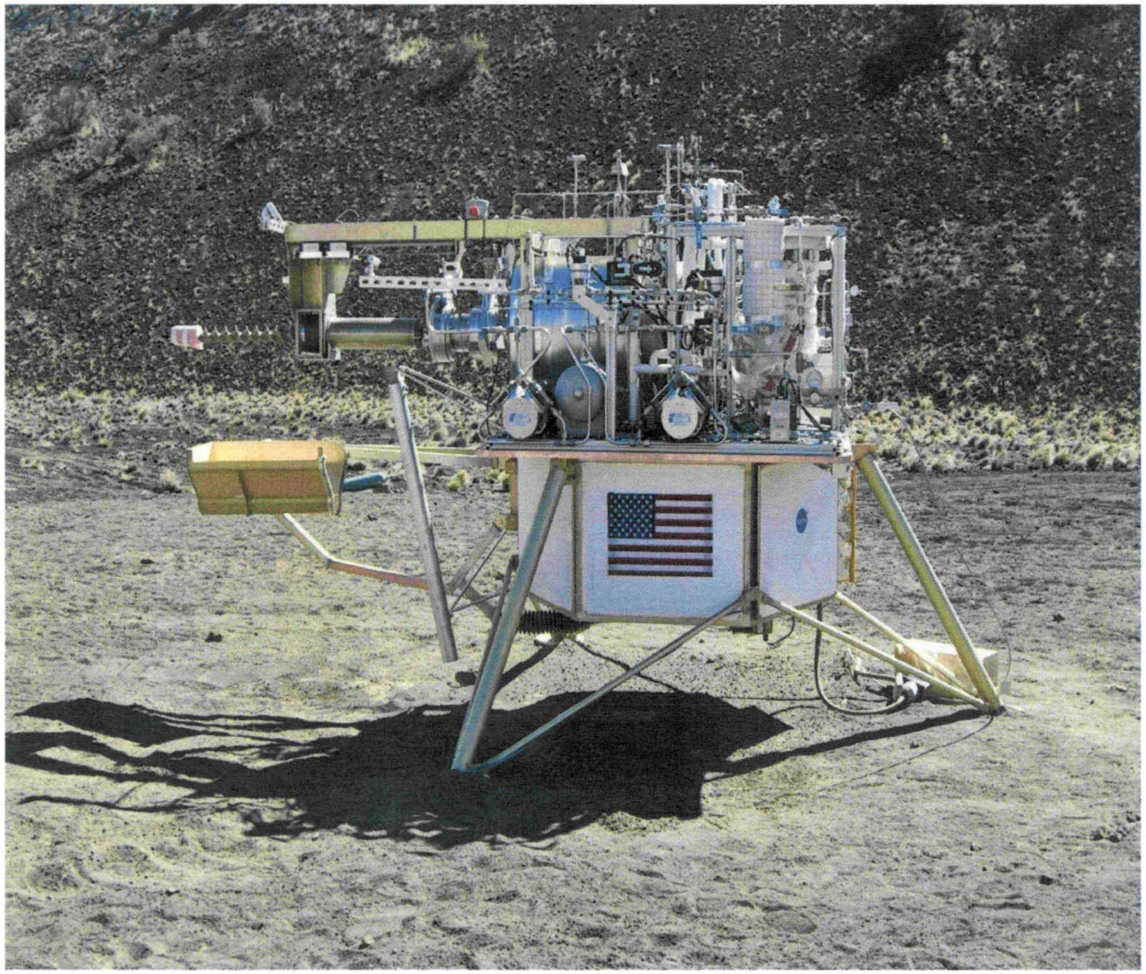
Robert P. Mueller: rob.mueller@nasa.gov

Roxygen Phase II (Hydrogen Reduction)



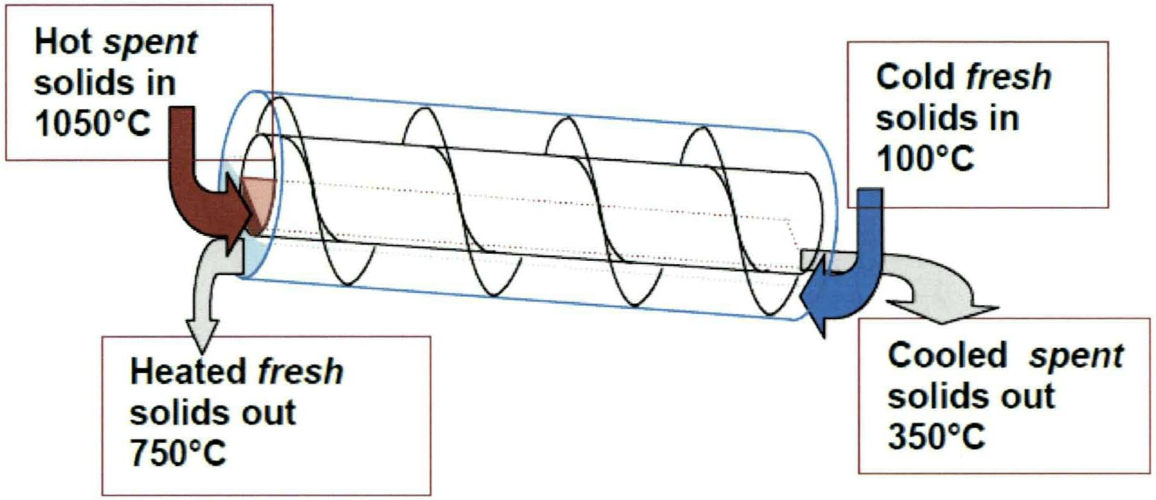
Pneumatic Feed System

PILOT (Hydrogen Reduction)



- Precursor In-Situ Lunar Oxygen Testbed (PILOT) – Lockheed Martin Denver
- Auger Feed System

Counter Flow Augers for Heat Recuperation



Hot *spent* solids in 1050°C

Cold *fresh* solids in 100°C

Heated *fresh* solids out 750°C

Cooled *spent* solids out 350°C

- •Heat Transfer = 62% (with gas)
- •Reduce Heating by 80%
- •Reduce power by ½

(Zubrin, 2009)

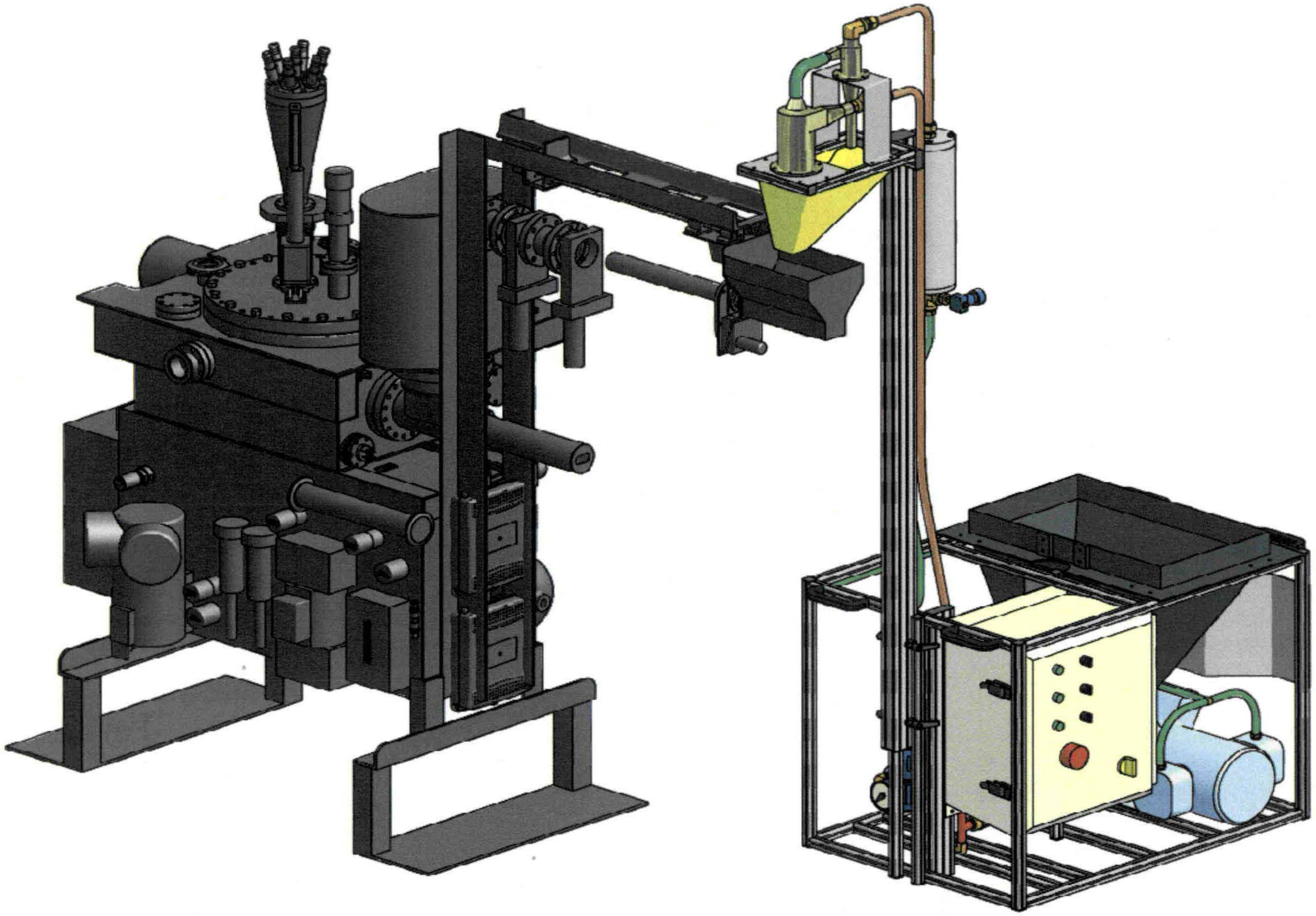
Grainflow Dynamics, 2009

Robert P. Mueller: rob.mueller@nasa.gov

Reduced Gravity Flight Testing: Pneumatic Feed

Roxygen II Proof of Concept Experiment

Carbothermal O2 Production



- Carbothermal O2 System with Auger Feed – Orbitec, inc
- Pneumatic Vertical Lift Feed System – Honeybee/NASA

Robert P. Mueller: rob.mueller@nasa.gov

Gravity Feed Systems, Percussive Vibration and Magnetic Pumping

- Gravity feed system was tested in 1/6th G Reduced Gravity Flight
- Did not flow without assistance

- Percussive Vibration was used to achieve a reasonable flow
- Low frequency achieved best flow
- High frequencies risk compaction

- Magnetic pumping experiment showed promise in 1g benchtop experiment using JSC-1a and iron spiked NU-LHT-2M, OB-1 and CHENOBI
- 1/6th G test apparatus had some deficiencies so results were inconclusive

Robert P. Mueller: rob.mueller@nasa.gov

Conclusions

- Auger based systems have been shown to be feasible in 1G O2 production regolith feed systems using a variety of lunar regolith simulants
- Augers provide some packaging and configuration challenges
- Long term auger mechanism wear with regolith and 1/6th G is unknown at this time

- Gravity feed is feasible in 1g but most likely not in 1/6th G
- Percussive vibration assisted gravity feed is feasible in 1/6th G

- Pneumatic feed systems are feasible but closed loop particle filtering from the pneumatic gas was 99.7% effective
- 0.03% Fines must be filtered with a new technology
- Pneumatic feed systems package well
- Pneumatic feed systems can have a dual use compressed air source and valves shared with the reactor gas transport system

Robert P. Mueller: rob.mueller@nasa.gov

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Robert P. Mueller: rob.mueller@nasa.gov