

Pneumatic Regolith Transfer Systems for In-Situ Resource Utilization

Robert P. Mueller¹, Ivan I. Townsend III², and James G. Mantovani³

¹Surface Systems Office, National Aeronautics & Space Administration (NASA),
Mailcode: NE-S, Kennedy Space Center, FL 32899, USA PH (321) 867-2557;
Email: Rob.Mueller@nasa.gov

²Arctic Slope Regional Corporation (ASRC) Aerospace, Mailcode: ASRC-9,
Kennedy Space Center, FL 32899, USA PH (321) 867-9442; Email:
Ivan.I.Townsend@nasa.gov

³Surface Systems Office, National Aeronautics & Space Administration (NASA),
Mailcode: NE-S, Kennedy Space Center, FL 32899, USA PH (321) 867-1870;
Email: James.G.Mantovani@nasa.gov

ABSTRACT

One aspect of In-Situ Resource Utilization (ISRU) in a lunar environment is to extract oxygen and other elements from the minerals that make up the lunar regolith. Typical ISRU oxygen production processes include but are not limited to hydrogen reduction, carbothermal and molten oxide electrolysis. All of these processes require the transfer of regolith from a supply hopper into a reactor for chemical reaction processing, and the subsequent extraction of the reacted regolith from the reactor.

This paper will discuss recent activities in the NASA ISRU project involved with developing pneumatic conveying methods to achieve lunar regolith simulant transfer under 1-g and 1/6-g gravitational environments. Examples will be given of hardware that has been developed and tested by NASA on reduced gravity flights. Lessons learned and details of pneumatic regolith transfer systems will be examined as well as the relative performance in a 1/6th G environment.

INTRODUCTION

The Lunar Surface Systems (LSS) Project Office was established within the NASA Constellation Program Office in 2007 to “develop a sustained human presence on the moon to promote exploration, science, commerce, and the United States’ preeminence in space, and to serve as a stepping stone to future exploration of Mars and other destinations” (Culbert 2009). The LSS Project Office supports efforts to define a viable Lunar Architecture that will allow humans to return to the moon, and helps define the technology needs and priorities jointly with NASA’s Exploration Technology Development Program.

One concept for a Lunar Outpost that the Constellation Program Office found both technically feasible and consistent with the transportation system provides:

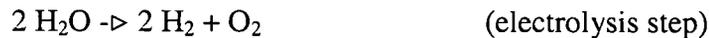
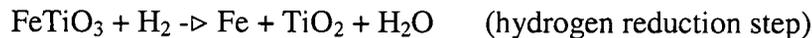
- 1) Habitation systems supporting a crew of 4 for 180 days on the lunar surface

- 2) An ability to produce ISRU based oxygen at a rate of 1 metric ton per year
- 3) Pressurized roving systems to travel hundreds of kilometers from the Outpost
- 4) Power – >35 kW of net power production/storage for crewed eclipse periods
- 5) Surface based laboratory systems and instruments to meet science objectives
- 6) Sufficient functional redundancy to ensure safety and mission success.

The second requirement to produce oxygen on the lunar surface is essential to developing a self-sustaining Lunar Outpost. Oxygen production through ISRU will also lower the operational costs needed to support the Outpost by requiring fewer supplies of oxygen to be transported from the earth.

Among the viable methods of producing oxygen on the moon from local mineral resources are hydrogen reduction, carbothermal reduction, and molten oxide electrolysis. Each of these processes requires the transfer of regolith from a supply hopper into a reactor for chemical processing, and the subsequent removal of the reacted regolith from the reactor. The two methods of conveying significant amounts of lunar regolith (i.e., tens of kilograms) to and from an ISRU reactor involve using either a mechanical system of physically pushing the regolith along a flat surface or a tube (e.g. using a rotating auger) which can operate either in the open lunar vacuum or within a closed pressurized volume, or by using a pneumatic system which can only operate inside a closed pressurized volume.

A mechanical system is normally the simplest method for conveying regolith from one location to another, albeit with some possibility of failure due to exposure to abrasive lunar regolith particles that can cause jamming of moving parts. However, in the case of ISRU oxygen production, the method of pneumatically conveying lunar regolith becomes a viable option. The reaction products that result from ISRU chemical process are transported away by a circulating gas from the source of the reaction (the regolith particles in the reactor) to a collection chamber where the reaction products are condensed out of the circulating gas. For example, the hydrogen reduction process yields water as a direct product, which must be collected so that oxygen can be extracted through a secondary electrolysis step:



The hydrogen reduction process requires a circulation pump to move the hydrogen gas and water vapor from the chemical reactor to the water collection chamber. Hence, it becomes feasible to utilize the existing hydrogen gas pumping system to pneumatically convey the granular lunar regolith material from the supply hopper to the reactor chamber rather than using a separate mechanical conveyor. Besides providing a savings in terms of physical space, a pneumatic regolith conveyor does not have any moving parts that are susceptible to jamming over time when exposed to abrasive lunar regolith particles.

The terrestrial application of pneumatic conveying to granular materials for industrial purposes is a topic that dates back, at least, to 1847. A number of excellent

reviews of methods for pneumatically conveying particulates have been published in recent years (Mills 2004, Dhodapkar 2006).

A basic pneumatic conveyor system 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. An open-loop pneumatic conveyor system does not attempt to recover the convey gas, whereas a closed-loop system does recover the gas.

Industrial types of pneumatic conveyor systems on earth can be open-loop or closed-loop depending, for example, on whether or not the convey gas is inherently valuable or is environmentally hazardous. However, 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. Although a pneumatic lunar regolith conveyor system that is developed for field testing on earth may be operated as an open-loop prototype, the technology must develop eventually into a closed-loop system for the moon. Consequently, the effect of the gravitational environment must be taken into account when developing a lunar regolith pneumatic conveyor system (Liu 1988, Sullivan 1992, Sullivan 1994, Schunk 1999, Crosby 2008).

This paper 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. Examples will be given of hardware that has been developed and tested by NASA in analog field test locations. Lessons learned from this feasibility study and the details of pneumatic regolith transfer systems are examined as well as systems integration into an ISRU oxygen production plant.

EXPERIMENTAL DESIGN AND PROCEDURE

Background

ROxygen is a current NASA ISRU project that is concerned with extracting oxygen from lunar regolith using the hydrogen reduction process within a fluidized-bed reactor system. The ROxygen regolith transfer team has identified the flow and transfer characteristics of lunar soil simulant to be a concern for lunar oxygen production efforts. It is important to develop hardware designs that have the ability to flow and transfer a given amount of lunar regolith simulant to a desired vertical height under lunar gravity conditions. In this study, we used a method of vertically transferring lunar regolith simulant that avoids exposing moving parts to simulant particles by pneumatically conveying the regolith. The granular material is finally separated from the convey gas (air) using existing cyclone separator technology.

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.

Pneumatic conveying will prove to be viable for the moon if the transported dusty gas can be filtered sufficiently at the delivery end to allow for recovery of the transport gas for repeated use. Since membrane filters are impractical on the moon due to high maintenance costs, cyclones appear to be the only maintenance-free alternative for separating pneumatically conveyed lunar regolith particles from the convey gas. 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 μ 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 three 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.

Experimental Design

The configuration of the experiment is depicted below in Figure 1, and the specific details are as follows:

- The experiment assembly in Figure 1 consists of a polycarbonate secondary containment box with a secondary High Efficiency Particulate Arresting (HEPA) filter, supply and discharge containers for lunar regolith simulant, an eductor for pneumatic conveying, a convey pipe, two cyclone separators connected in series with HEPA filters on the exhaust of the final cyclone, air pressure and flow rate meters, and dust particle counters connected to the dusty gas inlet and the clean gas outlet of the second cyclone. Optional is a high voltage power supply that allows the second cyclone B to act as an electrocyclone if desired.
- Two lunar regolith simulants, known as NU-LHT-2M and Tephra, were studied. One simulant at a time was contained within the experiment assembly shown in Fig. 1. NU-LHT-2M is a NASA/USGS-Lunar Highlands Type lunar regolith simulant that is based on the chemical composition of NASA averaged Apollo 16 regolith samples. Tephra is a volcanic ash and cinder material from Mauna Kea, Hawaii.

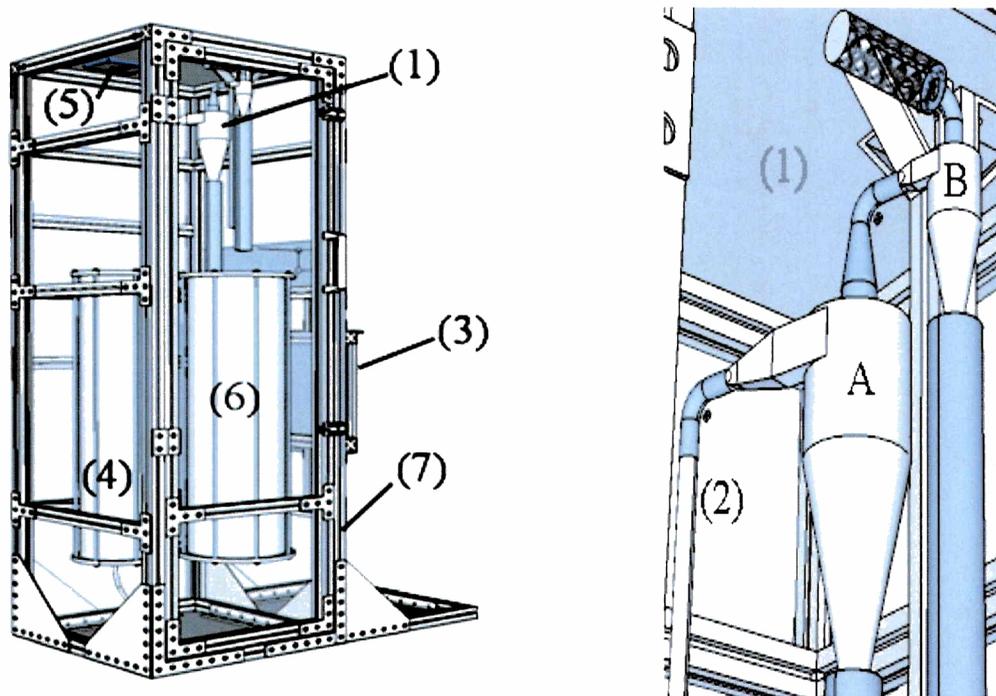


Figure 1. Graphic of the reduced gravity (1/6-g) experiment hardware including a close-up view (right-side graphic) of a series array of cyclones with the upper most having a HEPA filter attached to its exhaust gas outlet. The same setup was also used for ground tests at 1-g. (1) Two cyclone array using a mechanical cyclone (A) and an electrocyclone (B); (2) SS pipe; (3) Interface panel for gas inlet and gauges; (4) Regolith supply container and venturi eductor; (5) HEPA filter on the secondary containment box (7); (6) Regolith discharge container representing an ISRU reactor mockup; and (7) Secondary containment box using aluminum frame and supports, and polycarbonate sheets. Total mass of the flight rig including lunar regolith simulant: 195 Kg.

Figure 1 shows the experiment hardware contained within an aluminum framed housing, and enclosed by sheets of transparent polycarbonate around the sides and by sheets of aluminum at the top and at the base. The housing structure was designed to allow the pneumatic regolith transfer experiment to fly in a safely contained manner onboard an aircraft which conducted a series of parabolic flight paths. During each parabola, the RGF experiment was performed for 25 seconds under simulated lunar gravity conditions after which time the air flow was shut off during a period of time in which the experiment experienced variable gravity conditions including increased gravity. The use of HEPA filters ensured that particles larger than 0.3 microns would not exit into the ambient atmosphere outside of the pneumatic conveyor system. The polycarbonate sheets allowed for the pneumatic regolith transfer to be visible outside of the box, and also served as a secondary containment in case of dust leakage from the system. A secondary HEPA filter was mounted on the secondary containment box to prevent the filtered air from pressurizing the box. Compressed dry air was used as the convey gas so that the exhaust gas from the cyclones did not have to be vented outside of the aircraft.

The regolith supply container (transparent acrylic) in Fig. 1 could be filled with 16.5 kg of lunar regolith simulant that was to be transferred to the regolith discharge container (also transparent acrylic), which served as a mockup of an ISRU reactor chamber. Height restrictions onboard the RGF aircraft limited the total transfer height to 1.5 m for conveying the lunar simulants from the bottom of the regolith supply container to the inlet of the first cyclone located above the regolith discharge container.

The gas/solids mixer shown in Fig. 2 is a stainless steel venturi eductor. The eductor pulls granular material out from the center of the bottom plate of the regolith supply container, and it is used to entrain the lunar regolith simulant into the air flow and to convey the dusty gas along a stainless steel pipe to the cyclone separators.

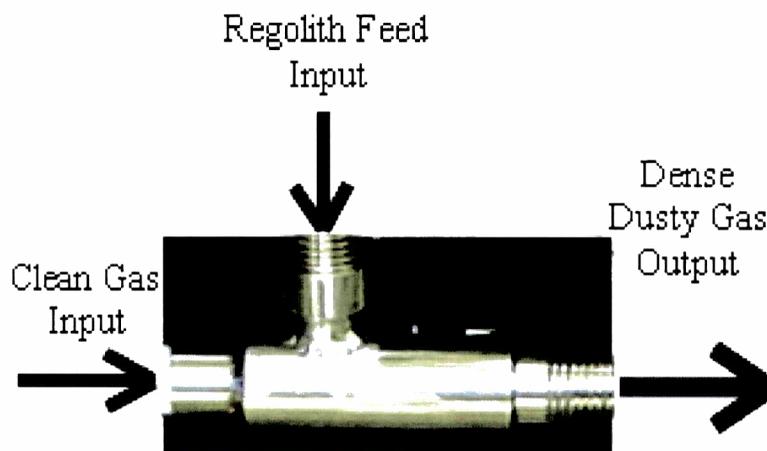


Figure 2. An eductor produces a dense flow of dusty gas by creating a partial vacuum via the Venturi effect that entrains lunar regolith feedstock material into a flow of clean dry air.

The cyclone body and air exhaust pipe of the two cyclones shown in Fig. 1 were fabricated from stainless steel, and they were joined using a non-metallic cap to electrically insulate the exhaust pipe from the cyclone body when the cyclone (B) is operated as an electrocyclone. Except for the air exhaust pipe of the electrocyclone, which is connected to the high voltage output cable of a high voltage DC power supply, the cyclone body and all other metal components contained within the secondary containment box are connected to the electrical ground.

Results

Figure 3 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 discussed next. The RGF results are discussed later in further detail.

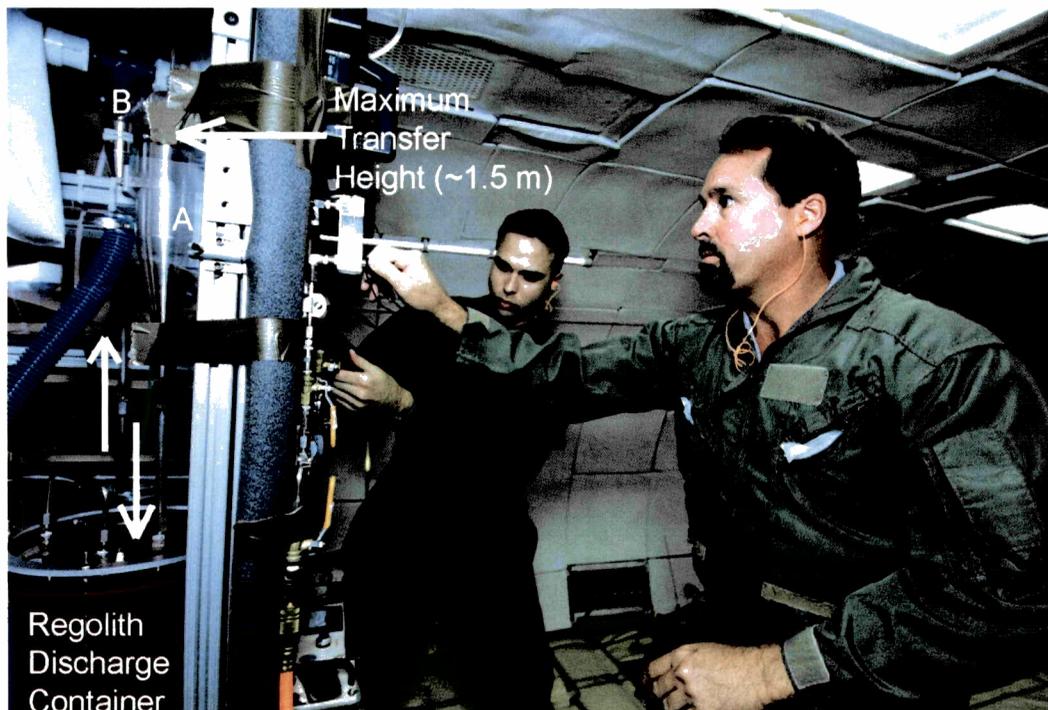


Figure 3. Photo of the RGF experiment showing Tephra that fell from cyclone A into the Regolith Discharge Container. The Tephra flowed vertically upward along a convey pipe from the eductor located at the bottom of the Supply Container (not visible in photo). The convey pipe had a vertical-to-horizontal 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.

Terrestrial Experiments

When compressed dry air was applied to the gas inlet of the venturi eductor, the partial vacuum created by the eductor was found to immediately begin feeding lunar regolith simulant material into the input air flow to the eductor, thus producing a very dense flow of dusty air that exited the eductor along the convey pipe towards the cyclone separators. Tephra, being less dense than NU-LHT-2M and having a different particle size distribution, was found to be relatively easier to convey pneumatically than NU-LHT-2M. Although, the supply container had a flat bottom rather than a funnel shape in order to reduce the overall height of the container, each simulant material was successfully educted from the center of the supply container's base plate. The total amount of material that was transferred from the regolith supply container depended on the magnitude of the air pressure applied to the gas inlet of the eductor, and on the efficiency by which the regolith simulant could be fluidized within the container before being drawn out by the eductor.

The dusty air flow that was produced at the eductor traveled a vertical height of 1.5 m before entering the first cyclone. Most of the granular material collected by the first cyclone exited the solids outlet port at the bottom of the cyclone to be deposited into the regolith discharge container. The dusty exhaust gas that exits from the top of any cyclone contains fine particles having sizes typically no larger than nine times the cut diameter of the cyclone. However, the actual size distribution of the particles contained in the flow between our two series cyclones could not be determined without disturbing the dynamics of the dusty air flow. The exhaust gas from the first cyclone became the input dusty gas flow for the smaller second cyclone, which was designed to have a cut diameter of a one micron or less. However, due to the very dense flow of dusty air (also observed in 1/6-g) entering the second cyclone, it was not possible to operate the second cyclone as an electrocyclone, which only performs effectively on a dilute particle input flow that was not able to be achieved using only two cyclones separators connected in series. Since the regolith feed to the eductor was not being metered during the terrestrial and reduced gravity tests, the continuous dense flow of dusty air overwhelmed the cyclones.

The supply container would typically be filled with 15 – 17 kg of lunar regolith simulant. Each of the lunar regolith simulants, NU-LHT-2M and Tephra, was able to be pneumatically transferred from the center of a flat-bottom regolith supply container. With some fluidization of the simulant in the supply container, it was possible to transfer all but ~1kg of simulant to the discharge container, which served as a mockup of an ISRU reactor chamber. Depending on the effectiveness of the fluidization of the granular material inside the supply container, typical mass transfer rates of 2 – 4 kg/min were achievable with an unmetred regolith feed to the eductor. Although metering the feed of regolith to the eductor would reduce the mass transfer rate and lengthen the overall transfer time, this would likely result in an improved performance of the cyclone separators in removing particles from the dusty air flow and depositing these particles into the regolith discharge container. These tradeoffs must be considered in designing a pneumatic regolith transfer system for lunar operations.

Reduced Gravity Experiments

A flight rig was constructed at NASA Kennedy Space Center to meet the safety requirements for conducting reduced gravity (1/6-g) tests onboard an aircraft. The aircraft achieves short periods of reduced gravity by flying a series of parabolic flight trajectories. During the parabolic trajectory, the aircraft also experiences periods of increased gravity (~1.8 g) which the experiment must also endure. The RGF pneumatic transfer experiment was initiated immediately after the lunar gravity condition was achieved and was terminated approximately 25 sec later at the end of the reduced gravity experience. Figure 3 shows the pneumatic transfer of Tephra under simulated lunar gravity conditions.

As in the terrestrial tests, it was observed that most of the Tephra transferred from the supply container to the discharge container located beneath the cyclone, but the dense flow overwhelmed the cyclone separators. Insufficient visibility through the secondary containment box prevented the precise determination of the number of parabolas required to transfer the Tephra under 1/6-g conditions. Although the mass transfer rate of Tephra could not be determined, it was observed that approximately 15 kg of Tephra was easily transferred pneumatically from the supply container in less than the ~15 minute duration in simulated lunar gravity.

When the NU-LHT-2M transfer process began under 1/6-g conditions, this granular material was also transferred easily from the supply container to the discharge container despite being more compactable than Tephra. However, after ten parabolas (~250 sec), it was observed that the transfer process had stopped. Although the NU-LHT-2M was assumed to have been sieved, a post analysis showed that a ~0.5 cm diameter "rock" had become clogged in the eductor's solids inlet which prevented regolith simulants particles from entering the eductor and being entrained in the air flow. Nevertheless, it was observed that 8.8 kg of NU-LHT-2M could be transferred vertically resulting in a mass transfer rate of 2.1 kg/min. The Tephra mass transfer rate is believed to be probably greater than this value given that Tephra is less dense than NU-LHT-2M.

The efficiency of our particular series cyclone filtration system in separating particles, including the use of an electrocyclone, could not be determined due to the dense flow of dusty air having overwhelmed the cyclones in 1-g and in the 1/6-g environment. The dense flow must be factored into a re-design of the cyclone system and 1/6-g effects must be included in the design parameters. It is likely that different cyclone systems will be required for the terrestrial 1-g system and for the lunar 1/6-g system due to the expected higher mass transfer rate of regolith in 1/6-g (Sullivan 1992, 1994).

Conclusions

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 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.

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