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NASA Lunar Dust Filtration and Separations Workshop Report

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Summary

NASA Glenn Research Center hosted a 2.5-day workshop, entitled “NASA Lunar Dust Filtration and Separations Workshop” at the Ohio Aerospace Institute in Cleveland, Ohio, on November 18 to 20, 2008. The purpose of the workshop was to address the issues and challenges of particulate matter removal from the cabin atmospheres in the *Altair* lunar lander, lunar habitats, and in pressurized rovers. The presence of lunar regolith dust inside the pressurized volumes was a theme of particular interest. The workshop provided an opportunity for NASA, industry experts, and academia to identify and discuss the capabilities of current and developing air and gas particulate matter filtration and separations technologies as they may apply to NASA’s needs. A goal of the workshop was to provide recommendations for strategic research areas in cabin atmospheric particulate matter removal and disposal technologies that will advance and/or supplement the baseline approach for these future lunar surface exploration missions.

1.0 Introduction

NASA’s future lunar surface missions will be faced with the challenges posed by the effects of lunar dust. Recent NASA assessment studies of lunar dust effects suggest that contact with lunar dust will affect crew health as well as the stability and durability of sensitive equipment and instrumentation on long-duration missions. Concerns have been raised, based on experiences during the Apollo missions, about the health effects of the long-term human exposure to airborne lunar dust. In particular, incidences of respiratory and ocular irritation from the lunar dust were reported during these missions. For reference, the Biological Effects of Lunar Dust Workshop (Ref. 1) held in 2005 addressed in depth many of the health hazards of lunar dust. Recent data obtained at the NASA Glenn Research Center have shown that lunar dust has a significant fines fraction that may overlap with the range of particle sizes over which high efficiency filters are least efficient at capturing. Particles in this size range are categorized as the “most penetrating particle size” since they are the most likely to avoid being captured onto filter fibers by one of the three capturing mechanisms: Brownian diffusion, interception, and impaction. In addition to health effects, certain properties of lunar dust may also affect the nominal performance of equipment and instrumentation. In light of these effects, effective ingress infiltration barriers and removal and disposal technologies of lunar dust from the habitable environments will be of prime importance.

Particulate filtration will serve as a primary approach for cleaning up the recycled air on lunar surface exploration missions by removing internally generated dust as well as the lunar surface dust introduced into the cabin. To meet the challenges of these missions, more capable filtration systems—likely supplemented with particle separation (from the gas phase) techniques—will need to handle both the longer duration missions and the load of lunar dust particles. Among the desired features of cabin atmospheric particulate filtration and separations technologies being sought are improved efficiency, high load capacity, low energy consumption, low mass and volume, and the ability to be regenerated. The workshop provided an opportunity to assess the compatibility of current technologies with some or all of these features, and to identify areas for further development. In addition, novel techniques and materials were discussed.

To support this development, the Glenn Research Center is developing a testing facility to evaluate filter media and filtration and gas-phase separation technologies. The aim of the facility is to test for

efficiency and practicality of filtering lunar dust under the constraints of exploration vehicle and cabin design. The facility will be available to test the technologies proposed by this workshop.

A list of acronyms used in this report is given in Appendix A to aid the reader.

2.0 NASA Programmatic Overview

NASA's Exploration Technology Development Program (ETDP) sponsored the NASA Lunar Dust Filtration and Separations Workshop. The ETDP supports the development and maturing of high-priority exploration technologies for NASA's flight exploration programs addressed in several projects related to the characterization and mitigation of lunar dust effects for lunar surface missions. An important ETDP goal is to reduce the mass, volume, power requirement, crew time, and consumables required by a technology, thereby reducing the launch mass and resupply requirements. Additional technology objectives are to improve performance and meet new requirements. The general focus of the ETDP program is to mature the technologies required for human space exploration to a technology readiness level (TRL) of 5, where the technology has been tested and demonstrated in a relevant environment. There are two ETDP projects that have relevance to the topic of the workshop. The first is the Dust Mitigation and Control task under the Exploration Life Support (ELS) project which directly funds technology development for filtration of airborne lunar dusts and vacuum cleaning technologies. The other is the Dust Management project which conducts multidisciplinary research on the characterization of relevant lunar dust properties.

The charter of the ELS project is to develop a suite of environmental control and life support system (ECLSS) technologies for use on human spacecraft for the Constellation Program. This includes the crew exploration vehicle (*Orion*), lunar lander (*Altair*), lunar outpost, and pressurized rovers. The objectives are to develop and mature life support systems technologies that fill capability gaps (enabling) and significantly improve the state of the art (substantially enhancing). This will lead to the development of efficient, safe, and reliable technologies with reduced resource requirements (mass, power, heat rejection, volume, crew time, and consumables). Under this project, the Dust Mitigation and Control task is responsible for development of the next generation air filtration systems for lunar surface systems, which are expected to improve in efficiency and performance while reducing the number of replacement units either through higher capacity or regeneration of the filter unit. This technology is expected to mature and be available by the vehicle's Preliminary Design Review (PDR), with further development and refinement until the System Readiness Review (SRR), by 2013 and 2014, respectively.

The ELS project will look to the broader scope Dust Management Project for help in determining some of the aerosol characteristics of lunar simulant dust. Comprising researchers throughout the Agency (with a strong Glenn component) and multiple outside collaborators, the Dust Management Project aims to be the "go-to" place for definitive answers on how physical properties of simulants relate to lunar regolith properties for verification of material and component performance of lunar equipment on the surface and in the habitat in order to reduce risk to mission safety, cost, and success. The project's activities include high-quality and sophisticated measurements of some of the key properties of lunar dust.

An indication of the importance of lunar dust issues to the Agency are the results of the last round of programmatic prioritization, in which the mitigation and filtration of lunar dust ranked high as a technology development area for lunar surface missions, which include the *Altair* lunar lander and outpost habitat. The Constellation Program Technology Prioritization Panel (TPP) identified several reasons to develop airborne particulate matter removal technologies as shown in Table I.

TABLE I.—RELEVANT RESULTS OF CONSTELLATION PROGRAM TECHNOLOGY PRIORITIZATION PANEL (2008)^a

ID	Title ^b	Mission ^c	Category
105	Lunar Dust Filtration Need improved filtration methods for lunar dust. Control below SOA HEPA filtration is desired to protect crew per medical operations. Filtration to 0.1 μm is desired.	Lunar transport	Critical
594	Advanced Airlock/Suitlock with Dust Filtration Large number of EVAs (extravehicular activities) will require minimum gas loss suitlock that can depress and repress quickly and keeps suits in suitlock for dust mitigation.	Lunar transport	Critical
627	Lander Dust Mitigation Materials and/or mechanisms that do not collect dust and do not abrade when in contact with lunar regolith and/or do not remove lunar regolith from surfaces.	Lunar transport	Highly desirable
469	Lunar Dust Filtration Need improved filtration methods for lunar dust. Control below SOA HEPA filtration is desired to protect crew per medical operations. Filtration to 0.1 μm is desired.	Lunar surface	Critical
623	Dust/Regolith Mitigation Techniques within Habitable Cabin Approaches to prevent regolith/dust from entering the habitat from suits and instruments are required. A reliable system for collecting and removing regolith/dust from the habitat is also required. Extensive exposure to lunar dust can lead to respiratory problems. Includes dust characterization and establishment of human health standards. Dust-proof containers, filtering system, pumps are example technologies that need to be developed. Sensor/monitor of dust levels within the airlock and methods for dust removal (e.g., electrostatic methods, nitrogen air shower).	Lunar surface	Critical
625	Dust Control/Remove Airborne Dust Technologies to remove airborne dust (down to submicron range) from cabin atmospheres without incurring high expendable filter resupply burdens.	Lunar surface	Critical

^aPresented by Daniel Barta of NASA Johnson Space Center.

^bSOA HEPA filtration is state-of-the-art high-efficiency particulate air filtration.

^cLunar transport = initial lunar missions (lunar lander); Lunar surface = extended lunar missions (outpost).

3.0 Workshop Objectives and Management

The objectives of the workshop were threefold. The first was to provide basic information exchange at the programmatic and technical level, in light of the diverse background and expertise of the participants. The second was to obtain an industry perspective on the problem at hand and solutions used in the field. The third objective was to obtain recommendations for strategic research and technology development.

The management of the workshop is described here to provide a reference for any future follow-on workshop that may take place. The workshop was structured to produce a free exchange of ideas, problem solving, and team cooperation. Workshop attendees are listed in Appendix B. Because of the diverse audience background, the presentations were structured to provide high-level programmatic information, whereas the technical presentations were kept at a level appropriate for a general engineering audience. The splinter sessions were also organized to have a good mix of interaction between NASA researchers, managers, and filtration experts.

The first day of the workshop and part of the morning of the second day was used for exchange of information through technical presentation. Most of the second day was devoted to splinter sessions. The participants were broken up into four groups and asked to probe and discuss ideas as well as provide recommendations on filtration and separations technologies. The third day was left for general discussions and for touring some of the Glenn facilities.

4.0 Workshop Presentations

There were 20 presentations made at the workshop (see App. C). They were subdivided into background information, filter testing, filtration technology, and Small Business Innovation Research (SBIR) presentation categories. The background information included programmatic presentations, presented in the previous section, which exposed the general audience to some of the priorities and

tentative requirements for the spacecraft and habitats. Two of the presentations provided perspectives of lunar dust experiences during the Apollo missions. These highlighted that the missions were successful overall, but indications of dust contamination were quite obvious. The technology presentations provided a good level of detail on filters and particulate separations technologies, educating the NASA audience on some of the fundamentals, standards, and practices of state-of-the-art filtration. Some cutting-edge research and developmental technologies were highlighted in these presentations. Lastly, there were four SBIR presentations that showed promising prospects for exploration filtration systems. Some of the key information and points provided by the workshop presentations are presented here.

4.1 Background Information

Background information provided in the presentations included overviews of lunar dust properties, toxicology, hardware issues, the Apollo experience, and spacecraft airlocks and cabin air revitalization. The Apollo talks provided extensive perspective on the experience with lunar surface dust, and therefore a few lists of issues and recommendations from lessons learned are provided below. Recent NASA internal data and studies provided estimates of lunar dust entry into the spacecraft and standards for acceptable air quality that were highlighted in the presentations.

4.1.1 Lunar Dust Properties

Lunar regolith refers to the crushed (comminuted) lunar rock produced as a result of space weathering that led to the formation of a surface soil with particles that are <1 cm (no organic component is implied). The prime constituents are aluminosilicate and other silicate minerals that make up 90 percent by volume of lunar rocks. The lunar rock or soil is also comprised by up to 20 percent of various oxides that can potentially be tapped for oxygen extraction. The fine particle content of the lunar regolith is known as lunar dust and is categorized based on application: (1) Lunar dust involved in surface (external) operations has been defined as <20 μm and (2) airborne (or respirable) lunar dust is defined as being <10 μm . There is therefore a departure in the use of the term “lunar dust” in the life support systems communities from the traditional use in lunar surface operations.

Specifically, particles 10 μm and below are expected to be readily entrained and aerosolized in the cabin airflow. As a cautionary remark, it should be mentioned that despite the 10- μm cutoff for terrestrial aerosols, larger particles (>10 μm) may also become aerosolized in the lunar reduced-gravity environment.

Lunar regolith dust particles—particularly the larger particles—also tend to have very irregular (nonspherical) shapes. Irregularly shaped particles tend to have larger surface areas and more angular (sharper) edges than regularly shaped particles. Larger surface areas provide increased surface interactions that can lead to larger net charged or reactive states of the particle. The sharper edges can contribute to particle abrasiveness. This irregularity is mainly due to micrometeorite impacts, which produce local melts and fracture the regolith particles. In contrast, recent scanning electron microscopy (SEM) images of very fine lunar dust particles (Ref. 2) do not tend to feature such irregular shapes. Also, particles derived from volcanic vent activities tend to be more spheroidal in shape. Given the different formation mechanisms, one would expect that lunar dust particles should exhibit a characteristic shape distribution. Indeed more data and analysis is needed to address this.

Another property of lunar dust particles that merits attention is its reactive states. Multiple types of space events and conditions contribute to the excited energy states of the particles, including solar wind, solar flares, galactic cosmic rays, micrometeoroids, large thermal cycles, and ultrahigh vacuum. The result is the bombardment by high-energy particles onto the surface of particles, which produces charged and chemically active states that persist because the high-vacuum environment offers little passivation. It is unknown to what levels lunar dust will remain activated when introduced inside a pressurized environment with a finite humidity level. If there is little passivation, human exposure to activated lunar dust particles is potentially quite toxic.

4.1.2 Toxicology of Lunar Dust

A common thread through the technology needs presented in the previous section (Table I) is the protection of the crew from exposure to lunar dust particles. The known toxicological effects of dust are dermal irritation and penetration, ocular irritation and corrosion, and upper- and lower-airway injury. The respirable dust content refers to particles from 10 μm down to 0.1 μm . The lower-airway injuries are more critical, involving the smallest particles ($<1 \mu\text{m}$), which can provoke edema, inflammation, fibrosis, and possibly cancer. Particles less than 0.1 μm are expected to pass through the airways undeterred and exhaled back out.¹ NASA's Lunar Airborne Dust Toxicity Assessment Group (LADTAG) was formed to determine the toxicological effects of lunar dust. Based on the literature and studies, the LADTAG has recommended a permissible exposure limit (PEL) for lunar dust particles of 0.05 mg/m^3 for aerodynamic particle size range of 0.1 to 10 μm (see also the Constellation Program Human-Systems Integration Requirements (HSIR) document, Ref. 3). Note that this is a mass-based requirement, which is independent of particle size in the 0.1 to 10 μm range, and therefore does not discriminate whether there are more particles closer to 0.1 μm , (more penetrating) than at 10 μm in size.

The LADTAG is currently pursuing additional characterization and physiological studies to better assess the effects of long-term exposure to lunar dust. An area of particular interest is the reactivity of lunar dust and how it interacts inside the moisture-rich environment of the human pulmonary system. Their research agenda includes a study of activation and deactivation properties of lunar dust particles, which will lead to further studies on the reactivation and the process of passivation of dust particles. Pathological studies of exposure to lunar dust via inhalation (intratracheal and intrapharyngeal instillation), cell culture toxicity, and mechanical and chemical toxicity through cutaneous and ocular contact are also on the agenda. One of the nearer term objectives is establishing a 6-month PEL by 2010.

4.1.3. The Apollo Experience and Lessons Learned

The Apollo missions were highly successful, accomplishing six remarkable Moon landings in just over 3 years. However, they also pointed out the nuisances and problems associated with operating on the lunar surface. It is now well known that the lunar dust entered and floated everywhere in the lunar excursion module (LEM) during the microgravity portion of its ascent to the command module. The dust affected the crew's physiology (eyes, nose, and ears), producing some mild to allergic effects. As a result the crew tended to keep their helmets on until they reached the command module. The crew also observed that the dust did not appear to be filtered from the environment through the LiOH air revitalization system.

Apollo 17 Commander Gene Cernan made a notable quote that summed up his experience with lunar dust:

“You have to live with it but you're continually fighting the dust problem both outside and inside the spacecraft. Once you get inside the spacecraft, as much as you dust yourself, you start taking off the suits and you have dust on your hands and your face and you're walking in it. You can be as careful in cleaning up as you want to, but it just sort of inhabits every nook and cranny in the spacecraft and every pore in your skin.”

Apollo 11 Astronaut Buzz Aldrin made a brief appearance at the workshop. When asked about the lunar dust, he could not recollect any specific problems or issues regarding it. However, he noted that he was only there for a few hours.

¹ Dissenting opinion on this premise arose arguing that the diffusional particle transport mechanism, which dominates particles $<0.1 \mu\text{m}$, can produce increased interactions and consequently, adhesion with surfaces (i.e., tissue and vessel walls).

The Apollo crew debriefings recount first-hand experiences during the missions in dealing with lunar dust. The list below provides some of the key solutions and shortcomings obtained from the debriefings. (These were taken directly from the presentation material.)

What worked:

(1) Thermal and micrometeoroid garment (TMG) and dust covers were effective in protecting portable life support systems (PLSS) and suit components such as regulator sense ports, sublimators, and oxygen purge system (OPS) actuators.

(2) Scrupulous brushing did reduce dust brought into the LEM after extravehicular activities (EVAs).

(3) Arranging airflow from the command module to the LEM decreased dust transfer after ascent docking.

(4) Cabin filters did remove dust from command module atmosphere.

What did not work:

(1) Brushing for dust removal was time consuming and not fully effective.

(2) Significant dust always reentered the LEM with suits, gear, and samples after EVAs.

(3) Significant dust transfer from suit to crew and liquid cooling garment (LCG) occurred during doffing.

(4) Any cavities and crevices in the floor accumulated dust that later became a problem.

(5) Sealing issues and sticky mechanisms took place on the Moon and on return flights.

(6) Filters in the command module required frequent cleaning in return flight.

These experiences comprise the most direct and relevant demonstrations of mitigating practices and challenges. However, it should be noted that the Apollo missions were generally short, from a few hours to a few days, and therefore these solutions may not be the most feasible over longer mission periods where significantly more lunar dust accumulation is expected.

Also presented during the workshop were a collection of photographs that showed the extent of lunar dust contamination on the Apollo hardware. There were many photographs revealing the numerous pieces of hardware that were contaminated with lunar dust, particularly in the suit loop connectors and lines and in the air ducts of the command module. Figure 1 provides a telling example of lunar dust contamination on the cabin return air duct in the command module, a critical piece of life support equipment.



Figure 1.—Cabin air return duct in Apollo 11 command module after return to Earth.

4.1.4 Impact on Hardware

In addition to toxicological effects, the lunar dust can impact or adversely affect equipment and instrumentation. Dust in general can have consequences in a wide range of hardware components, specifically causing degradation of seals and valves, breakdown of lubricants, jamming of moving parts, and creation of flow blockages. A good analog to lunar operations are Arabian Desert aircraft operations, where multiple problems associated with dust have been reported. The following is a list provided during the presentations (Ed Hogdson, Hamilton Sundstrand) on the Arabian Desert operations, which seems to have strong relevance to what may be expected from the lunar dust during lunar missions:

- (1) Frequently blocks filters
- (2) Damages bearings—need to preclude dust from bearings
- (3) Minimizes fan starts and stops
- (4) Erodes heat exchanger coatings and fins
- (5) Accumulates in small-diameter passages of valves
- (6) Accumulates in unique locations as a result of significant pressure changes
- (7) Erodes coatings and material on fan rotor leading and trailing edges
- (8) Clogs small orifices and builds up in eddy current areas, resulting in coefficient of discharge shifts

It was noted that the sand did not affect packed bed performance or conformal coated electronics and that accumulation in the tip clearance of fans was not an issue.

Additional hardware problems associated with the ECLSS of Constellation lunar surface systems are envisioned to include

- (1) Fouling of lubrication
- (2) Dust accumulation on the valve seats yielding internal leakage
- (3) Contamination of moving parts of rotary or linear multiport valves
- (4) Significant bearing damage, requiring particle separation management
- (5) Dust trapping and bypassing in sliding seals at filter edges
- (6) Dust accumulation similar to the International Space Station (ISS), causing flow blockage
- (7) Air quick-connects either not being connectable, or leaking

There were also several general recommendations offered for future missions:

- (1) Provide high-recirculation-rate air cleanup with high-speed fans and high-efficiency particulate air (HEPA) filters.
- (2) Provide air showers in airlock. There will be a need to determine the effects of low-density gas in 1/6g.
- (3) Provide vacuum cleaner fans and HEPA filters.
- (4) Include air sensor block (sensor assembly) with robust filters to withstand depressurization and repressurization of the cabin and airlock.
- (5) Protect all direct openings to the cabin.
- (6) Provide dust protection on depressurization and repressurization valves.
- (7) Design ECLSS for dust robustness.
- (8) Adapt operational scenarios to accommodate dust.

As implemented in cleanroom protocols, a series of dust barrier stages may be used to provide general dust suppression for the pressurized cabin environment. Three recommended stages of dust barriers provided by the Hamilton Sundstrand representative are provided below.

- (1) First dust barriers (bottom of ladder)
 - Cleaning suits and equipment
 - Pad on ground with brushes
 - Sticky tape or materials wipes
 - Magnetic or electrical wands
 - Other methods

- (2) Second dust barriers (airlock and platform at top of ladder)
 - Floor with sticky peel and/or magnetic coats
 - Partial airlock repress with air jets and depressurization vacuuming of surfaces
 - Part of full airlock depressurization gas captured in collapsible bag
 - More surface brushes, wipes, and wands
 - Vacuum cleaner
 - Narrow port with high suction capability (high pressure difference) for cleaning surfaces
 - Wide port with high flow rate for filtering airborne dust

- (3) Third dust barriers (airlock and cabin)
 - Filtration for 0.1 μm
 - Forced airflow through hatch from *Orion* to *Altair*
 - Particle counter for 0.1 to 10 μm that must have a size separator at the inlet

4.1.5 Airlocks and Cabin Air Revitalization

The Apollo missions lacked an airlock on the LEM, which exacerbated the transfer of lunar dust into the module. In light of this, future lunar surface spacecraft will be equipped with airlocks to greatly reduce the amount of lunar dust that is tracked back in after an EVA. Additional dust barrier technologies and approaches can be used to further suppress dust infiltration. For example, suitlocks are an attractive approach where the suits are donned and doffed through an interface directly on the suit. Techniques and approaches to more effectively clean off the extravehicular mobility units (EMUs), or surface spacesuit, and EVA equipment right outside and inside the airlock such as electrostatic methods, and nitrogen showers will be significant enhancements to dust mitigation. To accomplish this, a sister task under the ELS project led by NASA Johnson Space Center is developing portable air cleaning and vacuum cleaning technologies that will aid in the abatement of lunar dust in the airlock.

The dust inside the vehicle ultimately has to be removed by the onboard elements of the life support system. The cabin air is maintained by a set of atmosphere revitalization systems, which cleanse and maintain breathable air inside the crew cabin. For spacecraft atmosphere revitalization, there are needs to recover, recycle (e.g., dry and purify), produce, store, and distribute the atmospheric gases. This processing involves separation, such as physical adsorption, absorption, and particulate filtration. For particulate removal, filtration—including inertial- and field- (e.g., electrostatic-) directed separations—is the prime method used. A proposed approach to spacecraft filtration is a multistage filtration consisting of screen filters, an inertial filter, and a high-efficiency filter. Similarly, most filtration systems used in terrestrial applications, which are at least two-stage systems consisting of a prefilter and a high-efficiency filter. The prefilter typically is used to reduce the load on the high-efficiency filter. In the proposed concept, the prefilter will capture particles $>800 \mu\text{m}$. The inertial filter will capture particles $>5 \mu\text{m}$, and the final high-efficiency filter will capture $<5 \mu\text{m}$.

The Constellation Program has provided estimates of lunar dust infiltration into the pressurized cabin of 227 g/suit-EVA (derived). Of the lunar dust particles that enter the spacecraft, only particles below 10 μm are expected to become airborne. This constitutes only about 7 percent by mass of the lunar regolith. This is still a significant amount of contamination that will lead to high levels of airborne dust. Although the focus of the workshop was of the entry of lunar dust into the cabin, there will also be a generic, biologic component: internally generated dust. Table II summarizes the separate particulate PELs

for both internally generated and lunar dust as well as biological matter. Just as on the ISS, particulate matter will be generated from background materials in the interior of the cabin and from biological matter, such as skin flakes, hair, and lint. The rationale for the lunar dust permissible limit has been provided in Section 4.1.2 on lunar dust toxicology. The remainder of the table mimics the ISS PELs for internally generated dust and biological growth. An issue regarding the two particulate matter requirements is that the lunar and generic dust will be indistinguishable to the filtration system. Therefore, the combined load of the lunar regolith and generic dust will have to be treated and maintained at the accepted LADTAG PEL of $<0.05 \text{ mg/m}^3$ for the particle range of 0.1 to 10 μm . As a result, the allowable dust load of lunar dust is actually more stringent than the PEL represents.

TABLE II.—PARTICULATE REQUIREMENTS FOR LUNAR SURFACE SYSTEMS

Type	Requirement
Internally generated particulate contamination	0.5 to 100 μm aerodynamic diameter, $<0.2 \text{ mg/m}^3$ 0.3 mg/person-min
Lunar dust contamination ^a	>0.1 and $\leq 10 \mu\text{m}$ aerodynamic diameter, $<0.05 \text{ mg/m}^3$
Bacterial ^b	$<1000 \text{ CFU/m}^3$ 1640 CFU/person-min
Fungal ^b	$<100 \text{ CFU/m}^3$ 1640 CFU/person-min

^aLimit under review, final by 2010.

^bCFU is colony-forming unit.

These permissible limits (Table II) and more details on them can also be found in the Constellation Program HSIR document (Ref. 3).

4.2 Testing Concepts

The testing phase is an important component of filter and separations technology development. Several presentations were provided in this area. Two of the presentations highlighted (1) the Lunar Dust Filtration Testing Facility being developed at the NASA Glenn Research Center and (2) industrial testing standards and methodologies used in current testing facilities. An overview was also provided of the lunar simulant development being led by the NASA Marshall Space Flight Center. Lunar simulant development is ongoing and continues to lead to higher fidelity soils and dust particles that can be used for testing. Lastly, the capabilities of reduced-gravity facilities as testing platforms were also provided.

The Lunar Dust Filtration Testing Facility directly supports particulate matter filtration and separations technologies under the ELS project. The facility is designed with a closed-loop architecture that is capable of operating at reduced pressures of 8.3 psia for the *Altair* lunar lander and outpost habitat and 4 psia for pressurized airlocks. The facility also features variable flow rates up to 100 scfm (standard ft^3/min) without a filter, an internal particle delivery system, and multiple window and instrument ports. Instrumentation and diagnostics included in the facility are an orifice flow meter; differential, absolute and vacuum pressure transducers; optical particle detectors; laser light sheet imaging; high-speed imaging; and particle image velocimetry (PIV).

A presentation on industry testing standards was provided by Dr. Hanley of RTI International. At the outset it was stated that industry standards apply to specific technologies and applications. When the application deviates from the baseline, the assumptions and protocols of the standard may not be valid. The standard used in industry is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 52.2 (Ref. 4). Many valuable guidelines and tips were provided for testing in the filtration facility. Chiefly, it was strongly suggested that qualification and control tests with

standard well-characterized media be performed to verify the facility performance. As data is interpreted, it was cautioned that results should closely follow well-established filtration theory. It was also mentioned that testing in a relevant environment (or conditions), as is the case with the Lunar Dust Filtration Testing Facility, was a proper approach.

An overview of the simulant development managed at Marshall was given. The chief activities are determining users needs, lunar dust characterization, finding sources and processes for simulant production, developing and characterizing simulants, and educating users on the handling of the simulants. The main properties being characterized are particle size distribution, particle shape distribution, and bulk density properties. These are precisely the properties that impact the measurement of irregularly shaped airborne particle or aerosols. Figures of merits are being established to provide an accepted comparison between granular assemblies of particles. The use of Glenn's new multistage axial cyclone was touted as a key piece of equipment for lunar simulant characterization research. This device can size classify particles from 10 μm to 20 nm.

Several key pieces of information are needed to gain confidence in the use of simulants in filter testing as they relate to particle measurements. The shape distribution of lunar regolith and simulant dust particles is considered critical information. Aerosol measurements are based on the assumption of spherically shaped particles. For particle size measurements using optical particle counters (OPCs), the index of refraction of these particles is needed. For calibration purposes, Glenn's axial cyclone can be used to provide monodispersed particle samples of lunar simulant to perform a set of controlled calibration tests. Although use of OPCs for filter testing is widespread, it was suggested that consideration be given to mass-based measurements that relate better to the capturing mechanisms of filters.

An overview of available reduced-gravity facilities to conduct research, demonstration, and testing was also presented. The Reduced Gravity Office (RGO) at Ellington Field, Houston, provides the C-9B aircraft to support conceptual development (TRL of 1 to 3) of components and systems and to support limited technology demonstrations and evaluations (TRL 5 to 6) of components and systems under planned operational environment (i.e., short-duration microgravity and partial gravity). Recently, the RGO has provided aircraft support through the privately owned ZERO-G aircraft. NASA Glenn also has two drop facilities: the 2.2-Second Drop Tower and the Zero Gravity Research Facility. These facilities provide engineering and technician support for hardware buildup. Interfaces ranging from video, analog data, and programmable logic control during the drop can be provided.

4.3 Filtration Technologies

The presentations ranged in scope from state-of-the-art technologies to developmental technologies. A good overview of the state-of-the-art high-efficiency filtration was given by Dr. Vijayakumar (Aerfil LLC). Applications of HEPA filters in tractor cabins were presented as relevant to spacecraft filtration. Developmental filtration media and technologies included ceramic filter and multistage or component cyclone separators.

There is a lack of international consensus on the definition of high-efficiency filtration. In fact some of the standards are quite disparate:

- | | |
|---|---|
| (1) European standard EN 1822-1 (Ref. 5): | 85 percent |
| (2) U.S. standard AHSRAE 52.2 (Ref. 4): | 95 percent and higher |
| (3) NASA (ISS) standard: | 99.97 percent at 0.3 μm (per MIL standard 282, Ref. 6) |

The ones most relevant to NASA's exploration goals are the U.S. and NASA standards. NASA's lunar missions can consider the industry best practice of 99.99 percent capturing efficiency as an initial target.

The virtues of fibrous media filters in high-efficiency filtration were stressed. Invariably these are used in conjunction with a prefilter, to extend the life of the filter. The advantages are, first, that filtration takes place throughout the media (surface and depth). The particle loading or removal can range from

very low to very high, based on configuration and application. Capturing occurs over a wide range of particle sizes down to ultrafines. Flow resistance, however, increases with efficiency as well as over time with the cumulative particle loading. Because fibrous filters are generally depth filters, particles are subjected to the three capturing mechanisms: diffusion, interception, and impaction. This simply implies that all particle sizes are captured, except in the range from 0.1 to 0.3 μm where they are captured with a moderately lower efficiency (in the range of 99 percent and lower depending on filter face velocity). This is not strictly the case for surface filters, which only capture particles larger than their pore size (or what is captured in the dust cake).

Another advantage is that these filters are well characterized. In fact, the industry does an excellent job of characterizing the performance efficiency under standardized test conditions, which are sufficient to extrapolate to give performance and life estimates based on application. In particular, all HEPA filters are 100 percent tested before they go to market. A roll filter concept was introduced as a type of filter configuration that would provide extended filter life by periodic advancement of the filter media. This configuration could incorporate any of the filter media types presented in Table III. Potentially, the rolling process can be automated to reduce or eliminate crew maintenance time. Another configuration is a portable fan filter unit that can be used under circumstances where elevated levels of airborne dust are expected for localized and short-term filtration.

TABLE III.—FIBROUS MEDIA COMPARISON CHART

Medium ^a		Property					
		Efficiency	Capacity	Thickness	Mechanical	Processability	Typical filter uses ^b
Fabrication	Dry laid	Very low	Very high	Thick	Robust	Easy	Prefilter
	Spun bond	Low	High	Various	Robust	Easy	Prefilter, backing layer
	Melt blown	Medium to high	High	Thick	Robust, soft, and multilayer	Easy except close pleat	HVAC, appliance
	Glass blanket	Medium	High	Thick	Robust, dusty, and multilayer	Easy except close pleat	HVAC
Material	Cellulose	Low	High	Moderate	Robust and stiff	Easy	Engine, turbine
	Microglass	Medium to very high	Low	Thin	Delicate	Hard	HVAC, ULPA and HEPA
	PTFE	Very high	Very low	Very thin	Robust and soft	Specialized	HEPA and ULPA

^aPTFE is polytetrafluoroethylene.

^bHVAC is heating, ventilation, and air conditioning; ULPA is ultralow penetration air; and HEPA is high-efficiency particulate air.

Fibrous filter media fabrication encompasses several web formation methods and fiber fabrication techniques, which include (in order of increasing efficiency): dry laid, spun bond, melt blown, glass blanket, cellulose, microglass, and PTFE (or Teflon (DuPont)). A summary of the different media types and their general uses are presented in Table III. Media selection is based on four main criteria: performance needs, cost benefit, filter design, and end use. “Performance needs” refers to the efficiency and capacity balanced against resistance. Typically, cost scales with efficiency. However, cost is not expected to be a real driver since NASA is expected to seek custom filter designs. Filter design and end use depend upon the application, which can range from prefilters to HEPA and ultralow penetration air (ULPA) filters. NASA’s final filter design for lunar surface systems will undoubtedly include the use of high-efficiency filters to capture all particles of concern to NASA, 0.1 to 100 μm (see Table I), before entering the next segment of the life support loop. Note, however, that as stated above, particles below 0.1 μm should, in principle, all be captured by the fibrous filter because of the diffusional capturing mechanism. Another important factor that impacts performance is media velocity (Fig. 2). Efficiency

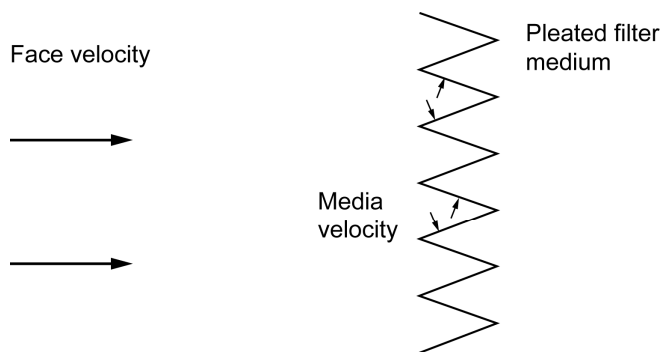


Figure 2.—Flow in front of filter medium showing filter face and media velocities.

decreases exponentially with increasing media velocity and increases significantly with decreasing media velocity. The key message is that fibrous filters can be configured to play a primary role in a multistage filtration system.

The site construction industry offers another perspective on the use of air filters. Tractor vehicles operate in extremely dusty environments, relying on the cabin filters to provide the only protection against the environment. A three-stage filter stack, consisting of a prefilter, HEPA filter, and carbon filter is used in fresh air intake and recirculating modes. The American Society of Agricultural Engineers (ASAE) S525 standard dictates that the air intake filters should be 95 or 99 percent efficient at 3 μm , with and without recirculation, respectively. It is important in this application to periodically inspect the seals around the filter stack. The seal is maintained by compressing the filter stack to ensure contact between the filter housing gasket and the supporting flange. Field data indicate that leaks in the filter stack can increase particle penetration by an order of magnitude. Recirculating the air, on the other hand, increases protection factors by an order of magnitude.

Lesser known in air filtration, sintered porous metal filters offer features that cross the boundary between high efficiency and prefiltering efficiency. Typically used for high-pressure gas filtration, they have several advantages that make them attractive. These include a high-strength matrix, washability, high loading capacity, and a wide range of filtration efficiencies from prefiltration to high-efficiency filtration. However, they usually produce high pressure drops. Their rugged construction allows them to be easily backwashed for regeneration. A possible application for spacecraft could be as a prefilter. It should be noted that ceramic filters potentially offer similar advantages as the sintered porous metal filters.

Lastly, Professor David Pui, Director of the Center for Filtration Research at the University of Minnesota, which is a consortium of filtration companies and academic researchers, presented the work being conducted at the Center. The Center is involved in a wide range of cutting-edge research topics, such as nanoparticle and nanofiber filtration, cabin air filtration, and multicomponent cyclone filtration. The concept of thermal rebound of nanoparticles was introduced, which although intriguing, is not thought to play a major factor in the filter efficiency. A nanofiber filter and cyclone combination was proposed as a concept for lunar dust filtration.

4.4 Small Business Innovation Research Technologies

Several principal investigators from active Small Business Innovation Research (SBIR) projects with ties to lunar dust filters and simulant development presented details of their work. These projects showcased the advanced developments funded by NASA, incorporating cutting-edge technologies. These technologies included carbon nanofibers, a novel electro spray technology for charging particle surfaces, and lunar simulant particle development.

Connecticut Analytical Corporation presented a novel approach to electrostatically enhancing particulates. It relies on electro spray ionization, in which desorbed electro spray droplets exhibit a capacity

to attract polar molecules and particulates from the surrounding air with a high degree of efficiency. This technology can be used to assist filtration capturing of particulates onto surfaces of conducting fibers and surfaces. Experimental demonstration by the company has shown that by using the electrospray technology, lunar simulant dust particles can be effectively scrubbed from the air. The technology offers extremely low power consumption, zero pressure drop, and no ozone production.

Seldon Technologies presented their phase I work on the development of a fused carbon nanofiber filter using their patented Nanomesh filter medium for lunar dust filtration. The advantages of carbon nanofibers are their high fiber strength, large surface area that can be chemically functionalized, conductivity, and low flow resistance. Seldon's carbon nanofibers also offer high aspect (length-to-diameter) ratios, which reduces the chances for shedding of fibers from the matrix. The company is investigating the performance of two flow configurations: a flow-through and a cross-flow configuration. Results show that the flow-through configuration yielded an efficiency of 99.6 percent for particles in the size range of 0.3 to 0.5 μm at elevated velocities of 12 m/min, but at significant pressure drops (i.e., 450 Pa). In the cross-flow configuration an efficiency of 84 percent was achieved but at a pressure drop of only 5 Pa. Modified filter designs are being pursued to improve the performance and capacity of both filter configurations.

Agave Biosystems is also developing novel carbon-nanofiber-based filter system for lunar dust filtration. The company grows the carbon nanofibers onto stainless steel meshes and arranges them in a stack with an emitter and a receiver mesh, to form a novel electrostatic device capable of capturing microparticles and nanoparticles. The multilayer design of carbon-nanotube- (CNT-) based filter significantly reduces the system footprint. Besides the advantage of its high surface area for capturing efficiency, the CNT elements are excellent conductors and make highly efficient field emission devices. The emitters charge the incoming particles, which are then collected with greater affinity onto the receiver mesh (last layer). Because of the geometric enhancement factors—greater than 1000 for nanofibers—lower threshold voltages ($\sim 1 \text{ V}/\mu\text{m}$) will be required to achieve field emission. In their next-generation devices, Agave plans to scale up their devices by incorporating multicomponent CNT stacks in parallel plate and concentric tube configurations.

Orbital Technologies Corporation is developing high-fidelity simulants that better represent the agglutinate character and Fe^0 -rich particles found in the lunar regolith particles. The company has produced several simulants based on earlier JSC-1a (Johnson Space Center Number 1a) and NU-LHT (NASA/USGS (United States Geological Survey)-Lunar Highlands Type) simulants. Characterization has shown striking similarities between these prototype simulants and the lunar regolith particles.

5.0 Splinter Sessions

The workshop provided an opportunity for in-depth interaction, exchange of ideas, and a brainstorming of ideas among the industry experts, NASA researchers, and NASA programmatic managers. The four topics on the agenda helped to provide focused discussion although there were some obvious overlaps between topics. The workshop participants were broken out into four groups based on their expertise and stake on these topics. The splinter session was conducted during most of the second day and included a report-out session.

In addition to guidance given by the topic descriptions, the participants were also asked to discuss and address the following:

- (1) Identify objectives or requirements (e.g., higher efficiency of ultrafines).
- (2) Identify viable state-of-the-art technologies and discuss how they will address the needs.
- (3) Address knowledge or technology gaps.
- (4) Identify all viable research and technology areas and prioritize.
- (5) Develop a roadmap for technology development and implementation.

The splinter sessions proceeded with the notion that the requirements for the lunar surface system vehicles were still not well defined, and therefore assumptions were made when needed. The following assumptions were considered. First with respect to the pressurized cabin, assumptions about the air handling rates were made based on cabin volume and the number of air exchanges. The lander cabin was approximated at 20 m³ with a 15-m³ airlock. Five air exchanges are typical in terrestrial applications, which in this case would yield a total cabin flow rate of approximately 60 cfm. For reference, the ISS Destiny module total flow rate is driven by bacterial removal and can get as high as 232 cfm. Note that the Destiny module has a volume 3 times as large, which indicates that the volumetric flow rate requirements are actually similar. These air handling rates will vary based on spacecraft architecture and the requirements for cooling and mixing of gases of the breathable air.

Another unknown was the airborne lunar dust loading conditions in the cabins due to EVA activities. From the presentation material it was assumed that about 227 g/suit-EVA with typical two-person EVA passes into the cabin. However, not all the dust particles become aerosolized, but rather only particles 10 µm and below, which amounts to only about 7 percent of the lunar dust, do so. This can still become a significant loading condition. An estimate of the airborne lunar dust loading condition amounting to about 1.5 g/m³ was recently derived by the ELS project Dust Mitigation and Control task (Jan. 2009).

The conceptual paradigm for vehicle cabin air filtration used in the discussions was a multistage filtration system that will facilitate both performance and regeneration efficiency. The two main components will be a prefilter or bulk filter for the first stage and a high-efficiency filter in the last stage. Their applications were discussed separately because of the different requirements they entail. It was thought that even for portable filters and vacuum cleaners both technologies will play a role, although they may have different requirements or operational protocols than in vehicle cabin filtration in general. Finally, testing was thought to be a vital part in demonstrating and qualifying candidate filtration component and systems.

Each of the sessions provided valuable information and recommendations. The High-Efficiency Filtration and the Bulk Filtration and Regeneration sessions provided more detail on the main filtration requirements. The other sessions built on or referred to these requirements and contributed other application specific requirements. Each session identified important gaps and provided sensible research and technology directions. Details from each of the individual session are provided in the next few subsections.

5.1 High-Efficiency Filtration

High-efficiency filters will be essential to maintaining a safe environment for the crew during lunar landing and outpost missions. The lunar dust that enters the pressurized cabin is thought to contain a significant amount of fines and ultrafines that will need to be filtered out. Decisions have to be made about the requirements for these filters, and about the most suitable type of filters and/or filter enhancing techniques and materials. For guidance, the currently established allowable particulate matter limit set by the Lunar Airborne Dust Toxicity Advisory Group (LADTAG) is 50 µg/m³. Effects regarding the properties (or currently known properties) of the lunar regolith dust on the capturing efficiency and longevity of the filter, as well as the impact on equipment (e.g., blowers and other air revitalization systems), should also be addressed.

5.1.1 Requirements

High-efficiency filters are expected to fill several needs in lunar surface systems. They will play the prime role in the capturing of fine and ultrafine particulates, thereby making their use indispensable where crew presence is involved. The PELs for these filters were given in Table II. They are listed here again for discussion:

- (1) For lunar dust particles (LADTAG PEL):
>0.1 and ≤10 µm aerodynamic diameter

- (2) For internally generated dust particles (ISS PEL):
 - 0.5 to 100 μm in aerodynamic diameter
 - and/or
 - 0.3 mg/person-min in this size range
- (3) For bacterial particles (where CFU is “colony-forming unit”):
 - <1000 CFU/m³
 - and
 - 1640 CFU/person-min
- (4) For fungal particles:
 - <100 CFU/m³
 - and
 - 1640 CFU/person-min

The first two requirements reflect the particulate requirements. Note that high-efficiency filters are sensitive to the penetration of the particles of sizes around the lower bound of these requirements. The implications of this are discussed and will be presented subsequently. The second two requirements regarding bacterial and fungal growth were adopted from the ISS requirements on biological contamination. Lastly, it was emphasized that the filters or dust mitigation methods employed in the airlock must be able to handle the intrusion of 227 g/suit-EVA (derived) of lunar dust.

5.1.2 State-of-the-Art Technologies

The PEL is mostly achievable by state-of-the-art high-efficiency filters. Thus this session provided much detail on fibrous filters. Their applications will be in the atmosphere revitalization systems, in vacuum cleaners and portable filters, and in supply lines of suit loops (suit loops will run at 2.8×10^{-3} to 3.8×10^{-3} m³/s (6 to 8 cfm) per person, 1.1×10^{-2} to 1.5×10^{-2} m³/s (24 to 32 cfm) total). Although highly efficient in most of the particle ranges, in the range of 100 to 300 nm the mechanism of diffusion tapers off while that of interception starts to ramp up, leading to a slight drop in efficiency in this range that is exacerbated by increasing flow face velocity. This range is coincidentally within the range of respirable particles that can affect the lower airway of the human physiology. It should be noted that there is no 100 percent efficient filter, so it needs to be determined if this drop in efficiency can be contended with through operational parameters, filter design changes or filter capturing enhancements in order to meet the PEL.

Fibrous filters are depth filters and as such the three capturing mechanisms—diffusion, interception, and impaction—propagate throughout the depth of the media, allowing for more capturing area and therefore higher efficiency. Microfiberglass is the dominant material for these, which is rated at a range of 1 to 10 log reductions or (known in the industry as seven 9s or more technically as 99.99999 percent efficient) depending on configuration and flow face velocity. Its advantages are its simplicity and industrial track record, and that it can be scalable in size and performance. The disadvantages are that it can become consumed or loaded quite rapidly, depending on configuration and environment, and it is also susceptible to moisture. However, there are methods to engineer them to be moisture resistant.

Some discussion was given on the effects of air handling rates. Consider that the LADTAG PEL is hourly based, with no peak requirements provided (currently). Modifying the flow rates will have competing effects. First, increasing the number of air exchanges an hour, thus increasing the flow rates, will tend to increase the capturing efficiency since the volume of air in the cabin is cycled through the filters more rapidly and more frequently. However, as stated above the filter efficiency decreases exponentially with increasing face velocity. Clearly, a trade study or assessment of hourly efficiency versus volumetric flow rates is required.

It was emphasized that “we have the technology we just need to know how to package it.” In other words, state-of-the-art filters will do the job; they just need to be packaged in a system that is responsive to NASA’s long-duration filtration goals. Firstly, they have to be tailored to meet NASA’s requirements and needs; that is, the lunar dust PEL, the handling of lunar dust intrusion rates and cabin flow rates. Some of these requirements are tentative until more relevant data become available and may not be finalized until NASA’s first return to the lunar surface. Additionally, the filtration system will have to be packaged to meet the low-upmass, low-maintenance, and power requirements. Regeneration will be desirable, but it was stressed that high-efficiency fibrous filters are very difficult to regenerate.

5.1.3 Knowledge and Technology Gaps

Several knowledge and technology gaps were discussed. Methods for the safe removal, storage, and disposal of disposable filter elements will need to be developed. Note that both lunar regolith dust and generic particulate matter will be lumped together in the captured material in the cabin filtration system. Therefore a revised PEL for the combined matter, based on an analysis of the proportions of lunar and generic dust, may be needed. Estimates need to be derived for the weight and volume of filter systems, as well as for operational parameters such as power consumption, waste handling, crew involvement, and lastly cost. The additional effects of humidity on small particulate dust in the cabin atmosphere, which can cause clumping of particles, should be studied. The abrasiveness of dust, which can damage moving parts and shorten material life, including the filter element, also needs attention. Finally, modeling of spacecraft fan volumetric flow rates, filter system volume, and particulate removal performance and efficiency, are needed to help derive requirements.

5.1.4 Viable Research and Technology Areas

Viable technologies included those associated with the SBIR technologies. Carbon nanotubes (CNTs) may provide high loading capacity and high efficiency. In certain configurations they can also be regenerated, as is being considered by Seldon. An issue with CNT is the shedding of fibers off the webbing or fiber matrix. Seldon uses extremely long fibers (high aspect ratio) in their patented Nanomex filter media, which should preclude this effect. The electrospray work by Connecticut Analytical Corporation for charging the dust is also attractive as a way to enhance a filtration system by capturing through electrostatic attraction of charged particles.

Several brainstorming ideas were also provided, mostly dealing with barrier technologies inside the airlock. The first was the idea of using an airlock electrostatic system, in which the suit is the cathode and walls or floor area is the anode, to drive off the dust from the suit. This must be considered as part of an overall spacecraft dust mitigation system. A few other operational concepts to mitigate dust in the airlock were also provided. To prevent dust from entering the cabin, the airlock pressure should be slightly negative with respect to cabin, including when the hatch is opened. This will ensure that the airflow between these volumes is always toward the airlock. A vacuum cleaning system for the airlock could simply be a hose connected to the outside vacuum of the lunar surface. In this case a system trade study against gas loss needs to be performed; it was emphasized that the direction of air circulation in general should be maintained in the direction from clean to dirty areas.

5.1.5 Roadmap and Schedule

Several priorities in the development of high-efficiency filters were identified. A multistage filter housing was envisioned. In this case, the filter housing will be the first development. Thereafter the replaceable filter elements can continue to be developed late in vehicle development since housings and specifications are fixed ahead of time. Correspondingly, there are two requirement developments: specify (1) the interface requirements between the housing and the air revitalization loop and (2) the interface requirements of the filter elements with the housing. Demonstration and proofs of concepts will be part of this roadmap.

5.2 Bulk Filtration and Regeneration

Lunar surface filtration systems will likely be designed as multistage systems. Prescreens and prefilters prior to the high-efficiency filter will likely be used. The particle size and mass fraction handled by the prestage bulk filters should be addressed. Regeneration, or cleaning of the filters, will be helpful in reducing the upmass and accumulation of filter elements during these long missions. The following questions will be addressed and discussed:

- (1) What filtration or separation techniques are most appropriate?
- (2) What level of regeneration makes sense?
- (3) How much power and downtime should be given to regeneration?
- (4) Are there any in-place or in-service regeneration systems that can be used?

Keeping in line with the multistage filtration concept, the bulk filtration stage will be a key component in helping meet the requirements of the high-efficiency filter. Because it is the first stage of filtration, this prefiltration stage has to capture as much of the bulk particulate material as possible in order to protect and extend the life of the high-efficiency filter. The high-efficiency filter will capture the remainder of the particulate load to meet the PEL; therefore, the atmospheric particulate requirement for the bulk filter can be less stringent than the PEL. In this case, an interface requirement between the prefiltration and the high-efficiency filter should be established. Other major drivers for the bulk filter will be operational and maintenance optimization, as well as upmass constraints.

5.2.1 Requirements

Recommendations for requirements were that the bulk filter should possess

- (1) The ability to capture 100 percent of particles larger than 20 μm , and most of the particles down to 5 μm
- (2) No expandable media
- (3) Extended (5-year) operational life
- (4) Less than 249 Pa (1 in. H₂O) pressure drop
- (5) Requirement constraints for weight, power, and volume
- (6) Flow requirement (needed for full-scale test)
- (7) Minimal maintenance

5.2.2 State-of-the-Art Technologies

There are two main bulk filter options. One is a prefilter or precleaner where dust is collected by a more porous filter. Over time a dust cake eventually forms increasing the flow resistance, and the filter has to be cleaned or discarded. Although not usually performed as a common practice, these filters because of their higher porosity can potentially be regenerated. Screens are typically used for prefilters. These are simple filter structures that capture the larger bulk material and can be easily cleaned using a vacuum cleaner. However, they allow a significant amount of small particles through, which increases the particle load on the next stage of filtration. A good alternative may be the sintered metal or ceramic filters described in Section 4.3, "Filtration Technologies." These filters are better at capturing the smaller particles and provide high loading capacity.

The other technology option is an inertial filter, which could take the form of a cyclone filter, impingement plate, or baffle. A (sharp) bend or trap could serve the same purpose but may not be as effective. These devices are governed by the interception and impaction mechanism, and their theory is well established. These devices are very efficient at capturing particles above a specified cutoff size. The advantage of cyclones is that they can provide very large inertial force to separate out a larger range of

particle sizes and densities. The larger the inertial force the lower the cutoff size of particles it can capture, that is, they capture down to a smaller particle size. They can also handle large amounts of dust, which makes them well suited for large industrial materials handling applications. The capturing efficiencies of cyclones are typically specified in terms of the d_{50} (the median cut point, or the particle diameter corresponding to the midpoint of the penetration curve) efficiency and can go down to single micron levels. However these devices typically produce relatively large pressure drops.

Bulk filters may also be more amenable to regeneration since the bulk material is more loosely held by the filtration media or surfaces. Regeneration could either be performed in place or via some maintenance process where there is some physical removal of the dust, outside of the flow loop. The former is obviously more advantageous. As an example, the cyclone separator has the advantage of larger retention capacity, but if used in a collection cup/bag configuration, as is typical, the dust mass needs to be physically removed by someone, or through a mechanism when the system is offline, and discarded. Alternatively, screens or porous (e.g., ceramic and sintered-metal) filters can be regenerated in place through backflow and backflow pulsing. The backflow can potentially be vented outside. This raises the question of whether biological dust can be vented out onto the lunar surface as well.

5.2.3 Knowledge and Technology Gaps

Several knowledge and technology gaps were identified. First, there is a need to refine or generate alternate lunar regolith load models in order to better define the intrusion rate inside the pressurized volume. The Constellation-derived estimate may be overly conservative. A higher fidelity model of the intrusion rate will help better refine the expected airborne particulate concentration after an EVA. Another unknown is the future direction of the health standard. During the workshop there was talk of movements in the community for considering particle surface area as a standard for the measurement of permissible limits. A shift in the standard can strongly affect the technology now being considered.

For regenerative filters, methods for the capture, removal, storage, and disposal of collected particulates need to be developed. The regeneration method (e.g., whether reverse airflow or vacuum pulse) will require development and demonstration. Lastly, the effects of the lunar dust abrasion on the filter media life and filter life after repeated regenerations also need to be determined.

5.2.4 Viable Research and Technology Areas

In general, the consensus in this session was also that the technology exists. The challenge is to select the right combination that produces the desired performance. A proof of concept will be required to demonstrate feasibility and show that it can meet power requirements. A conceptual model was provided (Fig. 3).

Several general research recommendations were provided. The first order of business should be to firm up requirements. This will facilitate an assessment of the trade space for the different filter technologies. Once the technologies have been narrowed down, their feasibility has to be shown through scaled and full-scale models and their performance demonstrated. At a more basic level, the

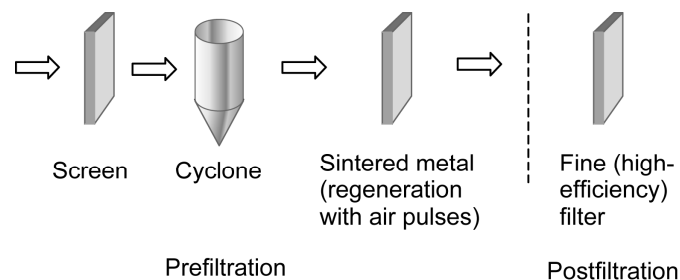


Figure 3.—Multistage filtration concept.

effects of cohesion of the lunar dust and its adhesion to surfaces should be investigated. These areas of investigation will benefit from a facility that can serve as an airlock suitable for low-g aircraft. Also importantly, the facility should be able to simulate the reduced pressures that will be encountered in lunar surface systems.

5.2.5 Roadmap and Schedule

A list of priorities and schedule milestones were formulated. First, the requirements need to be firmed up, backed by relevant basic research. The Lunar Dust Filtration Testing Facility at Glenn Research Center should be finalized, and its performance and capabilities should be demonstrated. In the development, the top contenders in the trade space need to be established. From these, down selection to the top two is advisable. Detailed development can take place thereafter, which includes testing and evaluation, incorporating reduced gravity and low pressure. The final design should be ready for infusion into the Lunar Lander PDR in 2014.

5.3 Portable Filtration and Vacuum Cleaning Systems

Portable filtration and efficient dust removal is essential for the lunar lander's habitable volume and outpost missions. Currently, there is no prevention or capture mechanism in place for dust mitigation. NASA Johnson Space Center is investigating current industry technologies and filtration systems to address dust removal in the habitable volumes and airlock. The following questions will be addressed and discussed:

- (1) What filtration and separation techniques are most appropriate?
- (2) What requirements should the vacuum cleaner consider (e.g., power, filtration, flow rates, air pressure, etc.)?
- (3) What are some methods to separate out internally generated particles from lunar dust?
- (4) Is there a conservative estimation on how much dust that can enter the airlock, and then how much that may enter the habitable volume?
- (5) Are there any existing technologies that can be utilized for capturing varying particle sizes in portable systems?

The technology development objective here is a modified portable vacuum cleaner to filter air in all habitable volumes, including the airlock after represses, and in the pressurized cabins in *Altair* and *Orion*. The vacuum cleaner will need to capture varying-sized dust particles (from less than 0.05 μm up to pebble-sized Moon rocks). The vacuum cleaner will have the ability to clean suits (via vacuum attachments, like stiff brushes), and mechanical hardware.

5.3.1 Requirements

A list of requirements was formulated:

- (1) Lightweight unit
- (2) Short crew time for filter replacement and/or vacuum maintenance
- (3) Low power consumption
- (4) Filtration of airlock air to a determined counts per cubic meter, complete in 30 min to 1 h
- (5) Acoustics levels to be determined
- (6) Vacuum surviving repressurization and depressurization in airlock
- (7) Heat rejection to be determined
- (8) Resistance of unit to abrasion and sharp edges
- (9) Human factor considerations with donned suits, maintenance of the vacuum cleaner (filter change, use of attachments, etc.)

An operational scenario (presented by H. Rotter of NASA Johnson Space Center) was adopted in which it takes an estimated 30 min for a crew member to enter the airlock from the lunar surface, repressurize the airlock, and doff the suits. It is envisioned that the use of a vacuum cleaner to clean the suits and filter the air before opening the hatch will reduce crew time waiting on complete airlock filtration. The Constellation Program assessment of 227 g of lunar regolith per crew member per EVA should be considered in the analysis for determining the requirement for the vacuum cleaner unit.

5.3.2 State-of-the-Art Technologies

It is assumed that current state-of-the-art vacuum cleaning technologies will play a role in the spacecraft vacuum cleaning and portable filter development. The state-of-the-art technologies for high-efficiency and bulk filtration as described in the two preceding sessions will also apply to this development. In addition, any breakthroughs and future directions in these technologies will be considered.

5.3.3 Knowledge and Technology Gaps

A few knowledge and technology gaps were identified. First, the type and amount of power that will be available to the vacuum cleaner in each vehicle (airlock, *Altair*, *Orion*, etc.) should be determined. While this will drive the power consumption requirement for the vacuum cleaner, it may in turn indicate necessary system power allocations on the spacecraft. Secondly, more guidance on the toxicology requirements is needed. For example, will there be different requirements for short-term versus long-term exposure? The short-term exposure is particularly relevant in the airlock. Therefore better guidance is needed on the requirements for particle counts in the airlock before the hatch to the cabin is opened relative to the pressurized cabin.

5.3.4 Viable Research and Technology Areas

Two areas of research were provided. The first called for computational fluid dynamics (CFD) modeling analysis to calculate the quantity of particles in the air and how long they take to settle in 1/6g environment—based on the known 1g environment. The other is in the area of testing and the development of a potential airlock simulator. The simulator would be used to properly test and demonstrate vacuum cleaners as well as portable filters and their prototypes (whether as a single or separate units) in a relevant environment.

5.4 Testing and Measurement

Filters and filtration concepts for lunar dust should be tested in a relevant environment that simulates the conditions of the pressurized cabin in a lunar lander or habitat. Decisions have to be made about the testing and measurement methods that will be needed to assess the performance of lunar dust filters; in particular, about the testing protocols and standards (or modified standards) that should be followed. One should also consider how to use simulants that mimic the properties of lunar dust in a testing scenario. Some thought should also be given to the types of sensors needed—or that need to be developed—to monitor the performance and status of filtration systems.

The prime objective for testing and associated measurement is to characterize and quantify the performance of selected filter technologies. However, some important details remain unresolved. For example, the filter efficiency targets have to be set. This is dictated by several performance variables such as flow rates, volume size to be cleaned, and acceptable cleanliness levels. These variables were discussed in preceding sections. Another important performance parameter is the allowable range of pressure drops across the filter element. Because the performance of filters depends on particle size and also because the toxicity of lunar dust is also size (or size range) dependent, a dosimetry metric(s) (performance vs. particle diameter) may be required. These performance variables translate into test parameters and impact the overall test matrix for any filter element.

5.4.1 State-of-the-Art Technologies

The industry standard for testing is the ASHRE 52.2 (Ref. 4), which provides a reasonable framework for what is envisioned to be needed. These standards, particularly within the last decade, reflect more recent advances in instrumentation, and increased attention to ultrafines. It was the assessment of the industry experts that Glenn's measurement capabilities are current and adequate. NASA's filter test facility is reasonably generic and appears suitable for the tasks at hand.

The existing industry standards address the majority relevant issues. These include

- (1) Aerosol generation
- (2) Mixing
- (3) Sampling
- (4) Data interpretation
- (5) Data sufficiency

The participants did not perceive any significant issues affecting test and measurement arising from (1) simulant versus regolith or (2) 1g versus 1/6g.

5.4.2 Knowledge or Technology Gaps

It was recognized that some knowledge gaps still exist regarding dispersal and transport in situ (i.e., What will the filters actually see?). Evolving requirements due to the ongoing lunar surface system development (*Altair*, lunar habitat) are also anticipated. Therefore it was questioned how good the filter needed to be in quantitative terms at this point. Although terrestrial testing is appropriate and useful, on-orbit and in-transit assessment and performance validation is also important.

Regarding Glenn's testing facility, it was recognized that certain test objects may not fit directly into our test facility. Other questions that arose were "What materials should we use for full-load efficiency tests?" and "What margins of excess are appropriate for each test parameter?" It was noted that lunar dust is not the only material the filters will see. There is generic dust composed of biological matter and degradation of material in the cabin, as well as larger debris—especially in transit (i.e., microgravity).

Recommendations were given for procedural testing. Emphasis should be placed on challenge particle (particles used for filter testing) dispersion in the facility flow. There will be a need to verify uniformity and concentration from the challenge particle dispersion mechanism. Particularly, attention should be given to verify and calibrate all measurements, particularly at low pressure. In general, frequent zero count checks should be performed. These checks will help in assessing the extent and frequency of the cleaning of the facility that will be required. They may also aid in determining if cleaning methods as part of testing need to be improved or modified. The low pressure conditions should also be given special attention as it may affect other testing conditions or measurements.

As a starting point, the tests should consist of replicating prior data for known reference filters at standard test conditions. The results should be compared with manufacturer's performance data. The use of independent testing labs is advisable. Once verification is satisfied, one can proceed to lower pressure testing. It is emphasized that theory should guide data interpretation (data should make sense). The general attitude of "inherent skepticism" (Are my observations reasonable?) should be adopted. Also the role of other potential effects (e.g., humidity) should be investigated.

5.5 Splinter Session Summary

Each session contributed much insight on the particulate matter permissible limits, filter technology and design, and operational practices. It was felt that the particulate requirements still need to be firmed up, backed by relevant basic research. Also several assumptions need to be verified, in particular the lunar dust intrusion rate. A higher fidelity model of the intrusion rate will help better refine the expected airborne particulate concentration after an EVA. Estimates need to be derived for the weight and volume

of filter systems, as well as for operational parameters such as power consumption, waste handling, crew involvement, and lastly cost. Methods for the safe removal, storage, and disposal of filter elements should be included in this assessment. Dust properties such as abrasiveness, particle cohesion, adhesion to walls, and effects of humidity were considered important. The consensus of the industry participants was that the current state-of-the-art technology is adequate to develop filtration systems for lunar surface systems. A multistage filtration concept was adopted, which included a prefiltration stage, an intermediate filtration stage if needed, and a final high-efficiency filtration stage. It was also their assessment that Glenn's Lunar Dust Filtration Testing Facility appears adequate and appropriate for evaluation of developed filtration systems. The uniformity and concentration of dispersed challenge particles, calibration of instrumentation, and tests with known reference filters was deemed critical in filter testing. Several suggested research and technology areas included nanofiber filters using carbon nanotubes, electrospray particle charging, sintered metal and ceramic filters, three-stage filtration with an intermediate cyclone separator, and an airlock simulator for testing vacuum cleaning systems.

Report Summary

The 2.5-day NASA Lunar Dust Filtration and Separations Workshop was held in Cleveland, Ohio, in November 2008 to share requirements, technical knowledge and knowledge gaps, and research concepts for lunar dust filtration and separations technologies. There were a total of 32 participants. Roughly half were from industry or academia, and most had strong research and development credentials in filtration technologies. NASA participants included managers, researchers, and technologists from Glenn Research Center, Johnson Space Center, and Marshall Space Flight Center. The workshop featured 19 presentations plus 4 splinter sessions to discuss concepts for future research. In the end, it was felt that the workshop met and even exceeded the intended goals.

Appendix A

Acronyms

Below is a list of acronyms used in this report:

ASAE	American Society of Agricultural Engineers
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CFD	computational fluid dynamics
CFR	Center for Filtration Research
CFU	colony-forming unit
CNT	carbon nanotube
ECLSS	environmental control and life support system
ECS	environmental control system
ELS	Exploration Life Support (project)
EMU	extravehicular mobility unit
ETDP	Exploration Technology Development Program
EVA	extravehicular activity
HEPA	high-efficiency particulate air
HSIR	Human-Systems Integration Requirements (document)
HVAC	heating, ventilation, and air conditioning
ISS	International Space Station
JSC-1a	Johnson Space Center Number 1a
LADTAG	Lunar Airborne Dust Toxicity Assessment Group
LCG	liquid cooling garment
LEM	lunar excursion module
NU-LHT	NASA/USGS-Lunar Highlands Type
OPC	optical particle counter
OPS	oxygen purge system
PDR	Preliminary Design Review
PEL	permissible exposure limit
PIV	particle image velocimetry
PLSS	portable life support systems
PTFE	polytetrafluoroethylene
RGO	Reduced Gravity Office
SBIR	Small Business Innovation Research
SEM	scanning electron microscopy
SOA	state of the art
SRR	System Readiness Review
TMG	thermal and micrometeoroid garment
TPP	Technology Prioritization Panel
TRL	technology readiness level
ULPA	ultra-low penetration air
USGS	United States Geological Survey

Appendix B

Workshop Attendees

The names and affiliations of the NASA Lunar Dust Filtration and Separations Workshop (November 2008) participants are provided below:

1. Juan H. Agui	NASA Glenn Research Center
2. Buzz Aldrin	StarBuzz Enterprises LLC
3. Joseph J. Bango	Connecticut Analytical Corp.
4. Daniel Barta	NASA Johnson Space Center
5. Erin Brach	ESCG Jacobs
6. George G. Chase	University of Akron
7. Da-Ren Chen	Washington University
8. James R. Gaier	NASA Glenn Research Center
9. Eric L. Gollither	NASA Glenn Research Center
10. Paul S. Greenberg	NASA Glenn Research Center
11. Nancy R. Hall	NASA Glenn Research Center
12. James T. Hanley	RTI International
13. Edward W. Hodgson	Hamilton Sundstrand Corp.
14. Mark Hyatt	NASA Glenn Research Center
15. Beatrice M. Iliescu	Seldon Technologies
16. Noreen Khan-Mayberry	NASA Johnson Space Center
17. Jeffrey R. Mackey	ASRC Aerospace Corp.
18. Marit E. Meyer	Washington University
19. Brian J. Motil	NASA Glenn Research Center
20. Ernest S. Moyer	Retired from NIOSH
21. Scott Munson	Orbital Technologies Corporation
22. Masami Nakagawa	Colorado School of Mines
23. Jay L. Perry	NASA Marshall Space Flight Center
24. David Y.H. Pui	University of Minnesota
25. Henry A. Rotter, Jr.	NASA Johnson Space Center
26. Kenneth Rubow	Mott Corporation
27. Christian M. Schrader	BAE Systems
28. Dennis P. Stocker	NASA Glenn Research Center
29. Kenneth W. Street	NASA Glenn Research Center
30. Joel S. Tabb	Agave BioSystems
31. Katherine P. Toon	NASA Johnson Space Center
32. R. Vijayakumar	AERFIL, LLC

Appendix C

Workshop Presentations

Listed below are the titles and presenters for the NASA Lunar Dust Filtration and Separations Workshop (November 2008) presentations. The affiliations of the presenters can be found in Appendix A.

I. Background (on the challenges of lunar dust and need for filtration and separations)

- Programmatic Context for Spacecraft Cabin Lunar Dust Filtration and Separation Technology Development (Daniel Barta)
- Cabin Atmosphere Quality Maintenance Background and Requirements: The Challenge of Lunar Dust Infiltration (Jay L. Perry)
- Apollo Command Module Environmental Control System (ECS): Design for Dust and Lessons Learned (Henry A. Rotter, Jr.)
- Lunar Dust Filtration in an Historical and Exploration Systems Design Context (Hodgson)
- Lunar Dust 101 (James R. Gaier)
- Lunar Dust Toxicity: Human Health Concerns (Noreen Khan-Mayberry)
- Lunar Dust & Simulant Characterization Activity at GRC (Kenneth W. Street)

II. Testing

- Lunar Simulant Development and Characterization (Christian M. Schrader)
- Lunar Dust Filtration Testing Facility (Juan H. Agui and Nancy R. Hall)
- Air Cleaner Test Methods: Capabilities and Shortcomings (James T. Hanley)
- Reduced Gravity Testing Capabilities (Nancy R. Hall)

III. Technologies

- A Multi-stage Axial Cyclone for Dust Separation (Da-Ren Chen)
- Filter Media, and Test Practices (R. Vijayakumar)
- Environmental Tractor Cabs, Pressurizers and Filters (Ernest S. Moyer)
- Use of Sintered Metal Filters in Gas Filtration Applications (Kenneth Rubow)
- Research Highlights of the Center for Filtration Research (CFR) at the University of Minnesota (David Y.H. Pui)
- Lunar Dust Filtration Using Electrospray Gettering (Joseph J. Bango)
- Application of a Fused Carbon Nanomaterial Filter for Lunar Dust Abatement (Beatrice M. Iliescu)
- Developing Lunar Dust Simulants (Scott Munson)
- Carbon Nanotube Based Electrostatic Filters for Micro- and Nanoparticulate Lunar Dust (Joel S. Tabb)

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1. NASA Lunar Science Institute: Biological Effects of Lunar Dust Workshop. NASA Headquarters and NASA Ames Research Center, Sunnyvale, CA, 2005.
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