

Proposed protocols for defining requirements and sizing of media-based filters for spacecraft and planetary lander applications

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The air quality control equipment aboard future deep space exploration vehicles provide the vital function of maintaining a clean cabin environment for the crew and the hardware. This becomes a serious challenge in pressurized space compartments since no outside air ventilation is possible, and a larger particulate load is imposed on the filtration system due to lack of sedimentation in low gravity, and can experience short durations of peak dust loading from planetary surfaces for Lunar or Mars landers. The filter industry has established methods to properly size filters for a given particulate load, but requirements for the space or planetary application introduce additional considerations.

In this work, a methodology for evaluating and sizing particulate filters for a Lunar surface pressurized environment will be presented, including estimating the loading and particle size distributions of the loading based on mission requirements. In addition, a scaling analysis from single filter media sheet to full-scale filters for this application, based on recent testing, will also be presented. The results of this study may provide meaningful guidance in early design phase for air revitalization systems utilizing media-based particulate filters for deep space exploration missions.

Nomenclature

AES	=	Advanced Exploration Systems
BFE	=	Bacteria Filter Element
C_0	=	mass concentration immediately downstream of the filter (in mg/m^3)
C_1	=	mass concentration immediately upstream of the filter (in mg/m^3) [= C_{PM}]
C_{PM}	=	mass concentration of particulate matter in habitat volume (in mg/m^3)
EVA	=	Extra-Vehicular Activity
ft	=	foot/feet
G_{PM}	=	total particulate matter generation rate (in mg/min)
g_{crew}	=	PM generation rate per crew member (in mg/min)
$g_{Lunar\ Dust}$	=	Lunar dust generation rate per crew member (in mg/min)
HALO	=	Habitation and Logistics Outpost
HEPA	=	High-Efficiency Particulate Air
IEST	=	Institute of Environmental Sciences and Technology

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ISO = International Organization for Standards
ISS = International Space Station
m = meter
$m_{LD,0}$ = mass of Lunar dust brought into the habitat in a single post-EVA event
mg = milligram
mm = millimeter
n_{crew} = number of crew
$n_{EVA\text{-}crew}$ = number of crew performing a Lunar surface EVA
nm = nanometer
PM = particulate matter
Pa = pascal
s = second
t = time
V = Spacecraft habitable volume (in m^3)
v_0 = volumetric flow rate (in m^3/min) v_o is the total air ventilation flow rate,
yr = year
η_f = filter particulate removal efficiency (in %)
η_p = filter particulate penetration efficiency (in %)
μm = micron

I. Introduction

ONE of the key functions of air revitalization aboard a spacecraft or planetary lander is removal of particulate matter (PM) from the cabin environment. To control particulate matter level in the pressurized environment of a spacecraft, traditional media-based filters have been the technology of choice in heritage spacecraft design for LEO space systems, NASA's shuttle and the International Space Station (ISS). For example, the ISS utilizes a distributed particulate matter filtration architecture in pressurized modules to remove airborne particulate matter and maintain levels to minimize the risk of any detrimental effects of suspended particulates to both crew health and on-board equipment. The filters, referred to as Bacteria Filter Elements (BFEs), are HEPA media-based components within this architecture. The ISS primarily sees particulate loads from internally generated sources, and with two decades of operational experience, maintenance consists of frequent vacuuming of filter inlets of collected large size debris, along with scheduled BFE replacement intervals of 2.5-5 years. Preliminary but limited PM measurements on ISS indicate acceptable PM concentrations although more extensive characterization is still on-going.[1]

Conversely, experience with significant external sources of particulate matter, namely planetary dust, has been limited to the Apollo program, and active control of dust into the pressurized environment of the Lunar Module (LM) was primarily performed via manual means, brushing or shaking dust off of Extra-Vehicular Activity (EVA) suits and equipment. In this work, we propose an overall approach to size the filters for a habitat such as Gateway's Habitation and Logistics Outpost (HALO) module, or a planetary lander, such as an Human Landing System (HLS) Lunar lander, and attempt to point out differences in assessment and additional considerations that may differ from terrestrial filtration designs. We will utilize the limited information on estimates of expected Lunar dust intrustion along with general characteristics of pressurized spacecraft habitats to illustrate this process.

II. Particulate Matter Loading and Maximum Concentration Levels

The airborne particulate matter occurring in a spacecraft pressurized volume can be categorized into 2 general sources, the particulates generated internal to the pressurized environment from both crew and equipment, and particulates brought in via crew exchanges and EVAs.

A key first step in design of a filtration system is to estimate this particulate matter load that will need to be removed from the pressurized volume of a crew habitat to achieve a maximum level or concentration; this concentration level can be driven by crew health or systems and equipment exposure considerations. For a spacecraft, particulate load sources include: (1) Crew generation rate, (2) Microbial matter, and (3) Planetary dust.

A. Internal generation rate estimates and assumptions

The generation of particulate matter by humans has been extensively investigated as part of hygiene studies and other terrestrial-related work. Limited PM assessments has been done for aerospace vehicles, including results from

NASA Shuttle cabin filter analyses[2], from debris collected in an ISS vacuum bag[3], along with an updated assessment of ISS particulate load sources[4].

Perry[5] has performed a literature survey and summarized these estimates into a total average mass generation rate of 1.33 mg/min/crew member in two particulate size ranges:

1. Size: 5-10 μm PM generation rate = 0.02 mg/min/crew member
2. Size: >10 μm PM generation rate = 1.31 mg/min/crew member

In addition to this PM internal generation source, there is the microbial load which also contributes to crew health concerns and must be controlled accordingly. This microbial load consists of bacterial and fungal related particulate matter from the crew and various sources within the crew environment. Perry[5] also summarizes the literature for microbial loading as of 2019, but it should be noted that the research efforts in better understanding this health hazard have intensified because of the COVID-19 pandemic and new guidelines and standards for both internal terrestrial and spacecraft environments are likely to be developed in the near future. For the purposes of this work, we will neglect this portion of the internal generation rate.

B. Lunar dust intrusion estimates and assumptions

Dust intrustion via EVA estimates are based on Apollo experience and are a significant and challenging PM generation source. A 2009 study[6] during the Constellation Program estimated that 227 g of Lunar regolith per crew member in the size range of <10 microns could be collected on EVA suits and equipment and returned to a lander or habitat. It is anticipated that a portion of this accumulated dust could be removed from suits and equipment via mechanical or manual cleaning methods including shaking, brushing, pressurized gas, etc. while still external to the pressurized volume. An additional amount of accumulated dust could also be removed during the re-entry process, examples include an airlock pre-filter system or a vacuum cleaning system. Finally, a portion of this dust will remain embedded in suit fabrics and boots, and not pose a PM airborne hazard. These "barrier" methods were estimated to result in 7% of the dust to become airborne in the pressurized crew volume from a single 2-person EVA event, for a "dust barrier effectiveness" of 93%.

If this dust load is assumed to be dispersed over a 24 hr period, this would result in a time-averaged generation rate of 22.1 mg/min for comparison purposes with the PM generation rates in the previous section. But, the introduction of Lunar dust into a crew habitat will likely not be a steady-state particulate matter load but would more likely be introduced at a relatively high rate and in a short period of time as the crew ingresses from an EVA event, with a lower residual decaying load rate over a longer time period. For the purposes of presenting this initial design methodology, the Lunar dust load will be assumed to disperse in the crew cabin instantaneously after an EVA event.

In terrestrial environments, sedimentation is another mechanism for removal of particulate matter from the airborne environment. The settling time, calculated from settling velocity, is a common criteria for evaluation of the particulate sizes that will sediment vs. those that remain airborne. In 1-g environments, PM larger than 10 µm are generally treated as removed by sedimentation. But Sumlin and Meyer[7] perform this calculation in Lunar gravity and still air at the reduced pressures being considered for Lunar habitats and show that Lunar dust particles in the 10-20 µm (aerodynamic) diameter range would have settling times of 30 min to 1 hour, indicating particulate matter in this range (and smaller) would likely remain suspended in typical ventilation flows in a Lunar pressurized habitat. So, the Lunar dust intrusion estimate described previously may need to be revised to include PM larger than 10 µm.

C. Particulate Matter control standards

NASA-STD-3001[8] specifies a particulate matter concentration as follows: The total PM (dust) concentration should be maintained to <3 mg/m^3. For the respirable fraction of this total dust (i.e. size range <2.5 µm), the PM concentration should be maintained to <1 mg/m^3. For the ISS Program, the PM concentration requirement was significantly lower, as it specified that PM concentration be maintained to <0.05 mg/m^3 for the size range of 0.5-100 µm.[9]

For Lunar dust, NASA-STD-3001 specifies that "the system shall limit the levels of lunar dust particles less than 10 µm in size in the habitable atmosphere below a time-weighted average of 0.3 mg/m^3 during intermittent daily exposure periods that may persist up to 6 months in duration." This requirement implies that the Lunar dust can be distinguished from other particulate matter generated in the cabin atmosphere, at least from a monitoring standpoint; this work will, from a modeling standpoint, address these as two separate requirements.

III. Filter Sizing Protocol/procedure

In this section, the PM generation estimates along with PM concentration limits will be utilized to assess the range of flow rates and filter specifications needed to meet these limits. The design protocol begins with development of a simple "Habitat Volume" model to estimate the range of flow rates and filter efficiency needed to meet the PM mass concentration levels, followed by a discussion on filter media selection and sizing. In order to provide example values in this design model, we will utilize the ISS LAB (Destiny) module as an example, given the early phase design status of Gateway/HALO and HLS. For the ISS LAB module the following design conditions apply, the habitat volume, V = 108.6 m^3 (3834 ft^3) and the air ventilation flow rate, v_0 = 11.3 m^3/min (400 cfm).

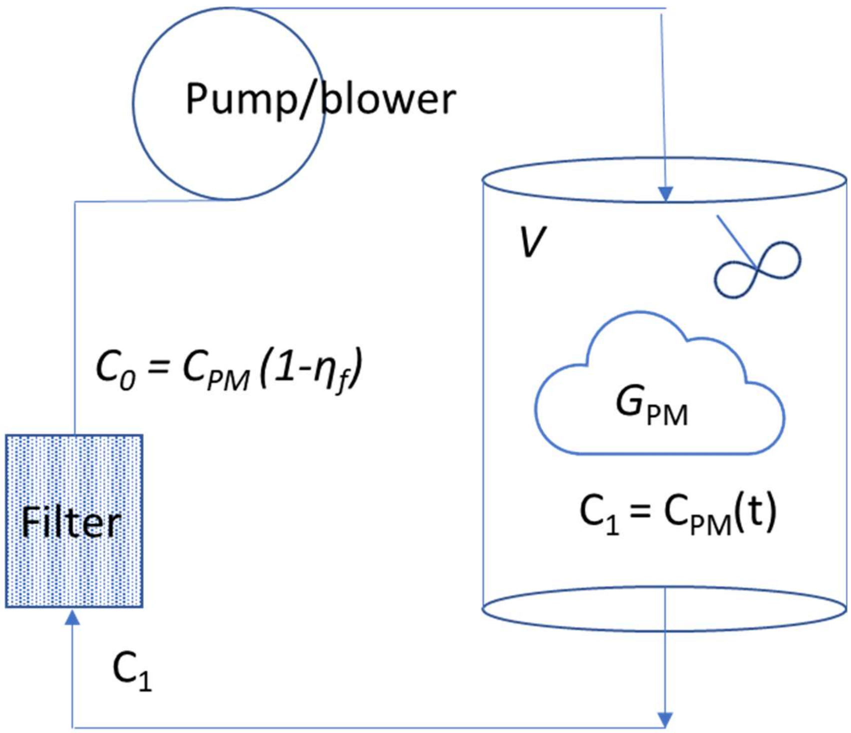

Figure 1. Schematic of Habitat Volume model. *Key assumption is the concentration of particulate matter is uniform within the habitat volume, V, i.e. the well-mixed assumption.*

A. Habitat Volume Model

The objective of the 1-D air revitalization model described here is to perform a preliminary assessment of the flow rate(s) and filter type/efficiency needed to achieve PM level limits in a habiltat volume. Further details on the derivation and assumptions rationale for the model are provided in the appendix. Equation (1) is an unsteady-state mass balance on the simplified schematic of an air revitalization system shown in Figure 1, where V is the habitat volume, C_{PM} is the mass concentration of particulate matter in V, v_o is the total air ventilation flow rate, and C_0 is the PM mass concentration immediately downstream of the filter:

$$V\,\frac{dC_{PM}(t)}{dt} = v_0\,C_0 + G_{PM} - v_0\,C_{PM}(t) \qquad (1)$$

Inherent in this 1-D model is the assumption that the habitat volume is well-mixed such that C_{PM} can be considered spatially uniform and therfore only a function of time. The G_{PM} is the total particulate matter generation rate and consists of the sum of internal generated PM and externally introduced Lunar dust "generation", via EVA events, where n_{crew} is the number of crew nominally in the habitat, g_{crew} is the average PM generation rate per crew member, $n_{EVA\text{-}crew}$ is the number of crew performing a Lunar surface EVA, and $g_{Lunar\ Dust}$ is the Lunar Dust generation rate per crew member:

$$G_{PM} = n_{crew}\,g_{crew} + n_{EVA-crew}\,g_{Lunar\ Dust} \qquad (2)$$

1. Habitat volume model steady-state solution for internal PM generation

The internal PM generation rates estimated are time-averaged, although in practice a crew member is likely generating particles at different rate while sleeping vs. exercising, etc. These internal time-averaged PM estimates are used as constant values and the external PM portion is neglected. The steady-state solution to Eqn (1) is:

$$C_{PM} = \frac{G_{PM}}{v_0(1.0 - \frac{\eta_P}{100})} = \frac{n_{crew} g_{crew}}{v_0(1.0 - \frac{\eta_P}{100})} \quad (3)$$

Where η_p is the particulate penetration efficiency which is directly related to the particulate removal efficiency, i.e. $\eta_f = (1 - \eta_p)$. This parameter will vary with the particle size, flow rate, and dust loading, but for the purposes of this model, we will assume this parameter is constant in the operating regime being assessed.

2. Habitat volume model transient solution for external PM generation (Lunar dust intrusion)

Equation (1) is a first order ordinary differential equation that is separable and has the closed-form solution:

$$C_{PM}(t) = \frac{G_{PM}}{v_0(1 - \frac{\eta_P}{100})} + \left[C_{PM}(t = 0) - \frac{G_{PM}}{v_0(1 - \frac{\eta_P}{100})}\right] exp\left[-\frac{v_0}{V}(1 - \frac{\eta_P}{100})t\right] \quad (4)$$

This solution can be used as a preliminary design tool to evaluate the transient response of the ventilation system in removing the Lunar dust from a Lunar dust intrusion event. For this analysis, it is assumed the Lunar dust is instantaneously introduced into the habitat volume as a uniformly dispersed load. The boundary condition simulating this is defined by Eqn. 5 where $m_{LD,0}$ is the mass of Lunar dust brought into the habitat in a single post-EVA event:

$$C_{PM}(@t = 0) = \frac{m_{LD,0}}{V} \quad (5)$$

B. Habitat volume modeling results and discussion

3. Steady-state analysis

Figure 2 shows the results from the steady-state analysis using the total internal PM generation rate estimate in Section II.A over a range of flow rates. The ISS flow rate easily meets the defined NASA-STD-3001 requirements

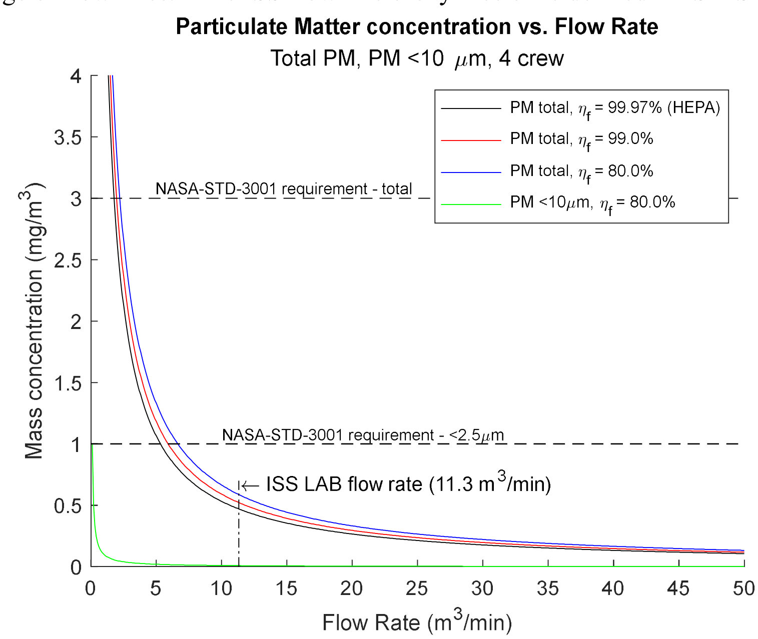

Figure 2. Steady-state solution for total and <10 μm PM generation rates over a range of volumetric flow rates. *PM generation is total internal generation rate as described in Section II.A. No external generation source (i.e. Lunar dust)included.*

for the total PM generation, and even the more strict level for the smaller PM (<2.5 µm) range. For just the PM generation rate <10 µm, the NASA-STD-3001 requirement is met at even the lowest flow rates.

In addition, the solution for several filter particulate removal efficiencies are also included in Figure 2. This shows that sensitivity of this parameter is lower than flow rate and the difference declines at both high and very low flow rates. This observation can be utilized in design as a lower particulate removal efficiency filter typically has a lower resistance for a given flow rate, which translates to being able to operate an air ventilation system at a higher flow rate utilizing less blower power, potentially achieving lower PM levels than simply selecting the highest efficiency filter. For example, the ISS flow rate of 11.3 m^3/min noted in Figure 2 corresponds to an air exchange rate, v_0/V, of 6 hr^{-1}, which means an equivalent volume of air to the habitat volume passes through the filtration system 6 times per hour, typical of standard ventilation rates in office buildings, labs, etc. As a comparison with a mid-tier clean room application, the International Organization for Standards (ISO) 4 (i.e. 4th most clean classification) specification for cleanrooms requires meeting a standard of < 1020 particles/m^3 for sizes > 0.3 µm and ≤ 2 particles/m^3 for sizes > 5.0 µm. To achieve this, an IS0 4 cleanroom typically has an air exchange rate two orders of magnitude larger (v_0/V = 500-600 hr^{-1}), than the ISS exchange rate considered here, in addition to ULPA level filtration ($\eta_f \geq 99.9995\%$).[f]

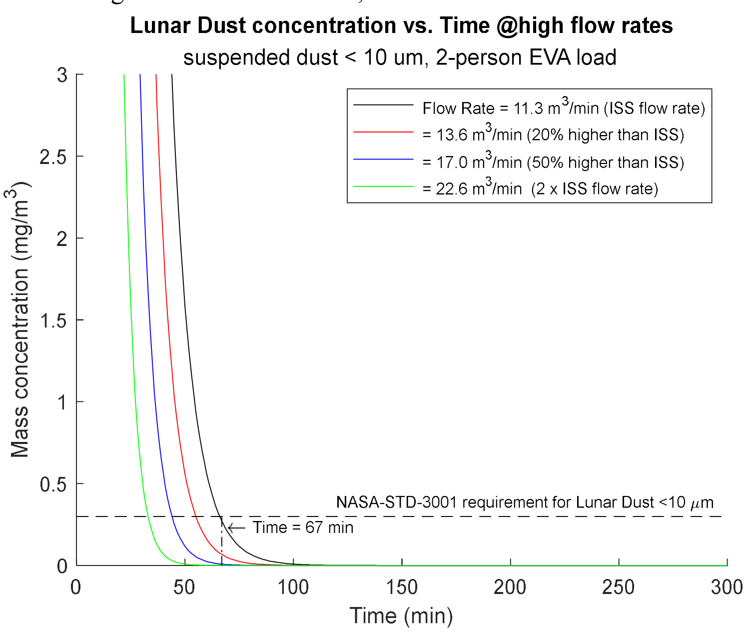

Figure 3. Transient response to a single EVA Lunar dust intrusion event. *Plot of the PM concentration transient response for several flow rates. A filter particulate removal efficiency (η_f) of 99.97% (HEPA grade) was used for all flow rates.*

4. Transient analysis results

Figure 3 shows the transient response of the results of the ingress post-Lunar EVA event with the quantity of Lunar dust estimated in Section II.B assumed to disperse instantaneously in the habitat volume, resulting in an initial mass concentration, $C_{PM}(t=0)$ = 293 mg/m^3. The response at the ISS flow rate shows that the C_{PM} can be reduced below the NASA-STD-3001 Lunar dust requirement in a little over an hour. The response to several higher flow rates are shown in Figure 3 and the time-to-reach the NASA-STD-3001 requirement are extracted and presented in Table 1. The reduction in time is roughly linear as the 67 min for the ISS flow rate drops to 34 min at double this same flow rate. The C_{PM} approaches essentially a value of zero at approximately 100 min for all 4 flow rates in Figure 3. Note that for this particular transient analysis, Lunar dust alone was considered (i.e. $n_{crew} g_{crew} = 0$), otherwise the PM concentration (C_{PM}) will approach the steady-state solution in the previous section.

In addition, Table 1 provides the time required to reach a condition where the time-averaged C_{PM} is below the 0.3 mg/m^3 limit, which is a more correct interpretation of this NASA-STD-3001 requirement. Obviously, this requirement

[f] URL: https://www.americancleanrooms.com/cleanroom-classifications/ Accessed on 02/28/2022.

is more difficult to meet under this simple analysis, and implies that the cadence of EVA events is a design limitation. In order to reduce the time the crew is exposed to high Lunar dust concentration levels, an increase in the air revitalization flow rate for a period of time post-EVA can decrease the time to get below this limit along with reducing time to reach the time-averaged limit. This design solution is somewhat analogous to "demand-controlled filtration" of clean rooms[10], with the motivation being energy savings[g]. Other solutions, to reduce time of crew exposure to the high PM concentrations after a Lunar dust intrusion event, would include implemementation of some type of secondary filtration protection. One example of a low technology solution would have the entire crew don properly-fitted N95 face masks for the first 30-60 minutes post-EVA to reduce their exposure to the initial elevated levels of Lunar PM.

Table 1. Summary of times to reach NASA-STD-3001 Lunar dust concentration limit. *Data extracted from Figure 3.*

Flow Rate, v_0 (m^3/min)	Time to reach C_{PM} < 0.3 mg/m^3 (min.)	Time until time-averaged C_{PM} < 0.3 mg/m^3 (days)
11.3 (ISS rate)	67 min.	6.5 days
13.6 (1.2 x ISS)	56	5.4
17.0 (1.5 x ISS)	45	4.3
22.6 (2.0 x ISS)	34	3.3

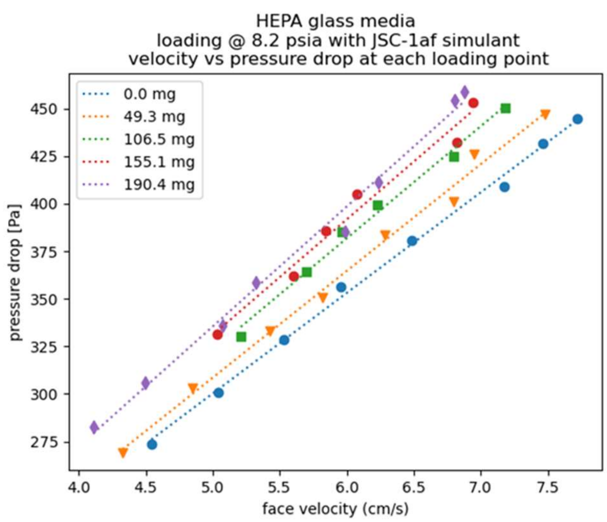

Figure 4. Pressure drop curves for HEPA glass media for several Lunar dust simulant (JSC-1AF) loading levels. *Tests performed at 0.0565 MPa (absolute). From Ref. 11.*

C. Filter Sizing for a Lunar habitat volume

1. Filter media choice and filter sizing considerations

The filter media choice and sizing proceed after the design defines the flow rate required and PM concentration requirements/limits. A key design consideration is the pressure drop vs. media face velocity, i.e the velocity (cm/s) of flow normal to the media surface. We will utilize recent data taken on a commercially available HEPA glass-based media that was recently tested under reduced pressure of 0.0565 MPa (8.2 psia) being considered for Lunar habitats[11], and is shown in Figure 4. The specification sheet for this HEPA media gives a particulate removal

[g] Many clean room large scale users, i.e. semiconductor and pharmaceutical manufacturers, are reluctant to implement demand-controlled filtration due to concerns that energy savings are minimal compared to potential loss of valuable product caused by variations in particulate contamination that could occur in transient operation.

efficiency rating of 99.97%[12] at a media face velocity of 5.3 cm/s with a resistance (pressure drop) of 343 Pa. From Figure 4, it is seen that the pressure drop is ~320 Pa (line corresponding to 0.0 mg loading); the lower pressure drop observed for this condition is due to lower flow slip effects on the filter media fibers at this sub-atmospheric pressure, another advantage of operating a habitat at reduced pressure.

The slope of the resistance curve for 0.0 mg loading is ~51 Pa-sec/cm, so the increase in pressure drop for increased flow rates can be evaluated. For example, increasing the media face velocity from 5.3 to 10.6 cm/s, equivalent to doubling the habitat flow rate, v_0, would result in an ~84% increase in pressure drop. This increase in blower power may result in a significant increase in the power or energy storage system of the lander or habitat. As a minimum, for the design consideration of using a transient larger flow rate to reduce C_{PM} as after an EVA event, the blower has to be sized for intermittent operation at this increased flow rate.

The sizing of the filter once a filter media type is chosen is driven by the flow cross-section size and number of filter assemblies when the ventilation ducting for the habitat is designed to provide uniform distribution. Once these are known, the specifics of the filter assembly design are provided by the filter manufacturer. The performance of a filter is increased/optimized for a given cross-section by pleating to increase the total media and thereby reducing the total media face velocity. In general, pressure drop decreases with increased pleat count (due to decreased media velocity) but will begin to increase at higher pleat counts due to increased viscous drag and optimal count is typically in the range of 2-6/cm (5-15/in.). Pressure drop is also affected by pleat shape, use of pleat separators, frame design and other specific design features of the filter vendor.

As a specific example, we will use the ISS BFE discussed earlier. According to the design specification, a clean unused BFE is required to have a particulate removal efficiency of 99.9 % at the 0.3 µm particle size, have a pressure drop < 82 Pa (0.33 inches H_2O) at a flow rate of 1.88 m^3/minute (66.7 ft^3/minute)[9]. From test data provided by the vendor, the ISS BFE filter actually meets the HEPA rating of 99.97%[13]. The ISS BFE has a cross-section area of 10.2 cm x 73.7 cm (4 in. x 20 in.) with 10 cm (4 in.) pleats and total pleat count of 226, resulting pleat density of ~3/cm (~7.5/in.).[h] So, the design flow rate of 1.88 m^3/min corresponds to a media face velocity of 0.7 cm/s. This media face velocity is significantly lower than the 5.3 cm/s spec. mentioned above and allowed the BFE to achieve initial pressure drops of 65-75 Pa (0.26-0.30 in. H_2O)[13] at this design flow rate to meet the 82 Pa requirement. Designing and operating at lower media face velocities also offers improved particulate removal efficiencies.

As an alternative to HEPA, MERV filters with a MERV rating between 8 and 12 can provide particulate removal efficiencies in the range of 70% to 85%. For a MERV filter to get close to the efficiency of a HEPA filter, it should have a minimum rating of MERV 13. In Figure 2, a filter with particulate removal efficiency of 80.0% is included and provides a perspective on the sensitivity of the particulate removal efficiency vs. flow rate.

2. Filter life considerations.

The filter life is typically driven by increased pressure drop due to loading which has system impacts, mainly increased blower power or reduced air flow. In some terrestrial applications like clean rooms, the HEPA or ULPA rated filters can last for many years due to pre-filtering of makeup air and careful controls in place to reduce both internal and external PM generation (airlocks containing decontamination procedures such as air showers, wearing of booties, cleanroom garments, periodic cleaning of surfaces).

For the ISS filter example, the end-of-life is defined as the BFE pressure drop should not exceed 124 Pa (0.5 inches H_2O) and a scheduled replacement interval of 2.5-5 years along with maintenance consisting of frequent vacuuming of inlet BFE screens by crew to remove the larger PM debris. A small sample of returned-from-ISS BFE filters showed the pressure drops were below this limit for filters installed and operating on-orbit as long as 2.5 years.[13]

For the Lunar lander/habitat, loading will be a significant challenge, compared to the ISS example. As can be seen in Figure 4, the plot provides pressure drop data for several loading levels of a Lunar dust simulant, JSC-1AF. The heaviest loading curve, labelled 190.4 mg corresponds to a media surface density loading of 0.988 mg/cm^2. The result is a pressure drop of 360 Pa at the 5.3 cm/s spec media face velocity, which is a 12.5% increase in pressure drop. If we compare with the ISS LAB module we have been utilizing as an example habitat, the dust from a single Lunar EVA event of 15.9 gm (93% barrier effectiveness) is brought into the habitat, it would result in an 0.06 mg/cm^2 loading per EVA event if evenly distributed on the 6 BFE-sized filters using the design info in the previous section. This kind of preliminary calculation can be used to estimate the replacement interval needed for media filters. If the 0.988 mg/cm^2 loading is considered end-of-life, the time for filter replacement for the ISS LAB example would be reached

[h] Data is not from filter vendor. Approximate values via inspection and measurements of a flight unit by one of the authors (R.G.).

after ~17 EVA events. Again, procedures to increase the barrier effectiveness prior to habitat ingress along with incorporation of pre-filtering to lower loading on air revitalization filters could prolong filter life.

IV. Conclusion

This work provides an early air revitalization design approach to get a preliminary estimate on filter type and sizing. A number of simplifying assumptions are made to perform these estimates, in particular, the Lunar dust intrustion amounts and rates. The well-mixed assumption in the habitat volume is also an early design assumption, but detailed CFD modeling should be performed when the design has matured and details of habitat volume and ventilation ducting are available.

A key variable in this design analysis process is the ventilation flow rate (# of air exchanges). As shown, it can have a larger effect than the particulate removal efficiency of the filter, especially when evaluating high efficiency filters. The optimum ventilation flow rate for particulate matter control may not be optimum for other air revitalization systems. It will need to be balanced with requirements for other air revitalization system functions, including CO_2 removal, trace gas removal, and humidification control.

Sizing the media-based filters can proceed once the total flow rate range is determined. The media face velocity is a key filter sizing design factor since it affects the pressure drop in the air revitalization system, thereby having system impacts such as required blower power. To a lesser extent, it also impacts the particulate removal efficiency of the media. Once the media is specified, the filter assemblies can be designed. The cross-section and number of filters to be used in a habitat depend on the ventilation ducting design which is driven by achieving uniform flow distribution in the habitat, and the other air revitalization system functions. The specific design of the filter unit, including pleating, is performed by the filter manufacturer when the flow rate, filter cross-section, and volume restriction requirements are provided, as they typically have the correlations/tools to estimate the performance of the filter assembly based on their specific frame design, pleating, and fabrication methods.

Appendix

This appendix is included to show further details on the derivation and assumptions of the habitat volume model presented in Section III. This general type of model is often referred to as a "mixing problem" or compartment analysis[14,15] in applied mathematics texts; in the chemical engineering discipline, this type of model is referred to as a CSTR (Continuously Stirred Tank Reactor) problem.[16] Similar model work has been applied to air revitalization work in various forms for aerospace revitalization[5,17] and terrestrial clean room applications[18], but a derivation specific to the air revitalization application is not provided. We provide here to illuminate simplifications, assumptions, and limitations.

The derivation of this first order model is based on a simple mass balance on the habitat volume, *V*, in Figure 1 that results in Eqn. (1) of Section III:

PM accumulation = PM mass in (after passing thru filter) + PM mass generation - PM mass out

$$V \frac{dC_{PM}(t)}{dt} = v_0\, C_0 + G_{PM} - v_0\, C_{PM}(t) \qquad (A.1)$$

Each term is in terms of a mass flow rate with units of PM in mass/time (units of mg/min in this work). The volumetric flow rate, v_o, is at actual (not standard) conditions if the analysis is being applied at pressures other than 1 atm. Also, the volumetric flow rate is assumed low enough with no gas reactions occurring, such that a constant gas density can be assumed. The habitat volume is the "open" volume occupied by air, i.e. subtracting the volume displaced by equipment, furnishings, etc. in the habitat.

C_0 is the PM concentration after passing through the filter and is defined as:

$$C_0 = C_{PM}(t)\, \frac{\eta_p}{100} \qquad (A.2)$$

Where η_p is the particulate penetration efficiency. This parameter is a property of the filter measured by testing with a well-characterized challenge aerosol with a particle size distribution at or near to the maximum penetrating particle size (or MPPS). HEPA filters actually have a lower η_p (i.e. higher η_f) for particles both larger and smaller than the

MPPS. For conservatism, this value of η_p is used as a constant even though the value is lower for the range of PM sizes considered here.

Substituting Eqn. A.2 into A.1 results in:

$$V\frac{dC_{PM}(t)}{dt} = G_{PM} - v_0\,C_{PM}(t)\left(1-\frac{\eta_p}{100}\right) \quad (A.3)$$

For the internal generation analysis in Section III.A.1, Eqn A.3 is solved for a steady-state condition, so the left hand term is zero and C_{PM}, no longer a function of t, can be directly solved for, resulting in Eqn. 3 in the main text.

For the external generation analysis in Section III.A.2, a transient solution is required. Eqn. A.3 is a first order separable ordinary differential equation. The general solution is:

$$C_{PM}(t) = \frac{G_{PM}}{v_0(1-\frac{\eta_p}{100})} + a_1 exp\left[-\frac{v_0}{V}(1-\frac{\eta_p}{100})t\right] \quad (A.4)$$

Where a_1 is an integration constant. For the analysis in Section III.A.2, the boundary condition defined such that after a post-EVA event, the Lunar dust brought into the habitable volume is assumed to immediately disperse and the PM concentration is uniform thoroughout the volume. This corresponds to the initial boundary condition defined in Eqn. 5 in the main text. Substituting Eqn. 5 into Eqn A.4 and solving for a_1:

$$a_1 = C_{PM}(0) - \frac{G_{PM}}{v_0(1-\frac{\eta_p}{100})} = \frac{m_{LD,0}}{V} - \frac{G_{PM}}{v_0(1-\frac{\eta_p}{100})} \quad (A.5)$$

Eqn. A.5 can be substituted into Eqn. A.4 to obtain the transient solution:

$$C_{PM}(t) = \frac{G_{PM}}{v_0(1-\frac{\eta_p}{100})} + \left[\frac{m_{LD,0}}{V} - \frac{G_{PM}}{v_0(1-\frac{\eta_p}{100})}\right] exp\left[-\frac{v_0}{V}(1-\frac{\eta_p}{100})t\right] \quad (A.6)$$

Because the Section III.A.2 transient analysis is only considering a Lunar dust intrusion event and is estimating the Lunar dust portion of the PM generation, G_{PM} is set to zero resulting in the following solution:

$$C_{PM}(t) = \frac{m_{LD,0}}{V} exp\left[-\frac{v_0}{V}(1-\frac{\eta_p}{100})t\right] \quad (A.8)$$

This solution approaches zero for long times, and was used to compute a time-averaged concentration of the Lunar dust in this work. The solution would approach the steady-state solution in Section III.A.1 if G_{PM} is a constant value consisting of a internal and external generation components.

This 1-D model assumes a spatially uniform value of C_{PM} (the "well-mixed" assumption) which is typically not valid in an actual application, but there is some presidence for using in preliminary air revitalization studies. Agui et al.[17] did perform a 2-D CFD transient analysis of a cylindrical habitat volume and compared it with the 1-D transient solution; they concluded the PM concentration decay rate was similar. Reference 18 (in an appendix) provides a short review of steady-state 1-D models of varying complexity for terrestrial clean room applications. In addition to flow distribution, C_{PM} will be affected by sedimentation both in 1-g and partial gravity environments as noted in main text. In general, this type of simplified model should be only be applied in preliminary assessment work, and more detailed analysis of ventilation flow and mixing via use of CFD should be performed when the habitat geometry design is better defined.

Finally, it should be mentioned that the term, v_o/V, can be used to normalize the steady-state solution when a good estimate of the habitat volume is not known. The term, v_o/V, was defined as the air exchange rate in this work, but this parameter also appears in other applications with different terminology, e.g. it is referred to as the "space velocity" in chemical reactor design[16]. The inverse of this parameter is also referred to as the "space time" and is somewhat analogous to a mean residence time.[19]

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