Life Support Filtration System Trade Study for Deep Space Missions

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The National Aeronautics and Space Administration's (NASA) technical developments for highly reliable life support systems aim to maximize the viability of long duration deep space missions. Among the life support system functions, airborne particulate matter filtration is a significant driver of launch mass because of the large geometry required to provide adequate filtration performance and because of the number of replacement filters needed to a sustain a mission. A trade analysis incorporating various launch, operational, and maintenance parameters was conducted to investigate the trade-offs between the various particulate matter filtration configurations. In addition to typical launch parameters such as mass, volume and power, the amount of crew time dedicated to system maintenance becomes an increasingly crucial factor for long duration missions. The trade analysis evaluated these parameters for conventional particulate matter filtration technologies and a new multi-stage particulate matter filtration system under development by NASA's Glenn Research Center. The multi-stage filtration system features modular components that allow for physical configuration flexibility. Specifically, the filtration system components can be configured in distributed, centralized, and hybrid physical layouts that can result in considerable mass savings compared to conventional particulate matter filtration technologies. The trade analysis results are presented and implications for future transit and surface missions are discussed.

Nomenclature

ARS	=	atmosphere revitalization subsystem
BFE	=	Bacteria Filter Element
CM	=	crewmember
d	=	particle diameter
d_m	=	mean particle diameter
E	=	efficiency
ESM	=	equivalent system mass
EVA	=	extravehicular activity
FOM	=	figure of merit
H.E	=	high efficiency filter
HEPA	=	high efficiency particulate air
ISS	=	International Space Station
L	=	particle load
m	=	meter
M	=	mass
MPPS	=	most penetrating particle size
P	=	penetration
PM	=	particulate matter
Q	=	flow rate

QF	=	quality factor
SFS	=	Scroll Filter System
T	=	filter lifetime
V	=	volume

I. Introduction

THE National Aeronautics and Space Administration's (NASA) technical developments for highly reliable life support systems aim to maximize the viability of long duration deep space missions. The removal of airborne particulate matter (PM) through filtration and separation techniques is a prime function of life support systems. Clean cabin air is vital to optimum and fully functioning crew performance and well-being. Additionally, the filter system is an integral part of the atmosphere revitalization subsystem (ARS) and provides a level of protection and preconditioning of the air prior to entering other vital life support system functions.

Among the various life support system functions, airborne PM filtration can be a significant driver of launch mass and equipment volume depending on the technology selected and its implementation. Particulate matter filtration equipment selection and architecture is a significant determinant for the launch mass, volume, and maintainability logistics required to provide and maintain the adequate filtration performance needed to sustain a mission. In order to feasibly incorporate adequately sized hardware and replacement units in a spacecraft cabin architecture for future deep space missions, significant mass, volume, and power savings must be realized over conventional equipment designs and physical layouts. Regenerative filter systems may play an important role, specifically by significantly reducing the number of replacement units.

A trade study incorporating the relevant physical and operational parameters of candidate filter system architectures was conducted. The goal of the trade study was to determine how well filter systems incorporating non-conventional components, features, and regenerative techniques trade against conventional filter systems. The utility of the trade study is also to provide a methodology and guidance in the selection process of future spacecraft filter systems.

II. Hardware Basis and Study Methodology

In 2008, the NASA Lunar Dust Filtration and Separations Workshop[1] was held to assess the application of current and developing air filtration and gas/solid separation technologies to spacecraft life support systems on future lunar surface missions. Participants from industry, academia, and NASA provided different perspectives on the most effective solutions. The workshop resulted in a general recommendation for a filter system that provides effective multi-stage filtration and offers some level or form of regenerability.

The Scroll Filter System (SFS) which is under development at NASA's Glenn Research Center (GRC) embodies the features recommended by the 2008 workshop. The filter system will be described in more detail in a later section. For the purposes of this particular trade study, a one-to-one comparison between the SFS and conventional high efficiency particulate air (HEPA) filters, namely the Bacterial Filter Elements (BFE's) used aboard the International Space Station (ISS) and shown by Fig. 1, formed the basis for the trade study. In addition, the filter system architecture, which refers to the number of components and their configuration within the filter system, was a key consideration in the trade study. The concept of different ventilation system architectures was introduced in Ref. 2. The methodology involves a quantitative comparison of the features and functions between the two filter systems. The methodology was applied to two different mission scenarios related to Mars transit and surface missions with specific mission operational parameters.

Equivalent System Mass (ESM) is often employed in trade studies to draw comparisons among several payload hardware options. It provides a convenient method of comparison in terms of one variable, namely in mass units. Reference 3 documents how ESM can be calculated using various mass equivalent factors. In the present case, the main drivers of ESM are the actual mass of the filter system and spare components, volume, crew-time and power. In addition, the filtering efficiency is also a key parameter.

A model of filters in a series arrangement is used to determine the overall capturing efficiency of a multi-stage filtration system. Figure 2 shows how the first filter component captures some of the incoming particle load and allows the remaining load fraction to pass to the next stage. Successive stages capture different particle size fractions to yield the overall filtration performance.

Figure 1. An ISS Bacteria Filter Element. *Each filter element weighs 2.6 kg and occupies 7.3 liters.*
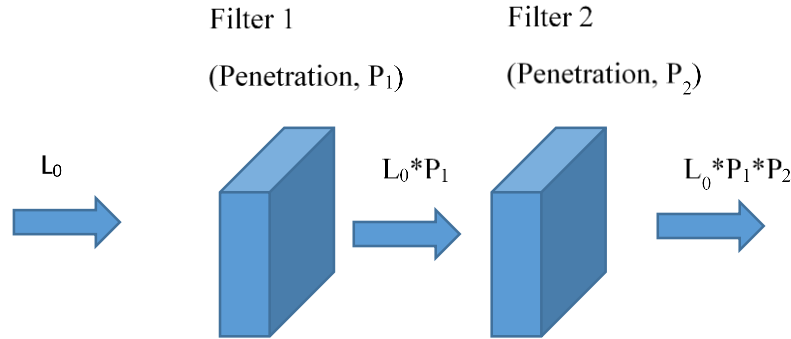
Figure 2. Combined filter efficiency model.

The particulate matter load exiting each filter stage is a function of the penetration, *P*, of each stage as shown by Fig. 2. The load exiting Filter 1 is defined as L_0*P_1 and the load exiting Filter 2 is correspondingly $L_0*P_1*P_2$. This progression continues with each successive filtration stage. In such a staged filter arrangement, the overall penetration is given by Eq. 1.

$$P = P_1 * P_2 * P_n..... \tag{1}$$

And correspondingly, the efficiency is given by Eq. 2, where *P* is particle penetration of the filter, *E* is the total filter

$$E = 1 - P_1 * P_2 * P_n..... \quad \text{or} \quad E = 1 - (1 - E_1)*(1 - E_2)*(1 - E_n)..... \tag{2}$$

efficiency. The subscripts refer to the filtration stage number. Therefore filter efficiency can be calculated from either of the two forms of Eq. 2. Equation 3 defines the quality factor, *QF*, which is another useful parameter used in the filtration field as a figure of merit (FOM).[2] In Eq. 3, the *Δp* term is the pressure drop across the filter or the series

$$QF = -\frac{\ln(P)}{\Delta p} \tag{3}$$

of filters in this case. A larger *QF* generally indicates a better performing filter.

III. Design Considerations and Assumptions

Given that exploration mission design is in its early development stages it is necessary to make appropriate assumptions to define the analysis framework. The assumptions used in this study are the following:
1) The target is a 3-year mission or a minimum of 1000 days of operation, including a 500-day surface mission.
2) Assume a pressurized spacecraft or habitat volume of approximately 100 m^3, similar to ISS modules in the U.S. Segment, and based on recent Mars mission studies (Ref. 3, Table 7.1 for 4-person crew).
3) Planetary dust will significantly increase the PM load on the filters as it enters the cabin and becomes suspended.
4) Filter efficiency goal of 99.97% for the 0.3 μm particle size.
5) Some mass savings is gained with centralized components because of reductions in frame material, approximately 70% mass savings in frame mass is assumed.
6) Use of new lighter weight materials and structures, where applicable, will help reduce mass

A Mars mission will last a minimum of three years.[4] This includes the transit trip to and from the destination and a period of surface operations. Operationally, these two phases of the mission will be quite different, owing to the airlock which breaches the closed pressurized volume of the spacecraft. Loss of atmospheric gases and intrusion of planetary surface dust are additional operational factors. Therefore, the impact of planetary surface dust on the hab-

itable cabin environment should be given serious consideration. Planetary surface dust often in the form of fine particle dust will become airborne in the cabin and the airlock ventilation flows and could stress or overwhelm the system beyond its nominally operational parameters. Other properties of the planetary dust could pose additional hazards as well. These may include the particle's abrasiveness, surface active states, and ultra-fine particle size.[5] Models of the rates of planetary dust intrusion into the cabin have been suggested.[5,6] It is estimated that 227 g/suit for each extravehicular activity (EVA) will enter the cabin environment, but only a small percentage of dust, below 10 μm particle diameter, will become airborne in the ventilation flows.[1] If these rates, or even a fraction of these rates, hold then significant increases in filtration rates, cabin ventilation flow rates, and filtration capacity have to seriously be considered.

The ISS Program has adapted the Federal Standard 209, Revision E, for a class 100000 clean room standard as the allowable particulate matter concentration requirement aboard the ISS.[7] This adapted version of the cleanroom standard maintains airborne PM concentrations in the cabin atmosphere to 0.05 mg/m^3 of PM ranging in size from 0.5 μm to 100 μm with allowable periodic peaks to 1 mg/m^3.[7] Providing this level of cleanliness as well as maintaining safe levels of microbial air contaminants requires HEPA-rated filters with an efficiency of 99.97 percent for airborne particles 0.3 μm in diameter. This requirement is approximately four times lower than the maximum recommended to maintain crew health, which suggests PM concentrations in the cabin atmosphere of <1 mg/m^3 for particle sizes ranging from 0.5 μm to 10 μm (respirable fraction) in aerodynamic diameter and to <3 mg/m^3 for 10 μm to 100 μm.[8] Maintaining the ISS standard for deep space missions may impose overly conservative design requirements on the spacecraft where excessive cumulative PM loads are expected over a multi-year mission as well as with the prospect of planetary dust contamination in the cabin. A reassessment of the standard based on updated load models, increased filtration rates and capacity, and effective pre-filtration could significantly relax the requirement while still meeting safety and crew health standards.

Mass and volume savings can be realized through larger systems that function as centralized units. Just as in modern building construction, centralized air filtration is more often used as opposed to individualized systems within each building unit. Other areas of mass savings may come from using lightweight materials and designs as well as a reduced number of smaller mechanical, electrical and control components.

IV. Hardware Architecture

The following describes the components that comprise the SFS and presents architectural concepts for their implementation in an exploration vehicle cabin ventilation system.

A. The Filter System

The SFS has been under development within NASA's portfolio of technology development for several years. The filter system is quite scalable within the design space of cabin ventilation systems and adaptable both in performance and geometry. For example, one of several prototypes that the NASA GRC is developing is specifically designed to fit within the rectangular, low aspect ratio, housing of the current ISS BFE and provide similar performance. The SFS consists of four stages (including the Scroll media stage) of configurable and tunable filtration performance providing a specific filtration function at each stage. The following sections describe the features of each stage with notation of their advantages and disadvantages.

1. Screen Roll Filter

The Screen Roll Filter (SRF) is a pre-filter which uses screen mesh material of specific mesh size opening. Its purpose is to capture large lint matter and other large airborne debris. The SRF uses a supply roll of the screen material to provide multiple changes of the screen through a motorized (autonomous or manually activated) mechanism. The loaded screen media is then rolled up on one side of the filter to store the captured PM matter. Advantages of the SRF include the following:
  1) No maintenance required, except for very prolonged missions that may require occasional change outs of the roll of screen material.
  2) Eliminates the need for crew to vacuum or clean the accumulated debris from the screen.
  3) Low mass
  4) No replacement filter units, only changing the roll cartridge is required.

A disadvantage of the SRF is a higher mass than the passive screen filters used on the ISS BFEs.

2. Impactor Filter

The Impactor Filter stage is uses inertial impaction for separating and collecting particles several microns and larger on collection bands. The collection bands are regenerated by using a band conveying mechanism and a scrap-

er. During surface exploration missions, the particulate matter collected by this stage may be collected for external disposal dependent upon planetary protection protocols. Advantages of the impactor filter include the following:

1) No maintenance required, except possibly on yearly basis to clean out the compartment containing the accumulated PM.
2) Significantly reduces load of micron size particles on downstream media filters, including HEPA filters, thus protecting them from larger particles that can erode or damage the filtration media.
3) No replacement or consumables needed.

Disadvantages of the impactor filter include the following:

1) Complexity (many parts)
2) Higher pressure drop
3) Larger mass

3. Scroll Media Filter (pleated)

A Scroll Media Filter (SMF) is a pre-filter or intermediate stage filter that provides multiple changes of the filter media inside the ventilation flow volume through a motorized scrolling or indexing mechanism. Like the SRF, the loaded media is rolled up on one side of the filter to both contain and compactly store the loaded PM. A series of supports are used in the flow volume to arrange the media in a pleated pattern. Advantages of the SMF are the following:

1) Provides long filtration life through multiple media changes provided by the reserve media. It should last a multi-year mission, and can be extended by changing out the roll of media.
2) Reduces the load of micron to submicron particles on the next stage HEPA or high efficiency filter. Consequently, it extends the operational life of the HEPA or high efficiency stage filters.
3) The pleats help to reduce pressure drop, increase hold capacity, and increase efficiency performance of the media.
4) Increases overall efficiency by combined efficiency with the next stage HEPA or high efficiency media according to the combined efficiency model discussed in Section II.
5) Low pressure drop/power
6) Eliminates crew exposure to dust due to limited maintenance requirements

Disadvantages of the SMF are the following:

1) Complexity (number of parts)
2) Larger mass/volume than heritage filters

4. HEPA Filter

The HEPA filter component is based on the heritage filter elements used aboard the ISS. This filter provides at least 99.97 % efficiency for particles 0.3 µm in aerodynamic diameter. Advantages of the HEPA filter are the following:

1) Heritage and tested filters.
2) High efficiency.
3) Low pressure drop.

Disadvantages of the HEPA filter are the following:

1) Not regenerable, typically multiple replacement units are needed over long missions if not sufficiently pre-filtered.
2) Large volume (including replacement units)

B. Centralized versus Distributed Architectures

The filter system components described in the previous section can be arranged in many different ways. Figure 3 shows four possible filter system architectures. For simplicity, Fig. 3 shows only the filtration system components in the air ventilation loops. Two of the architectures, A and C, are fully distributed systems with all filter components placed at the ventilation system supply or return registers of the cabin. Some aspects of architecture C may be advantageous from functional and logistical perspectives. Functionally, contaminants, including particulates, could be generated internally in one or more of the other life support system functions requiring their removal before they reenter the cabin. Logistically it may also be beneficial to distribute the hardware between the ventilation system supply and return points to optimize accessibility for servicing. These two integration considerations are confronted in architecture C by placing the HEPA filters at the ventilation system return registers to the cabin. Architecture B is representative of a completely centralized filter system with one supply and return ventilation register. Finally, architecture D is a hybrid architecture that consists of a single centralized high efficiency filter stage and pre-filter stages located at the ventilation system supply registers.

(A) Distributed filtration

Screen filter
Scroll media filter
Inertial impactor
Fan
HEPA

(B) Centralized filtration

(C) Distributed pre-filtration at air intake and distributed HEPA filtration at supply air.

(D) Distributed pre-filtration combined with centralized HEPA filtration
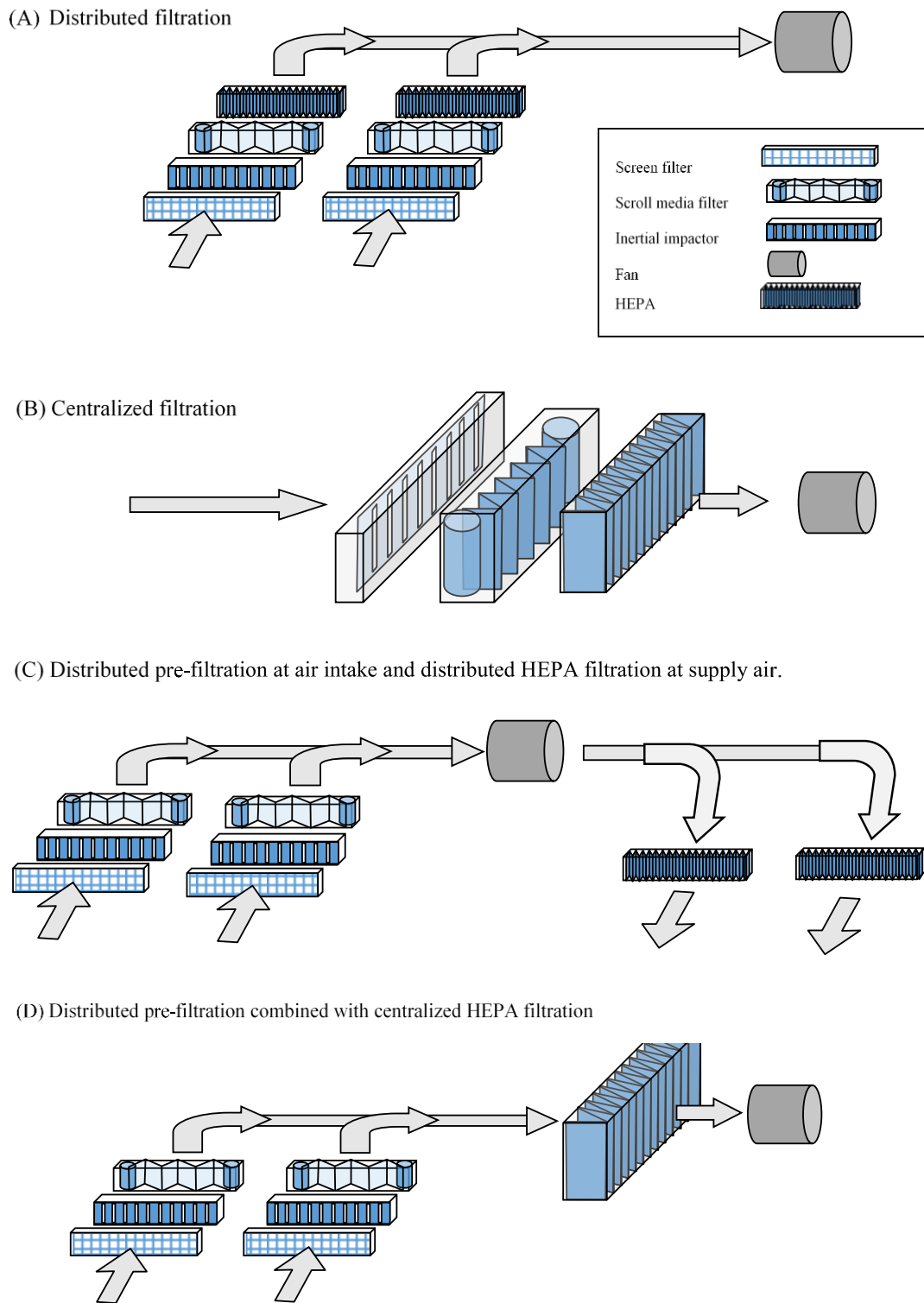
Figure 3. Exploration filtration system concept architectures.

Depending on mission specifications not all the components of the SFS will be needed. Table 1 provides a breakdown of different variations of the configurations using varying numbers of components. Two options were considered for the SMF—a pleated and non-pleated option. Two options were also considered for the finishing filter—a HEPA-rated filter and an alternative high efficiency filter with a lower performing grade than HEPA. The letter designation of the architectures in Fig. 3 and the number assignment of component options in Table 1 define the different filter system configurations. For example, architecture configuration A1 consists of distributed architecture A with a screen roll filter and a HEPA filter.

In this trade analysis two base architectures of the cabin ventilation system as well as a hybrid architecture that consists of a combination of components from the two base architectures were considered. The first base architecture is a distributed ventilation system architecture based on architecture A in Fig. 3 that consists of filter components at multiple inlet and return points to the cabin. This is the architecture used in most of the ISS modules that comprise the U.S. Segment and it has been shown to provide for a well ventilated, uniformly mixed cabin atmosphere. The second base architecture is a centralized architecture which consists of a single unit comprised of large volume filter elements. In its simplest form, as depicted by architecture B in Fig. 3, the centralized system consists of a single unit with one inlet and one return line to the cabin. Optionally the system may use multiple inlet and return points, as with the distributed architecture, but with no filter components at these points. In this case though, the hardware may have limited access for maintenance since it will likely be embedded in a distributed ventilation duct network. This system is assumed to possess the necessary flow balancing to maintain a well ventilated, uniformly mixed cabin atmosphere. The main advantage of the centralized system is that more filter media can be packed with less frame material than in multiple individual units providing the same filtration rates. Therefore a corresponding volume savings is also realized. Lastly, a hybrid configuration is also considered which is represented by architecture D in Fig. 3 consisting of a mix of centralized and distributed filter units that maximizes centralized components and places serviceable filter components at the distributed inlets and returns.

Table 1. Scroll Filter System configurations.

Configuration	Screen Roll Filter	Impactor Filter	Scroll Media Filter	Scroll Media Non-pleated Filter	HEPA Filter	High Efficiency Filter
1	x				x	
2	x	x			x	
3	x		x		x	
4	x	x	x		x	
5	x		x			x
6	x	x	x			x
7	x			x	x	
8	x	x		x	x	
9	x			x		x
10	x	x		x		x

V.   Filter System Trade Analysis

The filter system trade analysis was conducted using ESM and *QF* as the primary FOMs. The analysis variables, filter assembly component characteristics, and mission scenarios are described. Analysis results for two exploration mission scenarios are presented.

A. Operational Variables, Values, and Metrics

The trade analysis will use two main metrics to form the basis for a quantitative assessment of payload size and system performance. The main metrics are the filter system ESM and *QF*. The ESM is the mass of the filter system plus replacement or consumables units, and mass equivalents of other operational variables, for the duration of the mission. The *QF* is determined via Eq. 3. Mass equivalency factors of 215.5 kg/m^3 for pressurized volumes, 228 kg/W for the power and 1.25 kg/crewmember-h (CM-h) for crew time maintenance were used to calculate ESM.

Nominal reference values of payload mass and volume based on current SFA prototypes and heritage filters are provided in Table 2. Unit values of individual components and architecture (full complement of several components depending on configuration) values are listed. In the next section, the masses and volumes of each component from

Table 2 can be added to determine the full system architecture mass. For reference, a full architecture of just heritage filters

Table 2. Scroll Filter Assembly component masses and volumes.

Component	Component Mass (kg)	Mass of 6 Distributed Units (kg)	Mass of Centralized Unit (kg)	Component Volume (m³)	Total Distributed Volume (m³)	Centralized Volume (m³)
Screen Roll Filter	2.1	12.9	6.5	0.0032	0.0192	0.00576
Impactor Filter	3.5	20.7	10.4	0.007	0.042	0.0126
Scroll Media Filter	6.2	37	20.4	0.0095	0.057	0.0171
Non-pleated Scroll Filter	2.5	14.8	8.2	0.0038	0.0228	0.0064
HEPA Filter	2.6	15.6	4.7*	0.0064	0.0384	0.01152
High Efficiency Filter	2	12	2.3	0.00448	0.02688	0.008064

*Equivalent mass of 6 heritage filters or BFE's

would require six BFEs for a total flow rate of 680 m³/h (400 cfm), as in the ISS U.S. Lab module. Therefore the total mass of a distributed architecture given in Table 2 also incorporates the total of six distributed units. The additional mass and volume of replacement components and media spares will also be addressed under each scenario.

B. Mission Scenarios

A Mars mission will entail a transit phase of about 600-900 days and a surface operation phase of 500 days. The nature of the PM will be quite distinct depending on its source. The PM associated with the intrusion of planetary dust will be very different in nature than the basic internally generated PM.

The estimated basic particulate matter load generated by the crew ranges between 0.6 mg/person-minute and 1.6 mg/person-minute.[7] The particulate matter will mostly be in the form of large lint fibers that typically is trapped by the screen filters of the BFEs. By contrast, nearly all the intruded planetary dust will be very fine dust that is easily dispersed throughout the cabin that would require high efficiency filters to remove. In order to prevent accumulation, the filtration system will have to remove the planetary dust at the same rate or better than it is introduced into the cabin.

The estimate of the number of EVAs expected during a Mars surface mission is summarized in the Appendix. A total of 1136 EVA-crewmember events are estimated to take place over the course of 500 days of surface operations. For reference, an estimate of the amount of lunar dust intrusion of particles below 10 µm in diameter of 15.9 grams dust/EVA-crewmember has been reported.[1,2] The size fraction of planetary dust below 10 µm, which accounts for about 7% by mass of the intruded dust into the cabin, is what is expected to become airborne. Because of a lack of Martian regolith particle size data, this estimated rate of dust intrusion is used in the analysis. This amounts to a total surface dust load of about 18 kg over the 500 days. This metric of planetary dust will be used to assess the different filter systems and architectures.

If we assume each heritage filter element can handle twice the qualification test load or ~100 grams at the end-of-life pressure drop condition,[9] then this requires 180 heritage filter elements if only heritage filters are used to remove the 18 kg of planetary dust. The media load density on heritage filers has been calculated based on this load and on the total surface area of the BFE to be about 39 g/m².

The different architectures comprised by the SFS components are assessed for their performance for handling the basic and surface dust loads. Towards this end, the two mission scenarios were evaluated—a 500-day surface mis-

sion with only planetary dust intrusion, and a full mission consisting of a 620-day round trip transit and a 500-day surface exploration period with only the basic particulate matter load.

1. *Mission Scenario 1: Mars Crewed Surface Mission*

Parameter targets for Mission Scenario 1 are the following:

1) 500-day surface mission
2) 4 crewmembers
3) Planetary surface dust intrusion into the cabin.
4) Filter system flow rate: 680 m^3/h

Fine planetary surface dust entering the cabin will swiftly be swept up in the cabin ventilation flows and ultimately reach the filters. Because of the fine nature of the dust, screen pre-filters will not be effective and therefore one or more of the remaining stages of the SFS will serve as the main performing components. Nevertheless, the screen pre-filter will still be incorporated into the mass calculation because it will be needed for capturing the basic particulate load (to be discussed in mission scenario 2). The options in configuring the filter system will be in selecting which or all of these components and what architecture (distributed, centralized or hybrid) are to be used.

From the filter architectures in Fig. 3 and configurations in Table 1, trade analysis cases A3, A4, D3, and D4 were selected for this mission scenario. The trade analysis cases chosen represent variations of partially to fully distributed and hybrid architectures. Table 3 provides the specifications used for each SFS component. These specifications are based on current prototypes for which performance data are available.

Table 3. Scroll Filter Assembly specifications.

SFA Stage	Performance
Screen Roll Filter	40 mesh size
Impactor Filter	20 to 50% efficient at ~5 µm cut size)
Scroll Media Filter	80% efficient at MPPS
Heritage HEPA Filter	97% at 0.3 µm
High Efficiency Filter	95% efficient at MPPS

The impactor will be expected to capture some 20% to 50%, and perhaps more, by mass of the particles assuming the mean particle diameter of the planetary regolith airborne in the cabin is of the order of a few microns. This collection efficiency is derived from the estimate of the airborne regolith in the cabin being below 10 µm. The Scroll Media Filter will serve as a pre-filter to the HEPA filter using a medium to high efficiency media. A good design point for the Scroll Media Filter is a capturing efficiency of 80%. Any of the surface dust that evades the impactor and/or lower efficiency media and will collect on the heritage filter or high efficiency filter. The high efficiency (H.E) filter is an alternative to the heritage filter because it can offer a few benefits such as lower pressure drop, smaller mass and volume, and more holding capacity, while if used in conjunction with the other pre-filters could provide comparable capturing efficiency as the heritage filter alone.

Using these design points, the following calculations are used to determine the total surface area of Scroll media needed in the SFS. The amount of planetary dust the Scroll Media Filter will need to collect will depend on whether the Impactor Filter is used (analysis cases A4 and D4). Without the impactor the Scroll Media Filter will need to capture 14400 grams (18000 grams × 0.8), and 7200 grams (18000 grams × 0.8 × 0.5) if used with the upfront impactor filter that captures 50% of PM. In the latter case, the overall efficiency of the impactor and scroll media filter is 90% (i.e. [1-(1-0.8) × (1-0.5)] × 100%). In terms of PM holding capacity, it is expected that the lower efficiency Scroll media will tend to have larger capacity because it captures coarser dust with a larger mean particle diameter, d_m. As a comparison, if the d_m of the captured dust on the HEPA filter and the Scroll Media Filter is 2 µm to 5 µm respectively with similar number of captured particles in each case, then the ratio of media holding capacities is 1:15 since mass $\sim d^3$. As a conservative estimate, ten times the holding capacity of the heritage filters is adopted, i.e. 390 g/m^2. Therefore with this holding capacity, approximately 36 m^2 (without impactor) and 18 m^2 (with impactor) of the total media surface will be needed.

The total media volume needed for the mission can also be calculated. For a 0.5 mm thick media, media volumes of 0.018 m^3 (without impactor) and 0.009 m^3 (with impactor) would be needed respectively. Assuming a packing efficiency of 70%, the total volume needed is estimated at 0.0257 m^3 and 0.01285 m^3, and weighing 2.8 kg and 1.4 kg, respectively, based on 78 g/m^2 media density per area. Assuming an approximate roll diameter of 10 cm (4 inches) based on current prototypes, an additional 26 and 13 rolls of media will be needed respectively for replacement. In addition, 30 heritage filters beyond the six installed and 12 heritage filters beyond the six installed will be needed

to capture the remaining dust without and with the impactor, respectively. For the centralized architecture, five and three additional large HEPA filters will needed without and with the impactor filter. Because of the limited access to the centralized HEPA filter, increasing the size of the filter by about five times in order to avoid replacing the filter in flight should be considered based on the trade analysis calculations.

Table 4 summarizes the ESM for each of the configurations. The FOM calculated from Eq. 3, crew time, power, volume, and actual mass ESMs are listed. For the crew time ESM, 1 CM-h per media or replacement filter changeout is assumed because of the ease of access to the installed and stowed components.

Table 4. Trade analysis of Mars surface mission considering only the filtering of planetary dust.

Architecture	Δp (Pa)	E (%)	FOM	Number of Scroll Media Replacements	Number of Heritage Filter Replacements	Crew Maintenance (CM-h)	Crew Maintenance ESM (kg)	Power ESM (kg)	Volume ESM (kg)	Actual Mass ESM (kg)	Total ESM (kg)
A3	78.5	99.994	0.00021599	26	30	56	70	3.379	26.636	86.220	186.235
A4	158.5	99.997	0.0001146	13	12	25	31.25	6.822	37.626	72.784	148.483
D3	78.5	99.994	0.00021599	26	5	31	38.75	3.379	20.843	78.900	141.872
D4	158.5	99.997	0.0001146	13	2	15	18.75	6.822	31.834	61.864	119.270
Heritage	62.5	99.97	0.00022637	0	172	172	215	2.668	245.498	462.800	925.965

The data show that all the SFS architectural configurations result in significantly lower ESMs compared to a heritage filter architecture. In this case a 5 to 7.7 savings in ESM, mostly attributed to the mass savings from the significant reduction in the number of heritage filters needed to fly, is possible.

2. Mission Scenario 2: 620-day Transit and 500-day Surface Mars Mission Basic Load

Parameter variable targets for Mission Scenario 2 are the following:
1) Filter life time, 620-day round trip transit and 500-day surface mission
2) 4 crewmembers
3) Filter system flow rate: 680 m^3/h

The same architectural configurations used in Mission Scenario 1 are considered here (A3, A4, D3, and D4) to maintain hardware compatibility between the two missions. The total PM load is calculated at the per crewmember generation rate for the full 1120 day mission to be 8960 grams of PM. This equates to sending ~90 heritage filters on the Mars mission if only heritage filters are used. This number drastically reduces if we use the SFS. In this scenario, it is assumed that the bulk of the PM is composed of the lint matter that is larger than 50 μm and constitutes about 80% of the PM load (based on load models). The screen roll filter is employed in this case to capture nearly all of the lint material. The remaining PM is finer in size and is expected to be removed by the other filter system components. Most of the generated 8960 grams of dust will be captured with the Screen Roll Filter, the Scroll Media Filter and the Impactor Filter before it reaches the HEPA filter. If we use the Scroll Media filter (with an 80% overall efficient rated media) and the impactor filter (capturing 50%), then using similar calculations as in the previous section the Scroll Media Filter needs to collect 717 grams and the HEPA collects 179 grams of PM. The latter means that one extra heritage filter will be needed in the distributed architecture. Assuming that the screen mesh can hold the same mass density of PM, in this case mostly lint, as the scroll filter media and using a screen weight density of 86 g/m^2 (based on a measured value), the amount of screen material needed would be 1.58 kg and a volume of 0.013 m^3. Adopting a similar volume for the media roll used in the Scroll Media Filter, 16.5 rolls of screen mesh material will be needed for the mission. In addition, the amount of Scroll filter media needed would be 143 grams and a volume of .0013 m^3, or 1.6 media rolls.

The SFS without the impactor will require a little more media. In this case the Scroll Media Filter needs to capture 1434 grams and the heritage filter 358 grams. Again, using similar calculations as in Mission Scenario 1, this translates into 286 grams and 0.0026 m^3 of total SFS media, or 3.3 rolls, for both architectures. Two extra HEPA filters will also be needed in the distributed architecture.

Table 5 compiles these calculated values in terms of ESM. As in Mission Scenario 1, there a significant savings in ESM by using the SFS, from 2.5 to 4 times the savings compared to the heritage filters alone. The FOMs, the *QF* calculated from Eq. 3, correspondingly stay about the same as in Mission Scenario 1.

Table 5. Trade Analysis for transit and Mars surface mission considering only basic PM loads.

Architecture	Δp (Pa)	E (%)	FOM	Number of screen and Scroll Media Replacements	Number of Heritage Filter Replacements	Crew Maintenance (CM-h)	Crew Maintenance ESM (kg)	Power ESM (kg)	Volume ESM (kg)	Actual Mass ESM (kg)	Total ESM (kg)
A3	78.5	99.994	0.00021599	19.8	1	20.8	70	3.379	28.0581	86.220	187.657
A4	158.5	99.997	0.0001146	18.1	2	20.1	31.25	6.822	32.9715	72.784	143.828
D3	78.5	99.994	0.00021599	19.8	0	19.8	38.75	3.379	22.26546	78.900	143.294
D4	158.5	99.997	0.0001146	18.1	0	18.1	18.75	6.822	27.17886	61.864	114.615
Heritage	62.5	99.97	0.00022637	0	90	90	112.5	2.668	124.128	234.000	473.296

VI. Discussion

The two trade analyses detailed above clearly show advantages in ESM by using the SFS under various architectures versus using the heritage (HEPA) filters alone. ESM savings of 2.5 to 6.5 times the heritage ESM are possible depending on the chosen architecture and mission scenario. For a full mission, consisting of a 620 day round trip transit and 500 days surface mission, where both the basic PM and planetary dust intrusion, the total ESM can be obtained by combining the results of both mission scenarios. In this case the total ESM savings are still in the same range of values. The FOM, the *QF* calculated from Eq. 3, is also another discriminator. In this case, the heritage filters have the largest FOM. Architecture A4 and D4 tended to have FOMs close to this values. In general, architecture D3 provides a good balance of large FOM and one of the lowest ESMs.

The performance grade of the media or choice of finishing filter can also help improve ESM. For example, a 95% efficient filter can be used instead of a HEPA filter to provide a combined efficiency of 99.9% with the rest of the SFS filter stages while providing a mass and volume savings because of the likely smaller volume format of the filter. Additional media types that have an expanded or lofted structure, or composite microstructure, that may have appreciably larger holding capacity may be considered. These alternate filter media could significantly reduce the amount media needed. The selection of the media can be decided when the mission is better defined.

Additional ESM savings may emerge from using lightweight materials and structures of the filter frame and construction. This also can include the filter interface housing that accepts and connects the filter to the ventilation loop. The current heritage filter interface housing mass is about 5 kg for each installed unit. Potentially, the SFS interface housing could be efficiently designed to save on material or through the use of appropriate lightweight materials and structures.

VII. Conclusion

The general conclusion drawn from the trade analysis is that the Scroll Filter System trades well against the heritage filters. Specifically for the 500 day Mars surface mission, the Scroll Filter System provides a minimum 5 times and a maximum of 6.5 times savings in ESM compared to a mission using only heritage filters. Slightly lower ESM savings were found for the basic PM load during the full mission. These large ESM savings were mostly attributed to the mass savings from the significant reduction in the number of heritage filters required for these missions. The hybrid architecture, with a centralized HEPA filter, and the screen roll filter, Impactor Filter and Scroll Media filters at the distributed inlet and return vent points provided the best ESM savings. Lastly, comparable filter performance, defined by the quality factor or FOM, to the heritage filters were found when all the components of the SFS were used.

Appendix

Planetary surface dust calculations are based on guidance from Human Exploration of Mars Design Reference Architecture 5.0 Addendum #2, NASA-SP-2009-566-ADD2, dated March 2014. The guidance on EVA crew size and EVA frequency is the following:

a) 2-crewmember EVAs on alternating days, ADD2, p. 173.
b) For a 500-day Mars surface mission: 12 hours EVA/crewmember in a 48-hour period and 24 hours EVA/crewmember per 7-day period. Duration is variable between 3 to 6.5 hours, ADD2, pp. 399, 402.

Using the 2-crewmember EVA convention and the EVA frequency more recent DRM 5.0 ADD2 EVA frequency assuming 6-hour EVA average and 4 crewmembers:

a) 71 weeks with 24 hours EVA/crewmember or 4 EVA events/crewmember yielding 16 total EVAs/week.

b) Assuming EVA is done in pairs, the 16 total EVAs/week occur as 8 two-crewmember EVA events/week or 568 two-crewmember EVA events over the 500-day surface mission. This equates to 1136 total EVA-crewmember events.

c) At 15.9 grams dust/EVA-crewmember the total surface dust load could come to about 18 kg over the 500-day surface mission.

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