

Results of the Particulate Contamination Control Trade Study for Space Suit Life Support Development

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ABSTRACT

As the United States makes plans to return astronauts to the moon and eventually send them on to Mars, designing the most effective, efficient, and robust spacesuit life support system that will operate successfully in dusty environments is vital. Some knowledge has been acquired regarding the contaminants and level of infiltration that can be expected from lunar and Mars dust, however, risk mitigation strategies and filtration designs that will prevent contamination within a spacesuit life support system are yet undefined. A trade study was therefore initiated to identify and address these concerns, and to develop new requirements for the Constellation spacesuit element Portable Life Support System.

This trade study investigated historical methods of controlling particulate contamination in spacesuits and space vehicles, and evaluated the possibility of using commercial technologies for this application. The trade study also examined potential filtration designs. This paper summarizes the results of this trade study.

INTRODUCTION

The filtration of fluid subsystems on the Portable Life Support System (PLSS) is motivated by the Apollo Program experience in which lunar dust presented an unexpected difficulty. Lunar dust clogged mechanisms; abraded,

coated, and contaminated equipment and instruments; caused seals to fail, and irritated crew members (CMs) by obscuring their vision and through inhalation. Filters that are located in the vent and water loops of the current Constellation spacesuit element (CSSE) PLSS schematic, which is shown in Figure 1, are intended to mitigate CM exposure and equipment damage. Details of the three PLSS subsystems – the ventilation subsystem or vent loop, the thermal control subsystem or water loop, and the oxygen (O₂) subsystem – are shown in Figures 2, 3, and 4, respectively. Filters that are in the current system are identified independently as FL-XXX or when they are in connectors or fittings as QF-XXX and FF-XXX [1].

The goal of this study is to evaluate the filter configuration that is in the current PLSS schematic and to offer recommendations for a configuration that provides the required filtration of lunar dust without exceeding expected pressure loss limits. This study approaches this goal first with a review of the properties of lunar dust, including characteristics that may affect CM health. This is followed by a review of the exposure criteria that are established for lunar dust and other particulate matter (PM), the health basis for PM exposure limits, and changes in exposure standards since the Apollo missions. Filtration theory is then reviewed, and typical filter equipment is considered for appropriateness in this application. Finally, a model is developed that considers system pressure drop and filter efficiency following a best and a worst case fouling event.

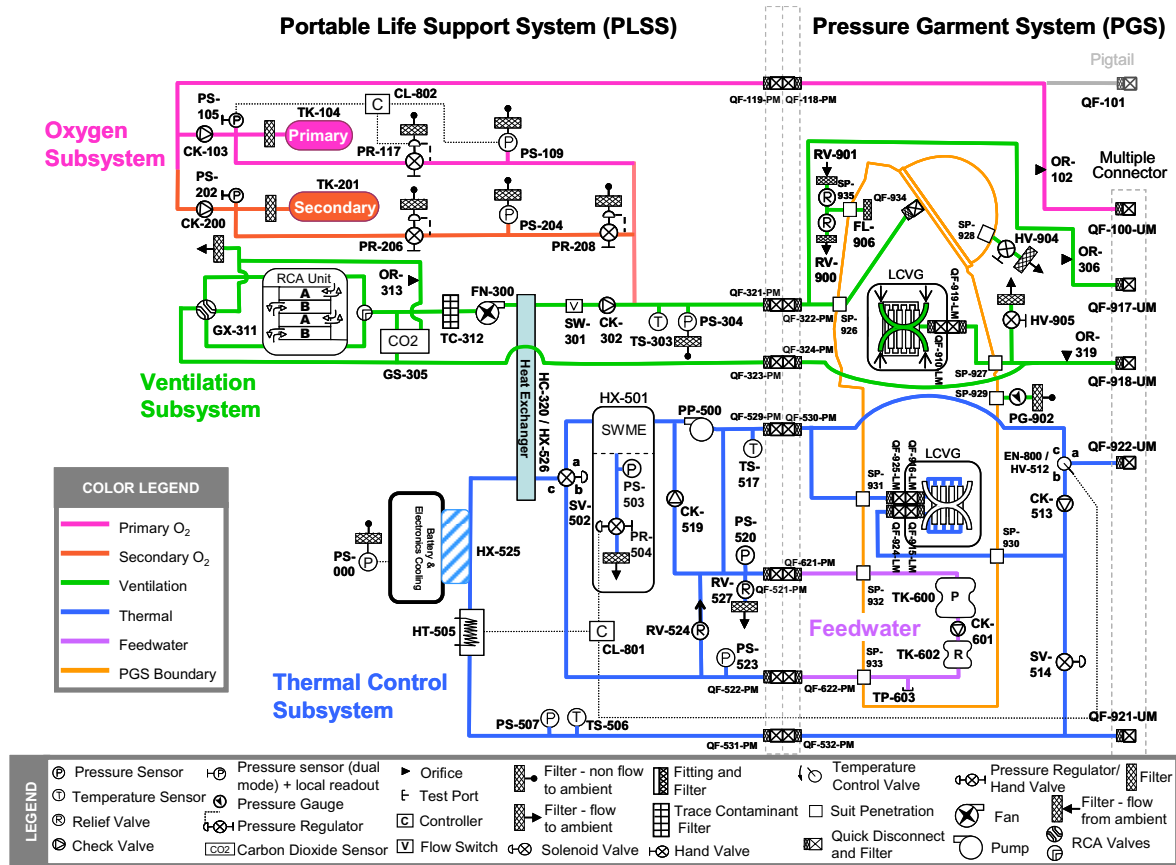


Figure 1. Current CSSE PLSS schematic.

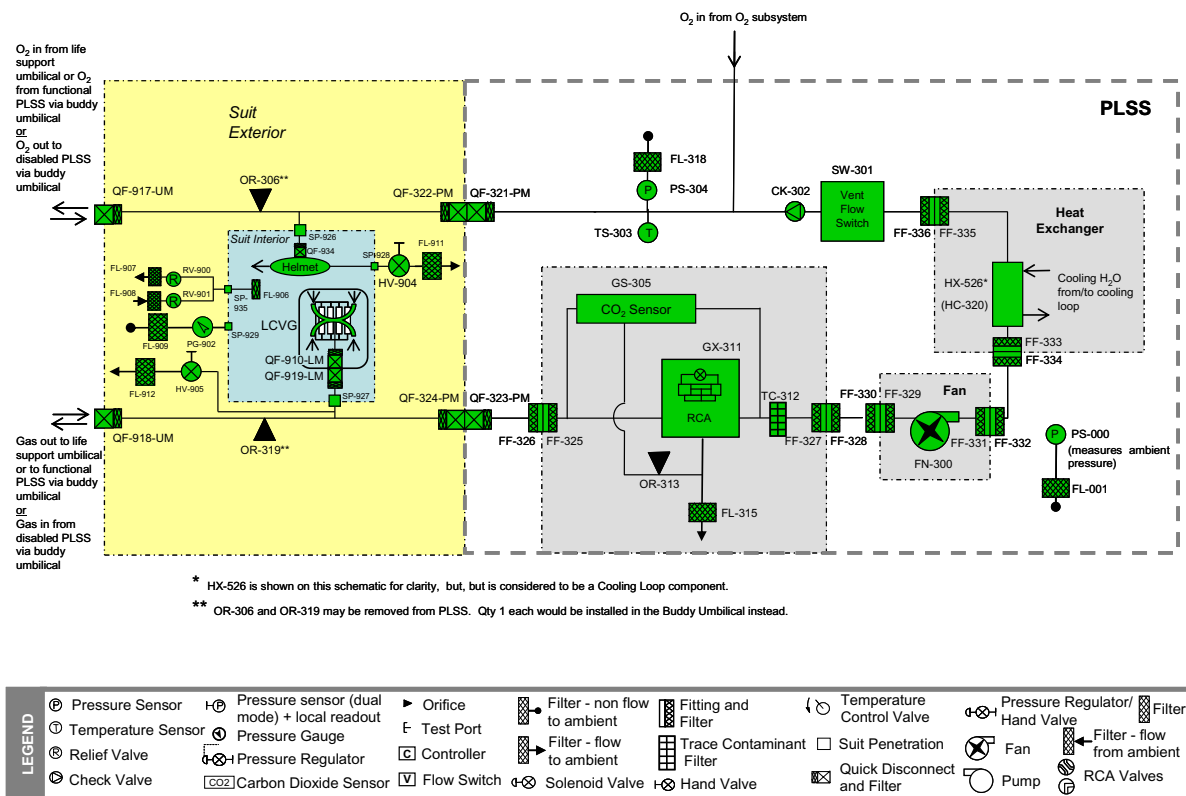


Figure 2. Detail of vent loop in the current PLSS schematic.

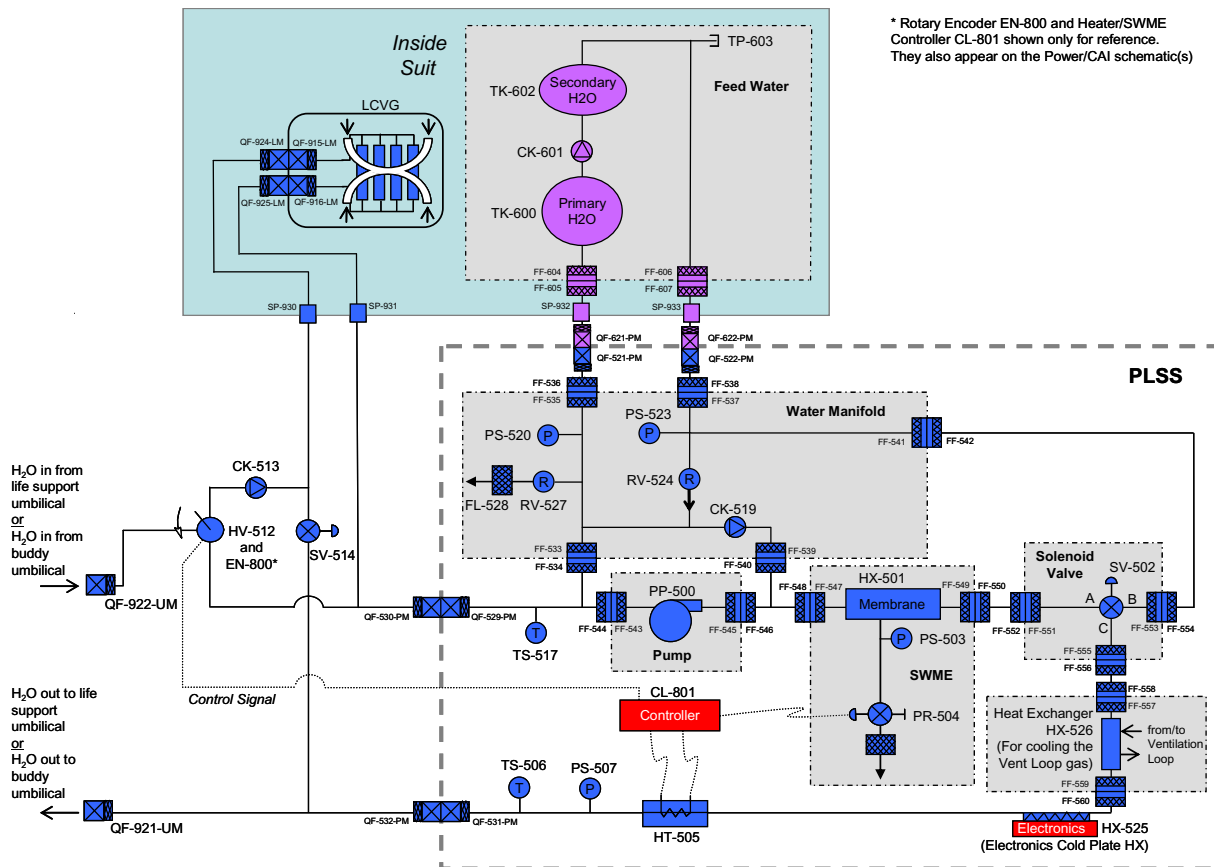


Figure 3. Detail of water loop in the current PLSS schematic.

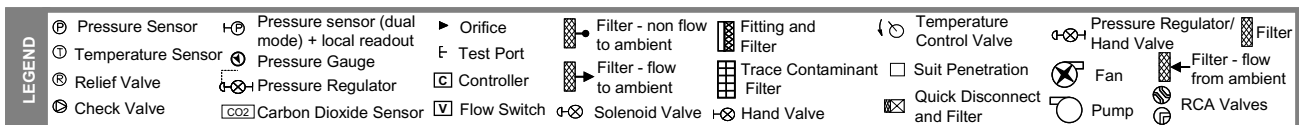
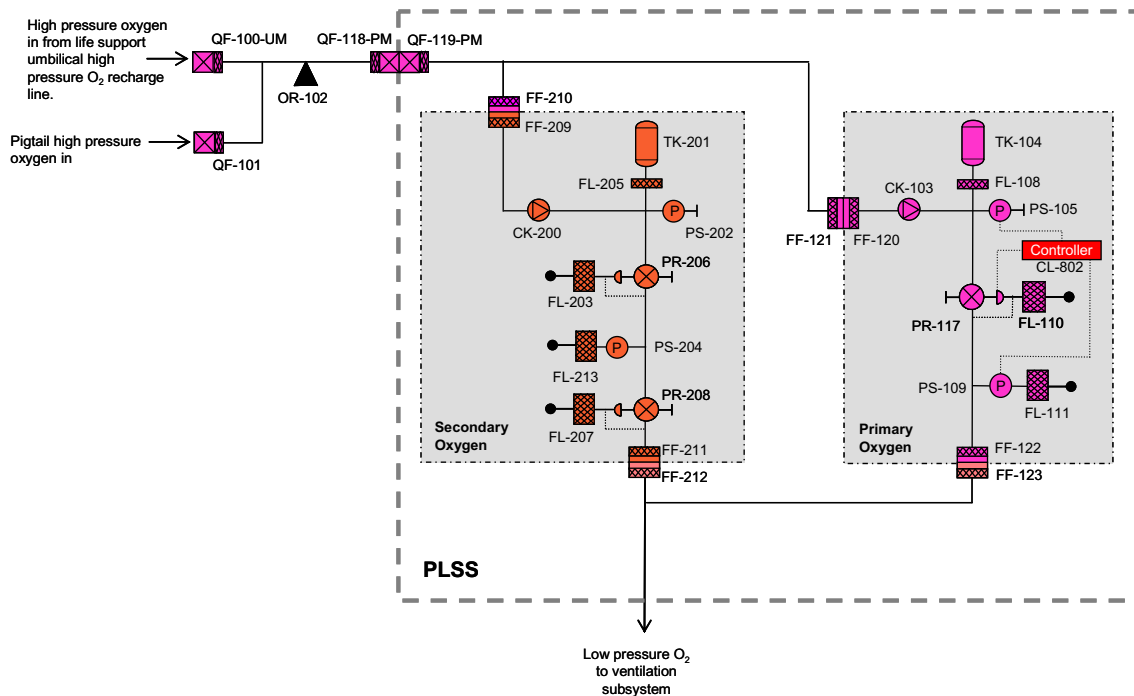


Figure 4. Detail of the O₂ subsystem in the current PLSS schematic.

PROPERTIES OF LUNAR DUST

Dust is a powder or a collection of fine, dry particles that some define as being smaller than 100 μm [2]. The lunar surface is considered very dusty, as over 70% of the lunar regolith, which is the layer of loose material covering the lunar surface, consists of particles that are smaller than 100 μm . Several general characteristics of lunar dust are given in Table 1. Lunar dust is seen as a problem because of the features of the lunar environment in which it is formed and that affect its behavior.

Table 1. Lunar dust characteristics [3]

Characteristics	Description	Remarks
Size	90% < 1,000 μm 70% < 100 μm	Very small with high ingress and penetration
Shape	Sharp and irregular	Penetrates fabrics
Color	Dark gray, brown, black	
Bulk density (0–30 cm)	1.58 $\pm$ g/cc	Higher density, deeper
Hardness (Mohs scale)	5–7	Very hard material
Porosity (0–15 cm)	52% $\pm$ 2%	Volume of void space
Cohesion (0–15 cm)	0.52 kPa	Higher cohesion, deeper
Friction angle (0–15 cm)	42 degrees	Holds together, trenching
Electrostatic properties	Highly charged	Highest charge during lunar night
Magnetic properties	38 $\pm$ gammas (Apollo 15)	Not global, local fields
Thermal conductivity	0.9–1.3 W/cm K	Good insulator
Compressibility (loose)	0.3 (compression index)	Top 5–10 $\pm$ cm easily compressed
Penetration resistance	0.15 N/cm ³	Based on lunar roving vehicle [LRV] tracks

Lunar dust is formed in a weathering process that is made possible by the moon's vacuum environment. Lunar weathering predominantly involves micrometeorite

impacts that break large particles into finer ones. Silicate melts are formed in these impacts, which also weld small grains of soil into glassy agglutinates. Lunar dust particles tend to be small, are sharp and irregular in shape, and have a very high porosity as a result of these processes. Micrometeorite impacts also drive an auto-reduction of the ferrous oxide content of dust into native iron (Fe) particles that are distributed within glassy agglutinates and in the vapor-deposited Fe- and silicon-rich patina that is present on the surface of most lunar soil particles [4].

The dry environment and particle composition make lunar dust highly prone to electrostatic charging [2,3,5,6]. This lends to attraction and adhesion of dust to equipment. Once dust is attracted to a surface, adhesion and wear are aggravated by the shape and hardness of the dust particles; there are many examples of difficulties in removing dust and of dust injuring joints, seals, and equipment in the literature [3].

The lunar surface is unprotected from solar influences. The effects of solar radiation, such as photoemission, leave “unsatisfied” chemical potentials on particle surfaces that are not met for the lack of an atmosphere. The presence of Fe from weathering and unmet chemical potentials at the surface of particles could make the dust reactive and, thus, potentially toxic [2,7].

FILTRATION GUIDELINES FOR CM EXPOSURE

The Lunar Airborne Dust Toxicity Advisory Group (LADTAG) is investigating the toxicity and human exposure limits for lunar dust. LADTAG is not due to release a final recommendation for exposure limits to the NASA Chief Health and Medical Office until 2010 [8]. On its inception, however, LADTAG members suggested the estimated ranges for the limits of exposure that are shown in Table 2. These ranges are time-weighted average values over the specified exposure period.

Table 2. LADTAG lunar dust exposure limit estimates [9]

Particle Size	Long-term Exposure (6 months)	Short-term Exposure (1 hour)
<10 μm	0.01 to 3 mg/m ³	0.5 to 10 mg/m ³

Terrestrial experience indicates that exposure to fine PM, even where the material is inert [7], can affect the lungs and pulmonary system, causing respiratory problems, a decline in pulmonary function, cardiovascular diseases, and premature mortality [10,11]. Studies suggest that the deleterious effect to living tissue that is caused by fine PM is caused by oxidative stresses [7,11], or by facilitating the reaction of “free radicals” with cell structures. The mechanism that facilitates this stress is believed to be related to the high specific surface area that is presented by small particles. The relationship between PM and respiratory function is intuitive; but the connection to cardio-vascular function is not well

understood, so sources pose several plausible explanations that include the passage of sufficiently small particles into the cardiovascular system to cause direct or indirect damage, autonomic reaction to the particles, and particle affects to the coagulation and clotting status of blood [11].

The Environmental Protection Agency (EPA) has defined standard limits of exposure that are based on terrestrial studies on the effect of fine dusts. These standards are described by National Ambient Air Quality (NAAQ) standards for particle pollution. This U.S. national standard outlines the PM standards PM10 and PM2.5 that are shown in Table 3. In 1971, the NAAQ defined a total suspended particles (TSP) limit, as shown in the table, that was replaced by the PM10 standard in 1987. The PM2.5 standard was defined in 1997 when studies showed that there were greater health risks associated with this finer range of particle sizes [12]. The limits are generally time-weighted averages, but the prescribed weighting method considers a 3-year average of daily or annual exposures [13].

Table 3. EPA terrestrial dust exposure limits [13,14]

Stand.	Particle Size	Long-term Exposure (1 year)	Short-term Exposure (24 hours)
TSP	<50 µm	None [75 ug/m ³ (1971)]	None [260 ug/m ³ (1971)]
PM10	<10 µm	None [50 ug/m ³ (1987)]	150 ug/m ³
PM2.5	<2.5 µm	15 ug/m ³	35 ug/m ³

Many studies suggest that a greater health risk is posed by the fine particles of the PM2.5 standard, as these can easily reach the deepest recesses of the lungs [7,10,11,13,15]. Particles that are greater than 50 µm are not addressed by NAAQ [13,14,15]. PM that is larger than 10 µm is not believed to pose serious health hazards, however, as the nose effectively filters these sizes [3]. Large particles nevertheless may present a nuisance if they are present in high quantities by irritating nasal passages and by affecting electronics, machinery, and other hardware.

Preliminary air quality standards for the next lunar program fall within the PM10 limits that were established by the EPA; that is, they (1) meet the 1987 long-term exposure standard for PM10, and (2) are 33% more stringent than the current short-term exposure for PM10. Specifically, these standards state that

- [HS3006D] The system shall limit levels of lunar dust contaminants of less than 10 and equal to or greater than 0.1 micron (TBR-006-004) size in the internal atmosphere below 0.05 mg/m³. (6 month episodic exposure) [16].

- [CSSE3053] The PLSS shall limit the particulate matter in the ventilation gas to the levels specified in the Particulate Matter Table (TBR-CSSE-128)

TABLE 3.7-15 - PARTICULATE MATTER TABLE (TBR-CSSE-128)

Particulate Size (microns)	Number	Total Load (mg/m ³)
x > 150	0	
100 < x < 150	5	
50 < x < 100	47	
10 < x < 50	Unlimited	
x < 10	Unlimited	0.1 (TBR)

The CM is subject to short-term, episodic exposures to lunar dust during extravehicular activity (EVA), typically for durations that are much shorter than 24 hours; a 1-hour standard is most appropriate for the design of a filtration system on the PLSS. To address the deleterious and potentially toxic health effects of lunar dust, this study applies the most stringent short-term limits that were offered; i.e., 100 µg/m³ over a 24-hour period and the LADTAG estimate of 500 µg/m³ over 1 hour.

FILTRATION GUIDELINES FOR VENT LOOP EQUIPMENT

The above, which generally addresses the human health effects of particles, is appropriate for breathing air or gas in contact with the CM. In the PLSS, these guidelines apply to the condition of the breathing gas in the schematic of Figure 2 downstream of QF-934 and upstream of QF-910-LM, which would include the helmet and much of the PGS. Conditions within the remainder of the vent loop might exceed the health exposure criteria, so long as mechanical equipment is not damaged nor any dust accumulation criteria are exceeded.

This study does not address the filtration needs of mechanical equipment in the PLSS in great detail. Further study is warranted, but, these components may be well protected by filtration that meets CM exposure guidelines. Past filtration practice can serve as a useful guide for this region of the vent loop. Apollo 13 and later missions used filter media that were rated to remove 98% of PM that was larger than 30 µm in the crew module cabin filter [3]. Commercially available air intake filters for machinery typically filter particle sizes to 10 µm with a 99% removal efficiency [17].

FILTER TYPES AND CHARACTERISTICS

The basic function of a filter is to separate and retain particles from a gas stream. Three principle mechanisms are applied in a filter: Inertial deposition occurs where a particle that is approaching a collecting body deviates from the local stream-lines, due to inertia, and strikes the body. Diffusional deposition occurs mainly with very small particles, typically under 0.3 µm in diameter, that exhibit considerable Brownian motion and diffuse from the gas to the surface of a nearby collecting body. Flow

line deposition occurs where a particle that is traveling along a streamline passes very near a collecting body (i.e., within a 1-particle radius) such that it touches and may be collected without the influence of inertia or diffusion. These mechanisms are shown graphically in Figure 5 [18]. Other mechanisms, including sieving, electrostatic deposition, and gravitational deposition, may be in operation in particular circumstances.

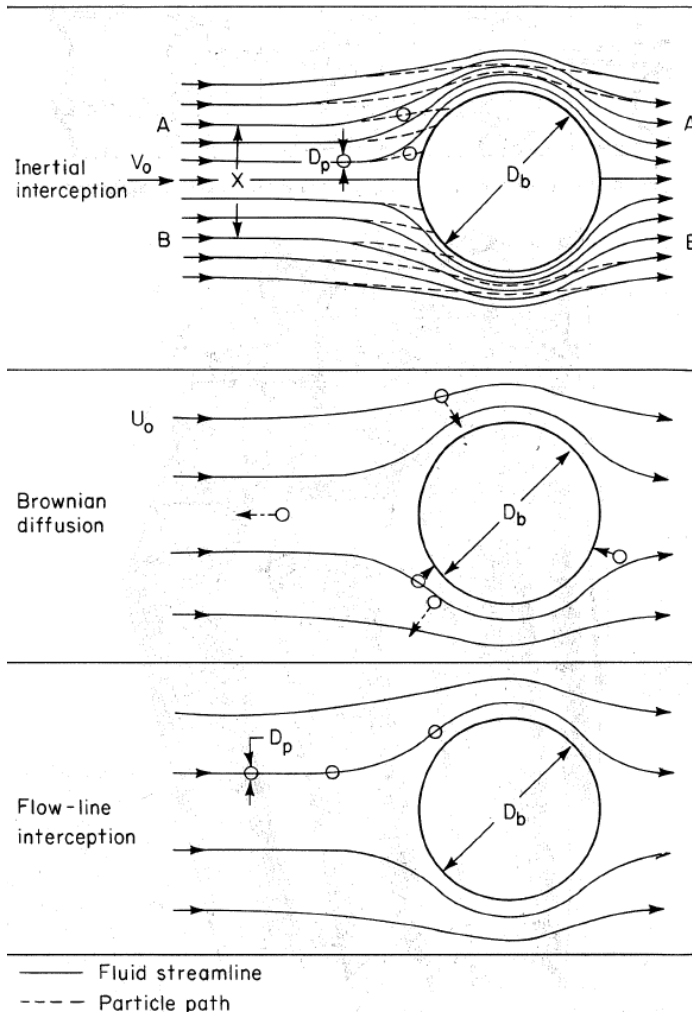


Figure 5. Primary mechanisms of particle separation and deposition [18].

Seven types of equipment that are typically used for dust filtration include gravity settling chambers, impingement separators, cyclone separators, mechanical centrifuges, wet scrubbers, electrostatic precipitators, and fabric filters. Not all of these are suitable for use in the PLSS, however. The equipment needs to be safe, compact, robust, and uncomplicated; equipment cannot be dependent on the presence of gravity nor on orientation relative to gravity. The filtration method that is used must also be effective at removing dust sizes that are smaller than 10 μm in diameter.

These criteria are sufficient to eliminate five of the seven types of equipment from consideration for the PLSS. Two of these types, the settling chamber and cyclone

separator, rely in whole or part on gravity. A settling chamber functions only in the presence of gravity. A cyclone separator typically relies on orientation to gravity to remove separated particles from the primary chamber. A mechanical separator, while it might be implemented as a modified blower, presents the problems of mechanical reliability, parasitic power draw, and additional complexity. The gravitational mechanism, in the first type of equipment, and inertial mechanism, in the latter two types, are primarily applied for separation, so efficiency is typically low for the collection of particle sizes smaller than 10 or 20 μm . The two remaining unsuitable types of equipment – electrostatic precipitators and wet scrubbers – operate on mechanisms that are efficient at collecting small particles, but nevertheless have serious drawbacks. Dielectric or insulator failure in an electrostatic precipitator could result in sparking, which may lead to combustion in an O_2 environment. Wet scrubbers use a liquid (usually water) to assist in collecting dust. This introduces substantial complexity into the system, particularly as the liquid must be stored and pumped, and the resulting effluent must be cleaned and recycled, stored, or disposed of.

Fabric filters and impingement separators are most apt for this application because they can be compact and are uncomplicated, very robust, and insensitive to gravity; they also require no additional systems or moving equipment to implement. An impingement separator might find use as an annular-cup-type chamber into which gas flow enters at the center, impinges on a fibrous material, and is then redirected to the chamber exit through an outer annulus. Impingement, however, largely depends on the inertial deposition mechanism, so it may be limited to removing dusts that are predominantly larger than 10 μm in diameter. Fabric filters, which are well-characterized in the literature, use inertial, diffusion, and flow-line interception mechanisms to efficiently separate particles to fractions of a micron in diameter.

FILTER MODEL DEVELOPMENT

The fabric filter alone is used for this model based on the good fit of its attributes to this application and the available information that is found in the literature describing filtration efficiency and pressure performance. Pressure drop through a fabric filter is typically expressed by [18,19]

$$\Delta p = K_1 \cdot V_f + K_2 \cdot \omega_f \cdot V_f, \quad (1)$$

where the K_1 and K_2 coefficients are determined empirically and represent a clean and a fouled filter contribution to pressure drop, respectively, V_f is the fluid face velocity across the frontal area of the filter, and ω is a measure of dust loading on the filter. This is a variation of Darcy's Law, which describes flow through a porous medium along a streamline. Darcy's law is valid, in theory, at low Reynolds numbers, although, in practice, this equation is used under broader laminar flow conditions. It is typically applied where a is assumed to be