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ISS Ambient Air Quality: Updated Inventory of Known Aerosol Sources

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Spacecraft cabin air quality is of fundamental importance to crew health, with concerns encompassing both gaseous contaminants and particulate matter. Little opportunity exists for direct measurement of aerosol concentrations on the International Space Station (ISS), however, an aerosol source model was developed for the purpose of filtration and ventilation systems design. This model has successfully been applied, however, since the initial effort, an increase in the number of crewmembers from 3 to 6 and new processes on board the ISS necessitate an updated aerosol inventory to accurately reflect the current ambient aerosol conditions. Results from recent analyses of dust samples from ISS, combined with a literature review provide new predicted aerosol emission rates in terms of size-segregated mass and number concentration. Some new aerosol sources have been considered and added to the existing array of materials. The goal of this work is to provide updated filtration model inputs which can verify that the current ISS filtration system is adequate and filter lifetime targets are met. This inventory of aerosol sources is applicable to other spacecraft, and becomes more important as NASA considers future long term exploration missions, which will preclude the opportunity for resupply of filtration products.

I. Introduction

Indoor air quality is of great importance to human health, and has been studied extensively in homes and work places. On Earth, a large proportion of the indoor aerosol sources are from cooking, smoking and cleaning. Homes and workplaces have different activities and thus different sources. Surprisingly, outdoor air is a major source of indoor pollutants, bringing vehicle and industrial emissions, pollen and dust into buildings. The International Space Station (ISS) is a unique indoor environment that serves as both home and workplace for crewmembers, and has some aerosol sources in common with buildings on earth, but can be considered an isolated volume of air with only internally generated aerosols from occupants, their activities and ISS infrastructure. Therefore the filtration system is of utmost importance for quality of life and health. An aerosol source model was developed for the purpose of filtration and ventilation systems design, and has been successfully applied, however, since the initial efforts, the number of crewmembers on board the ISS has increased from 3 to 6 and they are engaged in new processes and activities. Therefore, it is prudent to evaluate the current state of ISS ambient air quality in terms of particle emissions and determine what new aerosol sources should be identified, even if they are not quantified. Only aerosols generated in living spaces are considered in this effort which excludes potential aerosol generation from equipment in racks and from other ISS subsystems. This topic should be periodically revisited as existing or new aerosol sources may become evident in the future.

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Aerosol Transport Properties on ISS

Sizes of indoor aerosols typically span several orders of magnitude, but on ISS, the range of interest is much larger. Respirable particles are 10 μm and below, and can travel to the pulmonary portion of the lungs where gas exchange takes place in the alveoli, whereas particles from 10 to 100 μm typically impact in the nose or possibly the bronchi. The smallest particles can be detrimental in the long-term,[1-4] but larger particles can potentially cause eye, nose and throat irritation, as well as allergies. Particles behave differently on ISS compared to Earth with the absence of gravitational settling. Thus, extremely large particles persist in the air until they are removed by the ISS filter elements of the air handling system. An important variable in this type of particle removal is the transport behavior of the particle in air. Particles are subject to aerodynamic drag which is a function of particle diameter and the ambient air pressure. In atmospheric pressure, particles greater than about 3 μm in diameter experience the same type of resistance to motion as larger rigid bodies, since the air is considered a continuum which exerts a drag force on the surface of the body. Below this size, air surrounding the particle cannot be considered a continuous medium, and the particle experiences fewer collisions with air molecules, so drag is reduced. Particles with diameters less than 20 nm are considered to be in the free-molecule regime where Knudsen diffusion effects dominate. In-between these two extremes (for particle diameters from 20 nm to 3 μm) is a transition regime. Similarly, in planetary or lunar missions with lower pressure cabin environments, there are fewer air molecules present which causes reduced drag. In these conditions filtration is enhanced once the particle enters the filter, as reduced drag enhances the inertial capture of the particles on the filter media.[5]

Another factor affecting particle motion is shape, as spherical particles will experience less drag than non-spherical particles. Dust is defined as a solid particle resulting from mechanical disintegration of material.[6] Most dust particles have jagged, irregular morphology which will slow their motion in air, relative to smooth spheres. Fibers also have increased drag which is accounted for analytically by a dynamic shape factor. For example, spheres have shape factor 1.0 whereas cubes have shape factor 1.08—the drag is 8% higher for cubes.[6] Cylinders have different dynamic shape factors based on their aspect ratio. Averaged over all orientations, a fiber with a 2 to 1 aspect ratio has a shape factor of 1.09, whereas a fiber with 10 to 1 has a dynamic shape factor of 1.43 (effectively increasing the drag by 43%). Fibers undergo both translational and rotational motion as well.[7] Generally, the filtration efficiency of fibrous aerosols is higher than that of spherical particles, with a strong dependence on aspect ratio: the longer the fiber, the greater the collection efficiency.[8]

II. Original Aerosol Source Emission Rates for Filtration Design

The initial aerosol source model for filtration design was based on reports which quantified rates for human-generated particles from the literature, as well as several Shuttle cabin air filter analyses.[9] This inventory included particles ranging from 1μm to 1270 μm, with binned size distribution information for coughs and sneezes. The remaining sources are described by a range of particle sizes, with no mean or standard deviation to describe the particle size or mass distributions. Eight types of fabric fibers were listed individually in the table, most with only one particle size given. Emission rates were specified in terms of both aerosol number and mass generated per person, and quantified viable colony forming units of bacteria and fungi in these particles. The original data is shown in Table 1. This effort to update the aerosol sources and generation rates does not attempt to address microbial contamination, but rather focuses on aerosol quantities on ISS as they relate to general air quality and filter performance, therefore the microbial data is not included in Table 1.

Intakes for the air handling system on ISS have a 20 x 20 pre-filter Nomex mesh with opening size 841 μm which prevents larger particles from entering the ISS filter element media.[9] In the absence of gravitational settling, these large particles can remain airborne but are easily entrained in the flow towards the filters. Regular vacuuming of the pre-filter is necessary to prevent a significant build-up of these larger dust and lint particles on the screens. Air quality on ISS is affected by all the sources listed in the table, whereas filter performance is influenced by the particles that can pass through the 841 μm mesh openings.

Approximately 25% of the total particle mass in Table 1 is attributed to fibers, mostly clothing (with the exception of glass and Nomex fibers). It is assumed that the particle sizes given in the table are fiber diameters, and that the geometry of particles attributed to these sources have a large aspect ratio, with the aerodynamic behavior of cylinders. Nearly 5% of the particle mass is human hair, but it is assumed that the pre-filter mesh will prevent most hairs from entering the ISS filter element. The rule-of-thumb width of a human hair is about 100 µm (give or take 50 µm), so a very short hair could conceivably pass through the mesh if it had the proper orientation. This is consistent with a recent debris analysis performed on a HEPA vacuum bag returned from ISS, which showed that hair remained in the sieving operation that removed debris smaller than 500 µm, but was not identified in the smaller fractions.[10] Similarly, the 'Miscellaneous' category in Table 1 does not affect filter performance, as the size of these fragments exceed the pre-filter mesh opening size.

Table 1. Original Airborne Particulate Generation Load Model (based on Shuttle data)

Type	Particle size, µm	Distribution		Generation Rate	
		By Part (%)	By Mass (%)	Particulate (#/person-minute)	Mass (mg/person-minute)
Skin Fragments	20.0	8.44E+01	5.00E-03	1.91E+04	1.54E-05
	< 10.0	9.38	1.39E-04	2.30E+03	4.27E-07
Sneeze	> 22.0	1.38E-02	5.64E-09	3.12	1.74E-11
	8.0 - 16.0	1.10E-01	1.74E-08	2.50E+01	5.34E-11
	4.0 - 8.0	4.10E-01	8.08E-09	9.31E+01	2.49E-11
	2.0 - 4.0	8.58E-01	2.11E-09	1.94E+02	6.49E-12
	1.0 - 2.0	2.10E+00	6.46E-10	4.76E+02	1.99E-12
	< 1.0	2.45	9.42E-11	5.56E+02	2.90E-13
Cough	> 22.0	2.60E-04	1.07E-10	5.90E-02	3.28E-13
	8.0 - 16.0	1.50E-03	2.36E-10	3.40E-01	7.27E-13
	4.0 - 8.0	3.95E-03	7.78E-11	8.96E-01	2.39E-13
	2.0 - 4.0	4.90E-03	1.21E-11	1.11E+00	3.71E-14
	1.0 - 2.0	6.43E-02	1.98E-11	1.46E+01	6.09E-14
	< 1.0	2.02E-01	7.77E-12	4.58E+01	2.39E-14
Cotton fiber	12.9	3.38E-03	2.19E+01	7.67E-01	6.74E-02
Wool fiber	20.5 - 23.0	3.81E-05	8.18E-01	8.64E-03	2.52E-03
Acrylic fiber	20.3	4.55E-05	1.53E-01	1.03E-02	4.71E-04
Polyester fiber	16.0 - 18.0	5.29E-05	2.92E-01	1.20E-02	8.98E-04
Glass fiber	4.0 - 5.6	2.52E-04	4.86E-01	5.72E-02	1.49E-03
Nylon fiber	16	3.08E-06	5.34E-04	6.97E-04	1.64E-06
Nomex fiber	14	8.49E-05	7.35E-01	1.92E-02	2.26E-03
Cashmere fiber	16.7	5.54E-06	1.35E-01	1.25E-03	4.16E-04
Human hair	58.8 - 68.4	2.32E-05	4.89E+00	5.30E-03	1.50E-02
Metallics	813	1.66E-04	9.70E+00	3.76E-02	2.98E-02
Paint chips	51.0 - 1270.0	1.44E-04	3.85E+00	3.26E-02	1.18E-02
Plastics	813	3.96E-04	1.32E+01	8.98E-02	4.05E-02
Miscellaneous*	> 2540.0	2.77E-06	4.38E+01	6.27E-04	1.35E-01
TOTAL		100.00	100.00	2.28E+04	0.31

* Tissue, food, yarn, woven and glass tape, finger nail clippings, pencil lead

Cough and sneeze are important for microbial analysis but do not contribute significantly to the ambient aerosol on ISS. These particles in Table 1 make up 6.2% of the number count, but account for a miniscule percentage (3.4E-08%) of the total mass of particles. Cough aerosols are assumed to be liquid droplets that would evaporate quickly in the typical ISS environment (4.4 to 15.5 ^{o}C dewpoint). Numerical computations modeling droplets expelled in respiratory activities show that a 20 µm droplet will evaporate in about 0.5 seconds under this range of conditions.[11] Sneeze aerosols may be liquid and evaporate, or possibly solid. Cough and sneeze droplets are not expected to significantly contribute to the ISS aerosol concentration and thus will be neglected in the updated table.

III. Updated Aerosol Sources on ISS

While the original table of particle sources is based on reported data, only larger aerosol sizes are accounted for. Particles less than 100μm are considered inhalable, and are further classified based on their deposition location in the head and lung airways, or pulmonary regions.[6] Many governments have regulations for ambient aerosol concentrations for particles with diameters less than 10μm and less than 2.5μm (known as PM10 and PM2.5 [also known as fine particles]) Age, gender and level of activity are all factors affecting penetration and deposition of inhaled particles, but research shows that smaller particles present greater risks to human health.[1-4] Therefore the updated aerosol inventory should include known particle emissions below 10μm, including the ultrafine range (100 nm and below). Furthermore, particles that are close to 300 nm are considered the most penetrating particle size in filtration, so size segregated aerosol sources in this range are very relevant to filter efficiency calculations.

Table 2 contains the updated aerosol sources, each of which will be explained in detail. Most generation rates found in the literature were in terms of number of particles per unit time. Some sources were in terms of aerosol mass per unit time. In general, it is difficult to convert between aerosol number and mass, because the particles must be assumed spherical and also a density must be known. Often particle material densities differ significantly from the density of a parent material because of occlusions and/or complex shapes. Therefore, in Table 2, when both mass and number generation rates were available, they were both included in the table from the separate literature sources (they were not converted). Also, a number of entries from Table 1 were retained, as there was no newer data available in the literature for these sources. Additional aerosol sources that are not quantified are listed at the bottom of Table 2, and these are the subject of ongoing research to either quantify them or determine whether they can be omitted.

The human body is a significant generator of indoor aerosols from both skin and clothing, and research shows that the level of activity has a direct effect on emission rates.[12,13] Skin flakes, also known as squames, are the result of normal shedding of the outer skin layer (ranging from 1 to 40 μm in diameter, with average diameter of 14 μm.[14] In an indoor environment, the rate of squame generation per person has been quantified at 200,000 to 600,000 per minute, or 30 to 90 mg per hour.[15,16] These rates vary dramatically from person to person, which makes this input a good candidate for a sensitivity study in future filtration performance modeling. The most significant change from the original aerosol source model is the squame emission rate per person, and is of great importance since the number of crewmembers on the ISS has doubled since the original calculations for filtration performance.

The concept of a 'personal cloud' has been studied, as people emit aerosols not only from their skin but also from their clothing. Clothing on the body has the effect of capturing some squames, thus reducing emissions, however this is balanced by the emission of lint. Byrne et al. investigated the relative contribution of human body surfaces to the 'personal cloud' by selectively covering the face, hands and hair of test subjects with plastic wrapping while they carried out a repeatable activity pattern which was not specified.[17] A laser particle counter provided number concentration in bins with sizes >500 nm, 500 nm to 1 μm, 1 μm to 2 μm, 2 μm to 3 μm, 3 μm to 5 μm, and 5 μm to 10 μm, which are significantly smaller than the sizes of clothing fibers in Table 1. The results of this study showed that face, hands and hair contribute a negligible portion of the concentration compared to the clothing, that is, concentrations for skin and hair particles were at most 1/6 of the measured concentration of lint in the 3 to 5 μm range and only 1/20 of the measured concentration in the < 500 nm bin. Emission rates were not given in this reference, and it is assumed that no attempt was made to account for particles that were exhaled by the test subjects while in the test chamber. You et al. (2013) studied the short term personal cloud emission rates of males with different clothes and activity rates, which included both particles emitted from the clothed human body, as well as particles that may have been exhaled.[13] The exhaled particles were shown to have a negligible contribution to the personal cloud. The clothing tested included a clean room smock, polyester jogging suit, and a cotton suit. As expected, the clean room smock had the smallest particle emissions, but the polyester typically emitted slightly more than the cotton clothing. Emission rates are measured for different size ranges up to 10 µm, with the largest fraction of particles between 300 to 500 nm in diameter. The upper size limit for the personal cloud is based on the measurement range of the aerosol instrument used in this study. Activity levels did not include running on a treadmill (as crew members would exercise), but the classification of 'strong activity' consisted of brisk walking combined with periods of sitting with vigorous upper body and arm movements. This reference provides a guideline for estimating different emission rates between crewmember diurnal activities such as exercising and working versus sleeping.

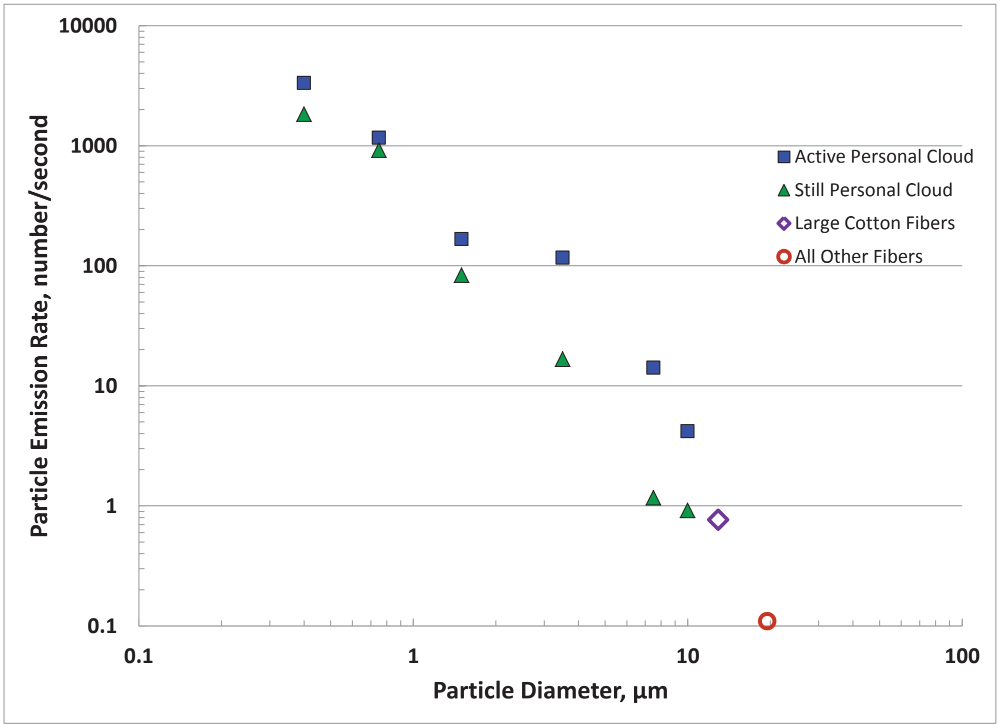

Figure 1: Personal cloud and fiber emission rates combined to account for a larger size range of lint data. Solid symbols are from personal cloud data (You et al.) and open symbols are the original fiber emission data in Table 1.

In Table 2, active and still rates were averaged for the given rates per minute, as it was assumed that crewmembers would spend 12 hours active (exercise and work) and 12 hours still (sleep and quiet work) per day.

Crewmembers prefer cotton clothing, so part of the lint emission rate estimate in the new table is based on the cotton suit 'personal cloud' data, with each 24 hour period assumed to be divided equally between strong activity and inactivity. However, lint particles are known to be much larger than 10 µm, as evident in Table 1. So the personal cloud data makes up only part of the lint estimate, and is augmented by the fiber emission rates in the original load of Table 1. Figure 1 shows that the approach of combining data from the two sources is reasonable. Note the logarithmic scales for both axes, which accounts for lint in all size ranges, from 300 nm to about 20 µm. The majority of the fiber emissions were cotton, and all other fiber types in Figure 1 were combined in a single data point for simplicity. While Nomex and glass fibers cannot be attributed to crewmember clothing, they were separate entries in the original table, making up only 0.08% of the particle number emission rates. They are not treated separately in the new table, although this could be re-considered in future updates if data provided justification that they are significant aerosol sources.

The large proportion of lint in the load model is consistent with data from the ISS vacuum bag sieving analysis in which 51% of the total weight of debris greater than 500 µm consisted of lint.[10] Another report summarized the analysis of a used ISS filter element by microscopy, which concluded that most of the debris was fibrous, predominantly cotton lint.[18] Pictures of some lint fibers from the ISS filter analysis in Figure 2 generally confirm the fiber diameters in Table 1.

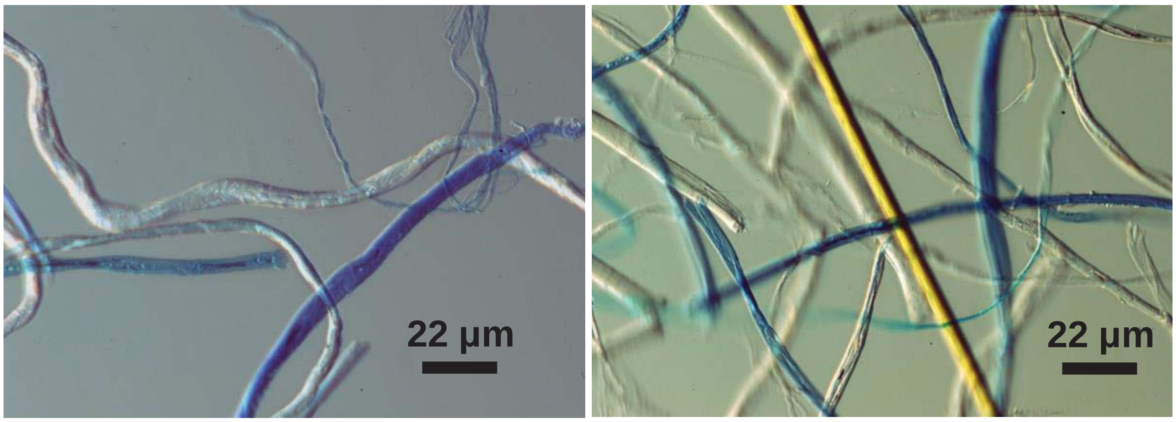

Figure 2: High magnification of cotton fibers and cotton linters (very thin, short fibers) on left, more cotton fibers and a yellow synthetic fiber (right), 443X magnification. Photos courtesy of Victoria Bryg.

Vacuuming is a common source of indoor aerosols, and this is a known phenomenon on ISS since it is a common practice to turn off the smoke detectors during cleaning to avoid false alarms. Some emissions from vacuuming are from the vacuum motor brushes which emit particles below 0.3 µm,[19] however, the largest sources of vacuum particle emissions are from re-suspension of disturbed dust on adjacent surfaces, or re-emission of vacuumed particles when the incoming air passes through a paper or cloth vacuum bag. The ISS vacuum does not emit the latter type of dust since the air sucked into the machine passes through HEPA filter to remove dust from the exhaust air. A conservative estimate for aerosol mass concentration emissions from vacuuming on ISS is 0.07 mg/minute,[19] which would be representative of the entire size range of squame and lint diameters. An alternate source gives size-segregated data in terms of number emissions of 3.797E+10 particles/ minute for 0.02 to 0.3 µm, and 3.0E+7 particles/ minute for 0.3 to 1.0 µm (based on the measurement ranges of the research instruments).[20] The given size ranges of the number emissions data are important for modeling size-dependent filter performance. These generation rates are considered conservative because the type of vacuum used for this data was not specified, but in all likelihood was not a HEPA vacuum. Squame and lint can be classified as ‘dust’ in this context, and these two combined make up the largest proportion of the matter that is removed by vacuuming. This is confirmed by the debris analysis on the contents of the vacuum bag returned from ISS.[10]

A source of particles that was not in the original load model is laser printer emissions. Early studies showed a large range of particle emission rates from one printer to another.[21-23] There are various particle formation mechanisms, and emissions vary with cartridge age, toner coverage and temperature (which is related to number of pages printed in succession). A 2011 study by the California Air Resources Board (CARB) on office equipment showed that an emission rate in terms of particles per second of printer operation is approximately the same as the particles emitted during the printing of one page.[24] The emission rate of 1.E+09 particles per page is a conservative value to assume for standard conditions covering a variety of cartridge ages, and at both cold and warm starting temperatures. The table reflects an estimate of 15 pages printed per minute. For a mass concentration emission rate, the German eco-label The Blue Angel award criteria requires, among other things, that particle emissions should be below 4 mg/(device-hr).[25] Toner particles range between 2 and 10 µm, however, particles emitted from printers have much smaller median diameters, on the order of 100 nm[26] and are thought to be formed by secondary chemistry during the printing process which produces volatile organic compounds from heated paper and toner, and ozone which is a by-product of the electro-photographic process. Research is ongoing to understand particle formation mechanisms in laser printing. Currently there are two printers, one in the U.S. lab and the other in the Service Module. The amount of laser printing on ISS varies, but a realistic estimate is an average of 10 pages per day.[2]

Table 2. Updated Aerosol Generation Rates

Type of Aerosol	Particle size	Generation Rate per Person		Reference, Comments
		Number of particles [#/(person*minute)]	Mass [mg/(person*minute)]	
Squames	14 µm, average	2.0E+5 to 6.0E+5	0.5 to 1.5	Gowadia 2001, Milstone 2004
Personal Cloud	.3 - .5 µm	2583.33		You et al. 2013 (Combined Lint Generation Rate)
	.5 - 1 µm	1041.67		
	1 - 2 µm	125.00		
	2 - 5 µm	66.67		
	5 - 10 µm	7.67		
	>10 µm	2.54		
	total	3826.88		
Cotton Fiber Lint	12.9 µm	0.767	0.0674	Table 1 (Combined Lint Generation Rate)
Other Fiber Lint	19.5 µm	0.109	0.00806	Table 1 (Combined Lint Generation Rate)
Human hair	58.8 - 68.4 µm	0.0053	0.0150	Table 1 (not expected to load the filter significantly)
Metallics	813 µm	0.0376	0.0298	Table 1
Paint chips	51.0 - 1270.0 µm	0.0326	0.0118	Table 1 (particles > 841 µm will not enter the filter)
Plastics	813 µm	0.0898	0.0405	Table 1
		Generation Rate by Event or Activity		
		Number of particles [#/minute]	Mass [mg/minute]	
Vacuuming	.02 to .3 µm	3.797E+10		Afshari et al. 2005
	.3 to 1 µm	3.00E+07		
	.3 to 20 µm		0.07	He et al. 2004, size based on squame & lint diameters
Laser Printer	median ~100 nm	2.50E+08	0.0667	CARB report CEC-500-2011-046, Blue Angel Env. Standard
3D printer	11.5 to 116 nm	1.90E+11		Stephens et al. 2013
Velcro	7 to 50 nm			GASP Laboratory Testing
Secondary Organic Aerosol	30 to 200 nm			Wierzbicka et al. 2009, Sarwar & Corsi 2006

Another process that was newly introduced on ISS is 3D printing. The '3-D Printing In Zero-G' technology demonstration experiment is the first step towards establishing the ability to manufacture parts on ISS.[27] The experiment is expected to be launched in summer of 2014 with the expectation that a permanent Additive Manufacturing Facility (AMF) will eventually be created. Thus, 3-D printing will potentially affect the future ambient air quality on ISS. While the 3-D printing market is experiencing massive growth, there have been few studies on aerosol particle emissions during additive manufacturing. One study documented emissions rates from two different thermoplastic feedstocks, acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), which produced 1.9E+11 and 2.E+10 particles per minute, respectively.[28] The '3-D Printing In Zero-G' experiment will demonstrate how the behavior of ABS is affected by microgravity. Some 3-D printers have relatively open configurations, while others have walls surrounding the heads, mainly for the purpose of temperature control. Particles emitted during printing are in the ultra-fine range, so on Earth, their settling velocities are very low owing to slip, and the particle sizes in Stephens et al. have settling velocities ranging from approximately 7E-08 to 9.E-07 m/s. Thus, they could remain airborne for days and months as they fall in still air from a 1.0 m bench top.

In addition to squame and lint emitted during exercising, there are mechanically generated metal wear particles from exercise equipment. The time allotted for exercising is 2.5 hours per crewmember per day on ISS, although it has been documented that the average time spent exercising is significantly less.[29] Some estimates could be made based on particle data generated from a sliding contact and particle emissions from metal friction testing. Particles ranging from 20 nm to 10 µm were generated from chrome steel (100Cr6) at rates between 500 and 4000 particles per minute under different conditions.[30] Generation rates are a function of sliding speed and contact pressure, which are highly design-dependent. Table 1 includes a category called 'metallic', which would encompass this type of

[2] Conversation with astronaut Dr. Karen Nyberg, 3-20-14.

particle, however, the size given is 813 μm, which is not in the range of the wear particles in the literature. There may be an opportunity to measure emissions from a prototype of ISS exercise equipment or from similar exercise devices in order to quantify this source. For the current study, the metallic category from Table 1 is retained as it originally appeared, with a 'per person per minute' generation rate.

An additional known source that has not been quantified is the generation secondary aerosols from terpenes reacting with ozone (which was discussed in the laser printer section). In most buildings, the typical indoor concentration of ozone (which originates outdoors) ranges from 10 to 50 ppb.[31] The secondary organic aerosol (SOA) emissions are highly dependent on the species of reactive organic gases are present, some which are generated from ISS infrastructure, and other gases from cleaning products, personal care products and cosmetics brought by crewmembers that are unquantified. The cleaning product used outside the hygiene compartment consists of disinfectant wipes, which are used to wipe down panels which capture sweat, dust and lint. Future work can be done to estimate an upper bound of organic gas quantities based on some SMAC (spacecraft maximum allowable concentration) limits which would allow an estimate of SOA on ISS. Ozone is not monitored and there is no SMAC limit. From the many papers available about specific reactions that produce SOA, mean particle sizes are in the range from 30 to 200 nm.[32,33]

Velcro is ubiquitous on ISS, and is a known source of particles, however, it was not included in Table 1. Measurements of Velcro particle emissions were made in the fire characterization facility at Glenn Research Center (Gases and Aerosols from Smoldering Polymers [GASP] Laboratory), which has a 326 liter glovebox which can be purged to nearly zero initial concentration. Two aerosol reference instruments were used to measure Velcro particle concentrations. A Scanning Mobility Particle Sizer (SMPS) Spectrometer (Model 3936, TSI, Shoreview, MN, USA) provides a 64-bin particle size distribution in the sub-micrometer range. The SMPS requires a two minute scan through a range of voltages to acquire a size distribution based on the particle electrical mobility. The Water Condensation Particle Counter (WCPC, Model 3787, TSI Inc.) measures aerosol number concentration of particles between 5 nm and 3 μm. This device operates by initially cooling the aerosol sample and then passing the sample stream through a region of supersaturated water vapor where the particles grow as water condenses on them. When particle-containing droplets pass through a laser and scatter the light, a pulse is created, which is detected and counted.

The maximum allowable size of a Velcro piece on ISS is 4" x 4", per JSC 27301F and Cargo Mission Contract CMC-NFS-000078-MP-SPL Rev. E. Three different samples were tested: unused flight Velcro (black), unused 'Industrial Strength' Velcro from a retail store, and one used piece from a Space Food Kit from the Glenn Research Center Education Office, which had been returned from a Shuttle mission (this piece was only 1" x 4"). The goal was to see if any debris embedded in the Velcro would become resuspended, potentially creating significantly larger particles than those generated from the Velcro itself.

Results of the tests are shown in Figure 3, which were measured with the SMPS once steady-state concentrations were achieved in the glovebox while mating and demating the samples approximately 48 times per minute. The flight qualified Velcro samples produce very high particle concentrations in the smallest portion of the measurement range, with the steady-state WCPC concentrations at 3.76E+5 particles/cm^3 for the black Velcro, and 3.87E+5 particles/cm^3 for the Food Kit Velcro. The white sample purchased at a retail store has significantly lower particle concentrations over the entire size distribution, reaching a steady-state WCPC concentration of 1.85E+4 particles/cm^3, with a mode below 10 nm similar to the others. The SMPS measurement range was adjusted when measuring the Food Kit Velcro in hopes of seeing a second mode at larger sizes, potentially indicating the liberation of embedded debris in the Velcro pile into the air. There is a small increase in the particle population above 400 nm, however, further testing would be required to verify this behavior, preferrably with 'dirtier' Velcro.

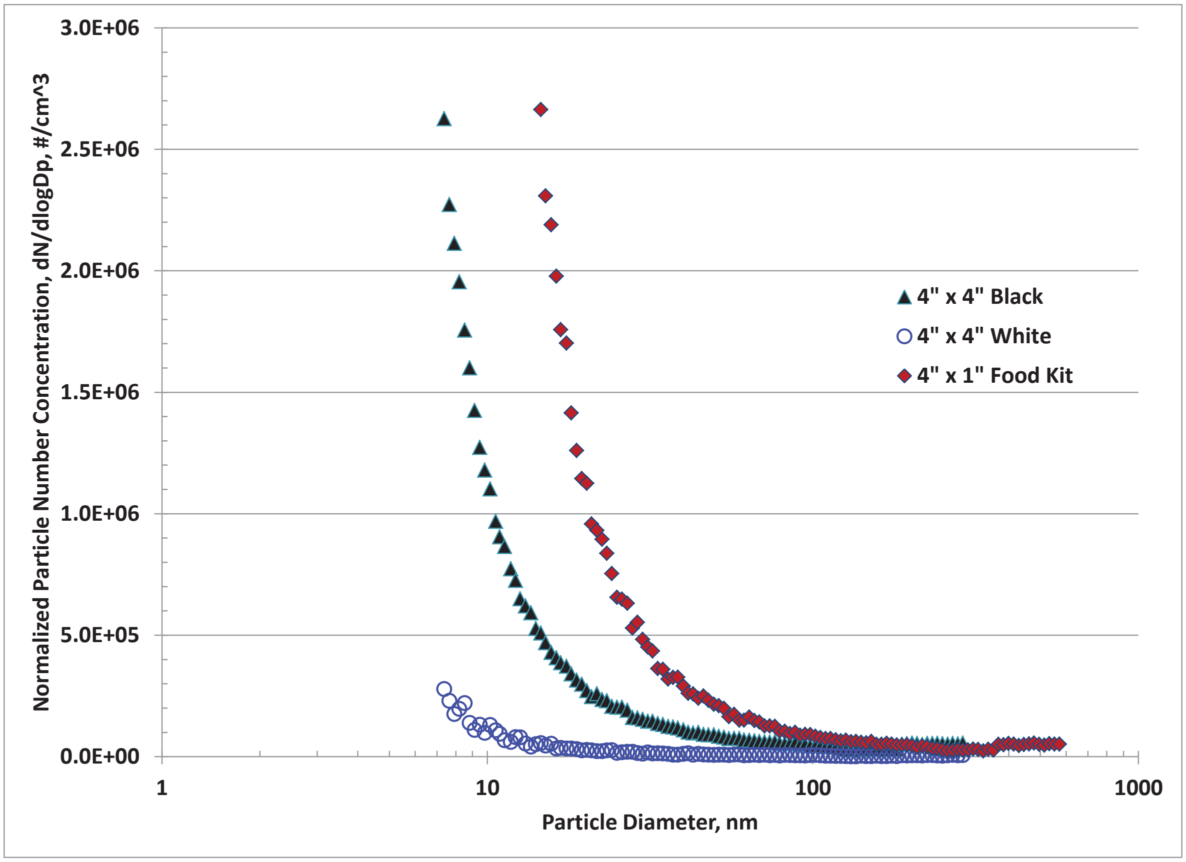

Figure 3: SMPS particle size distribution measured while mating/demating Velcro in a purged glovebox. The highest concentrations are from flight qualified Velcro vs. the white sample, which was purchased at a retail store.

The Velcro pile side of the fastener is mounted on ISS walls, while the hooks are mounted on the object to be secured. Dirt, lint and sweat are undoubtedly collecting in the fibers of the pile and are available to be re-entrained in ISS cabin air upon de-mating. Resuspension of particulate matter from carpets due to human activity has been studied and modeled, having a significant effect on indoor air quality.[34] The Velcro on ISS walls can be considered a similar source of pollutants. Only the particle size distribution of Velcro particles is given here, not an emission rate. Regardless, the size range and high concentrations recorded indicate that particle emission rates from Velcro should be quantified and included in a future refinement of the ISS aerosol inventory.

IV. Conclusions and Future Work

ISS aerosol emission rates used in the original ISS filter element model has been updated with literature sources, and health-relevant particle sizes have been included, bringing particle sizes down to the nanometer range. Ideally, the most penetrating particle size, 300 nm, and other size-segregated data would be included in size-dependent filtration efficiency modeling. Ongoing work may reveal additional sources, which can be estimated or quantified for future updates. Future experiments can be performed to measure potential reductions in lint emissions with various fabrics and pre-treatment options, as well as quantifying Velcro emissions and resuspension of debris in old 'dirty' Velcro returned from ISS. Another investigation that may be of value is to measure metallic or other particles generated from prototypes of ISS exercise equipment. Sensitivity studies of the filtration model to all quantities in the updated tables would shed light on which sources have the most effect on the ISS indoor air quality.

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Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Aeronautics and Space Administration or the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

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