Aerosol Sampling Experiment on the International Space Station

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The International Space Station (ISS) is a unique indoor environment which serves as both home and workplace to the astronaut crew. There is currently no particulate monitoring, although particulate matter requirements exist. An experiment to collect particles in the ISS cabin was conducted recently. Two different aerosol samplers were used for redundancy and to collect particles in two size ranges spanning from 10 nm to hundreds of micrometers. The Active Sampler is a battery operated thermophoretic sampler with an internal pump which draws in air and collects particles directly on a transmission electron microscope grid. This commercial-off-the-shelf device was modified for operation in low gravity. The Passive Sampler has five sampling surfaces which were exposed to air for different durations in order to collect at least one sample with an optimal quantity of particles for microscopy. These samples were returned to Earth for analysis with a variety of techniques to obtain long-term average concentrations and identify particle emission sources. Results are compared with the inventory of ISS aerosols which was created based on sparse data and the literature. The goal of the experiment is to obtain data on indoor aerosols on ISS for future particulate monitor design and development.

Nomenclature

BFE	=	bacterial filter element
COTS	=	Commercial off-the-shelf
CCSEM	=	computer controlled scanning electron microscopy
EDS	=	energy dispersive x-ray spectroscopy
EMI	=	electromagnetic interference
GMT	=	Greenwich Mean Time
HEPA	=	high efficiency particulate air
HR-SEM	=	high resolution scanning electron microscopy
ISS	=	International Space Station
PMM	=	Permanent Multipurpose Module
SEM	=	scanning electron microscope
STEM	=	scanning transmission electron microscopy
TEM	=	transmission electron microscope
TPS100™	=	Thermophoretic Personal Sampler 100[2]
UNC-PAS	=	University of North Carolina Passive Aerosol Sampler
C	=	Celsius
cm	=	centimeter
g	=	gram
kg	=	kilogram
m	=	meter
mg	=	milligram

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[2] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Aeronautics and Space Administration (NASA), nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

min	=	minute
mL	=	milliliter
mm	=	millimeter
nm	=	nanometer
μm	=	micrometer

I. Introduction

IN reduced gravity, the size ranges aerosols are much larger and persist longer than on Earth because they are not removed by gravitational settling. This presents unique challenges for maintaining the indoor air quality in spacecraft. High concentrations of inhalable particles, with diameters of 100 µm and below, are responsible for respiratory and eye irritation and crewmembers have complained about 'dusty' air. It is noteworthy that the British astronaut Tim Peake was quoted as saying, "It's wonderful to be back to fresh air" within hours of returning to Earth.[1]

A. Filtration on ISS

Filtration is the current control strategy for airborne particles on the International Space Station (ISS). Near-HEPA performance is achieved by the Bacterial Filter Elements (BFE) on ISS,[2] and to prolong filter life, a Nomex® screen with 841 µm openings covers the filter media, preventing larger particles from building up on the filter pleats themselves. This debris is vacuumed by crewmembers during weekly housekeeping chores. Figure 1 shows the function of the Nomex® screen which protects the filter media from damage during vacuuming. Filtration models have predicted that the ISS filters are properly sized with appropriate air handling system variables and clean the air sufficiently.

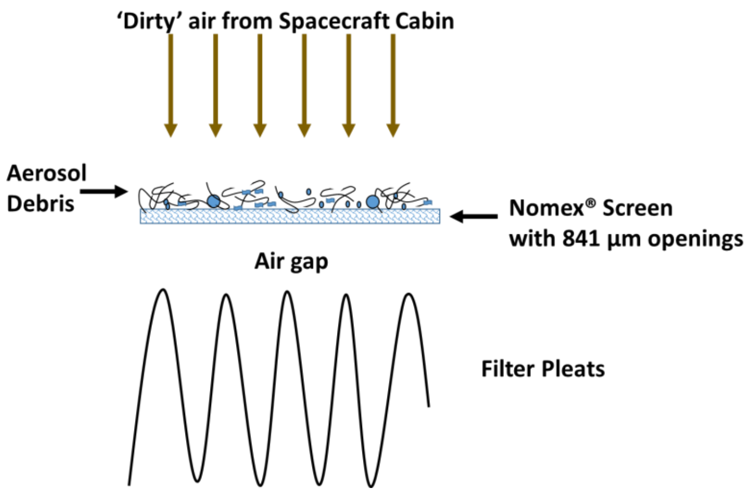

Figure 1. Graphic showing airborne debris collection on Nomex® screen preceding ISS BFE filter media.

B. Aerosols on ISS

Although gas sensors for space applications have been an area of active research for quite some time,[3,4] particulate monitoring for the indoor spacecraft environment is an identified technology gap and is now being addressed.[5] The health effects of elevated CO_2 levels and the toxic post-fire scenario are well-documented, however, exposure to 'nuisance dust' in the spacecraft cabin is less dire. Health effects from aerosol exposure are dependent on many factors, including the type of pollutant, solubility in water, particle size and shape, not to mention the health of the individual. The particulate matter requirement for missions longer than 14 days[6] limits the "concentration for total dust to <3 mg/m^3 and the respirable fraction of the total dust <2.5 µm in aerodynamic diameter to <1 mg/m^3." There is currently no measurement capability for airborne particles on the ISS to verify whether the requirements are met.

An experiment was performed on the Space Shuttle in 1990 and 1991 to characterize airborne particulate matter[7] and results showed that the air quality was comparable to that of a typical office environment on Earth. This is not surprising, as samples were taken on days 2 and 7 of an 11-day mission which started with 'clean' air in the 71.5 m^3 habitable volume. In contrast, the ISS is ~810 m^3 and has been continuously inhabited for over 16 years without the ability to replace the existing air. The current ISS filtration system was designed based on estimates of particle sources from crewmembers and their activities. Recently an updated inventory of aerosols on ISS has been compiled and documented in which new sources were identified and emission rates are updated based on indoor air quality data in the literature.[8] In the absence of real data, this survey is the best information available, but it cannot predict whether the ISS particulate matter requirements are met. Therefore, an aerosol investigation was justifiable to obtain data on indoor air pollutants on ISS.

II. Experiment Concept

The Aerosol Samplers experiment was funded by the Advanced Exploration Systems Life Support Systems project to address the need for data on airborne particles in the spacecraft environment. The experiment was designed to collect data from different locations on ISS as well as during particle-producing activities, such as exercising. This experiment was designed with redundancy to maximize success and with multiple units to minimize required crew time for operations.

A. Sampling Particles vs. Real-time Measurements

The long-term goal is real-time measurement of particles in the spacecraft, however, optimal instrument design depends on knowing the types and sizes of aerosols to be measured. Aerosol instruments often rely on light scattering or other indirect measurement techniques which may have limitations such as dependence on a certain morphology or material. For example, particles that are flakes or fibers scatter light differently than spheres, and refractive index is a factor for darker materials whereby a portion of incident light is absorbed, reducing the quantity of light scattered vs. a lighter colored material. Furthermore, different measurement techniques are required for different size ranges of aerosols, particularly in the spacecraft cabin environment which includes a large fraction of particles on the order of tens and hundreds of micrometers. The ultimate particulate monitor will most likely combine two aerosol measurement techniques in one instrument. Another challenge in measuring aerosols is the design of the instrument inlet. Larger particle and smaller particle loss mechanisms differ so two different inlets may be required as well. Therefore, it is prudent to investigate aerosols on ISS in two stages: 1) Collect particles and bring them back to Earth for microscopic analysis, and 2) Send an instrument to ISS for real-time measurements of aerosols in the spacecraft cabin. The outcome of the first flight experiment is data which will guide the design of the instrument flown in the second flight experiment. The Aerosol Samplers flight experiment fulfilled the first stage of this sequence with particle collection activities on ISS in December 2016 and January 2017. Two different samplers were flown to collect the entire size range of particles of interest.

B. Active Sampler

The Active Sampler used in the experiment, shown by Fig. 2, is the commercial off-the-shelf (COTS) TPS100™ Personal Nanoparticle Sampler by the company RJ Lee Group in Monroeville, PA.[9,10] The COTS version measures 122 mm × 63 mm × 38 mm, weighs 320 g and samples for eight hours with a volumetric flow rate is 5 mL/min, after approximately three hours of charging. It is optimized to collect particles from 10 nm to 250 nm in diameter. The principle of operation is based on the thermophoretic force acting on a particle as it passes through a narrow channel with a very large thermal gradient. Particles are driven to the cold side of the channel where the collection substrate is placed, which in this case is a transmission electron microscope (TEM) grid. Thermophoretic samplers have been used to collect smoke particles in NASA's spacecraft fire safety work in the past.[11,12]

Figure 2. The Active Aerosol Sampler is the modified COTS TPS100™ Personal Nanoparticle Sampler. *Commercialized by RJ Lee Group.*

Some aspects of preparing the payload for flight were simplified by starting with COTS hardware but extensive assistance was provided by RJ Lee Group in creating the Safety Data Package, adapting aspects of the design and simplifying operation. The TPS100™ required modification for low gravity operation because the heat of the electronics sinks to the outer metal case is cooled by natural convection in Earth applications. In the absence of buoyant air flow on ISS, it required a copper heat sink and fan for active thermal control to maintain a safe touch temperature for the crew, and also to ensure successful operation, because the thermal design of the device includes a firmware thermal breaker which shuts the sampler off when the internal set temperatures are not maintained. This ensures that the thermal gradient is preserved and sampling takes place only under user-prescribed conditions. Figure 2 shows the ISS Active Sampler with the fan, which is at the opposite end of the aerosol inlet. Smoke visualization tests were performed to ensure that the fan operation did not interfere with the sample inflow. The addition of the fan slightly affected the sampling duration that can be achieved on one battery charge.

The COTS active sampler operation requires the user to input the ambient temperature and relative humidity, as well as the temperatures defining the thermal gradient for particle collection (hot side temperature can range from 85 °C to 120 °C, and cold side from 25 °C to 35 °C). To simplify crew operation for the experiment, typical ambient ISS conditions and prescribed hot and cold setpoints were programmed into the memory and the firmware was modified to only require one button to initiate sampling. Electromagnetic interference (EMI) and sound tests were performed and the batteries and chargers underwent testing. EMI susceptibility testing was waived since the device has a history of commercial use and no critical decisions concerning crew health would be based on the operation or outcome of the Active Sampler.

The sampling cartridge of the Active Sampler effectively replaces the inlet channel with every use to prevent cross-contamination between samples. As shown in Fig. 3, a cover keeps the cartridge free of contamination before and after sampling, and particles are collected on the 3 mm diameter nickel TEM grid which is held in place by a small magnet. The sampling port is keyed to ensure that the cartridge is inserted with the TEM grid in the proper orientation.

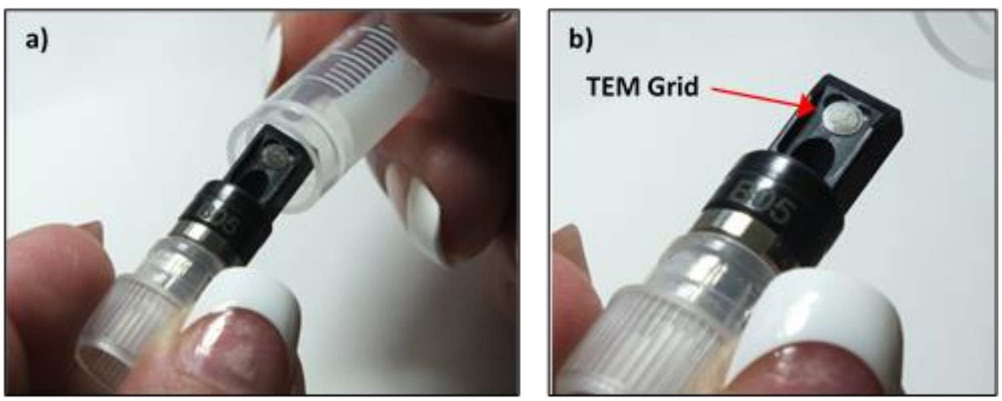

Figure 3. The Active Aerosol Sampler inlet cartridge. *a) A protective cover keeps the cartridge free of contamination before and after sampling, b) The TEM grid, where particles are deposited, is held in place by a small magnet. Photos credit: RJ Lee Group.*

C. Passive Sampler

The Passive Sampler design was inspired by a COTS design which relies on gravity, also commercialized by RJ Lee Group. The University of North Carolina Passive Aerosol Sampler (UNC-PAS)[13,14] has been used in air pollution studies and requires longer sampling durations than typical active aerosol sampling, on the order of weeks.[15,16] Initial studies are required to determine the exposure duration for optimal particle coverage. In the case of too heavy coverage, the particles overlap and boundaries are indistinguishable even under high magnification. Conversely, in the case of too sparse coverage, there are fewer particles to look at and it requires significantly more time for the microscope operator to find them. Since a simple preliminary study on sampling times is not feasible on ISS, the Passive Sampler was designed with five separate sampling substrates that would be exposed for different durations (2 days, 4 days, 8 days, 16 days and 32 days), with the expectation that one of the surfaces will have optimal particle coverage for microscopic analysis.

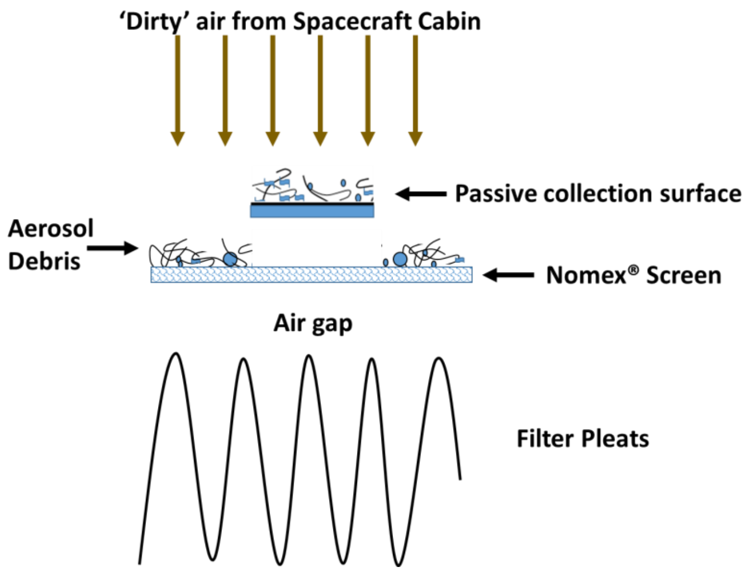

Figure 4. Passive sampling concept in low gravity. *Airborne particles are collected on a substrate in the path of air flowing into the ISS filter*.

The biggest challenge with passive sampling on ISS is the absence of gravity, but as shown in Fig. 1, the screens on the ISS BFEs present a logical location for capturing airborne debris with a passive device. Figure 4 shows the concept for the ISS passive sampler, in which a sampling substrate interrupts the particle-laden air flow into the filters. The final Passive Sampler design for the Aerosol Samplers experiment is shown in Fig. 5. The construction is virtually all metal, weighs 0.5 kg, and has individually bored housings for each drawer to prevent cross-contamination between samples. Collection substrates are removable 3 cm × 1.5 cm aluminum blocks which can be placed directly in the electron microscope. Each drawer is are O-ring sealed and has a full-stop sensation when opening, to prevent ambiguity. In order to equalize the pressure when a drawer is closed, a small cylindrical polyethylene frit (3.8 mm diameter × 3.9 mm long) allows the venting of the displaced air. Aside from the O-rings and frits, the only other nonmetal parts are pieces of carbon sticky tape that cover the aluminum collection blocks so flammability and off-gassing requirements are easily met. Thus, the Passive Sampler was nearly trivial to flight-qualify for ISS, and as a re-usable device that gives archivable samples, it can be re-flown in future aerosol experiments.

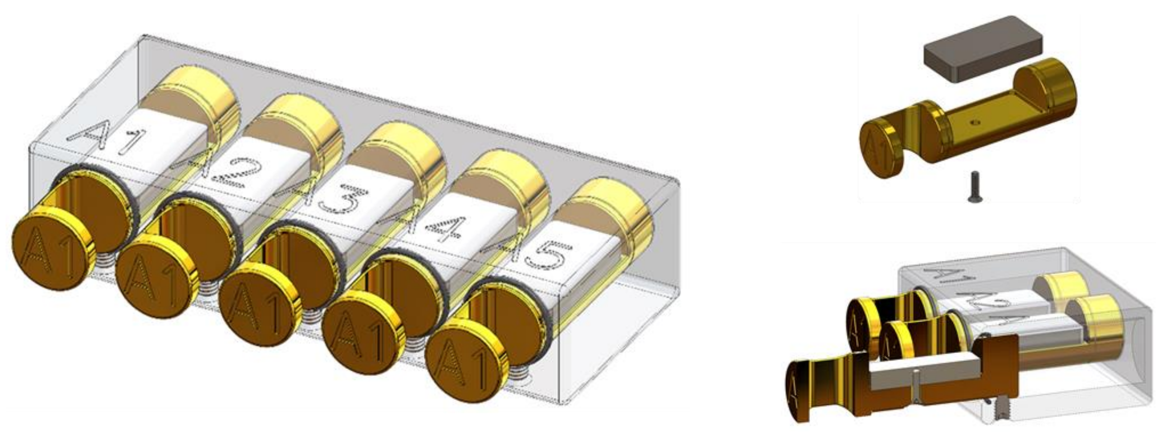

Figure 5. The Passive Aerosol Sampler has five drawers to collect particles for different durations. Collection substrates are aluminum blocks which can be placed directly in the electron microscope. Each drawer is O-ring sealed in a separate bore to prevent cross-contamination between samples. Drawers were closed on days 2, 4, 8, 16 and 32 after the initial deployment.

III. Operations

The Aerosol Samplers Experiment took place in Increment 49/50 with seven Passive Samplers deployed for 32 days, and during that time, Active Samplers were deployed in the vicinity of each Passive Sampler for six hours. This was accomplished in four deployments with the two Active Samplers. In this way the same air was sampled by both samples at some point during the experiment. The Passive Samplers collect all sizes of particles but the expectation is that the larger particles (tens to hundreds of micrometers in diameter and larger) will be captured. The Active Samplers are expected to have significant populations of smaller particles below 1 μm. Particles collected in the combination of these samplers cover all the sizes of concern for ISS air quality.

The initial deployment of all the Passive Samplers was also the first deployment of the Active Samplers. Charging of the batteries took place early in the crew day so that the Active Samplers could be deployed around the mid-day meal. This was intentionally scheduled so that the Active Samplers would be sampling for six hours while the crew was active and undertaking particle-producing activities. Once the Active Samplers were placed on the wall with Velcro, they sampled until the battery power was depleted and remained there until the next day, when the crewmember retrieved the cartridge, recorded the Greenwich Mean Time (GMT) and location on the cartridge bag before stowing. The Passive Samplers were on vents and filters which are normally keep-out zones for payloads, but exceptions were granted because the resulting data is valuable to the ISS program. Furthermore, considering that three drawers are closed in 8 days, the actual amount of area obstructed is small. Passive Samplers were deployed in the U.S. Lab (2 locations), Node 1, Node 2, Node 3 (2 locations) and the Permanent Multipurpose Module (PMM). Locations were chosen to capture particles during crew exercise, in the hygiene area, near a hatch opening from a visiting vehicle, and in a storage area (to compare particle numbers with locations with regular human traffic). A bonus science sampling was performed separate from the Passive Samplers during crew exercise in two locations in Node 3 as well. Figure 6 shows the Active and Passive Samplers deployed in Node 3 during the initial operations. The Sampler Cartridge Bag is attached to the wall with Velcro nearby and holds the Active Sampler plug and the handle of the cover of the cartridge in use. Note that the vent had debris and hair on it even before the Passive Sampler was attached to the frame with Velcro. Regular vacuuming chores took place during the 32-day deployment and the crewmembers were instructed to remove each Passive Sampler, place it on a nearby Velcro piece during vacuuming, and then replace it in the original position when done. Active Sampler cartridge retrieval and Passive Sampler drawer closing were flexible activities in the timeline and took 15 minutes or less each. Figure 7 shows Passive Sampler on a BFE in the U.S. Lab, with all drawers open in the left image (day 1), and with two drawers open in the right image (after day 8).

Figure 6. Active and Passive Samplers deployed in Node 3. *The Sampler Cartridge Bag is attached to the wall with Velcro nearby and holds the Active Sampler plug and the handle of the cover of the cartridge in use.*

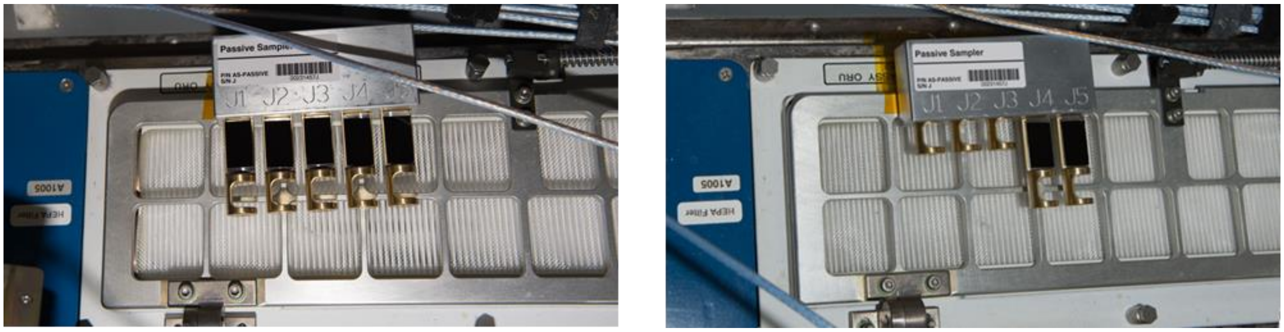

Figure 7. Passive Sampler S/N J shown deployed on a US Lab BFE. *Left: Upon initial deployment, all five drawers were open. Right: After 8 days, three drawers were closed, with the remaining drawers closing on days 16 and 32 from initial deployment.*

IV. Analysis Techniques

RJ Lee Group will perform the microscopic analysis of the returned samples, with a variety of techniques such as Scanning electron microscopy (SEM), High resolution scanning electron microscopy (HR-SEM), Ultra-high resolution scanning electron microscopy (UHR-SEM) with scanning transmission electron microcopy (STEM) capabilities. The resulting images will provide particle morphology and general size information, with the ability to identify chemical composition by Energy Dispersive X-ray Spectroscopy (EDS). For samples with optimal coverage, Computer controlled scanning electron microscopy (CCSEM) will be performed, which creates a particle size distribution by automated image analysis, counting millions of particles in a matter of hours. Results can be converted to number concentrations, and with an assumed density, to an estimate of particle mass concentration for comparison with the ISS particulate matter requirement. Raman spectroscopy can provide information on carbonaceous features, and stoichiometric information for particles from 0.5 μm to 1 μm. In addition to these capabilities, individual particles within a sample can be relocated between multiple instruments. The compiled data will provide insight for the design of the future particulate monitor for long-duration missions, and potentially identify significant sources of particles that can be mitigated in future spacecraft designs.

V. Conclusion

The Aerosol Sampling Experiment was first funded in January 2015, with payload hardware delivered to Cargo Mission Control in May 2016 and experiment operations were completed in January 2017. Using COTS hardware as the basis for the experiment accelerated the schedule significantly. The payload hardware has great utility for future air quality investigations, to provide insight and comparison data alongside a real-time aerosol instrument. The Aerosol Sampling experiment has obtained the first high-quality, archivable samples from multiple ISS locations to quantify particulate matter. This data will correct and/or validate the inventory of aerosol emission sources and will provide insight for future filtration systems and aerosol instrument design.

Acknowledgments

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