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Characterization and Measurement of Spacecraft Airborne Particulate Matter

Marit E. Meyer[a]*

[a] *NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio USA 44135*, marit.meyer@nasa.gov
* Corresponding Author

Abstract

The International Space Station (ISS) gives a 6-member astronaut crew the ability to live and work in low Earth orbit. It is a unique indoor environment, which has served as both home and workplace to over 230 people since the year 2000. In this low gravity environment, smoke does not rise and cookie crumbs do not settle the way they do on Earth, causing airborne particulate matter, or aerosols, to behave differently and pose unique hazards for crew members. In its existence, virtually the same volume of ISS air has been continuously conditioned and 'revitalized,' including the removal of particles by filtration. While gaseous constituents of ISS air are monitored meticulously, sparse data exists on the indoor aerosols. The quantity and types of ISS airborne debris have been investigated in NASA's Aerosol Sampling Experiment. Both active and passive samplers successfully collected airborne particulate matter in U.S. segments of the ISS, which were returned to Earth for characterization by microscopy and other techniques. The resulting data has informed the design of candidate particle instruments for spacecraft. In 2020, a reference-quality aerosol instrument will be flown to ISS, and will provide real-time data of particle concentrations in various modules. Smaller, more compact instruments will be necessary in future space missions, for example, in smaller vehicles, in habitats on lunar and planetary surfaces with ubiquitous dust, and also for use as wearable technology throughout missions. Miniaturized aerosol sensors, though lower fidelity than reference-quality instruments, can monitor the environment well when calibrated appropriately. Indoor air quality in spacecraft is fundamentally important to human health and comfort, and several particulate monitoring technologies will be at sufficient technology readiness levels for operational use within the next two years. Results of the Aerosol Sampling Experiment will be presented, along with the status of NASA's aerosol instrument technology demonstrations on ISS.

Keywords: aerosol, particle, spacecraft cabin, air quality

Acronyms/Abbreviations

ADI – Aerosol Dynamics, Inc.
APT – Applied Particle Technology
AST – Access Sensor Technologies
COTS – commercial off-the-shelf
CSU – Colorado State University
CTB - Cargo Transfer Bag
EDS – Energy Dispersive X-ray Spectroscopy
ESAP – Earth and Space Air Prize
FOD - Foreign object debris
HEPA - High efficiency particulate air
ISS - International Space Station
MAGIC - moderated aerosol growth with internal water cycling
MARS - Mobile Aerosol Reference Sensor
NOAA - National Oceanic and Atmospheric Administration
PM2.5 – Particle mass concentration for all particles 2.5 micrometres and smaller
PM10 – Particle mass concentration for all particles 10 micrometres and smaller
PMM - Permanent Multipurpose Module
POPS – Portable Optical Particle Spectrometer
SBIR – Small business innovative research
SD – Secure digital
SEM – Scanning Electron Microscope
TEM – Transmission Electron Microscope

1. Introduction

The quality of the air on a spacecraft has direct consequences for the health and well-being of the crew. The current mitigation technique for airborne particulate matter, or aerosols, in the air of the International Space Station (ISS) is high efficiency particulate air (HEPA) filtration. This is generally successful, but since humans and equipment are sources of aerosols, there can be localized higher concentrations. On Earth, gravity causes larger particles to settle, so under normal circumstances, humans do not have to contend with particles on the order of 100 µm in the breathing zone. In low gravity, however, particles of this size will remain airborne and follow the air flow patterns of the air handling system until they are deposited on surfaces and air intake vents.

At the outset of ISS filtration system design, potential aerosols were inventoried [1] and then updated for additional known particle sources with rates taken conservatively from the indoor air and building science literature, which are based on data from Earth research studies [2]. Vacuum bag debris provided additional information on ISS aerosols [3], and returned hook and loop fasteners were tested for aerosol emissions [4]. These fasteners had resided on ISS and collected airborne material which was embedded in the hooks, thus allowing ISS particles (from the fasteners themselves, as well as other debris) to be generated and measured in ground experiments. More complete characterization of ISS cabin particulate matter was necessary, so the Aerosol Sampling Experiment was designed and took place in Increment 50/51 on the ISS in December 2016. A repeat of the experiment has been completed on ISS in Increment 56, in 2018 and the analysis of the second set of samples is complete.

2. Experimental

The Aerosol Sampling Experiment has provided the bulk of the current information on airborne particulate matter in the spacecraft cabin. Two types of samplers were deployed in multiple locations to collect particles in two different size ranges.

2.1 Passive Aerosol Sampling

The Passive Aerosol Sampler design was created for this experiment by RJ Lee Group[*] with the goal of intercepting the flow path of dirty air flowing into the ISS vents, and collecting particles for up to five different sampling durations in the same location. Particles landed on five removable 2.5 cm × 1.5 cm aluminium substrates covered with double coated black carbon conductive tape (Ted Pella, Inc., P/N 16084-8). The passive sampler is shown in Fig. 1, in the US Lab, where it is mounted on the edge of the HEPA filter intake. Further details on passive sampling hardware can be found in reference [5].

The optimal sampling duration to get particle coverage appropriate for microscopic analysis varies by ISS location, so multiple substrates in one sampler provided different particle loadings to choose from as well as redundancy to reduce risk. Operations in Increment 50/51 collected particles for 2, 4, 8, 16 and 32 days with the ideal samples in the 8, 16 and 32-day durations. The operations in Increment 56 were simplified, with all substrates exposed for 26 days in order to collect larger amounts of particles for better statistics.

The passive aerosol samplers (each identified by a letter) were on vents and filters which are normally keep-out zones for equipment, in order to maintain the designed large-scale mixing pattern required to eliminate CO_2 pockets. However, exceptions were granted for this experiment in order to obtain valuable information on the state of the air quality on ISS. 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).

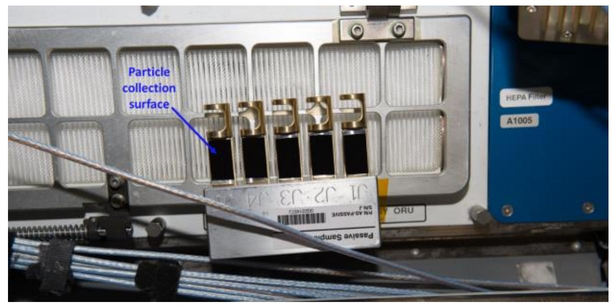

Fig. 1. Passive Sampler J is mounted on the edge of the HEPA filter in the US Lab in ISS during the Aerosol Sampling Experiment in Increment 50/51

2.2 Active Aerosol Sampling

The Active Aerosol Sampler is a commercial off-the-shelf (COTS) instrument created by RJ Lee Group, which uses thermophoresis to capture particles down to the nanometre range, directly on Transmission Electron Microscope (TEM) grids. The compact size (122 mm × 63 mm × 38 mm) and low-gravity compatible operation were distinguishing features for selection of this instrument over other aerosol samplers.

Fig. 2. The Active Aerosol Sampler is the modified COTS TPS100™ Personal Nanoparticle Sampler

Some modifications were necessary to adapt the sampler for space flight (Fig. 2), including addition of a

[*] Certain commercial software, 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.

heat sink and fan, and custom firmware for ISS operation. Further details on the instrument can be found in reference [6]. Active samplers were deployed near most passive samplers for six to eight hours to sample the same air at one point during the passive sampling.

3. Results

The final analyses of the second round of the Aerosol Sampling Experiment was completed by RJ Lee Group. This included a complete microscopic survey of the seven passive samplers and active sampler TEM grids deployed in 2018. Details of the computer-controlled microscopy analysis is given in references [6,7]. Select individual particles were imaged using backscattered-electron SEM and the elemental compositions were determined using Energy Dispersive X-ray Spectroscopy (EDS).

3.1 Typical Particles Sampled on ISS

Typical ISS particle types sampled in both increments include metal wear particles (Fig. 3), fiberglass fibres (Fig. 6), cubic salt particles (Fig. 4), and silver dendrites (Fig. 5).

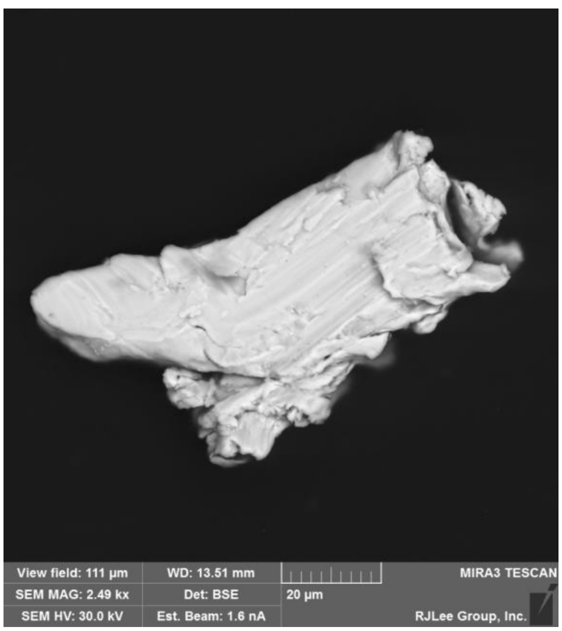

Fig. 3. Stainless steel particle (containing elements iron, nickel and chromium) collected in Node 3 during Increment 56

The stainless steel particle in Fig. 3 was sampled in Node 3, where there are two different exercise devices. Metal-on-metal contact between moving parts causes mechanical abrasion and produces particles. These emissions are ongoing during waking hours, as crewmembers must exercise two hours per day. The particle morphology is indicative of mechanical abrasion, as striations are visible. This particle is on the order of 80 µm by 50 µm (about the diameter of a human hair), and while it is not respirable, as foreign object debris (FOD) it would be an eye hazard.

The salt particles in Figure 4 were sampled in Node 1 where crewmembers eat meals. The salt that is provided as a condiment on orbit is in liquid form, because granulated salt cannot be applied to food in a low gravity environment. The liquid salt application produces micro-droplet ejections [8] which float into the cabin and evaporate, producing cubic salt crystals.

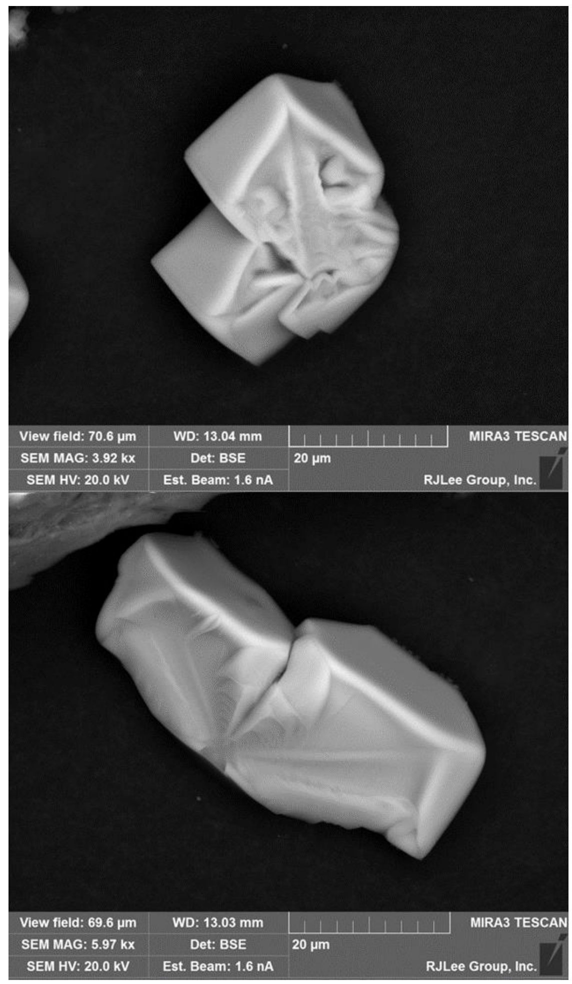

Fig. 4. Cubic salt particles (containing sodium and chlorine) collected in Node 1 during Increment 56

The silver particle in Figure 5 has unique morphology compared to other metal particles sampled. Multiple silver dendrite particles were sampled in both increments of the Aerosol Sampling Experiment. All silver particles sampled have sulphur present in the EDS spectra, as silver has a high affinity for sulphur.

These particle types were known to be in the Space Shuttle, as well [9]. Debris obtained from both ground samples and tape samples collected during flight had fiberglass and metal particles, which led to remedial actions, such as redesign, materials controls and process changes. The ground support equipment and processes that took place in the vehicle before launch were easily overhauled in the Shuttle program, however, on ISS, the ongoing ambient sources of particles in the cabin far outweigh the quantities that may be contributed from ground operations with respect to visiting vehicles.

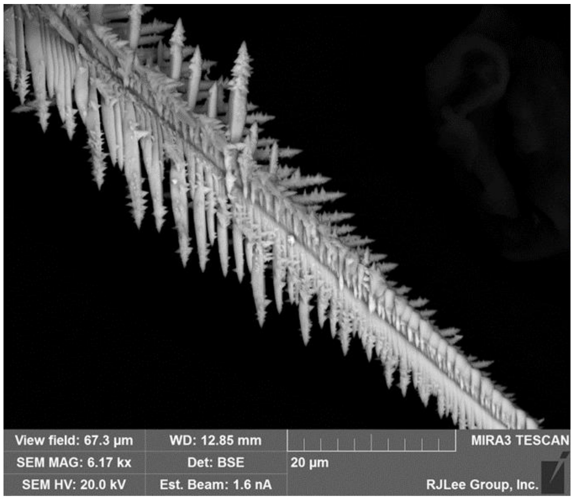

Fig. 5. Silver dendrite with trace sulphur, collected in Node 1 during Increment 56

3.2 Human-emitted Particle Types Sampled on ISS

Particle emissions from humans themselves comprised the largest fraction of collected particles, including skin flakes (Fig. 6), antiperspirant particles (Fig. 7) and clothing lint fibres (Figs. 8 and 9).

Figure 6 is a typical human skin flake, collected in Node 3 where crew exercise and hygiene take place. It has a thin wrinkled morphology, and the EDS spectrum shows carbon, sulphur, chlorine and potassium, which are indicative of human biology.

The particle in Fig. 7 has an EDS spectrum with elements aluminium, chlorine, and zirconium. This is the compound aluminium zirconium tetrachlorohydrex, which is the active ingredient in antiperspirant products. The particle was collected in Node 3, where antiperspirant is logically abundant in exercise and hygiene activities. Antiperspirant particles may be emitted during exercise, or while using wipes after exercising, in addition to the original application of the product. In the absence of laundry on ISS, the crew members wear clothing repeatedly, including exercise wear, before disposing of them in the trash. Thus, deodorant particles embedded in the fabric can be liberated and re-entrained into the cabin air when donning and doffing clothing. Antiperspirant particles are abundant in sampling results from all ISS locations.

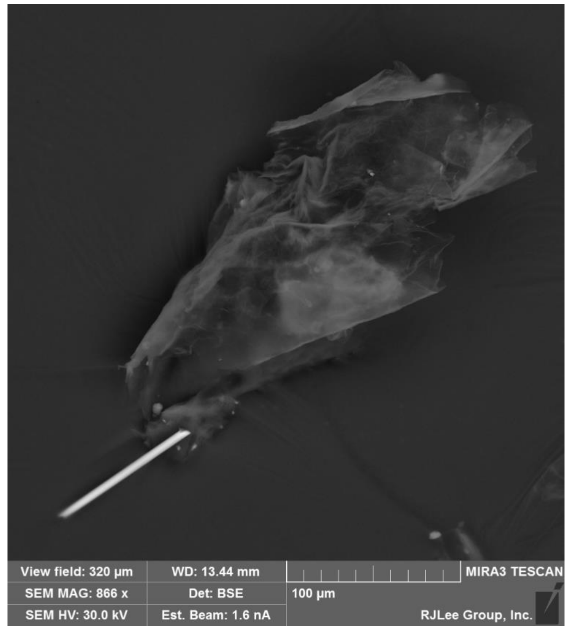

Fig. 6. Human skin flake collected in Node 3 during Increment 56, with signature elements carbon, sulphur, chlorine and potassium. The straight white rod in the lower left is a fiberglass fibre, recognizable by the signature elements aluminium, silicon and calcium.

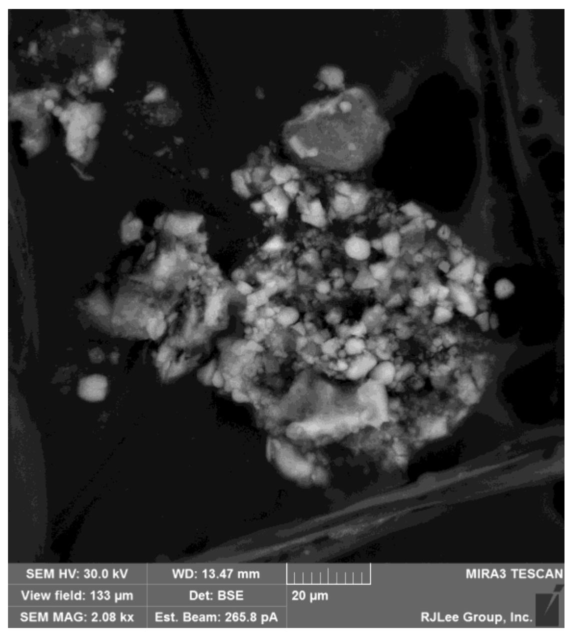

Fig. 7. Antiperspirant particle containing elements aluminium, chlorine and zirconium, sampled in Node 1 during Increment 56

Clothing lint fibres are the most ubiquitous and abundant airborne particulate matter category on ISS. Figure 8 shows a portion of a passive sampling substrate which was exposed for 32 days in Node 3 during Increment 51/52. The large quantity of lint fibres creates difficulties for microscopic analysis and image analysis of the samples, as the fibres overlap other particles and cross over each other. The choice of which passive sampling substrate to use for various microscopic analyses was heavily dependent on the quantity of fibres collected.

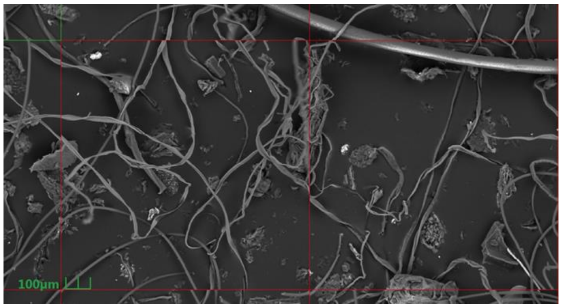

Fig. 8. Passive sampling substrate exposed for 32 days in Node 3 has multiple types of lint fibres, sampled in during Increment 51/52

The fibre examples in Fig. 9 include both cotton lint (the narrow grey fibre in the upper portion of the image) and a synthetic fibre. Cotton fibres are flat, having a twisted shape, with diameters between 10 to 20 micrometres. The U.S. crewmembers are supplied with, and generally prefer cotton clothing which is COTS. Some synthetic fibre clothing is used, particularly for exercise, and also Nomex cloth is used for many applications, such as acoustic insulation (on walls of modules) and Cargo Transfer Bags (CTB).

The larger diameter fibre in Fig. 8 has a silver coating, and is from a specialty sock, trade name X-Static®, which contains silver-coated nylon fibres. The silver coating gives the fibres antimicrobial properties and therefore may control odours. Figure 9 shows a close-up of the coating in the lower image, and it is evident that the silver has worn off in some locations, no doubt generating silver aerosols on ISS at some time in the past. X- Static® socks are not commonly used on ISS at this time, and the sampled fibre may be an artefact from prior increments.

Reference [9] includes results from the Space Shuttle fibre analysis which found cotton, wool and polyester (from garments) as well as fiberglass and Nomex fibres (from equipment). The number of cotton fibres that were counted (from crew clothing) typically exceeded other sources by a factor of 100 or more. Obtaining laundry capabilities for future missions may help reduce lint emissions in the spacecraft cabin, as well as choosing high quality fabrics and pre-washing garments.

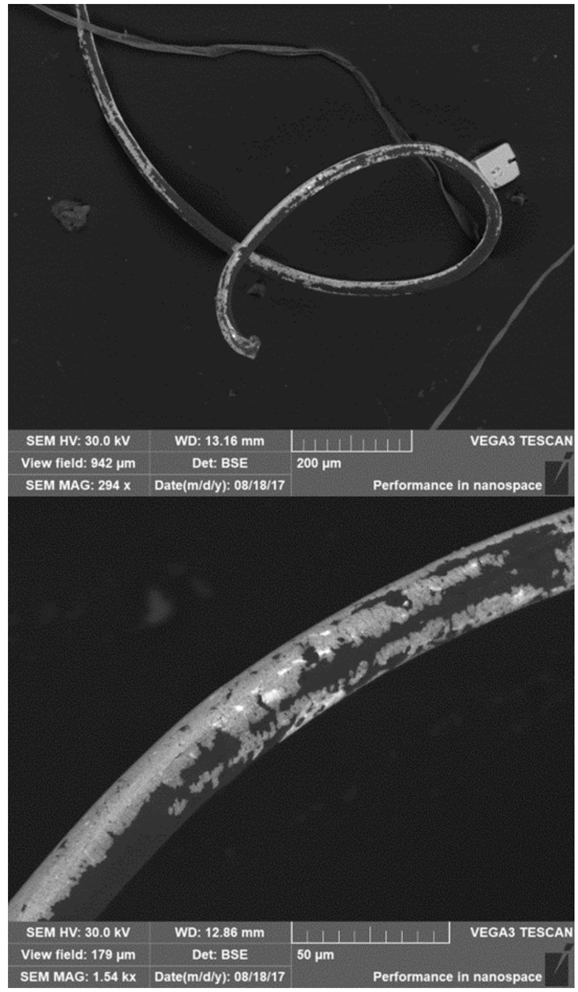

Fig. 9. Clothing lint fibres sampled in the Node 1 during Increment 51/52

3.3 Particles Collected with the Active Sampler on ISS

Active sampling did not collect large quantities of particles, and generally, the TEM grids had less than 1% particle coverage from a total of approximately 3.5 litres of sampled air. The smallest particles collected by the active samplers include titanium dioxide agglomerates (Fig. 10) and metal fume-like agglomerates (Fig. 11).

An example of a titanium dioxide particle is shown in Figure 10. These were found in all sampling locations of ISS. Most were agglomerated with primary particle sizes ranging from 60 to 100 nm in diameter and total diameters ranging from approximately 150 nm to 600 nm. Titanium dioxide is used in many consumer products including food, personal care products, clothing, paper, plastics, and paints. Many of the particles were collected in Node 3, which is adjacent to the Cupola windows. Crewmembers are advised to wear sunscreen (a known source of titanium dioxide) when near windows.

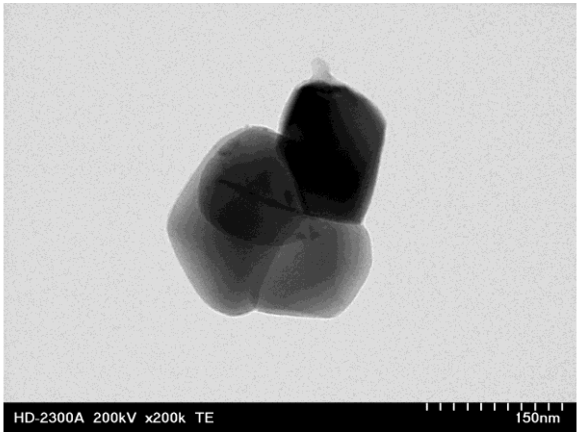

Fig. 10. Titanium dioxide agglomerate with primary particle sizes from 100 nm to 210 nm sampled in the US Lab during Increment 51/52

Figure 11 is an iron fume-like particles with zinc. Other sampled particles of this type were iron/copper, iron/chromium or iron/copper/chromium. Unlike the mechanically generated metal particles on the passive samplers (such as Fig. 3), the morphology of fume-like particles consists of spherical primary particles that have been generated by the heating of material. When a metal is subjected to high enough temperatures it vaporizes. When the vapor cools, spherical nanoparticles are formed by nucleation processes (due to surface tension) and subsequently grow larger by condensation. When present in localized high concentrations, the individual particles agglomerate, which reduces the number concentration and increases the average particle diameter significantly. The fume-like agglomerate particles sampled had primary particle sizes ranging from 3 to 20 nm in diameter and agglomerate diameters ranging from approximately 50 nm to 200 nm. The sources of these particles have not been identified.

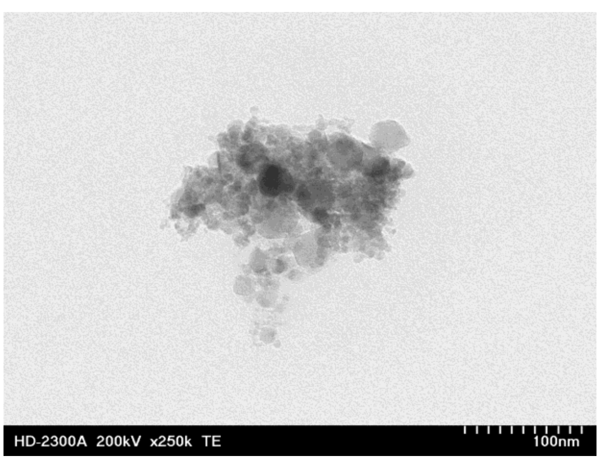

Fig. 11. Iron and zinc-rich agglomerate with primary particle size from 5 nm to 40 nm sampled in Node 3 during Increment 56

4. Aerosol Instruments for Spacecraft Cabin Particle Measurements

The characterization of ISS aerosols through active and passive particle collection with sample return has shed light on the types of airborne particles in the spacecraft cabin. The morphology and composition of many particles has allowed the identification of emission sources, however, defining actual concentrations from the results is not possible. Therefore, the next step and ultimate goal of NASA is to measure particles in real-time with instruments suitable for the low gravity environment.

4.1 Real-time particle measurements

Developing the optimal aerosol instrument 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 fibres scatter light differently than spheres. 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 particle material. Furthermore, different measurement techniques are required for different size ranges of aerosols, which is particularly important in the spacecraft cabin environment which includes a large fraction of particles on the order of tens to hundreds of micrometres. The Aerosol Sampling Experiment provided information on particle sizes, shapes and materials, which has been taken into account during the instrument selection and development process.

The NASA Life Support Systems project has sought instruments that measure indoor aerosols in spacecraft cabins to monitor air quality and for characterizing the background particle environment and major particle sources. This effort was accomplished through competitive means, such as the Small Business Innovation Research (SBIR) program. Businesses with 500 or fewer employees in the United States can propose to win government funding to perform research and development on technologies which are stated agency needs, particularly if the products have potential for future commercialization.

Currently, three different aerosol instruments are under development for space flight demonstrations on ISS.

4.2 Reference-quality Instrument for Mapping ISS Particle Concentrations

The Airborne Particulate Monitor (APM) will be the first real-time reference-quality particle measuring instrument on the ISS. It is funded by an SBIR Phase IIX grant, which covers all costs for flight hardware to be built by the company Aerosol Dynamics, Inc. (ADI). It also covers their subcontract with the hardware integrating company, ZIN Technologies for associated safety and flight documentation. The APM combines two instruments which enables it to measure both ultrafine and coarse particles. The smallest particles will be measured by the ADI instrument, MAGIC [10,11], which stands for "moderated aerosol growth with internal water cycling," which has become a commercialized product since the NASA SBIR investment. The space-friendly MAGIC prototype resulting from the SBIR phase I and II grants is a condensation particle counter with no liquid reservoir. It can be used in any orientation. This instrument will be combined with a COTS optical particle counter (the Portable Optical Particle Counter [POPS], by Handix Scientific) [12,13]. The POPS (originally funded by United States federal agency NOAA and NASA Upper Atmosphere Research Program) has been used on unmanned aerial vehicles and weather balloons to provide aerosol particle number density and size distribution measurements in atmospheric aerosol research campaigns.

The APM measures 13 cm × 28 cm × 35.5 cm and is shown in Fig. 12. It has a specially designed virtual impactor inlet to separate the particles by size for each instrument. First, a screen stops the largest particles and debris. This screen can be cleaned if necessary, and is not likely to be obstructed, as the area is a 5 cm diameter circle. After the screen, the flow is split into a large stream with 90% of the inlet air, and a minor flow stream with 10% of the air flow. The major flow takes the smallest particles to MAGIC, while the minor flow concentrates the larger particles for the POPS.

The output data from the APM is merged from the two instrument data streams and then is written to an SD card, while the APM display shows the crew only a particle number concentration for the entire size range of particles measured. The data will be transferred from the SD card and downlinked regularly during the ISS deployments, which will provide a rich data set including temperature, relative humidity, particle concentration for sizes from 5 nm to 2 micrometres, and a particle size distribution for particles from 1 to 20 micrometres. The size distribution is particularly important and will allow for the comparison of data from the Aerosol Sampling Experiment.

Twenty-four hour deployments are planned for ten ISS locations, including the areas where particles were previously sampled, and will give information on typical diurnal cycles of particle concentrations in the cabin. It is expected that the particle concentrations during crew working hours will be significantly higher than during crew sleep. The difference between these particle levels will quantify the particle emissions from operational equipment in the module.

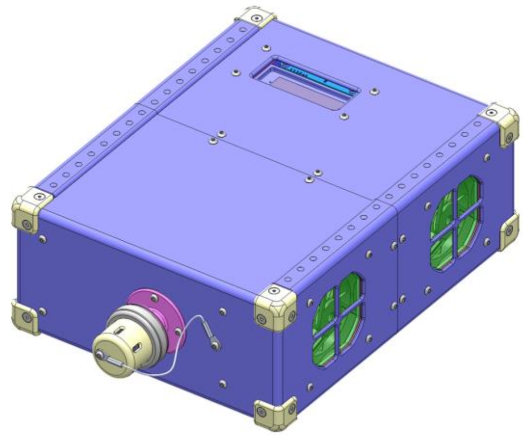

Fig. 12. The Airborne Particulate Monitor (APM) which measures particles from 5 nm to 20 micrometres and is scheduled for a technology demonstration experiment on ISS in 2020

Multiple deployments in the same location will provide better statistics and provide opportunities to measure during different activities. For example, when visiting vehicles arrive to ISS, hatch opening is a very interesting time to measure particles. A good comparison would be to have one 'general' deployment in Node 2, and then have one deployment near the mobile orange duct (that vents and mixes the air from the docked vehicle). This air is notoriously dirty in terms of gases, but has never been documented in terms of particle concentrations. It will be possible look at the daily payload experiment and exercise schedule to cross-reference the particle measurements with potential emission sources. Another scenario of interest is to look at data from co-located gas sensor payloads or systems for a complete characterization of air quality (both gases and particles).

4.3 Miniaturized Instruments for Spacecraft Cabin Monitoring

The Earth and Space Air Prize (ESAP) was a crowd-sourcing challenge launched in November 2017, to foster technology development of miniaturized aerosol sensors according to spaceflight hardware design guidelines. Three finalists were chosen out of 20 submitted proposals. The final prototype demonstration was held at the NASA Glenn Research Center in November 2019 where the three finalists technologies competed for the $100k grand prize.

The small business Applied Particle Technology (APT, St. Louis, Missouri, USA) won the grand prize with their multi-wavelength spectrometer which gives particle mass concentrations in terms of PM2.5 (the particle mass concentration for all particles 2.5 micrometres and smaller) and PM10 (particle mass concentration for all particles 10 micrometres and smaller). The instrument output includes a particle size distribution between 0.35 and 20 micrometres, in addition to identifying the particle material as either light absorbing or light scattering.

Figures 13 and 14 show data from APT sensor, taken from one test run of the final prototype demonstration event of the Earth and Space Air Prize challenge. Lunar simulant JSC-1A was aerosolized in a chamber and the sensor measured PM10 and PM2.5 particle mass concentrations (Fig. 13), as well as measuring a size distribution of the simulant (Fig. 14 shows a representative size distribution chosen at a discrete time during the test).

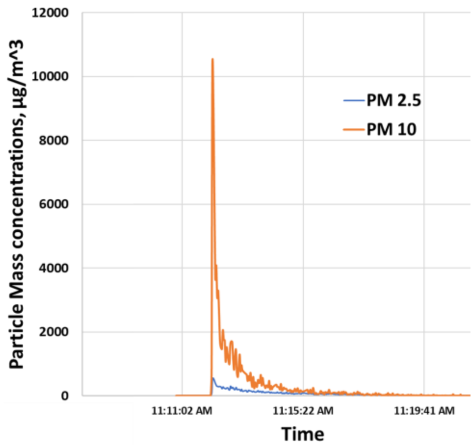

Fig. 13. Applied Particle Technology ESAP sensor measured PM2.5 and PM10 mass concentrations of lunar simulant

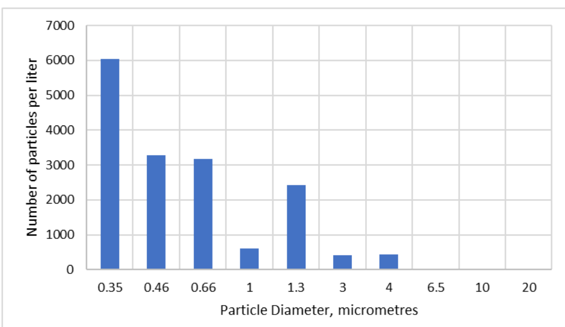

Fig. 14. Applied Particle Technology ESAP sensor measured the particle size distribution of lunar simulant from 0.35 to 20 micrometres

A contract is in work to fund improvements on the aerosol sensor for a future flight experiment, particularly with a goal of making a hand-held device that is compatible with the Astrobee payload interfaces [14]. The APT instrument development plan includes miniaturizing the design of the optical sensing component, sensor inlet improvement to minimize particle losses, circuit board re-design with attention to EMI best practices, and packaging in a new smaller case which is compatible with the Astrobee payload envelope. A test chamber will be built for calibration with generated test aerosols including metal aerosols (stainless steel), metal oxide aerosols (such as TiO_2), reference aerosols (Arizona road dust), Lunar simulant, and combustion aerosols (Smoke, black carbon and pyrolyzed plastics) covering size ranges from 300nm up to 10 microns. These test aerosols match aerosols which are expected to be encountered in a space application, with insight from the Aerosol Sampling Experiment results. Smart calibration factors will enable the machine learning algorithms to distinguish the material of the particles, including the discrimination between smoke and dust. This is a highly sought capability, as the current practice on ISS is to disable the smoke detectors during vacuuming, in order to prevent false fire alarms from cabin dust. The goal is for future particulate monitors to have 'smart' capabilities for vehicle autonomy and less operational complexity.

The runner-up team from Colorado State University (Fort Collins, Colorado, USA) designed the Mobile Aerosol Reference Sensor (MARS), which measures total particulate mass below 2.5 micrometres (PM2.5), as well as ambient temperature, pressure and relative humidity [15]. The follow-on work is contracted with team members working at Access Sensor Technologies (AST), a university-related company. Both ESAP instruments rely on light scattering measurements which must be correlated to actual particle concentrations through material-specific calibrations. Without calibration factors, the output may not reflect actual particle concentrations. It is advantageous to pursue flight experiments with both instruments, since the APT instrument has more sensitivity and capability, while the CSU/AST instrument has an internal filter which can be returned to Earth for gravimetric analysis, thus providing a calibration factor for typical ISS aerosols. Having this calibration would increase the accuracy of aerosol mass concentration measurements of both instruments, and both would be candidates for future space exploration vehicles and habitats.

The AST MARS instrument development includes updating the instrument enclosure for reduced weight and to accommodate a higher air sample flow rate of 2 litres per min through the sensor and filter train. The flow path will be widened to minimize losses of 10 um particles in the optical bench. Additional size-selective inlets will be designed and tested for sampling of PM10 (particulate matter 10 micrometres and below) and PM-respirable (particulate matter 4 micrometres and below) at 2 litres per minute airflow. A display panel will be added to the instrument to replace the cell phone interface and app, which is not compatible with ISS operation.

5. Conclusions

Prior to 2014, the airborne particulate matter in the International Space Station cabin was not addressed as part of the Life Support Systems Project. The rationale was that gaseous pollutants were a much greater threat to crew health, however, funds were prioritized for dust mitigation efforts. Since that time, a subset of ISS cabin aerosols have been collected, returned to Earth and characterized with multiple analysis techniques. The resulting data set of particle morphology, elemental composition, size and abundance of particles has led to knowledge of common particle types and many emission sources. While the sampling results are only a snapshot of the aerosols in two increments (end of 2016 and summer 2018), the real-time aerosol instrument development activities will provide a much larger data set, and allow the mapping of particle concentrations in various ISS locations. Technology demonstrations of the reference-quality Airborne Particulate Monitor and the miniaturized instruments from the Earth and Space Air Prize competition will increase the technology readiness levels of these sensors and are expected to make particulate monitoring on ISS operational in the near future.

Acknowledgements

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