Lessons Learned from the Airborne Particulate Monitor ISS Payload

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Particulate monitoring on spacecraft has not been undertaken for air quality purposes for the first twenty years of human habitation on the International Space Station (ISS). The Airborne Particulate Monitor (APM) is a reference-quality instrument technology demonstration that characterized the airborne particles in the ISS cabin in real-time. Onboard aerosols have been measured with this higher fidelity instrument, so future miniaturized low-power aerosol instruments can be reliably compared in future ISS experiments. Several issues were encountered during the payload operations that are a result of the unique environment on ISS, which could not have been anticipated or eliminated by ground testing. First, the ISS had very small amounts of particulate matter in the particle measurement size range of the APM, which was unexpected. Second, despite the measured 'clean' environment, larger debris such as lint accumulated regularly on the cleanable inlet screen, which required regular inspection and crew time. The third issue is that particle emissions measured on ISS depend only on the activities in the immediate vicinity of the particle instrument and total particle concentrations cannot be generalized for the entire module. Finally, the sampling efficiency of APM on ISS is unknown because aisle-deployed instruments attached to wall panels of ISS are in the boundary layer of the large-scale ventilation flow of the modules. These issues are discussed and potential solutions for future particulate monitors are presented.

Nomenclature

ADI	=	Aerosol Dynamics, Inc.
APM	=	Airborne Particulate Monitor
CEVIS	=	Cycle Ergometer with Vibration Isolation System
COTS	=	commercial-off-the-shelf
CPC	=	condensation particle counter
CTB	=	cargo transfer bag
ISS	=	International Space Station
MAGIC	=	Moderated Aerosol Growth with Internal Water Cycling
POPS	=	Portable Optical Particle Spectrometer
PM2.5	=	airborne particulate matter with an aerodynamic diameter finer than 2.5 µm
PPE	=	Personal Protective Equipment
PSL	=	polystyrene latex spheres
SBIR	=	Small Business Innovation Research
SD	=	Secure Digital
TRL	=	technology readiness level

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USOS = United States Orbital Segment (of the ISS)

I. Introduction

THE Airborne Particulate Monitor (APM) payload[1] was a technology demonstration on the International Space Station (ISS) and was first deployed in November 2020 (Increment 64). This instrument was the first to measure particles in the habitable volume of ISS for air quality purposes. Historically, spacecraft airborne pollutants, or aerosols, were first addressed on the Space Shuttle missions STS-32 (1990) and STS-40 (1991) with the Shuttle Particle Sampling Experiments.[2,3] These payloads not only had sample return of airborne particles, but also included a real-time nephelometer, which is an instrument that correlates light scattered by particles in a sensing volume to mass concentration. The results of these experiments showed that sampler particle mass concentrations for particles 10 µm and smaller ranged from 7 to 21 $\mu g/m^3$ but concentrations of particles greater than 100 µm were dominant, ranging from 25 to 30 $\mu g/m^3$. The Space Shuttle retired in 2011 and this data cannot be extrapolated to other vehicles with different mission durations, habitable volumes, crew populations, and filtration or ventilation systems. Subsequent aerosol-focused experiments in spacecraft include the Aerosol Sampling Experiment, which took place on the ISS in 2016 (Increment 50/51) and 2018 (Increment 56).[4-6] For this study, particles collected with two types of samplers in seven ISS locations were returned to Earth for subsequent analysis. The results from these experiments created a large data set which has shed light on the state of the air quality on ISS, and informed the design of the APM and future real-time instruments.

The need for real-time particulate monitoring in spacecraft has become much more important in light of the Artemis mission, in which hazardous lunar dust will be present in addition to typical spacecraft aerosols seen on the ISS. Requirements for the maximum allowable mass concentrations of both cabin dust and lunar dust are outlined in NASA Standard 3001 Volume 2, Revision B,[7] which states in paragraph 6.4.4.1:

> “The system shall limit the cabin particulate matter 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.”

For lunar dust, 6.4.4.2 outlines separate requirements:

> “The system shall limit the levels of *lunar dust* particles less than 10 µm in size in the habitable atmosphere below a time-weighted average of 0.3 mg/m^3 during intermittent daily exposure periods that may persist up to 6 months in duration.”

Particulate matter 10 µm and smaller is a concern because these sizes can be inhaled into the human body. Larger particles floating in the cabin can cause eye injuries and be a nuisance in general, but are not inhalable. These larger particles would be airborne on Earth for very short periods of time due to gravitational settling so they are not addressed in the body of aerosol and air quality literature, and available instruments measuring airborne particles are not capable of accurately sampling and counting them. For example, in a still air environment, a 100 µm particle would settle from the breathing zone of the average person in 6.6 seconds, not long enough to contribute to particulate matter pollution.[11] In microgravity, all particle sizes are airborne for extended periods and are predominantly transported by the ventilation system air flow until they deposit on walls, filters, or other air intakes such as cooling fan vents for electronic equipment. Creating an aerosol instrument for this unique environment is challenging and the constraints of operating on ISS are vastly different than test campaigns on Earth. Therefore, documenting the lessons learned from the APM ISS payload is important and can guide future particulate monitoring hardware development efforts. Lessons fall into two categories: first, in terms of the hardware or instrument design, and second, in terms of the ISS environment (which can potentially be extrapolated to other spacecraft).

II. APM Lessons Learned from the Hardware Perspective

The Airborne Particulate Monitor (APM) consists of two different aerosol measurement technologies combined in one case. A detailed description of the instrument and its preparation for spaceflight is documented in a previous paper.[1] The APM payload is centered around an ultrafine particle instrument built by Aerosol Dynamics, Inc. (ADI, Berkeley, California). The miniaturized water-based condensation particle counter (CPC) called MAGIC®,[8] which stands for Moderated Aerosol Growth with Internal water Cycling[*] was identified as suitable for microgravity operation and matured through Phase I and II SBIR grants to technology readiness level (TRL) 9 through the flight

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[*] 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.

demonstration on ISS in Increment 64 and ongoing operations. The MAGIC CPC had been available for purchase by aerosol researchers but was not fully commercialized at the time the payload process began.

In order to measure a wider size range of particles, a commercial off-the-shelf (COTS) instrument for measuring a larger size ranger of particles was integrated with the MAGIC into APM through the subsequently awarded Phase II-X grant. This instrument, the Portable Optical Particle Spectrometer[9] (POPS) was developed by Handix Scientific (Boulder, Colorado) and was designed to measure 16-channel particle size distributions between 0.1 to 3 µm. In order to complement the MAGIC measurement of smaller particles, POPS was adjusted to measure particles from 1 to 20 µm, including adapting the internal flow paths to minimize the loss of larger particles. The original factory calibration is performed with monodispersed polystyrene latex spheres (PSL), which are NIST-certified particle size standards. The POPS units that were assembled into APM flight units were specially calibrated with PSL spheres ranging from 1 to 11 µm.

A virtual impactor separates the flow from the APM inlet into two streams, one going directly to POPS and the other stream turning at a 90 degree angle and flowing into the MAGIC. This design was perfected by numerical modeling trajectories of particles between 1 and 32 µm and verified with PSL particle experiments.

The APM display shows only two numbers, the fine particulate fraction, which is the MAGIC concentration of smaller particles, and the coarse fraction, which sums particles from channels 5 through 16 of the POPS data. The full PSD from POPS is recorded in the data files on the SD card.

Figure 1 shows various views and features of the APM flight instrument.

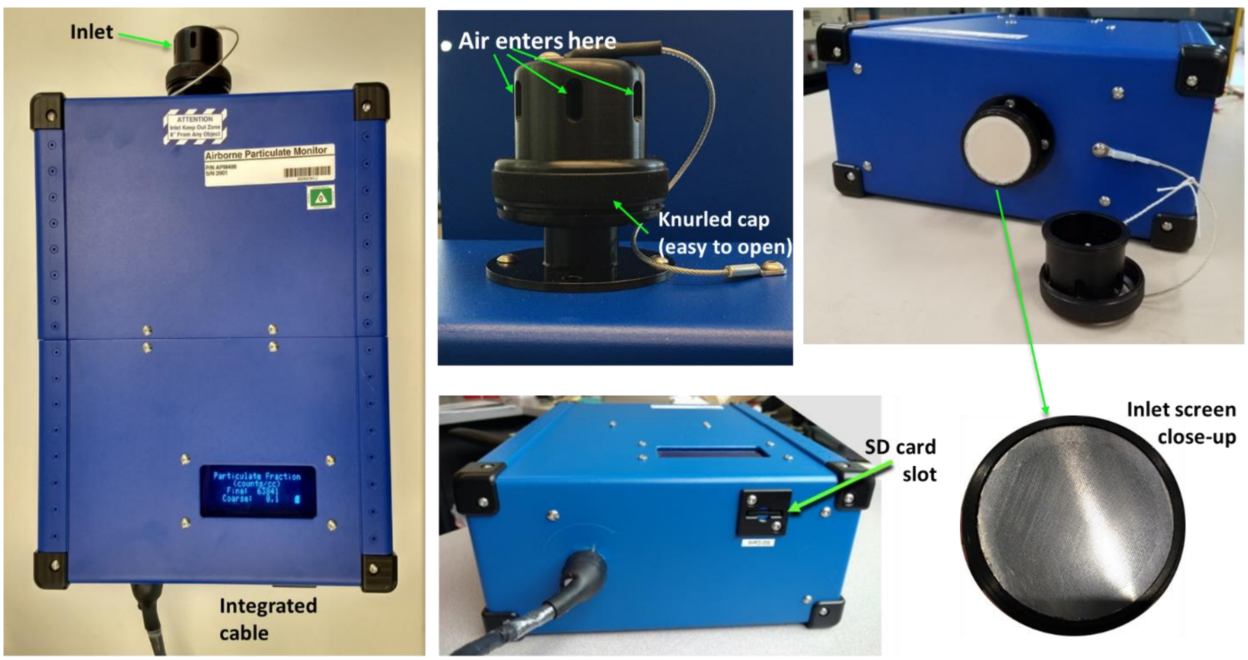

Figure 1. The Airborne Particulate Monitor has a cylindrical inlet with five circumferential slots for air sampling. The inlet screen can be cleaned by removing the knurled tethered cap. Below the vacuum fluorescent display, the integrated cable protrudes from the bottom of APM approximately 2 inches, which is opposite the SD card slot. Two ventilation inlets are on the right side of the instrument and two exhaust fan outlets are on the left.

A. Power

Considering that the APM has a nominal power draw of 30 W at a steady-state current of 1.2 A, it would be difficult for APM to be battery powered. Furthermore, an 8 to 12 hour battery life would have increased complexity for the concept of operations, requiring overnight charging activities and using large amounts of crew time, which is in short supply. Overnight charging would have given data only for the crew waking hours, so the diurnal variations in the particle concentrations, particularly the near-zero night time concentrations would not have been captured.

The APM had an integrated 10 foot power cable that connected to a Ku-Band power supply. A dedicated power supply was specified by serial number and assigned to APM for the entire duration of its operations, simplifying the crew procedure and logistics. This power supply had a 21 foot cable that extended range of deployment location options and enabled one plug-in configuration for two different deployment locations in Node 3 and the US Lab (Nodes 1 and 2 had only one deployment location each). Part of the procedure instructed the crew to coil and secure the extra cable length, tethering it to the wall with hook and loop fastener strips. This is a common step for many ISS experiment instructions and although it takes additional time, longer cables allow for simpler deployments and more location options.

B. Priming Times

CPCs use a working fluid to accomplish single particle counting of ultrafine particles down to 5 or 10 nm, whereby the aerosol flows through an annular wick containing a supersaturated environment, and liquid condenses on the particles as they pass through the wick. This growth increases the particle diameter sufficiently for them to scatter laser light, creating a pulse that is counted. The first CPC instruments used butanol, but ADI created the first water CPC, which had an elevated attached bottle as a supply reservoir for sustained operation. The water reservoir is gravity-fed as the wick needs replenishing and moist air is exhausted to room air at the end of the flow path. The MAGIC innovation eliminated this reservoir, by having a three stage condensation system in the wick, so that the saturated water vapor is recovered in the final cold stage and is transported back to the initial stage of the wick by capillary action (no gravity is necessary). The wick must be sufficiently wet in order to count particles, so there is an initial priming mode of operation for APM to 'collect' water from the relative humidity of the sampled ambient airstream. Once primed, the APM can operate indefinitely in an environment with a dew point temperature above 8°C, or 40% RH at 22°C. The average ISS dew point is 10°C so it was known that there would be sufficient water to sustain a wet wick. Before launch, however, the wick was deliberately dried to minimize the total quantity of water in the system. Liquid water in payloads is discouraged and generates additional safety requirements, which for APM, led to launching with a partially wetted wick. Technically, the water is not in liquid form as it is wholly contained in the wick material and no water escaped during the extreme vibration testing required in the payload preparation phase. Owing to the partially dry wick, the wick needed to take up additional water the first time it was deployed, and was in priming mode until an internal wick wetness sensor indicated that particle counting could begin. The first deployment on 11-20-2020 required 20 hours of priming time before MAGIC was able to count particles, as evident from the data files after-the-fact, or by the instrument display, which reads either 'Priming' or shows coarse and fine particulate fraction concentrations. This duration is acceptable and was roughly predicted by thermodynamic calculations based on the elapsed time between hardware delivery and deployment on ISS, however, it may require longer priming if the APM was dormant for significantly longer periods of time.

C. Particle Cut Size

The virtual impactor for APM was originally designed to have a cut size of 2 µm, which was designed and verified by numerical modeling, to separate and send the smaller fraction of particles to MAGIC and the larger particles to the POPS. The flight safety requirements for payloads consider the noise levels of continuously operating hardware, and an acoustic engineering evaluation of APM testing showed that there were exceedances that needed to be addressed. The noise sources were four fans for active cooling (two exhaust fans for the enclosure and one each for cooling a heatsink and a printed circuit board), as well as three pumps for the aerosol flows within the instrument. Several noise control mitigations were implemented, including baffles, mufflers, vibration-damping bushings for a pump, reduced speed for a heat sink fan and finally, the MAGIC pump flow was reduced. This change in flow rate affected the cut size of the virtual impactor and consequently, the upper size limit for MAGIC particle measurements increased to 3 µm. This size is equally relevant as the originally intended 2 µm cut because PM2.5 (particulate matter 2.5 µm and smaller) is called out in the ISS cabin dust limits for the more stringent requirement of 1 mg/m^3. Cut sizes are approximate (not perfectly one diameter), so the PM2.5 division can roughly be considered all the particles counted by MAGIC, or the fine fraction on the display. Ultimately after the hardware and operating parameter mitigations, there were still minor noise exceedances. However, when averaged across the entire instrument, they excceded in only one frequency, which was allowed an exception thus enabling APM to operate continuously on ISS.

The cut size of the virtual impactor would be well-suited to measuring lunar dust contamination in future missions by separately quantifying the health-relevant sizes and provide exposure data for the crew. The condensational growth by water in the CPC measurement technique provides reference-quality particle counts regardless of the particle material, morphology, or state of charge.

D. POPS Clog

The POPS portion of APM consistently showed 0.0 particles/cm^3 after less than a month of deployment. This was suspicious because there had been some small numbers populating the coarse fraction field of the display in the first weeks. The typical diagnostic for aerosol instruments in a lab on Earth is to deliberately create particles and look for the response in the display output. The difficulty with this approach on ISS is that the test aerosol would have to be made using what was already on station, and that any intentional particle generation could not pollute the environment for the crew. Ground tests with the APM engineering unit, verified the best method for creating particles, which was to rub towels together in front of the inlet. Multiple types of towels were tested, including new, washed, and worn towels. The abrasion method and hand positions were also noted, as well as distance from the inlet. It is interesting to note that three types of microfiber towels did not create any response in the coarse fraction numbers. Cotton towels created the most coarse fraction particles but rubbing one part of a towel against itself would only create some particles, not a sustained concentration, so moving the towel in the hands to rub a fresh section was needed to create more particles again. A methodical and stepwise set of instructions is always required before involving the crew in any activity, even for something as simple as rubbing a towel. First, the particle source was approved by the the ISS office and then a POPS troubleshooting procedure was created for the crew to execute the optimal towel rubbing technique three times in a row and observe any changes in the APM display coarse field numbers. Unfortunately, the procedure did not show an increase in the POPS coarse fraction display numbers, which continued to show only 0.0.

Additional information on the problem was in the instrument health parameters in the data files. During the 0.0 readings, the POPS sheath flow was higher than nominal. This indicates that there is a blockage of some sort in the flow system, causing a re-distribution of the air flow. MAGIC flow rates were nominal so the problem was deemed to be entirely downstream of the virtual impactor and only affecting POPS.

A speculative diagnosis of a clog in the internal POPS inlet is the current accepted root cause of the 0.0 readings. The inlet was intentionally designed to prevent this, with an array of 4000 100-µm holes creating a 50% cut point for particles 50 µm in diameter. The screen is only 50 µm thick but is robust enough for cleaning with Kapton tape, which was performed each time the APM changed locations. The flow path diameter immediately preceding the POPS sensing volume narrows to 0.8 mm (0.032") where a capillary tube is inserted into a larger tube without tapering the diameter transition. One explanation is that a fiber or elongated particle successfully passed through one of the 100 µm holes of the screen by aligning with the flow, and then it may have rotated as it passed through the virtual impactor such that it was oriented perpendicular to the tubing and blocked the section at the diameter reduction. Pictures of the inlet screen and accumulated debris from ISS are shown in Figure 2.

To fully diagnose the root cause of the POPS issue would require returning the instrument to Earth and performing a test, teardown, and evaluation of APM. This was ruled out because the MAGIC portion of APM was providing high-quality and important data on the cabin aerosols in a health-relevant size range. The technology demonstration aspect of the payload had been achieved and there was neither an urgent need to launch the second APM flight unit, nor the additional funding available. It is unlikely that this unit will be returned for diagnosis and the narrowest channel in future aerosol instruments will be evaluated.

The on-orbit options for removing an obstruction in the POPS inlet were not very feasible. Since the sensing volume beyond the particle-focusing tube is quite large, a powerful burst of air could potentially push the debris through the narrowest point into the larger section where it would not affect the instrument operation. There is no source of such clean air onboard so this option was ruled out. Alternately, the internal APM air flows could potentially be reversed by blocking the instrument inlet, which might force the debris back out the way it entered. The danger of this approach is that the destination of the debris is unknown, and could potentially go into the MAGIC flow path and damage it. The risk was deemed too great to carry out this second option because it could render the APM entirely inoperational and end the useful stream of ISS aerosol data.

The lessons that can be learned from this situation are many. Lint and high aspect ratio particles will always be present in the spacecraft cabin and careful aerosol instrument design can reduce the risk of clogging. First of all, it is very important to properly screen out larger debris and lint particles from the incoming flow of any air sampling instrument, potentially even making a series of grilles or mesh layers. This can increase particle losses, and must be modeled and tested for preserving the targeted particle sizes to be measured. Another important instrument feature is to have crew-friendly methods to thoroughly clean every pre-screen and potentially even engineer an air flush or other method to blow through an instrument flow path to remove a blockage. Very narrow sections in the flow path through an instrument should be avoided if possible, especially those with abrupt reductions in diameter where there are corners that can trap debris.

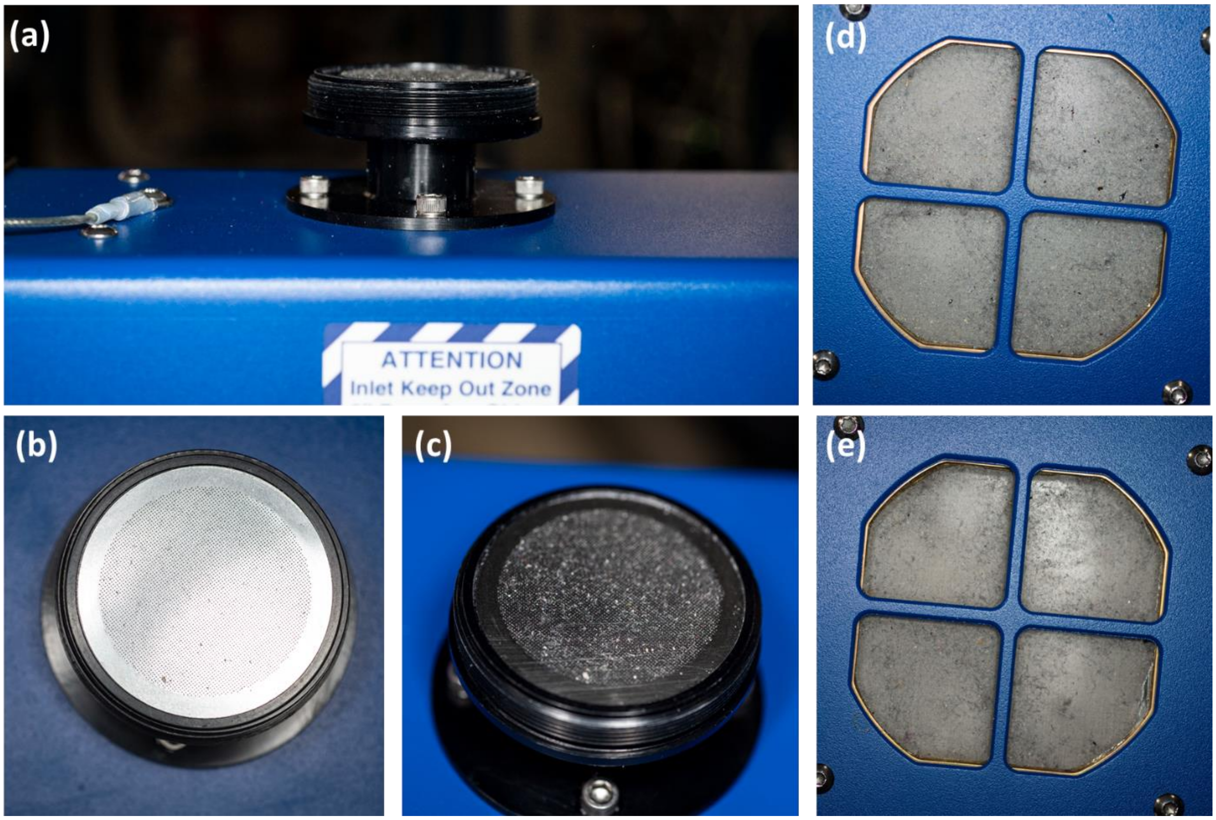

Figure 2. Pictures showing the debris that accumulates on every air intake on ISS. (a) The inlet screen after 19 days deployed in Node 2 (the tethered knurled cap is removed). (b) and (c) The inlet screen after 30 days in Node 1. (d) and (e) Debris accumulation on both inlet vents which draw in air for active cooling. It is unknown how long this amount of debris built up since there was no procedure to clean it and no record of when it was performed, however, based on payload pictures, it was cleaned after the 9th deployment.

III. APM Lessons Learned from the ISS Operational Environment Perspective

The concept of operations for the APM payload included moving the instrument around to different ISS locations to measure particles where different activities take place. Aerosol sampling[4-7] was performed in previous payloads in 2016 and 2018, so the dirtiest module had been identified as Node 3, where exercise and hygiene take place. There were three different deployment configurations in Node 3, including one position where the inlet was first pointing in the nadir direction, followed by rotating the inlet to the zenith direction. The US Lab had two different deployment locations, one closer to the Microgravity Science Glovebox, where experiments are performed, and one below the exercise bicycle called Cycle Ergometer with Vibration Isolation System (CEVIS). Nodes 1 and 2 had one location each. Overall, there were ten different deployments of APM between November 20, 2020 and April 12, 2021, with the goal of seeing where particle concentrations are higher and potentially tracing sources to different crew activities using the daily schedule. Out of 143 days of APM deployments, the cumulative proportion of the time in each location is roughly 20% in Node 1, 20% in Node 2, 40% in Node 3 (because it is the dirtiest), and 20% in US Lab.

A. ISS Clutter

One concern for the deployments of the APM was the cluttered environment on ISS. Figure 3 shows the temporary stowage of cargo transfer bags (CTBs) in the US Lab. Stowage and logistics is a difficult problem in such a constrained living space, so temporary stowage is necessary at different times. The CTBs in Figure 3 are not obstructing the inlet of APM, however, their presence changes the flow patterns of the ventilation system and can affect the particle concentrations in the immediate vicinity of APM. Pictures were taken only when APM was moved to a new location, so it is not known how long the CTBs were present during this deployment and there is no way to quantify this confounding factor.

A 20.3 cm (8”) radius hemispherical keep-out zone for the inlet was emphasized in the crew procedures, and the corresponding warning label on APM is shown in Figure 2a. The instructions stated that the inlet should be greater than 20.3 from solid objects, so potentially CTBs were not considered ‘solid’ and cables also were interpreted to be exempt. Figure 4 shows two locations where the keep-out zone was not ideally followed.

Figure 3. APM deployed in the US Lab (LAB1SD1) below Minus Eighty-Degree Laboratory Freezer for ISS (MELFI). The inlet is not crowded in this deployment, however, the temporary stowage of cargo transfer bags changes the air flow pattern which can affect the local quantities of particles that are available to measure.

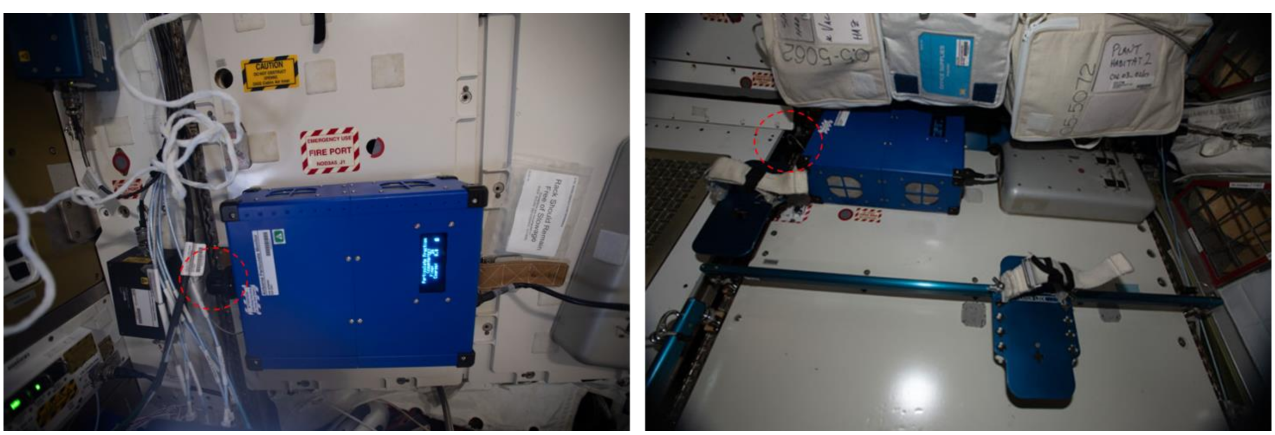

Figure 4. APM deployed (left) in Node 3 (NOD3A3) with the inlet pointing nadir and (right) deployed in Node 2. The red circles emphasize the inlet, showing how cables and CTBs are often close to or within the keepout zone.

Figure 5 shows the APM in Node 3, where a ziplock bag is nearly touching the top of the inlet cap. After this picture was received, additional instructions were called up to the crew to move the infringing ziplock bag. The ideal deployment is in Figure 6, with plenty of space around the inlet and no large items influencing the ventilation flow around APM.

Figure 5. APM deployed in Node 3 (NOD3A3) near the ARED exercise equipment on 1-21-2021. Note the bag of wipes near the inlet cap, which violated the keep-out zone specified in the crew procedures. A call to the crew removed the infringing ziplock bag.

Questions remain about how much clutter can affect the availability of particles for APM to measure. The ISS ventilation pattern is designed for large-scale mixing to eliminate pockets of high CO_2 concentrations. Aisle-deployed instruments attached on the walls with Velcro may be in the boundary layer of this flow, and the frequently changing configuration of CTBs is another source of uncertainty in the particle concentrations measured by APM. One potential solution is to deploy miniaturized particle instruments either on a free-flyer (such as AstroBee) or as a wearable device for the crew. The former would sample the bulk air in the modules and could perform autonomous air quality surveys in ISS, while the latter could give information about crew particle exposures. Neither of these options is currently planned, but the ability to measure airborne particle concentrations without being constrained to the walls is highly desirable.

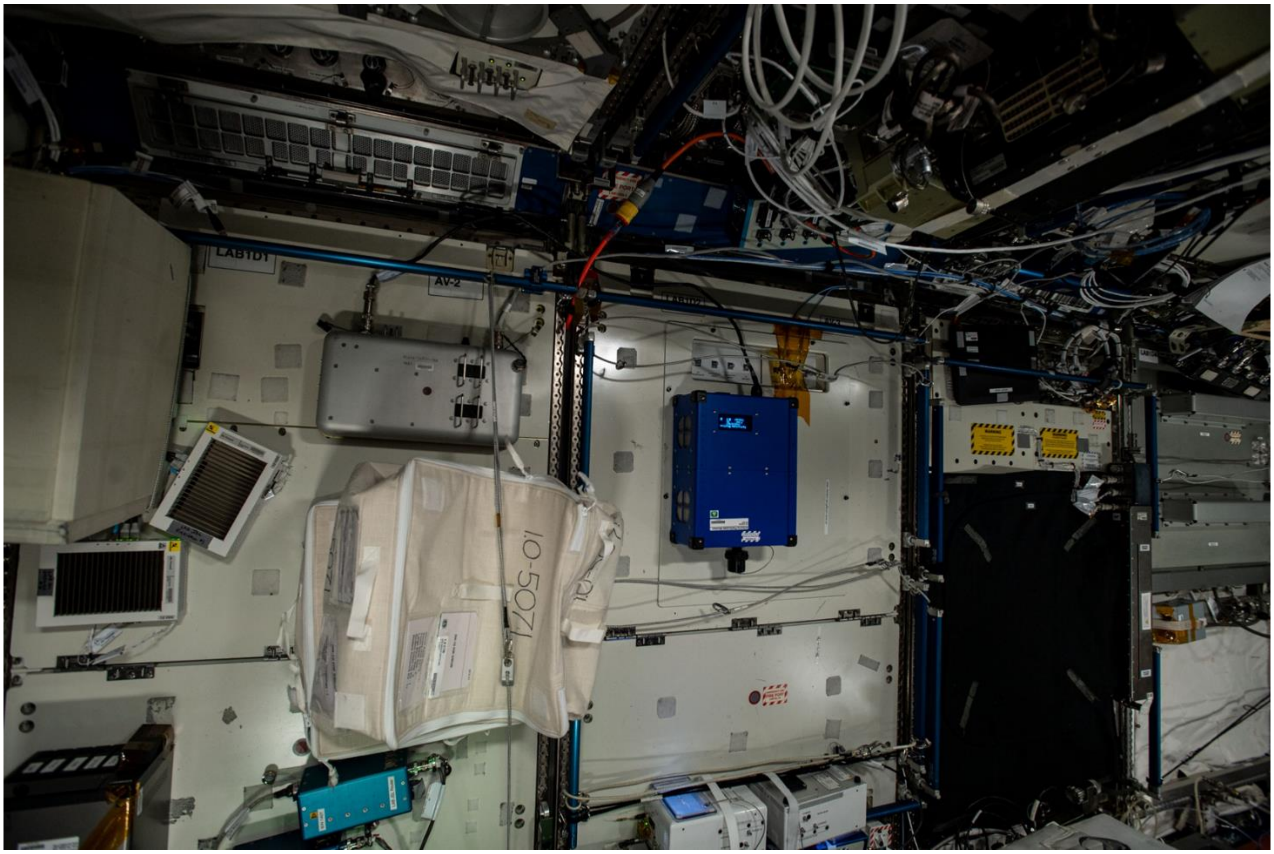

Figure 6. APM deployed in the US Lab (LAB1D2) below the CEVIS exercise bicycle on 1-14-2021.

B. ISS Air Quality

The results from the first APM deployments showed very dynamic fine fraction concentrations during crew work hours with intermittent spikes, but considering one-minute averages, particulate matter counts during the day were typically less than 20 particles per cm^3. For the coarse fraction, before the APM display consistently showed 0.0 particles/cm^3, the POPS had extremely low daily coarse fraction concentrations, less than one particle per cm^3, based on one minute averages. These numbers are in contrast with nights when the crew is not active and particle concentrations drop to near zero because of the high ventilation and filtration rate on ISS. The obvious conclusion is that humans are main source of particles in the ISS, whether it is from their bodies or from their activities. The full five months of data (over all locations) is shown in Figure 7. One-minute averages of concentrations are shown, and the durations of deployments in different ISS locations are highlighted.

The US Orbital Segment (USOS) of the ISS is equipped with high-efficiency particulate air (HEPA) filters that quickly remove particles nearly as fast as they are emitted, so the variability of the measured number concentration in a day is extremely high. The dynamic nature of the localized concentrations makes it meaningless to extrapolate a concentration for the whole module, and as noted before, there are doubts that APM measures concentrations in the bulk/mixed air towards the center of the spaces. However, the definitive conclusion from APM data is that ISS is extremely clean in terms of aerosols, and this is attributed to the filtation system. Typically aerosol data is plotted by averaging the data to smooth the graphs but this approach removes a lot of relevant information for the ISS. On Earth, monitoring instruments often collect data every minute or 5 minutes because concentrations change slowly, which also saves battery power and minimizes the size of data files. APM sampled one data point per second, and thus many particle emission events on the order of seconds were clearly seen. MAGIC counts each particle, thus the jagged nature of the data is not noise, but reflects rapidly changing concentrations in the vicinity of the inlet. Averaging data in this environment will always have the effect of reducing the maximum particle concentrations because of the very low baseline concentrations between particle spikes.

APM did not measure mass concentration of particles, which is spelled out in the ISS requirements in NASA Standard 3001, but it gives number concentrations of the smallest health-relevant particles, which are also in the same size range as smoke particles. These number concentrations can be converted (roughly) to mass concentration, mg/m^3, which gives interesting orders of magnitude that can be compared with the requirements. A conservative extrapolation of APM fine fraction number concentration data is based on multiple assumptions which cannot be validated. First, all particles are assumed spherical, which is definitely not the case based on aerosol sample return from ISS[4-6]. The density of spacecraft cabin dust is unknown, but is assumed to be 2.5 g/cm^3, about the same as Arizona Road Dust, also known as ISO 12103-1 A1 test dust. This is a standard test dust that sufficiently represents many ambient aerosols on Earth, including jagged mineral dusts. It would be the most conservative approach to take the upper cut size limit, 3 µm, as the assumed size of all the particles measured by APM. However, the virtual impactor inside the APM is not perfectly efficient so 2.5 µm would still be an extremely conservative assumption. That size conveniently corresponds to the PM2.5 portion of the ISS requirement, so this gross estimate conversion can be compared easily. Based on these assumptions for conversion, we look at the day of the highest peak measured in the US Lab (LAB1D1) in 2021, which was 102,217 particles/cm^3. Figure 9 shows 29 minutes of data during this peak with a log scale. This maximum was short-lived, with concentrations significantly reduced within 30 seconds and returned to the baseline concentration of 10 particles/cm^3 in less than 15 minutes. For that maximum (one data point), for one second, the highest mass concentration converts to approximately 3000 mg/m^3, but the 24-hour average mass concentration during which that peak occurred would convert to 1.2 mg/m3. While APM was deployed in that ISS location, the average concentration over those 9 days converts to 0.67 mg/m^3. The highest number concentration spike ever recorded exceeds the NASA Std. 3001 limit of 1 mg/m^3 for particles 2.5 µm and smaller, however, the 24 hour average gets close to that limit and the 9-day average mass concentration conversion is below the limit. A more common number concentration peak from the APM measurements over many months is on the order of 5000 particles/cm^3, which is 20 times lower.

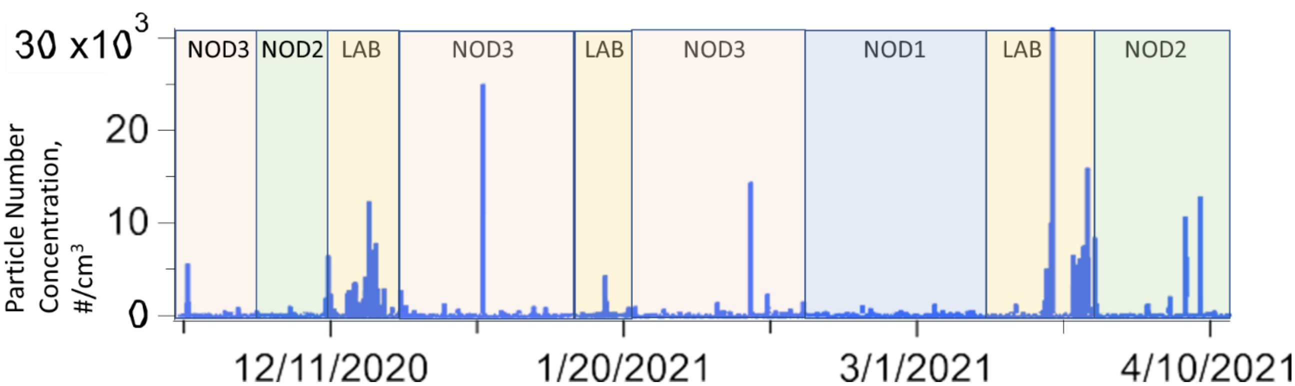

Figure 7. One-minute averages of APM MAGIC particle number concentrations for all locations/deployments combined. There are mostly isolated spikes but mostly near-zero concentrations. The maximum concentration of particles measured by MAGIC was 102,217 particles/cm^3 in the US Lab on March 19, 2021.

C. Identifying Causes of Particle Concentration Spikes

Figure 8 shows one week of APM data in Node 1, with a diurnal pattern of intermittent spikes during the day and near-zero concentrations at night. Spikes over 2000 particles/cm^3 are typically attributed to the crew performing housekeeping. This typically takes place on the weekends, at the crew's discretion so there are no exact time records, other than the extremely large power draws of the vacuum cleaner when it is plugged into an outlet. Many APM particle concentration spikes also were seen on weekdays, so this was investigated further to try and determine what activities could produce such large but short-lived quantities of aerosols.

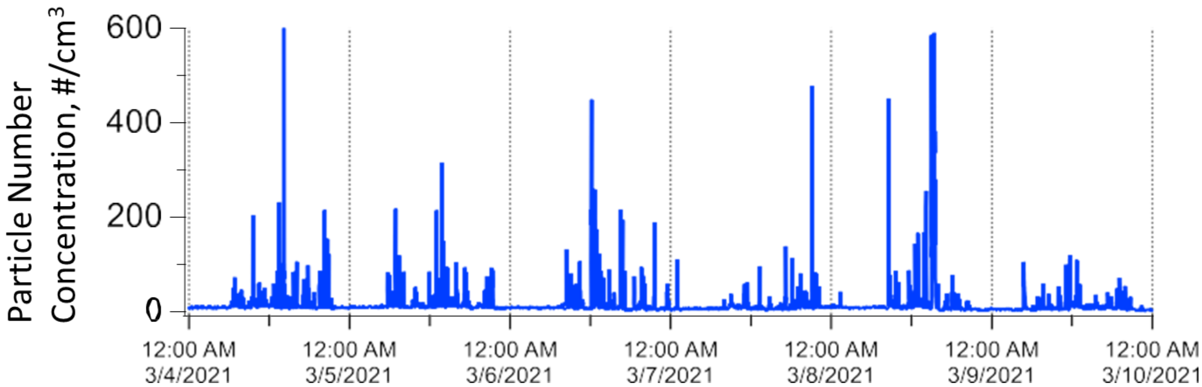

Figure 8. APM MAGIC particle number concentrations for one week in Node 1 show the typical diurnal pattern, with concentrations around zero at night, and spikes during the daytime associated with crew activities.

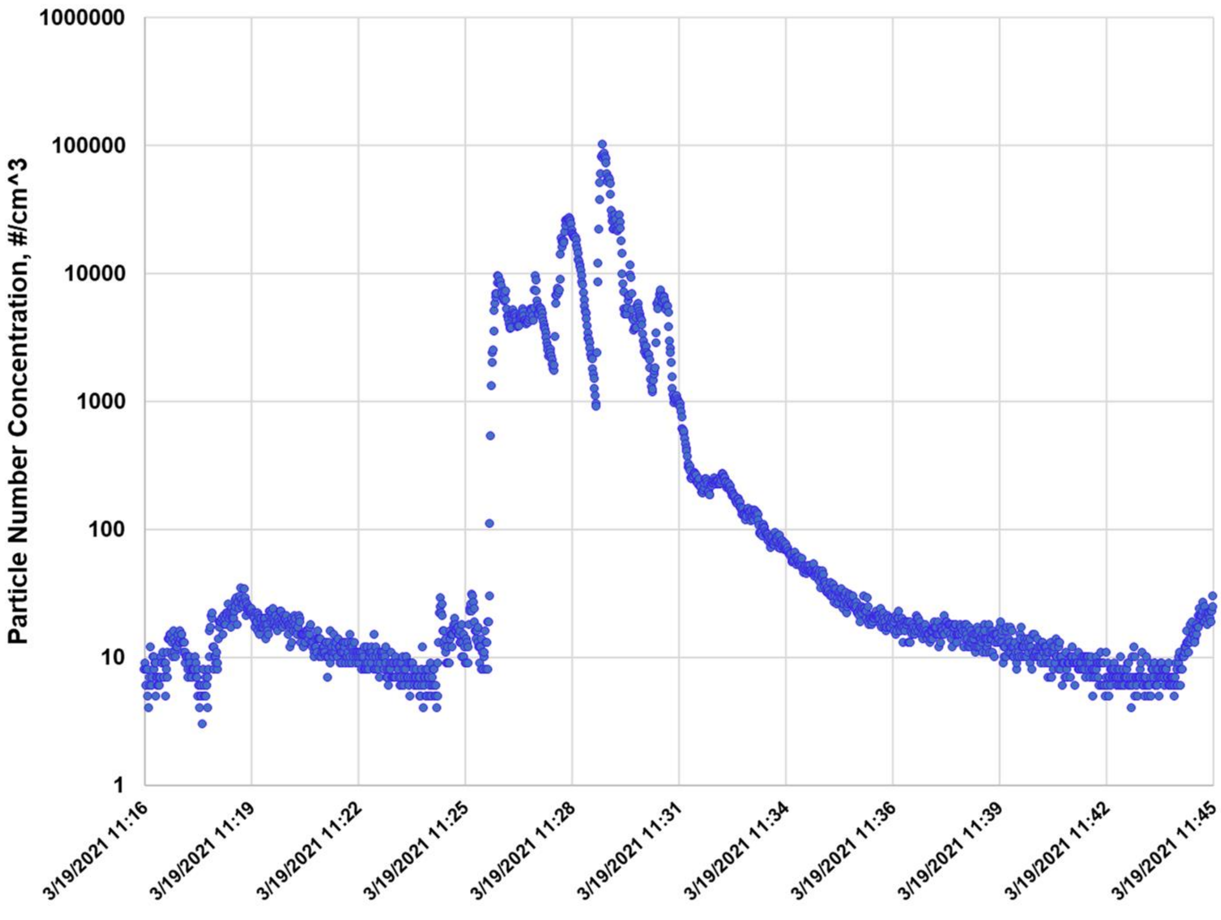

Figure 9. APM MAGIC particle number concentrations in the US Lab (LAB1D1) plotted over 29 minutes during the largest concentration spike measured in five months of continuous deployments (log scale).

The best method to determine when vacuuming took place, other than noting the power draws, is to look at the smoke detector telemetry status during particle spikes. False alarms from dust emissions have been prevented for years by temporarily changing the response state of smoke detectors. The USOS smoke detectors have two indicators which determine if they are active or not. The first indicator is whether or not the unit is powered. Finding the correct remote power controller (RPC) and determining if the RPC is open or closed shows definitively if the unit is powered. The second indicator is whether the unit is Enabled or Inhibited. This is a software state that either allows annunciation of the Caution and Warning alarm or not. In both states, the smoke detector is reporting information. The USOS smoke detectors are nominally Inhibited during maintenance activities such as weekly air duct vacuuming and other maintenance in areas near the smoke detector locations because these activities are known to liberate dust which causes smoke detectors to annunciate. Additionally, there have been instances where the smoke detector has been inadvertently kicked or otherwise impacted. These types of occurrences have also been responsible for annunciations which were deemed false.

Activities that require vacuuming, besides the normal weekend housekeeping, include reconfiguration activities when racks are rotated or wall panels are opened, the set-up or tear-down of experiments in the various facilities. These actions often expose large amounts of dust to the cabin environment and often the procedures call out vacuuming and wearing PPE if necessary. The available dust may migrate into the air, but some portions will always be re-entrained into the air when disturbed by a vacuum cleaner nozzle. The in-depth look at smoke detector data parameters revealed that simultaneous with almost every APM particle concentration spike over 2000 particles/cm^3 (in the five months of Increment 64 data), the smoke detector in the module nearest to the APM had been inhibited. It is interesting and certainly reassuring to have an understanding of most APM particle spikes, and investigations into the data are ongoing to decipher additional insights into particle emissions in spacecraft.

IV. Conclusions and Future Uses for APM

The APM payload provided the first real-time particulate matter measurements on ISS for the purpose of air quality quantification. The technology demonstration was successful and enlightening, and many lessons can be gained for future instruments in spacecraft, both from a hardware perspective and from a vehicle/environmental perspective. Particularly, any air sampling instrument that may operate in a future spacecraft can benefit from the cautions and best practices outlined in this paper. APM has shown that the ISS is extremely clean and when the peak number concentration recorded during the ten deployments (102,217 particles/cm^3) is extrapolated/converted to estimates of particle mass concentration, the ISS particulate matter requirements were not exceeded when considering multi-day averages. The most typical peak concentrations on the order of 5000 particles/cm^3 were approximately 20 times lower than that maximum, and ISS requirements would not be exceeded in those cases. Coarse fraction particles measured before the obstruction to the POPS showed extremely low daily concentations, less than one particle per cm^3, based on one-minute averages. The crew and their activities are the primary sources of aerosols on ISS as demonstrated by the near-zero concentrations during crew sleep. Most large spikes in concentration can be attributed to vacuuming, so this phenomenon could be addressed in the future, to mitigate the dust source and to prevent the necessity of smoke detector inactivations, which ultimately is a source of risk.

Additional APM operations on ISS are in Increments 66 and 67 to get a larger data set from two locations (LAB1D1 and NOD3A3) during direct crew handovers. APM will measure particle concentrations beyond the baseline of 7 crew members on ISS, when crew population is temporarily elevated in instances when a new vehicle arrives before the previous crew departs. This is expected to allow differentiation between the known baseline 7-crew concentrations and the higher concentrations of particles that will be emitted by the additional humans onboard (up to 11 crew members). Within these increments there will be approximately six instances of direct crew handovers, which can provide relevant data for estimating a per-person particle emission rate. This will fulfill the need to update the particulate load model that will be useful for designing filtration systems for future missions.

The MAGIC water CPC portion of APM has been chosen for an SBIR Civilian Commercialization Readiness Pilot Program (CCRPP). The resulting COTS ultrafine particle counter will be available for purchase by the public in late 2022. This instrument will be a research-grade instrument at a fraction of the price of current CPCs and the only one that can sustainably operate without a fluid reservoir. The marketing will target several sectors and applications, including indoor air quality, microcontamination for semi-conductor manufacturers, occupational exposure, and epidemiology (exposure assessment and bioaerosol research). This COTS version is planned to be included in the next particle instrument technology demonstration on ISS. The Aerosol Monitors payload will include miniaturized mass concentration instruments with co-located gravimetric samplers to calibrate these instruments, and the COTS MAGIC to reliably measure the smallest particles in the cabin.

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