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Presence of Metal Aerosols on the International Space Station

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During 2016 and 2018 Aerosol Sampling Experiments, Passive Aerosol Samplers (PAS) were placed on vents and filters around the United States Orbital Segment (USOS) of the International Space Station (ISS). Samples were collected on substrates for different durations and then were sent back to Earth for analysis using scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). This analysis provided size, morphology, and elemental compositions of not only many individual aerosol particles that were collected, but also of individual metal inclusions within multi-component particles. Using ISS filter area, vent flow rate, and the concentration of particles on the samplers, the airborne concentrations of various metal compounds within these inclusions were estimated and compared to the standards set by the Occupational Safety and Health Administration (OSHA). All the estimated atmospheric elemental concentrations on the ISS were below 1% of their corresponding OSHA standards. While this analysis does provide us with the first estimate of aerosol levels on the ISS, there are several assumptions that were made throughout this process and further research will be required to validate these assumptions.

Nomenclature

AAS = Active Aerosol Sampler
cfm = cubic feet per minute
ISS = International Space Station
mg = milligram
PEL = Permissible Exposure Limits
USOS = United States Orbital Segment
CEVIS = Cycle Ergometer with Vibration Isolation System
EDS = Energy Dispersive X-Ray Spectroscopy
OSHA = Occupational Safety and Health Administration
PAS = Passive Aerosol Sampler
SEM = Scanning Electron Microscopy

I. Introduction

PARTICULATE matter is emitted into the atmosphere from natural and anthropogenic sources and when inhaled can cause adverse health effects, depending on particle size and composition. While particulate matter air pollution is heavily regulated on Earth for the outdoor environment, indoor air pollution is rarely regulated though most humans spend upwards of 80% of their day indoors. One of the most comprehensive sources of indoor air pollutant regulations in the United States is through the Occupational Safety and Health Administration (OSHA)[1]. The regulations set forth by OSHA are established to protect workers from being exposed to high levels of potentially harmful air pollutants.

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Like other work environments, the International Space Station air quality is essential to crew health; unlike any other work environment, it is unique because of the lack of gravitational settling and that it is practically a closed system in terms of air. Apart from very small amounts air that are transferred when crews depart and arrive at the ISS, all the air contained within the living environment is recycled or produced by what is onboard the station. The main sources of aerosols on ISS are the crew members and their activities: skin flakes, lint, antiperspirant, sweat droplets, metal wear particles from exercise equipment. Other sources of particles include the equipment onboard such as the air revitalization system fans and pumps, electronics, and flame retardants, among other things.

In order to increase our understanding of cabin air quality and to characterize the design environment for future particulate monitors, the Aerosol Sampling Experiments were conducted in 2016 and 2018 to collect particles in the ISS Cabin air for return to Earth. The samplers collected particles over the span of several weeks before returning to Earth for analysis. The size, morphology, and elemental compositions of the particles collected were characterized using computer controlled scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). The complete description of the sampling hardware and experimental protocol is provided in references previous publications.[2,3,4,5,6] The physical analysis of the two sets of samples is completed, with some results summarized in references 1-5 as well, but there are many opportunities remaining to explore the bulk of the data.

This paper focuses on the metals analyses that included elements with an atomic number of 22 (Titanium) and higher that were present in the ISS aerosol samples either as individual particles or as metal inclusions within multi-component particles. This selection of metals was based on the computer-controlled microscopy technique, which relies on edge detection algorithms that look for contrasting in pixels in the SEM image. High atomic number materials tend to have higher contrast (bright white) against the black carbon tape substrate vs. grey-scale carbon and lower atomic number particles. Most of the elements are metals and some can be considered "Heavy Metals" and are released through the various actives that take place throughout the ISS. Non-metals included in the analyses were either agglomerated with a metal particle or present in metal compounds. The airborne concentrations of various metal-containing particles were calculated to compare to the standards set by the Occupational Safety and Health Administration (OSHA). This study did not consider whether a particle was an individual metal piece, or part of an agglomerate. It also did not consider whether a particle was small enough to be inhaled or the potential deposition location within the respiratory tract (also size-dependent). This affects the potential uptake of the substance in the human body (bioavailability). Therefore, in the strict sense, these estimates cannot be considered personal exposures, however, it is useful to estimate the overall airborne concentrations from this unique data set.

II. Metal Presence in ISS Aerosol Samples

The 2016 and 2018 Aerosol Sampling Experiments revealed various types of particular matter in ISS air. Many particle types in the samples were anticipated from a previous project.[7] Particle loading on the sampling substrates varied greatly by location, corresponding to the type and frequency of human activities performed in the areas.

The majority of materials sampled were cotton lint fibers and carbonaceous particles, including skin flakes. Metallic particles, many appearing as inclusions within carbonaceous particle matrices, were common, and a minor portion were metal wear particles, having characteristic jagged morphology. Additional common particle types included salt particles, antiperspirant particles, and fiberglass.

Metallic particles, or metal containing particles, are the focus of this paper; as they often originate from non-human sources, thus provide potential opportunities for air quality improvement. In 2021, a study was carried out to understand the presence of silver in ISS aerosol samples, as silver ion disinfectant is being used on ISS. The silver containing particle concentration in air was estimated, and compared to OSHA permissible exposure limits (PEL).[8] This paper will extend the analysis beyond silver, to all metal elements, and to quantify the metal concentrations in the ISS aerosol samples.

A. 2016 Aerosol Sample Overview

There were 7 separate Passive Aerosol Samplers (PASs) deployed in 2016 across the United States' Orbital Segment (USOS) of the ISS, mostly in high activity areas to capture the impact of human activity on air quality.[2,3] PASs were positioned in Node 1 (Eating), Node 3 (Exercise and Hygiene), Node 2 (Docking), US Lab (Experiments), and the Permanent Multipurpose Module (PMM) which was used for storage, as a comparison for a low-traffic area. The locations of the PASs and the relevant activities at these locations are listed in Table 1. Each PAS contains 5 sampling substrates. In the 2016 experiment, the sampling durations were 2, 4, 8, 16, and 32 days, respectively for substrates 1, 2, 3, 4, and 5. The progression in sampling durations was chosen because the ISS particle concentrations were completely unknown. On Earth, when aerosol sampling is undertaken, it is typically an iterative process with a feedback loop: 1) Start with an estimated duration for good particle coverage, 2) Collect particles and do microscopy analysis, 3) Adjust the sampling duration based on the results, 4) Repeat until ideal coverage is achieved. It is impossible to carry out this methodology in a space experiment, so the best alternative was to double the sampling duration for each successive substrate, as a start. Once the sampling was completed, the PASs were sent down to Earth for analysis and characterization. The result of the varying sampling durations in 2016 revealed that the substrates that collected particles between 16 and 32 days had the optimal particle coverage for microscopy. Typically, only one substrate from each PAS was chosen for microscopy (the one with the optimal particle loading) in the 2016 analysis. Other substrates on the PAS either had too few or too many particles to perform computer-controlled microscopy.

Table 1. 2016 Passive Aerosol Sampler Locations

Passive Sampler	Location	Relevant Activity
PAS B (NOD1D1)	Node 1 Deck 1	Eating
PAS D (NOD3D3)	Node 3 Deck 3	Exercise and Hygiene
PAS E (PMM)	PMM	Storage
PAS F (NOD2D2)	Node 2 Deck 2	Dock and Sleep
PAS G (NOD3F3)	Node 3 Forward 3	Exercise and Hygiene
PAS J (LAB1SD1)	US Lab Bay 1 Starboard Deck	Experiments
PAS K (LAB1PD3)	US Lab Bay 3 Port/Deck	Experiments

B. 2016 Aerosol Experiment: Types of Metal-Containing Particles

Metal-containing particles were identified during the 2016 Aerosol Sampling Experiment, as individual particles and particle inclusions within larger composite particles. Particles classes are grouped according to their main elements and presented in Table 2.

Table 2. Elements and Particle Classes in 2016 Aerosol Samples

Element	**Ag**	**Al**	**Ba**	**Bi**	**Br**	**Cd**	**Cr**
Particle Classes	Ag-bearing Ag-rich Ag-Zn	Al(Pt) Al-Cl-Zr Al-Cu Al-Fe Al-Ni-P Al-Si-Fe Al-Ti Al-Zn	Ba-S	Bi-bearing Bi-rich	Br-rich	Cd-bearing Cd-rich	Cr-rich
Element	**Cs**	**Cu**	**Fe**	**Mo**	**Ni**	**Pb**	**Pt**
Particle Classes	Cs-bearing	Cu-Ni Cu-rich Cu-S Cu-Si Cu-Zn Cu-Zn-Si	Fe-Cr Fe-Cr-Al Fe-Cr-Ni Fe-P-Mn Fe-P-Zn Fe-rich Fe-S Fe-Si Fe-Ti Fe-Zn	Mo-rich	Ni-rich	Pb-bearing Pb-rich	Pt-rich
Element	**Sb**	**Sn**	**Ti**	**W**	**Zn**	**Zr**	
Particle Classes	Sb-bearing Sb-Mo Sb-Mo-Cu Sb-rich	Sn-rich	Ti-P-Zn Ti-rich	W-bearing W-rich	Zn-bearing Zn-Cr Zn-Fe-Al Zn-rich	Zr-bearing Zr-rich Zr-Si	

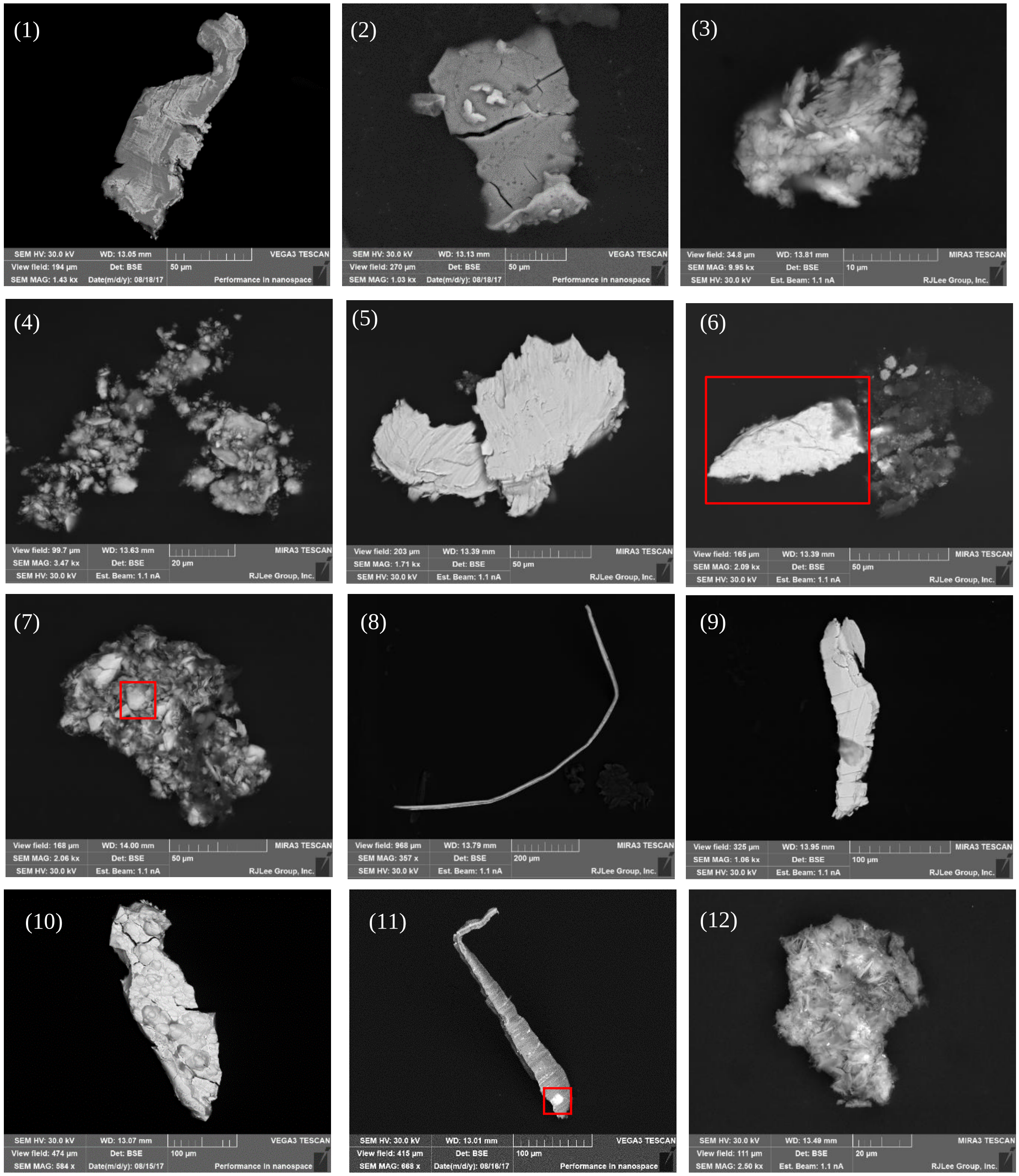

Figure 1. Some examples of typical metal-containing particles collected in 2016 ISS Aerosol Sampling Experiment.

Analysis revealed that substrates collected many particle agglomerates with individual metal particles embedded within a larger particle, most often within a carbon matrix. This particle type could be explained by electrostatic agglomeration effects, which have been previously observed by astronauts in informal ISS experimentation.[9]

Some representative particles were imaged separate from the metals analysis by manual microscopy, producing high-resolution micrographs with the corresponding EDS spectra. These were chosen to show detailed morphology of the typical particle types sampled. Figure 1 shows some of these examples of metal-containing aerosol particles sampled in the experiment. Individual descriptions are given below and include location, which sampler and sampling duration (for example, PAS B-16 denotes the substrate of passive aerosol sampler labeled 'B' which collected particles for 16 days) :

(1) potential wear particle composite of copper with a gold coating, on PAS B-16, located at Node 1 Deck 1, an eating area;
(2) some salt (Na-Cl) on the surface of a particle comprised of Al-Cl-Zr, also from PAS B-16 (Node 1);
(3) a particle composed of Ni and P, from PAS B-16 (Node 1);
(4) an iron-rich cluster, located on PAS D-16, located at Node 3 Deck 3, an exercise and hygiene area;
(5) stainless steel wear particles Fe-Cr-Ni, also from PAS D-16 (Node 3);
(6) Cd-rich potential wear particle in a complex structure, also from D-16;
(7) A complex structure comprised of molybdenum particles in carbonaceous materials, from F-32, located at Node 2, Deck 2, a docking and sleeping area;
(8) a stainless steel sliver, also from F-32;
(9) Coper/Zinc wear particle, from F-32;
(10) Nickel-rich particle indicative of wear debris with a surface texture with possible heat exposure, on PAS K-16, located at US Lab 1 Bay 3;
(11) an aluminum sliver with lead-Tin-Bismuth inclusion, from PAS K-16; and
(12) an iron-rich agglomerated structure, from E-32, located in the PMM.

C. 2018 Aerosol Sample Overview

In 2018, all the PAS samples were collected over a 26-day span based on the 2016 results for optimal particle loading (between 16 and 32 days). Some samples were also positioned in different areas of the US's section of the ISS, including two placed upside-down on diffusers (with the opposite direction of air flow vs. the filter vents). The PASs were deployed in Node 2 (Sleeping and Docking), US Lab, Node 1 (Eating), and Node 3 (Exercise and Hygiene), as shown in Table 3. All 5 sampling substrates of each PAS were analyzed and reported because all were suitable for microscopy (the ideal sampling time for sufficient particle coverage). For the 2018 data, the average value of the estimates from 5 sampling substrates is used to compare with the 2016 PAS locations. It should be noted that in some locations, the particle deposition varied widely between the 5 substrates (some by a factor of 10 or higher). This is attributed to the inherent randomness of the particle concentrations in the ventilation air flow, sampling artifacts associated with the sampler placement on the vents, and the temporary stowage of items in the immediate vicinity that may have obstructed the air flow to a sampler for a portion of the sampling duration. The 2018 sample analyses had many more particles, thus better statistics, whereas in 2016, only the substrate with the best coverage was analyzed for each PAS, as it was the first attempt at sampling and the optimal duration was unknown at the time.

D. 2018 Aerosol Experiment: Examples of Metal-Containing Particles

Mostly the same metal-containing particles were identified during 2018 Aerosol Sampling Experiments. Particles classes from the 2018 sample set are grouped into the main elements and presented in Table 4.

There are some differences between the particle classes of 2016 and 2018. The main elements are almost the same, with one addition of Ce in 2018 (the Ce-La particle class). These particle classes were based on the analysis of each sample set individually. Particle classes are user-defined by the analyst performing the computer-controlled SEM. In order to keep the analysis manageable, it is best to keep the number of particle classes at around 60. Any particle type that is present in trace amounts is not assigned to its own particle class, for example, there could be only 2 or 3 particles, so these are assigned to the 'miscellaneous' class. Since the sampling experiments took place two years apart, there were differences in what particle types were collected, and therefore, the particle classes were chosen according to the analysis of an individual payload, not with the goal of comparing payloads. Subsequent work has consolidated particle classes from 2016 and 2018 that allow comparisons across payloads.

Figure 2 shows some examples of typical metal-containing aerosol particles sampled in the 2018 experiment, including:

(1) A stainless steel particle Fe-Cr-Ni, on PAS B-1, located at Node 2 Deck 3, area for docking and sleeping,
(2) a nickel-rich particle, on PAS B-1,
(3) a zinc-rich particle, on PAS B-1,
(4) a nickel particle with an area with Cl, indicative of corrosion site, on PAS D-2, located at US lab 1 Port/Deck,
(5) a Pb-Cl particle, from PAS F-2, Located at Node 3 Mid-bay, an exercise and hygiene area,
(6) an iron-rich particle, on PAS F-2,

(7) a stainless steel particle cluster Fe-Cr-Ni, on PAS F-2,
(8) an aluminum particle, on PAS F-2,
(9) an Al-Zr-Cl cluster in a carbonaceous complex structure with some Si, on PAS E-5, located at Node 1, Mid-bay, an eating area,
(10) Si-Mg talc particles on PAS F-2,
(11) lead particles, on PAS H-2, Node 3 overhead supply diffuser, an excise and hygiene area,
(12) a cadmium wear particle, on PAS H-2,
(13) a particle containing Cd and Zn, with EDS mapping showing Zn in purple and Cd in green, on PAS H-2,
(14) Ni rich wear particles, on PAS G-1, located at Node 3, Forward 3, an excise and hygiene area,
(15) K-Cl particles, on PAS G-1, and
(16) an Al-Cl-Zr cluster, PAS G-1.

There are also silver containing particles in both 2016 and 2018 Aerosol Sampling Experiments; their examples can be found in an earlier publication.[8]

Table 3. 2018 Passive Aerosol Sampler Locations

Passive Sampler	Location	Relevant Activity
PAS B (NOD2D3)	Mid-bay HEPA Return Register	Dock and Sleep
PAS D (LAB1PD3)	US Lab Bay 3 Port/Deck Standoff HEPA Return	Lab Experiments
PAS E (NOD1D3)	Node 1 Mide Bay HEPA Return Register	Eating
PAS F (NOD3D3)	Node 3 Mid-bay HEPA Return	Exercise and Hygiene
PAS G (NOD3F3)	Node 3 Forward 3	Exercise and Hygiene
PAS H (NOD3OA3)	Node 3 Overhead Supply Diffuser	Exercise and Hygiene
PAS K (NOD3O2)	Upper Plenum Assembly	Exercise and Hygiene

Table 4. Elements and Particle Classes in 2018 Aerosol Samples

Element	Ag	Al	Ba	Bi	Br	Cd	Ce
Particle Classes	Ag-bearing Ag-rich Ag-S Ag-S-Cl Ag-Si-S	Al-Cl-Zr Al-Fe Al-Ni-Zn Al-Si-Fe Al-Sn Al-Zn	Ba-Cr Ba-S Ba-Zn	Bi-bearing Bi-rich	Br-bearing Br-rich Br-Sb	Cd-bearing Cd-rich	Ce-La
Element	**Cr**	**Cs**	**Cu**	**Fe**	**Mo**	**Ni**	**Pb**
Particle Classes	Cr-rich	Cs-bearing	Cu-rich Cu-S Cu-Zn Cu-Zn-Si	Fe-Cr Fe-Cr-Al Fe-Cr-Ni Fe-Mg Fe-Ni Fe-rich Fe-S Fe-Si Fe-Ti	Mo-rich	Ni-rich	Pb-bearing Pb-rich
Element	**Pt**	**Sb**	**Sn**	**Ti**	**W**	**Zn**	**Zr**
Particle Classes	Pt-rich	Sb-bearing Sb-Mo Sb-Mo-Cu Sb-Pb Sb-rich	Sn-Ag Sn-Cu Sn-Pb Sn-rich	Ti-rich	W-rich	Zn-Fe Zn-Ni Zn-rich Zn-Ti	Zr-bearing Zr-rich

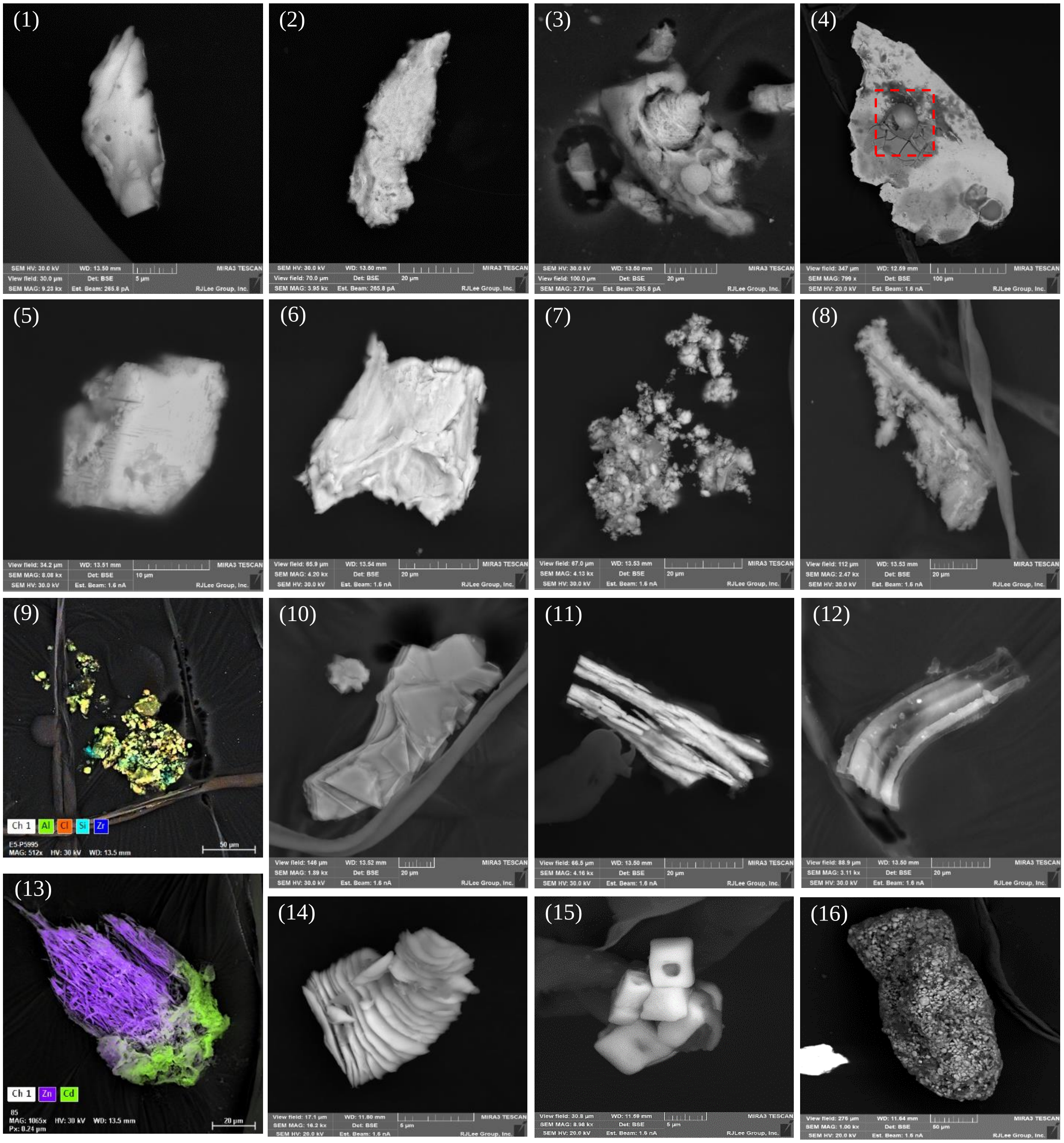

Figure 2. Some examples of metal-containing particles collected in 2018 ISS Aerosol Sampling Experiment, shown in SEM images, with or without overlaid EDS mappings (in color).

III. Estimation of Airborne ISS Metal Aerosols

To quantify the metals in ISS aerosols sampled, PAS sample analysis results are used to estimate the aerosol particle collection rate on the air filter surface, which can be used to estimate the aerosol particle concentration in the air, given the air flow rate. The aerosol particle concentration is used to compare with the OSHA PELs to evaluate ISS aerosol concentrations of various metals.

A. OSHA Air Pollution Limits

OSHA has established permissible exposure limits (PELs) for indoor air pollution, which are regulatory limits to ensure workplace safety. These levels are the "average airborne exposure in any 8-hr work shift." [10] This exposure limit is considered to be the highest level of a given pollutant an employee can be exposed to without increasing the risk of adverse health effects.

Each chemical substance has varying exposure limits due to factors such as solubility, bioavailability, and toxicity. Some elements have several PELs due to the form or corresponding elements in the substance. The most stringent PELs are used for comparison due to uncertainty in the specific forms of the collected particles. The limits that were used in this analysis were the values that were given in milligrams per cubic meter (mg/m^3).

It is important to mention again that when OSHA provides PELs in air quality data, i.e., particle concentration in air (mg/m^3) where an 8-hour work shift is considered. An important distinction from this scenario is that on ISS, the crew cannot 'go home' from their work place and they breathe the same air before and after work. Therefore, one approach is to use a correction factor to adjust the OSHA PEL for a 24-hour exposure period. In another words, in this initial evaluation, one third of the air quality limit (mg/m^3) of the OSHA PEL will be used to consider the ISS air pollutant exposure. This is a simplified first approach for the overall comparisons of the concentrations, but future analyses should go into more detail and account for these additional factors: (1) While the 8 hour work shift on Earth does not include weekend days, the ISS crew is exposed to their 'workplace air' for 7 days per week; (2) The volume of air that is inhaled by a person is different for active periods versus resting or sleeping periods, so the air exposure should not be simplified by generic one-hour segments; and (3) The tidal volume (amount of air inhaled) is different in microgravity because of fluid shifts in the body.[11]

B. Estimation of metal Particles Collection Rate and Their Concentration in Air

The method of estimation of the metal particle concentration in air was described in detail in reference 8. It is summarized briefly in the section below, using cadmium as an example. Table 5 and Figure 3 show the calculated cadmium particle loading collected on 2016 PASs at different ISS locations.

Table 5. Cadmium particles collected on PAS at different ISS Locations in 2016, reported in ng/cm^2/day.

Cd Particles	PAS B NOD1D1	PAS D NOD3D3	PAS E PMM	PAS F NOD2D2	PAS G NOD3F3	PAS J LAB1SD1	PAS K LAB1PD3	Average
Cd-bearing	0	0.10025	0	0	0	0	0	0.01432
Cd-rich	0	27.767	0	0	21.0642	0.0234	0.00173	6.97953
Total	0	27.868	0	0	21.0642	0.0234	0.00173	6.99385

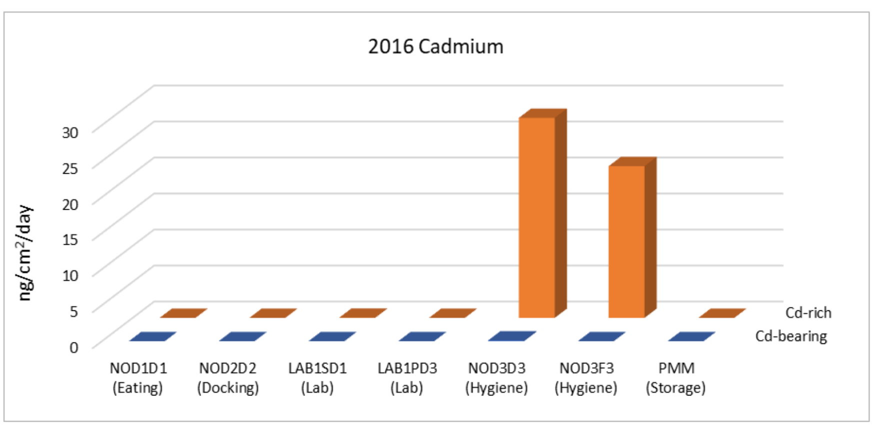

Figure 3. Average cadmium particles collection rates in 2016 at different ISS locations.

Table 6 and Figure 4 show the calculated cadmium particle loading collected on 2018 PASs at different ISS locations.

Table 6. Cadmium particles collected on PAS at different ISS Locations in 2018, reported in ng/cm^2/day.

Cd Particles	PAS B NOD2D3	PAS D LAB1PD3	PAS E NOD1D3	PAS F NOD3D3	PAS G NOD3F3	PAS H NOD3OA3	PAS K NOD3O2	Average (ng/cm^2/day)
Cd-bearing	0.0144	0.0011	0.4276	0.0019	0.0005	4.8833	0.0878	0.7738
Cd-rich	0.5125	16.3215	1.3927	1.3370	0.2007	48.5673	0.0621	9.7705
Total	0.5269	16.3227	1.8203	1.3389	0.2012	53.4506	0.1499	10.5444

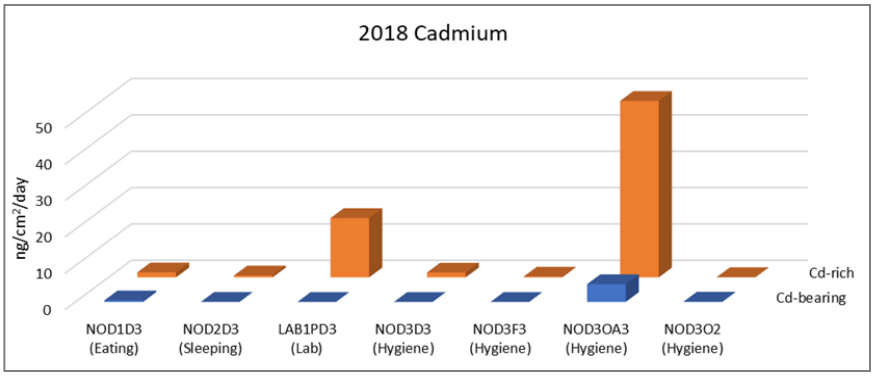

Figure 4. Average cadmium particles collection rates in 2018 at different ISS locations.

To calculate an estimate of the amount of airborne cadmium particles in the air on ISS, it was assumed that the cadmium particle collection on each PAS substrate is representative of the entire surface of the filter holding the PAS. This data was further employed to estimate the average amount of cadmium-containing particles in the air.

As shown in Equation (1), the particle collection rate, R, can be estimated from the amount of particles collected on the filter surface, or from the particle concentration in air and the air flow rate.

$$R = (\rho_A \cdot A)/t = C_{mass} \cdot Q \qquad (1)$$

Where R = particle collection rate; $\mu g/day$
ρ_A = surface density of particle loading; $\mu g/cm^2$
A = surface area of the filter; cm^2
t = sampling duration; day
C_{mass} = mass concentration of the particles in air; $\mu g/m^3$
Q = air flow rate; m^3/day

1. Estimated Cadmium Particle Collection Rate

Assuming that the average cadmium particle collection rate on the PAS samplers is representative for all filter surfaces in ISS, then for 2016 (from Table 5):

$$\rho_A/t = 6.99 \frac{ng}{cm^2 \cdot day} = 6.99 \times 10^{-3} \frac{\mu g}{cm^2 \cdot day} \qquad (2)$$

and the total filter surface area:

$$A = 21 \times 73.7cm \times 10.2cm = 15786.54\ cm^2, \qquad (3)$$

as there are 21 Bacterial Filter Elements (BFEs) onboard ISS, each has a length of 73.7 cm and a width of 10.2 cm.[12] So, the cadmium particle collection rate for 2016:

$$R = (\rho_A \cdot A)/t = 6.99 \times 10^{-3} \frac{\mu g}{cm^2 \cdot day} \times 15786.54\ cm^2 = 110.35 \frac{\mu g}{day}$$

Similarly, the cadmium particle collection rate for 2018 can be estimated to be about 166.5 $\mu g/day$. These are likely order-of-magnitude estimates, assuming that the average surface density of particle loading of the samples is representative of that of the filters.

2. *Estimated Cadmium Particle Concentration in Air*

Based on equation (1), the cadmium particle concentration in Air is:

$$C_{mass} = R/Q$$

Based on the approximate average on-orbit data from April 2020, the air flow rate per filter is about 81.3 cubic feet per minute (cfm), or 2.30 m^3/min. Considering all 21 filters:

$$Q = 21 \times 2.30 \frac{m^3}{min} \times \frac{24 \times 60\ min}{day} = 69552\ m^3/day,$$

From 2016 data:

$$C_{mass} = R/Q = 110.35 \frac{\mu g}{day} / (69552\ \frac{m^3}{day}) = 1.59 \times 10^{-3}\ \mu g/m^3$$

For 2018, the cadmium particle concentration in air can be estimated at $2.3 \times 10^{-3}\ \mu g/m^3$ using the same methodology and parameters as the 2016 estimate. The OSHA permissible exposure limit (PEL) of cadmium (as of 10/02/2019) is 0.005 mg/m^3 or 5 $\mu g/m^3$.[13] It is clear that the estimated cadmium particle concentrations in ISS air are well below the OSHA PEL level, thus the likelihood of cadmium aerosol presenting a health concern is very low. Meanwhile, it is important to emphasize that this is a rough estimation due to the limitation of the sample collection method and material characterization techniques, as well as the assumption that the particle surface density of PAS samplers represents that of the entire filters. There are different ranges of flow rates for vents in different modules, which vary slightly based on the ventilation design, and also depends on how much particulate debris builds up on the protective filter screens between housekeeping chores. The amount of uncertainty in these estimates has not been quantified and is left for future work, but conclusions can be drawn based on the orders of magnitude differences between the OSHA PEL and the ISS concentrations.

The same approach is used to estimate various metal particle concentrations in ISS air and compare them to their OSHA PELs. In both 2016 and 2018 Cadmium, Nickel, and Silver were the three elements that were closest to the OSHA PELs. One thing to be noted is that nickel has 3 separate OSHA PELs which depend on their solubility and species, and of those three PELs "Nickel Soluble" had the lowest PEL. Since the EDS data gives only elemental composition, which does not include solubility, the lowest PEL was utilized during the comparison to be as conservative as possible. Using the methods as stated above, all the elements that had data available fell below 0.2% of their most stringent regulation standard. This number is strictly an estimate, as the element listed first in the particle class name was used to calculate the entire weight of the particles and minor elements in each particle were neglected due to lack of data.

There are several metals that were detected in the PAS but were either minor elements or were listed in the "miscellaneous" section because only one or two similar particles were collected, which did not warrant creating a dedicated particle class. These elements include vanadium, manganese, cobalt, hafnium, indium, and gold. There are also metals that don't currently have regulations under OSHA but were detected in the PAS and include neodymium, lanthanum, tungsten, and strontium. In the graphs that show the 2016 and 2018 data in terms of percent of OSHA limit, these elements listed above appear as if they are 0% of the OSHA limit. Figures 5 and 6 show the comparisons of the 2016 and 2018 sampling data as a percentage of the OSHA limit, with Figure 6 having a logarithmic scale.

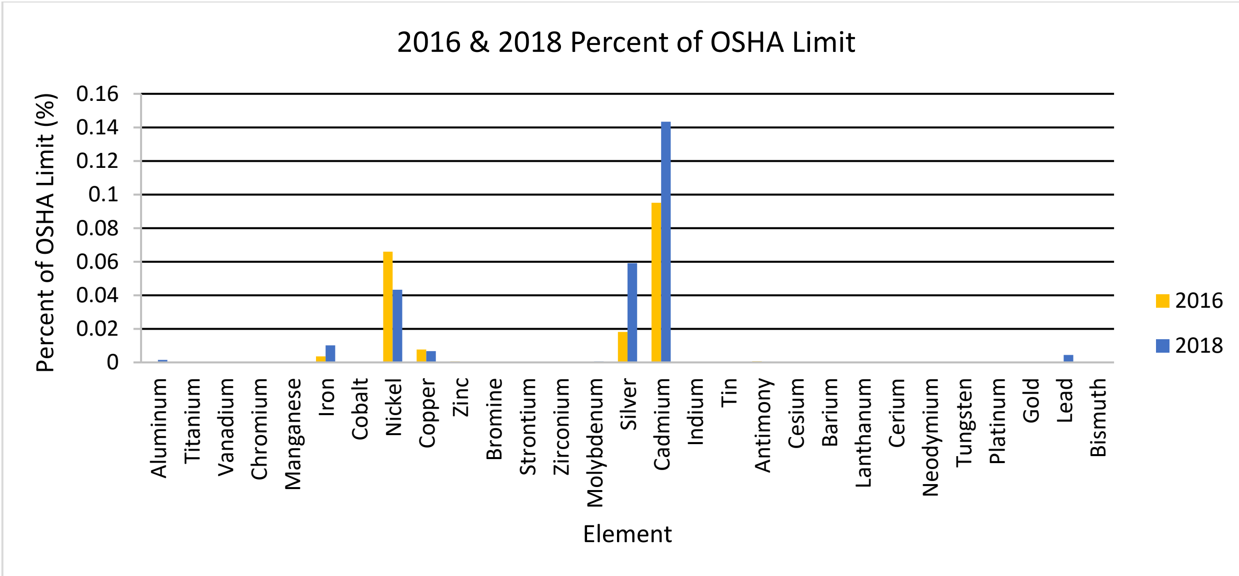

Figure 5. Chart of Elements versus their Percent of OSHA Limit.

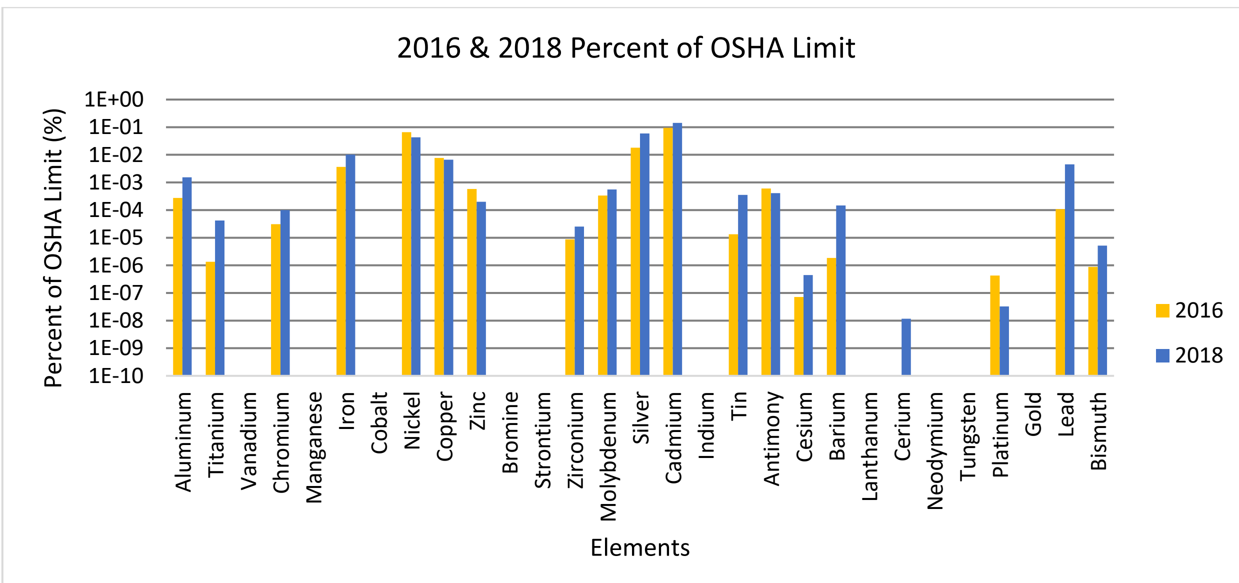

Figure 6. Chart of Elements versus their Percent of OSHA Limit on a logarithmic scale.

IV. Potential Sources of Cadmium, Nickel and Silver

Based on our first attempt at estimation, in both 2016 and 2018, the ISS aerosol concentrations of various metals are well below the OSHA PELs. That being said, Cadmium, Nickel, and Silver were the three elements that were closest to the OSHA PELs. Their potential sources are worth exploring.

A. Cadmium

Cadmium is a common component of batteries, pigments, coatings, and electroplating.[14] In early 1990, EPA and OSHA recommended a reduction in cadmium use due to its toxicity.[15, 16] In 2006, NASA started to eliminate cadmium from the crew living environment.[17] Some ISS structures were built before 2006, when Cd-plating was used for mechanical coating and corrosion protection.[18] Therefore some potential sources for Cd containing particles could be Cd plated bolts and fasteners (used by the Space Shuttle Program),[19] that can also possibly be used in exercise equipment and equipment the US Lab and in Node 3.

Figure 8 shows some examples of Cd-rich particles, (1) located at 2016 PAS D-16, NOD3D3, (2) 2016 PAS G-8, NOD3F3, (3) 2018 PAS H-2, NOD3OA3, and (4) 2018 PAS H-2, NOD3OA3, where the color mapping is based on the EDS spectrum (purple indicates Zn and green indicates Cd). As shown in Figure 3 and Figure 4, Node 3 is one of the locations where most of the Cd-rich particles were sampled, and it happens to be the exercise area. Their composition and dimensions are mostly consistent with Cd-plating sources;[20] Cd-plating is sometimes treated with phosphate or chromate, and typically has a minimum thickness range: 5 to 12 μm. Note that particles (1), (2) and (4) in Figure 7 have minor Cr peaks in their EDS spectra which could indicate chromate.

B. Silver

The potential sources of silver containing particles were investigated in detail in an earlier paper.[8] Some potential sources include silver disinfectants, coatings on heat exchangers, and possible silver plating for electronics.

C. Nickel

Nickel alloy and stainless steel are alloys are currently used on ISS. Nickel electroplating or electroless nickel-phosphorus plating are also common surface treatments on a wide range of metal substrates.[21]

Figure 7 shows the average nickel particle collection rates in 2016 and 2018 at different ISS locations. It is obvious that LAB1PD3 is the location with activities that consistently generate the highest quantities of Ni-rich particles. This sampling location is directly below the exercise bicycle, known as the Cycle Ergometer with Vibration Isolation System, or CEVIS. Any exercise device has numerous parts with metal-to-metal contact and thus mechanically generated particles are not surprising.

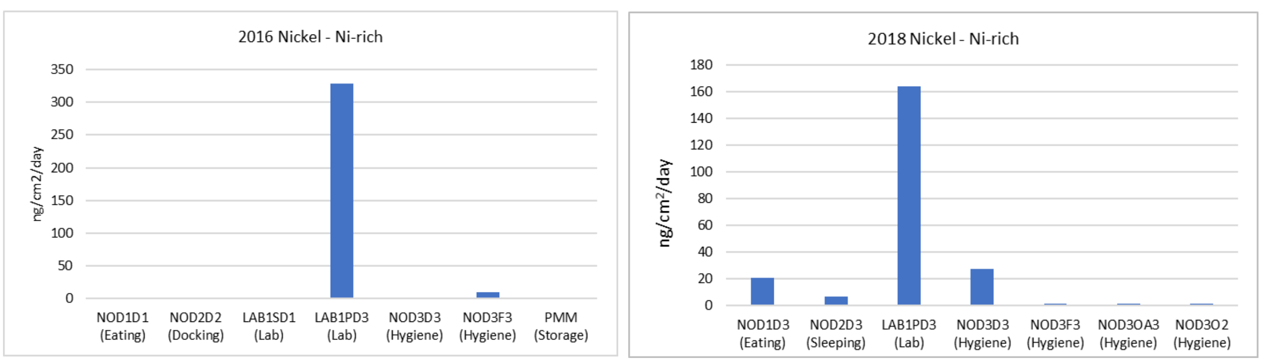

Figure 7. Average nickel particles collection rates in 2016 and 2018 at different ISS locations.

Figure 9 shows some examples of Ni-rich particles located at LAB1PD3, (1) on 2016 PAS K-16, while (2), (3) and (4) are on 2018 PAS D-2. Particles (1), (2) and (4) are Ni-rich particles with some P, and Al is also a minor element. Their compositions are consistent with Ni-P electroless coating, a widely used treatment for reducing the potential for wear and corrosion. It is often used to smooth the surfaces of hard disk drives made of aluminum alloy.[22] The dimensions of these particles are also consistent with the thickness requirement of the electroless Ni plating, which are often thicker than 25 microns.[23] Particle (3) is an almost a thin layer of pure Ni, with very little Fe. It is possibly a wear particle from a Ni electroplating on an iron article, but there is much less circumstantial evidence in this case.

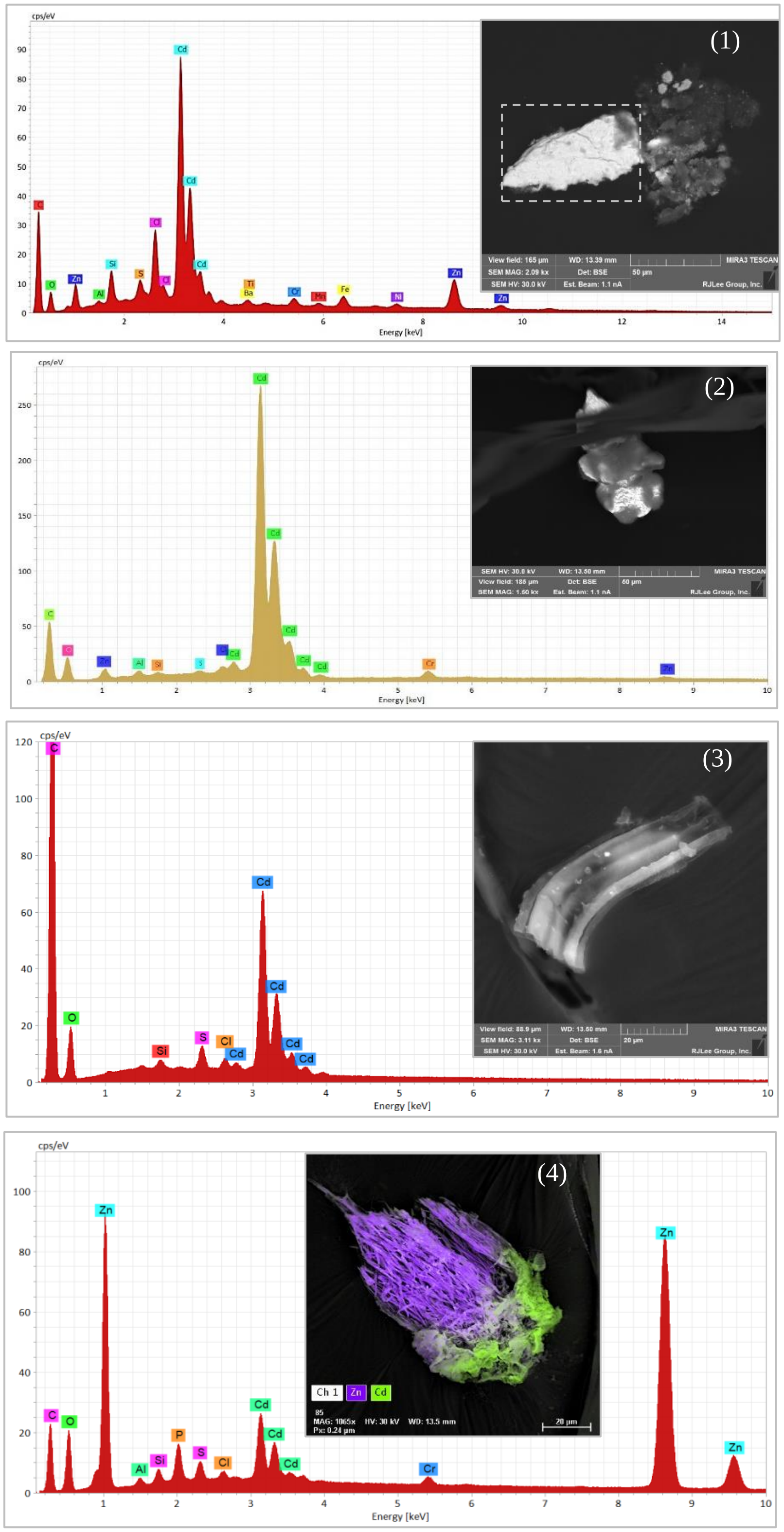

Figure 8. Examples of Cd-rich particles.

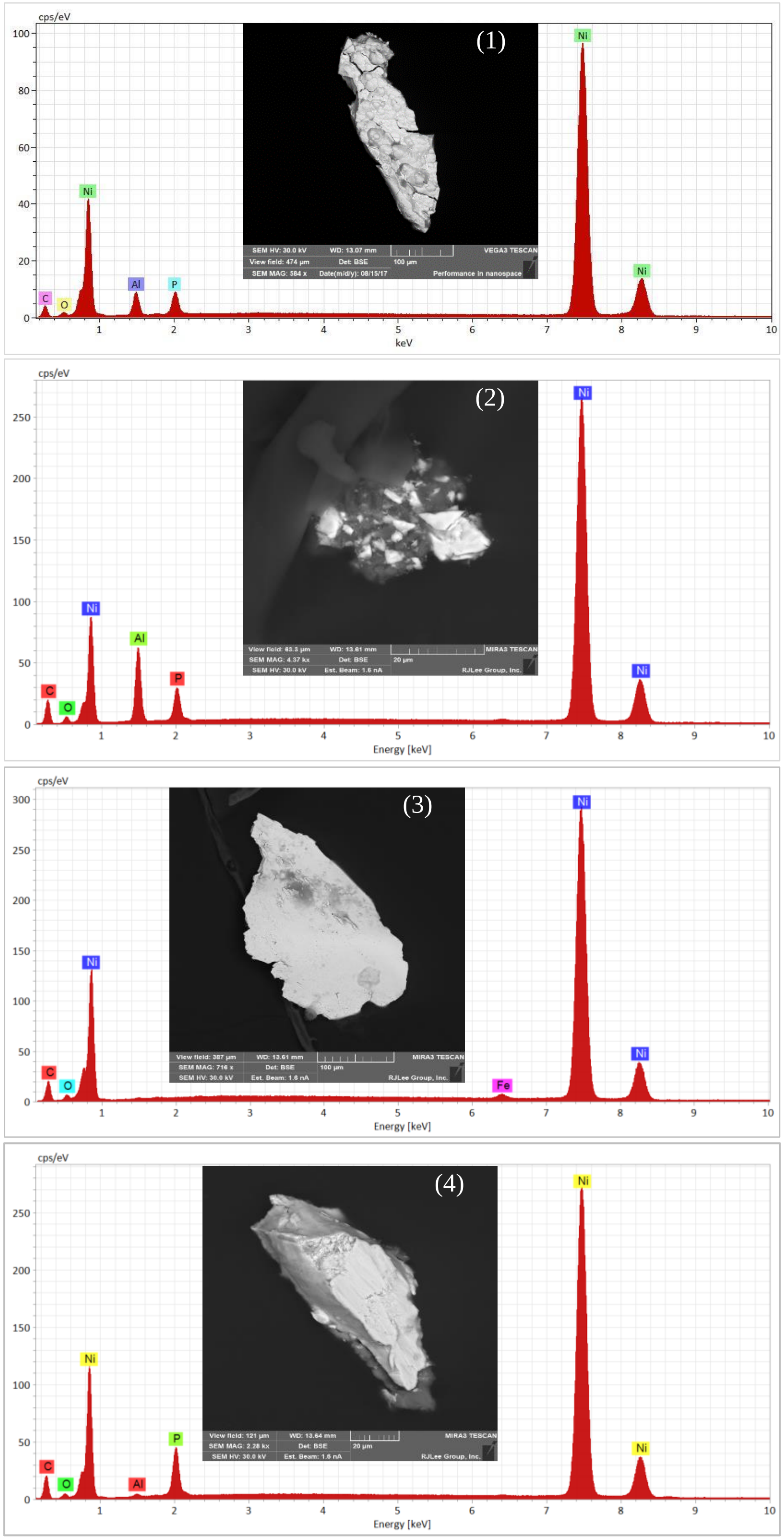

Figure 9. Examples of Ni-rich particles.

V. Summary

The 2016 and 2018 Aerosol Sampling Experiments have provided valuable information on the ISS air quality and helped define the requirements for future particulate monitors in spacecraft. The work presented on this paper focused on estimating the metal aerosol concentrations onboard ISS during the sampling periods by further analyzing the PAS sample analysis results. A first-cut calculation based on broad, but mostly conservative assumptions provided an estimate of airborne metal concentrations. These assumptions are as follows:

- PAS sample collection on one vent is uniform over all five substrates
- EDS results for particle composition are representative of the entire volume of the particle, not just the surface layer
- The surface density of particle deposition on the PAS can be extrapolated and encompasses the amount that is flowing into the entire surface area of the filter
- The value of the flow rate into the vent used in the calculations is an average value for vents in different modules with different levels of cleanliness
- OSHA limits were adjusted to represent the presence of the crew in their workplace 24 hours per day

Additional factors that can be considered in future more detailed analyses include:

- OSHA regulates for a typical 5-day work week, however, the ISS crew is exposed to their workplace air for 7 days per week
- The volume of air inhaled by a person varies by activity level (active/exercise vs. resting/sleep)
- The tidal volume in the lung is different in microgravity because of fluid shifts in the body

The estimated concentrations of various metal-containing particles in ISS air were compared to OSHA PELs, and were found well below their OSHA exposure limits. Node 3 and the US Lab had the most airborne metals compared to the other samling locations.

The potential sources of cadmium and nickel containing particles were also explored, as their concentration in ISS air are the closest to the OSHA PELs, but still orders of magnitude lower than the PELs. Based on these results, the ISS atmosphere is quite clean from a metal aerosol perspective, due to effective HEPA filtration and a well-designed ventilation system. An additional aerosol sampling experiment is planned and will add another particle data set for future comparisons.

Acknowledgments

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