Presentation from 2019 Aerosol Conference
Meyer, M.E., Sorek-Hamer, M. (2019). Database for Aerosols in the International Space Station,
37th Annual American Association for Aerosol Research Conference, Portland, OR, October 14- 18, 2019.
The current database online https://iss-particle-db.arc.nasa.gov/ may be different than graphics shown here.

Database for Aerosols on the International Space Station

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2 mm

Outline

- Background
  - Aerosols in low gravity
  - Sampling method
  - Unique morphology
- Formation mechanism
- Aerosol sample data
- Particle database examples
- Conclusions

Aerosol Behavior in Low Gravity

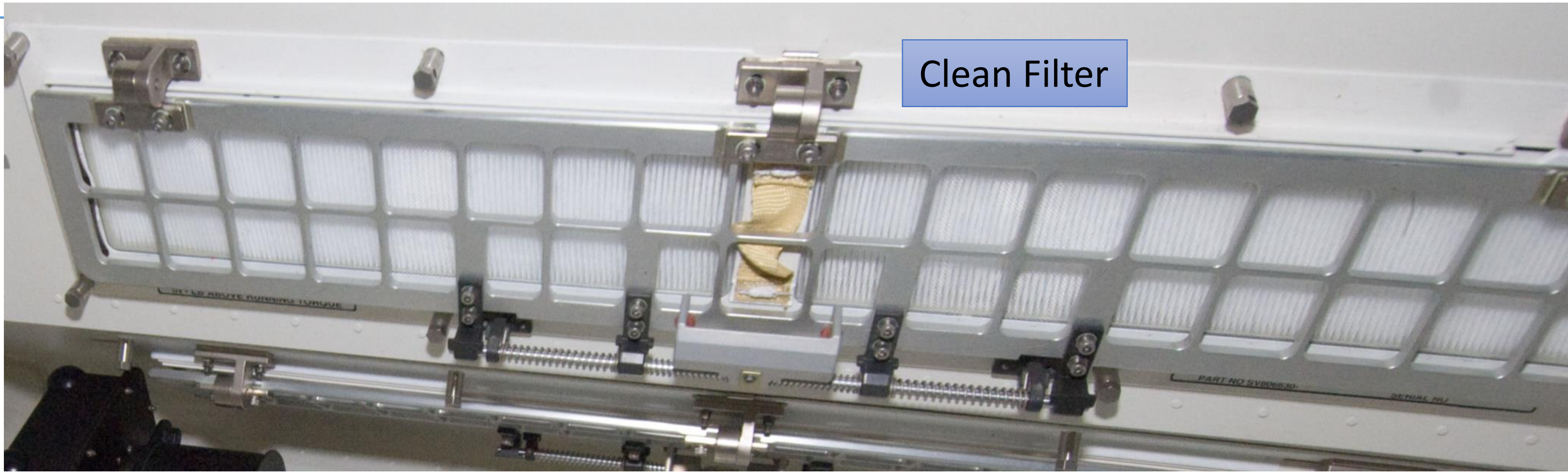
- Historic quote from Scott Carpenter
  - One of the Mercury 7
  - The second American to orbit the Earth in 1962
- "Every time I opened up the (food) bag, the crumbs would come crowding out like a swarm of bees”

Aerosol Behavior in Low Gravity

- On Earth, our air quality is improved by gravitational settling
  - In µg, all particles remain airborne until deposited on surfaces, air inlet screens or ventilation system filters

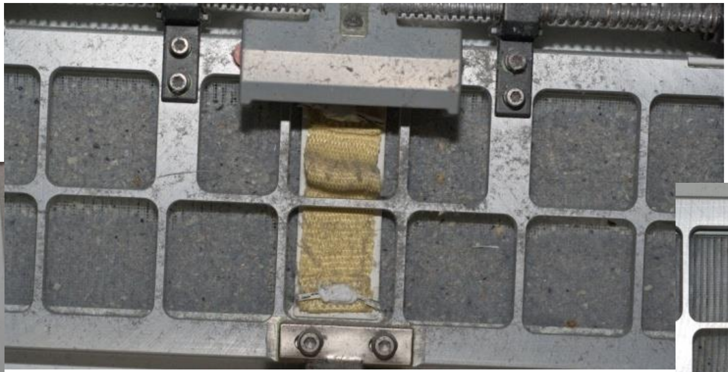
- 'Dusty air' has been a complaint of astronauts
  - Indicates high concentrations of inhalable particles
- No particle measurement capability on ISS…yet
- Filter inlets and fan intakes on equipment require regular vacuuming

Aerosol Deposition



12 days accumulation

Node 3

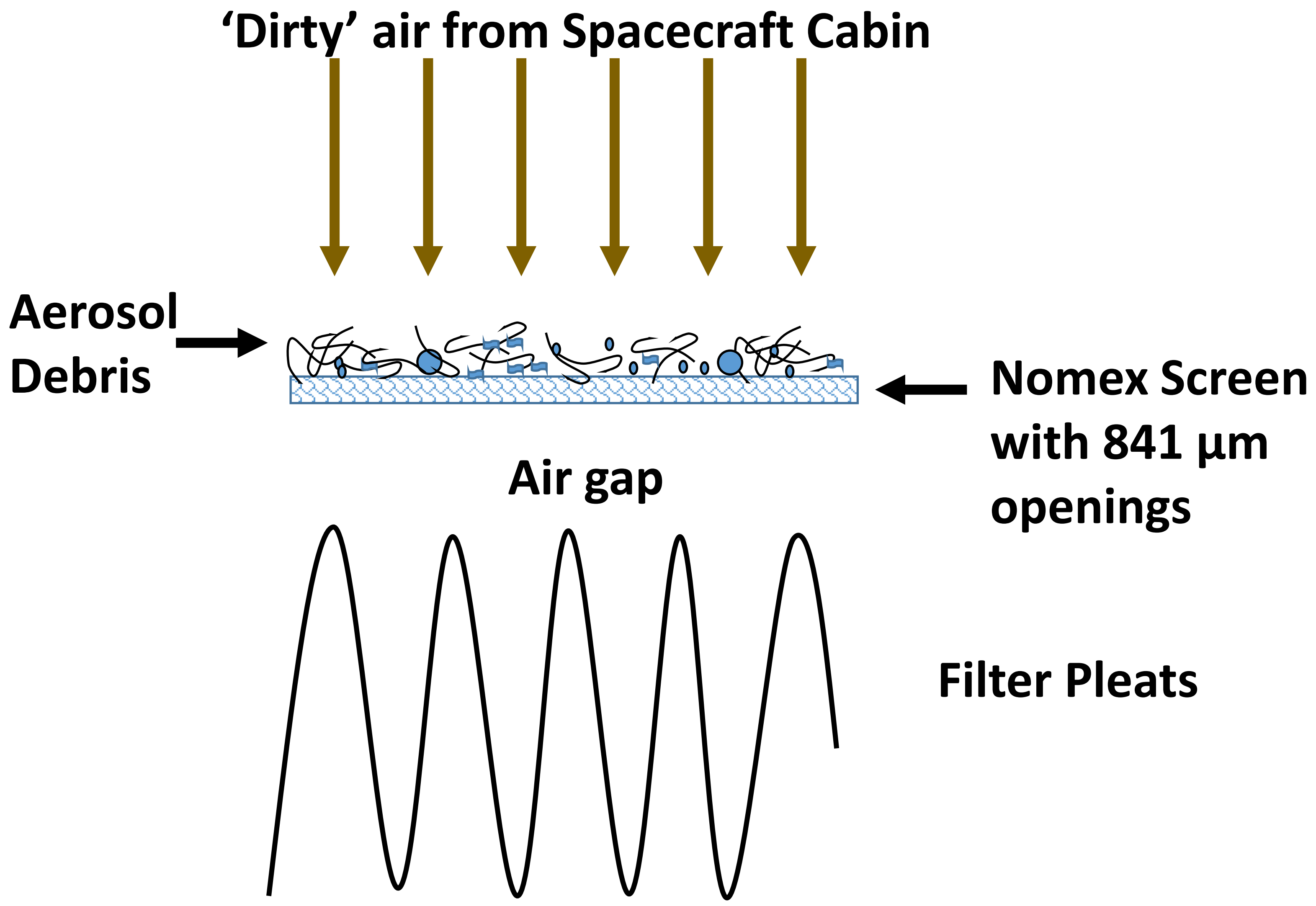


8 days accumulation

8 days accumulation

Node 1

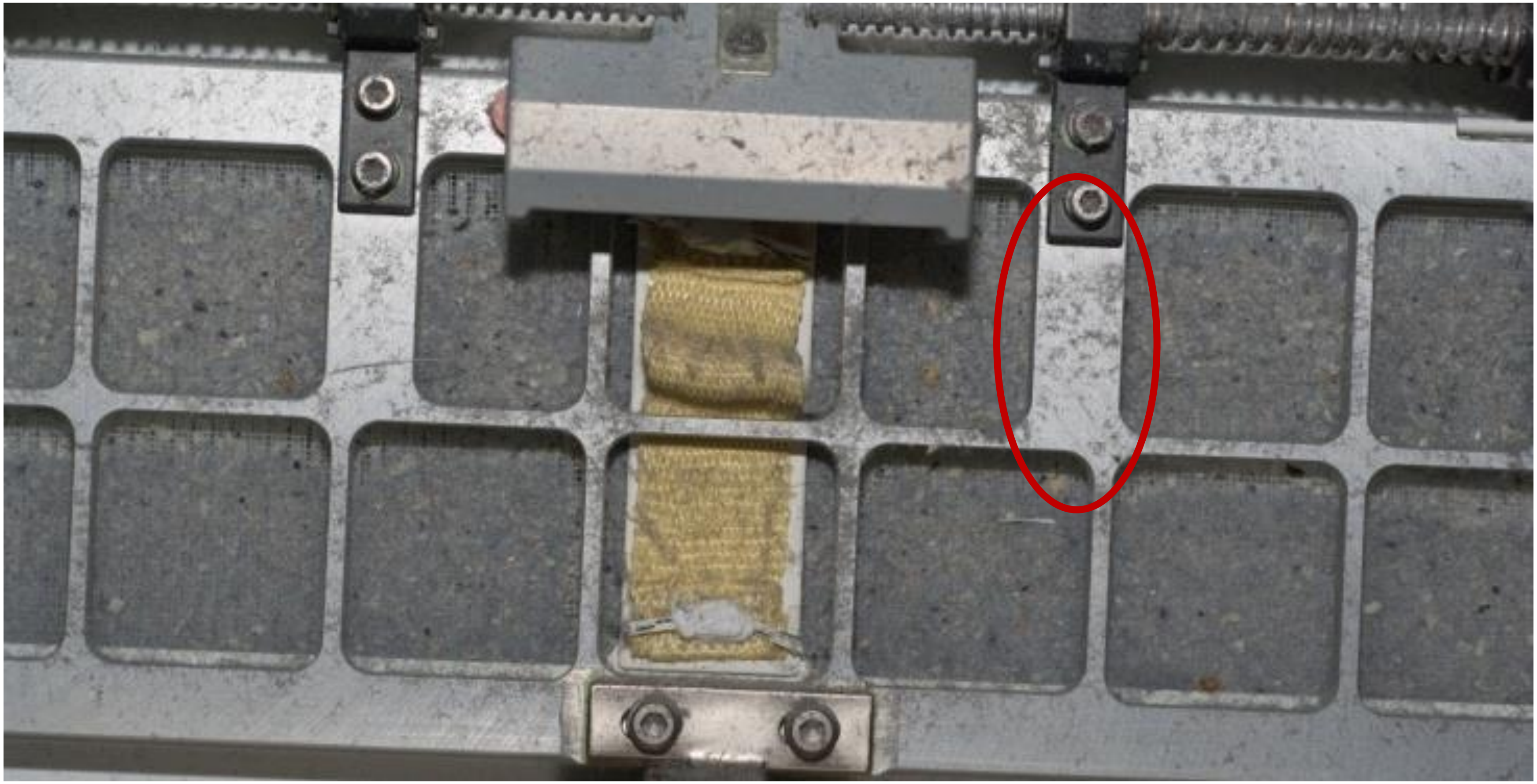
Aerosol Deposition



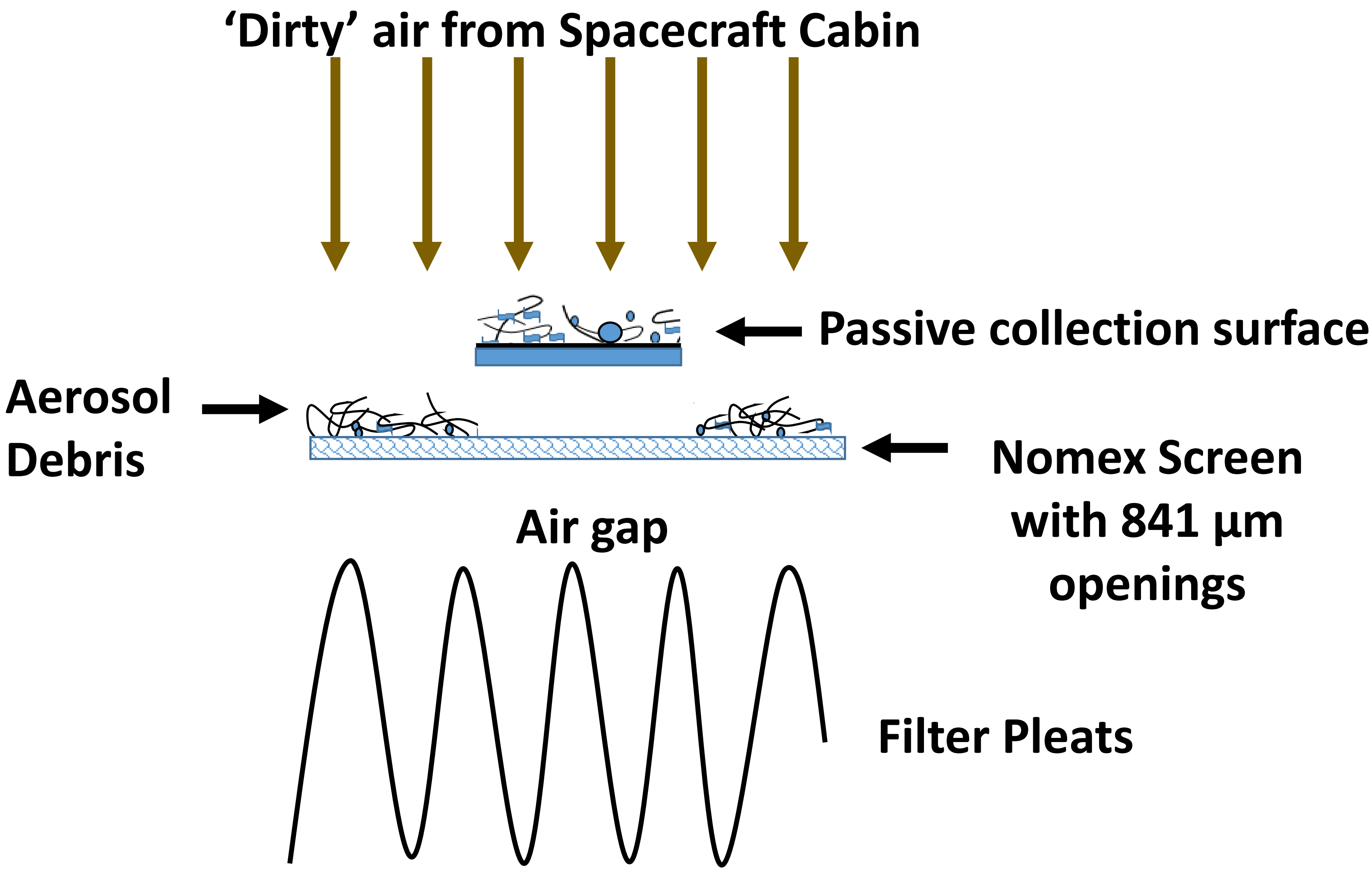
Aerosol Sampling Experiment

- First step in characterizing ISS aerosols was sampling
  - Capture particles, bring samples back to Earth for analysis
- Aerosol Sampling Experiment funded by Life Support Systems Project
  - December 2016
  - July 2018

Passive Sampling without Gravity

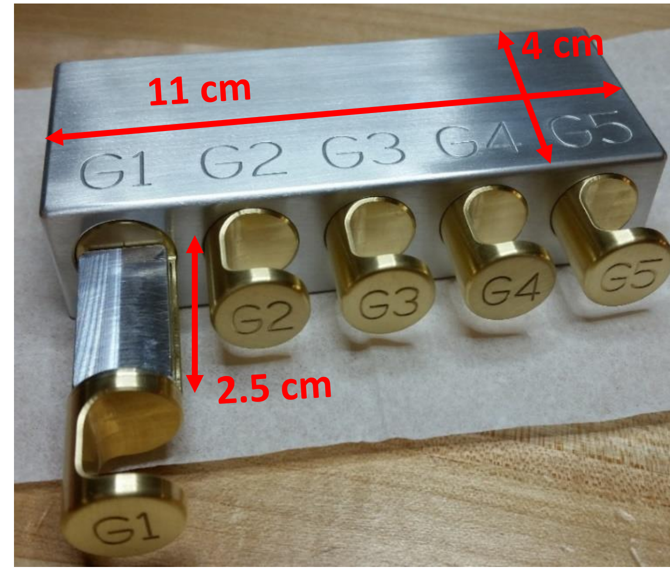


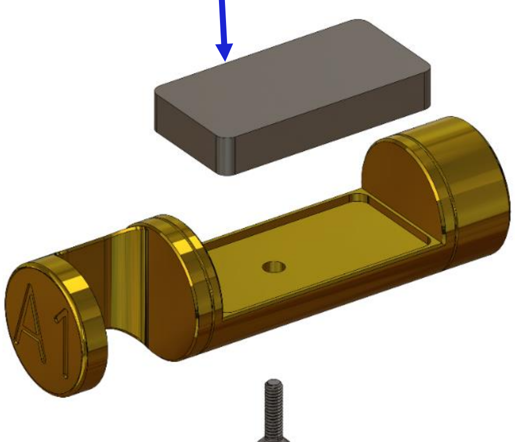
Aerosol Deposition



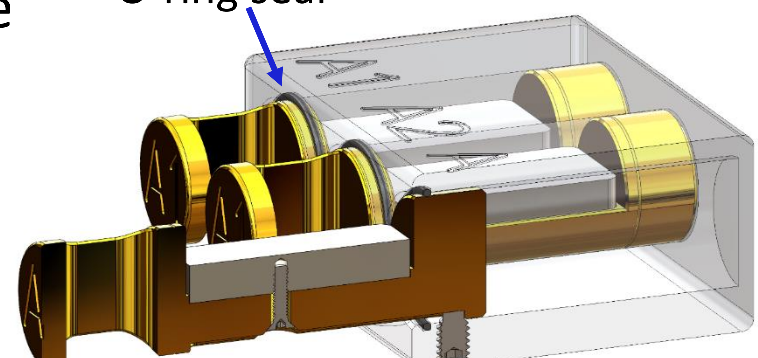
Passive Sampler

- Five individually bored, separately sealed collection ‘drawers’
- Drawers open, collect debris, and are closed to protect sample from contamination
- Aluminum block substrate with 2-way sticky carbon tape
  - Block fits in electron microscope





O-ring seal

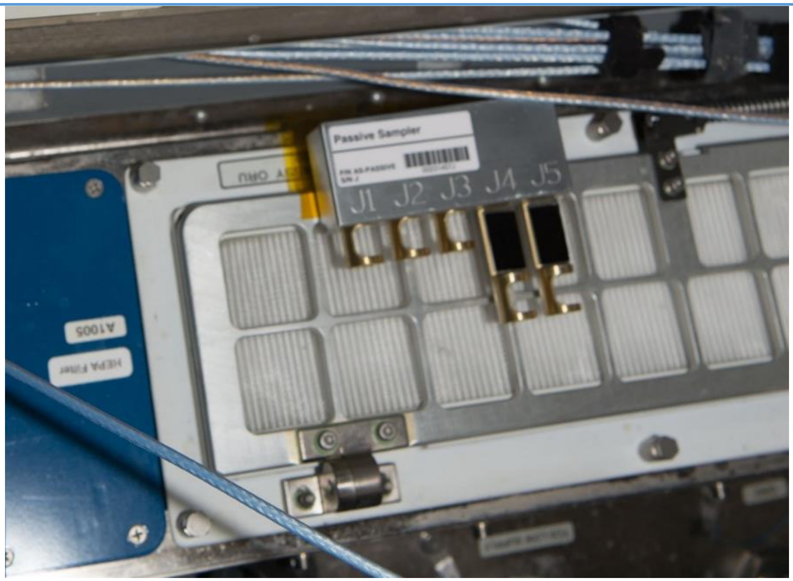


Frit for pressure equalization

Aerosol Sampling Experiment

- The optimal sampling duration to get the best particle coverage for microscopic analysis varies by location
- Five substrates provided different particle loadings to choose from as well as redundancy to reduce risk
- The operations in Increment 50/51 collected particles for 2, 4, 8, 16 and 32 days
  - Ideal samples for microscopy were mostly in the 16 and 32-day durations
- Operations in Increment 56 collected particles for 26 days on all substrates
  - Better statistics
  - Less crew time

Passive Sampler Deployments



2016 deployment, **between day 8 and day 16**

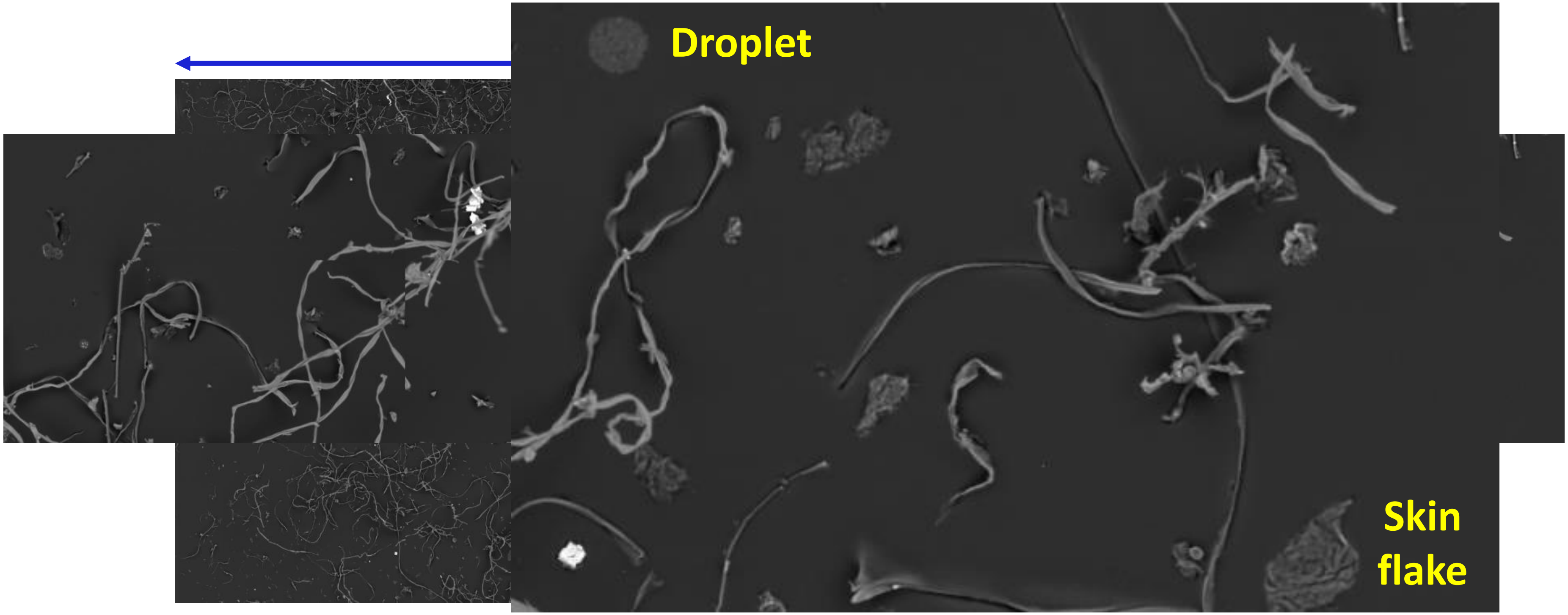
2018 LAB1PD3 US Lab Bay 3

2018 NOD2D3 Midbay
HEPA Return Register

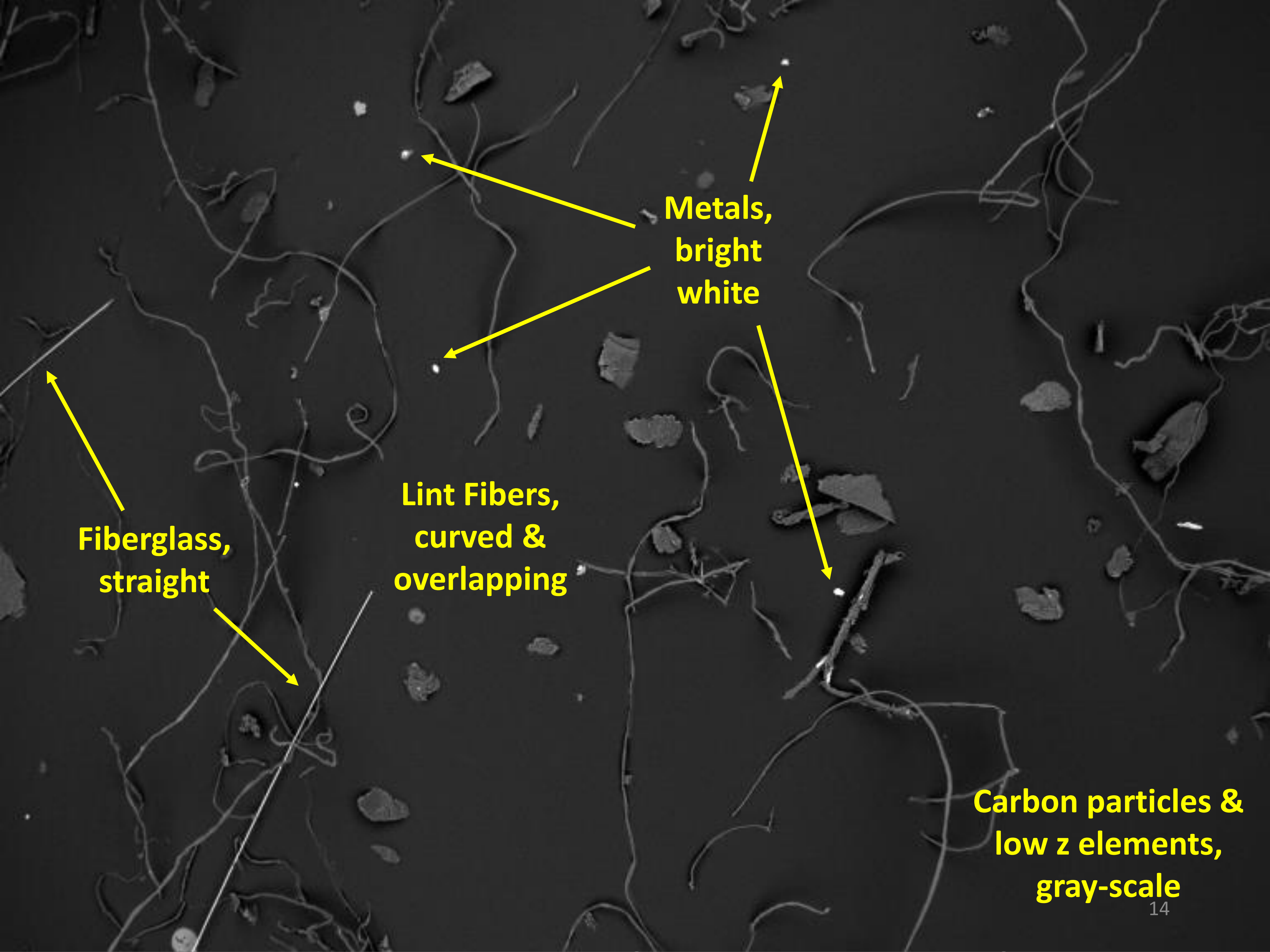
2018 NOD3F3
HEPA Register

Passive Sampler Microscopy

- A montage for each passive sample was created by combining fields of high-resolution SEM backscattered-electron images*

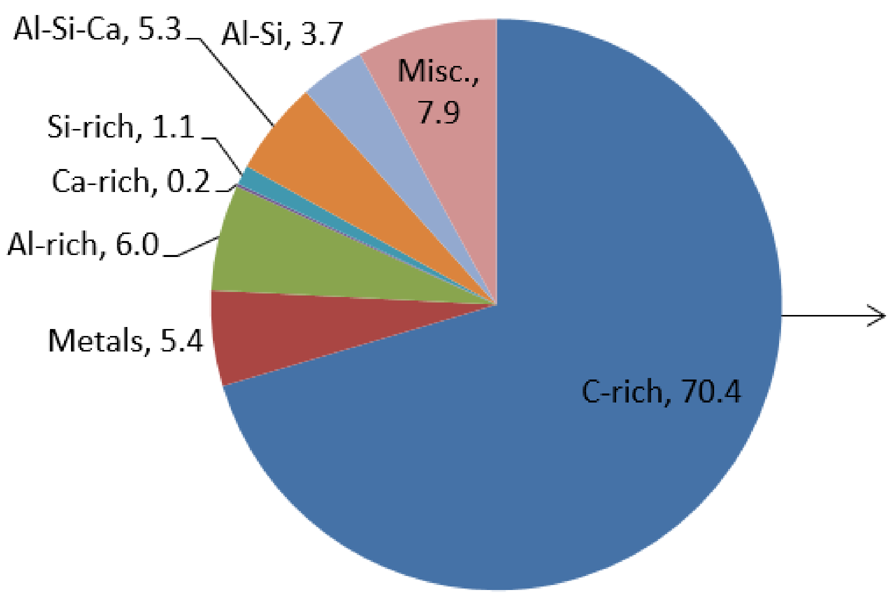


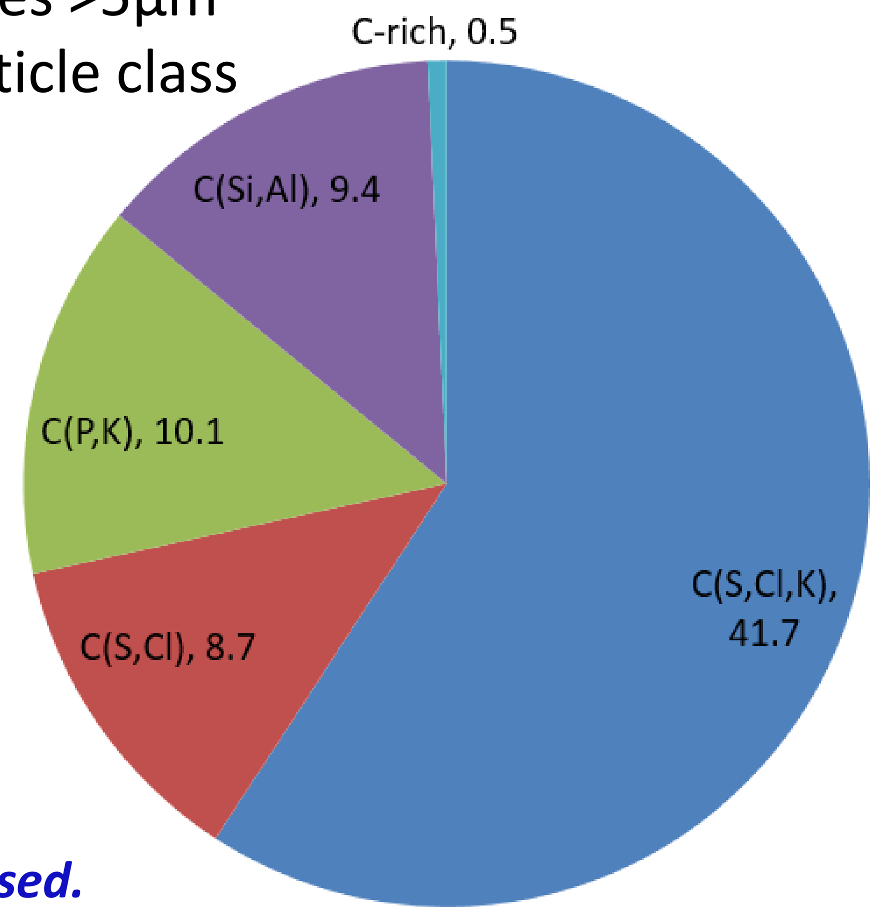
*Microscopy was performed through a subcontract with RJ Lee Group


Metals, bright white
Lint Fibers, curved & overlapping
Fiberglass, straight
Carbon particles & low z elements, gray-scale

Carbonaceous Particle Analysis

- Passive sampler in US Lab
- All non-fibrous individual particles >5µm
- Weight % concentrations by particle class





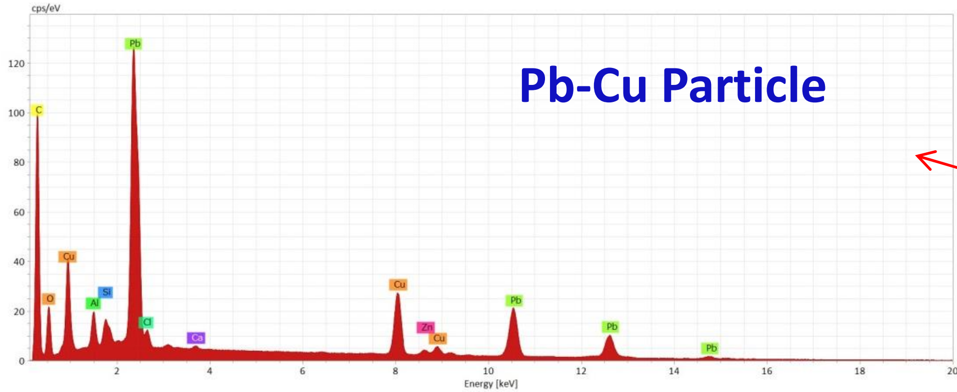
Breakdown of Carbonaceous Particle Classes

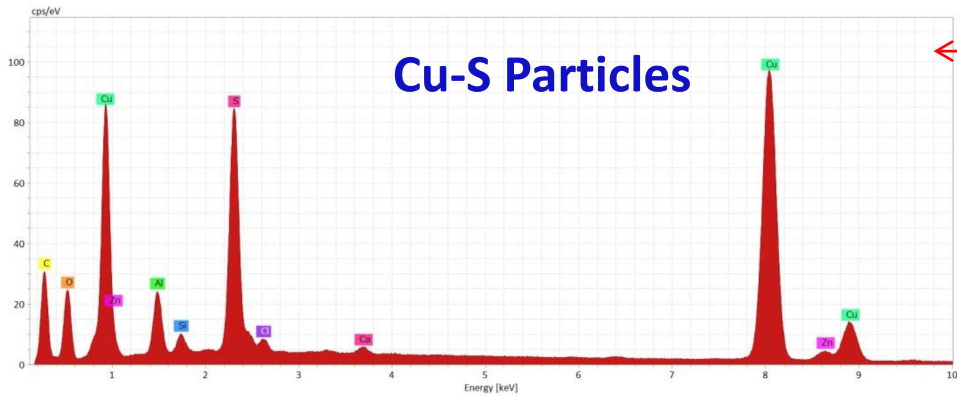
The majority of the particles are carbon-based. Metals are a small portion but easiest to analyze…see slide 23

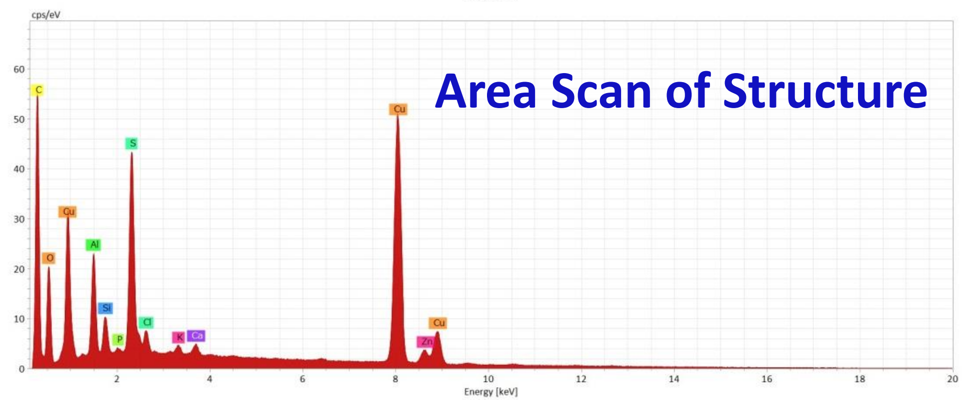
Unique Particle Morphology

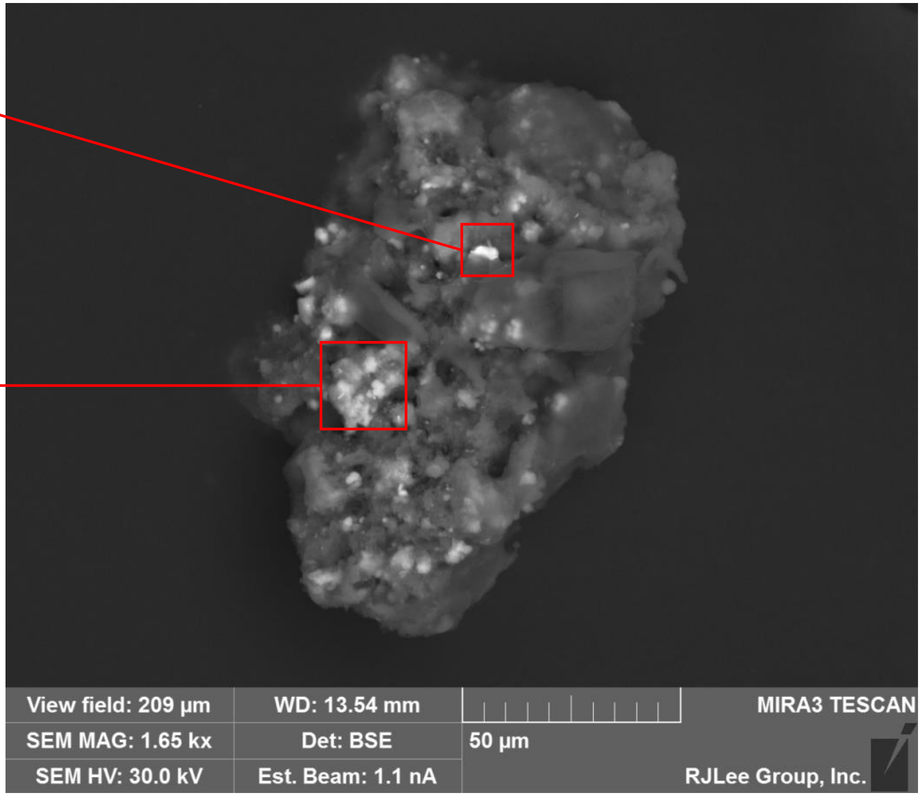
- ISS samples had many multi-component particles
  - Individual metal particles embedded in a carbonaceous matrix
- Presents challenges for counting particles by image analysis
  - Must distinguish edges to outline individual particles based on contrast thresholds
  - Fibers were a challenge as well

Multi-Component Particle









Copper/lead-rich particles and copper/sulfur-rich particles associated with carbonaceous material

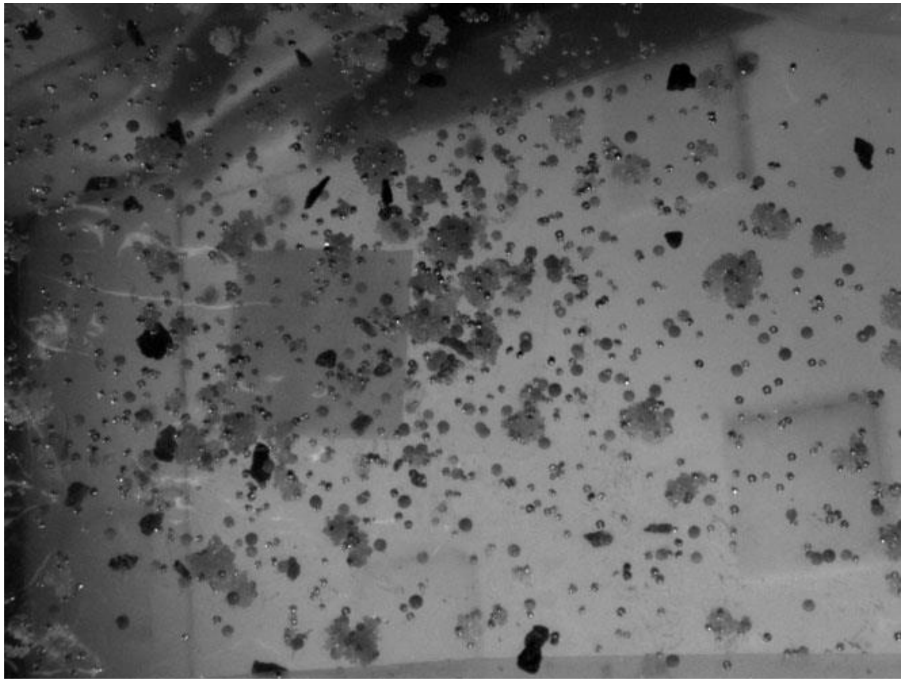
Formation Mechanism?

- Did many individual particles agglomerate after becoming airborne on ISS?
- Were the parent materials composites to begin with?
- Astronaut Don Pettit performed some "informal particle aggregation experiments" in plastic bags on ISS in 2003, 2008 and 2011*
  - CAPCOM/astronaut Stanley Love recognized these experiments could be representative of planetary accretion

*Love, S.G., Pettit, D.R., Messenger, S.R., (2014) Particle aggregation in microgravity: Informal experiments on the International Space Station, *Meteoritics & Planetary Science* 49, Nr 5, 732–739.

Agglomeration Experiment

- Several types of particle materials were mixed in different types of bags in microgravity
  - Particles between 100 and 7000 micrometers (7 mm)
  - Salt, sugar, coffee, meteorite particles, acrylic and glass beads
- Some particles aggregated with strong cohesion
  - Low number densities
  - On the order of seconds
- Smaller particles aggregated more quickly and with higher cohesive strength
- Angular particles aggregated readily whereas round smooth particles did not
- *Overall, electrostatic forces dominated the process*

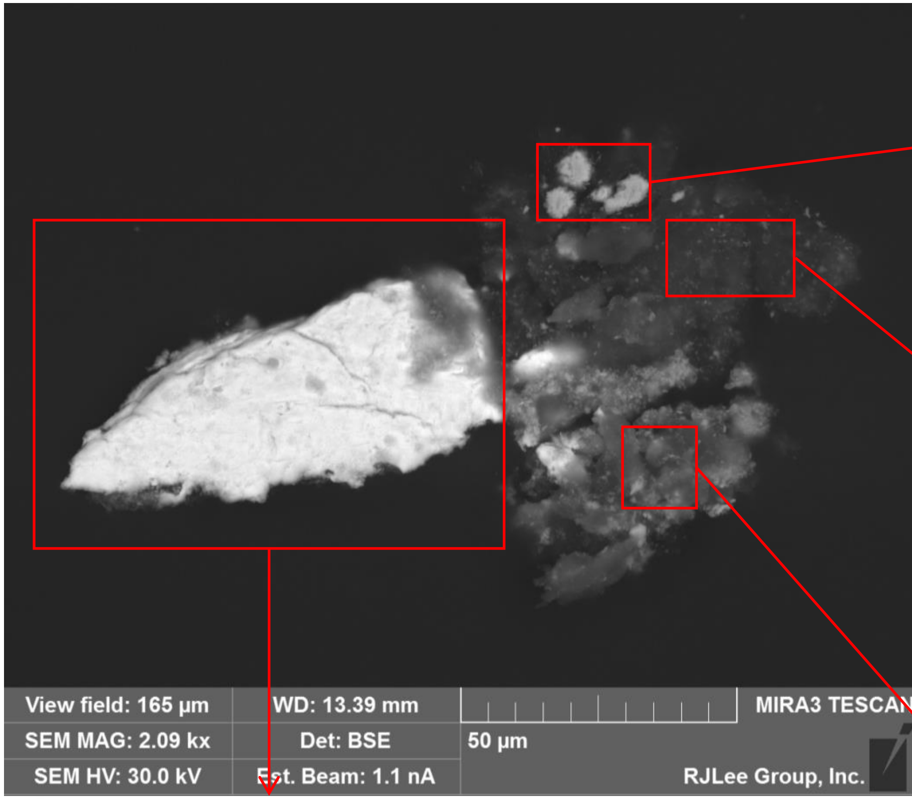


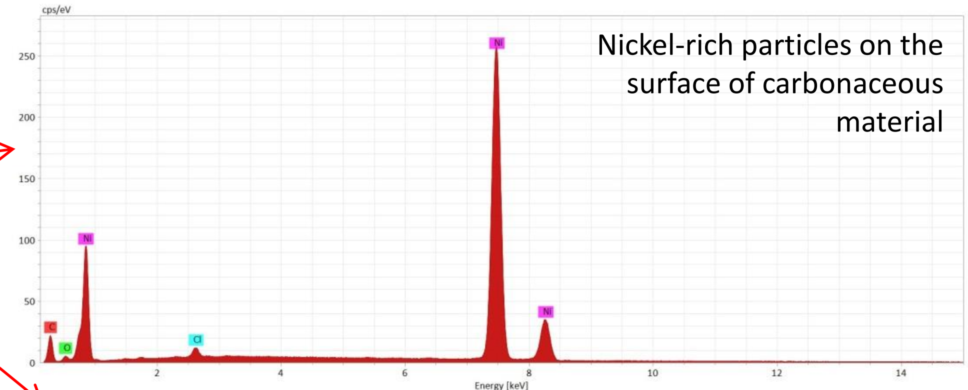
Clumps dominated by sugar, with incidental capture of acrylic spheres & meteorite particles

Possible Formation Mechanism of ISS Cabin Aerosols

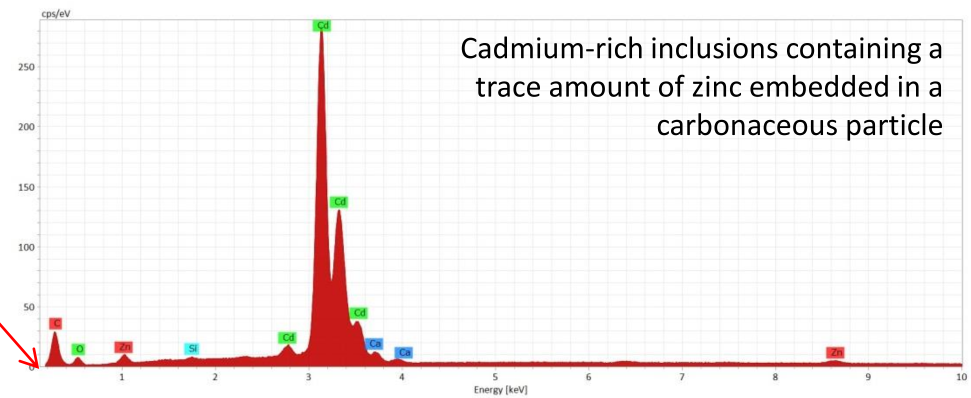
- The particle sizes in Don's experiments are similar to the passively sampled metal particles
- State of charge of ISS particles?
  - Mechanically generated particles are more likely to have high levels of charge
  - Sodium chloride and polymeric aerosols are more likely to exist in a charged state than conducting materials
- These informal experiments indicate that **agglomeration is a plausible formation mechanism** of the multi-component particles on ISS

Unique Particle Morphology

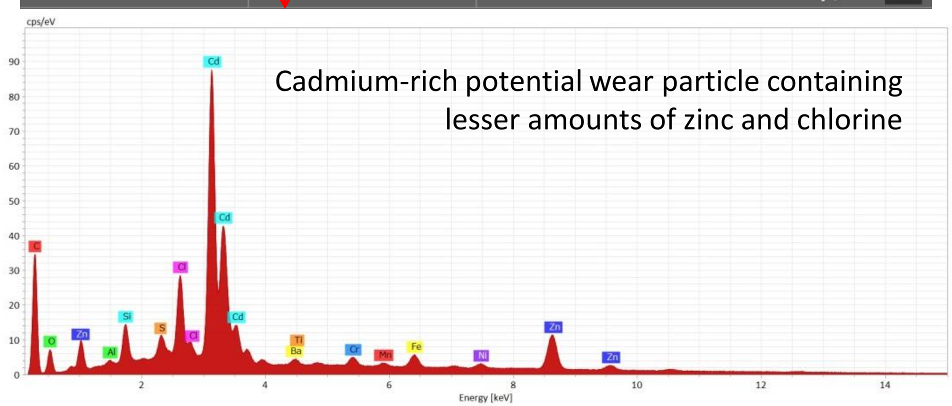




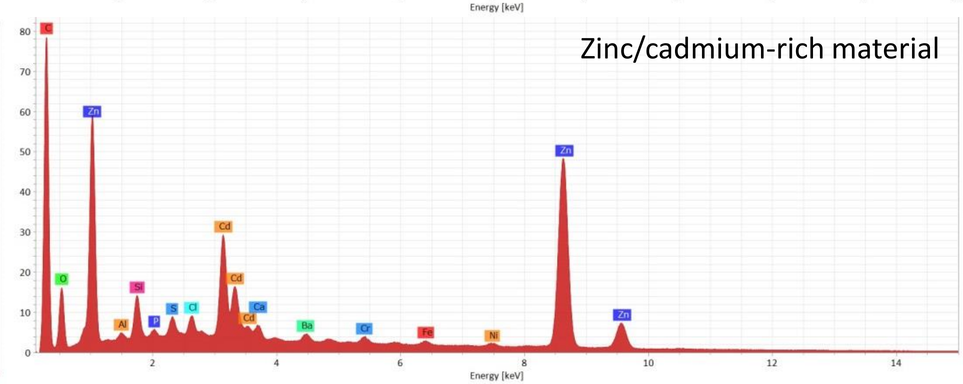
Nickel-rich particles on the surface of carbonaceous material



Cadmium-rich inclusions containing a trace amount of zinc embedded in a carbonaceous particle

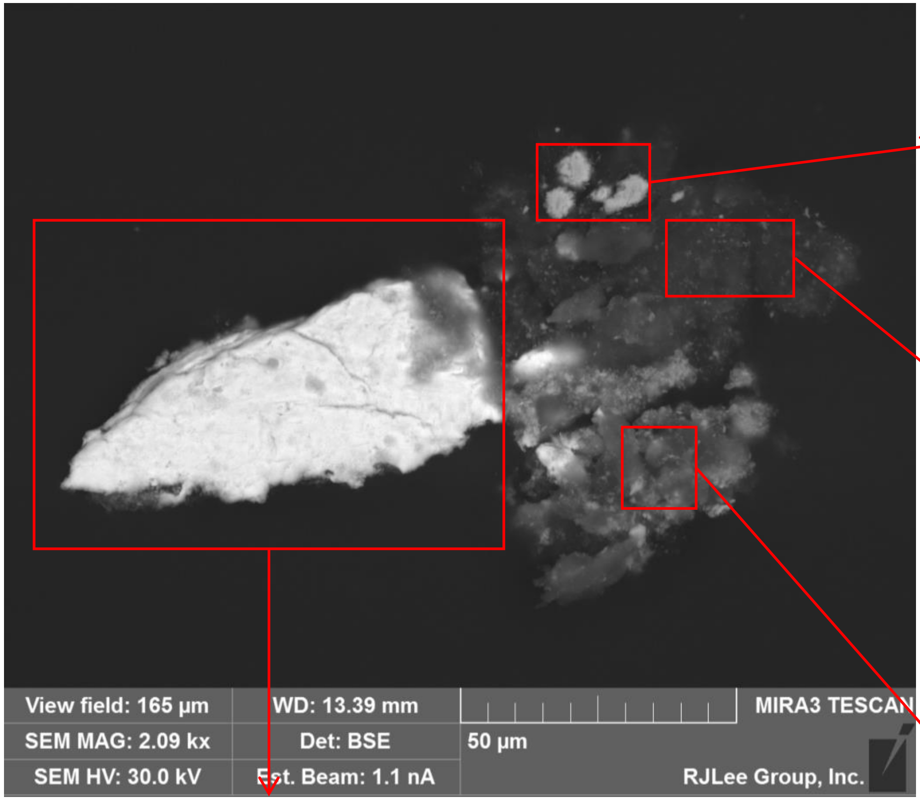


Cadmium-rich potential wear particle containing lesser amounts of zinc and chlorine



Zinc/cadmium-rich material

Unique Particle Agglomerate



Nickel-rich particles on the surface of carbonaceous material

Cadmium-rich inclusions containing a trace amount of zinc embedded in a carbon matrix

Zinc/cadmium-rich material

Mechanically generated wear particle, rich in cadmium and containing lesser amounts of zinc and chlorine

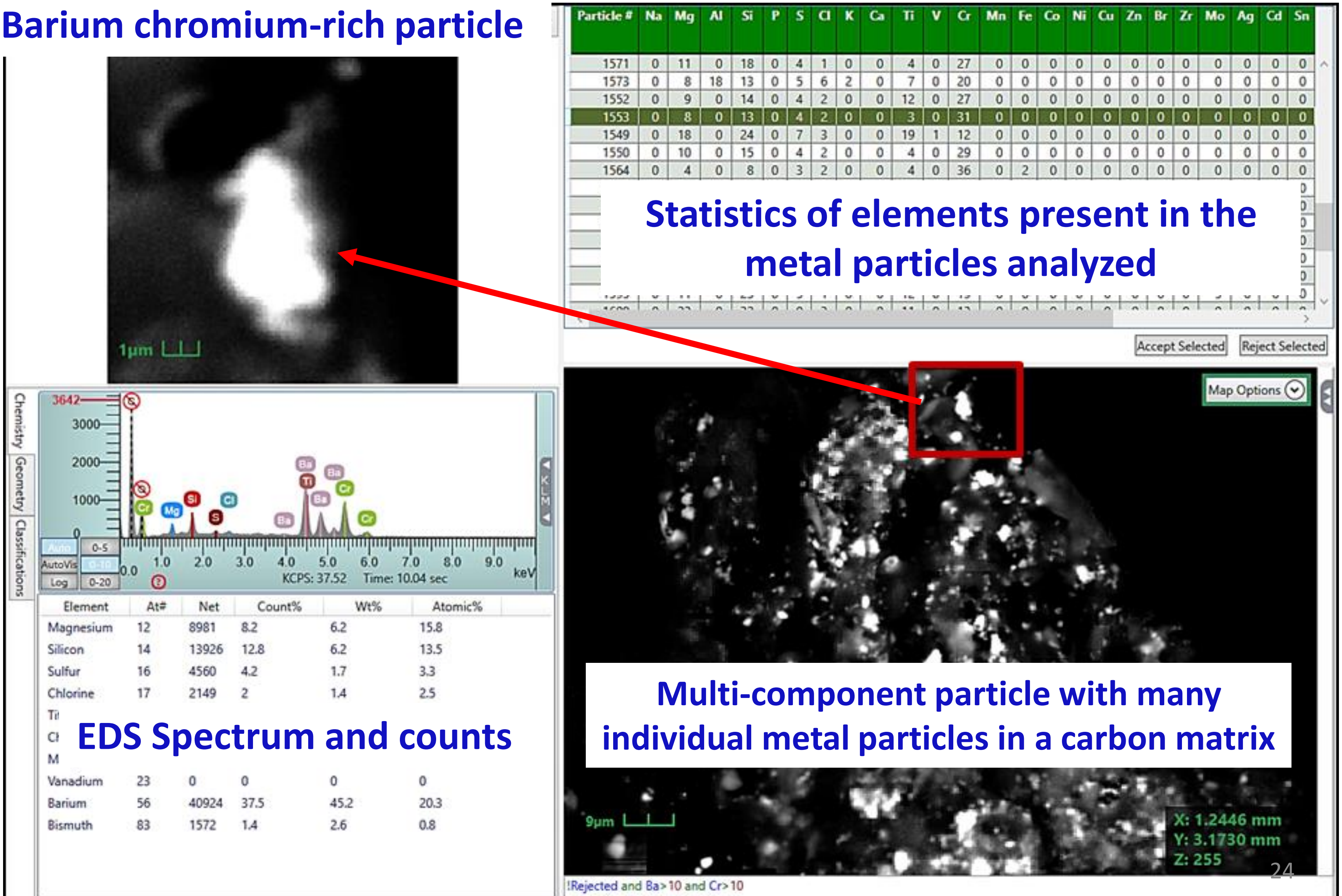
Sampled in Node 3

Sample Analysis Technique

- Computer-Controlled SEM (CCSEM)
  - IntelliSEM* software
- Bright metal particles within complex structures were analyzed *individually*
  - Atomic number titanium and higher (bright enough)
- The result was not total particle counts, but rather a characterization of metal inclusions in larger multi-component particles
- CCSEM metals analyses created a large dataset
  - Geometry and elemental composition

*IntelliSEM was performed through a subcontract with RJ Lee Group

Data Source: IntelliSEM Workbench



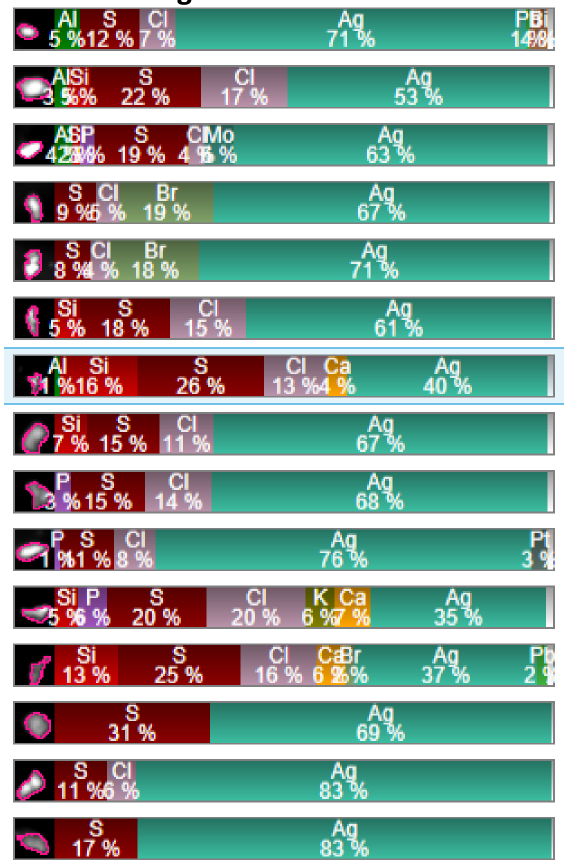
Particle #	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Br	Zr	Mo	Ag	Cd	Sn
1571	0	11	0	18	0	4	1	0	0	4	0	27	0	0	0	0	0	0	0	0	0	0	0	0
1573	0	8	18	13	0	5	6	2	0	7	0	20	0	0	0	0	0	0	0	0	0	0	0	0
1552	0	9	0	14	0	4	2	0	0	12	0	27	0	0	0	0	0	0	0	0	0	0	0	0
1553	0	8	0	13	0	4	2	0	0	3	0	31	0	0	0	0	0	0	0	0	0	0	0	0
1549	0	18	0	24	0	7	3	0	0	19	1	12	0	0	0	0	0	0	0	0	0	0	0	0
1550	0	10	0	15	0	4	2	0	0	4	0	29	0	0	0	0	0	0	0	0	0	0	0	0
1564	0	4	0	8	0	3	2	0	0	4	0	36	0	2	0	0	0	0	0	0	0	0	0	0

Element	At#	Net	Count%	Wt%	Atomic%
Magnesium	12	8981	8.2	6.2	15.8
Silicon	14	13926	12.8	6.2	13.5
Sulfur	16	4560	4.2	1.7	3.3
Chlorine	17	2149	2	1.4	2.5
Vanadium	23	0	0	0	0
Barium	56	40924	37.5	45.2	20.3
Bismuth	83	1572	1.4	2.6	0.8

Ag-rich Particle Class Example in IntelliSEM

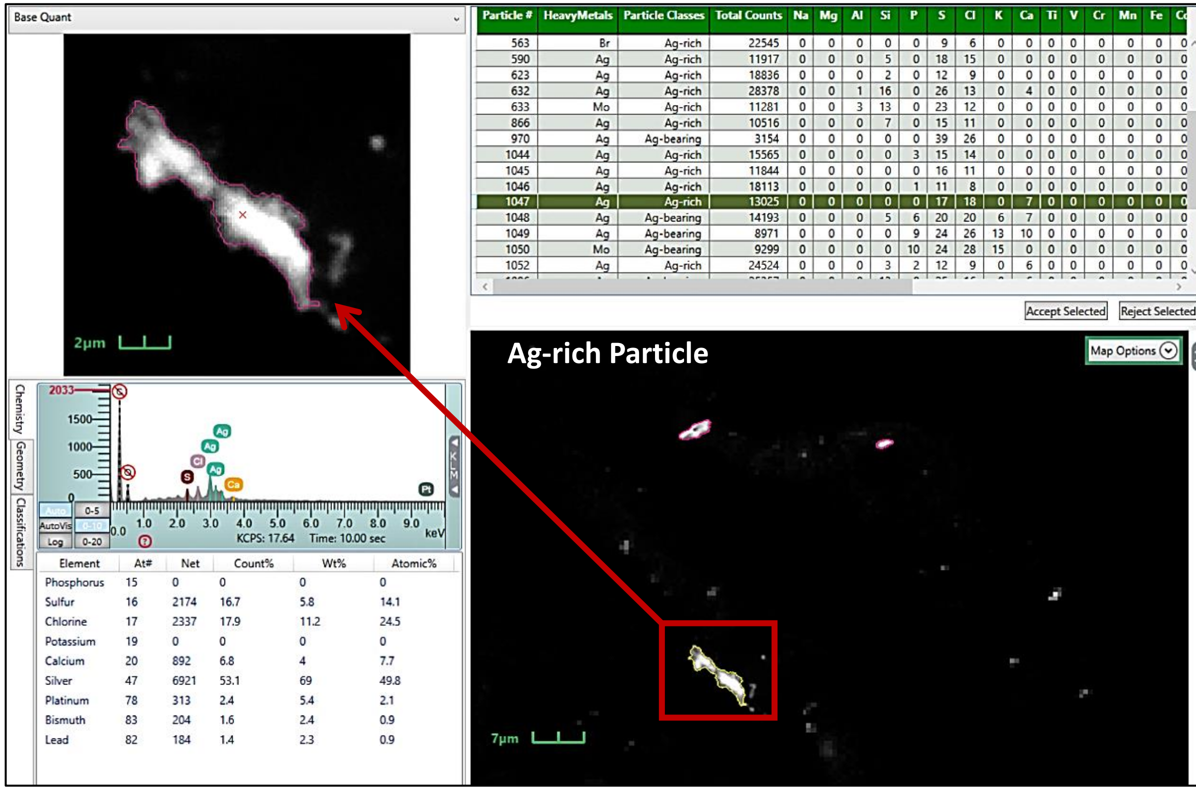
Particle classes rules were defined to categorize CCSEM results based on relative abundance of elements in the sample and frequently occurring combinations of these elements.

Single Particle EDS Results



Graphic representations of abundance of Ag in individual particles

Example from US Lab, sampler deployed for 26 days in 2018



Particle #	HeavyMetals	Particle Classes	Total Counts	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Co
563	Br	Ag-rich	22545	0	0	0	0	0	9	6	0	0	0	0	0	0	0	0
590	Ag	Ag-rich	11917	0	0	0	5	0	18	15	0	0	0	0	0	0	0	0
623	Ag	Ag-rich	18836	0	0	0	2	0	12	9	0	0	0	0	0	0	0	0
632	Ag	Ag-rich	28378	0	0	1	16	0	26	13	0	4	0	0	0	0	0	0
633	Mo	Ag-rich	11281	0	0	3	13	0	23	12	0	0	0	0	0	0	0	0
866	Ag	Ag-rich	10516	0	0	0	7	0	15	11	0	0	0	0	0	0	0	0
970	Ag	Ag-bearing	3154	0	0	0	0	0	39	26	0	0	0	0	0	0	0	0
1044	Ag	Ag-rich	15565	0	0	0	0	3	15	14	0	0	0	0	0	0	0	0
1045	Ag	Ag-rich	11844	0	0	0	0	0	16	11	0	0	0	0	0	0	0	0
1046	Ag	Ag-rich	18113	0	0	0	0	1	11	8	0	0	0	0	0	0	0	0
1047	Ag	Ag-rich	13025	0	0	0	0	0	17	18	0	7	0	0	0	0	0	0
1048	Ag	Ag-bearing	14193	0	0	0	5	6	20	20	6	7	0	0	0	0	0	0
1049	Ag	Ag-bearing	8971	0	0	0	0	9	24	26	13	10	0	0	0	0	0	0
1050	Mo	Ag-bearing	9299	0	0	0	0	10	24	28	15	0	0	0	0	0	0	0
1052	Ag	Ag-rich	24524	0	0	0	3	2	12	9	0	6	0	0	0	0	0	0

Element	At#	Net	Count%	Wt%	Atomic%
Phosphorus	15	0	0	0	0
Sulfur	16	2174	16.7	5.8	14.1
Chlorine	17	2337	17.9	11.2	24.5
Potassium	19	0	0	0	0
Calcium	20	892	6.8	4	7.7
Silver	47	6921	53.1	69	49.8
Platinum	78	313	2.4	5.4	2.1
Bismuth	83	204	1.6	2.4	0.9
Lead	82	184	1.4	2.3	0.9

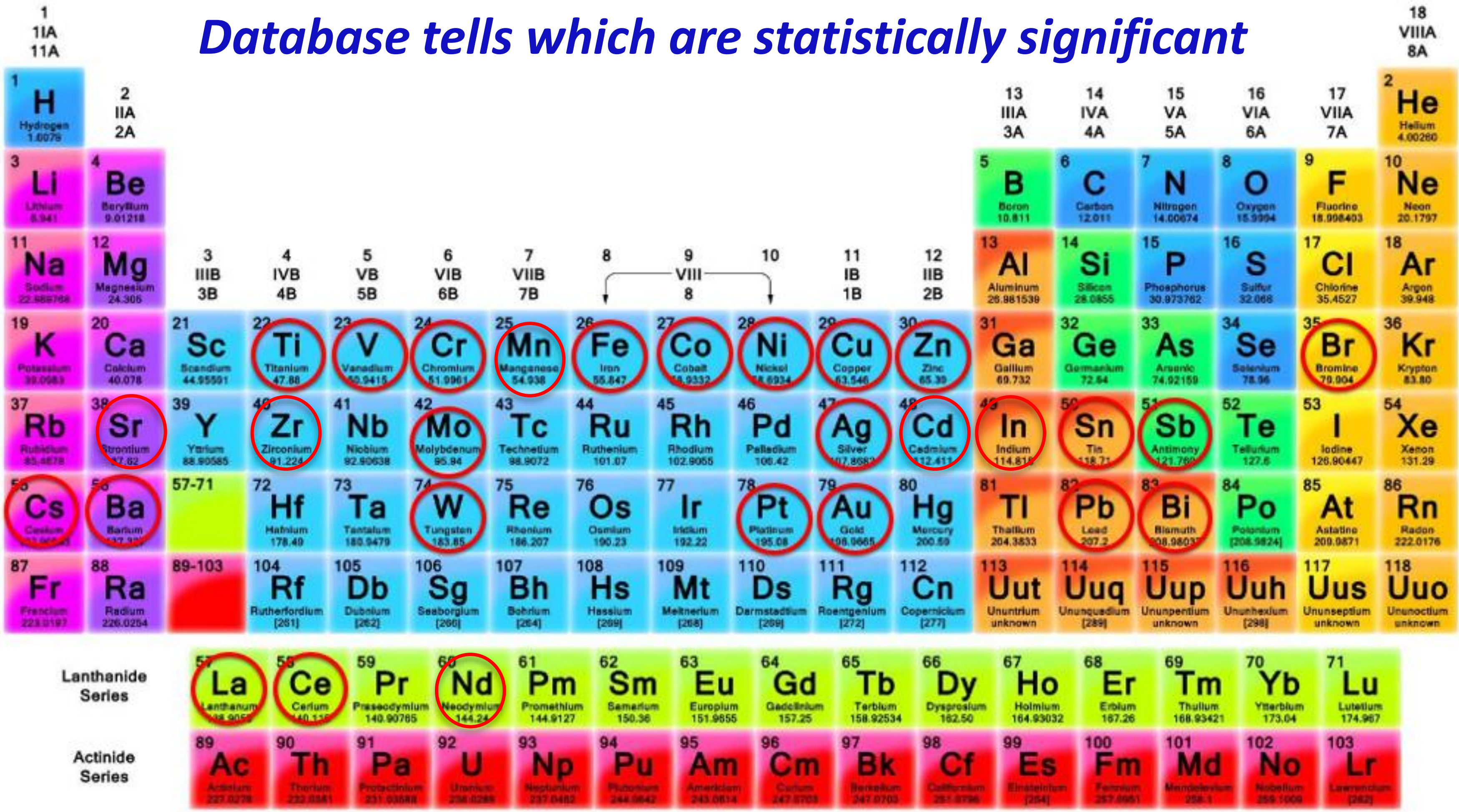
ISS Particle Database

- Collaboration with aerosol scientist Dr. Meytar Sorek-Hamer and Irina Hallinan at NASA Ames Research Center
- Database of the IntelliSEM results
  - R programming language, ‘Shiny’ software package
- 2016 Experiment 5738 particles
- 2018 Experiment 54,477 particles

27 Metals

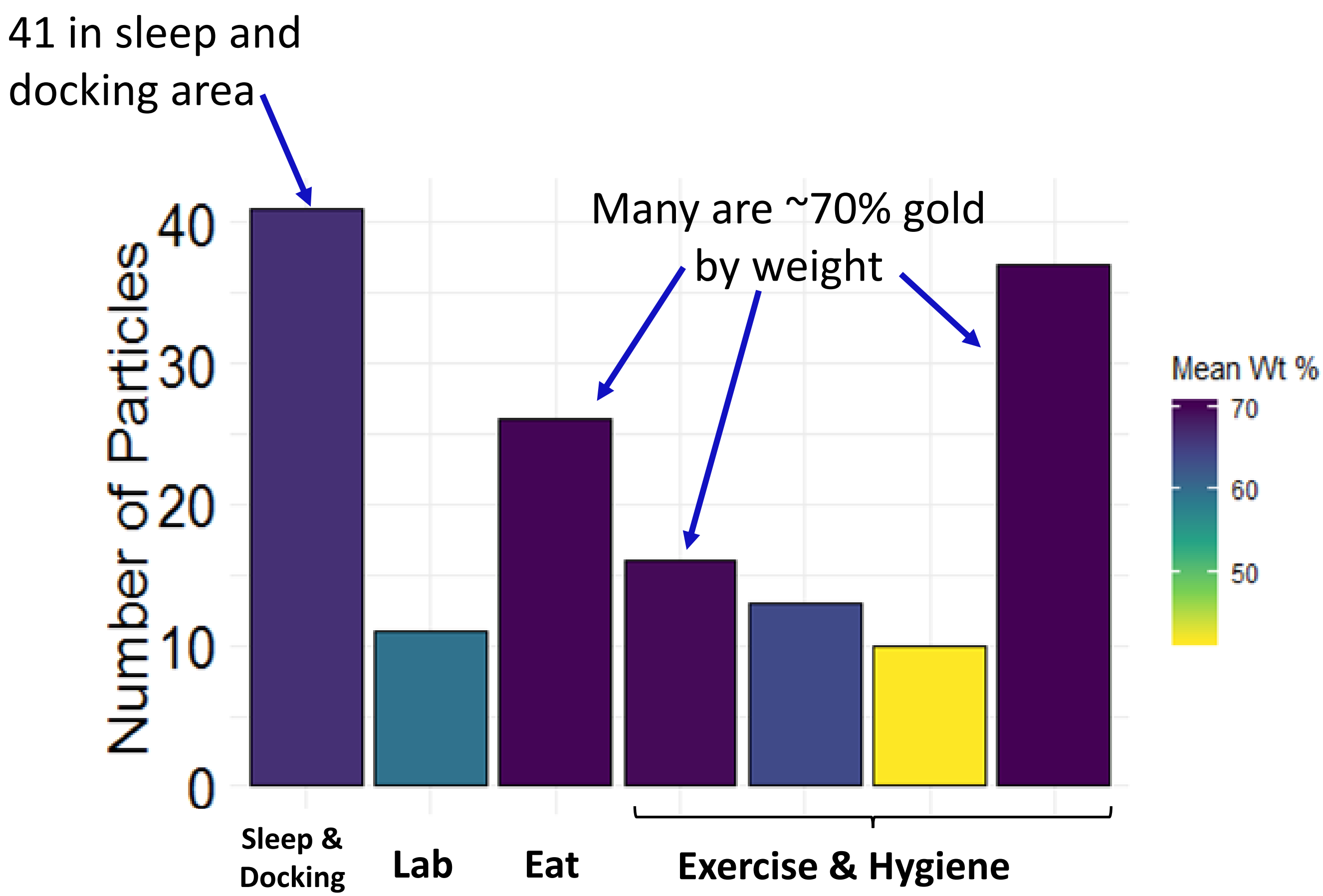
Titanium and higher atomic numbers identified in analysis

Database tells which are statistically significant



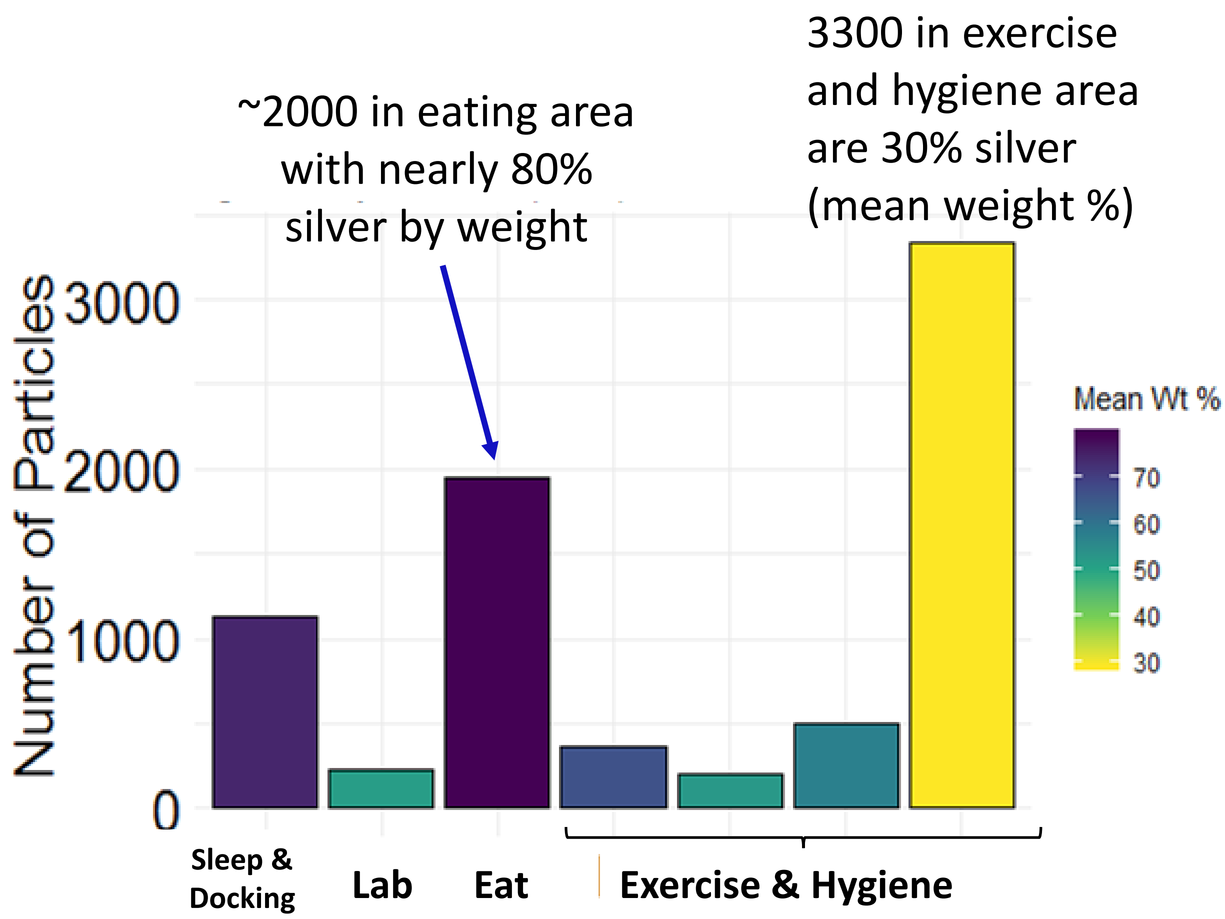
Gold on ISS - 2018

0.2 % of all particles (by weight) contain some gold



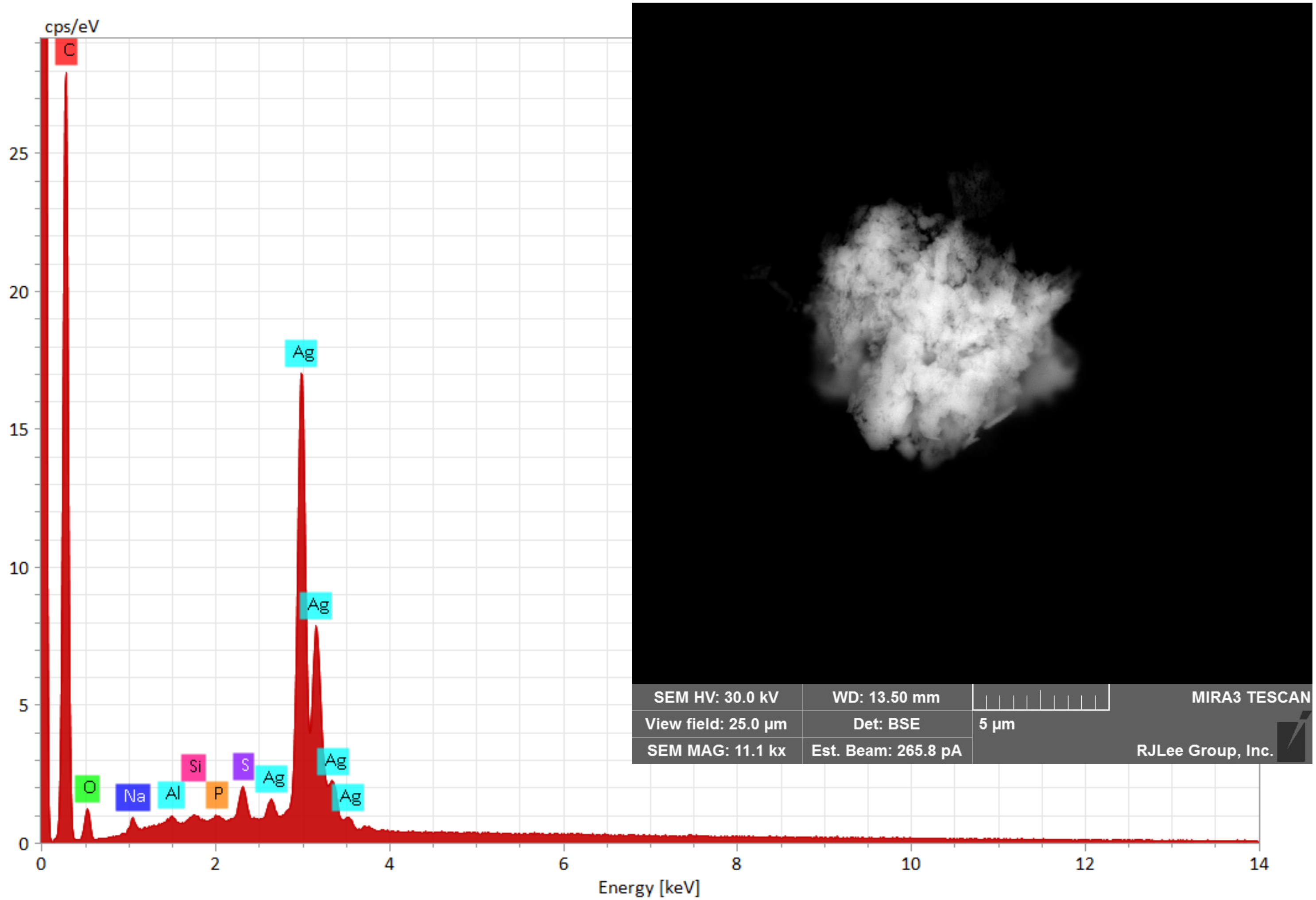
Silver on ISS - 2018

9.8 % of all particles (by weight) contain some silver



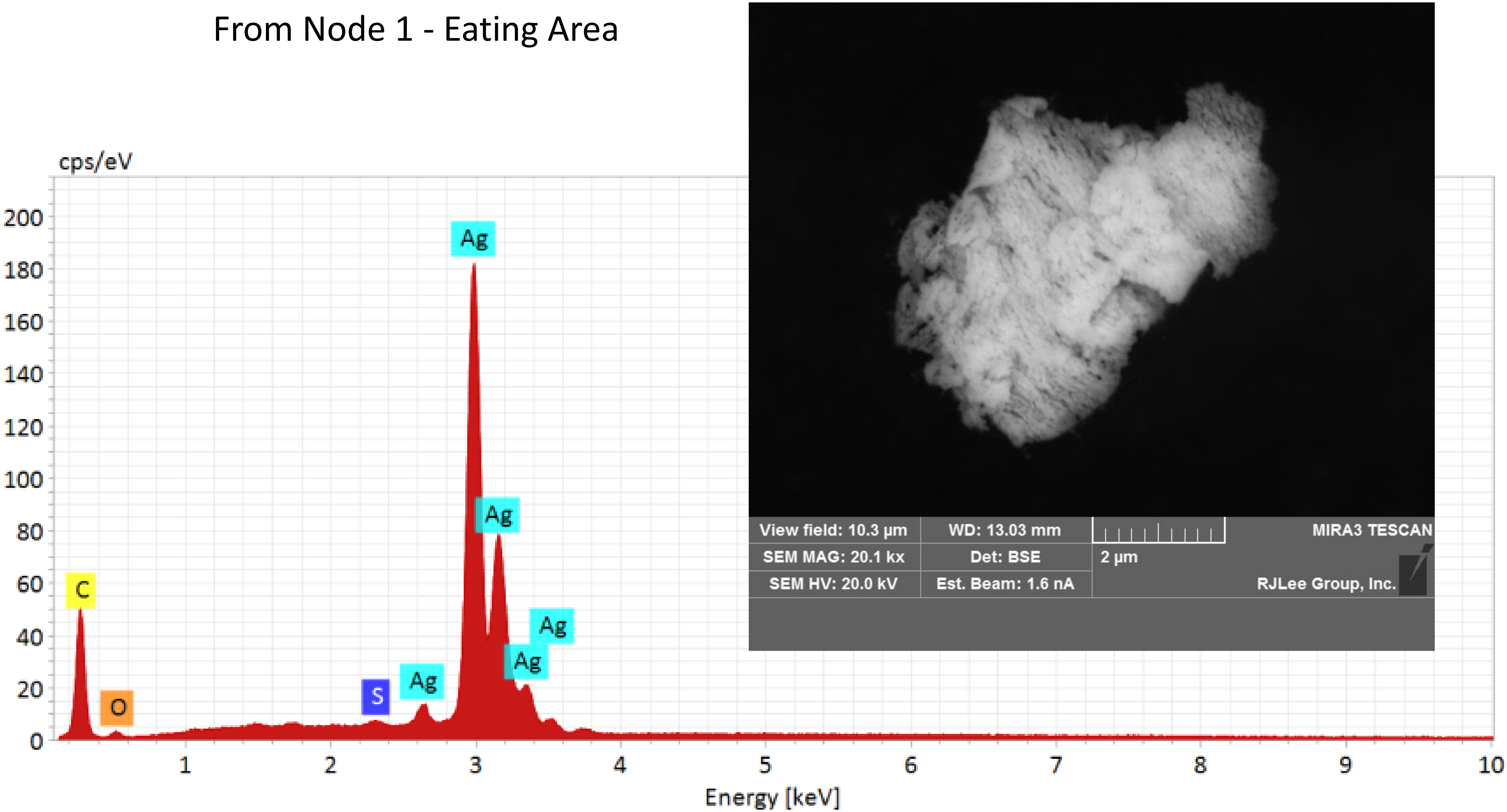
Silver on ISS - 2018

From Node 1 - Eating Area



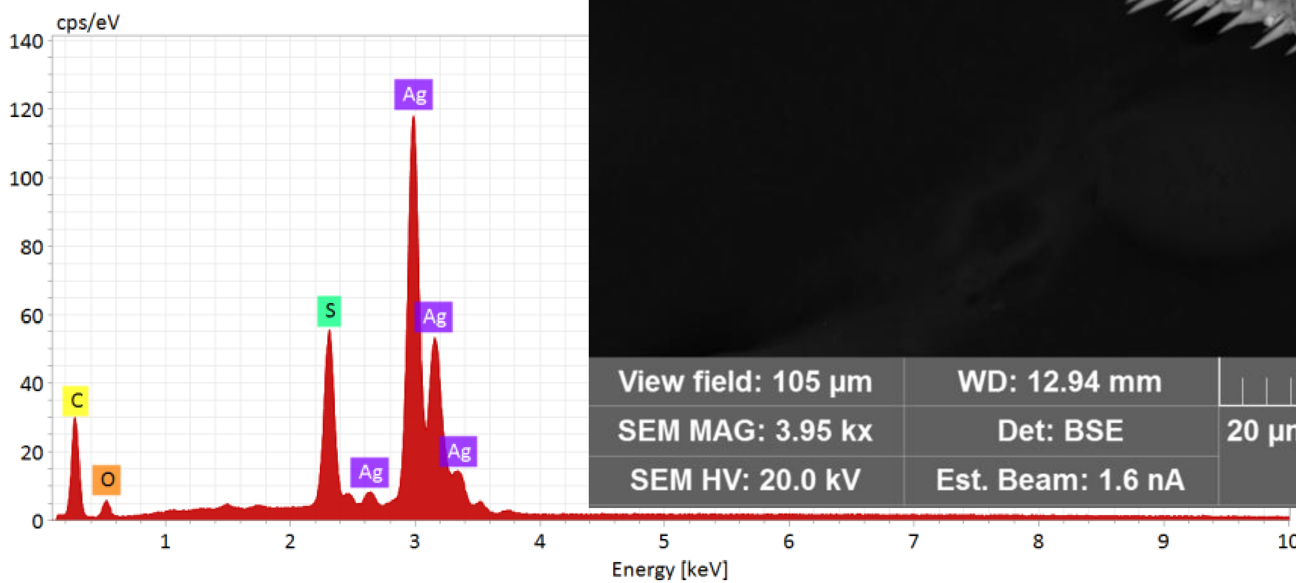
Silver on ISS - 2018

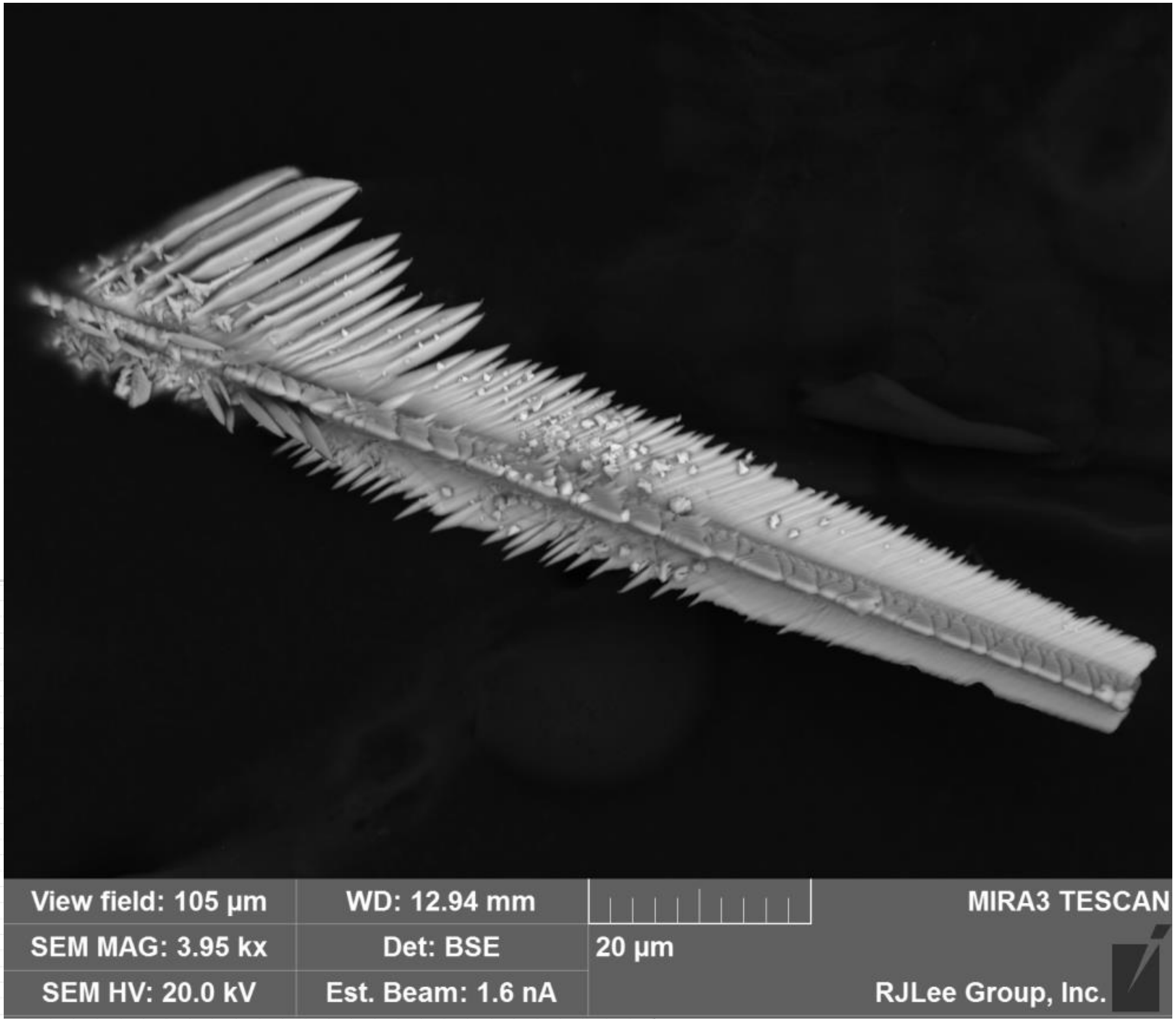
From Node 1 - Eating Area



Silver on ISS - 2018

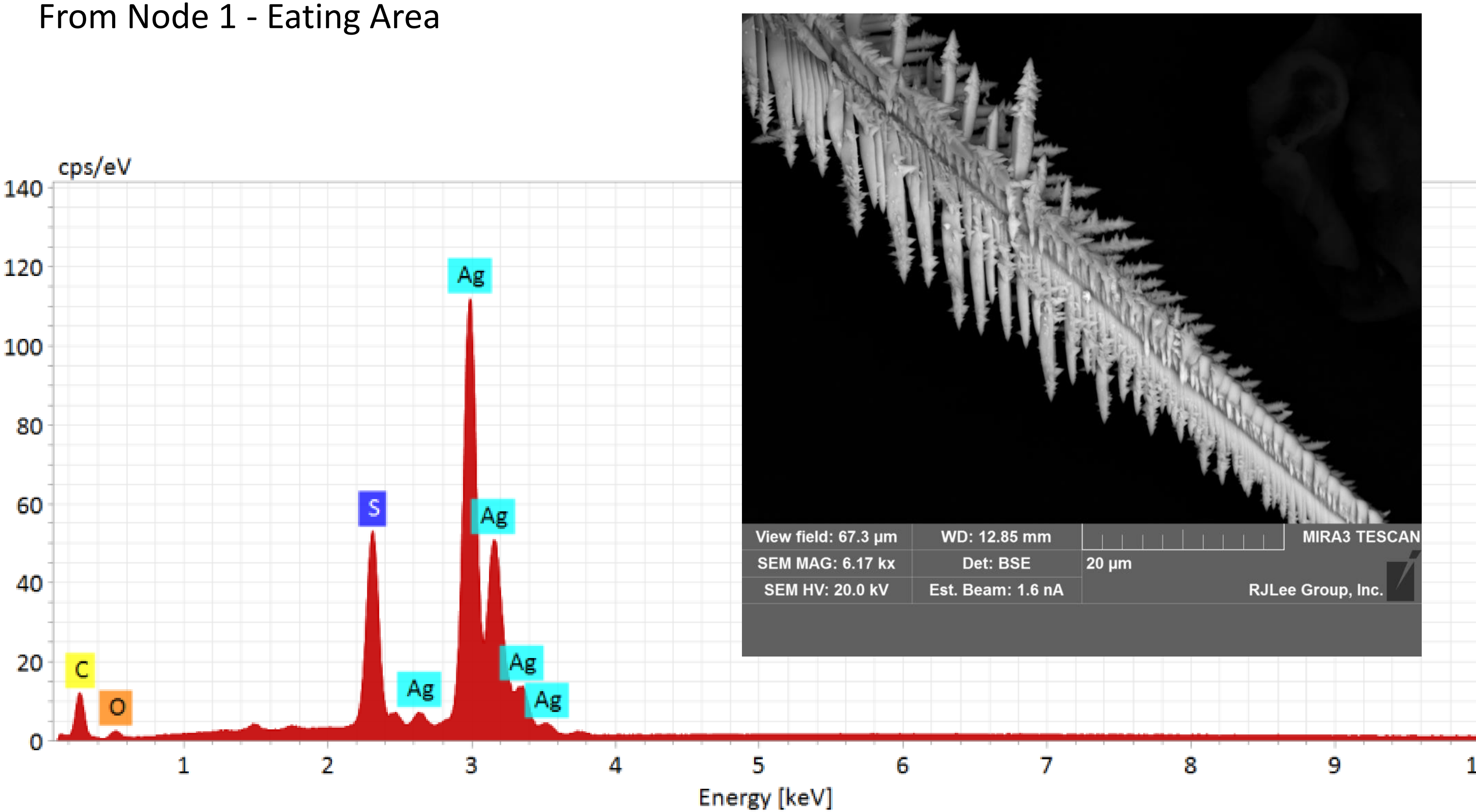
From Node 1 - Eating Area



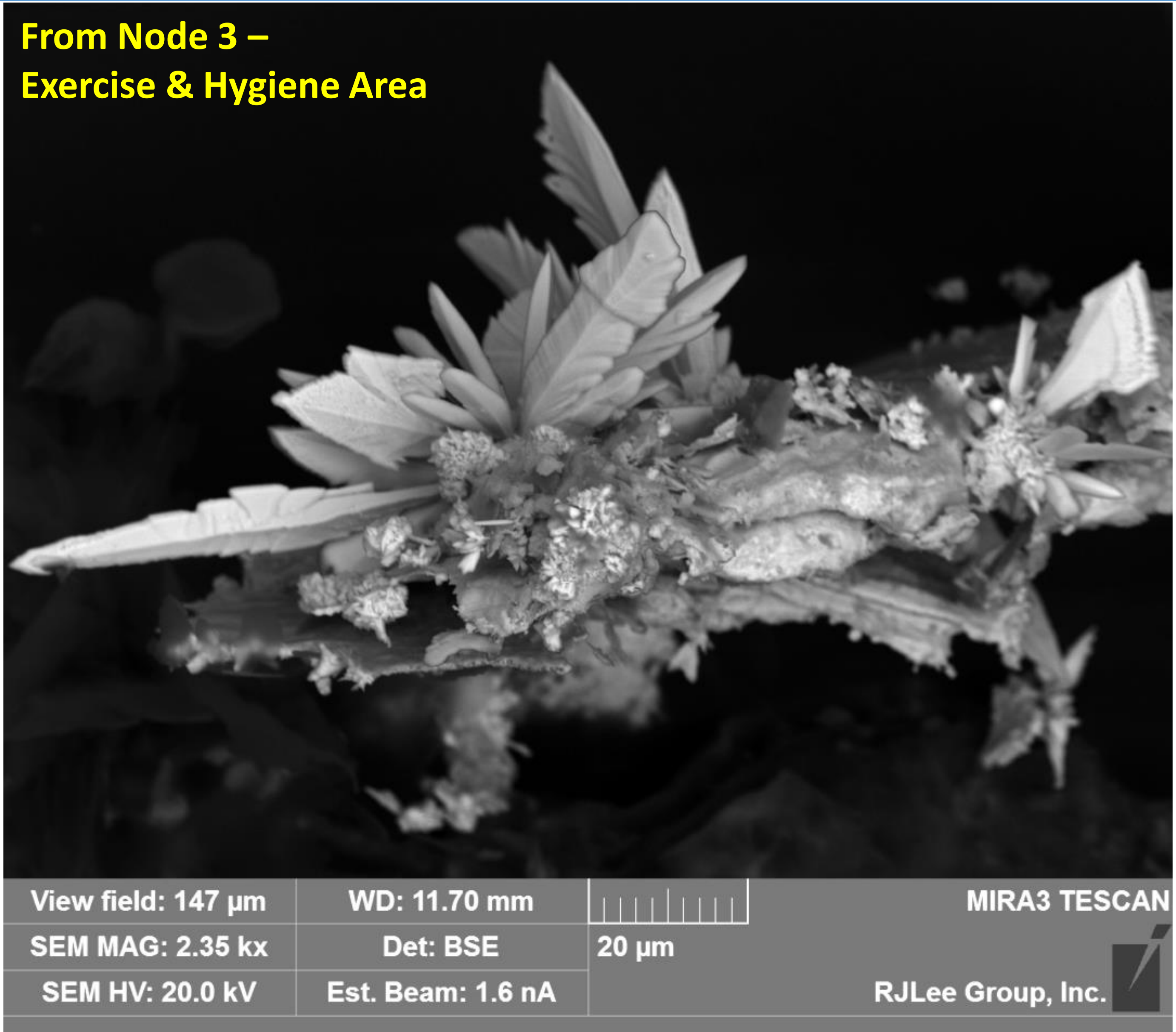


Silver on ISS - 2018

From Node 1 - Eating Area



Silver on ISS - 2018



ISS Bromine Particles

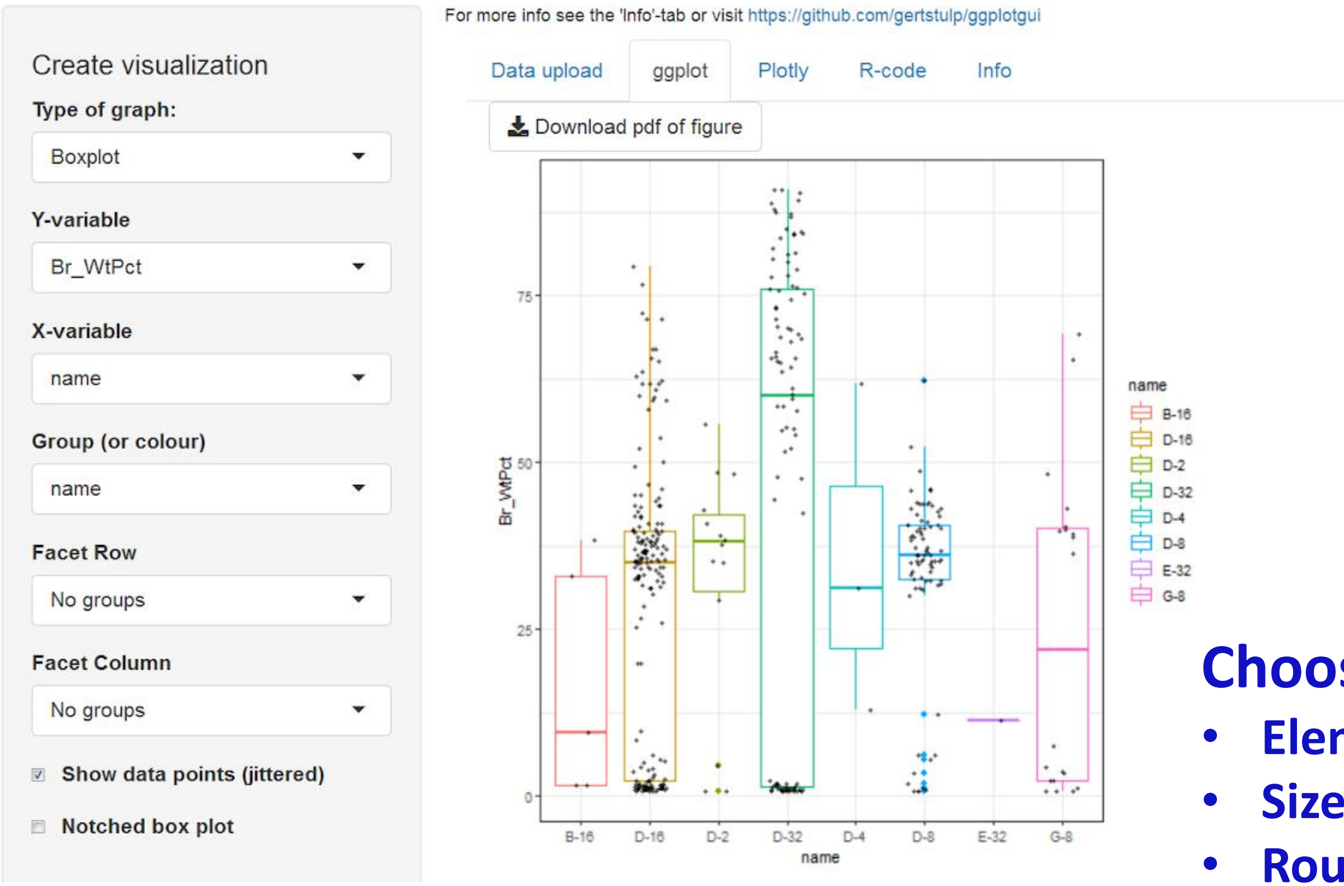
- Both smooth and angular morphologies
- Diameters of bromine particles in agglomerates ranged from 5 to 100 micrometers

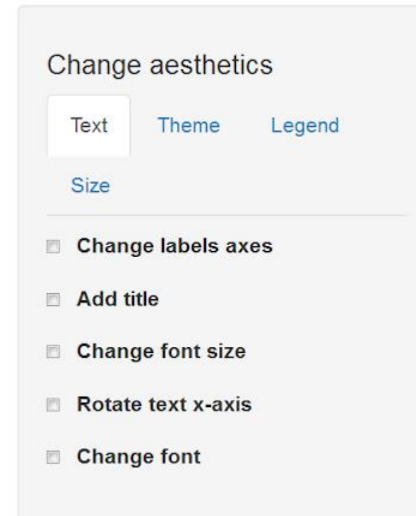
2016 Sampling Statistics

Passive Sampler	Location	Sample Duration, days	% Bromine Particles, by Number
B-16	Node 1 Deck 1	16	0.5
D-16	Node 3 Deck 3	16	8.1
E-32	PMM	32	0
F-32	Node 2 Deck 2	32	9.3
G-8	Node 3 Forward 3	8	1.7
J-32	US Lab Bay 1	32	0
K-16	US Lab Bay 3	16	1.2

Sources in Nodes 2 and 3

Bromine Statistics 2016



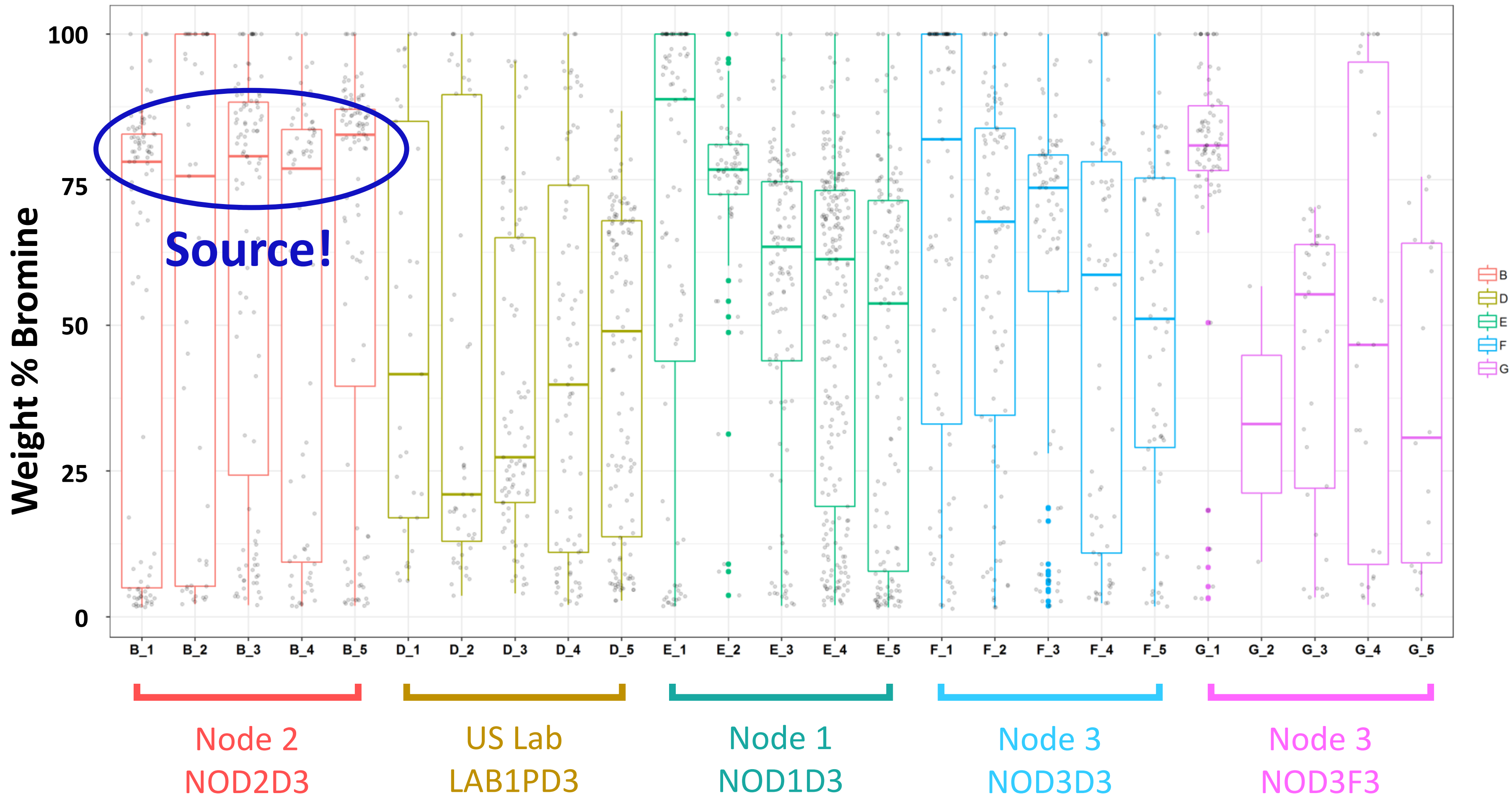


Choose Plot Variables:

- **Elemental composition**
- **Size**
- **Roundness**
- **Relative abundance**
- **ISS location**
- **Proportion of all particles by weight percent**

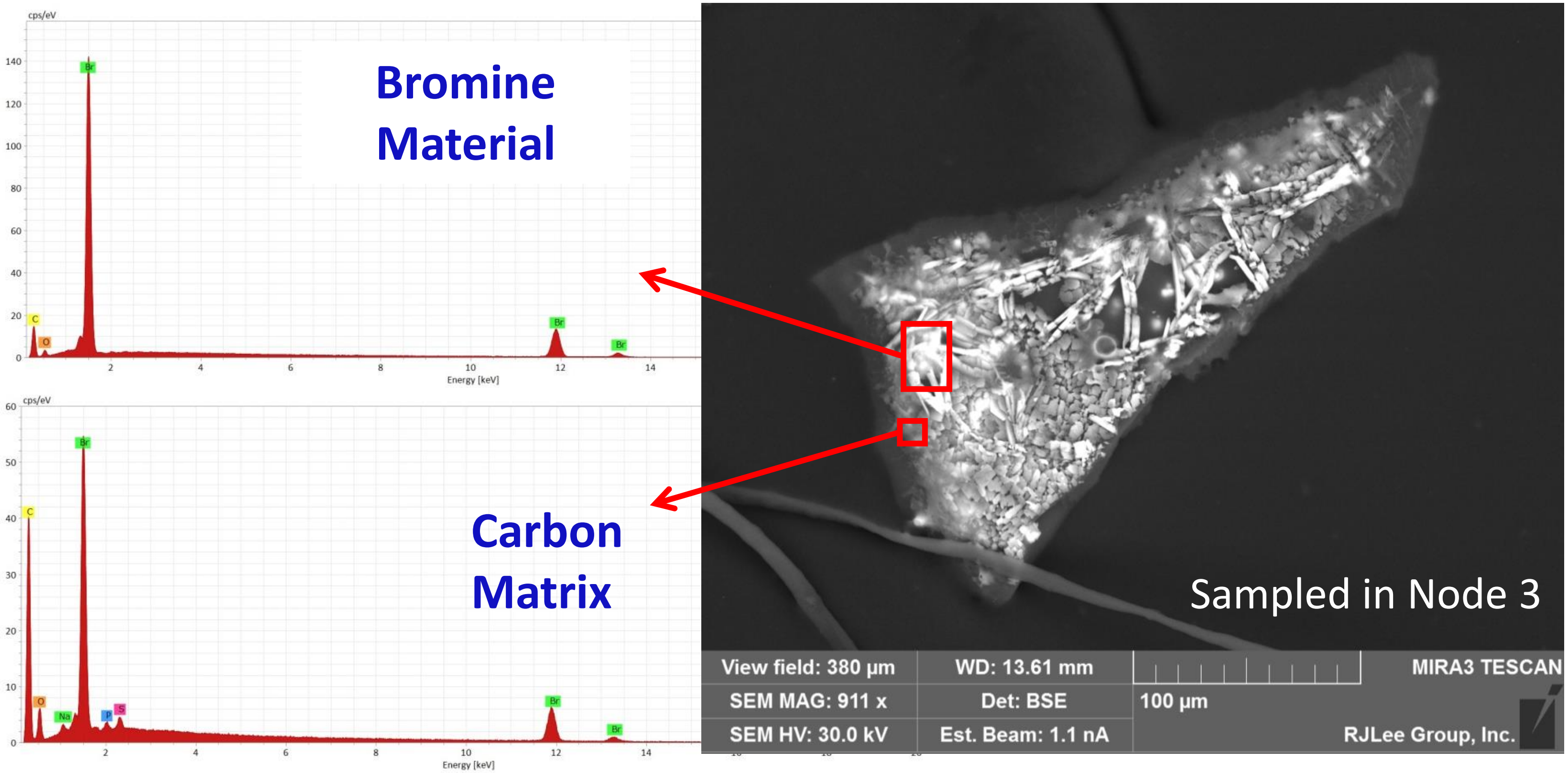
Bromine Statistics 2018

In Node 2, for Bromine-containing particles, the median weight % was consistently around 80%



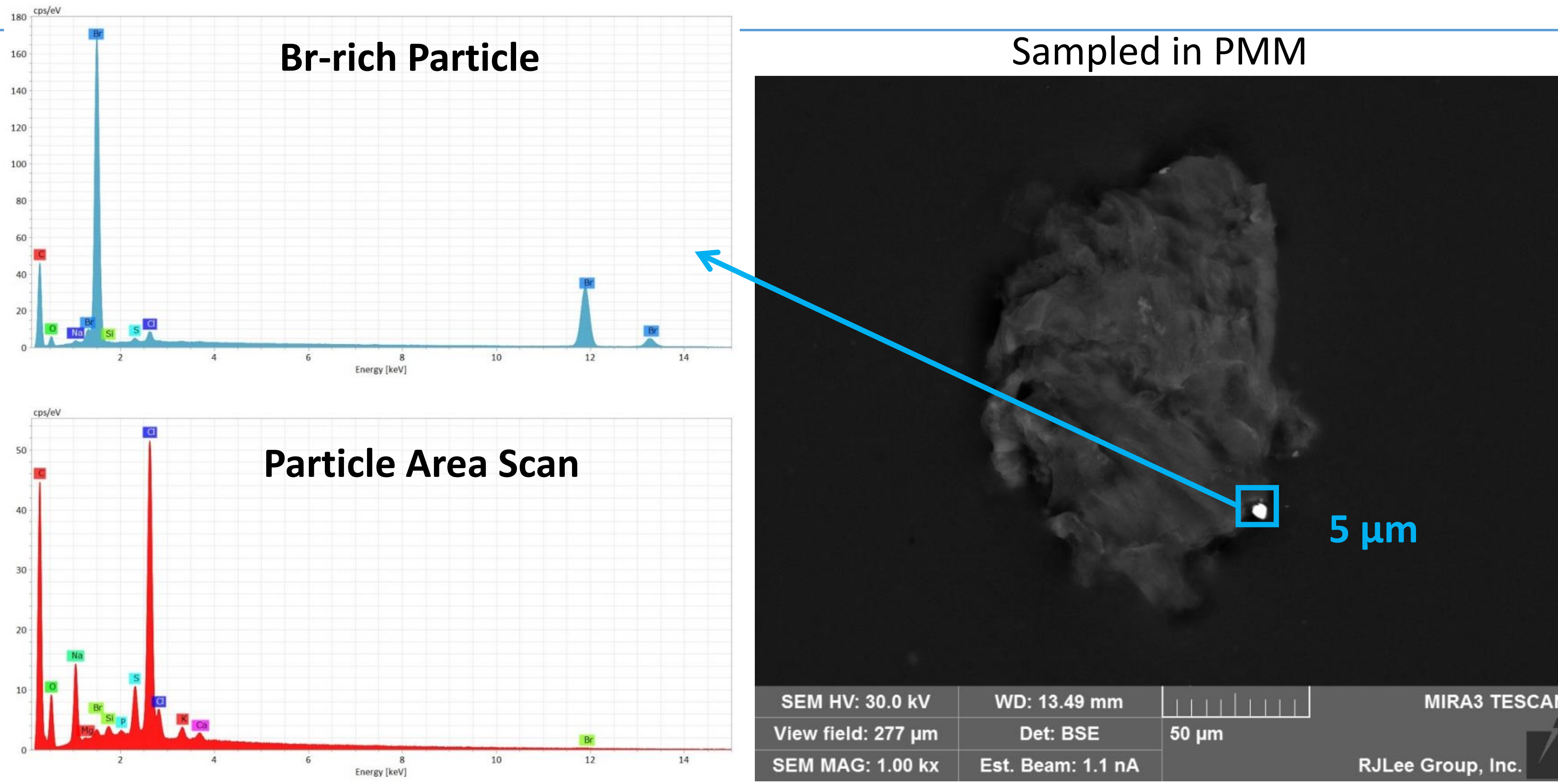
78787 analyzed particles, 2236 contained Bromine (2.8%)

Bromine



- Randomly oriented rod-like bromine particles are distributed over a carbon matrix
- Possibly abraded or fractured from a plastic parent material that contains bromine fire retardant dispersed in the carbon matrix

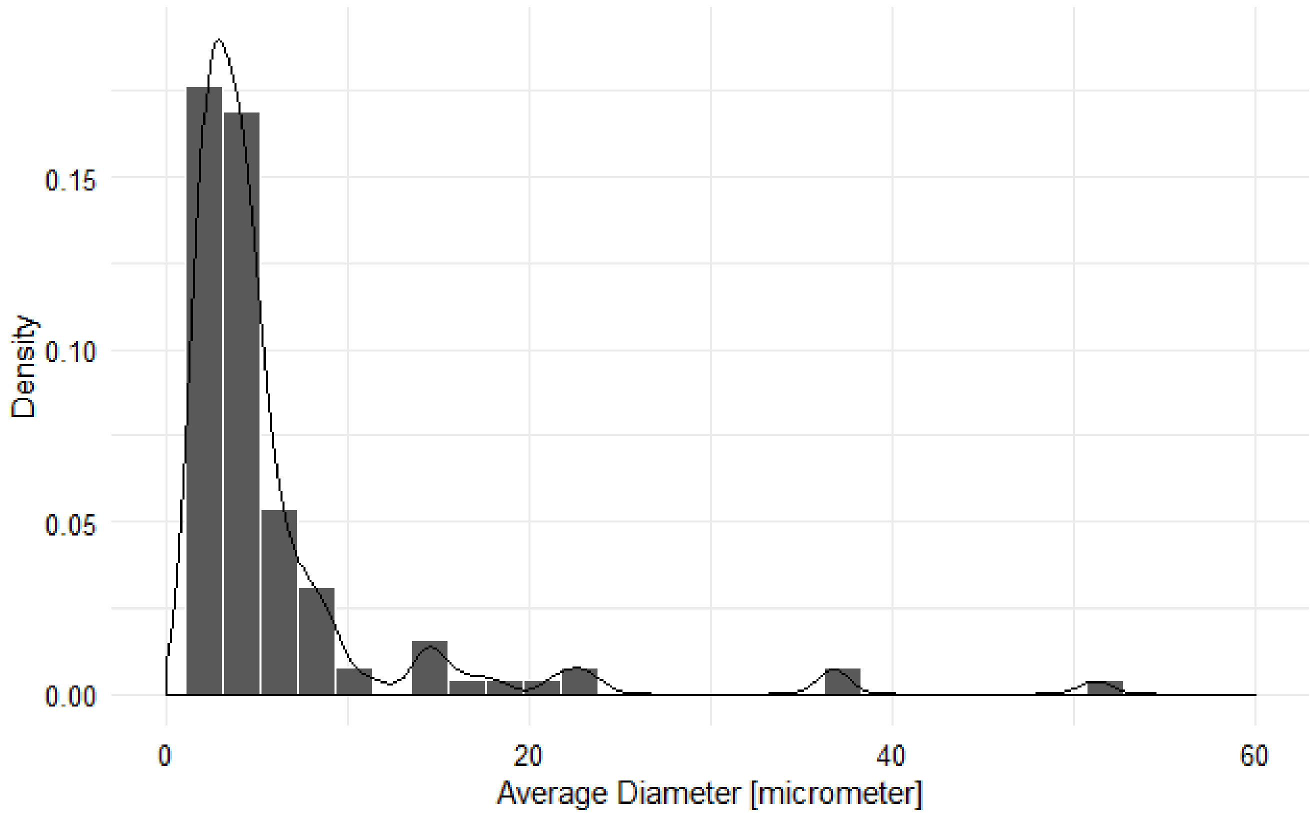
Bromine Particle on a Skin Flake



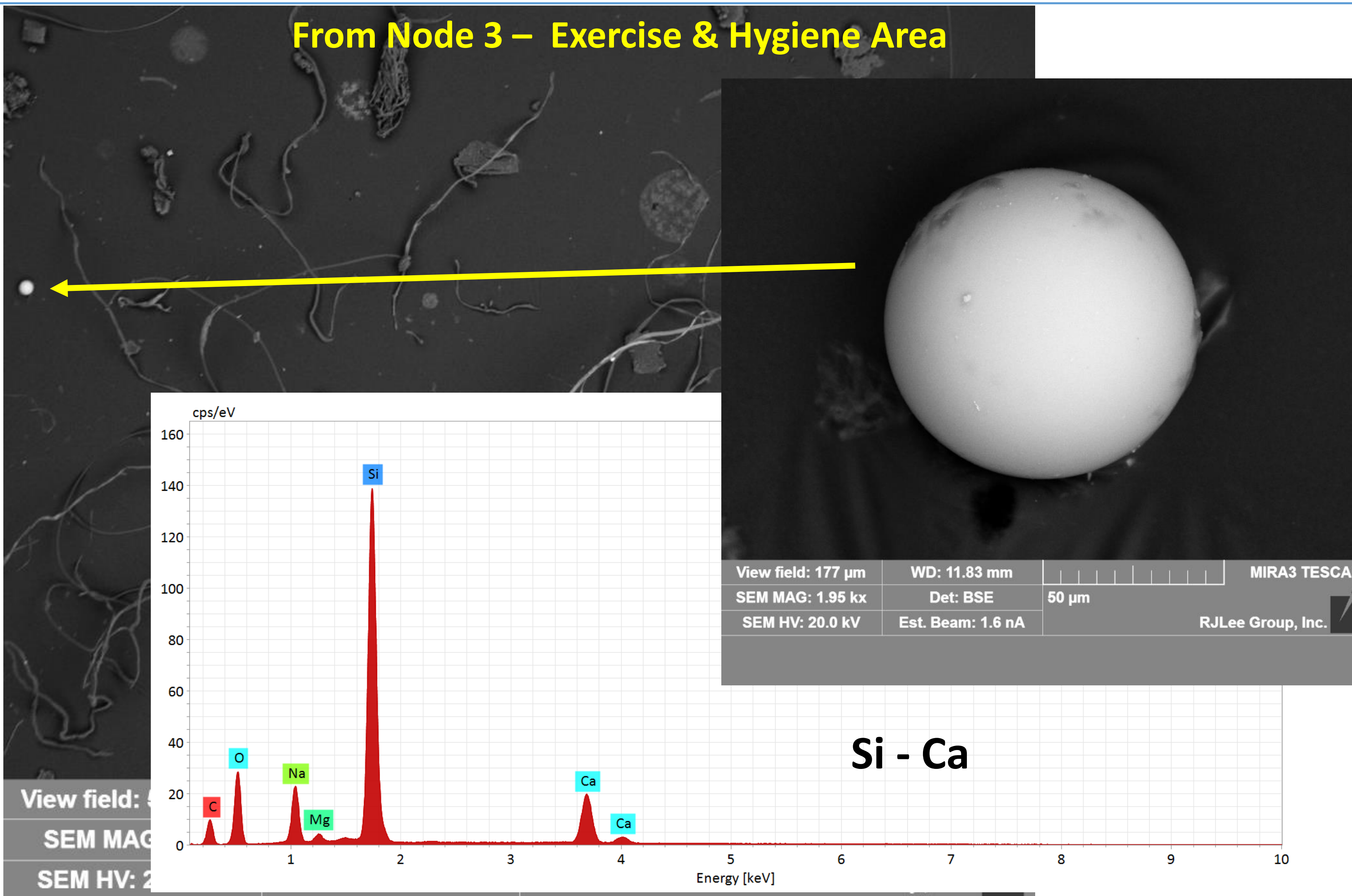
- Round morphology does not indicate mechanical abrasion
- May be representative of a homogeneous solid-phase fire retardant that was added to a raw material along with other additives

Spherical Particles

126 Particles with Roundness > 0.9



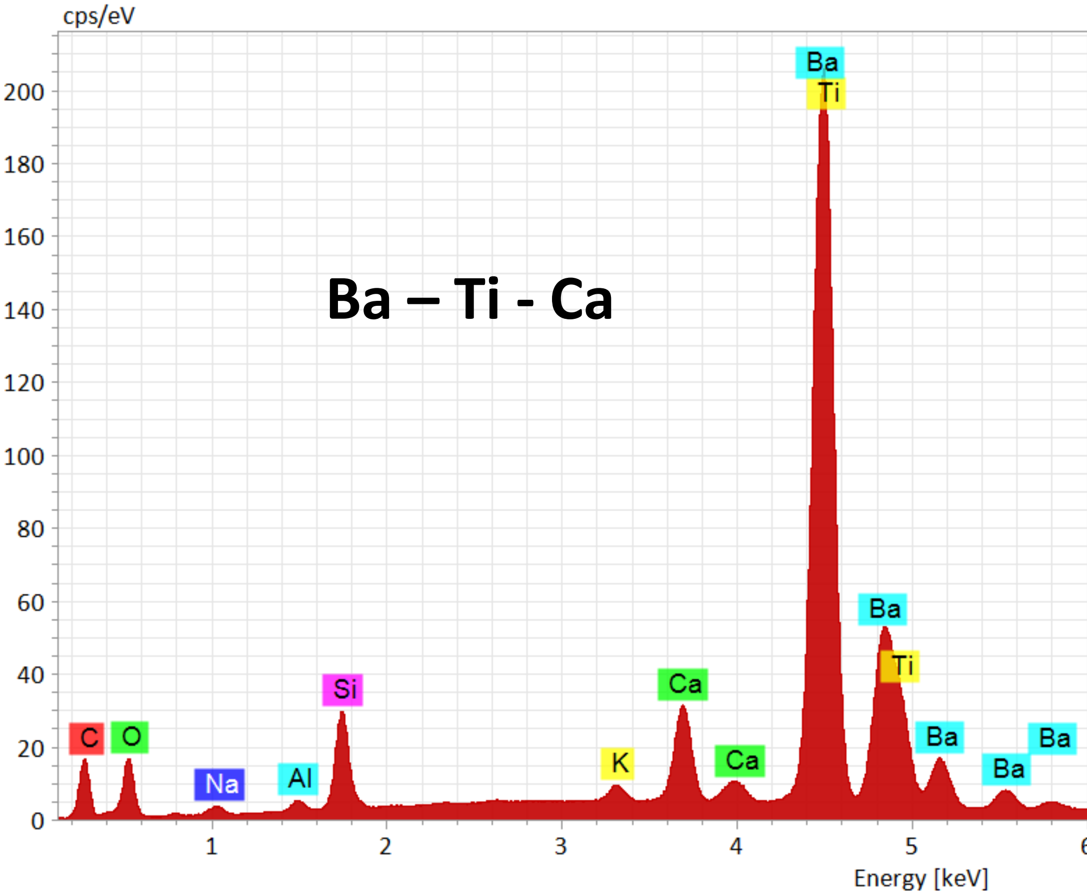
Spherical Particles

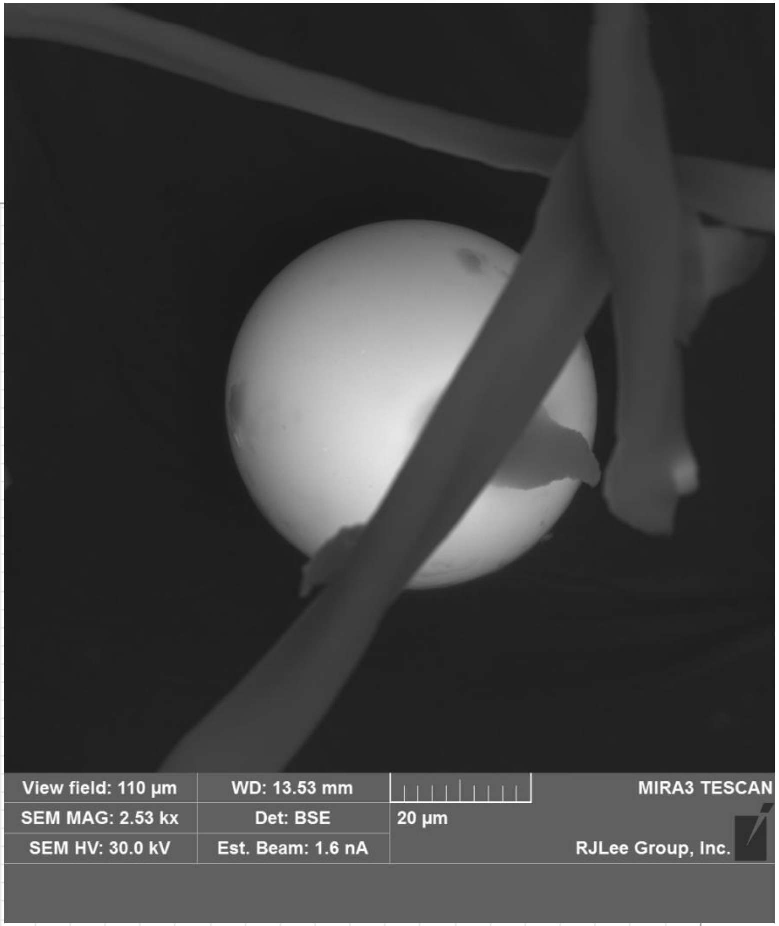


Spherical Particles

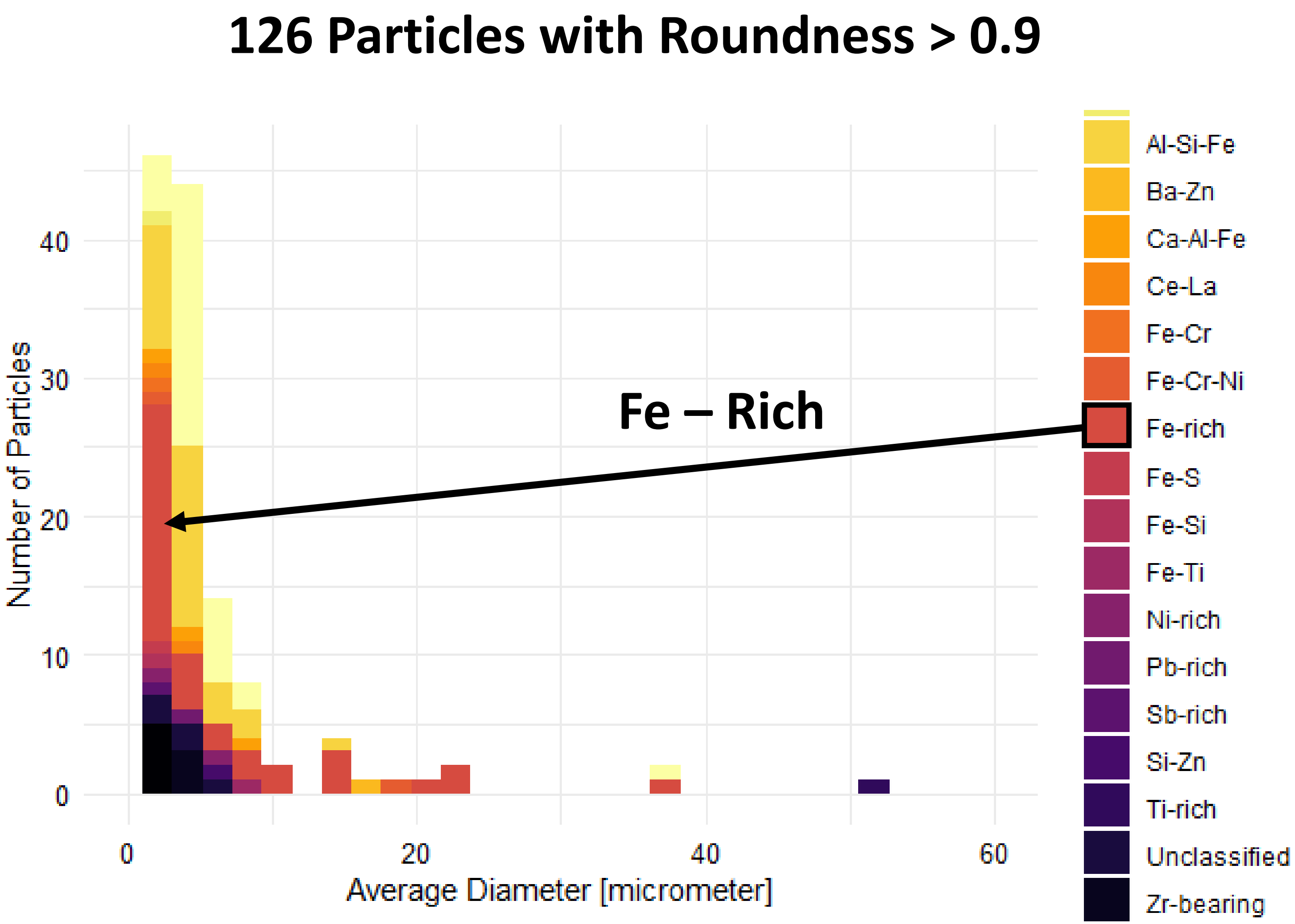
From Node 3 – Exercise & Hygiene Area

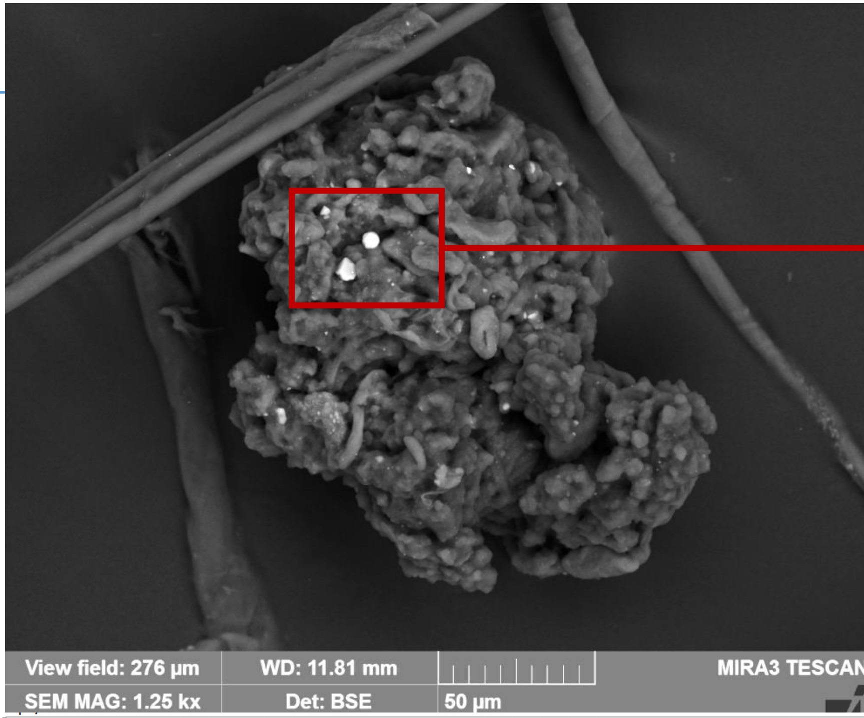
Image analysis cannot capture this as a sphere because the lint fiber 'cuts' it in half

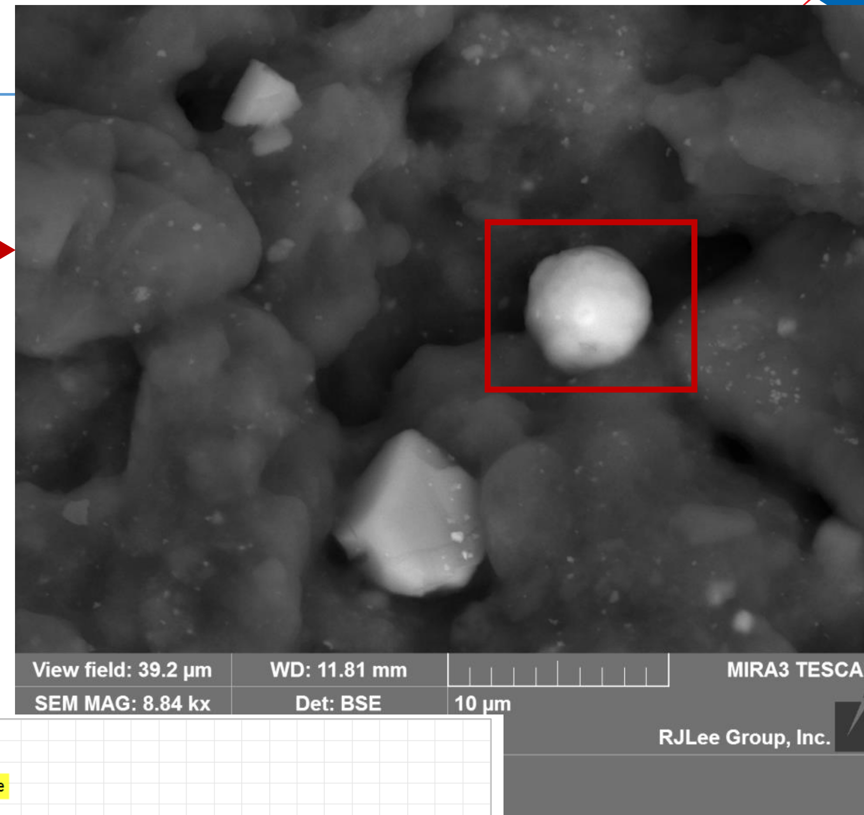


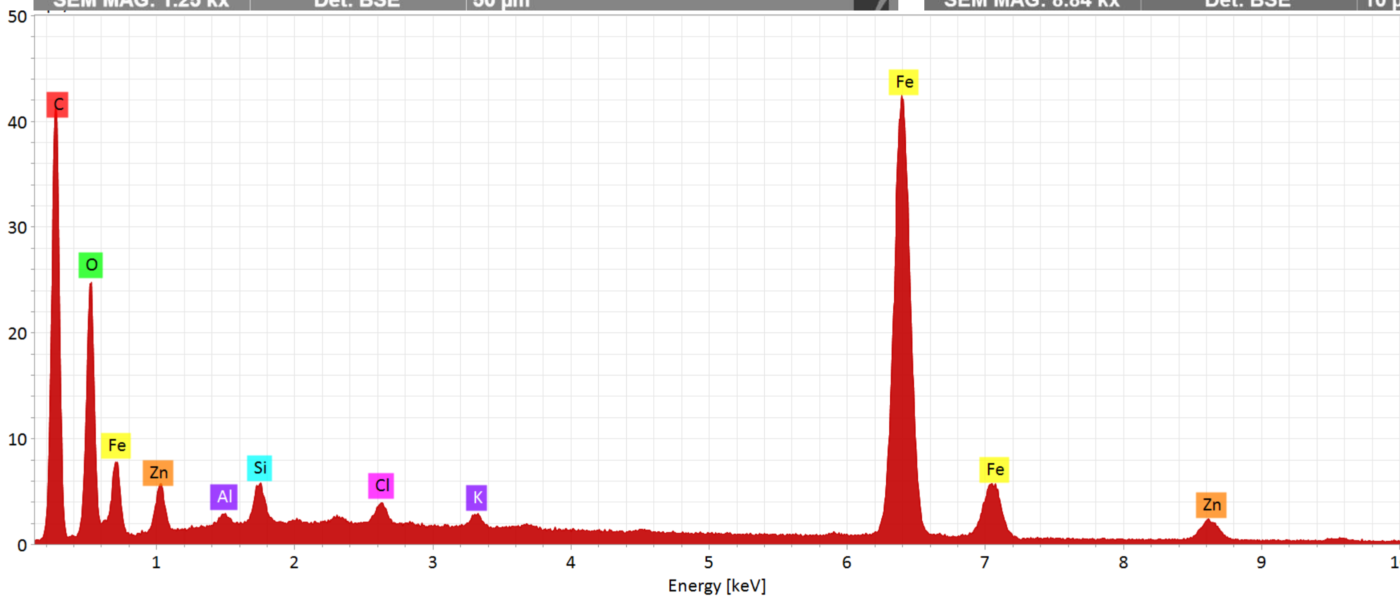


Spherical Particles




View field: 276 µm
WD: 11.81 mm
MIRA3 TESCAN
SEM MAG: 1.25 kx
Det: BSE
50 µm


View field: 39.2 µm
WD: 11.81 mm
MIRA3 TESCAN
SEM MAG: 8.84 kx
Det: BSE
10 µm
RJLee Group, Inc.


C
O
Fe
Zn
Al
Si
Cl
K
Fe
Fe
Zn
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10
Energy [keV]

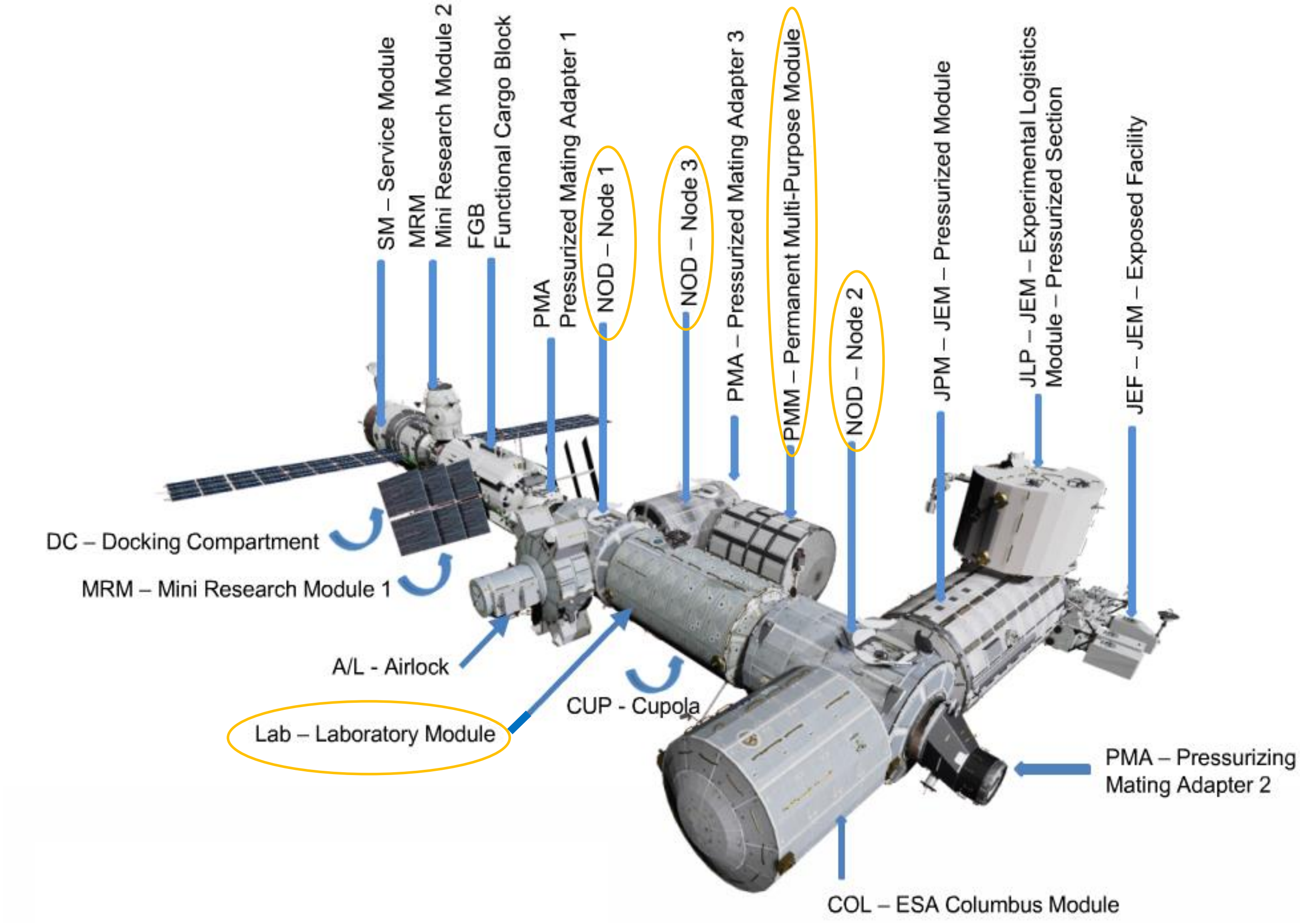
6 µm Fe - Rich

Conclusions

- Plausible ISS particle formation mechanism of complex particles
    - Agglomeration by electrostatic forces
- Extensive data set of individual metal inclusions in particles sampled in 2016 and 2018
- Searchable database can explore particles by
    - Elemental composition
    - Size
    - Roundness
    - Relative abundance by ISS location
    - Proportion of all particles by weight percent
- Working on making the database publicly available

Backup Slides

Sampling Locations



Definitions ASTM F1877-16

Standard Practice for Characterization of Particles

- *agglomerate, n*—a jumbled mass or collection of two or more particles or aggregates, or a combination thereof, held together by relatively weak cohesive forces caused by weak chemical bonding or an electrostatic surface charge generated by handling or processing
- *aggregate, n*—a dense mass of particles held together by strong intermolecular or atomic cohesive forces that is stable with normal mixing techniques, including high-speed stirring and ultrasonics.
- *roundness (R), n*—a measure of how closely an object represents a circle
    - The *R* varies from zero to one in magnitude with a perfect circle having a value of one

$$R = (4A)/(\pi\, d_{max})^2$$

where: A = area, and d_{max} = the maximum diameter