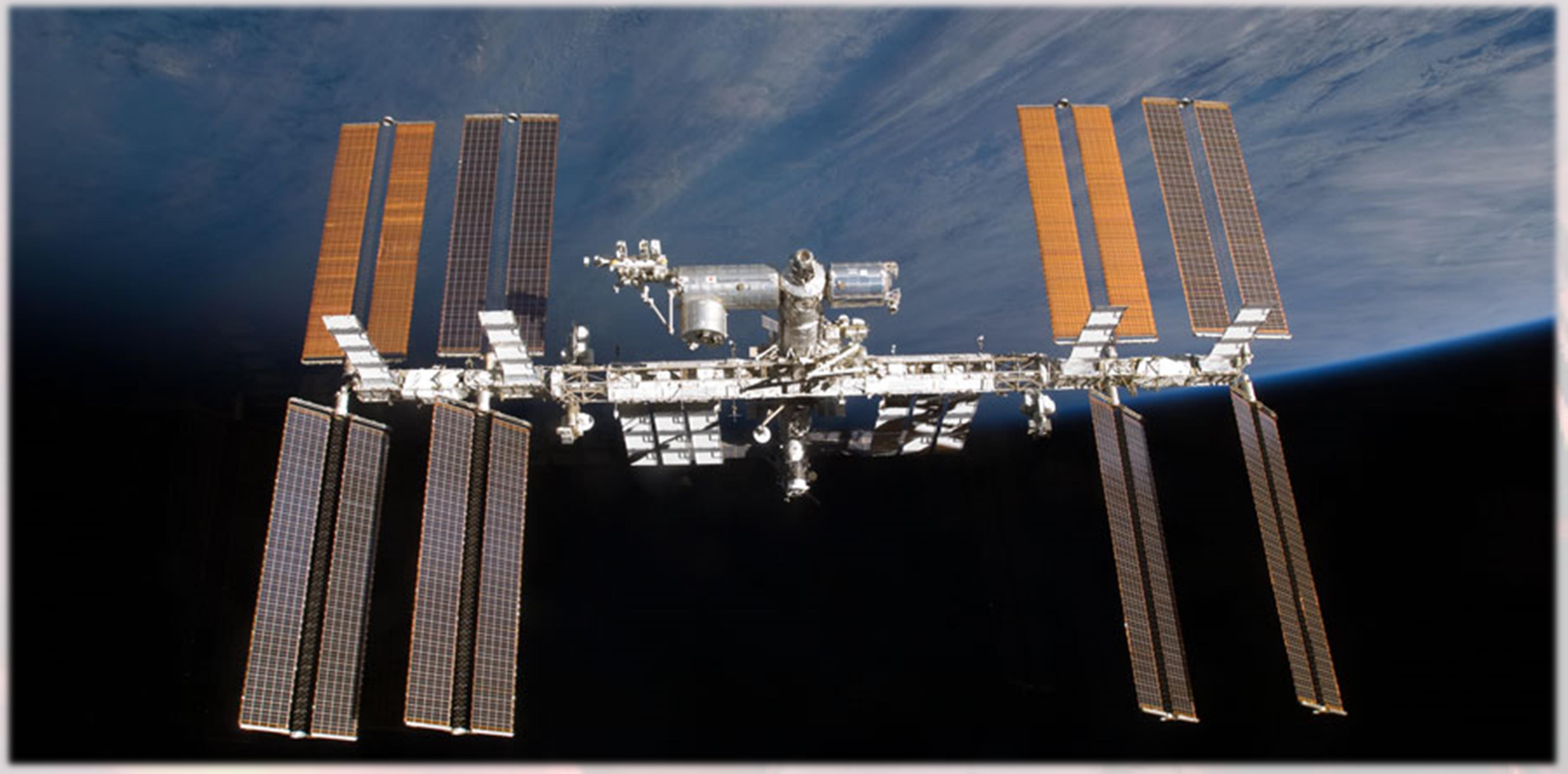
International Space Station (ISS) Bacterial Filter Elements (BFEs): Filter Efficiency and Pressure Drop testing of Returned Units

Robert D. Green, NASA Glenn Research Center (GRC)
Juan H. Agui, NASA Glenn Research Center
R. Vijayakumar, Aerfil LLC,
Gordon Berger, Universities Space Research Association (USRA)
Jay Perry, NASA Marshall Space Flight Center (MSFC)

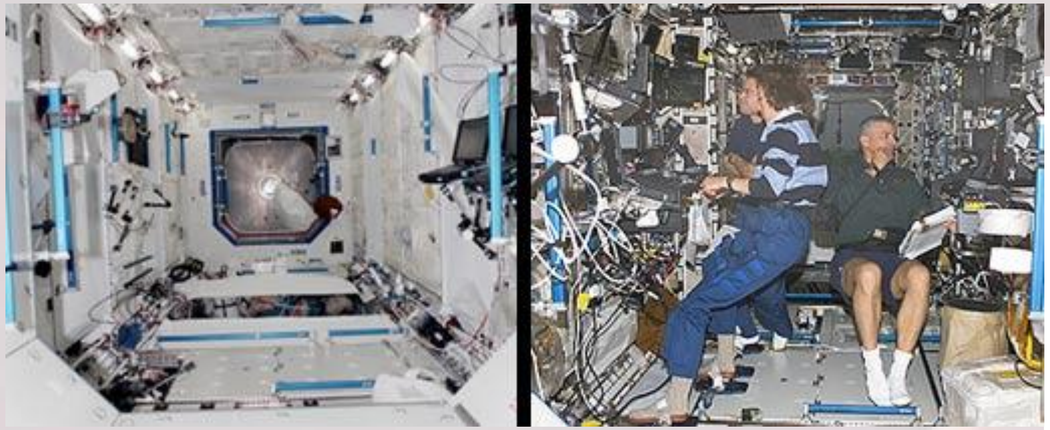
Objectives

- Develop test protocol for ISS BFE particulate filters, to evaluate extension of both operating and shelf life.
- Perform penetration and pressure drop testing of ISS filters returned to Earth replaced under 2 different replacement intervals.
- Long-term objective:
    - Extend filter test protocols for acceptance testing and inventory testing for future manned spacecraft exploration programs with air revitalization filtration needs.

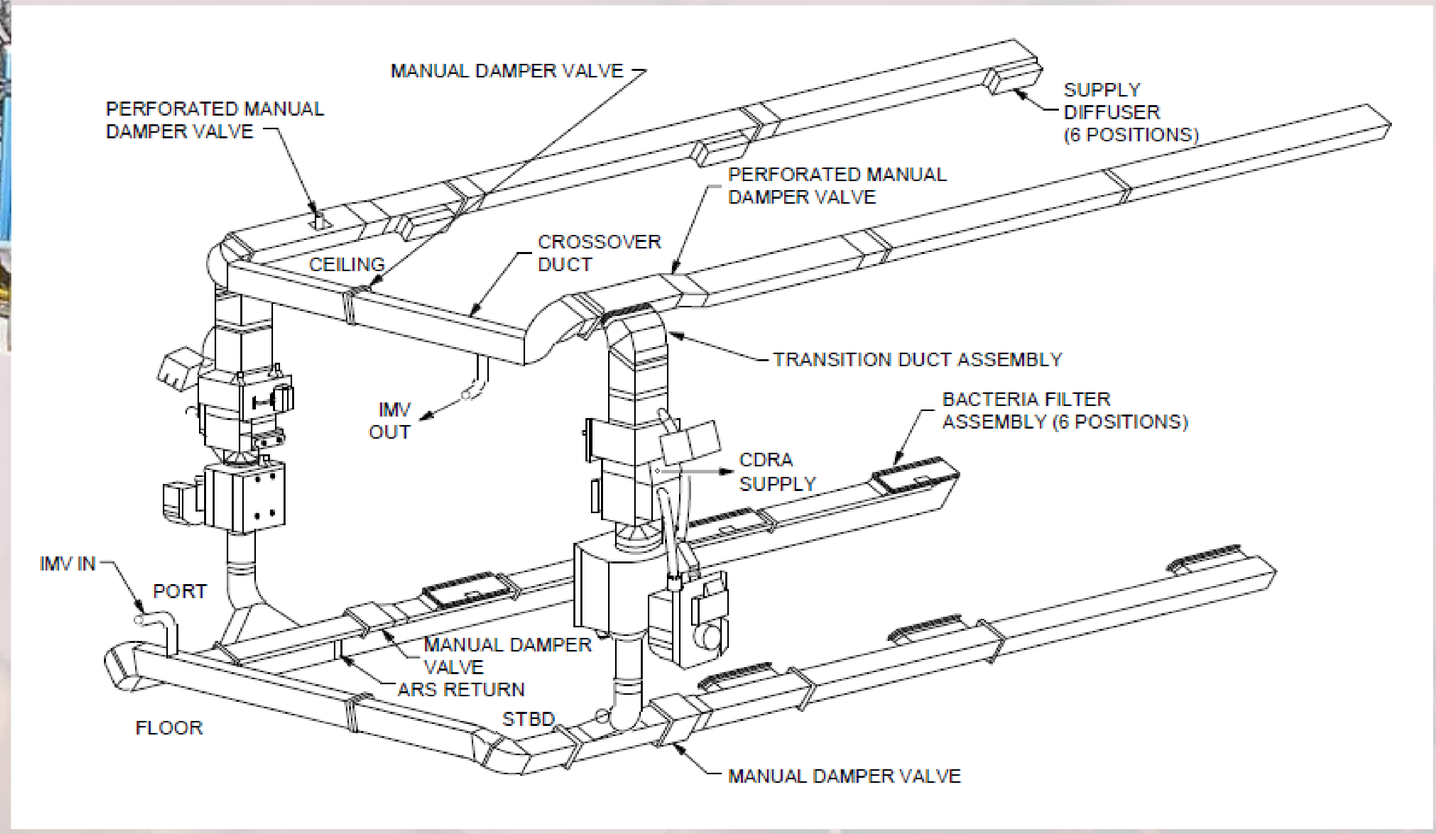


ISS has an internal pressurized volume of 915 m^3 (32,333 $ft^{3)}$ ~ equal to the pressurized volume of a Boeing 747.

ISS LAB module ventilation system



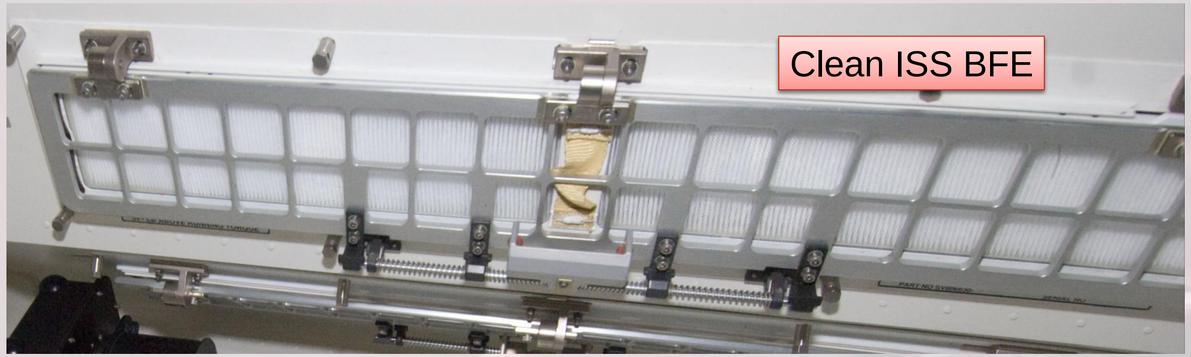
- ISS Lab module volume is 108.6 m^3 (3834 ft^3).
- Required ventilation flow rate is 11 m^3/min (400 cfm).
- 6 BFEs installed in ventilation system.



Introduction/Background

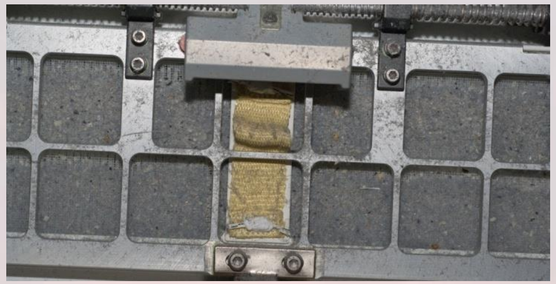
- The ISS Bacterial Filter Elements (BFEs) are HEPA-grade filters utilized on ISS to control particulates in the pressurized volume.
    - Total of 21 BFEs installed in US segment. Columbus and JEM use HEPA filters of a different design.
    - Original replacement interval of 1 year.
    - Replacement interval was extended to 2-5 years.
        - Replacement interval varies by location: US Lab/Node 2/Node 3 BFEs are replaced at 2.5 years; the airlock BFEs are replaced at 5 years, Node 1 BFEs are replaced at 2 years
    - On-orbit maintenance consists of frequent vacuuming to remove large particulate load.

Sedimentation (or lack of) in ISS microgravity environment



12 days accumulation

Node 3 Hygiene & Exercise Location



8 days accumulation

Inlet to avionics cooling fan

Intro/Background (cont.)

- ISS BFEs were delivered in several lots and were (in the 2012 timeframe) reaching the end of their “use life” of 10 years.
    - “Use life” is defined as in-service life + shelf life
    - Filters were supplied United Technologies Aerospace Systems (UTAS), in two phases: 1997 thru 1999 and 2003 thru 2004.
    - In 2013, approximately 54 units had reached the end of their “use life”:
- In 2013, filter use life was extended from 10 to 22 years, based on 2012 testing of 7 filters removed from controlled storage.

Filter standards

- **Mil-Standard 282** is the first HEPA filter standard developed based on a thermally generated Di(2-Ethylhexyl) Phthalate (DOP) smoke cloud as the challenge aerosol.
  - Hi-efficiency filtration became of interest to the military, after World War I, in order to protect troops from poisoned gas attacks
- Institute of Environmental Sciences and Technology's **IEST-RP-CC001.5** specification is an overall standard describing the types of HEPA filters (Types A thru K) and construction materials and requirements, but also describes the performance requirements (e.g. filter resistance or pressure drop) and need to perform both efficiency and leak test as part of penetration testing.
- **IEST-RP-CC034.3** specification discusses the HEPA leak testing, in particular, the choice of tests, aerosol oils, and recommended test procedures and scan test methods, uniformity of the challenge aerosol, and guide for aerosol particle detector which is dependent on filter type.
- **IEST-RP-CC007.2** provides similar test methodology for Ultra Low Penetration Air (ULPA) filters, not the subject of this paper, but does provide the component breakdown of typical filter test systems and appropriate recommendations.
- **ASHRAE 52.2-20** is a test method standard for the broader air filter application area, and not just restricted to HEPA and ULPA filters; applicable to our application are the requirements for air velocity and aerosol distribution uniformity of the test measurement system.

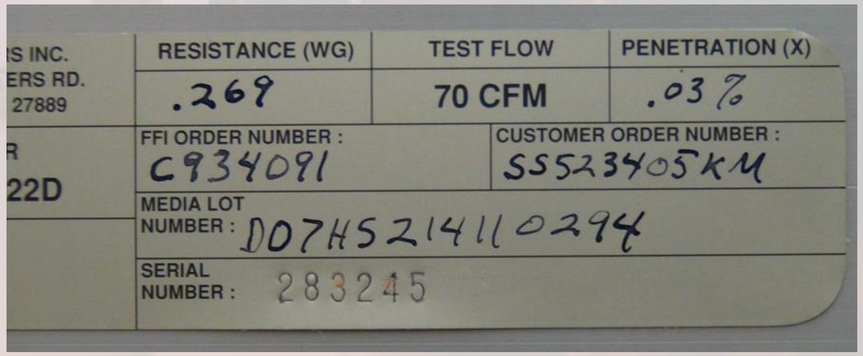
ISS Bacterial Filter Element (BFE)

ISS filters are bacterial filter elements (BFE) and contain pleated borosilicate HEPA media

Rectangular aluminum frame with outside dimensions of 73.7 cm × 10.2 cm × 11.1 cm (29 in. x 4 in. x 4.375 in.).

Filter media is covered with a 20-mesh (0.84-mm clear opening) prescreen (Nomex™) at the inlet and an aluminum mesh screen at the outlet.

- ISS filter specification:
  - Efficiency of 99.9% @ 0.3 microns @ 1982 L/min (70 cfm). NOTE: HEPA-grade efficiency is 99.97%.

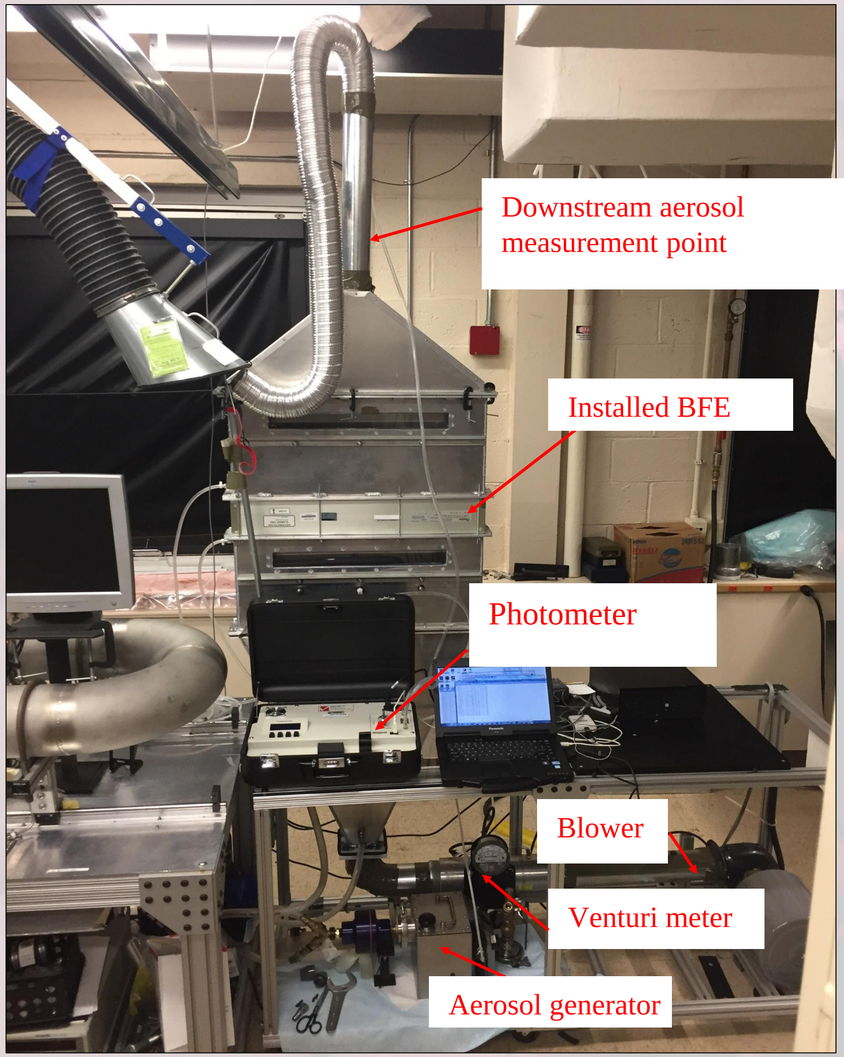


Aerosol generator and photometer

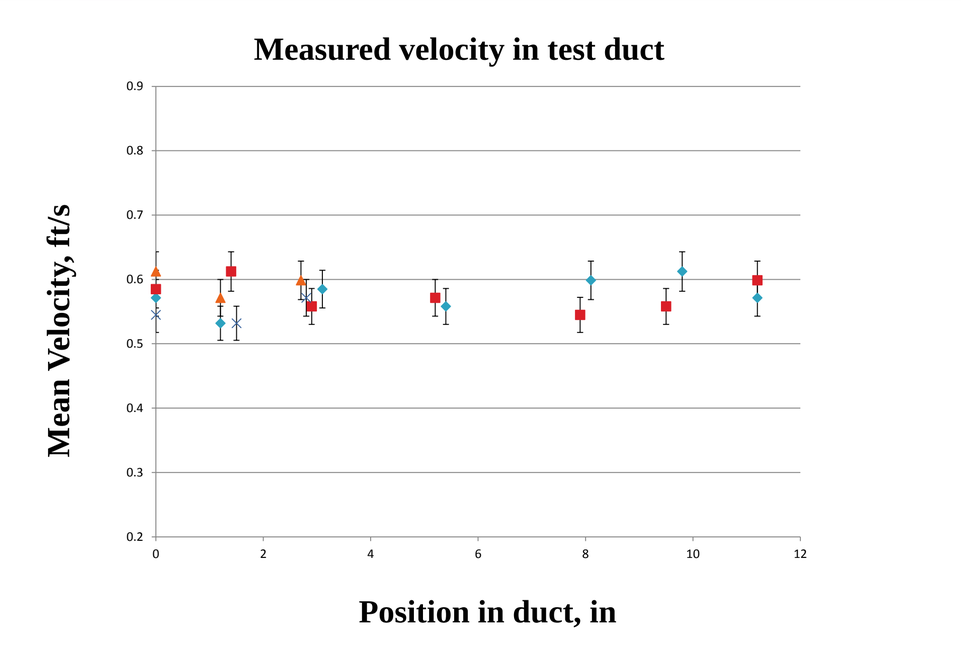
- Laskin nozzle design aerosol generator (ATI model TDA-4B) “cold” generated aerosol.
  - We are using PAO (polyalphaolefin) as the challenge aerosol.
    - Lower toxicity than DOP (dioctyl phthalate)
  - Impactor stage (custom ATI unit) installed to obtain proper aerosol size distribution
- Aerosol measurement device is an aerosol photometer (TEC Services, model PH-4)
  - Calibrated for use with DOP, PAO.
  - Output is % penetration.
  - Includes nozzle-like probe for leak testing.

Test Setup

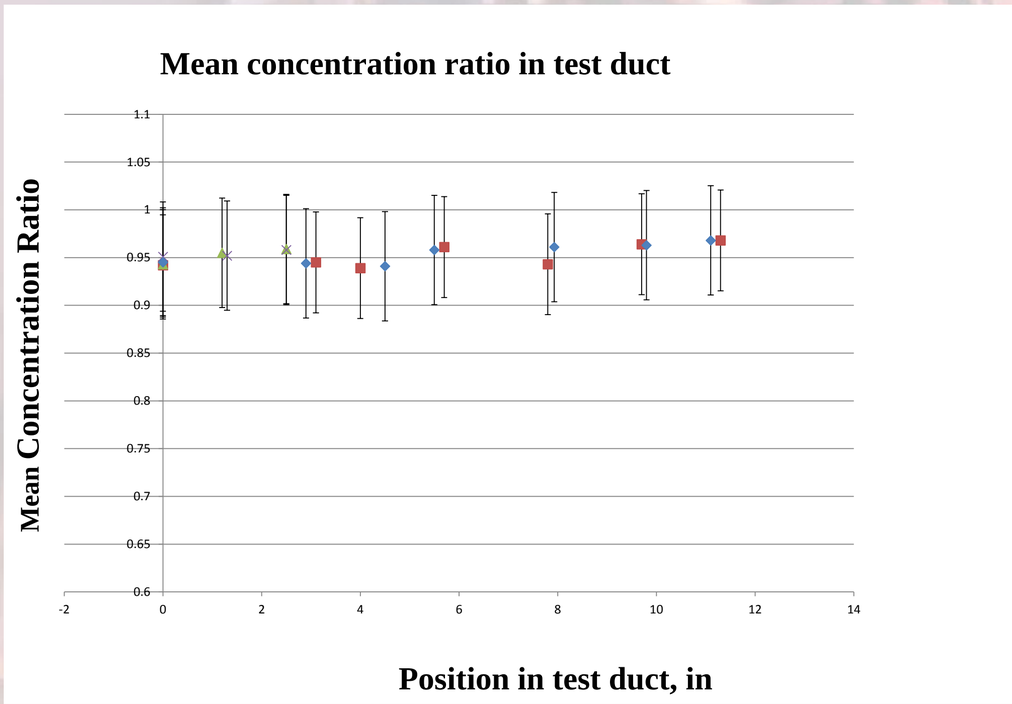
- Designed and fabricated upright test duct for unique BFE cross-section.
  - Taper inlet section (aerosol injected at base)
  - Blower mounted upstream.
  - Venturi meter used for flow measurements.
  - Conic section downstream of test article to allow for proper mixing prior to penetration measurement



Flow & aerosol distribution measurements in test duct



- Filter standards specify ± 10% flow variation and ± 15% variation in aerosol uniformity.



Concentration measured with photometer at 15 locations along test duct cross-section.
Variation in concentration < 10%.

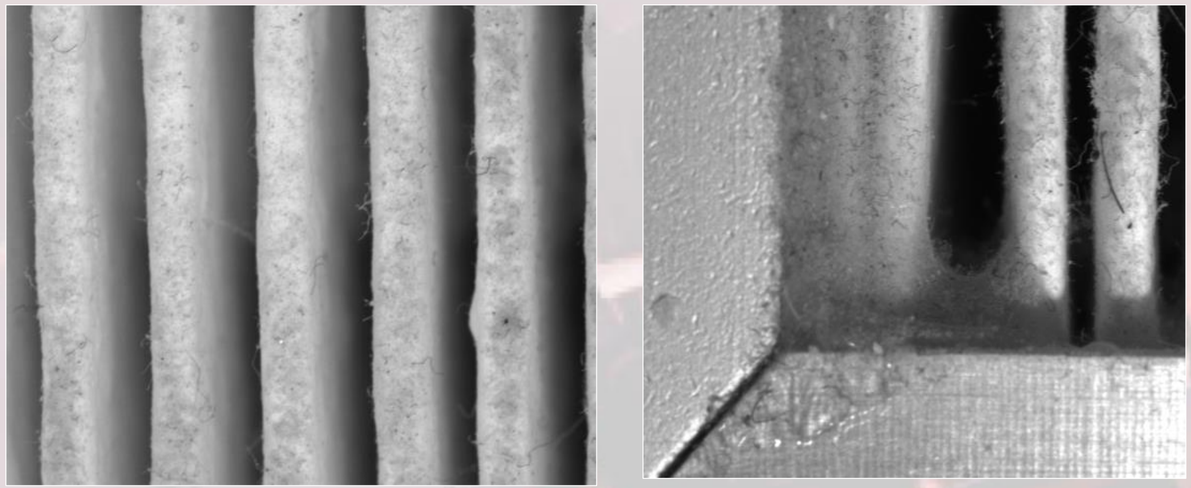
Air velocities were measured with a hot wire anemometer.

BFE Pressure Drop and Penetration Efficiency Testing

- Total of 10 ISS BFE filters tested:
- 8 Returned BFEs:
  - Varied in time in continuous operation from 0.8 years to 2.5 years
    - i.e. 6 followed early 1 year replacement interval, 2 were on revised 2.5 year replacement interval.
- 2 Engineering Development Units (EDUs):
  - These saw very limited time in operation (were installed for LAB module check-out on the ground; operated in a clean room).
- Both pressure drop and penetration efficiency measured at a constant flow rate of 1982 L/min (70 cfm).
- NOTE: Small sample set due to limitations on payload down-mass (i.e. how much hardware can be returned from ISS to Earth).

Visual inspection prior to testing

- BFE filter unpacked and visually inspected for damage.
- Any large loose clumps of debris (mainly lint) were removed with a tweezers
- Nomex screen removed for testing (to achieve tight seal on inlet test duct)
- One BFE tested for active biological content. (low, nominal levels consistent with those in indoor terrestrial spaces)



Images of the BFE S/N 0153 HEPA media. The images cover an 18.4 mm × 12 mm area.
LEFT: Inlet pleat edges near middle of cross-section.
RIGHT: Corner of inlet surface including aluminum frame and adhesive.

BFE pressure drop and penetration results

BFE TYPE	SERIAL NUMBER	Time in service	PRESSURE DROP		PENETRATION		
			Initial (in Pa)	Tested (in Pa)	Initial (%)	Tested (%)	Notes
Returned	0148	911 days/2.5 yr	72.2	96.1	0.01	0.0104	2016 paper
Returned	0153	911 days/2.5 yr	74.7	95.3	0.01	0.0377	2016 paper*
EDU	XSR08	ground testing	67.0	77.2	0.03	0.0245	2016 paper
EDU	XSR09	ground testing	68.7	72.2	0.01	0.0058	2016 paper
Returned	0009	299 days/0.8 yr	72.2	75.5	0.02	0.0142	This study
Returned	0010	299 days/0.8 yr	72.2	81.7	0.03	0.0605	This study
Returned	0013	299 days/0.8 yr	74.7	74.5	0.0025	0.0074	This study
Returned	0093	334 days/0.9 yr	67.2	71.0	0.01	0.0088	This study
Returned	XSR04	334 days/0.9 yr	65.2	65.8	0.01	0.0137	This study
Returned	XSR05	334 days/0.9 yr	68.2	67.7	0.01	0.0126	This study

Pressure drop test results

- All BFEs met end-of-life pressure drop requirement, i.e. did not exceed 124 Pa (0.5 inches H_2O).

Penetration results

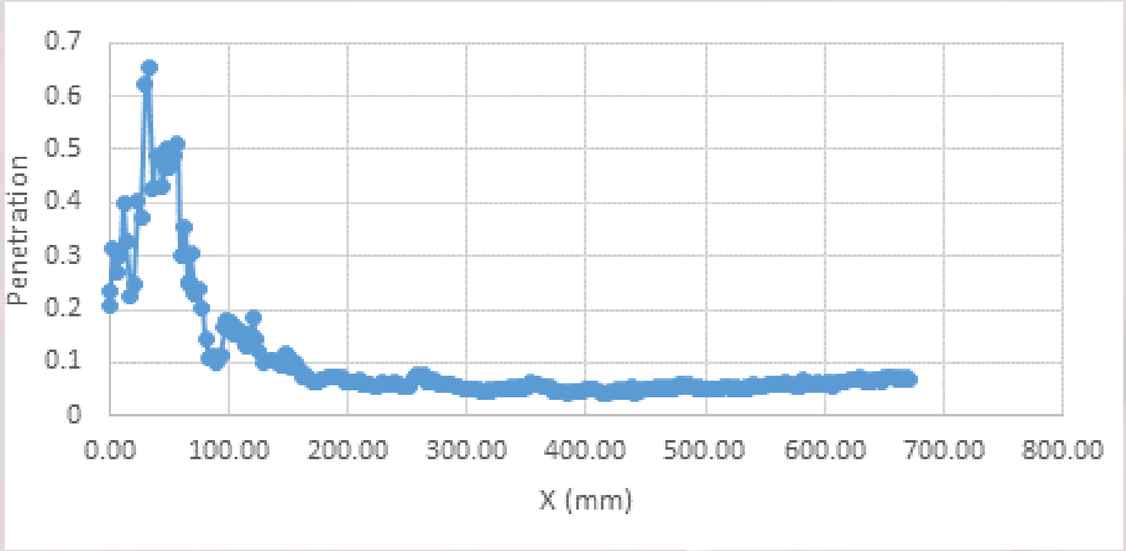
- All BFEs met ISS efficiency requirement of 99.9%. Results above reported as penetration efficiency. $E_T = 1 - P$, where P is the penetration efficiency and E_T is the filter's overall efficiency
- Two filters (S/N 0153, S/N 0010) saw increase in penetration from initial measured value.

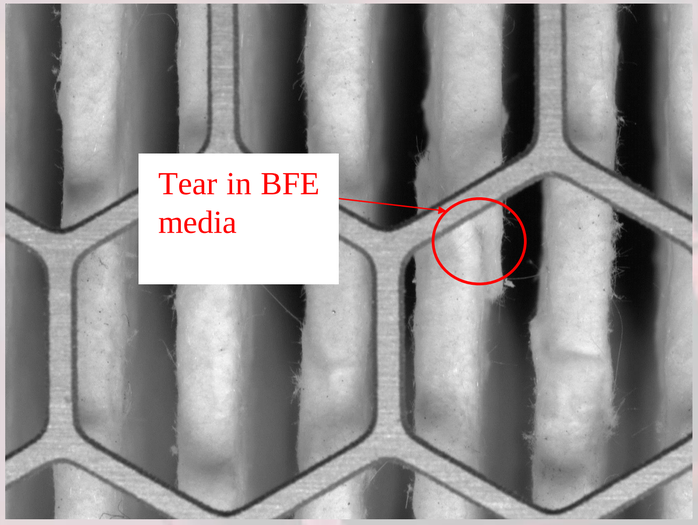
Stage 1 Leak test results

BFE TYPE	SERIAL NUMBER	PENETRATION	
		Flow = 1982 L/min (%)	Flow = 396 L/min (%)
Returned	0148	0.0104	0.0079
Returned	0153	0.0377	0.0041
EDU	XSR08	0.0245	———
EDU	XSR09	0.0058	———
Returned	0009	0.0142	0.0024
Returned	0010	0.0605	0.1064
Returned	0013	0.0074	0.0000
Returned	0093	0.0088	0.0000
Returned	XSR04	0.0137	0.0000
Returned	XSR05	0.0126	0.0000

- First stage leak test (measured penetration at 20% of design flow).
  - All BFEs passed except S/N 0010 (did not measure one order magnitude drop in penetration)

Stage 2 Leak test results





Performed second stage leak test on S/N 0153 and S/N 0010

- Linearly scanned entire filter cross-section by sweeping the aerosol photometer probe at approximately 1-2 cm/sec.
- For S/N 0153, detected leak but was unable to find protrusion via visual inspection.
- For S/N 0010, determined localized leak to small tear in BFE media (on pleat edge but on outlet side of filter).

Conclusions

- A test duct system was designed to test the unique cross-section ISS Bacterial Filter Elements (BFEs).
- The results showed that all BFE test articles tested exceed the ISS requirement for overall efficiency of 99.9% minimum for 0.3 micron particles for several replacement intervals. Small leaks were detected in 2 of the 8 returned units even though both met ISS overall efficiency requirement.
- All returned BFEs met the end-of-life pressure drop requirement of 124 Pa (0.5 inches H_2O).
- These techniques for characterizing the test duct and perform leak testing can potentially be applied to conducting acceptance testing and inventory testing for future manned exploration programs with air revitalization filtration needs, possibly even for in-situ filter element integrity testing for long-duration missions.

Acknowledgements

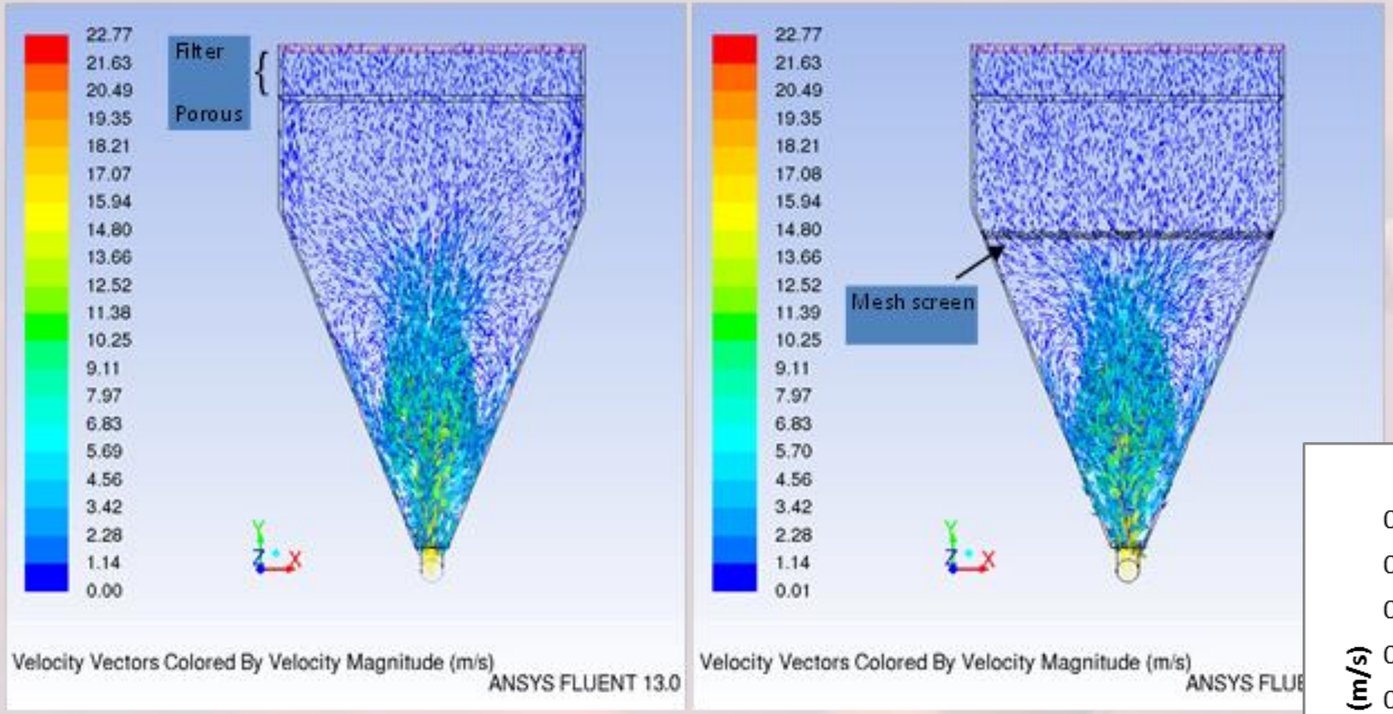
- This work was funded by the NASA Advance Exploration System's Life Support Systems Project and is gratefully acknowledged.

Backup Slides

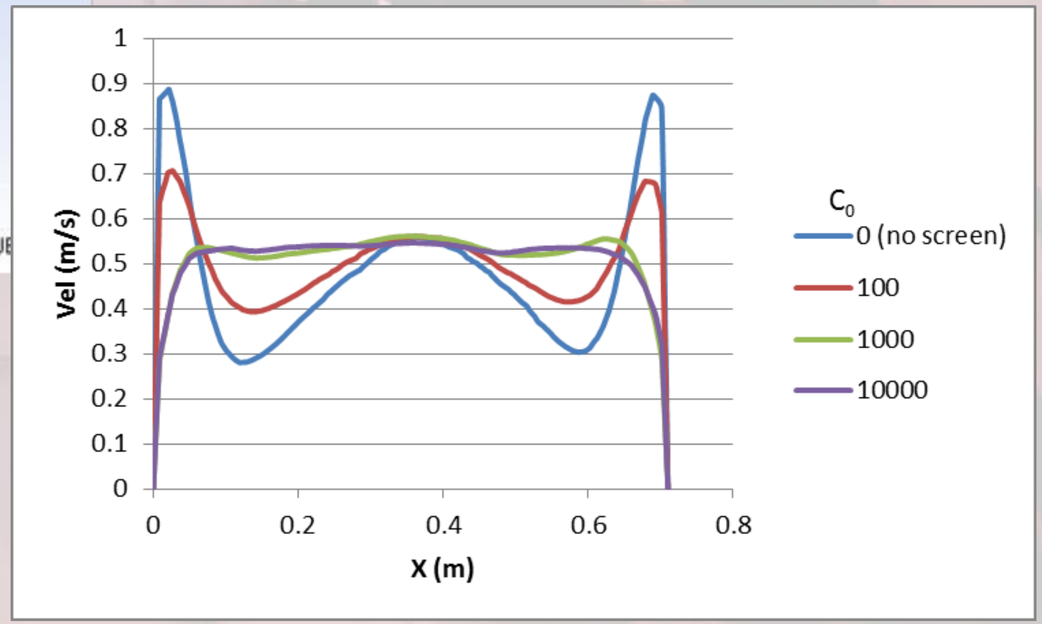
ISS Particulate Matter (PM) Loading Requirements

- NASA-commissioned panel recommended suspended PM concentration limited to 0.4 mg/m^3 for particles up to 100 µm in diameter.
- ISS Program adopted a suspended PM requirement of 0.05 mg/m^3 (i.e. 4 times lower than max recommended for crew health).
  - This requirement is identical to Federal Standard 209, Revision E, for a class 100,000 clean room.
  - Daily average of 0.05 mg/m^3 of PM with size range 0.5-100 µm, with peaks to 1 mg/m^3.

CFD analysis of test duct



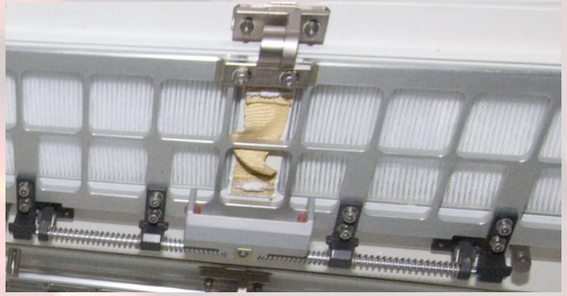
Performed 3D CFD analysis
using FLUINT with κ-ε turbulence model.
Filter modeled as a porous zone.



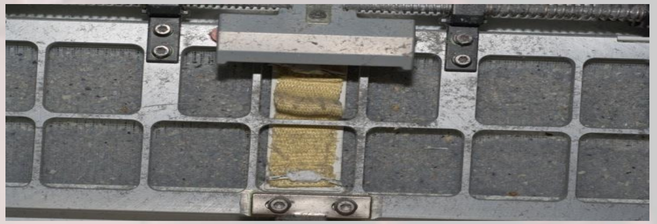
Analysis concluded that an added mesh screen
In tapered portion of duct provides a more uniform velocity profile.

Introduction/Background

- The ISS Bacterial Filter Elements (BFEs) are HEPA-grade filters utilized on ISS to control particulates in the pressurized volume.
  - Total of 21 BFEs installed in US segment. Columbus and JEM use HEPA filters of a different design.
  - Original replacement interval of 1 year.
  - Replacement interval was extended to 2-5 years.
    - Replacement interval varies by location: US Lab/Node 2/Node 3 BFEs are replaced at 2.5 years; the airlock BFEs are replaced at 5 years, Node 1 BFEs are replaced at 2 years
  - On-orbit maintenance consists of frequent vacuuming to remove large particulate load.



Clean BFE



8 days accumulation