Filter Efficiency and Leak Testing of Returned ISS Bacteria Filter Elements after 2.5 Years of Continuous Operation

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The atmosphere revitalization equipment aboard the International Space Station (ISS) and future deep space exploration vehicles provides the vital functions of maintaining a habitable environment for the crew as well as protecting the hardware from fouling by suspended particulate matter. Providing these functions are challenging in pressurized spacecraft cabins because no outside air ventilation is possible and a larger particulate load is imposed on the filtration system due to lack of sedimentation in reduced gravity conditions. The ISS Environmental Control and Life Support (ECLS) system architecture in the U.S. Segment uses a distributed particulate filtration approach consisting of traditional High-Efficiency Particulate Adsorption (HEPA) filters deployed at multiple locations in each module. These filters are referred to as Bacteria Filter Elements (BFEs). As more experience has been gained with ISS operations, the BFE service life, which was initially one year, has been extended to two to five years, dependent on the location in the U.S. Segment. In previous work we developed a test facility and test protocol for leak testing the ISS BFEs. For this work, we present results of leak testing a sample set of returned BFEs with a service life of 2.5 years, along with particulate removal efficiency and pressure drop measurements. The results can potentially be utilized by the ISS Program to ascertain whether the present replacement interval can be maintained or extended to balance the on-ground filter inventory with extension of the lifetime of ISS to 2024. These results can also provide meaningful guidance for particulate filter designs under consideration for future deep space exploration missions.

Nomenclature

ASHRAE	=	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATI	=	Air Techniques International
ATP	=	adenosine triphosphate
BFE	=	Bacteria Filter Element
DOP	=	dioctyl phthalate
EDU	=	engineering development unit
HEPA	=	High-Efficiency Particulate Absorption
IEST	=	Institute of Environmental Sciences and Technology

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ISS	=	International Space Station
PAO	=	polyalfaolefin
RLU	=	relative light units
UTAS	=	United Technologies Aerospace Systems
cm	=	centimeter
E_T	=	filter overall efficiency
ft	=	foot/feet
m	=	meter
mg	=	milligram
mm	=	millimeter
nm	=	nanometer
P	=	filter particle penetration
Pa	=	pascal
s	=	second

I. Introduction

ATMOSPHERE revitalization aboard the International Space Station (ISS) removes trace chemical contaminants, carbon dioxide, and particulate matter from the cabin environment. To accomplish the latter, the ISS utilizes a distributed particulate matter filtration architecture to remove airborne particulate matter and minimize the risk of any detrimental effects of suspended particulates to both crew and on-board equipment. Filters known as Bacteria Filter Elements (BFEs) are limited-life components within this architecture. The BFE supplier, United Technologies Aerospace Systems (UTAS), subcontracted with Flanders Corp. for the pleated High Efficiency Particulate Absorption (HEPA) filter media contained in the BFE. There are a total of twenty-one BFEs deployed throughout the ISS's U.S. Segment; the Japanese and European laboratory modules also use HEPA-rated filters but of a different design. The BFEs were originally specified for a 1-year replacement interval but a testing and analysis study indicated the lifetime could be extended to two years or more.[1] The BFE replacement intervals are based on location—Lab/Node 2/Node 3 BFEs are replaced at 2.5 years, airlock BFEs are replaced at 5 years; Node 1 BFEs are replaced at 2 years.

Deterioration of the resin binder in the media, oxidation or loss of volatile constituents in the sealing adhesive, and crystallization of the glass fiber media are all potential failure mechanisms for BFEs in service and stored in inventory.[2] To address the storage life of the BFEs, testing was conducted by UTAS in 2012 on seven BFEs that were in controlled storage and results indicated performance was still the same as the original acceptance testing for media tensile strength, 0.3-micron particle removal efficiency, random vibration, pressure drop, and proof pressure.[3] A decision was made by the ISS Program in early 2013 to increase the use life (in-service life + shelf life) from 10 years to 22 years.

In addition, the service life of the ISS BFEs may be impacted by the weekly vacuuming of the inlets of installed filters to remove the large particulate loading. Post-flight leak testing of returned filter units may need to be performed to assess any degradation due to vacuuming of the filter surface. A more methodical testing of returned filters will determine any degradation due to deployment in the ISS environment, including the effects of housekeeping activities.

II. Experiment Methods

The following discussion presents the testing standards and testing apparatus as well as an overview of the BFE test articles.

A. Discussion of Standards

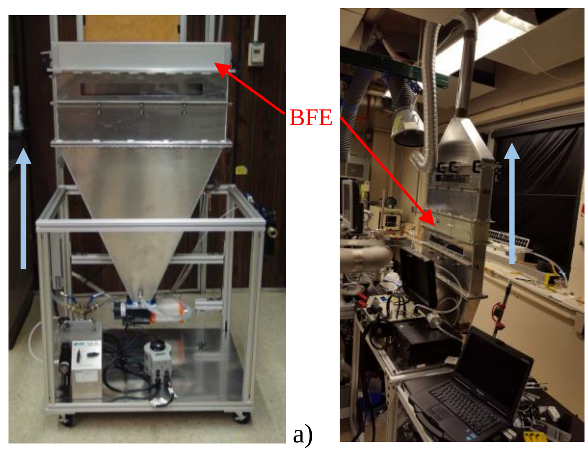
The filter industry has developed a comprehensive set of testing standards for certifying HEPA filters. After World War I, high-efficiency filtration gained interest from the military in order to protect troops from poisoned gas attacks.[4] The Mil-Standard 282 is the first HEPA filter standard developed based on a thermally generated dioctyl phthalate (DOP) smoke cloud as the challenge aerosol.[5] Subsequent standards have been developed by industry to further define filter testing standards for the broader range of HEPA applications.

For the work reported in this paper, our goal was to determine the filter performance on the basis of generally accepted principles on which the common test standards are based. A test system and protocol developed on the basis of the Institute of Environmental Sciences and Technology (IEST) and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standards for testing for integrity (or leak) of the filters was presented elsewhere.[6]

For the experiment reported here, the same system used for leak testing has been modified to add the capability to measure particulate penetration efficiency and filter pressure drop. Particle penetration efficiency, the number of particles crossing the filter divided by the number of particles incident on the filter, is defined as $P = 1 - E_T$, where P is the penetration efficiency and E_T is the filter's overall efficiency.[7] It is worth noting that whereas efficiency measures the performance of the filter in the aggregate, a leak test looks for minute variations in performance across the face of the filter. These minute variations may be due to inherent variability in the filter material used in the construction of the filter, or from actual blemishes or holes. Although a filter in the aggregate may meet the performance requirements, the leak testing ensures that there are not local spots with blemishes that can allow unfiltered air to pass through, potentially causing harm just down stream of the blemish. In other words, it is generally accepted practice that HEPA filters not only meet the efficiency requirements. The objective of this work along with the Ref. 6 study is to extend the same practice to the ISS filters.

B. Test Duct Design

An upright test duct system with an aerosol generator was designed and used for leak testing of the ISS filters; the details were discussed in Ref. 6. This same test duct system has been modified to perform overall efficiency tests on the ISS filters reported in this paper. These modifications include a venturi meter to measure volumetric flow, an impactor attachment for the aerosol generator, and a conical exit hood, added downstream of the test filter. Figure 1 is a photo of the original (Fig. 1a) and revised test duct setup (Fig. 1b) showing these upgrades and improvements.

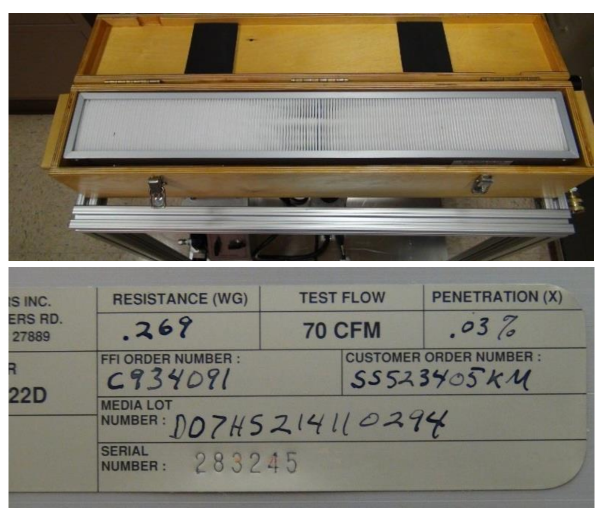


a) b)

Figure 1. Filter element testing setup. *a) Leak test rig; b) Modified test rig for efficiency testing — blue arrows indicate direction of air flow.*

Several modifications were made to upgrade this filter leak test rig, to allow particulate removal efficiency testing. The modifications include a higher flow rate blower to meet flow requirements for another project, an impactor attachment to the Laskin aerosol generator to achieve a specific aerosol size distribution in order to meet the filtration standard, downstream duct to capture exit flow from the test article, venturi meter to measure flow, and pressure transducers were installed in the inlet and exit ducts to measurement pressure drop across the BFE test article.

The Laskin nozzle aerosol generator, used previously in this test duct system, generates an aerosol particle size distribution slightly larger than specified in Mil-Standard 282 and Section 9.1 of IEST-RP-CC001.5.[5,8] After consultation with the manufacturer, Air Techniques International (ATI), the recommendation was to add an impactor attachment to the aerosol generator exit to allow a tighter controlled particle size distribution to meet the specification for efficiency testing. An impactor, designed and tested by same manufacturer, was installed for this work. The measured particle size distribution data sheet provided by the manufacturer, shows this generator/impactor combination generates a mass mean aerosol diameter of 0.303 microns.



a) b)

Figure 2. ISS Bacteria Filter Element. *a) Bacteria Filter Element in shipping container with Nomex® inlet screen removed; b) Vendor label.*

A conical section was fabricated from sheet metal and installed on the straight exit test duct of the system, such that all the air flow exiting the filter is then "collected" by this conical section and directed to a 7.6 cm (3 inches) diameter exit tube as shown in Fig. 2. The downstream samples are measured from a port ~6 tube diameters downstream of the entrance to this exit tube to ensure that airflow will be fully mixed and developed. This assumption was also verified by measurements across the cross section of the exit tube. It is worth noting that since the aerosol concentrations downstream of a HEPA filter are low—roughly four orders of magnitude lower than the challenge aerosol concentration—a well mixed sample is necessary for accurate and consistent efficiency measurements.

Polyalfaolefin (PAO) was used as the challenge aerosol. The aerosol was generated via an ATI Laskin nozzle generator with the impactor attachment installed, and injected into the test duct upstream of the BFE test article. The photometer, a TEC Services model PH-4, was calibrated for the PAO aerosol. The photometer's output measurement is penetration efficiency in percent of the upstream aerosol concentration.

C. ISS Bacteria Filter Element Test Article Overview

The ISS BFEs, shown by Fig. 1, contain pleated borosilicate HEPA media in a rectangular aluminum frame with outside dimensions of 73.7 cm × 10.2 cm × 11.1 cm (29 inches × 4 inches × 4.375 inches). The HEPA media is covered with a 20-mesh Nomex® screen on the inlet side of the filter and an aluminum mesh screen on the outlet side. Each filter has a metal stamped label on one side of the aluminum frame, as shown in Fig. 2, with the serial number, measured particle penetration rating, volumetric flow for efficiency test, and pleated HEPA media lot. The penetration efficiency requirement for the ISS BFE filter is 99.9% at 0.3 microns at a volumetric flow rate of 1980 liters/minute (70 ft^3/minute).[1] This specification is not a standard HEPA efficiency specification but likely the BFEs utilize HEPA filter Type C media to meet this requirement.[8]

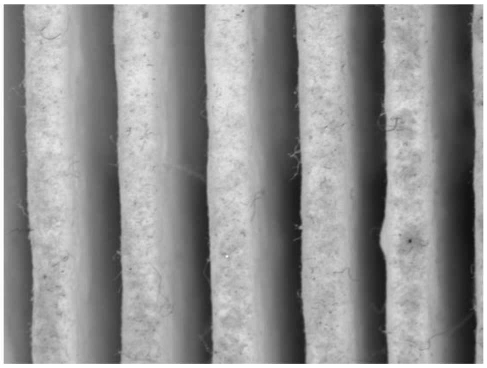
The test articles consisted of two returned filters—serial number (S/N) 0148 and S/N 0153—from ISS that were both installed and operated in the U.S. laboratory module, *Destiny*, for 911 days or approximately 2.5 years. In addition, two BFE engineering development units (EDUs), S/N's XSR08 and XSR09, were tested in a similar manner for comparison purposes. These BFE EDUs were used minimally in the pre-flight ground testing and checkout of *Destiny*.

The BFEs returned from the ISS were carefully unpacked, inspected, and photographed. It was noted that the Nomex® screen covers were covered with grey tape, and although some residual lint and other particulate material likely left over after vacuuming adhered to the underside of the tape, no filter cake was remaining on the screen. The tape did not appear to have adhered to the pleat edges of the HEPA media.

The Nomex® screen was removed from one of the returned filters (S/N 0148) and the filter media surface was tested for any active biological material content. A swab test was performed on two small areas of the media surface. A luminator, which provides measurements of biological activity based upon adenosine triphosphate (ATP) content in relative light units (RLUs), was used to test the swabbed samples. The range of the instrument is 0-10,000 RLUs. The readings for both areas were 38 and 2 RLUs, which are below the range of 50-100 RLUs considered acceptable for surfaces in terrestrial laboratory and other indoor living spaces.

D. Photographic Inspection of ISS BFE Inlet Surface

The inlet surface of each ISS BFE was scanned and imaged using a video camera with a 1:1 macrolens, on a scanning platform. Figure 3 shows two images of the pleated media surface. These close-up images of the media surface showed sparse embedded particulates in the pleat edges visible to the naked eye, primarily what appear to be cloth fibers and hairs. The interior of pleats appear to contain larger accumulations of particulate matter, but would require destructive means to provide a more thorough examination. A slight fraying of the HEPA media fibers was observed but visible pertrusions or compromised areas were not evident. Inspecting the filter in whole with the naked eye, the fraying appears to be more pronounced near the center of the short length cross-section, which would be indicative of wear due to vacuuming of the surface caused by pressing the Nomex® screen (without support in the center) against the pleat edges causing more abrasion, compared to pleat edges near the frame.


a)

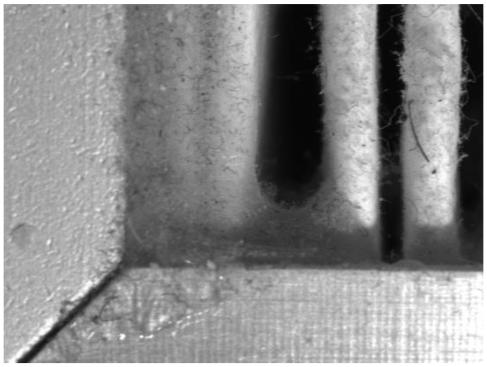

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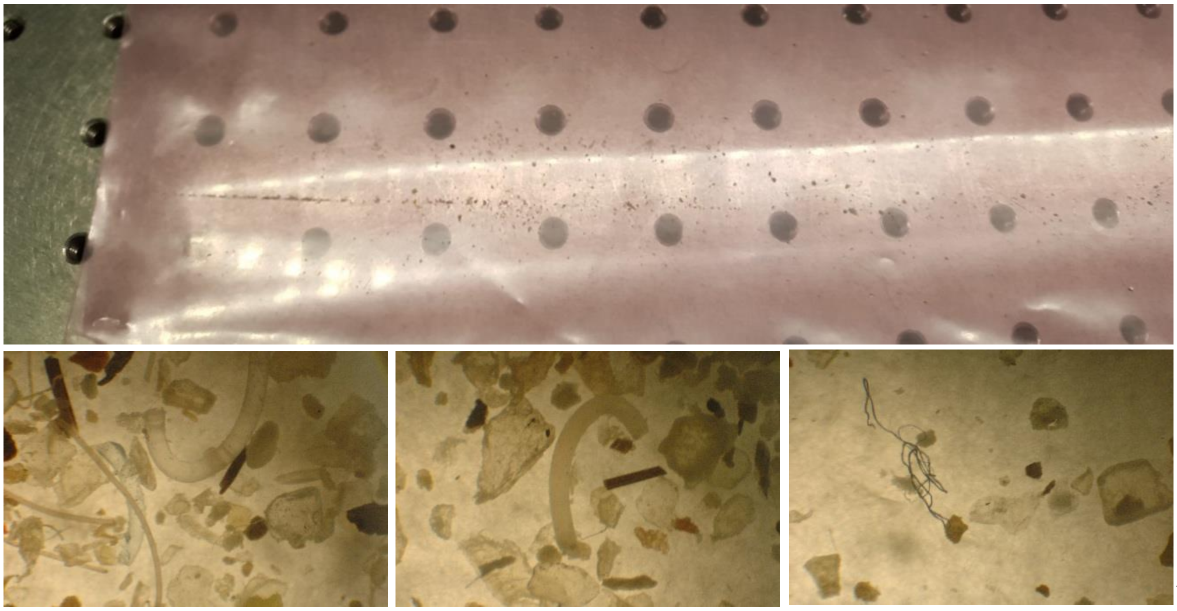
Figure 3. Images of the BFE S/N 0153 HEPA media. *The images cover an 18.4 mm × 12 mm area. a) Inlet pleat edges near middle of cross-section; b) Corner of inlet surface including aluminum frame and adhesive.*



a)

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Figure 4: Particulate matter collected from filter S/N 0153. *a) Loose particulate matter that settled onto a plastic lining during imaging; b) Microscopic images of matter collected from plastic lining (imaged at ~25X).*

For one of the returned BFEs (S/N 0153), it was noted during unpacking and removing the Nomex® screen for testing, a small amount of loose particulate matter fell out on the inlet side. A sample of this loose material was recovered for optical microscopy. Figure 4a shows the loose matter as it had settled onto the plastic lining placed underneath the inlet filter face during imaging of the back face of the filter. The plastic lining was lightly coated with this loose matter throughout the whole length where the filter was positioned. The loose particulate matter was collected for further microscopic analysis. Several microscopic images are provided in Fig. 4b showing the diversity of particles that were captured. Individual fiber, rod, and flake structures were found and the different color of the particles indicated different material types.

III. Results

Each of the BFE unit was installed in the test setup described in Section II for particulate removal efficiency and pressure drop measurement. For all tested BFE units, the Nomex® screen was removed and the filter element was mounted onto the test duct with the inlet face of the filter facing downward into the flow (Fig. 1b). Foam seals (changed frequently) were placed on the sealing surface of the inlet filter face to obtain a good seal; no seal was placed on the outlet filter face since a lip seal on this face provides adequate sealing.

When initiating testing for the BFE pressure drop measurement, the blower speed was adjusted to the desired volumetric air flow rate using a calibrated venturi meter. When the challenge aerosol injection upstream of the inlet was initiated, the volumetric flow rate was checked and adjusted to maintain the desired rate. Both the particulate efficiency and pressure drop measurements were made at 1980 liters/minute (70 ft^3/minute). The aerosol concentration in the inlet stream concentration was typically in the range of 15-25 mg/cm^3. The inlet concentration was reset to 100% on the photometer at the beginning of each efficiency measurement.

A. Pressure Drop Measurements

The pressure drop measurement across the returned units were 96.1 Pa (0.386 inches H_2O) and 114 Pa (0.456 inches H_2O) for S/N 0148 and S/N 0153, respectively. According to the design specification, a clean unused BFE is designed to have a pressure drop no more than 82.2 Pa (0.33 inches H_2O) at a flow rate of 1883 liters/minute (66.7 ft^3/minute); at the end-

Table 1. Pressure drop and penetration efficiency for all tested BFEs compared with initial data measured by the manufacturer. *Initial data are from the label attached to the respective BFE unit.*

BFE TYPE	SERIAL NUMBER	PRESSURE DROP		PENETRATION	
		Initial (Pa)	Tested (Pa)	Initial (%)	Tested (%)
Returned	0148	72.2	96.1	0.01	0.0104
Returned	0153	74.7	113	0.01	0.0558
EDU	XSR08	67.0	77.2	0.03	0.0245
EDU	XSR09	68.7	72.2	0.01	0.0058

of-life, the BFE pressure drop should not exceed 124 Pa (0.5 inches H_2O).[1] As reported in Table 1, both the returned BFEs, when new, had a pressure drop below the design specification, and after 2.5 years of continuous operation on ISS, met their end-of-life design specification. It should be noted that that S/N 0153, with a measured value of 0.46 inches H_2O, was within 9% of this design specification, indicating at least a portion of the BFEs in *Destiny* are seeing particulate loading levels such that a larger sample size of returned BFEs should be tested before a further extension of replacement intervals is considered.

B. Filter Efficiency Measurements

For the filter efficiency measurements, the photometer measures the challenge aerosol penetration efficiency which is reported in Table 1. For the returned units, the penetration efficiencies were 0.0104% and 0.0558% for S/N 0148 and S/N 0153, respectively. For S/N 0148, the measured penetration efficiency is identical to that measured when the unit was new, but conversely, for the S/N 0153, the penetration efficiency has risen significantly. It should be noted that penetration efficiency for a nominally performing HEPA filter either stays the same or can actually drop, due to slightly improved filtration from accumulated embedded particulates and filter cake build-up during use. Despite this increase in penetration efficiency, the filtration efficiency, $E_T = 1 - P$, of 99.99% and 99.95% for the returned BFE units still meet the design specification of 99.9% minimum.[9] The measured penetration efficiencies of 0.0245% and 0.0058% for the EDU filters were both lower than the 0.03% and 0.01% values measured for the new units. Since these filters experienced little or no loading in their use, this difference may likely be attributed to differences in testing setup from what the filter manufacturer utilized to make the initial measurements.

In addition to the one-point overall efficiency measurements, a linear scan of local particle penetration along the length of the filter was conducted as illustrated by Fig. 5. These scans were conducted for comparison purposes and to evaluate the performance uniformity of the filter. In this arrangement the conic duct assembly above the filter element (Fig. 1b) was removed and a motorized linear stage holding the photometer hand scanner was mounted to the open flange surface of the straight duct above the filter. The inlet sampling nozzle of the hand scanner was positioned 7 cm (2.76 inches) above the filter surface. Then the stage was programmed to scan along the filter length at 3 mm/s.

The penetration profile of filter S/N 0153 in Fig. 5 shows clear variations across the length of the filter. For most of the mid-section of the filter the efficiency is fairly uniform, close to values of overall efficiency obtained above, and then rises slightly on the right side. Small increases in penetration near the edges of filters are not uncommon in high efficiency filter testing. However, on the left side there is a well-defined and localized increase in penetration, strongly indicative of a leak. Direct leak testing of this filter is discussed in the next section.

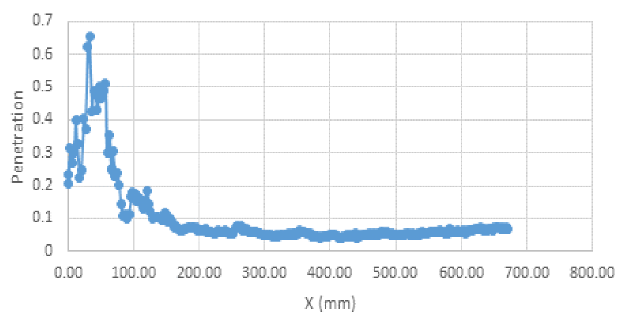

Figure 5. Penetration data for a linear scan measurement of the BFE S/N 0153 cross-section.

C. Filter Leak Testing

The filter leak testing was performed in two stages. In industry filtration practice, an indication of a potential leak in a HEPA filter can be inferred by performing a filtration efficiency measurements at both the design volumetric flow rate and a reduced volumetric flow rate, usually at 50% of the design flow rate. The resulting measured penetration efficiency should be an order of magnitude lower than the value measured at the design flow rate. The results of this first method are shown in Table 2. Although the penetration efficiency values measured for both returned BFEs were lower than those at the design flow rate of 1980 liters/min, they were not an order of magnitude lower.

In a second stage, a manual scanning leak test was performed on each filter using the method described in Ref. 6. The entire exit cross-section of the back face of the filter was scanned by slowly sweeping (at ~1-2 cm/s) the handheld probe down the long dimension of the filter, covering approximately one half the cross section, then sweeping the remainder of the cross-section in the reverse direction, looking for an area of the cross-section where a significantly higher reading

Table 2. Penetration efficiency data for first stage leak test.

BFE TYPE	SERIAL NUMBER	PENETRATION	
		1980 L/minute (%)	990 L/minute (%)
Returned	0148	0.0104	0.0079
Returned	0153	0.0558	0.0146
EDU	XSR08	0.0245	———
EDU	XSR09	0.0058	———

is observed. During the scanning, we typically observed penetration readings in the 0.5-2% range for both BFEs. For S/N 0148, we did not observe any peaks in readings, but for S/N 0153 we observed readings in the 1-5% range in one area approximately 10 cm (4 inches) from one end of the frame. Although we were able to repeat this measurement spike, no visible compromise or blemish of the filter media was discovered. Finally, no leak testing for either of the two EDUs was performed as both EDUs did meet (actually slightly exceeded) the initial penetration efficiency values measured by the filter manufacturer. Finally, no leak testing for either of the two EDUs was performed; both EDUs did meet (actually slightly exceeded) their initial penetration efficiency values. As noted in section II, this does not necessarily indicate that these filters are leak-free. But, there is a preference to minimize unnecessary testing (and further loading with challenge aerosol) to these minimally used BFEs in order to potentially track any long-term storage degradation and assess filter storage life.

IV. Conclusions

Presently, the ISS BFEs that provide the cabin atmospheric filtration function aboard the ISS have in-service lifetimes ranging between 2.5 years and 5 years depending on their location. In this work, we tested two BFEs that were returned from ISS after 2.5 years (911 days) in service. A filter test duct system, initially designed to perform leak testing, was modified to allow efficiency and pressure drop testing according to established filtration industry testing standards. A contracting exit duct, downstream of the filter, was shown to provide adequate aerosol mixing to provide a particulate penetration efficiency, verified by performing scanning measurements across the cross-section of the filter. Efficiency testing along with filter pressure drop measurements were performed on two ISS BFEs returned after 2.5 years of on-board operations.

The results of this work identifies a potential concern that the efficiency may be reduced for some BFEs during the extended service life, although both BFE test articles exceeded the ISS filtration efficiency of 99.9% minimum for 0.3 micron particles according to these test results. The finding that one out of the two returned BFEs installed on different locations on the ISS had considerable lint matter collected on the pleats points to disproportionately localized loading of particulate matter within the ISS module. This particulate filter also exhibited a fivefold increase in penetration which could indicate that either the additional particle load or combination of variations in inlet flow conditions or structure excitations (vibrations) could cause premature degraded (or even loss of) performance.

This work is focused on applying filtration industry standards to testing used and returned ISS BFE filters, but the methodology is general enough to be extended to other present and future spacecraft filters. The test duct system hardware and methodology could also 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 extensively long-duration missions. We also plan to address the unique needs for testing low profile cross-section filter, like the ISS BFEs, by preparing the initial version of a standard that can potentially be submitted to IEST or ASHRAE for consideration as a new standard or supplemental appendix to address low profile HEPA filter geometries.

Acknowledgments

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