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Filter Efficiency and Pressure Testing of Returned ISS Bacterial Filter Elements

Robert D. Green[1] and Juan H. Agui[2]
NASA Glenn Research Center, Cleveland, Ohio 44135, USA

Gordon M. Berger[3]
Universities Space Research Association, Cleveland, Ohio 44135, USA

R. Vijayakumar[4]
Aerfil LLC, Liverpool, New York 13088, USA

Jay L. Perry[5]
NASA Marshall Space Flight Center, Huntsville, Alabama 35812, USA

The air quality control equipment aboard the International Space Station (ISS) and future deep space exploration vehicles provide the vital function of maintaining a clean cabin environment for the crew and the hardware. This becomes a serious challenge in pressurized space compartments since no outside air ventilation is possible, and a larger particulate load is imposed on the filtration system due to lack of sedimentation. 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 Air (HEPA) filters deployed at multiple locations in each U.S. Segment module; these filters are referred to as Bacterial Filter Elements, or BFEs. In our previous work, we presented results of efficiency and pressure drop measurements for a sample set of two returned BFEs with a service life of 2.5 years. In this follow-on work, we present similar efficiency, pressure drop, and leak tests results for a larger sample set of six returned BFEs. The results of this work can aid the ISS Program in managing BFE logistics inventory through the station's planned lifetime as well as provide insight for managing filter element logistics for future exploration missions. These results also can 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
BFE	=	Bacteria Filter Element
DOP	=	dioctyl phthalate
EDU	=	engineering development unit
HEPA	=	High-Efficiency Particulate Air
IEST	=	Institute of Environmental Sciences and Technology
ISS	=	International Space Station
PAO	=	polyalphaolefin
STS	=	Space Transportation System (The US Space Shuttle)
UTAS	=	United Technologies Aerospace Systems
C	=	Celsius

[1] Aerospace Engineer, Fluid Physics and Transport Processes Branch, 21000 Brookpark Rd., MS 77-5.
[2] Aerospace Engineer, Fluid Physics and Transport Processes Branch, 21000 Brookpark Rd., MS 77-5.
[3] Research Associate, Combustion Physics and Reacting Processes Branch, 21000 Brookpark Rd., MS 110-3.
[4] Consultant in Chief, 300 Cyprus St., #41.
[5] Lead Engineer, ECLS Systems Development Branch, Space Systems Dept., MS ES62.

cm	=	centimeter
E_T	=	filter overall efficiency
ft	=	foot/feet
kPa	=	kilopascal
L	=	liter
m	=	meter
mg	=	milligram
mm	=	millimeter
nm	=	nanometer
P	=	filter particle penetration
Pa	=	pascal
s	=	second
yr	=	year

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 Air (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—the US Lab/Node 2/Node 3 BFEs are replaced at 2.5 years, the airlock BFEs are replaced at 5 years, and the 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 ISS BFEs are subjected to larger particulate loading compared to typical HEPA applications, due to the absence of sedimentation of airborne debris in a microgravity environment. The service life of the ISS BFEs may be impacted by the weekly vacuuming of the inlets of installed BFEs by the ISS crew to remove this increased 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.

In a 2016 paper[4], we presented pressure drop and particulate removal efficiency results of two returned ISS BFEs, both were installed and operated continuously for 2.5 years. In this follow-on work, we present results for an additional six returned BFEs which were installed and operated early in the ISS timeline when 1-year replacement was the recommended interval.

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 duct 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 in a 2014 paper.[6]

For the work 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. In other words, it is generally accepted practice that HEPA filters not only meet the efficiency requirements, but also pass a leak test. 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. 7. This same test duct system was modified to perform overall efficiency tests on the ISS filters reported in our 2016 work.[4] These modifications included 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. Slight modifications to this test duct were made for this work, namely a longer length duct and flow straightener were installed between the blower and venturi meter to reduce turbulence and lower the noise in the differential pressure measurements across the venturi, improving flow rate measurement. Figure 1 is a photo of the present test setup showing these upgrades and improvements.

Air flow through the test duct is from bottom to top as shown by the blue arrows in Figure 1. The flow expands through the lower tapered section to accommodate the cross-section of the ISS BFE test article; the challenge aerosol is introduced near the bottom of this tapered section to allow for uniform mixing prior to reaching the inlet of the BFE test article. A reverse tapered test section, collects the air flow exiting the filter and directs it to a 7.6 cm (3 inches) diameter exit tube. 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.

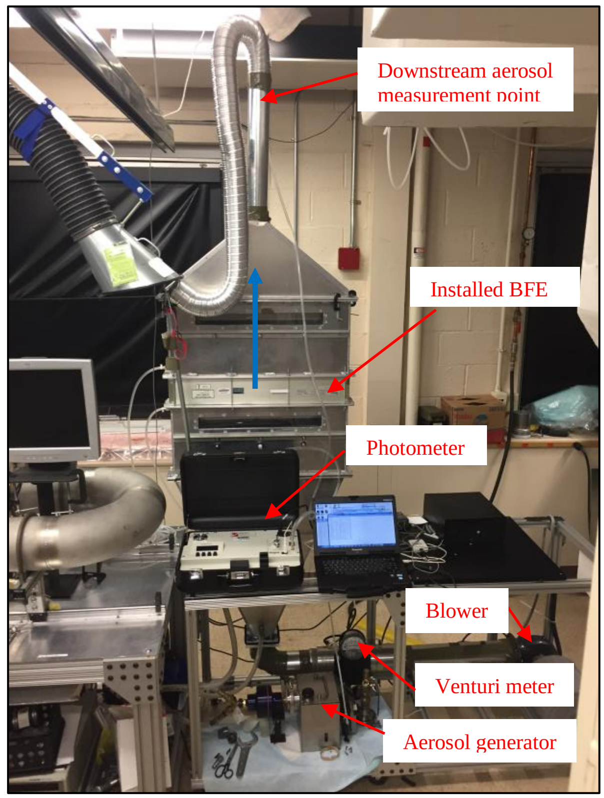

Figure 1. Filter element testing setup. *Modified test rig for efficiency testing — blue arrow indicates direction of air flow.*

The Laskin nozzle aerosol generator (ATI, model 4BLite) generates an aerosol particle size distribution slightly larger than specified in Mil-Standard 282[5] and Section 9.1 of IEST-RP-CC001.5.[9] An impactor, designed and tested by the same manufacturer was installed to tighten the particle size distribution to generate a mass mean aerosol diameter of 0.303 microns, meeting the challenge aerosol standard.

Polyalphaolefin (PAO) was used as the challenge aerosol. Due to DOP's toxicity, PAO is starting to replace DOP as the industry standard and generally yields similar results as DOP.[9] The photometer (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.

Tests were performed under ambient temperature and pressure conditions. Conditions were 29.8 °C and 97.8 kPa on first day of testing; 23.4 °C and 97.2 kPa on second day of testing. Exposure time to the challenge aerosol was recorded for each BFE, as there is a preference to minimize unnecessary testing (and further loading with challenge aerosol) in order to potentially track any long-term storage degradation and assess filter storage life, in particular the Engineering Development Unit (EDU) BFEs that were minimally operated in ground testing.

C. ISS Bacteria Filter Element Test Article Overview

The ISS BFEs, shown by Fig. 2, 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 L/minute (70 ft^3/minute).[1] This specification was derived to meet an ISS particulate matter requirement identical to the requirement for particulate matter loading defined by Federal Standard 209, Revision E, for a class 100,000 clean room.[1]

The test articles consisted of six of these ISS BFEs returned filters—serial numbers (S/N) 0009, 0010, 0013, 0093, XSR04, and XSR05. These filters were part of the initial set of filters installed and operated in the U.S. laboratory module, *Destiny,* and Node 1, *Unity*. These BFEs were continuously operated for 0.8-0.9 years, i.e. they were changed out per the initial one year replacement interval, as noted in the Introduction, in January 2002 and returned on STS 110/8A. In addition, test results from the two returned filters, operated for 2.5 years on-orbit and two BFE EDUs, which were tested and reported on in Ref. 4, are included in Section III for comparison purposes. The BFE EDUs were used minimally in the pre-flight ground testing and checkout of *Destiny*. Finally, one of the Ref. 4 tested BFEs, S/N 0153, was retested as part of this study, due to an anomaly in the leak test performed previously.

The BFEs returned from the ISS were carefully unpacked, inspected, and photographed. The Nomex® screen covers did not contain any large filter cake, although some residual lint and other particulate material likely left over after vacuuming adhered to the underside of the cover, and between the pleats of the filter media. The Nomex® screen was removed from each BFE prior to pressure drop and efficiency testing, in order to obtain a tight seal between the inlet surface and test duct. If any clumps of loose debris (mainly lint) were found on the filter media, it was removed with tweezers. None of the filters were tested for active biological material content, as they were stored for over 10 years after return from the ISS, and prior testing of a returned filter showed relatively low active biological levels, i.e. in the range nominally measured for terrestrial labs and other indoor living spaces.[4]

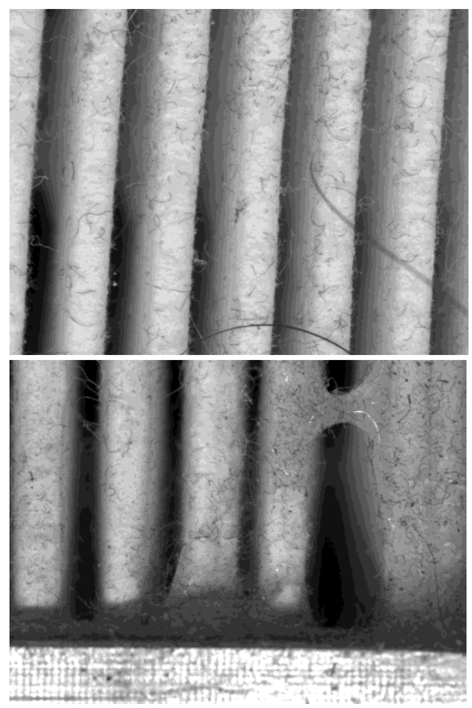
a)
b)

Figure 2. Images of the BFE S/N 0009 HEPA media. *The images cover an 18.4 mm × 12 mm area. a) Inlet pleat edges near middle of cross-section; b) Edge of inlet surface including aluminum frame and adhesive.*

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 2 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 in some areas but visible protrusions 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. There appeared to be concentrated accumulations of debris at edges of the inlet surface, possibly due to "tackiness" of the adhesive used to bond the media to the frame.

III. Results

Each of the BFE units was installed in the test setup described in Section II for overall efficiency and pressure drop measurements. 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.

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 articles. Number of significant digits recorded varied between test articles. *S/N 0153 was tested in Ref. 4 work but retested as part of this study.*

BFE TYPE	SERIAL NUMBER	TIME IN SERVICE	PRESSURE DROP		PENETRATION		NOTES
			Initial (Pa)	Tested (Pa)	Initial (%)	Tested (%)	
Returned	0148	911 days/2.5 yr	72.2	96.1	0.01	0.0104	Ref. [4]
Returned	0153	911 days/2.5 yr	74.7	95.3	0.01	0.0377	Ref. [4]*
EDU	XSR08	ground testing	67.0	77.2	0.03	0.0245	Ref. [4]
EDU	XSR09	ground testing	68.7	72.2	0.01	0.0058	Ref. [4]
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

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. Both the particulate efficiency and pressure drop measurements were made at 1980 L/minute (70 ft^3/minute). The aerosol concentration in the inlet stream concentration was typically in the range of 15-25 mg/L. The inlet concentration was reset to 100% on the photometer at the beginning of each penetration efficiency measurement.

A. Pressure Drop Measurements

The measurements of the pressure drop across all six returned units in this study, were in the range of 65.8-81.7 Pa (0.264-0.328 inches of H_2O); these pressure drop data are reported in Table 1 along with the initial pressure drop data measured by the manufacturer prior to delivery of the new BFEs to UTAS. 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 L/minute (66.7 ft^3/minute); at the end-of-life, the BFE pressure drop should not exceed 124 Pa (0.5 inches H_2O).[1] As reported in Table 1, all six returned BFEs, when new, had a pressure drop below the design specification, and still met the clean, unused specification after nearly one year of continuous use on ISS, and in general agrees with the pressure drop data on returned BFEs in Ref. 1 that lead to the decision to extend the replacement interval. It should be noted that Table 1 also contains the pressure drop data measured for two returned BFEs with 2.5 years of continuous use on ISS, that were reported on in Ref. 4. Both of these, S/N 0148 and S/N 0153, had a measured values of 96.1 Pa and 95.3 respectively, approximately 27% and 33% above their initial measured values. But these measured values are still approximately 25% below the 124 Pa pressure drop end-of-life design specification. It should be noted that S/N 0153, was retested as part of this study and the measured pressure drop is lower than what was reported in Ref. 4. The discrepancy is likely to being tested at a slightly different flow rate due to an improperly calibrated venturi meter.

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 six returned units, the penetration efficiencies were in the range of 0.0074-0.0142%, except for S/N 0010. These values were either at or slightly lower than the corresponding penetration efficiency data for the new unused filters measured by the BFE manufacturer. 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. For S/N 0010, the penetration efficiency was

0.0605%, significantly above the initial unused measured value of 0.03%. Despite this increase in penetration efficiency, the overall filtration efficiency, $E_T = 1 - P$, of 99.94% the returned S/N 0010 unit still meets the ISS design specification of 99.9% minimum.[9] But since the penetration efficiency did increase for this particular unit, it is a potential indication of a leak in the filter media and was subject to leak testing, discussed in the next section.

Table 2. Penetration data for first stage leak test. **S/N 0153 was tested in Ref. 4 work but retested as part of this study.*

BFE TYPE	SERIAL NUMBER	PENETRATION 1980 L/minute (%)	PENETRATION 396 L/minute (%)	NOTES
Returned	0148	0.0104	0.0079	Ref. [4]
Returned	0153	0.0377	0.0041	Ref. [4]*
EDU	XSR08	0.0245	———	Ref. [4]
EDU	XSR09	0.0058	———	Ref. [4]
Returned	0009	0.0142	0.0024	This study
Returned	0010	0.0605	0.1064	This study
Returned	0013	0.0074	0.0000	This study
Returned	0093	0.0088	0.0000	This study
Returned	XSR04	0.0137	0.0000	This study
Returned	XSR05	0.0126	0.0000	This study

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 at 20% of the design flow rate. The aerosol generator settings were kept the same for the lower flow rate, and as such, the challenge aerosol concentration in the inlet section increased and was typically in the range of 130-140 mg/L. 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, or first stage test, are shown in Table 2. One of the BFEs, S/N 0010 did not pass this first stage test, and in fact, the penetration efficiency actually slightly increased at the lower flow rate. Because S/N 0010 failed this first stage test, a manual scanning leak test was performed on it 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 photometer 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 is observed. During the scanning, we typically observed penetration readings in the 0.5-2% range. We observed readings in the 1-5% range in one area approximately 12 cm (4.7 inches) from one end of the frame. This measurement spike was repeatable with the photometer. After performing this scanning leak test, the BFE inlet and outlet surfaces were visually inspected. On the outlet side of the BFE, a small (1-2 mm) tear was visible in the same general location of the measurement spike (see Fig. 4). No visible compromise or blemish of the filter media was observed on the inlet side. This result is surprising, as the inlet side of the BFE is more susceptible to the ISS housekeeping activities mentioned earlier, and the outlet side of the BFE is protected by a more rigid, non-removable aluminum screen, as opposed to the flexible Nomex® screen on inlet side.

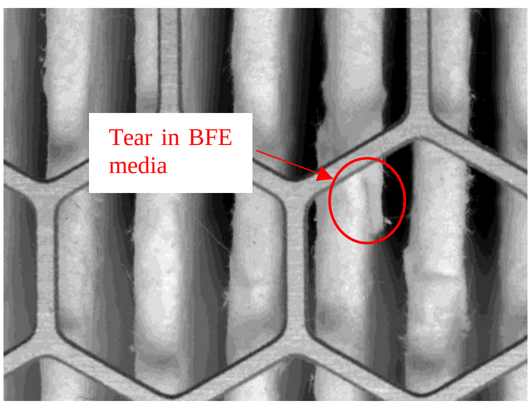

Figure 4. Image of the BFE S/N 0010 outlet side with tear in HEPA filter media. *The image cover an 18.4 mm × 12 mm area. Post-leak testing with photometer, visual inspection revealed a small tear in media (circled in red). Location is ~12 cm from one end of long edge and ~4.5 cm in from short edge of BFE. Rigid aluminum screen mentioned in text is also visible.*

Finally, it should be noted that S/N 0153, one of the returned BFEs reported in Ref. 4, was retested due to an incorrectly performed first stage leak test. The initial penetration efficiency was slightly lower than reported in Ref. 4, but at 0.0377%, still above the initial measured value of 0.01%. The first stage leak test showed a close to one order of magnitude lower value in measured penetration efficiency, but since a leak was detected in the previous test of this article, the second stage scanning leak test was performed, i.e. repeated. A leak was detected although the spike in the penetration reading was smaller than observed for S/N 0100, in the range of 0.05-0.06%. As reported in Ref. 4, a visual inspection did not find a blemish or compromise in the area of the detected leak.

IV. Conclusions

Presently, the ISS BFEs that provide the cabin atmospheric filtration function aboard the ISS have in-service life-times ranging between 2.5 years and 5 years depending on their location. In this work, we tested six BFEs that were returned from ISS after less than one year in continuous service, and have been in storage for 10+ years. Both penetration testing along with filter pressure drop measurements were performed on this set of filters.

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. One out of the six returned BFEs did exhibit an increase in penetration after less than one year of operation and was found to have a leak, detected both visibly and via an industry standard leak test. And, when summarized with the penetration efficiency data for returned BFEs in a previous work, determinted a leak in two BFEs of a total sample set of eight returned BFEs. There is a concern that degradation in efficiency of BFEs is occurring during operation in the ISS environment, but it is considered too premature to conclude in that (1) this is a small sample set of returned filters, and (2) these filters have been stored on ground for a considerable time after being returned from ISS, with degradation via several age-related mechanisms possibly occurring during this storage time.

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 filters, 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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