Technical Analysis of Filter Testing at the DOE Filter Test Facility

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ABSTRACT

High-Efficiency Particulate Air (HEPA) filters to be used by nuclear facilities of the U.S. Department of Energy (DOE) complex in some applications are first tested by the Filter Test Facility (FTF), as part of a safety program. The need for 100 percent quality assurance testing at FTF was examined with a statistical analysis using a database of test results from 2013 to 2020. Tests with large values of particle penetration were examined with extreme value distributions. The statistical analysis suggests that although some HEPA filters failed particle penetration tests, such does not necessarily imply those HEPA filters were defective. Truly defective filters can be identified from visual inspections. Nuclear facilities perform in-place leak tests which can also identify defective filters missed by visual inspections. It is concluded feasible to scale down particle penetration testing at the FTF without compromising safety at nuclear facilities. However, it is important to maintain visual inspections of sufficient rigor to detect defects and complement the manufacturers' quality control process.

INTRODUCTION

The U.S. Department of Energy (DOE) Filter Test Facility (FTF) serves as an intermediate facility between manufacturers of High-Efficiency Particulate Air (HEPA) filters and end-user nuclear facilities within the DOE complex, as part of a DOE safety program. The DOE technical standard DOE-STD-3020-2015 [1] requires verification testing at the FTF of HEPA filters to be installed in nuclear facility (Hazard Category 1, 2, 3, and radiological facilities) confinement ventilation systems, or to be installed in habitability systems (e.g., filters for protection of workers required to act for the control and mitigation of emergency situations). Filters needed by nuclear facilities are first sent to the FTF where they undergo visual inspections and resistance and penetration performance tests. Filters that pass FTF inspection and performance testing are shipped to end-user facilities; those that do not pass are rejected and returned to the manufacturer.

Independent quality assurance (QA) testing at the FTF arose from a need to avoid defective filters [2] and to ensure a high level of fitness for nuclear facilities [3, 4, 5, 6, 7]. The Nuclear Air Cleaning Handbook (DOE-HDBK-1169-2003) cites FTF rejection rates due to filter defects as high as 18.7% and as low as 1.6% in the historical record [6]. The Defense Nuclear Facilities Safety Board (DNFSB) noted two semiannual FTF reports covering fiscal year 2007 where rejection rates were 18.9% and 21.5%, higher than the 10-year historical average of 7%, thus justifying the DNFSB position that independent QA testing at the FTF is a necessary component of an overall program to ensure the quality of safety-related HEPA filters procured by DOE [8]. In practice, the DOE policy is 100 percent testing at the FTF of filters used in confinement ventilation systems, whether safety related, safety class, or non-safety related [9]. In other words, all filters for confinement ventilation systems are tested at the FTF regardless of their safety classification, as documented in a facility survey [9]. Sending all filters to the FTF has the practical benefit of eliminating additional analyses required to justify sampling testing [5]. It is highlighted that manufacturers test all supplied filters before shipping them to the FTF; the FTF duplicates visual inspections and performance testing of HEPA filters. The nuclear facilities perform further visual inspection and installation testing (in-place leak tests) of the FTF-approved filters.

The FTF publishes monthly summaries and semiannual summary statistics of filter test results at the DOE Organizational Excellence website [10]. The FTF collects filter test reports documenting detailed results from inspections and filter performance tests. The FTF provided test results from 2013 to August 2020 for this study. The objective of this study was to statistically examine those test results to evaluate the benefit of 100 percent HEPA filter verification testing at the FTF, especially considering overlapping testing by the manufacturers, the FTF, and the end-user nuclear facilities. Detailed results of the analysis are available in a comprehensive report published by the DOE Office of Scientific and Technical Information [11].

STATISTICAL ANALYSIS OF MONTHLY REPORT DATA

The FTF inspects the HEPA filters for manufacturing issues and for completeness and accuracy of documentation. If issues are detected by the inspection, those filters are returned to the manufacturer for replacement. Filters that pass the inspection are subjected to performance testing (particle penetration and airflow resistance). Approximately 20,000 filters were processed by the FTF from 2013 to August 2020. The distribution of filter rejections is presented in the bar chart in Figure 1. The dominant rejections under *label* correspond to documentation issues, such as missing or incorrect information (e.g., incorrect or missing specifications, wrong flow direction indication, missing test results by the manufacturer, and missing serial numbers). Having appropriate labels and documentation is important to ensure the correct HEPA filters are put in service.

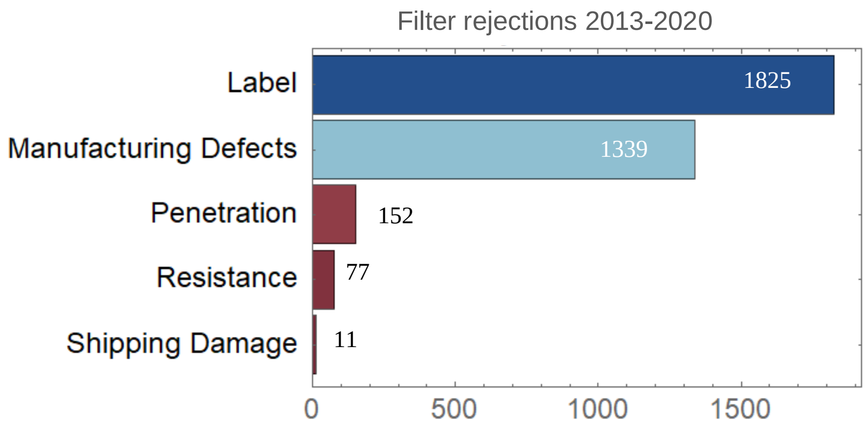


Figure 1. Distribution of filter rejections, in absolute numbers.

The second dominant cause of rejection are *manufacturing defects*, detected by visual inspections, and encompassing a broad range of defects. The total number of filters rejected from performance testing (particle penetration and flow resistance) was 229, which is 1.4% of the total number of filters tested in the period examined. Shipping damage was rare; only 11 filters were recorded as rejected due to shipping damage out of almost 20,000 filters processed by the FTF since 2013. Of those 11 filters, 4 were damaged in a single shipment (likely due to a common cause damage). Additional manipulations and handling associated with shipping to the FTF appear to not significantly compromise the HEPA filters.

Broad types of manufacturing defects are summarized in Figure 2. The dominant number of manufacturing defects are related to fluid seals, gaskets, out-of-square or out-of-geometry issues. The *workmanship* type is a general class including a range of defects (e.g., holes in frames and media, loose faceguards, missing bolts and nuts, separator damage, sharp edges, and splintered frames) and overlaps (without double counting) with other classes in Figure 2. The *separator* category is included in the monthly reports and in Figure 2; however, this category was not used by the FTF to classify defects. Instead, FTF recorded defects related to separators in the *workmanship* type.

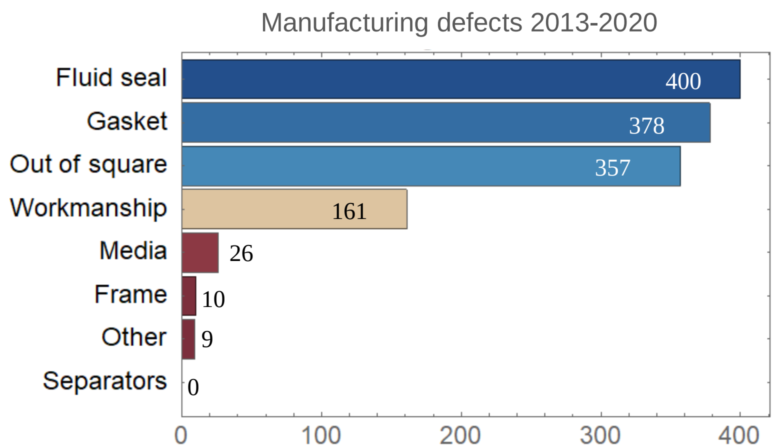


Figure 2. Types of manufacturing defects detected via inspections.

Rejection rates in percent are presented in Table 1**,** and compared to statistics in Table 8-1 of the Nuclear Air Cleaning Handbook [6]. The data show large differences in rejection rates associated with labels and manufacturing defects. By contrast, the rejection rates associated with particle penetration tests are comparable. Therefore, visual inspections implemented by the FTF or DOE nuclear facilities to identify labels and manufacturing defects, are an important addition to manufacturers' quality control programs.

The FTF rejects filters from performance testing (mainly particle penetration testing) at rates on the order of 1%, and this rate has remained relatively constant over time. Table 2 shows a comparison of rejection rates from particle penetration testing sorted by the number of supplied filters per manufacturer. The rejection rate from particle penetration testing is negatively correlated with airflow filter rating, which explains some differences in Table 2. Rates of rejection from particle penetration tests between manufacturers are similar when filters of similar airflow rating are compared (See Figure 3). As shown in Table 2, manufacturers having no rejections supplied only a small number of filters, and zero rejected filters is within expectation in those cases.

Figure 3 displays the particle penetration rejection rate versus airflow filter rating. The plot displays a five-element moving average of sequential airflow ratings and accounts for the number of tested filters. It shows that (i) rejection rates are similar when comparing filters of similar airflow rating, and (ii) rejection rates decrease with increasing airflow rating.

Table 1. Comparison of rejection rates from current data to data in Table 8-1 of the Nuclear Air Cleaning Handbook [6].

Rejection Rate	Current Data (%)	Table 8-1 of the Nuclear Air Cleaning Handbook (%)
Total[a]	17.20	7.10
Labels[a]	9.19	2.42
Manufacturing defects[a]	6.74 2016 – 2020: 2.54	1.25
Shipping[a]	0.06	0.14
Penetration + resistance[a]	1.16	3.45
Penetration[b]	0.91	1.35
Resistance[b]	0.46 2015 – 2020: 0.040	2.10 1998 – 2003: 0.013

[a] percent of the total number of received filters
[b] percent of the total number of tested filters

Table 2. Average rejection rates* from for the period 2013–2020 per manufacturer

Manufacturer	Supplied filters	Defects (%)[a]	Particle penetration testing (%)[b]	Flow resistance testing (%)[b]
A	14,236	6.07	1.08	0.64
B	3,579	9.28	0.64	0.06
C	1,367	9.95	0.36	0
D	508	0.98	0	0
E	61	0	0	0
F	37	0	0	0
G	30	6.67	0	0
H	30	0	3.33	0
I	12	0	0	0

[a] Percent of the total supplied HEPA filters
[b] Percent of the total tested HEPA filters
* The rejection rates were computed by adding the total number of rejections for the 2013–2020 period, divided by either the total number of supplied filters or the number of tested filters

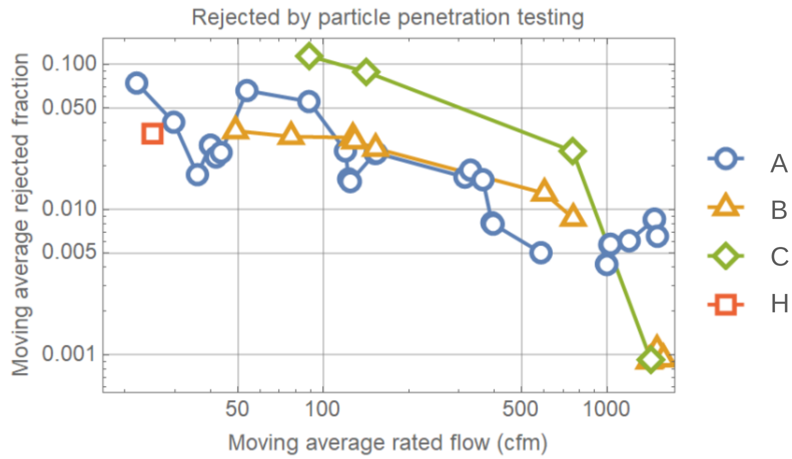


Figure 3. Moving average curves, rejection rates versus airflow rating, computed with five-element averages.

STATISTICAL ANALYSIS OF PENETRATION TEST RESULTS

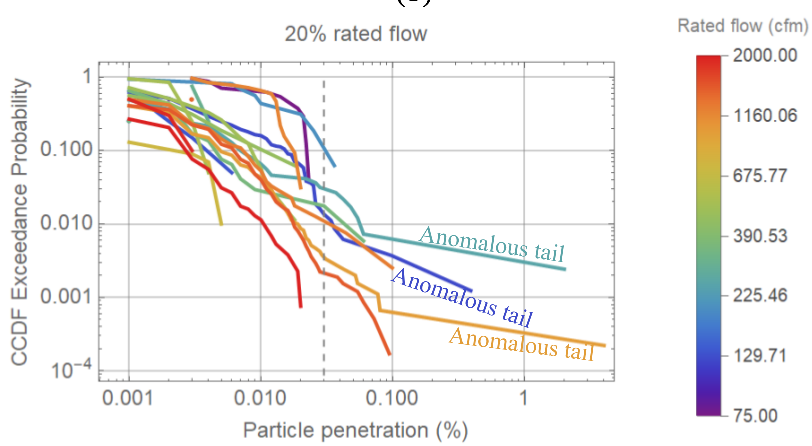
FTF testing occurs after similar tests by the manufacturers performed under ASME AG-1 FC-5000, standard HEPA filters, or FK-5000, special HEPA filters [12]. For filters passing visual inspections and with adequate documentation, the FTF performs particle penetration tests at 100% of the manufacturer rated airflow and 20% of the rated airflow for filters at a rating of 125 cfm or higher. The FTF also measures the resistance of filters at their rated airflow. It is intriguing that particle penetration testing by the FTF finds some filters not fit for service after they were tested by the manufacturer and found acceptable. The statistical analysis herein suggests that some tests could exceed particle penetration limits even though the filter is not defective.

The DOE technical standard DOE-STD-3025-2007 provides details on the particle penetration testing procedures, such as acceptable penetrometers, test aerosols, and information to be recorded from the particle penetration and airflow resistance measurements [13]. Appendix A of DOE-STD-3025-2007 defines a template for test information to be recorded, which is captured in the Air Techniques International (ATI) form number ATITL-010-FM. The form ATITL-010-FM records details such as testing conditions (e.g., temperature, ambient pressure, humidity), the rated flow, inspection results, and results of performance tests (e.g., flow resistance and percent of particle penetration). The FTF completes and prints the ATITL-010-FM forms, which are then scanned and archived in PDF files. PDF files containing the ATITL-010-FM forms were supplied for the present analysis. Information was extracted from PDF files from 2016 to 2020, through computer scripts and labor-intensive manual cleaning of records. A dataset with approximately 8,000 records of particle penetration and airflow resistance test results was assembled, which is a sample of sufficient size to be informative. Rejection rates predicted based on the small database considered in this section were compared to rejection rates from the FTF monthly summary reports, and were in excellent agreement.

The DOE standard DOE-STD-3020-2015 [1] refers to ASME AG-1 FC-4000 or FK-4000 [12] for acceptable particle penetration limits. ASME AG-1 FC-4210 and FC-5120 limits the total aerosol particle penetration through the filter medium, case, adhesive bond, and gasket to not exceed 0.03% for 0.3-µm particles at the rated airflow and to 20% of the rated airflow for HEPA filters rated at greater than or equal to 125 cubic feet per minute (cfm) [12]. Filters with penetration in exceedance of the 0.03% acceptance limit are rejected.

The extent of particle penetration in a test is a stochastic variable that may exceed the 0.03% limit for random reasons, not necessarily associated with manufacturing defects or other issues. Random variation in the filter medium (i.e., differences due to expected manufacturing variability) contribute to the extent of particle penetration, as well as aleatory particle trajectories in a test, and measurement uncertainty. Figure 4 displays complementary cumulative distribution functions (CCDF) of the extent of particle penetration of 20% and 100% airflow rating tests. Each single-color curve is associated with a specific filter airflow rating, independently of the manufacturer. The distribution tails extend as far as 6% penetration.

(b)



(c)

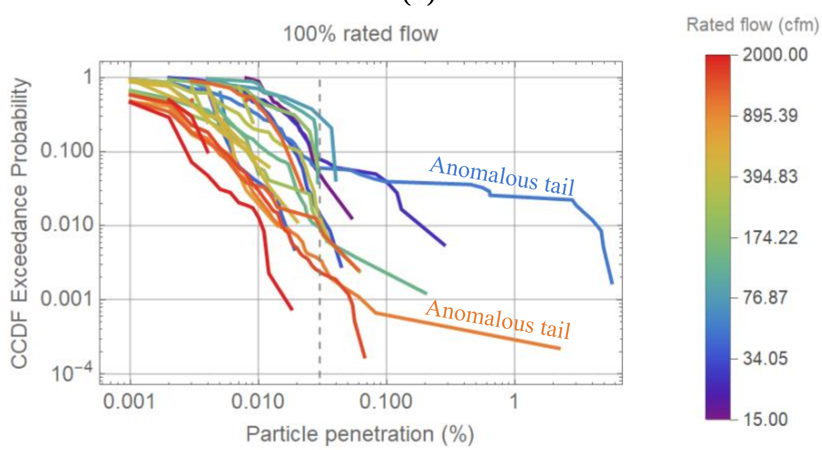


Figure 4. (a) Particle penetration exceedance probability curves from 20% flow rating tests, and (b) particle penetration exceedance probability curves from 100% flow rating tests.

The anomalous tails in Figure 4 arise from very few tests with high particle penetration, and visually start at particle penetrations exceeding 0.2%. When those anomalies are removed from the statistics, the distribution tails become regular extrapolations of trends by the bulk of the tests. Anomalies in the tails identify true outliers possibly associated with undetected or unrecorded manufacturing defects, measurement artefacts, or particle leakage. In Figure 4, the warm colored curves tend to lie below the cold colored curves. This indicates that more particles penetrate filters designed at low airflow rates than filter designed for higher airflow rates, which is consistent with the negative correlation in Figure 3.

To demonstrate that particle penetration tests exceeding 0.03% from time to time is a regular or expected result, an extreme value distribution analysis was executed. The premise is that distributions of "regular" random variables have tails that can be described by generalized extreme-value distribution (GEVD) functions. If tails are anomalies, then those tails are not describable by a GEVD (like the "anomalous tails" labeled in Figure 4). If regular random factors contribute to measurements of particle penetration, then a distribution of particle penetration test results should have a tail describable by a GEVD. It can therefore be inferred that exceeding the 0.03% penetration limit is a regular result from random variability, and not necessarily an indication of anomalies such as defects in a HEPA filter.

A brief definition of concepts for the use of extreme value distributions is provided; the reader is referred to other references for more detailed descriptions (e.g., [14]). The set $\{x_1, x_2, x_3, x_4, \ldots, x_n\}_j$ represents n measurements of the extent of particle penetration (i.e., n particle penetration tests by the FTF), with particle penetration percent denoted by the variable x. The subscript j represents a "block" or set of n measurements. The maximum of the block of measurements j is represented as M_{nj} (maximum penetration from a set of n measurements)

$$M_{nj} = \mathrm{Max}\{x_1, x_2, x_3, x_4, \ldots, x_n\}_j \tag{1}$$

If multiple maxima M_{nj} are selected from different n-size blocks, extreme value theory provides a distribution for the block-maximum values $\{z_j = M_{nj}\}$, in the limit when the sample size or block size n is large. Provided some regularity conditions of the underlying distribution (i.e., assuming that regular and concomitant random factors contribute to measurements) of the variable x, in the limit when the size n is large, the cumulative distribution of the set of block maxima $\{z_j = M_{nj}\}$ converges to the generalized extreme-value distribution (GEVD) independently of the underlying distribution describing the variable x [14]

$$G(z;\ \mu, \sigma, \xi) = \begin{cases} \exp\left\{-\left[1 + \xi\ \dfrac{z-\mu}{\sigma}\right]^{-1/\xi}\right\} \text{ if } (z-\mu)\xi > -\sigma \\ 1 \text{ if } z \geq \mu - \dfrac{\sigma}{\xi} \text{ and } \xi < 0 \\ 0 \text{ if } z \leq \mu - \dfrac{\sigma}{\xi} \text{ and } \xi > 0 \end{cases} \tag{2}$$

The parameter μ is the location, σ (>0) is the scale, and ξ is the shape parameter. As a practical approach the block size parameter n is selected with an arbitrary value. The parameters μ, σ, and ξ are selected so that the GEVD function $G(x; \mu,\sigma,\xi)$ fits the empirical CDF of the particle penetration, denoted as $F_e(x)$, raised to the power n; i.e.,

$$G(z;\ \mu,\sigma,\xi) = F_e(x)^n \tag{3}$$

The parameters μ, σ, and ξ are usually obtained as maximum likelihood parameters [14]. The empirical CDF function, F_e, on the right-hand side of Eq. (3) is derived from the different curves, for example, in Figure 4. Each curve in Figure 4 is a CCDF; the CCDF is related to the CDF as $CCDF = 1 - CDF$. The block size parameter n controls how proximal or accurate is the extreme value G function fit to the right tail of the particle penetration distribution. Larger and larger values of n would be selected to better approximate the distribution for higher and higher values of the particle penetration domain, but at the expense of the distribution becoming a poor approximation for lower values of the particle penetration domain. Also, larger values of n require more information (more measurements). As a rule of thumb, n may be selected on the order of 10% of the number of measurements. In this work, the value of the block size parameter was selected as n = 10, as a compromise to fit the upper end of the particle distribution domain, while the approximated distribution remained a reasonable fit for the complete domain. The following approach was implemented to determine the distribution parameters μ, σ, and ξ.

- Tests with particle penetration exceeding 0.2% were eliminated from the statistics (tests occurring with a frequency on the order of 1 in 1,000 of the tests).
- Moving statistics were computed with sets of 5 sequential filter airflow ratings.
- The block size parameter was set equal to 10, n = 10.
- For each 5-element group (sets of 5 sequential filter airflow ratings) particle penetration empirical CDF, F_e, the distribution parameters μ, σ, and ξ of the function G were simultaneously estimated with a maximum likelihood estimate algorithm to fit ${F_e}^n$.

Multiple values of the fitted parameters μ, σ, and ξ were found to correlate or trend with the filter airflow rating. The location parameter, μ (the variable f represents the average airflow filter rating, in units of cfm; the subscripts 20 or 100 represent the 20% or 100% rated flow testing) was approximated (from a curve fitting to μ versus f data from the individual fits) as

$$\begin{aligned} \mu_{20}(f) &= 0.062\ (1+f)^{-0.343} \\ \mu_{100}(f) &= 0.082\ (1+f)^{-0.372} \end{aligned} \tag{4}$$

The scale parameter, σ was approximated as

$$\begin{aligned} \sigma_{20}(f) &= 0.0176 - 0.002 \ln(1+f) \\ \sigma_{100}(f) &= 0.0153 - 0.00166 \ln(1+f) \end{aligned} \tag{5}$$

Finally, the shape parameter, ξ was approximated as

$$\xi_{20} = 0.413$$
$$\xi_{100} = 0.340 \tag{6}$$

The values of the shape parameter ξ were computed as simple averages of the multiple fits, as an approach to regularize the data. A closed-form equation *approximating* the CCDF,[1] based on the GEVD function G, is defined as

$$CCDF(x) = 1 - G(z;\ \mu, \sigma, \xi)^{\frac{1}{n}} \tag{7}$$

where the parameters μ, σ, ξ are approximated by Eqs. (4), (5) and (6). The complete sequence of steps to regularize distribution functions are visually summarized in Figure 5.

The starting step of the regularization process was removal of tests with particle penetration exceeding 0.2% [Figure 5(a)-(b), tests occurring with a frequency on the order of 1 in 1,000 of the tests], followed by the application of moving statistics [Figure 5(c)-(d)]. The GEVD was used to define a function approximating the particle penetration CCDF in the high particle penetration domain [Figure 5(e)-(f)], which output multiple values of μ, σ, ξ. Finally, equations defining the GEVD parameters, μ, σ, ξ as function of the average filter airflow rating [Eqs. (5), (6), and (7)] were used to compute the curves in Figure 5(g)-(h). Details are available in a comprehensive report [11].

The resulting closed-form approximation for the CCDF for the 20% and 100% rated flow tests are included in Eqs. (8) and (9), as function of the particle penetration, x, in percent and the airflow filter rating, f, in cfm units

$$CCDF_{20}(x,f) = 1 - e^{-\frac{1}{10}\left(1 + \frac{0.413\,\left[x - 0.0622\,(1+f)^{-0.343}\right]}{Abs[0.0176 - 0.002\ln(1+f)]}\right)^{-2.423}} \tag{8}$$

$$CCDF_{100}(x,f) = 1 - e^{-\frac{1}{10}\left(1 + \frac{0.340\,\left[x - 0.082\,(1+f)^{-0.372}\right]}{Abs[0.0153 - 0.00166\ln(1+f)]}\right)^{-2.943}} \tag{9}$$

The analysis demonstrated that distribution tails extrapolate trends delineated by the bulk of the distribution. In other words, distribution tails are regular (i.e., extensions of the bulk distribution). Factors related to manufacturing variation in filter media, uncertainty in equipment for penetration measurement, and random particle trajectories are possible persistent random components that produce regular particle penetration distribution tails. Anomalous tails, such as some exhibited in Figure 4, are not describable using extreme-value theory. Those tails may have been caused by anomalies and filter defects, not associated with through-paper particle penetration but possibly with leakage. In general, anomalous tails were removed by eliminating tests with particle penetration exceeding 0.2%. These anomalous tests occurred with a frequency on the order of 1 in 1,000 of the tests.

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[1] The approximation is designed to approximate the distribution in the domain of high particle penetration, ignoring the low particle penetration domain.

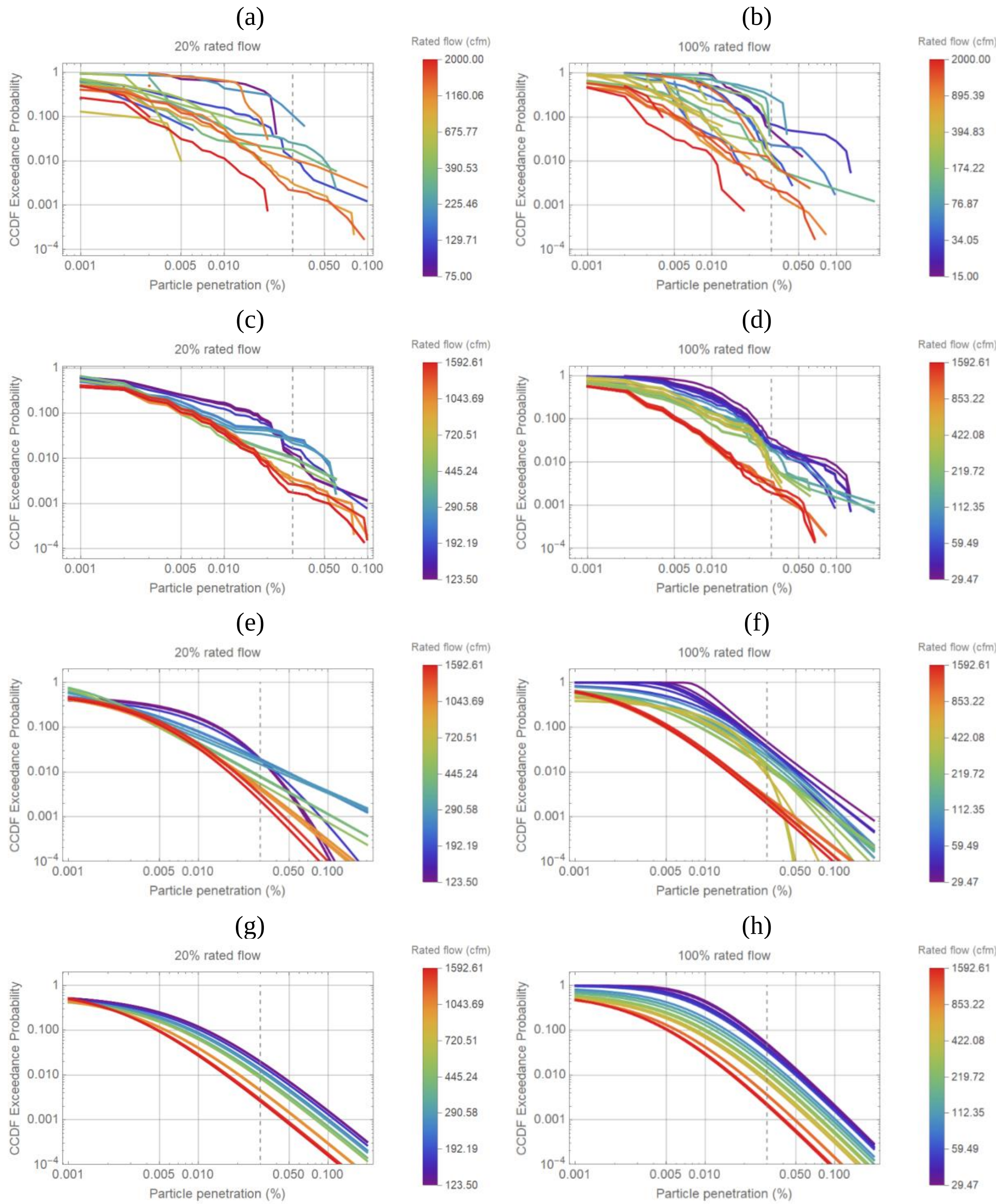

Figure 5. Data regularization approach. In (a)-(b) tests with particle penetrations exceeding 0.2% were removed. In (c)-(d), moving statistics were computed by grouping filters in sets of 5 sequential airflow ratings. In (e)-(f), GEVDs were fit to the data. In (g)-(h), parameters of the GEVD were computed as function of the average filter flow rating, using Eqs. (5), (6), and (7).

Equations (8) and (9) [plotted in Figure 5(g)-(h)] were used to estimate the expected rate of rejection. By substituting x=0.03 (0.03% maximum acceptable particle penetration) in Eqs. (8) and (9), the CCDF defines the expected rejection rate as a function of the filter airflow rating, f. Corresponding results are presented in Figure 6 and compared to data from the FTF monthly reports. The closed-form equations are consistent with the particle penetration testing rejection rates from 2013 to August 2020.

In summary, filters with particle penetration slightly above the acceptance limit of 0.03% penetration are not necessarily defective. Repeated testing of those filters is likely to yield measurements within the acceptance. Anecdotally, a representative from a manufacturer company indicated that rejected filters by the FTF are tested again by the manufacturer and often concluded to be acceptable. Those filters are later sold back to the nuclear facilities, and they are verified acceptable by subsequent particle penetration testing by the FTF. Such assertions were not investigated in this study, but if true they would be consistent with regular random factors contributing to individual measurements of particle penetration.

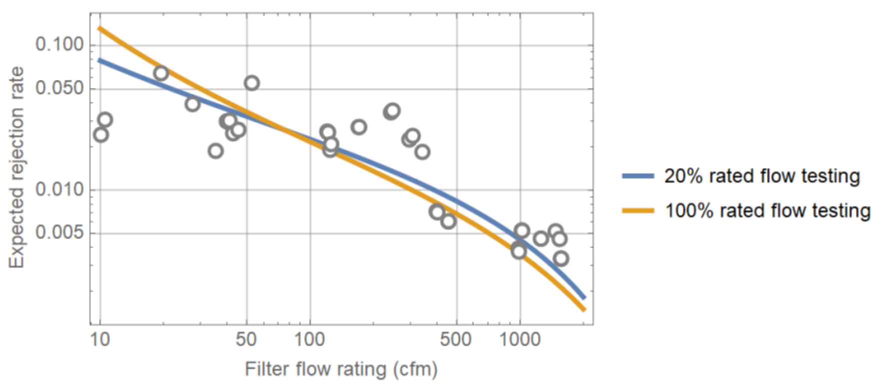

Figure 6. Comparison of estimated rejection rates [continuous curves computed with Eqs. (8) and (9)] to actual rejection rates from the period 2013 to August 2020.

DISCUSSION

The FTF rejects filters after performance testing (mainly particle penetration testing) at rates on the order of 1%. This rate has remained relatively constant over time and is independent of manufacturer. The statistical analysis in this work indicates that most filters are rejected due to slight exceedance of the acceptance criterion for particle penetration. The statistical behavior of performance testing results is consistent with the presence of regular random factors (e.g., measurement uncertainty, stochastic particle penetration) in tests by manufacturers and the FTF. Particle penetration (and the associated filter efficiency) is best described by distribution functions, which recognize uncertainty and stochastic variability of experimental tests, as well as a chance for tests to exceed acceptance limits for particle penetration. This work identified a negative correlation between the extent of particle penetration and the filter airflow rating (filters designed for lower airflow rate appear to allow more particle penetration and are rejected at higher rates). The negative correlation and the continuum distribution functions for particle penetration were used to predict rates of rejection as a function of the filter airflow rating, which was in excellent agreement with empirical rejection rates over the period 2013–2020.

Manufacturers experience similar rates of rejection from FTF particle penetration testing, provided that only filters of similar airflow rating are compared.

A recent survey by the DNFSB compiled technical safety requirements (TSRs) and credit adopted for HEPA filtration in documented safety assessments (DSA) of mitigated safety analyses [15]. TSR filtration efficiency ranged from 95% to 99.95%, and credit in DSAs from 95% to 99.9%. Nuclear facilities perform in-place leak tests to identify defective installation of HEPA filters or filter damage, for example due to shipping handling, paper and gasket damage during installation, inadequate pressure against intact gaskets, and housing penetrations [6]. In case of leaks, additional procedures are implemented to locate and correct those leaks at the nuclear facilities. In-place leak tests also are used to confirm the safety basis assumptions on HEPA filter system efficiency. Thus, in-place leak testing supports assumptions for removal efficiency adopted in DSAs [6].

In-place leak tests employ poly-dispersed test aerosols with particles of a range of diameters (ranging from 0.1 to 3 μm; 0.7 μm median diameter) [6, 12], which differs from particle penetration tests by manufacturers and the FTF performed with monodispersed test aerosols of 0.3-μm particle diameter. The particle diameter for penetration tests (0.3 μm) is theoretically selected to maximize particle penetration [6]. The Nuclear Air Cleaning Handbook recommends a minimum 99.95% minimum test leakage efficiency [6], which is consistent with the maximum filtration efficiency in TSRs surveyed by the DNFSB [15]. A common practice in DSAs is to include margin in filter efficiency to recognize HEPA filter performance uncertainty [15]. The surveyed HEPA filtration credit in DSAs [15] in general includes a level of margin with respect to the TSR value.

It appears feasible to reduce operations at the FTF, while still satisfying target TSRs by the nuclear facilities, without compromising safety. Different facilities have different tolerance for air cleaning, and some facilities with higher requirements for air cleaning and HEPA filtration efficiency may rely on multistage filtration systems. Visual inspections and required in-place leak testing after the installation of new filters can identify defective filters. Special consideration for independent testing may be required for facilities with higher filtration efficiency requirements and single stage filtration systems, and especially if the installed filters are designed for low airflow rates.

Most rejections after FTF particle penetration testing are associated with tests slightly exceeding the acceptable penetration limit (i.e., 0.03% particle penetration) which does not necessarily indicate defective filters. Those filters can be found acceptable after repeated particle penetration testing. If those filters were placed in service, they would not necessarily compromise technical safety specifications for air cleaning in confinement ventilation systems. For a small number of filters (on the order of 1 in 1,000 of the tested filters), tests at the FTF have reported anomalous particle penetration (exceeding 0.2%) that is not explainable as regular through-paper medium penetration. Those high penetration rates are likely associated with leakage, and therefore, detectable by in-place leak tests by the nuclear facilities. There is a concern that identifying defective filters at the in-place leak test stage can cause additional costs, because contaminated filters must be properly disposed as low-level waste. However, as concluded in the preceding section, truly defective filters not detected by the visual inspections and subjected to particle penetration testing are rare (on the order of 1 in 1,000 of the tested filters) and such may not correspond to a significant increase of rejected filters after in-place leak tests. It is recognized, however, that the actual proportion of filters rejected by nuclear facilities by in-place leak tests was not examined in this study.

CONCLUSIONS

In the examined database, filters were rejected at relatively high rates (i.e., on the order of 7%) by the FTF due to manufacturing defects identified by visual inspections. Such rejection rates suggest shortcomings in the quality control by some manufacturers. Therefore, independent visual inspections are a very important component of the DOE safety program and quality control process, complementing the quality control checks by the manufacturer. Particle penetration tests exceeding the 0.03% particle penetration limit are expected to occur from time to time (on the order of 1% of the tested filters, as shown in historical records). This is not, however, indicative of defective filters. Repeated testing may conclude those same filters are acceptable and fit for service. It is feasible to scale down particle penetration tests at the FTF without compromising the safety of the DOE nuclear facilities. Consideration could be given to continue testing filters rated for low airflow, as such filters appear to allow for more particle penetration. However, different facilities have different tolerance for air filtration and different strategies are available to reach target levels of air quality, such as multistage filtration systems. Visual inspections should identify the defective filters, without particle penetration tests. Defective filters potentially missed by the visual inspections would be identified by in-place leak tests at the nuclear facilities. Rejection rates from in-place leak tests would not necessarily be higher if particle penetration testing at the FTF was scaled down.

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