Pacific Northwest
NATIONAL LABORATORY

PNNL-31030

HEPA Filter Age Evaluation Report

March 2021

KR Schrank
JM Barnett
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary

In 2020, PNNL completed a literature search for high-efficiency particulate air (HEPA) filter age information. HEPA filters are used in many operations to remove particulate matter from effluent exhaust streams. They are thought to degrade over time both during proper storage and during normal operational service; however, the rate at which the filters degrade remains unknown. This brings into question if age is an adequate indicator of HEPA filter performance. Data from six previous reports were obtained from the literature search and combined to create a data set of 1600 operating filters. Filter usage was identified from multiple facilities. The various types of filters (e.g., axial flow, self-contained, and standard 24 x 24 x 11.5 inches; and both separator and separatorless) reported were constructed to the requirements Section FC (HEPA Filters) or Section FK (Special HEPA Filters) of the American Society of Mechanical Engineers AG-1 code. Filters were presumed to have continuously met the operational criteria and in particular passed both annual efficiency tests and annual DP measurements. The environmental conditions within the exhaust system were also assumed adequate for long-term filter operation. The data, by the nature of the reports, excludes rejected filters from quality assurance evaluations, intake, or installation testing. The collective data set shows over half of were operating past the current 10-year Department of Energy (DOE) limit. Data was evaluated for age lifetime using a linear trendline, survival function, probability functions, and failure rate; financial impacts were also addressed. This report supports the notion that HEPA filters can operate safely and efficiently under proper maintenance well past the 10-year lifetime established by DOE. Using the results of the four age evaluation approaches, they collectively point to the reasonableness of an operating HEPA filter lifetime of 20 years. The results are not necessarily definitive, but nevertheless, they are promising. The analysis provides reasonable assurance that when implemented using a graded approach with well-defined performance and operational requirements, extending the service life for HEPA filters beyond 10 years is low risk.

Acronyms and Abbreviations

DOE	U.S. Department of Energy
DP	differential pressure
HEPA	high-efficiency particulate air (filter)
LCL	lower confidence limit
PNNL	Pacific Northwest National Laboratory
WDOH	Washington State Department of Health

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1.0 Introduction

High-efficiency particulate air (HEPA) filters are used in many operations to remove particulate matter from effluent exhaust streams. At the Pacific Northwest National Laboratory (PNNL), HEPA filters are mainly employed in nuclear facilities to remove exhausted radiological particulate matter. Beginning in 2010, PNNL was required by the Washington State Department of Health (WDOH) to change out HEPA filters 10 years after the manufacture date of the filter. The WDOH referenced the Nuclear Air Cleaning Handbook, DOE-HDBK-1169-2003 (DOE 2003) as the basis for the requirement. Presently, the U.S Department of Energy (DOE) is in the process of updating the 2003 handbook into two parts consisting of a standard and a supplemental handbook. In 2019 after the WDOH reviewed PNNL's interim reports regarding HEPA filters, they extended the change-out rate up to every 15 years based on the PNNL graded approach and HEPA filter management program. HEPA filters are thought to degrade over time both during proper storage and during normal operational service; however, the rate at which the filters degrade remains unknown. This brings into question if age is an adequate indicator of HEPA filter performance. PNNL released a technical report on a 10-year HEPA filter lifetime study originally looking at 49 filters over a decade and subsequently expanded the study to the entire PNNL campus inventory of 651 HEPA filters (Schrank et al. 2020). Over the 10-year study period, a 4.3% failure rate (i.e., the total number of HEPA filers replaced over the 10-year period divided by the total number of HEPA filters in use during the last year of the study) was observed. However, the average annualized HEPA filter failure rate was only 0.5152% with a range from 0 to 2.0% during the 10-years of the study. PNNL recommends a graded approach for determining filter replacement (for dry-use filters up to 15 years) that was approved by WDOH in 2019.

PNNL has created a program for performance and operational requirements that uses a graded approach. The graded approach sets parameters that are established for testing the ability of filters to remove particulates from the exhaust system. Routine testing of filter performance is done through preventative maintenance work. Because the work is included in preventative maintenance schedules, testing may vary from annually to quarterly or whatever frequency is best suited for the facility based on best judgement of professional staff. Examples for which a regulated HEPA filter would need to be changed out early include:

- Temperature (<50°F or >100°F), a building-wide range
- Humidity (<10% or >80%), a building-wide range; or wetted filter
- Efficiency tests (<99.90%)
- Differential pressure (DP), or associated high mass loading, (>4 inches water gauge)
- Maintain fume hood velocity (<100 feet per minute)
- Radiation dose (Exceeds the "Radiation Area" level of 0.005 mrem in 1 hour at 30 cm)
- Flowrate through HEPA filter exceeds the rated flow of the filter (1000 cfm, 1500 cfm, etc.)
- Factory recall
- Other special conditions (e.g., perchloric acid hood operations).

Data from six previous reports were combined to create a data set of 1600 operating filters: 1) Fretthold and Stithem (1997), 2) Khabir (2017), 3) Kriskovich (2002), 4) PNNL (2013),[1] 5) PNNL (2014),[2] and 6) Wilson et al. (2018). The various types of filters (e.g., axial flow, self-contained, and standard 24 x 24 x 11.5 inches; and both separator and separatorless) reported were constructed to the requirements Section FC (HEPA Filters) or Section FK (Special HEPA Filters) of the American Society of Mechanical Engineers AG-1 code (ASME 2020). Filter usage was identified from the Hanford Site, the Electric Power and Research Institute, the Filter Test Facility at Air Techniques International, Rocky Flats Environmental Technology Site, and PNNL. Filter manufacturer information was not addressed. The data, by the nature of the reports, excludes rejected filters from quality assurance evaluations, intake, or installation testing.

Operating filters were presumed to have met the aforementioned criteria and in particular have a passing value for both annual efficiency tests and annual DP tests. We assumed that the environmental conditions within the exhaust system are adequate for long-term filter operation. Similarly, data are extrapolated from the Schrank et al. (2020) report to estimate the likelihood of a filter reaching 15 years and 20 years, or more. The purpose of this report is to support the notion that HEPA filters can operate safely and efficiently under proper maintenance well past the 10-year lifetime established by DOE (2003).

[1] Pacific Northwest National Laboratory (PNNL). 2013. *System Assessment RPL Primary HEPA Filter Age Assessment*. OPSA-MECH-006-2013 Pacific Northwest National Laboratory, Richland, Washington. (unpublished, internal only)

[2] Pacific Northwest National Laboratory (PNNL). 2014. *System Assessment 331 HEPA Filter Age Assessment*. OPSA-MECH-001-331, R0, Pacific Northwest National Laboratory, Richland, Washington. (unpublished, internal only)

2.0 Methods

In 2020, PNNL completed a literature search for HEPA filter age information. The initial search initially involved reviewing HEPA filter records for the last 20 years, but we later extended the search to 40 years to encompass a larger set of data. Note that the Military Standards of the 1980s were incorporated into the AG-1 verbatim as stated in the 2003 Nuclear Air Cleaning Handbook. This incorporation means current HEPA construction is similar to filters manufactured 40 years ago. Filters are essentially a fiberglass/glass fiber construction with various housing components. According to the records, all the filters were operational, passing both annual efficiency and DP tests. The collective data consists of 1600 HEPA filters; over half of which were operating past the current 10-year DOE limit (DOE 2003).

When determining an age of a filter, the date of manufacture was used to establish the beginning of the HEPA filter life. The end date used in this study may vary and is based on one of the following conditions: inventory assessment reports, dates associated with filter removal, and dates of research activities conducted on a filter (functional filter pulled from service for an arbitrary reason). In some cases, the end date could be a combination of two or more of the conditions noted. In this paper, age is based on the difference between the date of manufacture and the identified end date as determined in each report. Age is reported in years. Filters less than one year old have an age of zero years.

The environmental conditions inside the exhaust system are assumed to meet the best-practice operational preventive maintenance (normal) program requirements at the time. Variables such as temperature, relative humidity, and flowrate of the exhaust system are considered environmental conditions that would typically meet the graded approach parameters identified during normal operations. The environmental conditions of the exhaust system are essential for long-term HEPA filter service. If the conditions are not in accordance with listed programmatic requirements, HEPA filter performance will degrade and service life is expected to decrease. Therefore, the collective data set contains only operational filters that are presumed to meet the functional requirements except for the recently mandated 10-year age limit.

During the 2013 to 2014 time frame, PNNL collected filter ages for installed and operational HEPA filters at two facilities. Additional operating HEPA filter ages were gleaned from technical reports found during the literature search. In some cases, the estimated filter age was used as reported in the original technical report, and in other cases it was based on the data provided within the report. In the reports some of the ages of the filters were also given in a range (i.e., 5-15 years old, 10-15 years old, >25 years old); in these cases, the youngest estimated age was always used to keep a conservative approach. For example, if a filter was listed at >25 years old, the age selected was 25 years old although the filters could have been older. For the collective data set, data from Fretthold and Stithem (1997), Khabir (2017), Kriskovich (2002), PNNL (2013),[1] PNNL (2014),[2] and Wilson et al. (2018) were used. Once the filter ages were accumulated, the data were compiled in Table 1 which includes a reference column to indicate which report was the source of the information.

Table 1. Collection of HEPA Filters

Age	Number of Filters	Source[a] – Number of Filters
0	1	B-1
1	26	B-5, D-18, G-3
2	12	B-2, D-6, G-4
3	61	B-8, C-21, D-25, F-1, G-6
4	171	B-149, C-12, D-7, F-3
5	56	A-4, B-3, C-9, D-17, F-22, G-1
6	32	B-5, C-20, D-3, F-1, G-3
7	88	B-4, C-1, D-55, F-6, G-22
8	212	A-12, B-13, C-10, D-1, E-156, F-4, G-16
9	28	A-1, B-6, C-2, D-4, F-6, G-9
10	84	A-3, B-36, C-18, D-14, F-9, G-4
11	72	A-4, B-14, C-2, D-32, F-6, G-14
12	37	B-11, C-1, D-16, F-3, G-6
13	51	A-5, B-29, D-1, F-3, G-13
14	160	A-7, B-114, C-1, D-3, F-8, G-26
15	34	A-7, B-2, F-16, G-9
16	23	B-5, D-9, G-9
17	33	A-1, B-27, C-1, F-2, G-2
18	164	A-1, B-142, D-21
19	8	B-8
20	102	B-88, D-5, F-8, G-1
21	7	A-1, D-1, F-4, G-1
22	20	B-18, D-2
23	8	D-1, F-1, G-6
24	9	B-4, D-3, F-1, G-1
25	41	A-2, B-24, D-3, G-3
26	19	D-19
27	6	B-3, C-1, D-2
28	5	B-5
29	4	B-4
30	12	B-2, F-10
31	2	B-2
32	1	B-1
34	3	B-2, D-1
35	4	A-2, D-2
37	1	D-1
41	1	D-1
44	2	A-2
0-10	771	A-20, B-232, C-93, D-150, E-156, F-52, G-68
11-20	684	A-25, B-441, C-5, D-87, F-46, G-80
21–44	145	A-7, B-65, C-1, D-45, F-16, G-11

[a] The lettered references are associated as follows:

A- Wilson et al. (2018)
B- Khabir (2017)
C- PNNL (2014)[2]
D- PNNL (2013)[1]
E- PNNL (2013)[1]
F- Kriskovich (2002), and
G- Fretthold and Stithem (1997).

The data were evaluated first by fitting a linear trendline (Eq. 1).

$$y = mx + b \quad (1)$$

where:

y = Age of filters, years

m = Slope

x = Number of filters, unitless

b = y-intercept (maximum nominal operating lifetime), years.

Second, we assessed the survival function of the HEPA filters. The survival function is an estimate of life expectancy; it is similar in application to current age-specific mortality rates calculated with life table methods that are among the oldest and most fundamental tools of demography. In this case, we determined the cohort mean lifetime from the distribution of lifetimes for the 1600 HEPA filters in the group where the given time period begins at the date of manufacture for any given time period. The survival function (Eq. 2), then, gives the proportion of HEPA filers that survive to exact age 'a.'

$$l(a), a \geq 0 \quad (2)$$

where:

$l(a)$ = Survival function

a = Age, years.

The survival function is nonincreasing, with $l(0)$ = 1.0 and $l(\omega)$ = 0 for some advanced (e.g., maximum) age, ω (Bongaarts and Feeney 2003).

The third approach involved the use of the binomial and Weibull probability functions. The first step to this approach was to employ a binomial probability distribution to obtain a confidence-based estimate for the overall success rate (i.e., the proportion of filters that have an effective service life greater than 10 years). The overall success rate was estimated using a 95% lower confidence limit (LCL) on the success rate. The LCL is the lower bound on the estimated range of the success rate; using the lower end of the confidence interval keeps the approach conservative. We used the binomial probability distribution and the Clopper-Pearson approach to estimate the LCL on the overall survival rate. After this analysis was completed, a Weibull distribution (intended to represent the 10-year study data) was also generated. The Weibull distribution was used to estimate the probability that a randomly selected filter would survive 15 or 20-years of operation. Weibull probability functions often are used to model life expectancy or time to failure.

The fourth approach included using the failure rates reported in Shrank et al. (2020). The failure rate over time is a key piece of information missing in the combined data set of HEPA filters. Also, the combined data set does not consider filters that may have failed prior to the age evaluation in this study. The information required to calculate a failure rate for the 1600 filters from the literature survey is not available. Thus, a specific overall failure rate has yet to be established. Nevertheless, the Schrank et al. (2020) report on a 10-year study that tracked the replacement rate of 651 filters (operating within nuclear facilities) determined a 10-year replacement rate of 0.043. That is, 28 of the 651 filters tested did not meet at least one of the graded approach criteria listed above after a decade, for an observed failure rate of 4.3%. The average annual failure rate also is known in this study and is reported as 0.5152%. The decadal failure rate matches the current regulatory time limit. Based on the results from the 10-year study, 623 of the 651 filters tested met all performance requirements after 10 years of service, for an observed success rate of 95.7%. The reported failure rate values were used in conjunction with this data set of 1600 HEPA filter to make some age-based estimates on overall HEPA filter operational life. All of the historic filters were operating at the time of age determination and filter removal. Filter removal information (i.e., when the filter was taken out of service) was not archived. The experimentally determined failure rates of 0.043 over 10-years and 0.005152 over 1-year are used with this data set as the best failure rates available.

Finally, a cost savings estimate is included in this HEPA filter age evaluation. Extending the operating lifetime of a HEPA filter past 10 years results in overall programmatic cost savings. For nuclear facilities, these costs may be significant.

3.0 Results

The six reports combined make up a data set of 1600 operational HEPA filters as shown in Table 1. Of the 1600 HEPA filters identified in Table 1, 829 had been in service for more than 11 years. Of the operational filters in this data set, 52% surpassed the DOE 10-year change out requirement (DOE 2003). As stated previously, operational filters are deemed good if they pass the required operating requirements. The average life of filters in the data set is 12 years. This data set has a large range, starting with a filter that is brand new and less than 1 year old having an age of 0, extending to filters that are 44 years old. With three filters still fully operational after 40 years, some questions must be raised as to whether HEPA filter age and tensile strength have any relevant correlation. Tensile strength is the subject of a separate study currently being conducted; it is not addressed in this report.

The current 10-year limit is based partly on an expected weakening in HEPA filter tensile strength over time. Yet, when looking at the collective data in Table 1 and the data histogram in Figure 1, 43% of the operating filters are between the ages of 11 and 20 years old. Forty-eight percent of the data is from filters between the ages 0 and 10 years old. While the remaining 9% are 21 years and older, and with such a large percentage of the historical filters operating past the first decade after the currently recommended change out, the operational life for a HEPA filter may be reconsidered. This supports the graded approach concept that HEPA filters can operate safely after the present 10-year lifetime standard (DOE 2003).

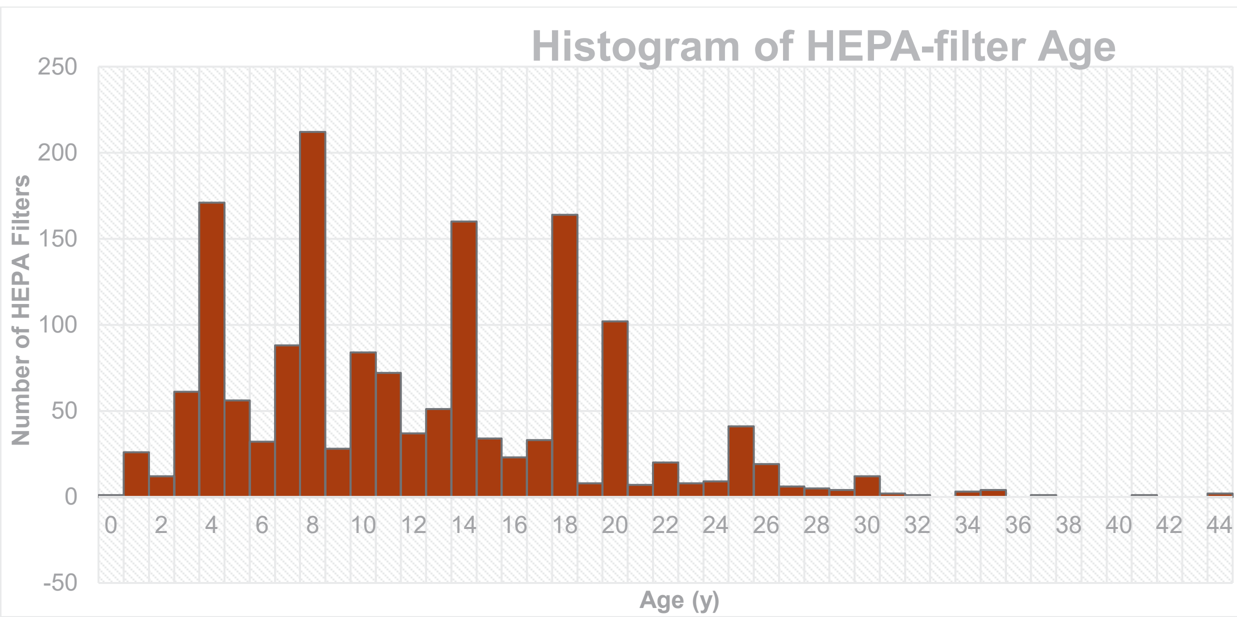

Figure 1. Histogram of the 1600 HEPA Filter Ages. The horizontal axis is age in years and the vertical axis is number of filters.

Proper environmental conditions within the HVAC system are essential for supporting long-term operating lives for HEPA filters. Controlled variables such as temperature, humidity, and flowrate are essential to the filter integrity, if not properly managed, HEPA filters are expected to be replaced (i.e., fail) at increased rates. An example can be found in the Schrank et al. (2020), when a door was left open to help combat an air balance issue inside the building. By leaving the doors open to the outside environment, dirt and dust particulates flowed into the building and HVAC system. During this same 1-year interval, 7 HEPA filters out of the 26 deployed in this building failed their DP tests. In situations such as this, HEPA filter age has nothing to do with the performance of the filter. Managing the conditions in which the filter operates is just as important, if not more, than the age of the filters. The environmental conditions will vary due to several factors such as: age of ventilation systems, the performance of the ventilation systems and the operational control of the ventilation systems. Poor environmental conditions will decrease the life of filters whereas proper building operations can increase the life expectancy having the potential to save millions of dollars in operations costs. Use of a graded approach takes into consideration these environmental conditions thus enabling facilities with proper HVAC controls to operate specific filters for a longer duration of time.

As mentioned previously, the DOE has put a maximum life of 10-years on HEPA filters (DOE 2003) and references Bergman (1999). The collective data in the Bergman (1999) report suggests that unfolded HEPA filter media tensile strength fails at 13 years. Yet, the collective data of 1600 functioning filters shows that HEPA filter operational life varies filter to filter. The mechanical tensile strength may not be the primary determinate of HEPA filters useful life (Fretthold and Stithim [1997], Johnson [1988], Ricketts [2010]).

3.1 Linear Trendline

The ages of the 1600 filters of the combined data set cover a large range, starting with a brand-new filter that is less than 1 year old and extending out to filters that are 44 years old. All the filters (including the oldest) in this data set were documented as operational at the time. Although we acknowledge the data set does not give any information on the rate of failure or rate of replacement, all 1600 filters were fully operational and still effectively removing particulates from the exhaust systems. The 1600 filters were all monitored by an effective preventive maintenance program. To evaluate the data, we started by plotting the data in a bar graph, Figure 2, and applying a trendline to obtain an intercept of 23.7 years. Hence, the maximum service life could be set at 44 years and a maximum nominal operating lifetime of 23.7 years could be set based on the data intercept. This approach infers that filter age, in this plot (Figure 2), represents filter lifetime.

Ages of the 1600 HEPA filters were plotted (Figure 2) and used to determine a linear fit that might be used to describe effective filter life. The x-axis in Figure 2 is just the index of filters, 1:1600; and the y-axis is the current age of the filters. The plot without the trendline (Eq. 3) is just a descriptive plot of the filter ages arranged in decreasing order with respect to age. The regression line from the linear fit provides a way to estimate effective filter life for filters in a hypothetical population of filters represented by the ages of sample of 1600 filters in the combined data set. For example, for x = 100, the corresponding y value would be $-0.0145(100) + 23.656 = 22.206$ years. The position of x = 100 among the 1600 values in the combined data set would correspond to 100/1600=0.0625, or the 6.25th percentile. Thus, we might expect 6.25% of the filters in the population to last 22.2 years or longer. Similarly, the y-intercept could be taken as the age of filter number zero, which could be roughly interpreted as the maximum nominal operating lifetime for the population.

$$y = -0.0145x + 23.656 \tag{3}$$

Note, this linear fit does not help for trying to predict the age of a new data point, such as filter number 1601. That is, if we consider a new filter for which operational data becomes available, we would not expect its age to be $-0.0145(1601) + 23.656 = 0.4415$ years.

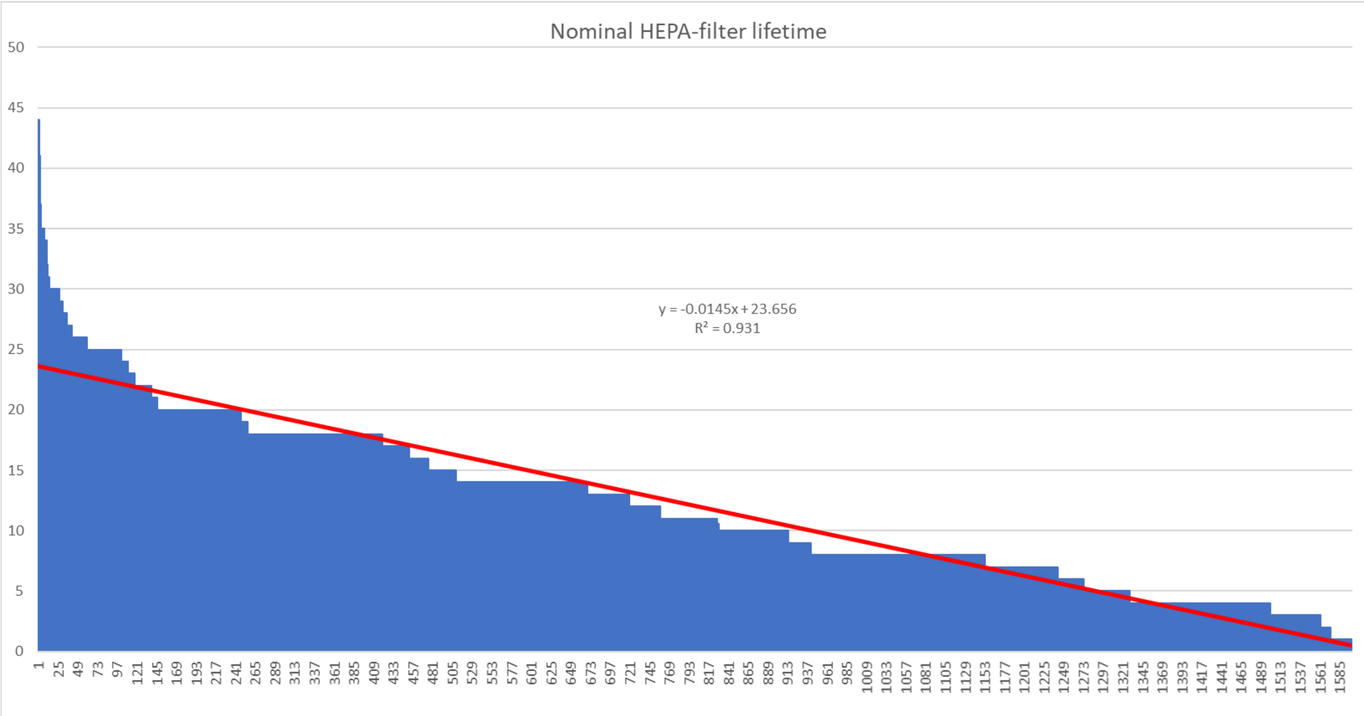

Figure 2. Horizontal Bar Chart of the Filter Lifetime vs. Number of Filters in the Historic Datasets

Note also that this use of a linear fit to estimate effective filter life is quite simplistic and is not ideal. It is not derived from actual time-to-failure data; instead, the 1600 filters in the combined data set are described by their respective years of operation (age). They were all still operational at the time the data were collected (i.e., none had failed). Still, the approach does illustrate how effective filter life might look based on what we know about the 1600 filters in the combined data set. While the linear fit is not as meaningful as desired, data from the 1600 HEPA filters, once plotted (Figure 2), can yield the equation of the trendline (Eq. 3) to provide a y-intercept (the place at which the trendline crosses the y [age] axis). In this case, where the trendline crosses the y-axis is the estimated HEPA filter maximum nominal operating lifetime based on this data set. Other methods could also be used to produce estimates of effective filter life. For example, the maximum effective filter life for the hypothetical population could be estimated using the maximum age of the 1600 filters in the combined data set (the maximum age was 44 years).

Although no predications as to how long the filters operate can be made from Figure 2, it displays the range of operation for these 1600 HEPA filters. For the 1600 filters, 48% are 10 years old and younger, 45% are between the ages 11 to 23 years old, and the other 7% are 24 to 44 years old. These results are similar to the those of the survival function.

3.2 Survival Function

Normalized survival functions are typically used on census data to estimate the age span of a population. The formula requires an input of maximum age possible (ω). For people, this is usually 100 years, and we used 50 years for the in-service filters in this analysis. Institutions may view 50 years as an impractical service life for any scheduled maintenance program. The computed results are much closer to 30 years as a maximum lifetime but could just as easily have been set at 44 years.

The 1600 HEPA filter lifetimes were plotted to obtain a normalized survival function (Figure 3). The survival function shows there are 913/1600 filters (or about 57.1%) 10 years old and older, 247/1600 filters (or about 15.4%) 20 years old and older, and 110/1600 filters (or about 6.9%) 24 years old and older. The survival function shows 6.9% of HEPA filters last longer than 23 years, and correlates with the presumed maximum nominal operating lifetime, based on the intercept (Figure 2), of 23.7 years. Hence, the large portion of operational filters at or beyond the 10-year change-out standard (greater than 57%) suggests the current restriction may prematurely replace filters. Both the linear estimate and lifetime analysis (using the survival function) indicate that filters may be in service for twice the currently allowed time. If the operating age limit were set at 20 years (say, based on the survival function, [Figure 3]), then there could feasibly be a window after the 20th year to change out a filter after 21–23 years provided the program plan were to allow such operations.

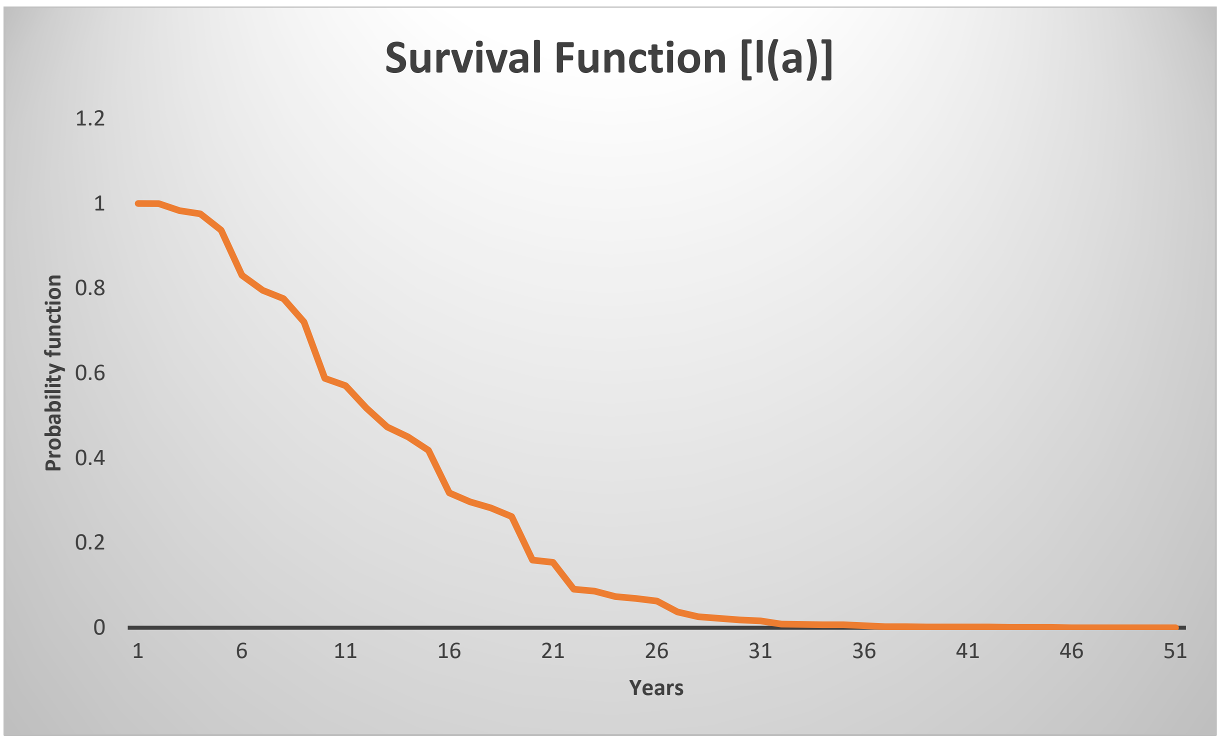

Figure 3. Normalized Survival Function of the 1600 Operating HEPA Filters

3.3 Probability Functions

To get a confidence-based estimate for the overall success rate from the Schrank et al. (2020) report, we used a binomial probability distribution to estimate the LCL on the success rate. This was obtained using the 10-year study data because the failure rate was documented. The LCL is the lower bound of the 95% confidence range on the estimated success (survival) rate, taking the lower end of the confidence interval keeps the approach conservative. The 10-year test data (623 filters passed out of 651 tested) resulted in a 95% LCL of 0.9415 (slightly lower than the observed success rate of 623/651 = 0.957). Therefore, with 95% confidence the overall filter success rate is estimated to be at least 94.15% (10-year survival).

After calculating the LCL we generated a Weibull distribution representing filter service life that had approximately a 94% probability that a randomly selected filter would make it to, or beyond, the 10-year mark. A plot of this Weibull distribution is shown in Figure 4. Based on this distribution, the probability that a randomly selected filter would last at least 15-years is approximately 89.4%, and for 20-years that probability is approximately 84.2%, which clearly shows that filters can potentially perform past the 10-year change out standard. Note that there are other Weibull distributions that could be generated that would have 94% probability beyond the 10-year mark. Other such distributions would have somewhat different shapes, and thus somewhat different probabilities associated with filter service lives beyond the 15-year and 20-year marks. Still, the example distribution provides some insight into potential filter life expectancy given the results from the 10-year testing. This re-examination of the 10-year test data supports the long functional life of filters in the historic records.

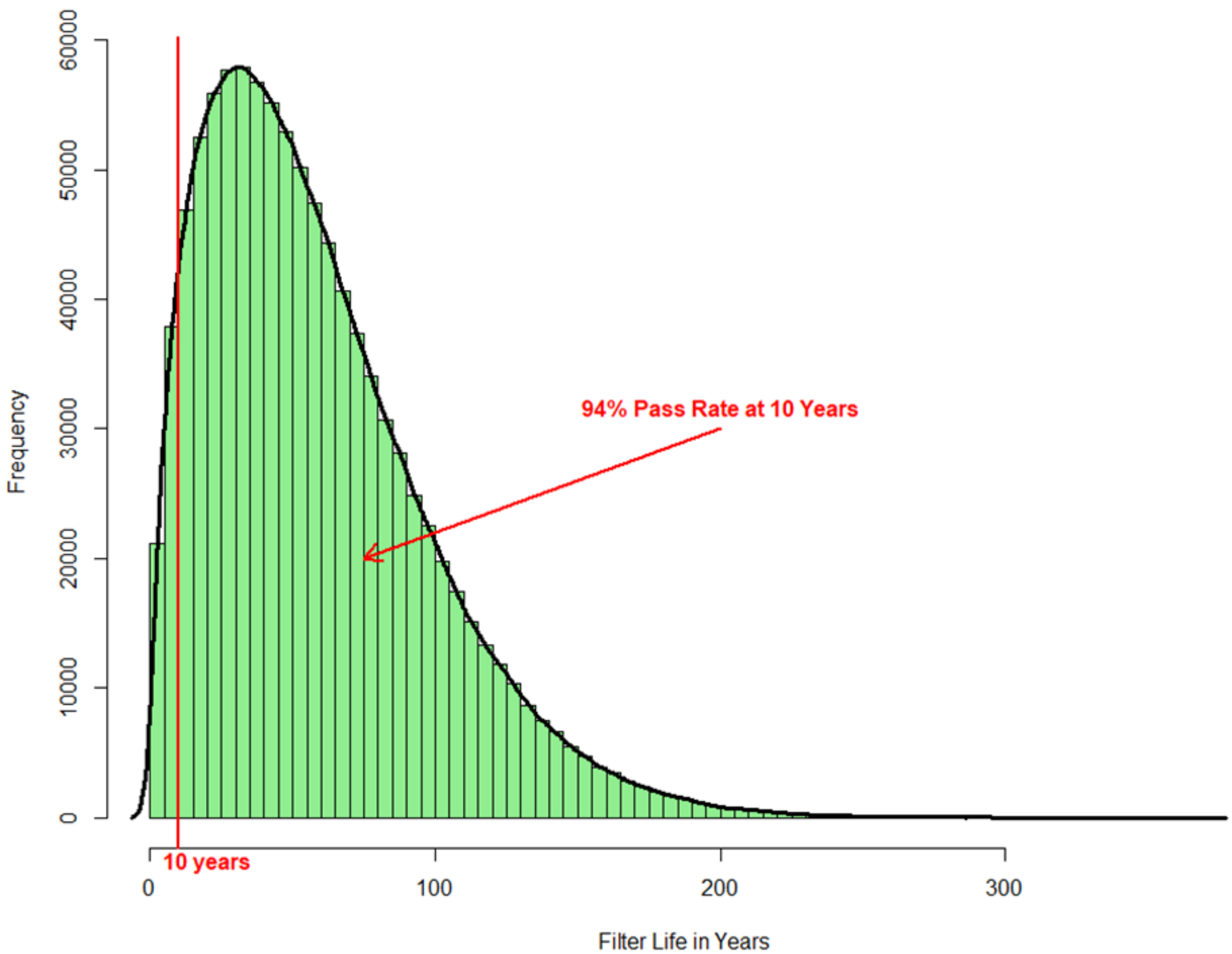

Figure 4. Weibull Distribution Depicting the 10-Year Study Using the Measured 4.3% Failure Rate at the End of the Study

3.4 Failure Rate

In the collective set of 1600 HEPA filters, the key variable missing is a specific HEPA filter failure rate. The Schrank et al. (2020) report does not give a specific cause of failure, but case-by-case replacement causes are noted. To make educated estimates as to how long HEPA filters can operate, the recently determined failure rates by Schrank et al. (2020) are is used in conjunction with this historic data to make a best effort predication with the data available. The failure rates are used to determine the success rate of HEPA filters, and it is assumed the failure rate remains constant. Hence, the success rate (one minus the failure rate) on a decadal basis is 0.957 (1 – 0.043), and on an average annual basis is 0.994848 (1 – 0.005152). In the case of determining the success rate, no rounding was conducted because all of the digits are considered significant. The success rates are then extrapolated out to 10, 20, and 30 years, as applicable. The succeeding success rates can be determined by Equation. 4, where *i* represents the number of periods in years.

$$(Operational\ HEPA)_i = (Success\ Rate)^i \tag{4}$$

The data shows (Table 2) that for a 20-year HEPA filter lifetime, there is a greater than 90% chance of survival. The survival rate is comparable to the survival function for filters through the 20th year of 90.9% while the probability distribution function for 20 years is about 84%.

Table 2. Estimated HEPA Filter Survival Rate Using Reported Failure Rate (Shrank et al. 2020)

	Survival Rate (%)			
HEPA Age (years)	1	10	20	30
Decadal Rate	99.6%	95.7%	91.6%	87.6%
Annual Rate	99.5%	95.0%	90.2%	85.6%

3.5 Impact

If HEPA filters were given the opportunity to service facilities past the 10-year change out period nuclear operational costs would be reduced overall. In the Schrank et al. (2020) report, they estimate that through a HEPA filters life the total cost would be $18,500 U.S. dollars per filter, excluding maintenance. The breakdown provided in the Schrank et al. (2020) report is shown below.

$2,100	HEPA filter purchase
$6,200	Installation
$10,200	Waste disposal
$18,500	Total cost excluding annual maintenance

Khabir (2017) reports that for Hanford Site Tank Operations, the cost of a simple filter change out was $18,000 U.S. dollars per filter. Hanford Site Tank Operations has three classifications for HEPA-filter change-outs—simple, medium, and complex. Table 3 shows the reported estimated filter replacement costs for each of these classifications.

Table 3. Estimates of Filter Replacement Costs Based on Complexity (Khabir 2017)

Facility	Simple Filter Change Out Cost/Filter	Medium Filter Change Out Cost/Filter	Complex Filter Change Out Cost/Filter
Single-Shell Tank Farm	$18,000	$34,000	$70,000
Double-Shell Tank Farm	$17,000	$26,000	$58,000
222-S Laboratory Facility	$18,000	$34,000	$45,000
242-A Evaporator Building	$17,000	None	$43,000

This shows that changing out HEPA filters can be vary in cost according the risk associated with the change out. Schrank et al. (2020) reported that PNNL could operate their HEPA filter up to 15 years. Doing so resulted in a total cost savings of around 15 million dollars. Other nuclear facilities would see similar cost savings as did PNNL because the cost of a single HEPA filter is substantial. Enabling longer filter operation would not only benefit the operational cost of nuclear facilities, it also allows HEPA filters to operate to their full potential.

4.0 Conclusions

Although the ages of the 1600 HEPA filters does not say anything about HEPA filter lifetime, age is used as a surrogate representation for estimating an operating HEPA filter lifetime. Within the data set of operating HEPA filters, over half are between the ages of 11 and 44 years old. The large number of filters operating beyond the recommended 10-year change-out requirement suggests that HEPA filters can operate safely and efficiently past that change-out requirement. The question now becomes how long after the recommended 10-year change-out time should filters be allowed to operate? In this study, we used four approaches to address HEPA filter lifetime: linear trendline, survival function, probability functions, and failure rate.

The linear trendline approach infers that filter age represents filter lifetime. It provided a maximum nominal operating lifetime of 23.7 years which could be set based on the data intercept, and the maximum service life could be set at 44 years. However, the linear fit does not help in trying to predict the age of a new data point, such as filter number 1601. The approach of using a linear fit to estimate effective filter life is quite simplistic and is not ideal. It is not derived from actual time-to-failure data; instead, the 1600 filters in the combined data set are described by their respective years of operation (i.e., their age). Hence a 20-year nominal operating lifetime may be reasonable based on the estimated maximum nominal operating lifetime of 23.7 years.

A normalized survival function was applied to the in-service HEPA filters in this analysis with a maximum possible age of 50 years. While institutions may view 50 years as an impractical service life for any scheduled maintenance program, the computed results are much closer to a service life of 30 years. The survival function shows that approximately 15.4% of the 1600 HEPA filters are 20 years old and older. The large portion of operational filters at or beyond the recommended 10-year change-out (greater than 57%) suggests the current restriction may lead to premature replacement of filters. The survival function, when compared with the linear trendline maximum nominal operating lifetime of 23.7 years, shows 6.9% of HEPA filters last longer than 23 years.

Tolerance limits on HEPA filters were established based on the failure rate provided by Schrank et al. (2020) because a specific failure rate for HEPA filters was not available for the 1600 HEPA filters used in this report. Using this failure rate and applying a binomial probability distribution resulted in an estimated overall success rate of at least 94.15% at the 10-year mark. Once the overall success rate was calculated, we generated a Weibull distribution that had approximately a 94% success rate at the 10-year mark. From these estimations, the probability that a randomly selected filter would make it to 15-years would be approximately 89.4% and for 20 years the result would be 84.2%. Because the selected Weibull Distribution is based on the 0.043 failure rate observed by Schrank et al. (2020) and the assumption of similar HEPA filter operating conditions over a 10-year period, no definitive estimations of how long HEPA filters operate can be made. In this application, the selected Weibull distribution indicates that the 1600 HEPA filters have up to an 84% chance of operating to 20 years.

Schrank et al. (2020) provides the best available failure data. The failure rates were assumed to remain constant and were used to determine the success rate of HEPA filter operations, and a decadal success rate of 0.957 and an average annual success rate of 0.994848 was determined. The success rates then were extrapolated out to other time periods (e.g., 20 and 30 years), as applicable. The data show that for a 20-year HEPA filter lifetime, there is a greater than 90% chance of survival. The survival rate is comparable to the survival function for filters through the 20th year of 90.9% while the probability distribution function for 20 years is approximately 84%.

Using the results of the four approaches, they collectively point to the reasonableness of an operating HEPA filter lifetime of 20 years (extended form the current lifetime 10 years). The results are not necessarily definitive, but nevertheless, they are promising. The analysis provides reasonable assurance that when implemented using a graded approach with well-defined performance and operational requirements, extending the service life for HEPA filters beyond 10 years is low risk. In particular, the linear trendline analysis indicates that filters may be in service for more than 20 years; the survival function through the 20 years is greater than 90%, the probability distribution function is 84% for 20 years, and the survival rate is also greater than 90% at 20 years. Presuming setting the operating age limit at 20 years is appropriately conservative, then there could feasibly be a window after the 20^{th} year to change out a filter after 21–23 years, provided the program plan were to allow such operations.

Impacts associated with a graded approach can potentially save millions of dollars in replacement costs for a large facility. The risk to the surrounding communities and environment would not be expected to change provided the safety protocols and graded approach criteria are followed properly by professional personnel. Finally, the actual amount of life extension would be facility and program specific.

5.0 References

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