

HEPA FILTER REPLACEMENT EXPERIENCE IN A BIOLOGICAL LABORATORY

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ABSTRACT

Integrity tests on 969 HEPA filters filtering air to and from rooms and laboratories have been done annually for 13 years. Filter replacements were analyzed by supply or exhaust air system, area serviced, primary or secondary situations and cause for replacement. The average annual filter replacement rate for installations filtering either supply or exhaust air, or vented gases were 2.9%, 1.9%, or 3.0% respectively. Initially, most failures occurred in the filter medium or the gasket seal. However, in recent years, there has been a general increase in filter reliability with filter blockage being the major reason for replacement. The replacement rates for exhaust filters in laboratory, animal room or other plant rooms were similar.

This study has shown that the critical biocontainment function of HEPA filters in this biological laboratory has been exceptionally reliable with little deterioration in performance over 13 years of service. Because a majority of filters (up to 78% for exhaust systems) have never been replaced, it was not possible to determine a meaningful life expectancy for filters.

INTRODUCTION

Historically, high efficiency particulate air (HEPA) filters were developed for the removal of radioactive particles from air streams in nuclear facilities. These filters have been used widely and are very effective also for the removal of infectious aerosols from air streams in medical, veterinary and other biological installations. The standards to which filters are manufactured and tested have been reviewed recently (First, 1996).

Where biocontainment is important, HEPA filters form a critical part of microbiological barriers. As air handling systems in buildings run continuously, the integrity and efficiency of HEPA filters must be checked at defined intervals to ensure

biocontainment standards are met. In general, annual testing of filters is adopted to ensure the filter medium is integral, the filter is effectively sealed in its housing, and that the pressure drop across the filter is acceptable.

Reports concerning the reliability and performance characteristics of HEPA filters in nuclear (Carbaugh, 1982) and both nuclear and non-nuclear (Robinson et al., 1985) installations have been published, but there is no information concerning the longevity of filters in biological facilities (First, 1996). This paper reports the reliability of HEPA filters in air handling systems in a large veterinary laboratory over a 13-year period since commissioning.

MATERIALS AND METHODS

Laboratory Design

The high containment, animal health laboratory described was designed and built following the box-within-a-box principle. Within the outer microbiological barrier are three large suites of laboratories, having floor areas ranging from 960 to 1376 m² each having their own microbiological barriers. Each suite contains laboratories, small animal rooms and higher containment laboratories for more hazardous work. Separate again is a suite of 28 animal rooms for large animals and a necropsy room. Surrounding these core work areas are support service areas including glasswash, laundry, electronics and engineering workshops, storage, staff facilities, engineering plant rooms for both air handling and sewage treatment as well as an extensive corridor network.

Air Handling

The whole complex of laboratories, animal rooms and support services receives 100% fresh air drawn from outside the building into a common plenum, and particulate matter removed by a Vokes Trivee DG20 Type 1 filter tested to Australian Standard AS1132 (1973), having an average efficiency of 97% for No. 2 dust at a flow rate of 944 Lsec⁻¹. Air

may be heated or cooled (but not humidified) prior to passing through another Vokes filter to one of the 45 air handling systems supplying air to various zones within the microbiologically secure area. A roughing filter pad (Email, Type 1, tested to Australian Standard AS1324.2 [1996], having an efficiency of 58% for No. 2 dust at a flow rate of 700 Lsec⁻¹) removes particles created by electric motors and belt-driven fans before the air finally passes through a 610 x 610 x 292 mm HEPA filter to its destination. For the 28 large animal rooms (that act as primary microbiological containment zones), necropsy and several isolation rooms, two HEPA filters are used in series for the supply air as a final safeguard against infectious particle backflow from contaminated rooms.

In large plant rooms, both supply and exhaust air are handled by banks of up to 28 filters in parallel. If the airflow through such banks falls below required levels (measured by a pressure drop >500Pa) because of medium blockages, it is likely that all filters in the bank need replacement.

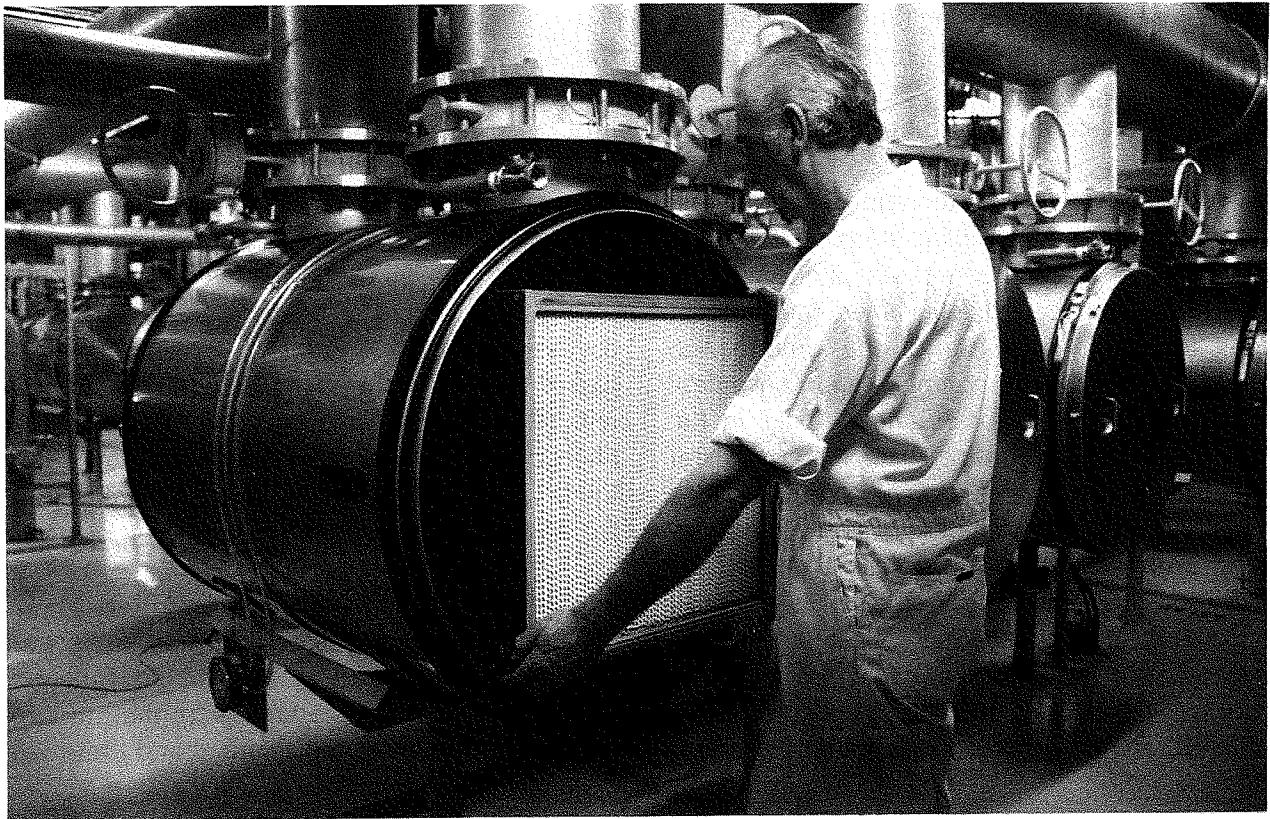
Air is exhausted from laboratory and other areas through preliminary clarification prefilters having an average efficiency of 83% for No. 4 dust at a flow rate of 540 Lsec⁻¹ prior to filtration through two 610 mm square, HEPA filters in series to ensure optimal removal of infectious aerosols. In animal rooms, both dander and roughing prefilters are included before the air leaves the room.

Filter Installations

All HEPA filters, whether supply or exhaust air, are mounted in separate, horizontal, cylindrical canisters with removable ends allowing direct access to both sides of the filter for examination and scan testing (Figure 1). The 610 mm square filters are sealed in mountings with compressible gaskets that meet required standards for airtightness measured by cold dioctyl phthalate (DOP) particle penetration. At the completion of testing, the canisters are pressure tested to confirm an integral seal of the end lids and the valves. Where two HEPA filters are installed in series, both filters are integrity tested sequentially.

FIGURE 1

Canisters with removable ends allowing easy servicing and scan testing of 610 mm HEPA filters.



In addition to supply and exhaust air systems, there are eighty-six 304 x 304 x 149 mm HEPA filters (mostly installed as pairs in series in vent lines) venting gases from effluent drains and collection vessels into engineering plant rooms. As these filters are usually exposed to air at higher relative humidities than the filters in supply and exhaust systems, the canister housings are routinely held at 50°C to minimize water condensation on the filters.

The same smaller HEPA filters are used in 55 local ventilation systems to filter air from seldom-used shower cubicles which cross architectural or microbiological barriers between the plant rooms or emergency exits. The 304 mm square filters are mounted in cylindrical canisters and integrity tested annually in the same way as the larger filters in air handling systems.

Filters

When the laboratory was constructed and commissioned in the years prior to 1985, excess HEPA filters were purchased from either Email Airhandling, Australia (now BTR Environmental Pty. Ltd.) or Gelman Sciences (now Clyde Apac, Australia) companies. A contemporary definition for such HEPA filters has been published recently (First, 1996) and all filters in this study conform with this description. Initially, all were acceptance tested on-site before installation using the British Standard Sodium Flame Test BS 3928 (1969) to ensure compliance with supply contract specifications. Surplus filters have been stored on-site ever since and used as replacements.

All installed filters are tested annually (or biennially) to meet integrity specifications and are replaced as soon as the acceptable limits are exceeded. There are no predetermined replacement periods for filters. Because of the unique and patented canister design, complete and convenient scanning can be done for "pinhole" leaks in the medium, gasket or mounting plate for every filter and canister, allowing all defects of consequence to be detected. This mounting design allowed comprehensive scan testing to Australian Standard AS 1807.6 (1989) and the opportunity for a defective filter to be discarded as soon as a local fault causing non-compliance was detected.

During testing, relevant data was recorded and considered. Minor defects noted during previous

tests could be checked thoroughly for any change. When pinhole leaks were detected in an otherwise sound filter, the filter was removed and the hole repaired with a silicone elastomeric sealant. After retesting for performance, such filters were available for re-installation in supply air canisters only.

During the years 1994-1997, 20 exhaust air HEPA filters were replaced by a similarly-sized but higher efficiency ultra low penetration air-filters (Flanders Filters, Inc., USA) for experimental purposes (Jamriska, Martin, and Morawska, 1997).

RESULTS

Replacement Data for All Filters

Initially, all air supply, air exhaust, vent or local area filters were checked annually for integrity as described in Methods and Materials. Since 1994, some supply and exhaust filters in areas having lower microbiological hazards have been tested only every second year.

Data on the total number of filter replacements has been recorded since 1985 and is shown in Figure 2. The data is divided to show the three types of filter systems—supply air, exhaust air, and sewage vent/local filters. Average annual replacement rates for these three filter systems were 2.9%, 1.9% and 3.0% respectively (Tables 1-3).

Replacement Data for Supply Air Filters

Reasons for replacement of filters at this laboratory have been ascribed to four groups: failure of the filter medium, failure of the gasket seal between the filter and mounting plate, insufficient air flow through the filter, and other miscellaneous problems.

Table 1 shows a breakdown of replacement reasons for the 317 supply air filters. Medium and gasket failures occurred infrequently after the first few years of installation. However, blockages of filters began to occur more frequently after 1990. In total, 121 (38.1%) were replaced for all reasons over the 13-year period.

Replacement Data for Exhaust Air Filters

Table 2 shows a breakdown of replacement reasons for the 511 exhaust air filters. Failure and blockage of the filter medium were the most common reasons for filter replacement and these values

FIGURE 2

Annual HEPA filter replacement percentages. Total filter installations were 317 filters in supply, 511 in exhaust, and 141 in vent and local systems.

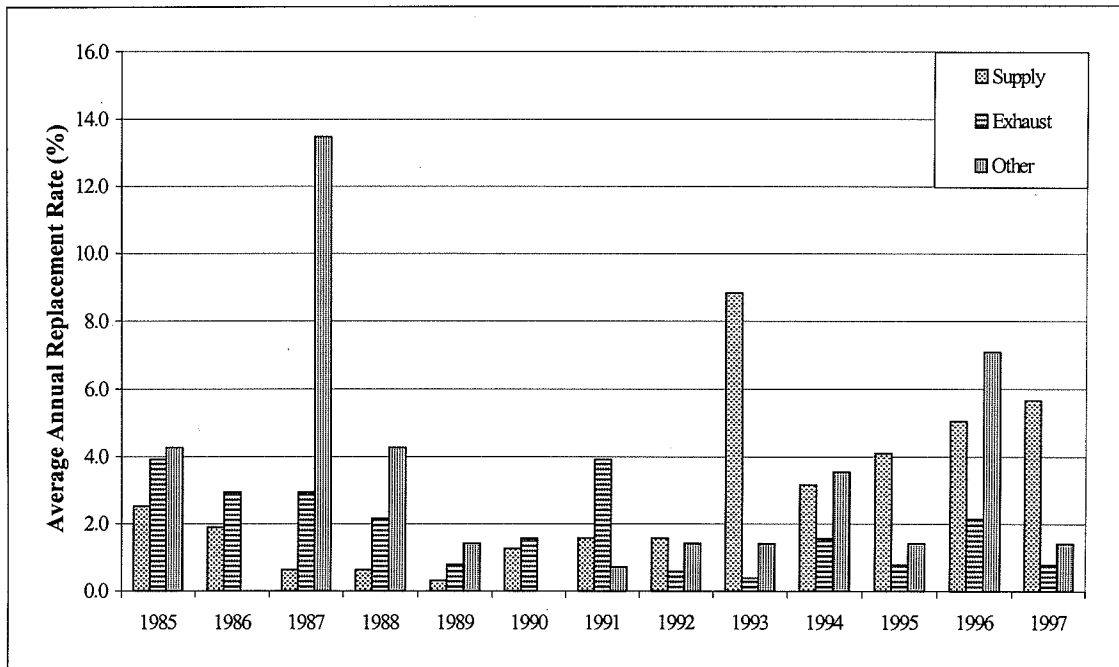


TABLE 1

Summary of Supply Air Filter Replacements
Of 317 supply air filters installed, 121 (38.1%) have been replaced for all reasons.

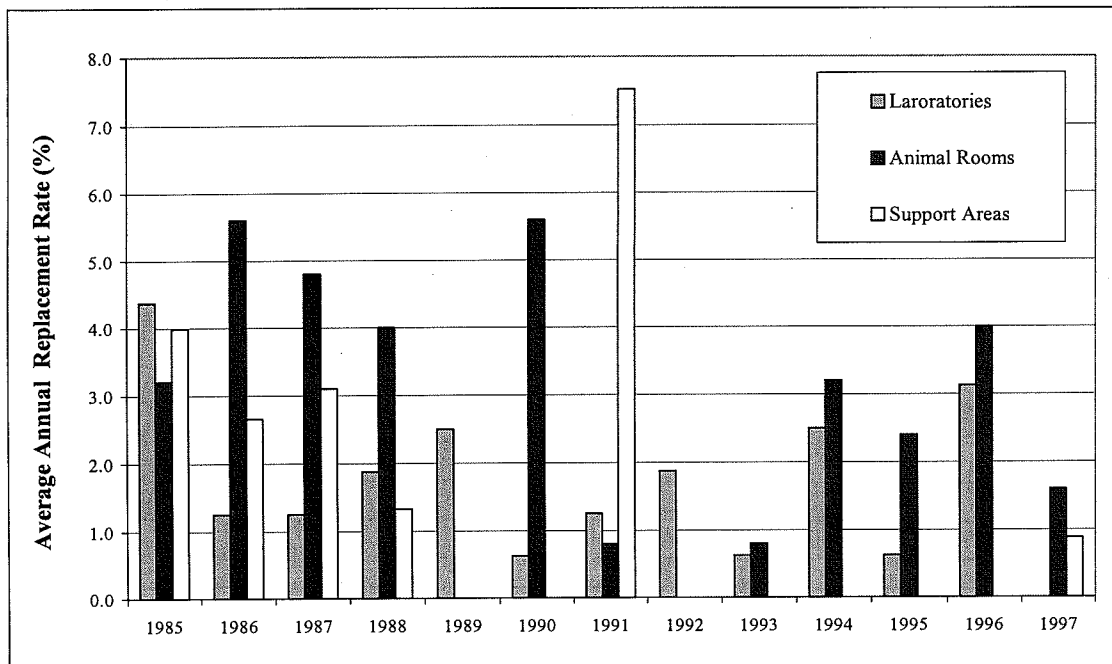
	MEDIUM FAILURE	GASKET FAILURE	BLOCKAGE	DAMAGE / OTHER	TOTAL
1985	7	4			11
1986	3	3			6
1987	1	2			3
1988	1		1		2
1989	1				1
1990	2	2			4
1991			4	1	5
1992			5		5
1993			28		28
1994		1	8		9
1995			13		13
1996		1	15		16
1997	1	1	16		18
TOTAL:	16	14	90	1	121

TABLE 2
Summary of Exhaust Air Filter Replacements
 Of 511 operating exhaust air filters, 125 (24.4%) have been replaced for all reasons.
 Numbers in brackets represent primary filter replacements.

	MEDIUM FAILURE	GASKET FAILURE	BLOCKAGE	DAMAGE / OTHER	TOTAL
1985	14 (10)	3 (2)		3 (1)	20
1986	7	1	6 (6)	1	15
1987	7 (3)	2 (2)	1 (1)	5	15
1988	11 (1)				11
1989	4 (3)				4
1990	6 (1)	1		2 (1)	9
1991	1 (1)		17 (17)	2 (1)	20
1992	2			1	3
1993	1	1 (1)			2
1994		1	1	6 ^a (1)	8
1995			1 (1)	3 ^a	4
1996				10 ^a (1)	10
1997	1 ^b		1 (1)	2 ^a (1)	4
TOTAL:	54 (19)	9 (5)	27 (26)	35 (6)	125

- a Optional replacements to test more efficient filters.
- b This failure occurred in one of the replacement filters (noted in a above) and not a HEPA filter.

FIGURE 3
 Annual HEPA exhaust air filter replacement percentages. Total filter installations were 160 in general laboratories, 125 in large animal rooms, and 226 in support areas.



were higher in the first four years after installation. The "damage/other" column included some mechanical damage done to filters while testing methods of biological assessment of the decontamination procedure (Abraham et al., 1996), and 18 optional replacements done (from 1994 to 1996) to test a different type of higher efficiency filter. Of 511 exhaust filters, 125 (24.4%) were replaced for all reasons over the 13-year analysis period.

The figures in brackets in Table 2 represent those filters replaced in the primary position of each pair in series. Of 125 replacements, 56 (45%) were in primary filters.

Analysis of Exhaust Air Filter Replacements by Zone

Of the 511 exhaust filters, 160 were in regular laboratories and small animal rooms, 125 in large animal rooms, and 226 in support areas and plant rooms. Figure 3 shows a breakdown of filter replacements in these three zones, the average annual replacement rates being 1.7%, 2.7%, and 1.5% respectively.

Analysis of Replacements of Vent and Local Filters

Table 3 shows a breakdown of reasons for all replacements in filters venting sewage collection pipes and local areas such as staff showers. All of these filters are 304 mm square filters (compared with 610 mm square filters in air supply/exhaust systems) and are considered together for this reason. Of 141 such filters, gasket failure was the most frequent reason for replacement. Vent filter canisters are held routinely at 50°C to minimize the possibility of water vapor condensing on the filters in these low air flow systems. On average, 3.0% of vent and local filters required replacement annually.

DISCUSSION

This report describes the reasons for HEPA filter replacements in *in situ* air handling systems in a large microbiological laboratory over a 13-year period. As previous authors (Carbaugh, 1982; Robinson et al., 1985) have reported on the life expectancy and aging of similar air system filters in nuclear energy plants, this study provides compara-

TABLE 3
Summary of All Vent and Local Filter Replacements
 Of 141 filters installed in a vent and local systems, 56 (39.7%) have been replaced for all reasons.

	MEDIUM FAILURE	GASKET FAILURE	BLOCKAGE	DAMAGE / OTHER	TOTAL
1985	1	2		3	6
1986					
1987	8	4		8	20
1988	4	2		1	7
1989	1	1			2
1990					
1991				1	1
1992		1		1	2
1993		2			2
1994		6			6
1995		1		1	2
1996		5		3	8
1997					
TOTAL:	14	24		18	56

tive data for filters acting as microbiological biocontainment devices in air handling systems. No consideration of biosafety cabinet filters was included in this study.

Until 1994, all filters in this study were checked annually for integrity as described in Methods and Materials. Since then, the testing of a minor proportion of supply and exhaust filters servicing lower microbiological risk zones was extended to two yearly intervals. This change is not considered to have altered significantly the data presented here.

For all filter types, the three main reasons for filter replacements since 1985 have been blockage of the filter medium, defects (usually "pinhole" leaks) in the filter medium and defects in the gasket seal securing the filter frame in its housing. Unexpected reasons for damage caused by handling accidents, smoke exposure and steam condensation were irregular and minor overall causes for filter replacement (Tables 2 and 3). Medium and gasket problems occurred mainly during the first five years of installation; there have been relatively few such faults during the past eight years (Tables 1-3). Of filters in 969 installations included in this survey, 302 (31%) have been changed for all reasons during 13 years. This corresponds to an annual replacement rate of 2.4% which is significantly lower than published values for U.S. Department of Energy nuclear plant sites (Carbaugh, 1982) where the annual average replacement rate over a three-year period was >19%. Carbaugh reported that 12% of all filters actually failed during this period because of ruptures in the filter medium, faults in the filter frame or defects in the filter seals. In contrast, the total number of actual failures for these reasons in the present analysis was 131, or an annual average of 1.0% over the 13-year period. No filters, even those accidentally wetted by steam leaks, have ever failed catastrophically at this facility. The largest point penetration in the filter medium detected during the past six years by the cold DOP method was 0.9%, and only six point penetrations have exceeded 0.5%.

Because of their critical function in minimizing the possibilities for disease escape via infectious aerosols, data relating to exhaust air filters was examined more closely. During the past seven years, the filter replacement rate has fallen to 0.1% for exhaust filters (compared with 0.2% for all fil-

ters), indicating an increasing reliability of this part of the biocontainment barrier; inherently defective or less robust filters having been "weeded out." The data was also studied to see if filters in particular exhaust canisters were replaced more frequently. Of the 125 replacements shown in Table 2, 110 were replaced once, 13 replaced twice and two replaced thrice. It follows that 401 (78.4%) of filters in the exhaust system have never been replaced. Calculations were attempted to determine the mean life expectancy for such filters. However, since more than half of the filters have not yet been replaced and their reliability is actually increasing (Table 2), the value derived had little practical meaning as it appeared to exceed the 50-year predicted life expectancy of the biocontainment laboratory (calculations not shown).

Carbaugh (1982) reported filters in nuclear industry facilities were changed five times more frequently for blockage than for other reasons. This contrasts with the present study where over the 13-year period, there were 117 replacements caused by blockages compared with 185 for all other reasons. Although some supply and exhaust filters in areas having lower microbiological hazards have only been tested every second year since 1994, we do not believe this variation has skewed the overall results as, apart from blockages in some supply filters, there have been relatively few filter replacements over this period.

The present data shows that HEPA filters are lasting significantly longer at this laboratory than has been reported elsewhere. There are a number of reasons that may contribute to, or be the cause of this effect. In general, data may be distorted for a number of reasons, but in this study, many of these can be excluded: 1) comprehensive records have been carefully kept since 1985, 2) criteria for filter replacement are stringent (see Methods and Materials) and conform with contemporary international standards, 3) annual filter testing has been completed on time for the majority of the period, 4) complete manual scan testing for each filter has been possible because of unique canister design allowing all pinholes of consequence to be detected, and 5) comprehensive staff training programs and adherence to strict quality assurance standards ensuring filter replacements were made at the earliest time faults were identified.

A number of factors can be suggested that have contributed positively to the relatively long filter life observed: 1) the unique design of each filter in its own cylindrical canister (Figure 1) has minimized filter handling and the possibilities for damage during decontamination and scan testing, 2) the initial filters were purchased following a well-researched analysis resulting in a tender specification document requiring only high quality materials and construction techniques, 3) the use of a laminated timber frame provided a more rigid structure than alternative metal frames, perhaps resulting in less distortion during installation and handling, 4) the method of securing the filters to the rigid canister mounting plate provided a more even load distribution on the filter frame than many commercially-available filter mounting frames thus contributing to the excellent performance achieved to date, 5) the filtration of all supply air through at least one HEPA filter reduces the particle impact on exhaust filters, 6) thorough efficiency and integrity testing of all filters prior to installation meant the initial quality of filters installed was high, 7) where two filters are installed in series, the secondary filter is somewhat protected from particles by its primary counterpart, and 8) since all filter housings are within the microbiological barrier, the filters have been held at a relatively constant temperature of 21-24°C (or 50°C for the 86 filters venting gases from sewage treatment pipes and vessels).

Water, dust and smoke led to premature deterioration of filters on occasions. Examples of these effects can be seen as fluctuations of replacement rates where condensation of water vapor in vent filters in 1987 caused permanent damage to eight filters (Table 3), and in 1991 to 17 filters following the release of smoke from a faulty incinerator (Table 2). In 1993, a large bank of 28 filters providing filtered air to a large plant room needed to be replaced because of an increased pressure drop across the filters caused by the blocking effects of dust particles (Table 1).

Most of the zones in the laboratory were relatively clean and dry in terms of air quality. Exceptions were engineering plant rooms where machinery and fans released particles to the surrounding environment. Relatively few chemicals that might cause filter damage were released from any area. This contrasts with the observations of Carbaugh

(1982) who noted that the highest frequency of filter change-outs occurred in environments having higher concentrations of hydrofluoric acid and other fluoride-containing gases. The only potentially damaging chemical consistently exposed to filters in the present report has been formaldehyde (Abraham, et al., 1996) and it is reasonably clear that it has had little effect on the aging of filters.

Animal rooms are zones where animal dander particles and possibly gases such as ammonia were considered likely to cause an increase in filter replacement rates. This effect is not substantial as the average annual replacement rate for animal rooms of 2.7% compares favorably with replacement rates of 1.7% in laboratories and 1.5% in support areas (Figure 2).

One of the types of fault leading to medium failure is a pinhole leak, or tiny holes where local concentrations of the test chemical, dioctyl phthalate, exceed the value permitted for an intact filter. Annual records for individual filters have allowed small pinhole leaks to be identified and then followed in subsequent years where the filter performance was still within the prescribed limits. The conclusion drawn by the authors (data not shown) is that small pinhole leaks do not get larger with time. It was also surprising to see that pin hole leaks and other medium defects do not seem to be caused by particle impact (Table 2) as the frequencies of primary and secondary filter replacements in exhaust systems were not significantly different. In such circumstances, the secondary filters would have been free from significant particle impact damage.

It is important to note that all filters used in this laboratory were of a similar age (14-16 years) as excess filters were purchased prior to 1984, tested and kept in storage. This reserve of filters has not yet been expended. The replacement rate for filters during this study has decreased with time (Figure 2). When considering failure of the filter medium and gaskets (Tables 1, 2, and 3), it became clear that aging has not yet led to a significant increase in defects in filter integrity. In this respect, this laboratory does not have predetermined times for filter replacement as a preventative maintenance measure. In addition, no catastrophic failure of filter medium has been observed during the whole of this study. This information provides some reassurance for the concerns of First (1996) who suggests that

there is a general lack of data concerning the longevity of HEPA filters in biological applications, and that there may be merit in replacing filters after some pre-determined "useful life" span. As far as HEPA filters in air handling ducts are concerned, this study shows >69% of filters installed in 1985 are still functional and integral, a period significantly longer than the nominal five years suggested by First (1996) for biosafety cabinet filters.

Another aspect of filter aging is a possible decrease in the tensile strength of the fibers in the filter medium. Such analyses have commenced at this laboratory and preliminary data suggests that after 14 or more years, either in service or in storage, the media of representative filters still conform with the relevant specification (MIL-STD F-51079) even though there is some loss of mechanical strength in the medium (S. Edwards, personal communication). Results of this work are to be published soon, but appear to be inconsistent with the reports of Robinson, et al., (1985) who observed filter deterioration in respect to paper strength and aluminum spacers in HEPA filters in both nuclear and non-nuclear facilities.

Filters were originally purchased from two manufacturers, Email and Gelman. The different filters were installed in the facility randomly. The available evidence during this study showed that the replacement rates for both types of filter were similar (data not shown), but exact figures were not available because when filters were replaced over the years, there was no specific policy to replace a particular brand of filter with a new one from the same manufacturer.

For economic reasons, filters with pinhole leaks failing to meet performance criteria were patched with silicon elastomer, tested and a few filters returned to service in specific, supply air situations associated with low microbiological hazards. Subsequent performance of such repaired filters was comparable to that of intact filters (data not shown).

Filters of two sizes were examined in this study. Data related to larger 610 mm square filters that filter supply and exhaust air is shown in Tables 1 and 2 while data related to smaller 304 mm square filters that service local zones and sewage vent lines is shown in Table 3. The annual, average replacement rates for the larger and smaller filters were

2.2% and 3.0% respectively. Although the filtration functions were different, their life spans were comparable indicating that major differences between the two sized filters probably do not occur. It is clear from Figure 3 that blockage has not been a problem with filters in local and vent systems and this is no doubt related to the lower airflow through and particle load on these filters.

Of the 141 filters included in the data in Table 3, 86 were servicing sewage vent lines. These filters were thus usually exposed to higher relative humidities than the filters in supply and exhaust systems. To minimize the possibilities of water condensation on the filters, the canister housings were routinely held at 50°C. Consequently, these filters were exposed to a more humid and warmer environment leading to a higher failure rate of the gasket seals (Table 3), relative to their medium failure, blockage or other problems.

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