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HEPA FILTERS

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ABSTRACT

The high efficiency particulate air (HEPA) filter has become an indispensable item in the maintenance of biological safety and is also used as a means of preserving cultures from contamination originating in the surrounding air. HEPA filters originated with military requirements for protection against chemical, biological, and radiological warfare agents and to avoid emissions from nuclear weapons production facilities. Everything about these filters was classified "secret" during WWII and for a number of years after the end of the war. When they were declassified and commercial production commenced, many new uses were found in medicine, microelectronics manufacturing, and pharmaceutical production. A thorough understanding of these filters proved to be so important that they stimulated research and development activities that established the science of air filtration on a firm theoretical basis and promoted rapid advances in materials of construction and production methods. The history of their origin and development is an interesting story in itself and helps our understanding of their capabilities and limitations.

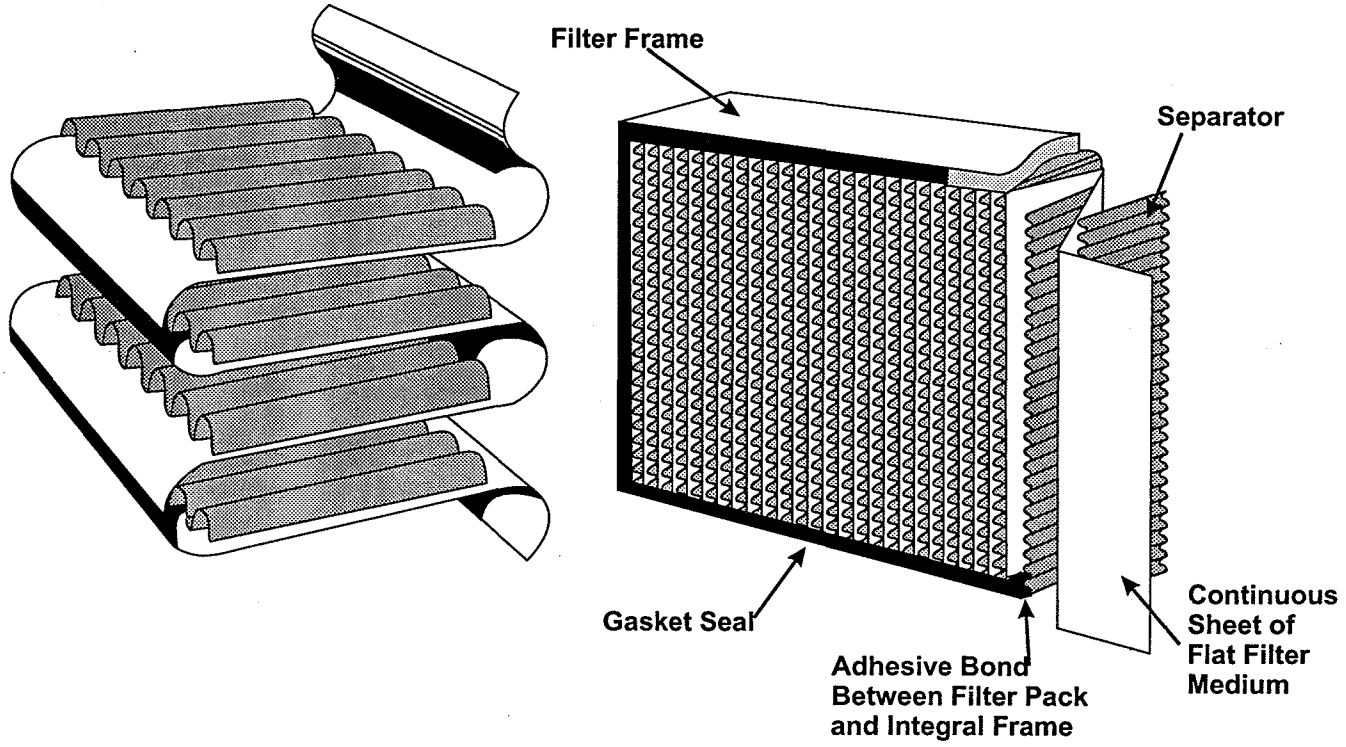
INTRODUCTION

The 1952 *Handbook on Air Cleaning*, published by the U.S. Atomic Energy Commission (USAEC), contained one of the earliest descriptions of the newly declassified high-efficiency filter. It was "made of CC-6 paper which was originally developed by the Chemical Corps for use in gas masks. It consisted of fine asbestos fibers mixed with coarse cellulose fibers to give mechanical strength and act as a support for the asbestos. The asbestos mesh does most of the filtering...cellulose-asbestos paper is expensive and not available in large quantities" [1]. The origin of these filters goes back to the early days of WWII, when the U.S. Army Chemical Corps received from the British army a piece of paper that had been removed from a captured German gas mask canister. Its remarkably high capture efficiency for chemical smoke caused the Army Chemical Corps and the Naval Research Laboratory to duplicate it and manufacture it in large quantities on conventional paper making machinery for use in service gas masks. The navy paper contained Bolivian crocdolite asbestos with cellulose pulp, the Army version (CWS) contained African crocidolite asbestos with esparto grass pulp. Crocidolite asbestos has long flexible fibers that can be cleaved to less than 0.25 mm diameter by mechanical beating.

Protection against warfare agents was also required for operational headquarters, where the wearing of an individual gas mask is impractical. For these situations, the Army Chemical Corps developed a combination mechanical blower and air purifier unit known as a "collective protector." As relatively large air flows were required, the filter, incorporating the same cellulose-asbestos paper used in the service gas mask, was fabricated into a deeply-pleated form with spacers between the pleats to keep them apart and serve as air passages. It was the precursor of the air filter we now know as the high efficiency particulate air (HEPA) filter (Figure 1). It was referred to then as an "absolute" filter. The nuclear version of the absolute filter was designated AEC No. 1. Its design efficiency was 99.9% for all particles down to 0.1 mm diameter.

To reduce dependence on imported materials, domestic fibers, such as Kraft paper, viscose, and even coarse glass, were found to be acceptable substitutes for esparto, but it was not until the Naval Research Laboratory found ways to make glass fibers as small as 0.25 mm in diameter, that a domestic substitute for crocidolite asbestos was available. It then became possible to make an all-glass filter paper with filtration characteristics superior to cellulose-asbestos composites. Elimination of the cellulose component made it possible to make noncombustible filters, an urgent safety concern, by incorporating: (a) high chlorine content, self-

FIGURE 1
Component diagram of a deep-pleat HEPA Filter.
(Courtesy Flanders Filters, Inc. Washington, DC)



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extinguishing, flexible organic adhesives to bond the filter pack to the filter frame, (b) fire retardant plywood filter frames, and (c) aluminum corrugated separators.

Development of HEPA Filter Test Methods

Filter performance standards and test methods also had their origin during WWII by the U.S. Army Chemical Corps with the advice of the National Defense Research Committee. The Army Chemical Corps asked Nobel Laureate Irving Langmuir to examine the physical basis for the capture of small particles by fibrous media and to recommend filter test methods. Langmuir concluded that the principal mechanisms involved were interception, which affected suspended particles substantially greater than 0.1 mm diameter when moving through a devious flow path in a bed of porous material, and diffusion, which affected suspended particles substantially less than 0.1 mm [2]. His analysis, later modified by Ramskill and Anderson to include inertia [3], indicated that the combined effects of these forces on a particle would be at a minimum when the particle was 0.3 mm in diameter; and he advised the Army Chemical Corps to test their gas mask filters with a smoke of this size. He indicated that, when particles were present during field use of the gas mask that were either greater or smaller than 0.3 mm, they would be removed at higher efficiency than the 0.3 mm test particles. Later investigations confirmed the existence of a minimum filterable particle size, but it has been found to be closer to 0.1 mm for the flow rates and paper compositions in use for currently manufactured nuclear grade HEPA filters [4].

Langmuir's theory affected U.S. filter technology profoundly and led directly to the development of a filter test by LaMer and Sinclair during 1942-1945 which used an aerosol containing dioctyl phthalate (DOP) droplets [5]. It has become the U.S. standard method for bench testing unused ultrahigh efficiency, or absolute, filters.

It was discovered as early as the initial installation of HEPA filters at the Oak Ridge National Laboratory's (ORNL) graphite reactor in 1950 that the full capabilities of HEPA filter performance were not being achieved because of damage during shipment and faulty installation. As a consequence,

in-place testing of all filters by methods initiated and developed at ORNL has become routine [6]. These tests take place before initial start-up of new facilities and periodically thereafter.

Specifications for HEPA filters, HEPA filter media, and installation and field test consensus standards are published by the American Society of Mechanical Engineers as ASME N509 [7], ASME N510 [8], and Nuclear Air Cleaning Equipment Code AG-1 [9], respectively. All utilize monodisperse DOP aerosols for bench testing and polydisperse DOP aerosols for field testing HEPA filters in conjunction with a forward light scattering photometer for aerosol concentration measurements.

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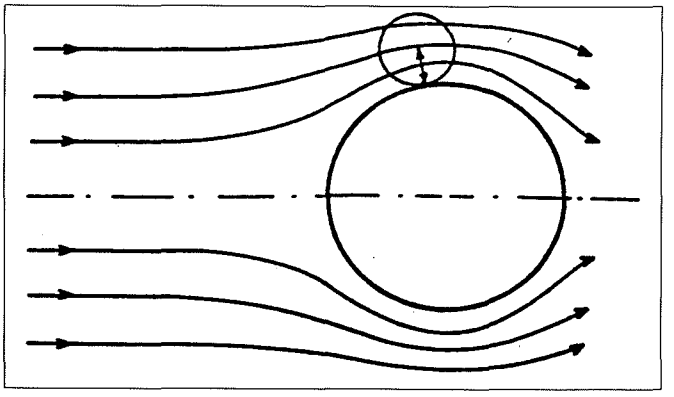
Air Filtration Theory

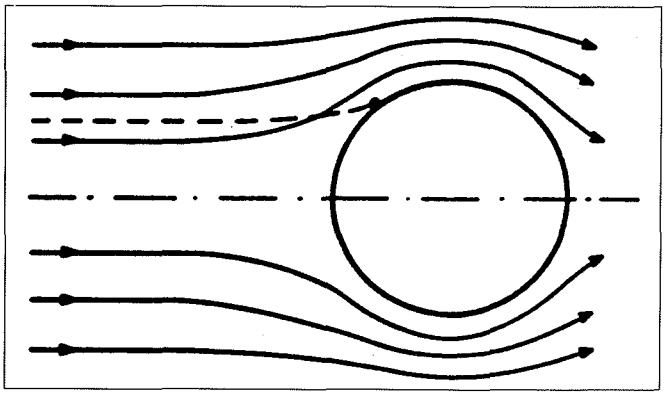
Filters. Although all manner of air and gas cleaning devices are often called "filters," in this paper the word filter will only be used to refer to "a porous mass through which a gas is passed to separate particulate matter in suspension" [10]. The filter structure exhibits considerable porosity for easy passage of the carrier gas. This means that the spaces between adjacent fibers will be larger than the particles the filter is designed to collect and that sieving, that is, retention of particles by openings too small to permit their passage, is not a primary mechanism for filtering fine particles. Instead, inertia and diffusion plus interception are the primary mechanisms. Particle size is the most important property of an aerosol because the smaller the particles the more stable the aerosol and hence, the greater the difficulty in separating particles from the gas phase in which they are suspended. It is common practice to characterize a particle's diameter in terms of a dynamic parameter, the aerodynamic quivalent diameter, defined as the diameter of a homogeneous sphere of unit density that has identical terminal settling velocity in still air as the particle under consideration. For example, a 1.0 mm sphere of UO_2, density 11 g/cm^3, has an aerodynamic equivalent diameter of 3.3 mm. In all cases in this paper, aerodynamic equivalent diameter will be the size designation.

Filtration. Figure 2 shows the streamlines around a single filter fiber lying normal to the flow direction. A particle entering the flow field surrounding the fiber must follow the curved path of the streamlines if it is to pass around the fiber.

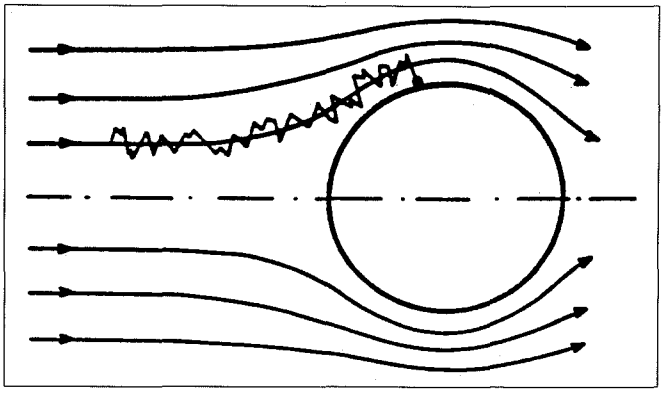
FIGURE 2
Streamlines around a filter fiber.
(Courtesy International Atomic Energy Agency)



Particle caught by interception.



The effect of inertial forces.



Particle caught by diffusion.

When particles possess sufficient inertia, because of their higher momentum relative to that of the conveying gas molecules, they resist following the curvature of the air stream and come in contact with the fiber. The effect becomes greater as aerodynamic equivalent diameter increases and as the velocity of the air approaching the fiber increases.

When suspended particles are very small, however, they tend to follow the curved streamlines closely, that is, they have little inertia, but they will be in vigorous Brownian motion. Therefore, when a streamline passes close to the fiber surface, the random movements around the streamline may result in some of the particles contacting the fiber and adhering there by Van der Waals force. This sets up a concentration gradient between the zone close to the fiber and the bulk of the aerosol which, in turn, results in particle diffusion in the direction of the fiber surface. The smaller the particles, the more vigorous will be their Brownian motion, and the more effective will be filtration by diffusion. Because the rate at which particles cross streamlines under the influence of diffusional force is slow relative to the effects of inertial force on large particles, diffusional separation of small particles is enhanced by slower velocities through a filter.

Particle collection by interception occurs when a particle traveling in a streamline that approaches a fiber within one particle radius touches the fiber and adheres. Interception is enhanced when the diameter of the collecting fiber or granule approaches the geometric diameter of the particle. Interception is independent of flow velocity.

The several filtration mechanisms of importance are shown together in Figure 3 where penetration (equal to 100 minus collection efficiency) is plotted against particle size. The penetration curves are not additive, inasmuch as particles can be collected but once, but the net effect can be approximated by the solid summation curve. Figure 3 makes it clear that there is a particle size for which both inertial and diffusional forces are minimal and only interception is unaffected. This explains the concept of a minimum filterable particle size. The exact minimum size depends on the fiber diameter, filter construction, and flow velocity. As noted earlier, the minimum filterable particle size for HEPA filter papers is close to 0.1 mm when operated at the design flow rate of 2.5 cm/s.

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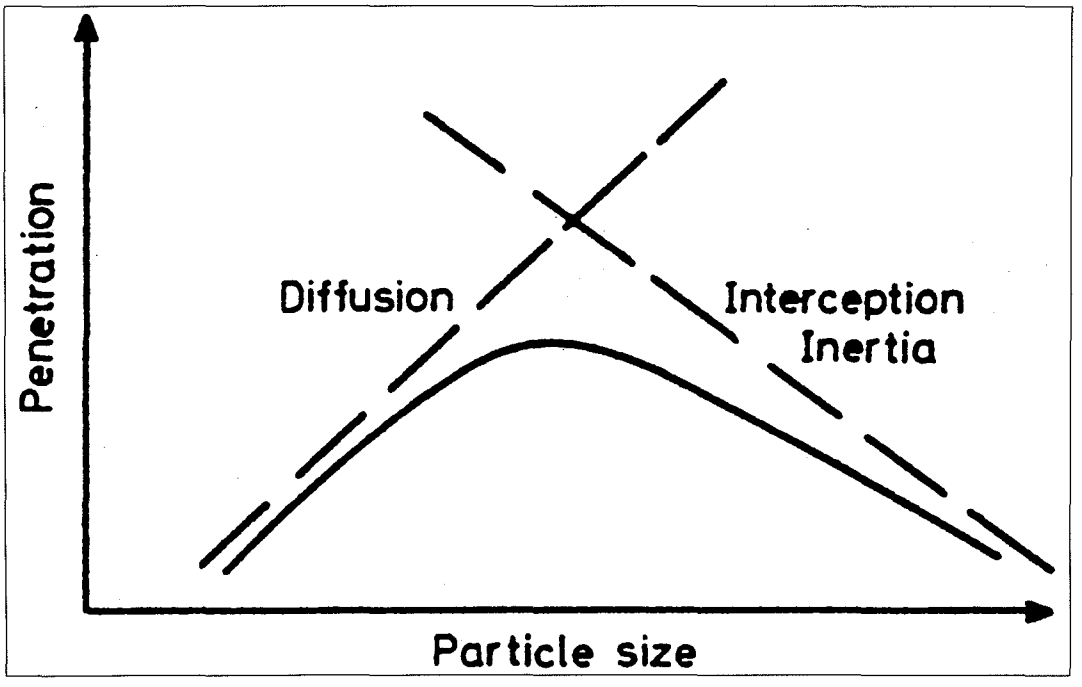
FIGURE 3

The effects of inertia, diffusion, and interception on the penetration-particle-size curve. (Courtesy International Atomic Energy Agency)



The effect of flow velocity on particle penetration for HEPA filter paper is shown in Figure 4. In this diagram, there is also a minimum efficiency point. In practice, the usual test velocity for HEPA filter paper occurs about midway on the steep ascending sector of the curve. This means that penetration should decrease when flow velocity decreases to the design rate of the full-scale filter, and, in fact, that does happen.

Particle Retention. After an airborne particle contacts a filter element, retention forces come into play to prevent reentrainment under the influence of the drag of the air. For small particles, the principal retentive force is a surface phenomenon referred to as the Van der Walls force, which is proportional to the total area of contact. For small particles, the fraction of the total surface area in contact with a filter fiber will be relatively large, whereas the projected area subject to air drag will be relatively small, resulting in a retention force that will exceed the reentrainment force. Seepage of particles collected on HEPA filters never occurs unless the filter paper becomes thoroughly wet. For this condition, different entrainment mechanisms are involved.

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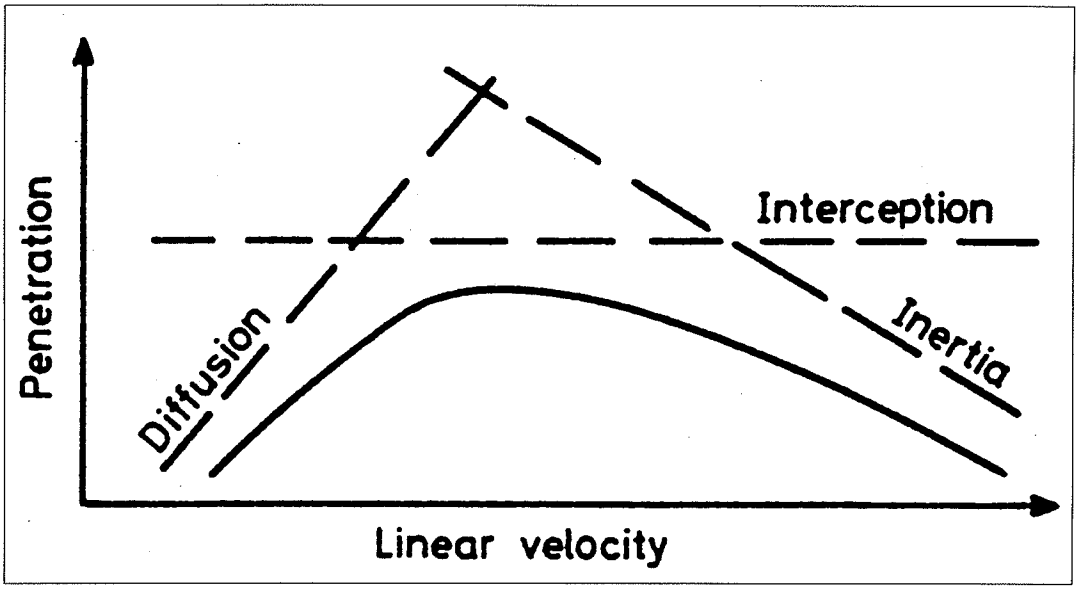
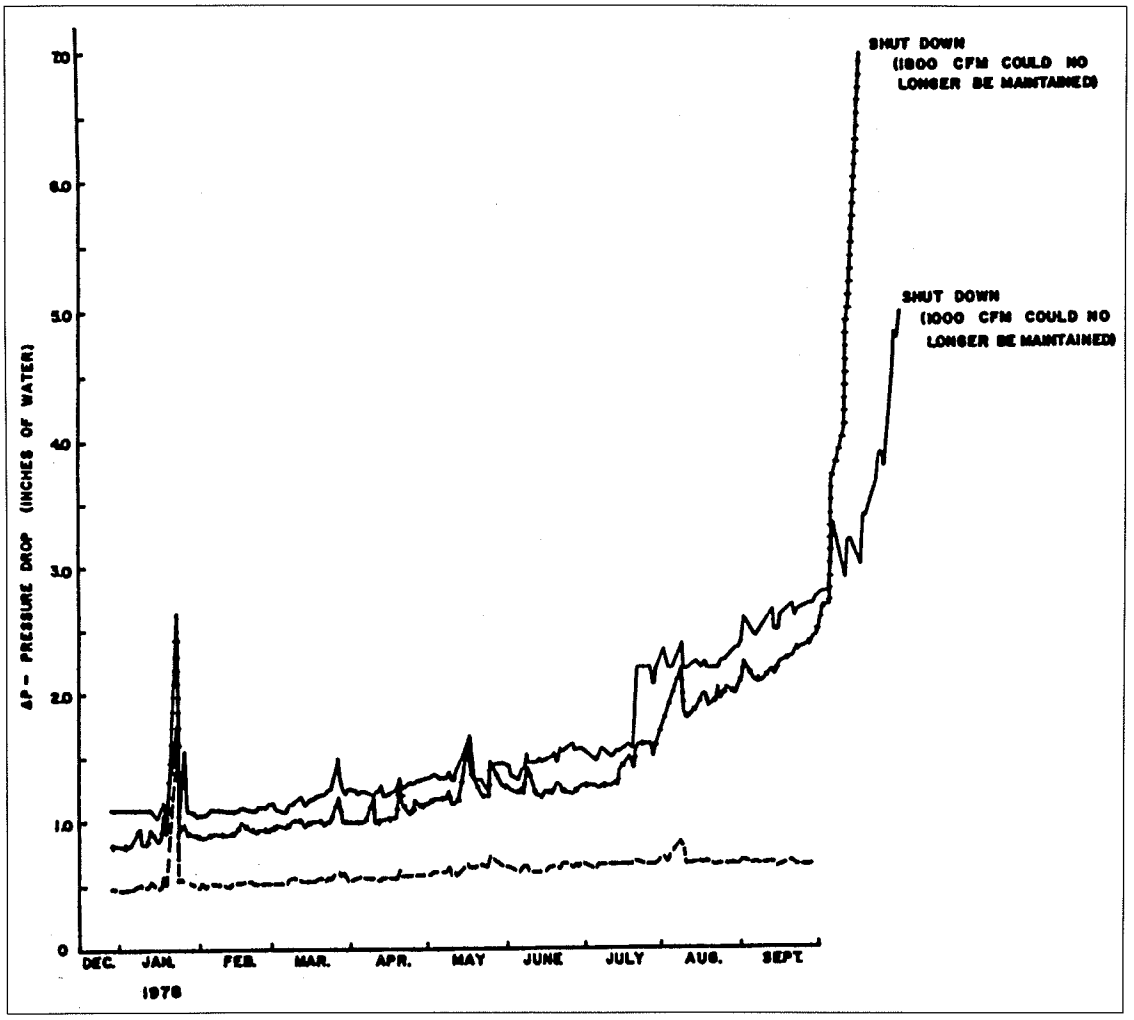
FIGURE 4
The effects of inertia, diffusion, and interception on the penetration-velocity curve for HEPA filter papers. (Courtesy International Atomic Energy Agency)



Filter Resistance Characteristics. As particles collect on the surfaces of fibers and in the interstices between them, the collected particles tend to form a coherent dust layer known as a filter cake. When this occurs, particle collection gradually shifts from media filtration (i.e., by the individual filter fibers) to cake filtration. This transformation produces two important changes: (1) efficiency increases in proportion to the increase in thickness of the cake and (2) after the formation of a coherent filter cake, the resistance of the filter to airflow, that initially increased at a slow and steady rate as particles accumulated, now increases at an accelerating rate in response to additional particle deposition and narrowing of pathways. Once this begins, the filter rapidly reaches its terminal design airflow resistance. Figure 5 shows a typical pressure rise curve for a HEPA filter exposed to atmospheric dust [11]. The long, slow pressure rise followed by a rapidly accelerating increase is clearly evident. The reason for the brupt change is the onset of sieving. It takes over when the collected particles form a structure containing less space between particles than the characteristic diameter of the particles being collected. When HEPA filters reach this stage, they must be replaced by new ones.

FIGURE 5

Pressure rise with operating time, atmospheric dust, deep-pleat and mini-pleat HEPA filters. (Courtesy U.S. Department of Energy)



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Construction and Service Characteristics of HEPA Filters

Filter Paper. Although originally composed of a mixture of asbestos and cellulose fibers, all high-efficiency filters are now made from a mixture of glass fibers of carefully graduated diameters that give the required particle retention efficiency without exceeding the maximum airflow resistance criterion at the design airflow rate. Consequently, there are innumerable combinations of fiber sizes that are capable of satisfying both requirements and each filter manufacturer has a proprietary formula that qualifies the product. The paper may incorporate up to 7% by weight of organic matter, divided between (1) a binder addition, such as latex, to give the paper strength and resistance to cracking at the bends and (2) a water repellent addition to protect the paper against wetting from deposition of liquid droplets, should they be present (9). Additional qualification criteria include:

1. Not less than 99.97% retention of 0.3 mm DOP particles at a flow rate of 32 L/min. through a paper area of 100 cm^2;
2. Clean airflow resistance not in excess of 40 mm of water (0.4 kPa) at a filtration velocity of 320 cm/min. (0.053 m/sec);
3. Average tensile strength after exposure to 6.0-6.5 x 10^7 rads (0.6-0.65 MGY) of not less than 179 g/cm of width in either direction; (not required for biosafety applications)
4. Resistance to excessive strength degradation after exposure to high temperature (370 ± 28 C) for 5 min. and to wetting by immersion for 15 min. (9)

HEPA filter papers acceptable for biological safety installations routinely give collection efficiencies greater than 99.99% when tested with 0.3 mm diameter DOP. By increasing the fraction of fine glass fibers that are less than 0.25 mm in diameter in the paper, it is possible to obtain efficiencies greatly in excess of 99.999% for 0.1-0.3 mm particles with a modest increase in filter resistance, typically about 25%. These papers are often referred to as ultra low penetration aerosol filters (ULPA) and are of special interest to manufacturers of microelectronic chips. These filters do not appear to have an advantage over HEPA filters manufactured to military, nuclear, or biological safety (NSF Standard 49) standards inasmuch as the sizes of bacteria and fungal spores are well above the minimum filterable size (where inertia provides increasing collection efficiency) and virus particles are well below, (where vigorous Brownian motion provides for high collection efficiency by the diffusional mechanism).

Deep Pleat HEPA Filters with Corrugated Separators. Filters constructed with paper pleated the full depth of the rigid outer frame and with adjacent pleats held apart by full-depth corrugated separators are widely used for biological safety applications. Construction requirements and acceptance criteria for filter units are provided by ASME (reference 9) that calls for the exclusive use of filter paper qualified in accordance with the criteria contained therein. The Institute for Environmental Standards has alternative consensus standards that have been adopted for "clean-room" use. It provides for three grades of high efficiency filter: The ASME or the IES "C" grade filters should be specified for biological safety applications. Both standards provide for: (1) standard rectangular filter sizes, (2) a variety of filter frame materials, (3) face gaskets constructed from flat strips of expanded closed cell neoprene sponge rubber having cut surfaces on both faces and notched or dovetailed corners, and (4) corrugated separators made of 0.4 mm thick, hardtempered aluminum foil. Often, the inside edge of the corrugated aluminum separator, that may be in contact with the paper is turned back on itself to form a less sharp edge to avoid paper cuts from this source during shipment.

Filter Mounting. Filters with gaskets should be mounted against a smooth, flat, continuously-welded structural-steel flange. Gasket compression is achieved with screw-down clamps. Single filter housings, referred to as caissons, can also be used for mounting individual filters. They are usually used when remote handling or "bag-in, bag-out" methods of filter changing are required. Whichever filter mounting method is selected, it has been found necessary to compress the gasket at least 80% to maintain a leak-tight seal for the life of the filter. Eighty percent compression of closed cell neoprene sponge requires a loading of approximately 1.4 kg/m^2 of gasket area, or a total clamping load of about 635 kg for a 61 x 61 cm filter unit. This is the reason that rigid structural shapes, rather than bent sheet metal structures, are needed for mounting frames, i.e., to avoid distortion under load.

Filter Operation and Maintenance. For biosafety installations, it is usual to design for enough filter capacity to give a clean filter resistance no greater than 0.25 kPa. New biosafety cabinet filters are likely to be even less, perhaps 0.15 kPa. Although HEPA filters are qualified to maintain their integrity and filtering efficiency up to a minimum resistance of 2.5 kPa, they are seldom operated up to that resistance level because of fan and fan motor limitations. A doubling of clean filter resistance before change is common for biosafety installations. Dust holding capacity is greatly influenced by the properties of the aerosol, with smaller particle sizes and greater size uniformity producing a more rapid increase in filter resistance for the same weight of deposited dust. For this reason it is not possible to give more than a general idea of filter service life. It is possible to monitor filter pressure drop and to change filters whenever the fan can no longer deliver the required air volume rate because of back pressure increase. It is important to keep in mind that airflow rate through the filter must be measured simultaneously with filter resistance, lest an acceptable pressure drop reading merely reflects a shift along the fan performance curve that responds to increased loading of the filters by a reduction in airflow capacity.

In a clean environment, HEPA filters may run for more than a decade before reaching their maximum design dirty filter resistance. This raises serious concerns regarding the detrimental effects of filter aging on loss of strength, paper embrittlement, loss of water repellency, shrinkage of adhesives, and a general lowering of safety factors to assure continu-

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ing design service performance until the next annual in-place filter test. These concerns have been expressed in a prior publication (12).

Filter Testing

Bench Testing of New Filters. Bench testing of new HEPA filters certified for biosafety service according to NSF Standard 49 [13] are conducted with a penetrometer, called a Q107, that was designed by the U.S. Army Chemical Corps during the 1950s [14]. The complete penetrometer consists of a monodisperse DOP aerosol generator, an instrument that measures the size and uniformity of the particles formed, a clamping device to seal the filter under test into the test rig, a forward light scattering photometer to measure DOP penetration, and a manometer to measure filter resistance at rated airflow rate. The size of the DOP aerosol is 0.3 mm. HEPA filters certified for biosafety applications will have test efficiency and filter resistance values marked on a side of the filter frame.

In-Place Testing of Filter Installations. Unlike bench tests for new filters that are designed to determine filter quality by means of an efficiency test utilizing an aerosol containing a substantial fraction of particles in the minimum filterable size range, in-place tests are designed to reveal the presence of defects in the filter unit that resulted from such things as rough handling during transportation, paper and gasket damage during installation, inadequate pressure against intact gaskets, and penetrations through the housing to which the filter units are attached. Inasmuch as each filter unit is assumed to have been satisfactory when it was certified by the manufacturer, aerosol penetration during an in-place test in excess of established limits is taken as a sign of a defective filter or installation, and standardized procedures are conducted to locate and correct the defects: e.g., gasket compression will be increased; gaskets will be examined for breaks and tears; and penetrations, cracks, and open seams in the filter house and mounting frames will be closed by welding. Each time, after repairs are made, the system must be retested until it meets established criteria for leak-tightness.

The standard method for in-place testing of filters for biosafety service is described in NSF Standard 49 [13]. It utilizes a polydisperse aerosol generated by compressed-gas nebulization of cold or heated liquid DOP. It is characterized by a light scattering median size of 0.7 mm, and a geometric standard deviation of 1.4 [13, sect. 2.8]. This aerosol has very different size characteristics from the one produced by the monodisperse DOP aerosol generator. The filter penetration values obtained by using a compressed gas-generated DOP should be, and are, different than when using the bench-test aerosol. This means that the in-place penetration criterion for acceptance cited in NSF Standard 49 is unrelated to the acceptance criterion for filter efficiency cited in reference 9. This should not be viewed as a defect in the procedure for assuring the quality of installed filter systems, but it must be recognized that the aerosol penetration numbers obtained from bench and in-place filter tests are not interchangeable.

Searching for Defects. The detailed examination that is undertaken to meet in-place acceptance criteria for biosafety cabinets is called filter scanning. It is conducted by generating an aerosol challenge in the usual way and then passing the probe of a direct-reading light-scattering photometer in overlapping strokes over the entire face of the filter (being careful to include all gasket edges and housing joints). This search for defects in installed systems is made easy by the use of direct reading aerosol detection instruments because, when the probe is located exactly in front of a leak, it draws in unfiltered aerosol and the indicator goes offscale. It is a tedious, but very sensitive, method for finding even small leaks, such as thin spots in the filter paper.

Filter Performance in Service

The wide diversity of aerosols generated in biosafety cabinets raises an important question regarding the relevance of the test procedures that are conducted with prescribed DOP aerosols, none of which will be likely to be encountered under normal service conditions. In fact, the standard qualification tests tell us very little about the performance of HEPA filters under realistic use conditions. Certainly, the aerosols present from microbiological operations are very different from the monodisperse DOP aerosols used to qualify filters for nuclear service, so that the efficiencies observed during the standard qualification tests are not necessarily the results that will be obtained in practice; they may

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be better or worse depending on the characteristics of the aerosol challenge.

Why perform the standardized tests if they do not tell us exactly how the filters will perform when called upon during normal service? The answer is that standard qualification test results should be looked upon as an index of merit, an indication of quality, rather than as a quantitative description of filter efficiency under unknown or ill-defined operating conditions. Passing a standardized qualification test gives reasonable assurance that the filters have been produced from high quality components and carefully assembled to exacting standards. Lacking test results with the precise aerosols that will be encountered during actual service conditions, this is probably the best that can be accomplished, and it is comforting to know that overall efficiency will not be lower than the value for the least filterable size. It is relevant to note that the qualifying penetration value was selected originally on the basis of what commercial suppliers of filters were reasonably expected to provide at that time. Today, filter efficiency usually exceeds the requirement by a substantial margin when the filters are manufactured in full compliance with the nuclear or applicable IES standard.

SUMMARY

The needs for high efficiency air cleaning systems have resulted in the development of very low penetration filters for submicrometer particles that represent the least filterable sizes (0.1-0.3 mm). The introduction of very low penetration filters made it necessary to develop testing methods capable of assessing a penetration fraction of 10^{-5}, or less. In-place testing of newly installed very low penetration filter systems has been incorporated into a number of national standards in recognition of the need for quantitative assurance that completed installations do not contain defects that reduce microbiological safety. For the same reason, periodic in-service retesting of filter systems is required. The current status of high efficiency air cleaning technology for aerosols is generally satisfactory, but improvements in materials for greater reliability, higher efficiency, improved capacity, and greater resistance to the detrimental effects of aging are possible and desirable.

REFERENCES

S.K. Friedlander, L. Silverman, P. Drinker and M.W. First, *Handbook on Air Cleaning* (U.S. Printing Office, Washington, DC, 1952), pp. 34-36.

I. Langmuir, *Report on Smokes and Filters*, OSRD 865 (OSRD, Office of Technical Services, Washington, DC, 1942).

E.A. Ramskill and W.L. Anderson, *L.Colloid. Sci.*, 6, 416 (1951).

W.L. Anderson (La Plata, MD), Personal communication to M.W. First, 1988.

V.K. LaMer and D. Sinclair, *A Portable Optical Instrument for the Measurement of Particle Size in Smokes*, (The OWL); and, *An Improved Homogeneous Aerosol Generator*, OSRD 1668 (OSRD, Office of Technical Services, Washington, DC, 1943).

W.G. Stockdale, J.C. Suddath, and W.K. Eister, "Control of Radioactive Air Contamination at Oak Ridge National Laboratory," in *Meeting of AEC Waste Processing Committee*, at Los Alamos, NM, TID-460 (Atomic Energy Commission, Technical Information Service, Oak Ridge, TN, March 1954), p. 55.

AM. Soc. Mech. Eng., *Nuclear Power Plant Air-Cleaning Units and Components*, American National Standard, ASME N509-1989 (New York, 1989).

AM. Soc. Mech. Eng., *Testing of Nuclear Air-Cleaning Systems*, American National Standard, ASME N510-1989 (New York, 1989).

AM. Soc. Mech. Eng., *Code on Nuclear Air and Gas Treatment*, American National Standard, ASME AG-1 (New York, 1996).

Webster's Third International Dictionary, Gore, Philip B., Ed. (G. & C. Merrium, Springfield, MA, 1963).

M.W. First and J.M. Price, "Performance of 1000- and 1800-CFM HEPA Filters on Long Exposure to Low Atmospheric Dust Loadings, III," in *Proceedings of 17th DOE Nuclear Air Cleaning Conference*, (National Technical Information Service, Springfield, VA, February 1983), p. 909.

First, M.W., *Aging of HEPA Filters in Service and in Storage*, J. Am. Biological Safety Assoc., Vol. 1, No. 1, p. 52. 1996.

NSF International, Class II (Laminar Flow) Biohazard Cabinetry, NSF International Standard, NSF-49, Ann Arbor, MI, 1992.

U.S. Dept. Of Defense, "DOP-Smoke Penetration and Air Resistance of Filters, Method 102.9.1," in *Filter Units, Protective Clothing, Gas Mask Components and Related Products, Performance Test Methods*, U.S. Military Standard, MIL-STD-282, (Edgewood Arsenal, MD, May 28, 1956), p. 33.

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