Session 9

CRITICAL REVIEW

TUESDAY: October 21, 1980

AEROSOL FILTRATION
M.W. First, H. Gilbert

AEROSOL FILTRATION

Melvin W. First
Harvard School of Public Health
665 Huntington Avenue
Boston, Massachusetts 02115

Humphrey Gilbert
Box 704
McLean, Virginia 22101

ABSTRACT

Significant developments in high efficiency filtration for nuclear applications are reviewed for the period 1968 to 1980. Topics of special interest include factory (bench) and in-place test methods, new developments in paper and filter unit construction methods, vented containment air cleaning systems for LMFBR and light water moderated reactors, and decontamination of offgases from nuclear waste volume reduction processes. It is noted that standards development has been vigorously pursued during this period but that advances in filtration theory have been few. One of the significant changes likely to occur in the immediate future is adoption of the European style of HEPA filters for those that have been in service for the past three decades to obtain the benefits of having almost twice as much filter paper in the same filter cartridge.

I. Introduction

In 1968, at the 10th Air Cleaning Conference, a review of the history and then-current status of aerosol filtration in the US nuclear industry was presented.[1] Because important aerosol filter developments that have affected construction and application in many ways have occurred during the intervening 12 years, it will be useful to bring the filter story up to date.

The single event that is likely to have the most profound influence on future developments in radioaerosol filtration is the loss of coolant accident at Three Mile Island (TMI) in March 1979 which must be considered a watershed event in the history of nuclear safety. Although the in-containment filters at TMI have not yet been examined,

two 30,000 CFM filter systems installed in the auxiliary building were called into service and they "removed essentially all of the particulates generated" in spite of the fact that these systems had never been retested since their installation[2]. The significance of this statement is unclear as the magnitude of the particulate challenge has not been defined up to the present. Whereas loss of particulate radioactivity from TMI was negligible, the widespread apprehension this accident engendered is likely to result in a demand for still higher collection efficiency and greater filter resistance to (a) internal disruptive events such as fires and explosions and (b) external natural disasters such as earthquakes and tornados. We will try to make some realistic judgments as to where we stand on these matters and where we seem to be heading in the development of better and more reliable aerosol filters. And finally, we will discuss what appear to be omissions in our development program.

II. Codes and Standards

Much progress has been made since 1968 in the documentation and codification of standards for filter installation and filter testing. An excellent compendium of essential information, mentioned in the 1968 review as "in preparation", The Nuclear Air Filter Handbook[3], has already appeared in a second edition and has become an essential reference source in this field. Of equal importance, and both available in 1980 revised versions, are ANSI N509, Nuclear Power Plant Air Cleaning Units and Components[4], and ANSI N510, Testing of Nuclear Air Cleaning Systems[5]. Although only intended to provide a standard for the construction and testing of engineered safety systems in US civilian nuclear power stations, the major part of each can be, and usually is, applied with equally salutary results to air cleaning systems in all manner of nuclear facilities in the US and abroad. The contents of the earlier editions of ANSI N509-1975 and ANSI N510-1975 have been substantially incorporated into US Nuclear Regulatory Guide 1.52 (Revision 1)[6]. It seems reasonable to anticipate the early appearance of Revision 2 of this document to reflect the changes that have been made in the 1980 update of these standards.

The oldest and most enduring of nuclear filter standards had their origin in military standards developed by the US Army Chemical Corps and NDRC during World War II. These are the military specifications for HEPA filters[7], HEPA filter media[8], and filter testing[9] that were adopted initially by the AEC and subsequently modified several times as a joint enterprise of DOD and the nuclear agencies. The principal modification in the military standards since 1968 centered around requirements for the resistance of the filter medium to radiation, the interest being prolonged survival of filter effectiveness following a core disruptive accident. For ease in procurement, the military (Edgewood Arsenal) have recently qualified a number of producers of HEPA filter paper and assembled filters and published their names in a Qualified Procurement List (QPL).[10] Under study at this time is a proposed standard to permit testing high volume filter units (1800-2000 cfm) at less than rated capacity (e.g. at 1000-1200 cfm). This will require the filter medium alone to be tested with 0.3 μm dioctyl phthalate (DOP) over a range of velocities so that test results obtained with an assembled filter unit at a lower air flow

rate can be normalized when calculating the efficiency that would be expected at the rated flow compared to the current efficiency standard of 99.97%. The purpose of this proposed test modification is to permit the continued use of test equipment with an airflow capacity limit of 1000-1400 cfm. More will be said about high capacity filters in a later section.

III. Developments in Filtration Theory

Studies of basic filtration mechanisms that are directly applicable to HEPA filter media have been few over the past 12 years and their achievements in helping us gain a better understanding of how particle separation and retention take place have been modest. Whatever small improvements in filter paper have been made in the interval have resulted from empirical experimentation rather than from the application of a more adequate, and hence more useful, theory. It is not clear whether this results from a conviction that we now know most, or all, there is to learn about aerosol filtration through fine fiber mats or a feeling on the part of many that commercial filter papers are now so near perfection that there is little to be gained by trying to make them still better. Although commercial filter papers are extraordinarily good, neither of these suppositions withstands searching examination, as will be brought out in the course of this review, and it is hoped that one outcome will be a renewed interest in solving the remaining problems associated with the manufacture and application of HEPA filters.

The sad state of affairs with respect to the advancement of filtration theory for HEPA filters is reflected in an overview paper presented by R.G. Dorman, entitled "Filtration Theory" at a November 1976 Seminar on High Efficiency Aerosol Filtration[11] that contained only 3 references out of 28 with a publication date later than our own 1968 review and with none of the three later than 1971.

Two exceptions to this dismal picture are (1) a paper presented at the 1974 Air Cleaning Conference by Anderson, Magee and Jonas that undertook to examine and analyze previously unreported filter performance data that had been collected at the Naval Research Laboratory[12] and (2) a basic study of the diffusional separation mechanism for submicrometer particles at the Harvard Air Cleaning Laboratory that was reported at the same 1974 Air Cleaning Conference[13]. The Anderson, et al. paper subjected voluminous empirical observations to multiple linear regression analyses by computer techniques into a factorial design that incorporated the basic filtration parameters of particle inertia, particle diffusion, and filter fiber interception with filtration velocity and particle size over the range 0.26-0.32 μm. The resulting machine-optimized linear regression equations account for all the important filtration parameters with correlation coefficients ranging from 0.844 to 0.999. The equations confirmed that (a) the inertia parameter makes an insignificant contribution to the filtration of particles of this size at the filtration velocities utilized (b) the interception parameter is independent of particle size and (c) the diffusion parameter is the most important for HEPA filtration and shows "a non-monotonic dependence on aerosol size[12]". Although this was a valuable study

in that it quantified more exactly prior knowledge about filtration mechanisms, it provided little new information about the laws of nature that govern fine particle filtration.

A more fundament study of diffusional separation of small particles (0.02-0.2 μm) by small diameter fibers (4, 8, and 12 μm)[13] showed that current diffusional filtration theory could be used to predict efficiency over a gas temperature range from 357-711°K. An important relationship developed in this study was the influence of single fiber efficiency and filter solidity on total filter penetration. The filters used in this study were of very low solidity, were composed of monodisperse fibers and were not meant to simulate HEPA filter media. Nevertheless, experimental confirmation of the diffusional separation parameter defined by Fuchs and Stechkina[14] by way of the Peclet number is a step forward in understanding the most important basic separating mechanism involved in HEPA filter particle collection.

IV. Developments in HEPA Filter Construction

US and UK HEPA filter construction is very nearly identical and this design has been the mainstay of the nuclear industry for the past three decades. This is understandable as these filters reached a state of near perfection with respect to retention of submicrometer particles when filter manufacturers found ways of improving their assembly techniques to the degree that they were frequently able to turn out filters that exceeded required particle retention efficiency by an order of magnitude, i.e., from 99.97% efficiency to 99.997%. In addition, the filters exhibit notable resistance to chemicals, flame, high temperature, and radiation. This is unusual as generally the reverse occurs, i.e., manufacturers have difficulty meeting equipment performance standards and often government regulations are designed to be technology forcing. Of special note, is the almost total substitution of aluminum for asbestos as construction material for corrugated separators and the introduction of urethane plastic as a sealant between filter pack and rigid casing in place of rubber cement. Both substitutions have proven acceptable when subjected to the test regimen of military standard MIL-F-51068[7].

To an important degree, the establishment of USAEC Quality Assurance (QA) Filter Test Stations in 1960 made it imperative for filter manufacturers to institute their own rigid quality control practices to avoid product rejection at the filter test stations. For example, forty-nine percent of filters manufactured prior to 1960 were rejected at the filter test stations whereas only 5% were rejected during the following 8 years.[15] By 1978, the rejection rate had declined to a point where the U.S. Nuclear Regulatory Commission was willing to forgo QA Filter Test Station inspection of filters intended for use as engineered safety feature (ESF) systems in commercial nuclear power plants on the basis that the marginal increase in the reliability of tested filters no longer justified the addition of 30% to filter costs[16].

Although UK filter construction methods and filter materials have closely paralleled US practice, a number of manufacturers in

other European countries have been making a different high efficiency filter for the past several years with US-manufactured paper. Instead of filter paper pleats that extend the full depth of the filter cartridge, their paper is folded into mini-pleats about 20-mm deep with a pitch of 3-mm. Adjacent pleats are separated by ribbons or threads of glass, foam, plastic and asbestos. A full size filter is assembled from several component panels of this construction arranged around a series of V-shaped air passages. This design allows considerably more filter paper to be incorporated into a given volume, making it possible for a standard US filter unit of 24 x 24 x 11½ in. to be displaced by one of identical dimensions that is able to handle 1,800-2,000 cfm instead of 1,000 cfm at a clean filter resistance of 1 in. w.g. and to meet the maximum DOP penetration standard of 0.03% at this higher volumetric flow rate. Alternatively, if a 1,800-2,000 cfm-rated mini-pleat filter is substituted for a US-design filter of equal size, the airflow resistance of the mini-pleat filter for the same air flow rate will be reduced to 55% of that of the US filter it replaces. Further, as there is almost double the amount of filter paper in a mini-pleat filter, dust will have a greater surface on which to deposit and the filter resistance increase from dust deposits will be only 55% as rapid as for the US filter unit of equal size. Combining these two effects, theory predicts that the overall rate of resistance increase of the mini-pleat filter will be only 30% as rapid (i.e., 0.55x0.55=0.3). Not only does this mean that the European style filters will last longer, but, in addition, the number of filters discarded will be reduced proportionately. Inasmuch as the cost of nuclear waste disposal services has made it more costly to discard used filters than to purchase and install them, this is an important consideration and tests have been underway for the past four years at the Harvard Air Cleaning Laboratory to learn if theory can be confirmed by experiment.[17] Conventional US filters and mini-pleat filters have been exposed to atmospheric air side by side without prefilters at rated capacity and, for the 1800 cfm mini-pleat filters, at 1000 as well, until they reach a filter resistance of 4 in. w.g. The mini-pleat filters have not fulfilled their theoretical promise of more than three times service life because the narrow air passages between the mini-pleats seem to bridge over with dust and lint earlier than do the wider spaced pleats of the US design. However, a considerable degree of extended life is achievable and this may be a worthwhile improvement in spite of the present much higher purchase cost of European mini-pleat filters. US filter producers have already recognized these advantages and at least two have begun manufacturing mini-pleat HEPA filters[18,19]. It has been recognized that we may be on the verge of a radical change in the design of HEPA filters intended for use in US nuclear facilities and this has been the stimulus for the search that was referred to earlier for an acceptable method of bench testing high capacity filter units with existing test equipment.

Inasmuch as mini-pleat high capacity filters give an indication of failing because of bridging of the extremely narrow air passages between pleats (an absolute necessity if almost twice as much paper is to be pleated into the same volume as the conventional design US and UK filters) rather than by a uniform coating of the entire paper surface, there is currently much interest in trying to prolong the ser-

vice life of mini-pleat high capacity filters by using low resistance prefilters, some of which have been reported to have acquired greatly improved particle retention characteristics by the use of electrostatics. One such prefilter uses the electrostatic properties of electret fibers that carry a permanent electric charge[20] and another employs a non-ionizing electric field in combination with a fibrous filter[21]. Both developments are reported to give a spectacular improvement in filter efficiency with no increase in air flow resistance, either initially or as dust accumulates in the fiber structure. Additional filter comparison tests with prefilters are underway at the Harvard Air Cleaning Laboratory and elsewhere to define the precise application conditions under which mini-pleat filters are likely to give optimum service life.

One aspect of the performance characteristics of mini-pleat high capacity filters that has not yet received sufficient attention is their ability to withstand rough usage and prolonged exposure to unfavorable environments. (See also Section XI.) Experiences up to the present with filters from a number of different sources have not been completely reassuring in this regard and it is doubtful that we should advocate their use for critical nuclear service until their ability to withstand adverse stress conditions of all kinds has been proven by test and service to be at least equal to the filters constructed according to the accepted US military and nuclear design standard. This is a critical matter because a thin membrane composed of fine glass fibers can become the final barrier between a highly contaminated area and the environment.

A novel filter design having air flow capacitymidway between the standard US units and the mini-pleat design is a filter fabricated without separators between full-sized pleats. Because of the absence of corrugated separators, more paper can be placed inside the same filter frame and, in addition, there is less area of filter paper blinded by contact with impervious separator corrugations. The manufacturer describes the product as follows: "The filter pack [is] constructed by pleating a continuous sheet of molded glass medium back and forth over itself so that the filter pack is self-supporting without the use of separators. The paper-making, forming and pleating of the medium [is] a single, continuous manufacturing process."[22] A wet paper, cast about 20% thicker than for a flat sheet, is formed on a conventional Fourdrinier paper making machine and then grooved by vacuum molding on a slight bias relative to the run of the paper so that after pleating the crests of contiguous pleats crisscross and prevent nesting. Because the paper corrugations are deeper than those formed by separators, some of the advantage of eliminating separators is lost, insofar as it is intended to increase effective paper surface by elimination of impervious areas of contact between paper and separator. These filters have met all the test conditions contained in military standard MIL-F-51068[7] but, up to now, there has been modest engineered safety system service experience to report, only suggesting we exercise the same caution recommended for the mini-pleat high capacity filters. (See also Section XI.)

V. Developments in HEPA Filter Paper

Asbestos, the original small diameter, high efficiency fiber in the filter medium, is no longer used in papers meeting military specification MIL-F-51079 [8]. This has not come about for the reason that asbestos is inferior to superfine spun glass for paper making (which it is), but rather because asbestos has been designated a carcinogen by the US Occupational Safety and Health Administration and paper makers are no longer willing to handle it. The use of asbestos persisted from the time of World War II because, for some, it was a cheaper fiber than superfine glass and, for others, it had greater resistance to hydrogen fluoride than all-glass paper. The Atomic Energy Commission supported research efforts to develop a paper made from more HF-resistant glass fibers for many years without notable success [23] insofar as the development of a commercial paper with all the required characteristics are concerned. A mixture of asbestos fibers with glass fibers was settled upon as the most acid-resistant medium then available. Although the paper furnish started out as a mixture of 95% glass and 5% asbestos, the finished paper contained only 1%-2% asbestos fibers because the fine diameter crocidolite fibers were becoming lost through the screen of the papermaking machine. Handsheets of filter paper containing increasing concentrations of asbestos were made to find a more acid-resistant formulation but the effort achieved little success and was finally abandoned. Some of the filters with glass-asbestos paper contained chrysotile asbestos separators and when they were exposed to acid-containing gases, magnesium leached from the asbestos separators and formed magnesium nitrate on the downstream face of the filters. A soluble form of this compound became liquid in the humid exhaust air and blew off to degrade successive banks of filters.

For nuclear applications when HF is present in more than trivial amounts, a substitute for asbestos-containing paper is urgently needed. Papers made from ceramic fibers composed of silicon dioxide and aluminum oxide have higher HF resistance than glass but these fibers have not been produced in fiber diameters small enough to give the required particle retention efficiency to the paper unless they are mixed with asbestos [24].

A recent development in the production of HF-resistant filter media that possess characteristics that conform with the requirements of military specification MIL-F-51079 is a glass-fiber paper containing 2% of temperature-resistant polyamid, or nylon, a medium which one filter paper manufacturer already has on the market [25]. Laboratory tests in a chamber exposing the medium to mild concentrations of HF and HNO_3 in a humid atmosphere were sufficiently encouraging to initiate tests of full-size filters exposed to 2-3 ppm HF and 100 ppm HNO_3 in a humid atmosphere. Filter life of the experimental filters was 10 months compared to 4-5 months for filters made with glass-asbestos medium [26]. The improved service was partially attributable also to the use of some filters without separators and to others with aluminum alloy separators completely covered with a thin coat of epoxy. These separators are now available from several filter manufacturers.

Another formulation has been manufactured with glass fibers and 5% of temperature-resistant nylon fibers. This has provided encouraging results from laboratory exposures, and filters containing this fiber mix are currently undergoing service life tests. Laboratory work is in progress to develop a filter medium incorporating a different nylon that may offer greater temperature and chemical resistance.

VI. Filter Testing

There is a significant difference in the method used to test filter efficiency in the factory (test stand) and in the field between European countries and the US. In the US, a 0.3 μm monodisperse DOP aerosol is used for factory and QA Test Station filter testing[9,27], but a 0.7 μm mass median diameter (MMD) polydisperse DOP aerosol[28] is used for in-place filter testing[5]. Light scattering photometry is used for both. In Britain, a polydisperse sodium chloride aerosol generated from dried brine droplets is used for factory testing and a flame-generated polydisperse salt aerosol of about 0.3 μm is used by some installations for in-place testing[29]. Measurement is by sodium flame photometry for both. However, the CEGB uses condensation nuclei, generated by a burner, and a Pollak nuclei counter for their in-place filter tests[30]. In France, the test aerosol contains polydisperse liquid-spray generated uranine particles having a count mean diameter of 0.08 μm. Simultaneous up and downstream samples are collected on membrane filters and measurement of the uranine, dissolved in a suitable solvent, is by spectrofluorimetry[31].

Considerable effort has been expended over many years with only partial success to discover conversion factors that would make it possible to convert filter efficiency measurements by one method to an equivalent value when measured by the others[32]. Although it would be very convenient if everyone used the identical filter test method, this is unlikely to occur in the foreseeable future. Lest this be considered an overly serious matter, it should be kept in mind that whatever bench test is used, it merely provides a convenient and standardized "index of filter efficiency" that is unlikely to be duplicated by the aerosols that will be encountered when this same filter is used in nuclear facilities, i.e., the size, shape, and specific gravity of nuclear plant aerosol particles are likely to differ substantially from those in the test aerosol. We expect that nuclear plant aerosols will be more easily filtered than our bench test aerosols, but this is not inevitable. Therefore, a search for precise equivalence between bench test results and field results is unlikely to be rewarding.

Interpretation of in-place tests in terms of filter efficiency is fraught with even greater uncertainty than attempting to find conversion factors between the several "standard" tests inasmuch as the original intent of in-place tests was a search for installation defects rather than an attempt to re-quantify penetration[33]. The decision of the Nuclear Regulatory Commission to by-pass the QA-Filter Test Stations in favor of in-place tests for filters intended for service in engineered safety feature (ESF) systems, combined with an emphasis on the use of very challenging aerosols in the British thermal sodium chloride test and the French uranine test (both of which use very

much smaller particles than are needed for spotting gross defects), suggests that in-place testing is being transformed in a gradual manner into some kind of an efficiency test that seems likely to become the primary reference standard for nuclear filtration systems in place of sole reliance on manufacturers' bench test results. As a further manifestation of this trend, the use of intercavity laser single particle counting and sizing devices has been proposed as an alternate US Standard for in-place testing[34]. Though accurate measurement of the particle size efficiency of a filter system after installation provides the kind of information most likely to satisfy regulatory agencies and reassure the general public, little attention has been given to quantifying the reliability of in-place efficiency tests in comparison with bench or laboratory tests. Further, the precise meaning of overall weight efficiency tests conducted with polydisperse aerosols is highly dependent on the particle size distribution of the aerosol particles. A special difficulty with the proposed single particle counting and sizing method is that no acceptance criteria have been formulated so that it is not a performance standard but merely a test method. This is a very real difficulty inasmuch as a full particle size-penetration curve resulting from the use of this proposed test method permits of no simple interpretation, e.g., should the maxiumum penetration criterion (whatever it might become) apply equally to each and every particle size measured, to the sum of all particles of every size, or to just certain critical sizes such as DOP particles 0.3 μm or 0.07 μm diameter? Until decisions have been reached on how to interpret the data obtained by the application of particle size - penetration measurement devices, the development of a standardized test method may be premature. Further, it would be prudent to gain wide experience with the method before accepting it as a US Department of Energy Nuclear Standard. In addition, the use of very high upstream particle concentrations, called for by this proposed test method, is self defeating as rapid agglomeration, with a corresponding change in particle size, occurs whenever submicrometer particles are generated in numbers that are substantially in excess of 10^6 per cc. Therefore, before we drift into a position of total reliance on a poorly defined in-place efficiency test, we should make a searching study of each proposed in-place test method in the laboratory and in the field to evaluate error functions and to determine whether such a reliance on in-place efficiency tests, as currently performed, will produce significant net benefits over currently used methods.

Indeed, a case can be made for entirely omitting factory bench and QA station testing with monodisperse 0.3 μm DOP (hot) and, instead, relying solely on a polydisperse (cold) DOP search for defects. The essential precondition for accepting such a radical change in our established methods for rating HEPA filters would be thorough testing and certification of filter papers prior to their fabrication into filter units. The basic assumption here is that when the filter medium meets all requirements of military specification MIL-F-51079, the only way in which the assembled filter can fail to deliver the required filtration efficiency would be because of defects in fabrication or physical damage to the filter web during shipment or handling. In either event, a simple defect test, such as the standard cold DOP in-place test procedure, will serve to detect defects reliably and rapidly, thereby performing the identical function that the

hot DOP test does - although we tend to term the latter, by long custom, a filtration efficiency test. It is useful in this connection to examine the in-place filter test procedures contained in National Sanitation Foundation Standard No. 49[35] for biological safety cabinets For this test, the entire surface of the installed HEPA filter, including gaskets, is scanned with a one-inch-diameter probe. The installation is acceptable if there is no penetration reading in excess of 0.01%. This standard permits patching of defective filters, thereby making most installed filters acceptable, along with easing the problems of filter installers. As a consequence, any filter passing this test will have average penetration less than 0.01%. This is a more rigorous acceptance standard than the usual 0.05% penetration overall. However, any proposal to apply procedures such as NSF No. 49 to nuclear operations must consider that scanning a filter surface for defects is manpower-intensive. Biological safety cabinets are equipped with few filters so that the work is not great for a single cabinet, but nuclear facilities use many filters in banks and frequently the work must be conducted in a radiologically contaminated zone requiring personal respiratory equipment and protective clothing. In addition, it has been found that the adhesive used for patching a filter burns through adjacent pleats when exposed to the 700°F heated air test prescribed in UL 586[36]. For this reason, patching is not allowed for nuclear filters although permitted for other HEPA filter applications. Therefore, a recommendation for improving the efficiency of nuclear filter installation by this procedure requires clear justification on a cost-benefit basis.

In addition to these standardized single filter tests, there has been a longstanding need to evaluate the efficiency of two or more HEPA filters in series when they are employed for critical operations such as filtering exhaust air from plutonium processing. After passing through two HEPA filters in series, the test aerosol no longer contains a sufficient particle concentration to induce a usable signal in the downstream detector when one of the two filters has an unacceptable penetration value; and sometimes, when neither alone would pass the usual test. To overcome this difficulty, it has been proposed that the intercavity laser single particle counter method, referred to earlier[34], be used for in-place testing instead of the method contained in ANSI N510.

It is well established in filtration theory that each identical filter in series will collect the same fraction of a monodisperse aerosol as the filters ahead of and behind it, regardless of the aerosol concentration with which it is challenged. Use of a monodisperse aerosol, such as hot DOP, would make it possible to calculate the overall efficiency of many filters in series by a knowledge of single filter efficiency alone, but it is not practical to generate monodisperse aerosols for in-place filter testing nor are the aerosols encountered in service likely to contain monodisperse particles. A partial solution to this problem would be to measure the particle size-efficiency of a single clean filter by some such device as an intercavity laser particle sizer and counter with size range from 0.09 μm upward and then to calculate the penetration of successive filters in series on the basis of the numbers of each size of particle that would penetrate all upstream filters[37]. However,

the calculation method is acceptable only for new, clean filters because the filters will increase in particle removal efficiency in proportion to the amount of dust previously deposited on the filter paper surfaces. Obviously, the first filter in the series accumulates much more dust than succeeding filters in the series and hence it may no longer be assumed that every filter in the train continues to exhibit identical particle retention properties nor that the precise particle size retention characteristics are still known. Therefore, an in-place test method for HEPA filters in series is still required if we wish to check the effectiveness of operating filter trains periodically.

The critical nature of the in-place tests specified in ANSI N510-1980 and US Nuclear Regulatory Guide 1.52 (Revision 1) for reactor safety have focused attention on the need for objective qualifications for the personnel who conduct these tests and those who supervise them[38]. To this end an ASME/ANSI nuclear standard entitled, Qualifications of Field Testing Personnel for Nuclear Air and Gas Cleaning Components and Systems, has been in preparation by the Committee on Nuclear Air and Gas Technology (CONAGT) for the past few years and has already received a favorable vote by CONAGT members. Preparation of a companion personnel qualification standard for those who perform laboratory acceptance tests on nuclear grade activated carbons is planned by the same committee.

With respect to the filter paper test procedure, a task force of the Government-Industry meeting on Filters, Media and Media Testing[39] critically examined the applicable military standard, MIL-Std-282[9], and determined that the Q127 hot DOP generator[40] was not, in all cases, capable of producing the aerosol prescribed by MIL-Std-282. Therefore, a modified standard was prepared by a task group composed of Government-Industry meeting members and transmitted to CONAGT with a recommendation for adoption. This is currently under consideration. The principal deficiencies relative to the existing standard are an aerosol concentration less than 100 µg/L, a median size of 0.3 µm that does not correspond with a setting of 29.5 degrees on the OWL particle size analyzer, and a geometric standard deviation of the aerosol particle size distribution that exceeds "plus or minus 10%". It was proposed by the task force that the standard be amended to agree with practice.

A different approach was taken by Edgewood Arsenal. Several years ago, they awarded a contract to A.D. Little Co. to re-examine the theory behind the measurement of the median size of hot (monodisperse) DOP aerosol and to design a new aerosol generator that would produce the desired aerosol characteristics more precisely and more reliably. An A.D. Little report[41] indicated that a recalculation of the light scattering properties of submicrometer aerosols according to Mie theory confirmed the results reported by Hinds, et al.[42] and Skaats[43], based on intercavity laser single particle counting[44], and that the standard setting of the particle sizing OWL on the Q127 DOP generator did not produce a monodisperse DOP aerosol of 0.3 µm diameter. A.D. Little Co. has constructed a single prototype hot DOP generator intended to be an improvement over the Q127 but this unit has not yet undergone testing and its performance characteristics are presently unknown. Although the development of an intercavity laser single particle sizer

and counter capable of detecting and measuring particles as small as 0.09 μm has been a notable technical achievement and a boon to aerosol scientists, its application to DOP measurement has disturbed nuclear filtration scientists greatly because of discrepancies between laser and traditional measurement results. It is apparent that all doubts regarding which method gives the most reliable results will not be laid to rest until expert aerosol scientists have had an opportunity to study the two systems side-by-side in a research setting.

A matter of grave concern over the past 6-7 years has been a persistent but unconfirmable rumor that DOP has been found to be carcinogenic. After the US Environmental Protection Agency listed DOP as a toxic substance in their Hazardous Waste Regulations, of May 9, 1980[45], this concern was intensified and tentatively confirmed by a Draft NTP Technical Report[46]. To forestall a cessation of in-place testing should DOP become a recognized carcinogen, the size distributions of a number of substitute substances were measured with an intercavity laser particle counter and sizer after aerosolization with a standard Laskin nozzle. It was found that medicinal grade mineral oil, dioctylsebacate, polyethylene glycol 400, and food grade corn oil gave essentially the same size spectrum as did DOP when aerosolized by the same device[47]. The median size by count of each was close to 0.25 μm (MMD=0.7μm) and the geometric standard deviation (GSD) was close to 1.5. The use of these potential DOP substitutes has not been investigated systematically in hot (monodisperse) DOP generators, although preliminary tests with pentaethylene glycol have given good results.[48]

VII. Sand Filters

A number of large sand filters were constructed at Hanford and Savannah Works by duPont in the late 1940's and early 1950's that closely followed the deep bed, graded granule techniques that had become widely accepted for building granular filters used for sulfuric acid mist elimination at acid manufacturing plants and for the purification of municipal drinking water supplies[49]. These filters had collection efficiencies for particles greater than 0.5 μm that compared favorably with the best fibrous filters then available and, in addition, have long service life, are non-flammable, and are largely unaffected by condensed water and strong acids. However, they are large, expensive, and non-disposable. The rapidly emerging glass fiber technology of that period shifted attention to the use of very deep beds (several feet thick) of graded glass fibers as a satisfactory substitute for sand filters when treating the gaseous effluents from chemical operations[50], and, as noted in the 1968 review[1], little interest remained in sand filters at that time. A decade later, there is renewed interest in sand filters for applications to liquid metal fast breeder reactors and emergency containment venting for light water reactors.

Experimentation with sodium aerosols has revealed how difficult it will be to provide adequate storage space and corrosion resistance in conventional glass paper HEPA filters for these chemically reactive and closely packing particles[51]. As a consequence, sand filters

are under study for engineered safety systems because of their desirable characteristics of nonflammability and nonreactivity in contact with sodium[52]. Their potential for storing large amounts of sodium in the interstices of the size-graded granules is highly regarded; in contrast to HEPA filters that retain particles on the paper surface and rapidly accumulate a high resistance filter cake.

A decision was reached during the design stage of the Clinch River Breeder Reactor demonstration plant to utilize vented containment in the event of a serious loss of coolant accident. This represented a departure from the past policy of total containment and it is possible, therefore, that deep sand filters may become the aerosol filter of choice for the liquid metal cooled fast breeder reactor. This seems to be the conclusion reached by investigators at the Nuclear Energy Research Center, Karlsruhe, Federal Republic of Germany[53], and at C.E.N., Cadarache, France[53].

The events at TMI have generated serious reconsideration of vented containment for light water reactors, also. The reason for this is a report that a hydrogen bubble substantially in excess of 100,000 standard cubic feet formed in the containment vessel of TMI-2. Burning of hydrogen is believed to have been responsible for a 28 psig pressure spike that was observed[2]. A more severe coolant loss might have resulted in hydrogen production rates 3 to 4 times those that were estimated for TMI-2 and if ignited, the temperature and pressures produced would be likely to exceed the strength of the containment vessel. The option of containment venting is thought to be essential to prevent such an occurrence and gas venting rates of 30,000 to 100,000 cfm are being considered. A 1979 UCLA concept study[54] indicated that a sand filter in excess of a quarter of a million cubic feet would be required for this purpose and would have to contain a hydrogen ignition chamber followed by cooling chambers, HEPA filters, and charcoal banks of appropriate gas flow capacity. These are large air cleaning systems by any standard and are estimated to cost ten million dollars or more.

Now may be the time to revive interest in the floating roof containment vessel concept that was proposed and investigated during the period that the nuclear rocket engine program was underway in the US. It was designed to provide long period leak-tight retention of waste gases with the option of decontaminating them slowly (days) in very high efficiency small scale apparatus[55]. It has a potential for greatly reducing the capital cost of gas cleaning systems capable of handling for a sustained period a maximum instantaneous emission rate from containment venting. Long period holdup has an added advantage of allowing much of the short lived noble gas activity to decay. This overcomes an obvious deficiency of prompt, large capacity, once-through air cleaning systems for containment venting that incorporate no significant gas retention period.

VIII. Filtration of Gaseous Effluents From Waste Treatment Processes

Incineration of a wide selection of solid wastes contaminated with radioactive materials of many kinds has been practiced widely

for the past three decades [56]. In the US, experience with decontaminating incinerator offgas was so unsatisfactory and costly that compaction and ground burial at specially prepared and guarded sites became the preferred disposal method in the 1950's and solid waste incineration ceased. In Europe, perhaps because of much greater difficulty in finding suitable remote burial sites, incinerator operation has been continuous.

The offgas cleaning systems employed for the early waste incinerators characteristically contained numerous stages in series and usually included: (a) one or more quenching and coarse particle collecting water scrubbers (b) one or more stages of high efficiency small particle collectors (c) a gas reheat stage to lower the relative humidity of the gases and (d) one or more banks of HEPA filters for the final cleaning stages. Charcoal filters might be added if radioiodine was thought to be present in a form that would not be collected by the wet stages. These gas cleaning trains became thoroughly contaminated with radioactive solids, making maintenance, of which there was a great deal, difficult. They discharged the collected radioactivity in many separate waste streams which usually required further processing - often of a very difficult nature. And finally, destruction of the HEPA filters after they became clogged often demanded a substantial fraction of incinerator working time.

Interest in solid waste incineration to reduce bulk, in preparation for storage, has been rekindled in the US in response to the widespread closing of waste disposal sites and a substantial increase in the cost of burial services. This renewed interest has taken two forms: (a) revival of the unsatisfactory systems in use 30 years ago and (b) development of new types of burning chambers and offgas cleaning systems. The incinerator development at Rocky Flats, Colorado, will serve as an example of the new breed of incineration facility for contaminated solid wastes [57]. It utilizes fluidized bed combustion and requires waste shredding as a preparation step. Because a sizable fraction of the waste consists of PVC items that form hydrogen chloride on burning, the fluidized bed is composed of sodium carbonate pellets that react with hydrogen chloride as it evolves from the waste. The hot gases pass through a cyclone collector where pellet fragments and coarse ash particles are extracted and then to sintered metal tubular filters where the bulk of the remaining dust is removed. Individual sintered metal tubes are cleaned periodically by reverse pulses of compressed air that dislodge the filter cake without interrupting gas flow. The cleaned gases are then cooled in a heat exchanger and passed through HEPA filters for removal of all residual dust. This all-dry system avoids the corrosion that occurs when handling hydrogen chloride gas by wet collection devices, delivers a reduced volume of dry particulate waste for disposal, and performs high efficiency cleaning of the waste gas stream.

Reverse-jet-cleaned sintered metal tubular dust filters are also being used in the gas cleaning train of the spray drying units operated at Richland, Washington for drying, sintering, and vitrifying high level liquid wastes derived from fuel processing [58].

For both operations, granular moving bed filters are being investigated as a substitute for the sintered metal tubular filters that have high airflow resistance (>20 in. w.g.) because they behave as sieves rather than as true filters and have a tendency to become permanently clogged. Granular beds act as true filters, have large voids for storing large amounts of filtered dust at low pressure rise, and, when cold pellets are cycled through the apparatus countercurrent to hot gases containing fine particles, the thermophoretic separating forces that are generated have a potential for greatly increasing collection efficiency for particles substantially below 1 μm[59]. Not only does such a filter act as a heat exchanger as well as a filter, thereby eliminating one piece of equipment, it also prolongs the service life of the HEPA filters that follow because of an ability to remove the finest particles that would otherwise clog the final stage of HEPA filters. Because the high temperature and corrosive conditions associated with solid and liquid waste reduction by heat processes generate an especially difficult environment in which to operate conventional HEPA filter trains, the types of more resistant gas cleaning units noted above will be needed to cope with the increasing waste load.

The effort to reduce the volume of radioactive waste generated from depleted HEPA filters has been unrelenting. A compactor has been designed and brought into operation which will punch out the filter pack of a 1000 cfm filter and, depending upon filter design, compress the pack to within 5% to 15% of its original volume. Some 600 spent filters have been handled successfully in recent months. Future development programs include plans to reduce stripped wood filter frames in a fluidized-bed incinerator.[60]

IX. Operation of Nuclear Offgas Cleaning Systems

Numerous studies of reportable failures of gas cleaning and other safety systems in US commercial nuclear power stations (licensee event reports, usually referred to as LER's) have been published since 1974. They cover the 12-year period from 1966 to 1978[61,62]. Although only commercial power station failures were covered in these studies, it is reasonable to assume that the findings have relevance to offgas cleaning systems designed and used in nuclear systems engaged in different operations. The objective was to identify failures that have safety implications for the purpose of finding ways to eliminate them from future operations insofar as that may be possible.

Many of the offgas cleaning system failures had serious safety implications that were easily recognized. Most seemed insignificant individually but, when considered in the aggregate, indicated that more serious events could have followed had operating conditions at the time been less favorable. Surprisingly, in the most recent of these studies[62], 50% of reported failures were attributed to human errors in the design, operation, or maintenance of reactor components and systems. The next most numerous category was the failure of instruments that were installed to monitor and control abnormal environmental conditions. During 1975-1978, approximately 13% of all reports pertained to failures in air monitoring, air cleaning, and

ventilation systems. In boiling water reactors, over half of these related to failures in equipment for monitoring the performance of air cleaning systems rather than to failures in the systems themselves. For pressurized water reactors, the percentage was 32%.

Many lessons have been learned from an examination of the accumulated record of serious and trivial failures of gas cleaning systems and this activity now seems to be firmly adopted by the NRC. Already, development of new educational and training programs for reactor and other operators are underway to try to reverse the frequency with which "personnel error" appears as a cause of failures. One of the clear messages that emerges from such a study of failure modes is the great value of passive gas cleaning systems as the ultimate barrier to the emission of radioactivity-containing gases to the atmosphere.

X. Retention of Filtered Alpha-Active Particles

A series of reports from Oak Ridge National Laboratory have concluded that alpha-emitting particles such as plutonium penetrate HEPA filter media more readily than do non-radioactive or beta-gamma emitting particles[63]. This anomalous behavior is attributed to migration through the paper by alpha emission recoil energy after deposition by conventional filtration mechanisms. The nature of the events causing migration is pictured as an energetic release of clusters of atoms from the filter substrate followed by repeated dislodgments caused by subsequent alpha recoils that result in a steady downstream migration under the unidirectional influence of the air flow. Some released atom clusters eventually penetrate the filter and are released unless there are additional HEPA filters in series; in which case they will be stopped a second time and the process repeated. Because of the extremely small size of the alpha-emitting atom clusters that are released, they are readily filterable on a downstream filter by the diffusional mechanism. Although the fraction of the collected dust that will be released by alpha recoil energy is always small, it is a matter of concern because the toxicity of plutonium is such that maximum retention is desired and this has motivated some facilities to utilize two and three HEPA filters in series for this type for service. At least one proposal has been made to increase this number to four[64] on the basis of random unexplained alpha activity penetration peaks at fuel reprocessing facilities over periods that have been monitored continuously for as long as 80 months. Some of these penetration peaks have been associated with moisture episodes that could account for penetration as blow-off of droplets containing dissolved or suspended plutonium salts and oxides but others are of mysterious causation. Penetration by alpha recoil energy is a possible mechanism but it does not satisfy all of the observed data and it must be concluded that the penetration of alpha-active particles through HEPA filters in series is a phenomenon that lacks a fully satisfactory explanation at this time.

XI. Structural Resistance to Blast, Shock, Tornado, and Earthquake

As previously noted, although HEPA filters are fragile, they are frequently the final barrier between a highly contaminated area and the environment. This has generated considerable concern over the mechanical resistance of HEPA filters to damage from disruptive natural phenomena such as earthquakes and tornadoes, and from internal and external explosions.

Early (1955-6) studies of blast effects on HEPA filters and prefilters were conducted at the Harvard Air Cleaning Laboratory and in the field in connection with the development of protective measures against the effects of nuclear weapons[65]. It was found that 6 in. deep HEPA filters made with corrugated paper separators and having a cross section of 24x24 in. sustained moderate damage at 6 in. Hg overpressure and complete destruction at 10 in. Hg overpressure. In 1966, Anderson and Anderson reported on the shock and blast resistance of several sizes of US-made HEPA filters with corrugated aluminum separators[66]. They confirmed the results of Billings, et al. in a general way, and found that the physical dimensions of the filter cartridge were a controlling factor in blast resistance, e.g., 8x8 in. filters, 6 in. deep, failed at an overpressure of 4.5 psi (9.2 in. Hg), whereas 24x24 in. filters of the same depth failed at an overpressure of only 2.2 psi (4.5 in. Hg). They recommended that the design limit for dirt-loaded filters with face guards be set at 80% of the values causing failure but only 55% for loaded filters without face guards. These values for the shock and blast resistance of all face sizes and depths of open face HEPA filters with separators were rationalized by Burchsted into a single chart relating shock overpressure resistance in psi to a ratio of filter depth to face dimensions[67]. These values have been widely accepted for the past fifteen years in spite of the important changes in filter components and construction methods that have occurred in the intervening years and the introduction of entirely new filter types, e.g., separatorless and European panel designs.

With a change of emphasis since 1965 toward engineered safeguards for civilian power reactors, attention has focussed principally on filter resistance to tornado and earthquake. The Nuclear Regulatory Commission has adopted a design basis tornado for compliance purposes[68] and has published several regulatory guides on seismic design.

Computer modelling and simulation testing of HEPA filters when exposed to tornados has been underway at Los Alamos Scientific Laboratory (LASL) since the early 1970's. Using a shock wave duration very nearly the same as Anderson and Anderson[66], they found a loss of structural integrity occurring on the average at almost the same overpressure (1.9 vs. 1.8 psi)[69] as that recommended as a safe design limit by Anderson and Anderson. It is not known whether this difference reflects a variation in the test protocol (no standard test procedure has been adopted) or a variation in the resistance to physical stress of currently manufactured filters. The latter option is thought to be the correct interpretation of these divergent results as all the filters tested by Anderson and

Anderson came from a single manufacturer whereas those tested at LASL came from a number of manufacturers. One manufacturer's filters in the LASL series had more than double the resistance of the weakest ones and this manufacturer's filters gave results that were not significantly different from those found by Anderson and Anderson, so it is clear that "the breaking point of the filters from shock overpressure is very dependent upon the manufacturer."[69] The peak pressures at which filters broke during simulated tornado loadings (a slower pressure buildup sustained for a longer period) were almost identical with those found for shock overpressures when using filters from the same manufacturer.

Shock and simulated tornado tests performed on four manufacturers' European-style high-volume panel filters and US separatorless filters showed that, on the average, they had only two-thirds the structural strength of conventional US filters containing corrugated separators between filter paper folds extending the full depth of the filter casing when subjected to simulated tornado loadings and only one-half the strength of conventional filters when subjected to identical shock overpressures. The averages are a little misleading as the products of the worst manufacturer of conventional US filters did less well than the products of the best manufacturer of the newer substitutes so it comes back once again to a difference of more than two to one among manufacturers in product strength to resist overpressure.

It was not stated which of the non-conventional filter types performed best in the shock overpressure and simulated tornado tests discussed in the preceding paragraph. In a series of seismic tests in which filters were stressed to destruction, it was found that separatorless filters were capable of withstanding higher acceleration levels on the seismic simulation shake table than were separator type filters from the same manufacturer[70]. The explanation that was given was that the separators vibrated relative to the filter paper during the tests and punctured the paper sufficiently to seriously reduce collection efficiency. Nevertheless, when this same manufacturer's US separator type and separatorless filters were tested within the seismic limits prescribed by the Nuclear Regulatory Commission[71], both types proved to be acceptable. Each of the filters subjected to seismic testing was secured in a side-opening, bag in-bag out housing of modular construction equipped with this manufacturer's "fluid seal" between filter and housing. A novel feature of this test program was a provision to test all filters continuously with cold DOP at full air flow through the test cycle, with qualification dependent upon observing no dip in efficiency below 99.97%. It was concluded that "the structure of. . .conventionally designed housing[s] would not be adequate to withstand the desired seismic loads"[70] and that design modifications to strengthen conventional housing structures are required inasmuch as they are not seismically rigid and are, therefore, likely to magnify the input motions.

These limited and somewhat equivocal test results seem to leave things very much up in the air with regard to establishing standardized test protocols and qualifying commercially available filters that are capable of meeting NRC-mandated resistance to physical stresses caused by internal and external explosions,

tornados, and earthquakes. It would seem to be highly desirable to incorporate appropriate tests for each of these properties into future versions of MIL-F-51068[7] and ANSI/ASME N 510[5] if all filter manufacturers are to be encouraged to meet the highest possible standards for products vital to safe operations of nuclear facilities.

XII. Future Needs

Up to now we have been taking a retrospective look at high efficiency filtration for the nuclear industry. It is only fitting that we look ahead and try to define what special needs and problems we will be likely to face in the decade ahead.

We have already identified a number of items that are of current concern, some of which are already under study. These include the design of filtration systems for vented containment of light water moderated commercial reactors and for liquid metal cooled fast reactors. Deep bed sand filters, after two decades of neglect, have emerged as the current favorite for a passive filtration unit for what may become an important part of new engineered safety feature systems. Improved filtration systems are also needed for nuclear waste volume reduction involving high temperature processes. Sintered metal filters are now in use in a number of high temperature waste reduction processes but because these units have a number of disadvantages, including high airflow resistance, there is a continuing interest in the development of moving granular bed filters that meet nuclear service requirements.

Although the past three decades have seen important improvements in the HEPA filter, notably, elimination of combustible components, a spectacular reduction in penetration, and increased air flow capacity, HEPA filter design and construction are still under close scrutiny. Steeply rising costs have stimulated renewed efforts toward mechanization and automation in filter manufacturing and the increasing diversity of applications in biological research and production, microelectronics, etc., have sharply increased performance requirements. It is obvious that new and innovative developments are needed in paper orientation and filter assembly--perhaps a return to a long-neglected technique of casting the filter pack into an integral unit wholly composed of glass fibers.[24]

Although examined many years ago and found wanting, the full potential of conventional and electrostatic prefilters for prolonging the service life of HEPA filters needs a systematic restudy in light of today's needs and today's prefilters. As a companion study, it will be important to determine if today's filters and filter components are capable of withstanding a much longer period under typical service conditions without serious material deterioration - another reason for looking critically at present day materials and construction techniques.

We seem to be at a crossroads with respect to filter test methods, filter test equipment, and quantitative specifications for the filters, themselves, We hear many competing voices advocating changes in the test techniques we thought had served us well for the past three decades and we hear, as well, many pleas not to rock the boat. Lest this important matter drift into chaos, we should promptly

subject the entire technology of paper testing, factory bench testing, and in-place testing to a coordinated study designed to identify the most effective and most economical overall system for defining the essential performance factors of high efficiency filters when placed in service. This is an urgent need if the nuclear community is to assure the public and Congress with a unified voice that the best possible equipment is in service for nuclear safety.

Although nuclear and military applications for HEPA filters represented the major usage for many years, this is no longer the case. Filters for industrial clean rooms and clean benches, for biological safety cabinets, for medical applications, and for a myriad of other uses are now the principal market for filter manufacturers. As a consequence, there has been a strong demand to reduce the strict requirements of the nuclear industry as a way of reducing filter costs. For example, few users outside the nuclear industry care at all about radiation resistance because their filters never see radiation and they would prefer to eliminate it as a requirement. However, having several grades of paper would result in high costs for everyone and would lead to endless confusion regarding what paper was in what filter. To the present, there has been general agreement to stay with the nuclear grade paper as the only acceptable product, but filter construction methods are diverging to accommodate the special requirements of these other applications. These alterations invariably degrade the filter for nuclear applications in the direction of less resistance to mechanical and chemical stress. It is clear that the nuclear industry must remain vigilant and militant to maintain the highest possible standards of filter construction and performance for their own use if filter failures are to be avoided.

Finally, we have the puzzling matter of the effect of alpha recoil energy on particle penetration through HEPA filters that calls for clarification. And this is merely one aspect of our need to rededicate ourselves to a renewed interest in sponsoring basic filtration research as the key to the development of more effective and more reliable filters.

References

1. First, M.W., Filters, Prefilters, High Capacity Filters, and High Efficiency Filters; Review and Projection, Proc. Tenth AEC Air Cleaning Conf., CONF-680821, First and Morgan, eds., NTIS, Springfield, VA, 1968 (p. 65).

2. Kemeny, J.G., Chairman, Report of the President's Commission on The Accident at Three Mile Island, U.S. Government Printing Office, 1979.| Rogorin, M. and Frampton, G.T., Jr., Three Mile Island, A Report to the Commissioners and the Public, Nuclear Regulatory Commission, Vol. II, NTIS, Springfield, VA, January, 1980 (p. 360).

3. Burchsted, C.A. and Fuller, A.B., Design, Construction and Testing of High-Efficiency Air Filtration Systems for Nuclear Appli-

cation, ORNL-NSIC-65; NTIS, ORNL, January 1970. Burchsted, C.A., Fuller, A.B. and Kahn, J.E., Nuclear Air Cleaning Handbook, ERDA 76-21, NTIS, Springfield, VA, 1976.

4. Am. Soc. Mechanical Eng., Nuclear Power Plant Air Cleaning Units and Components, ANSI/ASME N509-1980, Am. Soc. Mech. Eng., New York City, 1980.

5. Am. Soc. Mechanical Eng., Testing of Nuclear Air Cleaning Systems, ANSI/ASME N510-1980, Am. Soc. Mech. Eng., New York City, 1980.

6. NRC, Regulatory Guide 1.52, Design, Testing, and Maintenance Criteria for Engineered-Safety-Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants, Off. of Stds. Devel., USNRC, Rev. 1, July 1976.

7. Military Specification MIL-F-51068, Filter, Particulate, High Efficiency, Fire Resistant, Edgewood Arsenal, Md.

8. Military Specification MIL-F-51079, Filter, Medium, Fire Resistant High Efficiency, Edgewood Arsenal, Md.

9. U.S. Military Standard, MIL-STD-282, Filter Units, Protective Clothing, Gas Mask. Components and related products; Performance test methods. Edgewood ARsenal, Md.

10. Chemical Systems Laboratory, Qualified Products List of Products Qualified Under Military Specification MIL-F-51068D, Aberdeen Proving Ground, Md.

11. Dorman, R.G., Filtration Theory, Proc. Seminar on High Efficiency Aerosol Filtration in the Nuclear Industry, Commission of the European Communities, Luxembourg, 1976 (p. 15).

12. Anderson, W.L., Magee, W.S., Jr. and Jonas, L.A., Aerosol Filtration by Fibrous Filter Mats: Part III, Proc. Thirteenth AEC Air Cleaning Conf., CONF-740807, First, Ed., NTIS, Springfield, Va., March 1975 (p. 445).

13. Kornberg, J.P. and First, M.W., High Temperature Aerosol Filtration by Diffusion, Proc. Thirteenth AEC Air Cleaning Conf., CONF-740807, First, Ed., NTIS, Springfield, Va., March 1975 (p. 466).

14. Fuchs, N.A. and Stechkina, I.B., A Note on Theory of Fibrous Filters, Ann. Occup. Hyg., 6:27 (1963).

15. Gilbert, H., Octennial History of the Development and Quality of High-Efficiency Filters for the U.S. Atomic Energy Program, Proc. Treatment of Airborne Radioactive Wastes, IAEA, Vienna, 1968 (p. 227).

16. Collins, J.T., Bellamy, R.R., and Allen, J.R., Evaluation of Data from HEPA Filter Quality Assurance Testing Stations, Proc. 15th DOE Nuclear Air Cleaning Conf., CONF-780819, First, ed., NTIS, Springfield, VA, 1979 (p. 1159).

17. First, M.W. and Rudnick, S.N., Performance of 1,000 and 1,800 CFM HEPA Filters on Long Exposure to Low Atmosphere Dust Loadings, Proc. Second World Filtration Cong., Filtration Soc., Croydon, Eng., 1979 (p. 283). Performance of 1,000 and 1,800 CFM HEPA Filters on Long Exposure to Low Atmospheric Dust Loadings, II. M.W. First and S. N. Rudnick, Proc. 16th DOE Nuclear Air Cleaning Conf., CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p. 682).

18. Rose, C.E. and Rivers, R.D., Performance and Environmental Characteristics of a Compact, High-Capacity HEPA Filter Design, Proc. 15th DOE Nuclear Air Cleaning Conf., CONF-780819, First, ed., NTIS, Springfield, VA, 1979 (p.1176).

19. Gunn, C.A., McDonough, J.B., Survey of Loading Performance of Currently Available Types of HEPA Filters Under In-Service Conditions, Proc. 16th DOE Nuclear Air Cleaning Conf., CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p. 667).

20. van Tumhout, J. and Albers, J.H.M., Electret Filters for High-Efficiency Air Cleaning, Proc. Second World Filtration Cong., Filtration Soc., Croydon, Eng., 1979 (p. 521).

21. Bergman, W., et al., Electrostatic Filters Generated by Electric Fields, Proc. Second World Filtration Cong., Filtration Soc., Croydon, Eng., 1979 (unpaged).

22. Flanders Filters, Inc., Air Filtration Products, Washington, N.C., 1980.

23. Anderson, W.L., Government-Industry Meeting on Filters, Media, and Media Testing, Proc. Thirteenth AEC Air Cleaning Conference, CONF-740807, First, Ed., NTIS, Springfield, Va, March 1975 (p. 642).

24. First, M.W. and Graham, J.B., High Efficiency Dust Filtration at High Temperature, Ind. Eng. Chem., 50:63A (1958).

25. Terada, K., Buttedahl, O.I., Merlini, R.J. and Woodard, R.W., Development of Acid-Resistent HEPA Filter Components, Proc. 16th DOE Nuclear Air Cleaning Conf., CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p. 782).

26. Personal communication, R.W. Woodward, Rocky Flats Plant, Golden, Co., September 25, 1980.

27. Instruction Manual for the Installation, Operation, and Maintenance of the AEC Modified E-18 DOP Filter Testing Penetrometer, Report HOHF-4, Hanford Environmental Health Foundation, Richland, Washington 99352, November 1967.

28. Ettinger, H.J., et al., HEPA Filter Efficiencies Using Thermal and Air-Jet Generated Dioctyl Phthlate, Am. Ind. Hyg. Assoc. J., 30:20 (1969).

29. Dorman, R.G., Edwards, J., and Poynting, R., The Sodium Chloride Aerosol Test for High Efficiency Air Filter Installations, Proc. Seminar on High Efficiency Aerosol Filtration in the Nuclear Industry, Commission of the European Communities, Luxembourg, 1976 (p. 127).

30. Powell, A.W. and Wilkinson, B.A., The In-Situ Testing of High Efficiency Particulate Filters in the CEGB Southeastern Region Nuclear Power Stations, Proc. Seminar on High Efficiency Aerosol Filtration in the Nuclear Industry, Commission of the European Communities, Luxembourg, 1976 (p. 183).

31. Briand, A. and Dupoux, J., Mesure In-sita de l'Efficacite des Installations Fietrantes daus l'Industrie Nucleaire par la Methods a l'Aerosol de Fluoresceine sodee (uranine), Proc. Seminar on High Efficiency Aerosol Filtration in the Nuclear Industry, Comm. of the European Communities, Luxembourg, 1976 (p. 179).

32. Dorman, R.G., A Comparison of Methods of Particulate Testing of HEPA (HESPA) Filters, Proc. 16th DOE Nuclear Air Cleaning Conference, CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p. 56).

33. Parish, E.C. and Schneider, R.W., In-place Testing of High Efficiency Filters at ORNL, Proc. Eighth AEC Air Cleaning Conf., NTIS, Springfield, Va., 1963 (p. 484). Echols, W.H. and Young, J.A., Studies of Portable Air-Operated Aerosol Generators, NRL Report 5929, US Naval Research Lab., Washington, D.C., July 26, 1963.

34. USDOE, In-Place Testing of HEPA Filter Systems by the Single-Particle Spectrometer Method; RDT F 3-41, Proposed DOE Standard, US Dept. of Energy, Washington, D.C., September 1980.

35. National Sanitation Foundation, Standard No. 49, Class II (Laminar Flow) Biohazard Cabinetry, NSF, Ann Arbor, Mi., June 11, 1976.

36. Underwriters' Laboratories, UL-586, High Efficiency Air Filter Units, 2nd Ed. Chicago, Il., 1964.

37. Gonzales, M., Elder, J., and Ettinger, H., Performance of Multiple HEPA Filters Against Plutonium Aerosols, Proc. Thirteenth AEC Air Cleaning Conf., CONF-740807, First, Ed., NTIS, Springfield, Va., March 1975 (p. 501).

38. First, M.W., Training and Certification of Personnel Who Perform In-Place Filter Tests at Nuclear Facilities, Proc. Seminar on High Efficiency Aerosol Filtration in the Nuclear Industry, Commission of the European Commission of the European Communities, Luxembourg, 1976 (p. 215).

39. Anderson, W.L., Government-Industry Meeting on Filters, Media, and Media Testing, Proc. 15th DOE Nuclear Air Cleaning Conf., CONF-780819, First, Ed., NTIS, Springfield, Va., February 1979 (p. 1122).

40. ASTM, Standard Method for Evaluation of Air Assay Media by the Monodisperse DOP (Dioctyl Phthalate) Smoke Test. American Society for Testing and Materials, Philadelphia, Pa., 1971.

41. Arthur D. Little, Inc., Design Study of a Filter-Testing Dioctyl Phthalate (DOP) Penetrometer, Phase I, and Model Study for an Improved Dioctyl Phthalate (DOP) Penetrometer, Phase II, ADL, Acorn Park, Cambridge, Ma., January 15, 1976.

42. Hinds, W., First, M.W., Gibson, D. and Leith, D., Size Distribution of "Hot DOP" Aerosol Produced by ATI Q-127 Aerosol Generator, Proc. 15th DOE Nuclear Air Cleaning Conf., CONF-780819, First, Ed., NTIS, Springfield, Va., February 1979 (p. 1130).

43. Skaats, C.D., A Study of Dioctyl Phthalate (DOP) Generated in Penetrometers and the Devices Used Currently to Measure Their Size, 15th DOE Nuclear Air Cleaning Conf., CONF-780819, First, Ed., NTIS, Springfield, Va., February 1979 (p. 1127).

44. Particle Measuring Systems, Inc., Active Scattering Aerosol Spectrometer Probe, PMS, Model ASASP-X, Operating Manual, PMS, Inc., Boulder, Col., Undated.

45. USEPA, Hazardous Waste and Consolidated Permit Regulations, Fed. Reg., May 19, 1980 (p. 33126).

46. National Toxicology Program, Draft NTP Technical Report on the Carcinogenesis Bioassay of Di (2-ethylhexyl) Phthlate (LAS No. 117-81-7), NTP, P.O. Box 12233, Research Triangle Park, NC 27709, 15 October, 1980.

47. Hinds, W., Macher, M., and First, M.W., Size Distributions of Aerosols Produced from Substitute Materials by the Laskin Cold DOP Aerosol Generator, Proc. 16th DOE Nuclear Air Cleaning Conf., CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p. 125).

48. Gerber, B.V., Selected Polyethylene Glycols as "DOP" Substitutes, Proc. 16th DOE Nuclear Air Cleaning Conf., CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p. 109).

49. Lapple, C.E., Deep-bed Sand and Glass Fiber Filters, Air Cleaning Seminar, Ames Laboratory, September 15-17, 1952, WASH-149, TIS, Oak Ridge, Tenn., March 1954 (p. 98).

50. Blasewitz, A.G., Dissolver Off-gas Filtration, Air Cleaning Seminar, Ames Laboratory, September 15-17, 1952, WASH-149, TIS, Oak Ridge, Tenn., March, 1954 (p. 66).

51. Viles, F.J., Jr., Himot, P. and First, M.W., High Capacity-High Efficiency Filters for Sodium Aerosols, Report NYO-841-10, Harvard Air Cleaning Laboratory, Boston, Ma., August 1967. First, M.W. and Baldwin, T., Sodium Aerosol Filtration Studies, Proc. 11th AEC Air Cleaning Conf., CONF-700816, First and Morgan, Jr., Eds. NTIS, Springfield, Va. (p. 445).

52. Bohm, L., Jordan, S. and Schikarski, W., The Off-gas Filter System of the SNR-300, Proc. 13th AEC Air Cleaning Conf., CONF-740807, First, Ed., NTIS, Springfield, Va., March 1975.

53. Bohm, L., Jordan, J. and Schikarski, W., Sandbettfilter als Aerosolfilter Hoer Abscheideleistung in Kemtechnischen Anlogen, High Efficiency Aerosol Filtration in the Nuclear Industry, Commission of the European Commission of the European Communities, Luxembourg, 1976 (p. 661).| Calome, J. and de Cuy, G.D., Filtration des aerosols produits par un fen de sodium, High Efficiency Aerosol Filtration in the Nuclear Industry, Commission of the European Commission of the European Communities, Luxembourg, 1976 (p. 533).

54. Gossett, B. et al., Post-Accident Filtration as a Means of Improving Containment Effectiveness, Dept. Chem. Nuclear, and Thermal Eng., U. Cal., Los Angeles, unpublished study, 1977.

55. First, M.W., Silverman, L., et al., Floating Roof Containment Vessels, Proc. Ninth AEC Air Cleaning Conf., NTIS, Springfield, VA, 1967 (p. 371).

56. NCRP Report No. 37, Incineration of Radioactive Wastes, National Council on Rad. Prot. and Meas., Wash. D.C., Draft Report, 1968.

57. Ziegler, D.L. and Johnson, A.L., Fluidized Bed Incinerator Development, Proc. 14th ERDA Air Cleaning Conf., CONF-760822, First, ed., NTIS, Springfield, VA, 1977 (p. 70).

58. Bonner, W.F., Blair, H.T., and Romero, L.S., Spray Solidification of Nuclear Waste, ERDA Contract E(45-1)-1830, Battelle Pacific Northwest Laboratories, Richland, WA, August 1976.

59. Rudnick, S.N., First, M.W., Price, J.M., Filtration in a Moving Granular Bed in the Presence of Large Thermophoretic Forces, Proc. 16th DOE Nuclear Air Cleaning Conf., CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p. 772).

60. Personal communication, O.I. Buttedahl, Rocky Flats Plant, Golden, Co., October 6, 1980.

61. Moeller, D.W., Problems in Nuclear Air-Cleaning Systems, Nuclear Safety, 16:469 1975.| Failures in Air-Monitoring, Air-Cleaning and Ventilation Systems in Commercial Nuclear Power Plants (January 1, 1975-June 30, 1978), Nuclear Safety, 20:176, 1979.

62. ACRS, Review of Licensee Event Reports (1976-1978), USNRC, NUREG-0572, NTIS, Springfield, Va., 1979.

63. McDowell, W.J., Seeley, F.G., and Ryan, M.T., Penetration of HEPA Filters by Alpha Recoil Aerosols, Proc. 14th ERDA Air Cleaning Conf., CONF-760822, First, Ed., NTIS, Springfield, Va., (p. 662).

64. Frigerio, N.A. and Stowe, R.S., Plutonium and Uranium Experience, in U.S. Nuclear Facilities Using HEPA Filtration, Proc. Seminar on High Efficiency Aerosol Filtration in the Nuclear Industry, Commission of the European Communities, Luxembourg, 1976 (p. 457).

65. Billings, C.E., Dennis, R. and Silverman, L., Blast Effects on Air Cleaning Equipment--Results of Filter Tests, Proc. 4th AEC Air Cleaning Conf., TID-7513 (pt. 1), Tech. Info. Serv., Oak Ridge, Tenn., June 1956 (p. 79).

66. Anderson, W.L. and Anderson, T., Effect of Shock Overpressure on High Efficiency Filter Units, Proc. 9th AEC Air Cleaning Conf., NTIS, Springfield, VA, 1967 (p.79).

67. Burchsted, C.A., Environmental Properties and Installation Requirements of HEPA Filters, Proc. Symp. Treat. Airborne Radioact. Wastes, IAEA, Vienna, 1968; and in red. 3 (above) (p. 47).

68. USAEC, Regulatory Guide 1.76, Design Basis Tornado for Nuclear Power Plants, USAEC, Wash., DC, April 1974.

69. Andrae, R.W., et al., Investigation of Air Cleaning System Response to Accident Conditions, Proc. 16th DOE Nuclear Air Cleaning Conf., CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p.1142).

70. Yow, J.R., Holloman, R., and Algar, A., Seismic Qualification of HEPA Filters by Test in an Actual Operating Condition, Proc. 16th DOE Nuclear Air Cleaning Conf., CONF-801038, First, ed., NTIS, Springfield, VA, 1981 (p.1175).

71. USNRC, Regulatory Guide 1.60, (Revision 1), Design Response Spectra for Seismic Design of Nuclear Power Plants, USAEC, Wash., DC, Dec. 1973.

DISCUSSION

HOLLOMAN: I noticed in one section of the paper there was a statement that there is little evidence of Super-flow-type filter usage in nuclear applications. During the last four years, from January of 1976 until August of 1980, we have produced over 5,000 for DOE alone, and 6,500 that are in NRC commercial nuclear power plants. We feel that this does show that the filter is adequate for this application. There have been plenty of reports showing this in the past. You made another statement that there is a need for better in-place testing of two filters in series. This is another area in which we have put a lot of time and made an effort to prove that you can perform an adequate in-place test, a test that is not just adequate but is equal to or better than what you can do by injecting DOP ten duct diameters upstream and taking samples ten duct diameters downstream. This can be done in much less space and with improved results.

GILBERT: Regarding your last comment, the test you recommend can be done only with your customized equipment; that is to say, it is not a general type of in-place test. Is that right?

HOLLOMAN: That is true. It does take a special piece of equipment to do it.

FIRST: We will take due cognizance of your first comment and if you would like to send those figures, or any others, to me, I will be glad to acknowledge them.

BALFOUR: I did not notice that you mentioned the new liquid seals in lieu of the gasket. Do you have any data on that?

GILBERT: In nuclear applications, there is a little problem when it comes to the fluid seal. You have potentially contaminated material to get rid of when you pull the filter off the male contact member and silicone from the fluid seal clings to the male member. But we hope that one of these days that will be overcome.

HOLLOMAN: I believe everyone here understands the fluid seal. Mr. Gilbert's point is valid. Work is in progress to eliminate the problem of some fluid being retained on the male adaptor. However, it is not a major factor. Many filters have been removed and re-sealed without any problem.

RIVERS: One thing that happens at these conferences is that people project completion of studies by saying, "We are going to be working on this for the next three or four years." But then you do not hear any more about it. Particularly in the case of something like gaskets, these studies take a long time. I remember a couple of papers given by Hanford Environmental Health Foundation personnel on long-term gasket effects. Whatever happened to all that information? It looked to me to be very promising work, because we might get some better gaskets from it.

GILBERT: You have a long memory. That was the meeting in Boston, in 1966, in which Frank Adley gave those papers. I think they were good papers, and that his findings were valid, but I cannot assure you that anyone has followed up on them. I recall that he said you should not tighten the filter in place completely when the filter is first installed because the gasket takes a set and has a tendency to leak. Instead, he advised that the gasket be pulled down only slightly and then someone should return in two or three weeks and torque the filter fully. I don't know that the filter installers are following this all, but the data on which it is based are valid.

RIVERS: Retightening seals seemed to me to be an unhappy solution to the problem.

GILBERT: That's right.

DENNISON: On the subject just mentioned, I find that that is exactly what you have to do in biological safety cabinets. When a brand-new cabinet comes in, you must take it completely apart and go in and re-tighten all the filters that had been previously tightened to pass a certification test before they left the manufacturer's

factory. Many times, if you were to test the filters immediately upon receipt of the cabinets, you would find that the seals leak and the cabinet would not pass. Back to my question: I did not know that the National Sanitation Foundation had gotten involved in certification of filters. When did this happen?

FIRST: They are not engaged in certification of filters. They are engaged in certification of cabinets, which involves the testing of filters that are installed in the cabinets.

DENNISON: Is this the standard NSF-49 certification that I am familiar with?

FIRST: Yes. However, you may not know that there was a very strong effort on the part of the National Institutes of Health to develop a filter standard for biological safety cabinets that would replace the nuclear filter standard. They engaged Edgewood Arsenal to produce this new standard. There were a number of us, including Mr. Gilbert, Mr. Anderson and others, who objected to this very vigorously because we do not believe there is room for more than one high-efficiency filter standard.

BOYD: On the subject of filter testing, some people may read into your remarks that you are proposing to use cold DOP testing with photometers as a replacement for hot DOP testing with a penetrometer. Our experience is that the cold DOP challenge and photometer sampling method is great for an in-place test of filters after the filters have been installed. On the other hand, testing for the overall penetration of a filter must be done with hot DOP and a penetrometer to assure reliable and reproduceable results. So my question is: Are you suggesting that the cold DOP-photometer test method can be used as a substitute for the hot DOP-penetrometer test, or are you suggesting that in-place testing with the cold DOP and photometer should be used as a follow-up to the hot DOP test?

FIRST: The point being made was that if the filter paper passes the standard hot DOP test, the only tests needed from there on are defect tests to learn whether the paper was torn during manufacture, whether the seal between filter pack and frame was incorrectly joined, etc. When one starts with acceptable paper, only subsequent damage or poor manufacturing practices can produce a defective filter. Therefore, the question is asked, can we substitute a simpler and cheaper cold DOP defect test for the hot DOP efficiency test now conducted by manufacturers and quality-assurance test stations on filter cartridges? And if the answer is, Yes, can we then eliminate the quality-assurance test stations completely and rely on on-site preplacement cold DOP test procedures to find defective filters with the same reliability as the test stations? This may or may not prove to be an acceptable idea--certainly a thorough comparative study would be required to resolve the matter--but we think this is the kind of question that is very pertinent to bring up in the course of a critical review.