SESSION 14

AGING EFFECTS ON AIR CLEANING COMPONENTS

Wednesday: July 27, 1994
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As nuclear power plants and facilities age, one of the primary concerns that needs to be addressed, and repeatedly assessed in future conferences, is the effect of aging on component systems and structures. At today's session, we will hear presentations on filter and adsorber aging assessments, results of a study to determine the shelf life of HEPA filters, and the effect on efficiency of activated carbon after exposure to welding fumes. Two related topics will also be addressed; a method for estimating the efficiency of HEPA filters during and after a design basis accident and the performance of HEPA filters under hot dynamic conditions. I expect all of these topics to be of extreme interest to all members participating in the conference.

FILTER-ADSORBER AGING ASSESSMENT

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Abstract

An aging assessment of high-efficiency particulate (HEPA) air filters and activated carbon gas adsorption units was performed by the Pacific Northwest Laboratory as part of the U.S. Nuclear Regulatory Commission's (USNRC) Nuclear Plant Aging Research (NPAR) Program. This evaluation of the general process in which characteristics of these two components gradually change with time or use included the compilation of information concerning failure experience, stressors, aging mechanisms and effects, and inspection, surveillance, and monitoring methods (ISMM).

Stressors, the agents or stimuli that can produce aging degradation, include heat, radiation, volatile contaminants, and even normal concentrations of aerosol particles and gasses. In an experimental evaluation of degradation in terms of the tensile breaking strength of aged filter media specimens, over forty percent of the samples did not meet specifications for new material. Chemical and physical reactions can gradually embrittle sealants and gaskets as well as filter media. Mechanisms that can lead to impaired adsorber performance are associated with the loss of potentially available active sites as a result of the exposure of the carbon to airborne moisture or volatile organic compounds.

Inspection, surveillance, and monitoring methods have been established to observe filter pressure drop buildup, check HEPA filters and adsorbers for bypass, and determine the retention effectiveness of aged carbon. These evaluations of installed filters do not reveal degradation in terms of reduced media strength but that under normal conditions aged media can continue to effectively retain particles. However, this degradation may be important when considering the likelihood of moisture, steam, and higher particle loadings during severe accidents and the fact it is probable that the filters have been in use for an extended period.

I. Introduction and Background

The Phase I aging assessment of HEPA filters and gas adsorption units (adsorbers) described in this paper is part of an evaluation of the effects of aging on engineered safety feature (ESF) systems, one of the groups of systems of current interest in the NPAR Program.[1] The identification of potential safety-related aging issues, coupled with the need to avoid duplication, were the key considerations in identifying candidate ESF systems for initial study. Air-treatment or cleaning and ventilation systems were ultimately selected because failure of these systems can impact both plant and public safety. The first step in the Phase I study was to identify a boundary to isolate system

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components that would be assessed. The fundamental components in terms of providing plant and public safety are those designed to capture radioactive gaseous and particulate contaminants (namely, the adsorbers and HEPA filters, respectively). The particles could be radioactive chemical compounds or otherwise inert airborne material contaminated by radioactive species. Gasses of primary interest include the elemental and organic forms of radioiodine. Activated carbon is used to remove the gaseous or volatile forms of iodine and is usually impregnated with other chemicals to enhance the removal of the organic species. The adsorbers and filters can be the last barrier in preventing the release of radioactivity to the public following an accident, including that associated with the airborne iodine and cesium radionuclides which can provide a substantial contribution to total dose. Further, satisfactory performance is essential to ensure a controlled atmosphere for plant personnel, including control room habitability, during normal operations as well as accidents.

Activated carbon adsorption units and HEPA filters were selected as the focus for initial Phase I assessment not only because they are essential for safety, but in the case of the adsorbers, it has long been established, and was evidenced again during the Three Mile Island (TMI) accident, that aging mechanisms in these components can lead to impaired performance.[2,3] Aging is defined as the general process in which characteristics, including the performance of the two components, gradually change with time or use.[4] Related mechanisms and negative effects are discussed in the paper in conjunction with stressors, the agents or stimuli that stem from pre-service and service conditions which can result in the degradation. Aging mechanisms are the specific processes that gradually change characteristics of the components with time and use and include wear, embrittlement, corrosion, and other physical and chemical processes. Aging degradation is a negative effect or net change in a characteristic that can impair the ability to function within acceptance criteria. For filters, degradation includes loss of media strength, but for both filters and adsorbers, focus is ultimately on reduced performance in terms of particle and volatile iodine retention.

Failure experience, based on analyses of licensee event reports (LERs) and a survey of U.S. Department of Energy (USDOE) sites, is summarized in the report and, where possible, related to aging. The discussion of failure experience also includes exhaust-air treatment experience associated with the TMI accident.

Inspection, surveillance, and monitoring methods including specific surveillance tests that are performed periodically are reviewed and described. These methods and tests are used to establish the condition of the filters and adsorbers once the components have been placed in operation.

Information concerning the design and construction of the two air-treatment system components is briefly reviewed before the discussion of aging and failure experience. References to the documents that combine to provide basic physical, chemical, test, and performance standards for filter media and impregnated activated carbon as well as for assembled components are also included in the report.

II. Component Design and Construction

The particle filtration and gas (vapor) adsorption units (adsorbers) included in nuclear air-treatment systems are designed to remove radioactive materials. The materials, airborne particles or volatile species, may be suspended in or exist as gas phase constituents of recirculating aerosols, gaseous effluents, or accidental releases. The adsorbers, activated carbon beds, can effectively remove elemental radioiodine and are often impregnated with other chemicals to enhance the retention of organic species. The fine particle filters, HEPA filters, may also be significantly involved in radioiodine removal because iodine can be in the form of solid cesium iodide (CsI).

HEPA filters clean or treat aerosols by separating suspended particles from an essentially atmospheric pressure gas stream. The filter media is made from a mixture of glass fibers and is in the form of filter "paper." Particles are collected by interception, impaction, and Brownian diffusion. The continuous gas phase passes through virtually unchanged. A HEPA filter is defined as a "high-efficiency particulate air filter having a fibrous medium with a particle removal efficiency of at least 99.97% for 0.3 μm particles of dioctyl phthalate [DOP]."[5] An excellent review of the construction and service characteristics of HEPA filters has been prepared by First.[6] As indicated by First, "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 the most widely used." The glass fiber filter paper is usually in the form of a continuous sheet, pleated vertically.

As indicated above, adsorbers are used to remove gaseous radioiodine species from effluents. Various standards and specifications permit the use of any adsorbent medium that has been demonstrated to be equal to or better than activated carbon in terms of radioiodine retention. However, only activated carbon is discussed because it is essentially the only material used and supporting testing procedures and acceptance criteria are specific to its use. Gasses are directed through tightly packed beds of activated carbon granules. The carbon or charcoal is prepared by controlled heating in a steam environment to remove volatile organic material. The heating generates a material with a large surface-to-mass ratio and internal surfaces or sites where adsorption of iodine molecules can take place. The active media is usually "...activated charcoal that is derived from either coal or coconut shells. Although elemental radioiodine is retained efficiently by activated carbon alone..., the charcoal is often impregnated with additional chemicals to improve its retention of organic species (e.g., methyl iodide)."[3]

Basic qualifications for the filter media and assembled HEPA particulate filters are contained in two military specifications.[7,8] Primary standards for adsorbent media, assembled adsorbers, and related testing methods are presented in Sections FD, FE, and FF of ASME/ANSI code AG-1 and two ASTM specifications.[9,10,11] Numerous documents supplement and/or support the preceding five references, including USNRC and other ASME and ASTM publications. One of the most closely related USNRC publications is Regulatory Guide 1.52, "Design, Testing, and Maintenance Criteria for Post Accident Engineered-Safety-Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants."[12]

III. Stressors, Aging Mechanisms, and Degradation

The obvious effect of service associated with HEPA filter use is the increased pressure drop (resistance to air flow) through the filter media arising from particle retention (loading). In a relatively clean environment, filters may be used for several years before replacement is required. Dust loading, along with heat and radiation, also have the potential to reduce the effectiveness of the organic materials used to strengthen the filter medium and provide water repellency. High moisture content is another potential normal stressor, an agent or stimuli stemming from normal conditions and potentially producing aging mechanisms and effects which can lead to increased pressure drop as well as reduced filter medium strength. Filter media may embrittle from prolonged exposure to air containing normal concentrations of oxygen and oxides of nitrogen and sulfur.

Aging mechanisms or processes that can gradually change the physical characteristics of HEPA filter components other than the media include corrosion of metal members and physicochemical reactions that alter the properties of sealants, gaskets, and water repellents. Metal components that could be affected include the frames and corrugated separators. Heat and radiation are stressors associated with physicochemical reactions potentially affecting face gaskets and the adhesives and sealants that are used to splice the medium, fasten the gaskets to the filter face, and seal the filter pack to the frame.

Exposure to air containing stressors (namely, moisture and contaminants or pollutants) can slowly and continuously degrade the performance of gas adsorbers. This aging, also termed weathering, is inherent because of the nature of the material used, in that it has been "activated" to dramatically increase surface to mass ratio and provide countless reaction sites, and because of the essentially ubiquitous nature of the contaminants. Many airborne constituents, including moisture, can readily react or be adsorbed by carbon beds, reducing the number of active "sites" that otherwise would be available for radioiodine adsorption. During normal operation, charcoal may be exposed to air flows containing such contaminants as volatile organic solvents, sulfur dioxide, nitrogen oxides, and carbon monoxide. Because of system flow rates, even traces of pollutants can have a significant, cumulative effect. Oxidation as well as competitive loading can impair bed performance, including decreasing the efficiency of the impregnant. Because airborne constituents can vary dramatically with time and among sites, it is essentially impossible to provide criteria for the useful life of impregnated activated carbon.

It should be emphasized that the possibility of impaired performance in terms of radiodine retention as a result of the aging or weathering of impregnated activated carbon has been a concern almost from the start of the nuclear industry's existence. In fact, concern about the useful life of carbon could be considered one of the first, if not the first, aging issues.

IV. Failure Experience

An unusually large amount of potentially useful failure data were found in the literature. Analyses of LERs submitted by commercial nuclear power plant operators, covering the periods from January 1, 1975 through June 30,

1978, 1978-1981, 1985-1987, and 1988-1991, to identify those pertaining to air-monitoring, air-treatment, and ventilation systems, have been prepared by.[13,14,15,16] In summary, 15% of 43,500 reports were associated with the subject systems while an estimated roughly 100, or about 2%, of the system reports appeared to be associated with HEPA filters and carbon adsorbers. No relationship to aging was reported. Moeller and Kotra[17] and Moeller and Sun,[18] reviewed LERs for the periods 1981 through 1983 and 1984 through 1986, respectively, to isolate those pertaining to control room habitability. Of the approximately 20,800 reports, 4% were related to this subject. About 60 of the LERs were associated with impaired filter or adsorber efficiency. Several instances of the premature aging of carbon from error-induced conditions were reported.

Using a survey, Carbaugh[19] collected data on the numbers of and reasons for HEPA filter changeouts and failures at USDOE sites for the years 1977 through 1979. A total of 1,105 filter failures, or 12% of the 9,154 filter applications, were reported. A majority of the failures occurred for unknown or unreported reasons. Johnson et al.[20] explained the results of the above survey: "If one examines the categories reported for filter failure, it is evident that the effects of aging could contribute to 81% of these failures, except for the 19% resulting from handling or installation damage." These same investigators reported results of an experimental evaluation of the tensile breaking strength of aged filter media specimens that revealed that 42% of the samples did not meet the specifications for new material. A significant loss in water repellency from values specified for new media was also measured.[20]

Selection of adsorbers for Phase I study was reinforced by literature references revealing that the low radioiodine decontamination factors associated with the TMI accident were attributed to the premature aging of charcoal. Before presenting details related to aging issues, it should be emphasized that building ventilation systems played an important role in decreasing the radionuclide release associated with this incident and, in fact, prevented the release of most of the radioiodine. However, the terms "somewhat dismal results" and "rather unsatisfactory" have been used to describe exhaust air filtering experience during the TMI accident.[21,3] In summary, it was determined that the filtering systems installed at the time of the accident provided a decontamination factor (DF) of 9.5 for all species of radioiodine (corresponds to a retention efficiency of 89.5%) and the radioiodine releases were higher by about a factor of five than they would have been if there had been no system deterioration. The preceding values and reasons for the degradation are detailed by Rogovin and Frampton[22] and discussed by Bellamy[23] in a paper that was prepared to summarize pertinent (related to air-cleaning technology) efforts and recommendations of various investigative groups. Briefly, system degradation and the fact that radioiodine retention was associated with an efficiency of 89.5% were ultimately attributed to pre-accident aging of the impregnated activated carbon. For a number of reasons, ventilation air was passed through exhaust systems from the time of carbon installation to just shortly after the accident. This approximately one-year time frame included periods of exposure of the carbon beds to fumes from painting and cleanup efforts. Furthermore, exemptions to technical specifications postponed surveillance tests that could have revealed the extent of aging.

Review indicated that releases of radioactive material in particulate form during the TMI accident were negligible. Postaccident efforts included changeout of HEPA filters as well as carbon. As indicated by Rogovin and Frampton,[22] "These HEPAs were visually examined before changeout and were intact and in satisfactory condition, but were damaged during changeout....Unfortunately, no used HEPA filters or sections of filter media were retained for analysis."

V. Inspection, Surveillance, and Monitoring Methods

The use of surveillance tests, series of tests periodically performed to monitor component condition, is emphasized. Surveillance tests include in-place leak tests and visual inspections to evaluate filter banks and adsorbers in terms of component damage and bypass. Also included, and specifically related to aging concerns, are laboratory tests of used or aged carbon samples to determine remaining radioiodine adsorption capacity. In addition to the surveillance tests, HEPA filter pressure drop is continuously monitored (alarmed and indicated).

Surveillance leak testing of installed HEPA filters and adsorbers is specified because gradual deterioration and leaks could develop under standby as well as service conditions. These tests are based on a DOP or halide challenge aerosol or gas introduced upstream of the filters or the adsorbers, respectively. Concentrations upstream and downstream are then measured. It should be emphasized that these are leak rather than efficiency tests. For adsorbers, however, the leak test is supplemented with laboratory tests of aged or used carbon samples to determine system efficiency and remaining capacity for methyl iodide. It is stated in ASME N509 that "Sufficient test canisters or other means of obtaining samples... of used adsorbent shall be installed in the adsorber system to provide a representative determination of the response of the adsorbent to the service environment over the predicted life of the adsorbent. Test canisters shall be installed in a location where they will be exposed to the same air flow conditions as the adsorbent in the system, shall have the same adsorbent bed-depth as the adsorbent in the system, and shall be filled with representative adsorbent from the same batch of adsorbent as that of the system."[5]

VI. Conclusions

There appear to be adequate inspection, surveillance, and monitoring methods for normal conditions. It is recognized that, excluding local ruptures and tears, neither pressure drop monitoring nor surveillance leak testing of installed HEPA filters will provide indications of aging in terms of reduced filter media strength. However, even aged, intact filters can still effectively remove particles under normal conditions. On the other hand, this lack of indication may be important when considering reactor accident conditions. Regulations require atmospheric cleanup systems to mitigate the consequences of postulated accidents and, as indicated earlier, system components can be the last barrier against the release of radioactivity to the public.

The Phase I study established that the HEPA filters and adsorbers are considered to have a long service life, especially the filters. Thus, if a severe accident happens it is likely to occur at a time when these two final

confinement barriers have been in use for an extended period, even years. Even with existing ISMM, aged and possibly degraded components could fail to provide the radiation protection needed for safe shutdown or be the weak link that allows the release of radionuclides to the environment. Furthermore, the assessment has revealed the need for an improved definition of accident conditions and the possible need for additional information to evaluate the performance of aged components under such conditions. Past design basis evaluations based on the assumption that iodine is primarily in the volatile form may be neither correct nor conservative when evaluating air-cleaning system performance. It is recognized that improving the definition of accident conditions is outside the scope of the NPAR program. It is also recognized that comprehensive assessments limited solely to the development of information for performance evaluation could be made. However, for such studies to be definitive, knowledge concerning challenges must ultimately be obtained, as will be discussed below.

Some information concerning the range of challenges expected for filters and adsorbers during accidents is already available as a result of source term reassessment and reactor risk studies.[24,25] Subsequent work has revealed further insights into iodine chemical form. Although this follow-on effort did not address ultimate disposition, using calculated data from seven severe accident sequences, it was found that "in most of the calculations for the seven sequences, iodine entering containment from the reactor cooling system was almost entirely in the form of CsI with very small contributions of I or HI."[26] Additional insights concerning accident conditions should also become available as a result of recent regulatory efforts to provide improved source term definitions. As part of several regulatory activities to incorporate severe accident insights into the safety assessment of future plants, the NRC has issued a proposed revision of the reactor accident source terms. The proposed revision is in terms of fission product composition, magnitude, timing, and iodine chemical form, for release into containment.[27] Utilization of these revised source terms should provide improved estimates of accident conditions and the associated challenges to filters and adsorbers. For example, evaluation of iodine chemistry during the portion of the transient that follows release into containment will be needed, resulting in better estimates of whether iodine remains primarily in the particulate form or is converted to a volatile species before it reaches filters and adsorbers.

Even if details concerning accident conditions were available, there might be insufficient information to develop reliable predictions concerning the performance of aged components. Experiments to evaluate the behavior of filters and adsorbers under non-standard conditions including high humidity airflows, steam, and high temperature and radiation levels have been conducted. Nevertheless, statistically designed engineering-scale experiments, involving aged components and using the improved estimates of the ranges and combinations of challenges, may ultimately be justified. It is also possible that improved estimates of conditions could negate the need for further work, because either moderate or extremely severe stressors were predicted. In the case of moderate stressors, additional study would be unwarranted if near-normal operating conditions were identified. In the case of severe conditions, HEPA filters are simply not sized to handle the massive loading of nonradioactive particles that conceivably could result from molten core-concrete interactions.

An improved definition of accident conditions may also reveal that aging concerns associated with the filters and adsorbers of "normal" treatment systems may equal those of ESF systems and that the designations of primary and secondary used in RG 1.52[12] for ESF systems may be trivial in terms of accident considerations. One of the findings resulting from investigations into the TMI accident was the fact that "...a nonengineered safety feature filter system designed for normal operation only, i.e., the auxiliary building exhaust ventilation filtration system, greatly reduced the quantity of radioiodine release to the environment...the safety grade versus nonsafety grade designation [for the two air treatment systems operating at the time of the accident] was meaningless..."[22] An improved understanding of severe accident conditions could also further emphasize the importance of other air-treatment system components. For example, along with HEPA filters, greater emphasis would be placed on coarse or roughing pre-filters and even demisters if it were determined that high particle concentrations were involved.

Finally, it should be emphasized that information used to estimate the performance of aged air-treatment system components can have a significant impact on the calculated consequences of postulated accidents. This is illustrated by the analysis of a postulated loss-of-decay-heat-removal accident at Browns Ferry. The standby gas treatment system (SGTS) failure model used, listed as the area of greatest uncertainty with respect to informal sensitivity analyses, includes best estimates concerning the filter loading that will cause failure, the type of failure, and the functioning of the adsorber under the projected accident environment. It is noted that "the SGTS failure model assumes prime importance because the SGTS is the last barrier to the atmosphere in this accident sequence."[28]

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CRITERIA FOR CALCULATING THE EFFICIENCY OF DEEP-PLEATED HEPA FILTERS WITH ALUMINUM SEPARATORS DURING AND AFTER DESIGN BASIS ACCIDENTS*

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ABSTRACT

We have reviewed the literature on the performance of high efficiency particulate air (HEPA) filters under normal and abnormal conditions to establish criteria for calculating the efficiency of HEPA filters in a DOE nonreactor nuclear facility during and after a Design Basis Accident (DBA). This study is only applicable to the standard deep-pleated HEPA filter with aluminum separators as specified in ASME N509 [1]. Other HEPA filter designs such as the mini-pleat and separatorless filters are not included in this study. The literature review included the performance of new filters and parameters that may cause deterioration in the filter performance such as filter age, radiation, corrosive chemicals, seismic and rough handling, high temperature, moisture, particle clogging, high air flow and pressure pulses. The deterioration of the filter efficiency depends on the exposure parameters; in severe exposure conditions the filter will be structurally damaged and have a residual efficiency of 0%. Despite the many studies on HEPA filter performance under adverse conditions, there are large gaps and limitations in the data that introduce significant error in the estimates of HEPA filter efficiencies under DBA conditions. Because of this limitation, conservative values of filter efficiency were chosen when there was insufficient data.

The estimation of the efficiency of the HEPA filters under DBA conditions involves three steps. In the first step, the filter pressure drop and environmental parameters such as temperature and moisture are determined during and after the DBA. The second step consists of comparing the filter pressure drop to a set of threshold values above which the filter is structurally damaged. There is a different threshold value for each combination of environmental parameters. The filter efficiency is determined in the third step. If the filter pressure drop is greater than the threshold value, the filter is structurally damaged and is assigned 0% efficiency. If the pressure drop is less, then the filter is not structurally damaged; and the efficiency is determined from literature values of the efficiency at the environmental conditions. The efficiency of the HEPA filters within DOE facilities should be determined on a case-by-case basis.

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I. Introduction

The primary standard that governs the use of HEPA filtration systems in DOE facilities is DOE Order 6430.1A [2], which in turn refers to ASME N509 [1]. However, the standards do not provide guidance for determining their efficiency under abnormal or accident conditions. Under normal operating conditions, a HEPA filter will have a minimum efficiency of 99.90% [3]. This is the minimum filter efficiency at the most penetrating particle size of 0.15 μm diameter for a HEPA filter that has a minimum efficiency of 99.97% for 0.3 μm DOP particles. Previous publications had assigned a single value for the efficiency of HEPA filtration systems under all accident conditions. However the publications reviewed in this paper demonstrate that the efficiency of HEPA filters will vary greatly depending on the operating conditions, thereby requiring a case-by-case analysis.

Elder et al [4] prepared a guide for analyzing the accidental release of radioactive material from nonreactor nuclear facilities. This guide reviews the applicable DOE orders, provides a description of the design basis accidents, and evaluates the consequences of the accidents. In his section on reduction and removal factors, Elder discusses the efficiency of HEPA filters under DBAs. Elder recommended that the first stage HEPA be credited with an efficiency of 99.9% and each subsequent stage with 99.8%. These values were selected from an unofficial HEPA filtration guideline that was established in 1971 during a meeting between officials from the Atomic Energy Agency and Albuquerque Operations Office [5]. These guidelines represented the opinions of the meeting attendees, and were not supported by technical data.

Walker [6] tabulated the available data on HEPA filter efficiency as of 1978 and recommended efficiencies of 99.9% for the first stage, 99.0% for the second and third stages, and 83.0% for the fourth stage. Although Walker cited experimental data, the recommended values were based on his opinion. Walker further stated in the summary that further study of HEPA filter efficiency is needed "to better establish relationships with relative humidity and temperature of sweep gas, service aging, material loading, etc."

The Nuclear Regulatory Commission in Regulatory Guide 1.52, recommended an efficiency of 99% for a filtration system consisting of a two stages of HEPA filters with an adsorber in between [7]. The guide is applicable to light-water-cooled nuclear power plants, where the filtration system is off-line during normal operations and only activated during accident conditions. Table 1 of the code shows that environmental conditions to which the HEPA filters would be exposed are approximately atmospheric pressure, 180°F, 100% relative humidity, and 105 rads/hr. There is no explanation for setting the HEPA

filter efficiency at 99%, when the new filter is tested at 99.97% for 0.3 μm DOP particles and is also tested in-place for leaks at 99.95% as prescribed in ASME N510. [8]

The Nuclear Air Cleaning Handbook [9] recommended 99.8% efficiency for the first stage and 99.9% to 99.95% for each of the remaining stages. The Handbook presumably recommends a lower efficiency for the first HEPA filter and a higher efficiency for the second stage HEPA than the AEC 1971 draft because of the assumption that the first filter would take the brunt of any adverse effect from accidents. In discussing multistage HEPA filtration, the Handbook stated on page 38, "The purpose is to increase the reliability of the system by providing backup filters in the event of damage, deterioration, or failure of the first filters."

The major deficiency in the previous guidelines on HEPA filter efficiencies under DBA conditions is that the HEPA filter efficiency in DOE facilities can vary from 99.9% to 0% depending on which of the large number of different DBA conditions is applicable. In contrast, for light water reactors, there is a single DBA condition for which the HEPA filter efficiency is assigned 99% [7] We have proposed a method for computing the efficiency of HEPA filters on a case-by-case basis using the available data reported in the literature. In this paper we describe the development of criteria for calculating the efficiency of HEPA filters during and after a DBA. These criteria are intended to be used in a future DOE Standard.

The goal of this paper is to provide guidance for computing the efficiency of HEPA filters during and after a DBA. The computed filter efficiency can be used in determining off-site doses from postulated releases of airborne radioactivity for both existing and future facilities. However, this study is not intended to define criteria for HEPA filter survival or provide guidelines on how to construct a HEPA filter that survives a DBA. Since there are a large number of different DBAs that are applicable to the many different DOE facilities, the HEPA filter efficiency will be computed on a case-by-case basis.

II. Approaches for Computing HEPA Filter Efficiency Under DBA

Single Efficiency Value for All DBA Conditions

We considered various approaches for developing the criteria for computing HEPA filter efficiency under DBA conditions. The previous approach was to specify a single efficiency value for all conditions. We considered this to be unrealistic since the efficiencies of the available HEPA filters vary widely with different environmental parameters. Since there are no commercially available HEPA filters certified for

use in DOE facilities that can survive all of the postulated DBA conditions it is not possible to assign a single efficiency value to HEPA filters.

For the currently available HEPA filters, the only efficiency value that can be applied for all DBA conditions is 0%. However, since the HEPA filters in most DOE facilities will survive the applicable DBA, assigning 0% efficiency to these filters is unrealistic. We concluded that until a high-strength HEPA filter is developed, it will not be possible to assign a single efficiency to HEPA filters that will apply for all DBA conditions.

Efficiency Determined From Matrix of Three Severity Levels of Fire, Explosions, and Tornados

We then reviewed various matrix approaches in which there are multiple filter stresses and multiple responses. A filter efficiency would be assigned for each of the filter stresses. In our initial review, there appeared to be only a few realistic DBA scenarios that include combinations of anticipated stresses that reflect graduated levels of severity. For example, a remote fire usually represents a filter loading episode without a very high temperature or a pressure pulse; an explosion usually represents a temperature and pressure pulse, and it may be the pressure resulting from rapidly increased airflow that does the damage and rapidly dies away to be followed by a fire without excessive pressure or airflow volume increase; a tornado results in a rapid pressure increase and/or decrease but no fire or particle/droplet loading. Each scenario can occur in varying degrees of severity that can probably be classified as "below concern", "moderate stress", and "extreme stress". This represents a 3 x 3 matrix and should not be excessively complex.

Although the concept is great, we were not able to assign an efficiency value for each of the proposed nine elements of the matrix because the three stresses of fire, tornado, and explosions were not single stress quantities, but could very widely in terms of more fundamental parameters such as temperature, pressure, and aerosol quantity and composition. For example estimating the efficiency of a HEPA filtration system after a fire cannot be derived from categories such as below concern, moderate stress or extreme stress. In order to assess the response to the fire, it will be necessary to estimate the temperature, quantity of smoke, type of smoke, water spray from a fire suppression system, the system flow rate, and the pressure drop across the HEPA filter. The pressure drop across the filter is, in turn, a function of the flow rate, water contact, and the quantity and type of smoke.

There is not a single DBA sequence that represents a fire. For example the remote fire scenario only involves filter clogging with little temperature increase or pressure pulse. In reality, there are a large

number of different fire scenarios: a well ventilated fire generating slow plugging aerosols, an under ventilated fire generating rapidly plugging aerosols, a fire with high temperature flames, use or non-use of fire suppression system based on water sprays and demisters, etc..

If the fire is remote and well ventilated, then the only consequence would be a small or moderate increase in pressure drop and no loss in efficiency. However a remote fire that is under ventilated (oxygen starved) would cause rapid filter plugging. If the air blower does not exceed the breaking point of new filters (37 inches) then the effect would be a near or total shut down of the ventilation system. The efficiency of the clogged filter would be higher than the efficiency of the clean filter. If the smoke is diluted prior to reaching the HEPA filter, then the filter plugging will be reduced proportionately to the air dilution.

As another example dealing with fire, assume the fire is localized at the filter and reaches 400°C. If no water suppression system is activated and the filter pressure drop is below 15 inches then the filter will be structurally undamaged but have a penetration about of about 3% . However if the water spray system is activated, then the filter will rapidly plug due to water accumulation. If the air blower can pull greater than 10 inches of water then the filter will be structurally damaged and have dramatically reduced efficiency (conservatively set at 0%). However if the air blower cannot pull greater than 10 inches of water, then the plugged filter will shut down the ventilation system but still have the high efficiency.

Thus from these few examples we have shown that estimating the efficiency of the HEPA filters requires a more complex approach than categorizing a stress as below concern, moderate stress or extreme stress. There are also many other potential stresses than fire, tornado and explosion: for example, steam from a ruptured steam line, fire suppression system that sprays water, chemical effluents, and seismic stress.

In addition, the DBA stresses cannot be limited to a small number of different conditions because new DBA conditions will be established for new facilities and operations as DOE missions and directions change. New programs in weapons dismantlement, waste clean up, decontamination and decommission operations will bring their own set of stress factors.

Efficiency Determined from Generalized Matrix of Operating Parameters and Parameters Causing Structural Damage

We then evaluated a generalized matrix in which the efficiency is established at each level of stress for a series of fundamental parameters at increasing parameter level. Table 1 illustrates the

generalized matrix for tabulating the filter efficiency at each parameter level for a series of different parameters. These are the known parameters that have an effect on filter efficiency.

Table 1. Generalized matrix for establishing filter efficiency for operating parameters

	Efficiency at Different Parameter Levels		
Operating Parameter	Low	Moderate	High
temperature			
solid particle loading			
water/liquid particle loading			
air flow			

Although Table 1 shows only three parameter levels (low, moderate, and high), the complete table could consist of many parameter levels, each level defined by specific values of the operating parameter. The primary advantage of the generalized parameter matrix over the three-stress matrix is that the parameters are fundamental parameters that can be uniquely defined. It is also possible to use semi-empirical equations for computing the efficiency due to the different parameters. Since the four parameters can be considered to act independently on the filter, the filter efficiency for combination of parameters can be computed from the efficiency for individual parameters.

The effect of the four operating parameters on the HEPA filter efficiency can be explained in terms of particle capture and particle loading theory and experiments. For HEPA filters, the maximum particle penetration is determined by the Brownian motion and interception capture mechanisms [10]. As the temperature is increased, the Brownian motion will increase while the interception mechanism remains constant. Thus higher temperatures will result in higher filter efficiencies. As the air flow increases, the capture by Brownian motion will decrease because of the decreased particle residence time in the filter. Since air flow has no effect on the interception mechanism, the net effect of increased air flow will be a lowering of filter efficiency. At exceedingly high air flows, the particle inertia becomes important and increases the filter efficiency. For solid particle loading, the particles form dendritic structures that capture additional particles, thereby increasing filter efficiency [11]. For liquid particles, the particles coalesces within the filter and decrease the void volume within the filter medium. The decreased void volume results in higher internal velocity and thus less residence time for Brownian motion [12]. Thus, as liquid deposits form in the filter, the aerosol penetration will increase.

Unfortunately the direct approach for computing the efficiency of HEPA filters under DBA conditions described above is not possible because the HEPA filters are frequently structurally damaged, which lowers the filter efficiency. For example as the temperature is increased, the efficiency increases. Figure 1 shows the decontamination factor (DF = 1/penetration) as a function of particle diameter for a deep-pleated HEPA filter with aluminum separators at increasing temperatures up to 200 C.

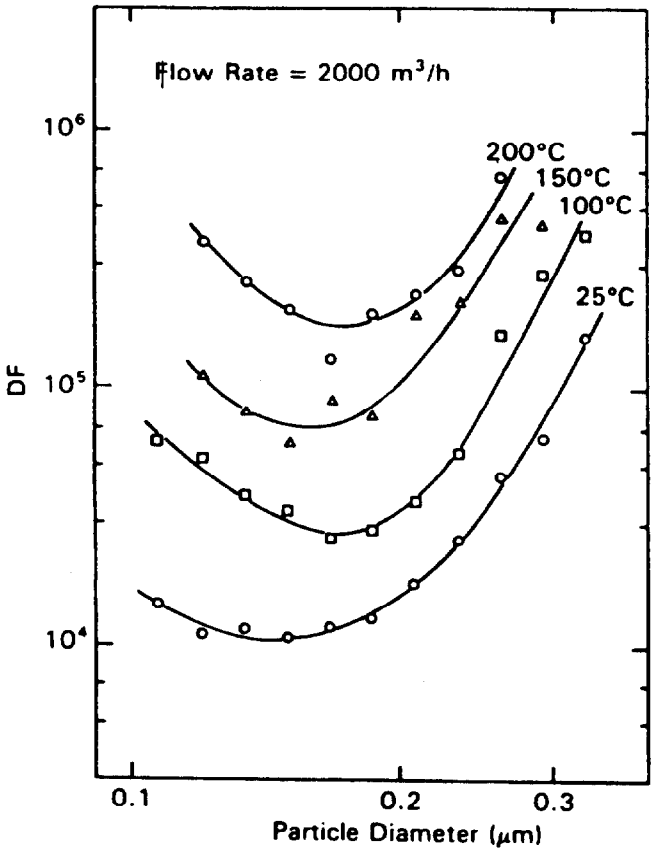

Figure 1 Decontamination factor (DF =1/penetration) for HEPA filter as a function particle diameter at increasing temperatures. Data from Osaki and Kanagawa [13].

With increasing temperature the organic components begin degrading and introduce leak paths through the filter. Figure 2 illustrates the effect of increasing temperature on the decontamination factor for HEPA filters with different frame materials.

The effect of increasing air flow provides another example of a stress having a direct effect on the filter efficiency due to the basic filtration mechanism and an indirect effect due to structural damage to the filter. Figure 3 shows the increasing DOP aerosol penetration as a function of particle size for a HEPA medium tested at increasing air velocities.

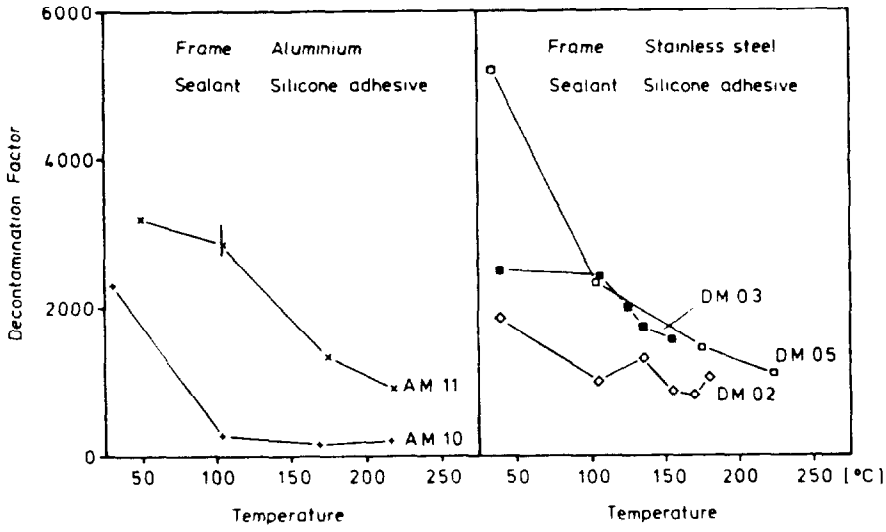

Figure 2 Decontamination factor for HEPA filters as a function of increasing temperatures. Data from Ensinger et al [14].

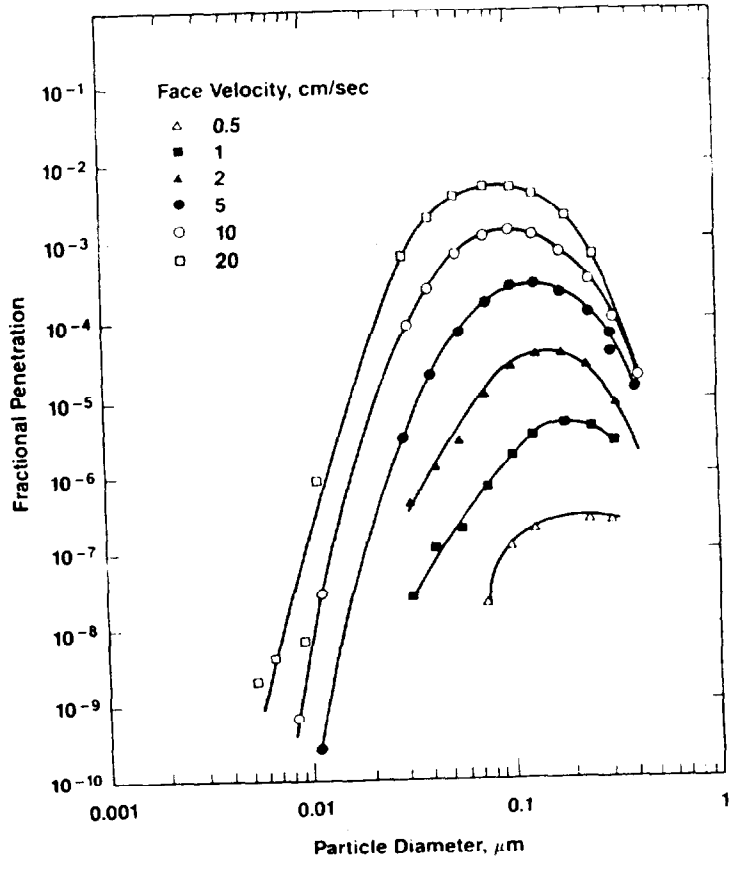

Figure 3. Penetration of DOP aerosols as a function of particle diameter at increasing air velocities for a HEPA medium, Lydall grade 213. Data from VanOsdell et al [15].

As the air flow is increased the increasing pressure drop on the filter stresses the filter medium and eventually causes medium tears At high air flows, the entire medium pack is blown out of the housing as shown in Figure 4. It is obvious that the filter has 0% efficiency.

Figure 4 Photograph of 15-19 year old HEPA filter after subjected to a 13 inch differential pressure Photograph from Johnson et al [16].

There are additional stresses such as age, radiation exposure, water/liquid loading, seismic or rough handling, and chemical attack that also can weaken or cause structural damage to the HEPA filter. Structural damage creates leak paths that lower the HEPA filter efficiency, whereas a weakened filter suffers structural damage at lower stress levels. Thus in order to determine the efficiency of HEPA filters under DBA conditions, it is necessary to include indirect effects due to HEPA filter damage in addition to the direct effects from the parameters listed in Table 1. However, incorporating structural damage and a weakened filter into a general method for determining filter efficiency is extremely difficult because a number of interacting parameters must be incorporated in the efficiency calculation. We will use data obtained from the literature to establish a method for computing the efficiency of HEPA filters under normal and DBA conditions.

III. Literature Review of HEPA Filter Efficiency Under Normal and DBA Conditions

The Minimum Baseline Efficiency for Each Stage of HEPA Filtration is 99.9%

Single HEPA Stage According to ASME N509 each HEPA filter must have a minimum efficiency of 99.97% for 0.3 μm DOP aerosols. However, recent studies have shown that the 0.3 μm DOP aerosol is not the most penetrating size and therefore is not the most conservative efficiency. The particle penetration through HEPA filters is a strong function of particle size as shown in Figure 5 taken from Bergman et al [17]. The maximum particle penetration at 0.15 μm diameter is about four times the penetration measured using 0.3 μm DOP particles. The penetration decreases at smaller and larger particles due to competing particle capture mechanisms [18]. Particles less than 0.15 μm have increasing Brownian motion with smaller sizes and therefore have lower penetration through the filter. Particles larger than 0.15 μm have greater inertia with increasing size and are unable to follow the tortuous path through the filter. This results in a lower penetration with increasing size. The two capture mechanisms result in the experimental penetration curve seen in Figure 5.

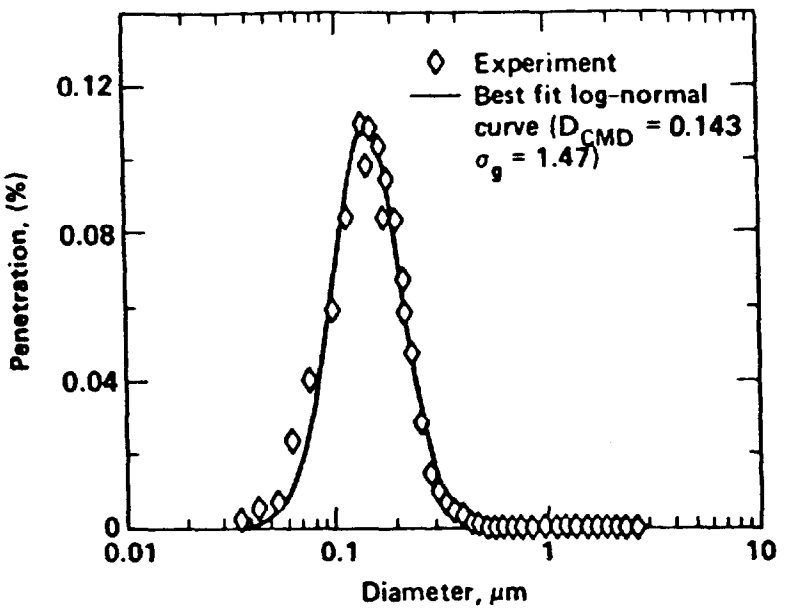

Figure 5 Penetration of DOS aerosols through a standard nuclear grade HEPA filter [17].

Scripsick et al [3] conducted a comparison study between the standard DOP test using 0.3 μm particles and the maximum penetration test in which penetration is measured as a function of particle size. They found that of 849 filters tested that had greater than 99.97% efficiency for 0.3 μm particles, 18% of the filters had less than 99.97% but greater than 99.90% efficiency for 0.15 μm particles. Thus the minimum efficiency for a new, undamaged HEPA filter is 99.90% at any particle size. The efficiency in most applications will be much greater, not only because the particle size is usually greater that 0.15 μm, but also because the particles generally have a greater density than the density of DOP (0.98g/cc). Anderson [19] and Tillery [20] have shown higher density aerosols have significantly higher efficiencies. However, if the aerosols consist of agglomerates of smaller particles, then the density will be significantly smaller than the bulk material density.

Multiple HEPA Filtration Stages. If the HEPA filter penetration is measured at the most penetrating particle size then the total maximum penetration for multiple stages of HEPA filters is the product of the penetration from each of the HEPA filters in series. There is no limit to the number of stages for which this computation will apply. However, each stage or combined stages must be leak-tested as specified by ASME N510 [8]. The penetration for each new, undamaged HEPA filter is 0.1% (99.9% efficiency). Untested HEPA filters with no visual damage are assigned a penetration of 10% (90% efficiency) based on the following field data using radiological measurements: Hetland and Russell [21] measured HEPA filter efficiencies of 94% and 83% for Pu aerosols in the second and third stages respectively. Frigerio and Stowe [22] measured an average efficiency of 99.4% for Pu and 92.9% for U in a third stage HEPA filter. Previously, untested HEPA filters were arbitrarily assigned a penetration of 0.2% (99.8% efficiency) [9].

The determination of total penetration for multiple HEPA filters from the product of the individual filter penetrations appears to contradict the widely held belief that the filter penetration increases (i.e. efficiency decreases) with each filter stage. Previous studies that have shown a decrease in filter efficiency with multiple stages of filtration were generally based on average efficiencies for heterodisperse aerosols and/or have had significant background measurements. If filter efficiencies are based on average measurements over a particle size distribution, then the apparent filter efficiency will change with successive stages of filtration because the average particle size has changed. Ortiz [23] showed that even heterodisperse aerosols with narrow distributions will be altered when passing through HEPA filters and thereby cause a shift in the average particle size and the filter penetration.

Gonzales et al [24] conducted experiments with plutonium aerosols that showed the penetration of each HEPA filter in a system consisting of three filter stages is 99.99% for the first two stages and 99.84% for the third stage. They measured the HEPA penetration as a function of particle size for the first

two stages. The extremely low concentration of plutonium particles challenging the third filter made measurements extremely difficult and is most likely responsible for the lower filter efficiency.

Osaki and Kanagawa [13] showed that the penetration of 0.15 μm DOP particles for the second HEPA filter in a two-stage filter system yielded identical results as the first HEPA filter. They also verified that the two filters continued to have the same efficiencies at various air flows.

The study by Gonzales et al [24] and filtration theory were used in ERDA 76-21 [9] to conclude that the particle penetration through multiple HEPA filters equals the product of the penetrations of individual HEPA filters. ERDA 76-21 [9] points out that the multiplication of penetrations is valid for any particle particle size

Literature Review of Parameters That Cause a Deterioration in HEPA Filter Efficiency

A number of laboratory studies have shown that the efficiency of HEPA filters will degrade under c- ain environmental conditions. In extreme cases, the HEPA filter will be structurally damaged and result in 0% efficiency. The identified parameters that can cause a deterioration in the filter include age, moisture, chemical attack, high temperature, overpressure, shock and rough handling, particle loading, and radiation. The effect of these parameters on HEPA filters is dependant on the materials used and the design of the HEPA filters.

We summarized the literature data for the differential pressure required to cause structural damage on HEPA filters for various parameters in Table 2 In some cases only media data were available, and we had to compute the pressure drop for an equivalent HEPA filter. The percent reduction in media tensile strength or bursting strength from before and after exposure to a given parameter was used in the computation. This percent was then multiplied by the measured pressure drop required to blow out the medium in a new HEPA filter as measured by Gregory et al [25]. For example , Breschi et al [26] measured a 33% reduction in medium burst pressure after exposure to 200 C for one hour. The medium thus had 67% of its original strength. Multiplying 67% by 37 inches of water (the minimum pressure required to blow out the medium from a new HEPA by Gregory et al [25]) yields 25 inches of water. Although no data was available on the structural damage from acid exposure, the filter is degraded with increasing exposure and will even collapse by its own weight with prolonged exposure.

Table 2 Threshold Values of Differential Pressure Required to Structurally Damage the Standard HEPA Filter

ΔP threshold, inches Avg.	Range	Parameter	Reference
66	(37-81)	Baseline (high air flow)	Gregory et al [25]
57	(38-72)	Baseline (high air flow)	Osaki et al [13]
63	(47-90)	Baseline (high air flow)	Ruedinger et al [27]
52	(29-70)	Explosion shock	Gregory et al [25]
38	(13-78)	Age (15-19 year old filters with Asbestos separators)	Johnson et al [16]
33[1]	(18-40)[1]	Radiation (5×10^7 rad)	Jones [28]
X[2]		HNO_3, HF exposure (variable)	Woodard et al [29]
		Temperature	
44[3]	(25-54)[3]	200°C (392°F), 1 hr.	Breschi et al [26]
33[4]	(19-41)[4]	300°C (572°F), 10 min.	Hamblin et al [30]
26[5]	(15-32)[5]	400°C (752°F), 1 hr.	Breschi et al [26] and Hamblin et al (30)
13[6]	(8-16)[6]	500°C (932°F), 10 min.	Pratt et al [31]
	(8-20)	500°C (952°F), 10 min.	Pratt [32]
23	(10-36)	Clean filter, water spray	Ruedinger et al [33]
20	(16-25)	Loaded filter, 100% humidity	Ruedinger et al [33]
18	(7-36)	Clean filter, water spray	Ricketts et al [34]
16	(3.6-25)	Loaded filter, 99% RH	Ricketts et al [34]
40[7]	(22-49)[7]	Clean dry filter, prev. wet	Ricketts et al [34]

Footnotes

1. Values computed from a measured 50% reduction in media tensile strength and base line values from Gregory et al [25].
2. No available data relating differential pressure threshold and acid challenge. Observations of HEPA filter after acid challenge show the HEPA media collapses and may fall out of its housing by its own weight.
3. Values computed from a measured 33% reduction in media rupture pressure and baseline values from Gregory et al [25].
4. Values computed from a measured 50% reduction in media rupture pressure and baseline values from Gregory et al [25].
5. Values computed from a measured 60% reduction in media rupture pressure and baseline values from Gregory et al [25]
6. Values computed from measurement of 80% reduction in tensile strength and baseline filter values from Gregory et al [25].
7. Values computed from measurement of 40% reduction in tensile strength and baseline filter values from Gregory et al [25].

Note: This table applies to HEPA filters having the deep-pleat design, organic sealant, and conventional glass fiber media. Other commercially available HEPA filters have lower threshold values for differential pressure.

Table 3 Effect of Parameters on the Penetration of HEPA Filters

Parameter	Effect on Filter Penetration	Reference
Baseline	0.1%	Scripsick et al [3]
HF Corrosion		
1,500 ppm-hr	0.1% increase	Brassel et al [35]
Temperature		
increase from 25 to 200 C	decreases penetration from 0.01 to 0.001%	Osaki et al [13]
200°C	.03-0.01%	Pratt et al [31]
240°C for 6 hours	0.01%	Osaki et al [13]
300°C	0.12-0.01%	Pratt et al [31]
350 C	0.4-0.03%	Pratt et al [31]
500°C	0.9-0.2%	Pratt et al [31]
500°C for 10-45 min.	0.9-0.1%	Hackney [36]
538°C	1.2-0.5%	First [37]
Moisture		
Up to 100% RH	Negligible effect	Osaki et al [13]
Water spray loaded to 8 in.	Increase by 10 times	Osaki et al [13]
Filter clogging		
Solid particle loading	Decreases penetration	Bergman [11]
NaCl deposits to 1.9 in.	Decreases penetration from 0.003 to 0.000001%	Osaki et al [13]
Liquid DOP loaded to 4 in.	Penetration increases by factor of 10	Osaki et al [13]
Oil aerosols	Penetration increase is 1.3 $P_i\Delta P/\Delta P_i$ increase	Payet et al [12]
Air Flow		
Increasing velocity from 0.5 cm/s to 20 cm/s	Penetration increases from 0.00003% to 0.5%	VanOsdell et al [15]
Increasing air flow by 10 times	Penetration of 0.1 μm particles increases by100 times	Osaki et al [13]
Air Pulse		
1 psi pulse	Penetration of 0.46 μm latex particles is 0.1%	Gregory et al [25]
Shock tests on filters preloaded with .46 μm latex	Penetration is 0.9%	Gregory et al [25]
Seismic (0.2- 0.3 g)	negligible effect	Bergman et al [38]

We also reviewed the literature for the effect of different parameters on the efficiency of HEPA filters and have summarized the data in Table 3. The HEPA filters in these studies did not suffer structural damage except for the higher temperature and acid exposure tests. Although the HF exposure shows only a single entry, the penetration will increase with increasing exposure due to chemical attack

on the filter medium. Table 3 also shows a range of penetration values that were observed for different HEPA filters after the high temperature exposures.

IV. Developing a Method for Determining Filter Efficiency Under Normal and DBA Conditions

Generalized Matrix Method is Not Feasible

Our initial approach was to incorporate the literature data on filter deterioration into the generalized matrix shown in Table 1. Unfortunately it is not possible to simply add additional parameters that weaken the filter or cause structural damage such as age and radiation exposure to the existing parameter list because the parameters are not independent. For independent parameters, it is not necessary to consider parameter interaction in computing filter efficiency. For example, when determining the filter efficiency under specific conditions of temperature, solid particle loading, water/liquid loading and air flow where there is no structural damage, one can add the contributions to filter efficiency by each of the three parameters. In practice the change in filter penetration (1 - efficiency) due to each parameter is added to the baseline penetration to yield the total penetration.

For dependent parameters it is necessary to consider the parameter interaction when computing filter efficiency. All of the parameters that affect filter strength or cause structural damage are dependent parameters because the filter damage or weakening from one parameter affects the amount of damage or weakening from a second parameter. For example the minimum pressure drop (or flow) required to rupture a new HEPA filter is 37 inches [25] whereas the minimum pressure drop for a 15-19 year-old filter is 13 inches [16] Both filters had 0% efficiency after the test. Intermediate pressure levels are required to burst HEPA filters less than 15 years old. A different series of pressure and age parameters define the limits for each efficiency level between 0% and 99.9%. In his study of water effects, Ricketts [34] showed that a combination of factors leads to a greater loss in filter efficiency than the cumulative effect of the individual factors alone. This illustrates that filter efficiencies derived from studies on filter structural failures require combination of parameters and cannot be determined by individual parameters.

The primary difference in a matrix consisting of independent parameters for filter efficiency and dependant parameters for structural damage is the number of matrix elements required. For N independent parameters and 3 values of each parameter, the matrix consists of 3N elements. For N dependent parameters and 3 values of each parameter, the matrix consists of 3^N elements. The parameters that affect the HEPA filter efficiency directly are temperature, solid particle loading, water/liquid particle loading, and air flow. Of these, the solid particle loading is the only independent

parameter since the other parameters can also cause structural damage and hence are dependent parameters. The remaining dependent parameters are age, radiation exposure, seismic or rough handling, and chemical attack.. Thus for one independent and seven dependent parameters, the matrix consists of $3 + 3^7 = 1{,}380$ elements. For a matrix with 4 values for each parameter, the matrix would consist of $4 + 4^7 = 16{,}388$ elements. Even if the matrix were reduced to the minimum parameters of temperature, water loading, air flow, and age, the 3 value matrix would consist of 81 elements, and the 4 value matrix 256 elements. These are obviously very large matrixes.

We believe that it is not practical to pursue the development of a generalized matrix for computing the efficiency of HEPA filters under normal and DBA conditions because there are far too many elements, the experimental data is highly variable, and a separate matrix would be required for each design and construction of HEPA filter. Although a large number of studies are reported in the literature on the efficiency of HEPA filters under adverse conditions, all of the studies have been limited to one or two parameters, whereas most DBAs involve several parameters. There are few studies on evaluating filter efficiency for combination of parameters . As shown in our matrix examples, the large number of matrix elements is due to the combinations of different parameters.

In addition most of the literature data pertains to the standard deep-pleated HEPA filter using the standard glass fiber medium with aluminum separators. If other filter designs and/or other materials are used, then a different filter efficiency matrix is needed. There are a large number of different combinations of filter media, filter pleat configuration, sealant, separators, frame and gaskets. Each combination of components yield a HEPA filter with a unique set of responses to applied stress. Unfortunately, there exists very little data for other filter designs or other materials. The other filter designs occasionally used are the mini pleat, the cylindrical cartridge with radial pleats, the cylindrical cartridge made with standard deep pleats and media and the deep pleated separatorless filter. The use of glass cloth reinforced filter media dramatically increases the filter strength and the value of differential pressure required to structurally damage the HEPA filter.

The final problem for computing filter efficiency that applies to the matrix and all other methods is the variability of the data. For example, Johnson et al [16] exposed 15-19 year-old HEPA filters to simulated tornados and measured the differential pressure across the filters during the approximately 5 second air pulses. They tabulated the differential pressure at which the filter showed the first signs of damage and the pressure drop for total medium blow-out The data is retabulated here in Table 4

All of the six filters tested had the media blown out as shown in Figure 4 except for the filter in test 17. Although no efficiency measurements were made on the filters, we added a column in Table 4

for the estimated efficiency at the end of the test. Since the filters in tests 18-23 had no media left in the filter housing, the efficiency was 0%. The filter in test 17 had the medium pack torn loose from the filter housing, but did not blow out at 77.8 inches pressure drop, which was the maximum applied stress during the test. A more powerful air pulse was needed to blow out the medium. We estimated the efficiency of the partially damaged filter at 98% based on efficiency measurements made on filters showing similar structural damage.

Table 4. Differential pressure for initial and total damage to aged HEPA filers from Johnson et al [16]

	Differential Pressure (in. water)		Estimated Efficiency (%)
Test No.	Initial	Total	
17	25.5	77.8	98
18	--	15.5	0
19	3.9	18.8	0
21	3.3	56.8	0
22	3.3	13.6	0
23	2.8	45.7	0
Average	7.8	38.0	

Table 4 illustrates the problem with trying to establish an efficiency value for a HEPA filter subjected to a given stress that causes structural damage. There is an initial stress value at which the filter shows the first indication of structural damage. For the six filters tested, the initial stress values varies from 2.8 to 25.5 inches of water and has an average of 7.8 inches of water. The initial damage consisted of a small segment of a filter pleat torn open. Based on efficiency tests on other filters with similar damage, the efficiency at the initial damage was about 99%. As increasing stress was applied to the filter, the efficiency would decrease until it reached 0% at total medium blow out. The differential pressure at total medium blow out ranges from 13.6 inches to greater than 77.8 inches with an average somewhat greater than 38 inches.

Experimental Measurements Under DBA Conditions Is the Preferred Method, But There Are No Facilities

The preferred method for determining HEPA filter efficiency under DBA conditions is to conduct experiments on a scaled HEPA filtration system under controlled test conditions that simulate the DBA. The scaled down, 1,000 cfm HEPA filtration system would be mounted in a test duct that would contain the desired air flow or air pulse, temperature, and water content. All of the components of the HEPA filtration system would be included such as prefilters, water deluge system, mist eliminator, and one or

more stages of single HEPA filters. The test would consist of a series of exposures that simulate the specific DBA. For example a simulation of a fire DBA might consist of a smoke challenge followed by a temperature increase and then a water deluge spray. The test filter could be preconditioned with particle loading, chemical exposure, seismic stress, etc. as needed to represent the exposure history for the DBA. Several repeat test would be conducted to establish the variability in the data.

The experimental approach has many advantages over a system based on determining the filter efficiency from a match with a catalog of test conditions and the corresponding efficiencies. The most important advantage is that the experimental approach will yield efficiencies for experimental conditions that match the DBA conditions as close as is experimentally possible. The problem with the catalog approach is that most of the available data is limited to HEPA filter efficiency for a single exposure parameter and a single or limited range of parameter values. This is in contrast to most DBAs that consist of a series of concurrent and sequential parameters. The catalog matching approach will undoubtedly require approximations and assumptions because the catalog will not contain the large number of matrix elements needed to fully describe the particular DBA. Moreover the exact filtration components and HEPA filters can be used in the simulation tests. In contrast, the catalog approach would undoubtedly contain data for different HEPA filters and system components. Another advantage is that conducting simulations of DBAs on HEPA filtration systems would be less costly than an attempt to develop catalogs of all the possible matrix elements in each of the many different matrixes that correspond to specific HEPA filtration systems.

Unfortunately, there is no test apparatus in the U.S. that can conduct DBA simulations or generate DBA matrix elements for HEPA filtration systems. A special test apparatus would have to be built for either application. The existing U.S. test equipment is limited to studying single parameters such as high air flow (New Mexico State U.), smoke loading (LLNL), and the quality assurance tests of heated air, overpressure, and rough handling (Rocky Flats). The quality assurance test equipment at Rocky Flats is designed for specific test conditions as part of the filter qualification prescribed in MIL-F-51068 [39] and cannot be varied to provide a range of DBA parameter values. Although the European countries have test equipment that can evaluate HEPA filters under a wide range of values for specific parameters, they do not have an apparatus that can expose HEPA filters to multiple parameters that simulate DBA conditions. Germany has a test rig that can expose HEPA filters to high humidities and water sprays at temperatures up to 151 C and another system that can expose HEPA filters to high air flows. England and France have test rigs that can expose HEPA filters to various temperatures up to 400 C. Much of the data on HEPA performance under off-normal conditions was generated in these European facilities.

We Selected the Method Based on First Determining Structural Damage and Then Efficiency

Since it is not feasible to determine HEPA filter efficiency under DBA conditions using the generalized matrix method, and since no experimental facilities are available, we examined alternative approaches that could make use of the data base of HEPA filter performance under off-normal conditions. We focused our efforts on a method for separating out the many dependent parameters that affect filter strength or cause structural damage since these parameters are responsible for the large matrix for establishing HEPA filter efficiency . The filter efficiency would then be determined in two steps: first determine the filter efficiency for the parameters that cause structural damage and then add any contribution to the efficiency by the parameters in Table 1 for an undamaged filter.

The parameters that affect the filter strength and structure are temperature, water/liquid loading, air flow (pressure drop), age, radiation exposure, seismic or rough handling, and chemical attack. We have placed pressure drop in brackets following the air flow because the two parameters are directly proportional. Of these parameters only air flow (pressure drop) and seismic or rough handling can cause structural damage directly. The other parameters only weaken the filter. Thus higher air flows and resulting pressure drops will produce greater structural damage in the filter.

Particle loading is an important factor in determining the filter pressure drop, but is is not important for the threshold value of pressure drop at which the HEPA filter shows structural damage. A HEPA filter will suffer structural damage at the same pressure drop, whether or not particles are present. Particle deposits will increase the filter pressure drop and cause the threshold pressure drop to be reached at lower flow rates. However, the particle deposits will not lower the threshold pressure drop. Particle deposits were therefore not included in Table 5. None of the studies reviewed in this paper show that particle deposits have much of an effect on the structural strength of HEPA filters. Ricketts et al observed a 5% reduction in tensile strength of creased media [34]. Particle deposits also significantly increase the amount of water absorption on a filter, which subsequently decreases filter strength. However, this decreased strength is due to water, not particle deposits. Ricketts et al [34] found no significant difference in structural strength between HEPA filters with or without particle deposits during exposure to humid air and water sprays. Smith et al [40] observed a small increase in the pressure drop required to cause structural damage with HEPA filters loaded with salt particles. The salt deposits had formed a crust over the protective wire screen, thereby protecting the HEPA filter medium.

We wanted to construct a table showing filter efficiency at increasing levels of structural damage produced by increasing pressure drop for the parameters that weaken the filter. Unfortunately, the literature data contained little or no information on the efficiency of partially damaged HEPA filters. Most

of the studies pertaining to HEPA filter damage only measured the pressure drop as shown in Table 2 ar ot the efficiency . The literature data was also limited to a single pressure drop measurement. In most cases, the pressure drop data corresponded to the threshold or first intermediate damage level. However, in a few cases, the pressure drop corresponded to the to total medium blow-out.

The level of structural damage is important since the efficiency can vary from 99% for a partially damaged filter to 0% for a totally damaged filter. Generally, the reported pressure drop data on structural damage due to high air flow corresponded to a partially damaged HEPA filter. Johnson et al [16] reported the pressure drop corresponding to both the threshold and the medium blow-out as shown in Table 4. The threshold and medium blow-out data were derived from a motion picture camera synchronized with the pressure pulse of a simulated tornado. In all of the other studies, only the final condition of the filter was available. Unfortunately, except for the high temperature studies, few efficiency measurements were made on the partially damaged filters, and few quantitative descriptions of the filter damage were made.

Because of the limitations in the literature data, we selected the method of first determining the structural damage on the HEPA filter and then the efficiency. If the HEPA filter suffered significant structural damage , the filter would be assigned 0% efficiency. If the filter was not significantly damaged, then the efficiency would be determined from literature values of the efficiency.

Justification for Assigning 0% Efficiency To Partially Damaged Filters: The selection of the filter efficiency that corresponds to the reported pressure drop for partially damaged HEPA filters in Table 2 was a major step in the development of a method for computing filter efficiency under DBA conditions. We decided to set the efficiency for all damaged HEPA filters, whether partially or fully, to 0% for several reasons. First, there is very little data on the efficiency of partially damaged HEPA filters. The few reported efficiency measurements show partially damaged HEPA filters have high efficiencies . For ample, a HEPA filter with a 5 inch slit along one pleat of the HEPA medium has an efficiency of 99%, while a filter that has the media pack loose within the frame and slightly pushed out of the frame has an efficiency of 94% [41]. The primary reason for selecting 0% efficiency for partially damaged HEPA filters is that there is a large variability in the differential pressure required to blow out the filter medium as seen in Table 4 for high air flow (from 13.6 to greater than 77.8 inches). This variability makes it prudent to select a conservative value of differential pressure at which the filter medium blows out of the filter.

Another important reason for selecting conservative values is that most DBA s consist of multiple challenges, whereas the available data generally applies to one parameter, not counting the differential pressure, that is responsible for the damage. We have assumed that using conservative values for the

pressure drop that is required to blow out the filter medium due to a single parameter will compensate for the additional damage caused by multiple parameters.

Establishing Threshold Values of Differential Pressure for Structural Damage and 0% Efficiency:
The threshold value of the differential pressure for structural damage depends on the structural strength of the filter, which in turn is a function of filter age, radiation exposure, corrosive chemical exposure, temperature and moisture exposure. These parameters cause a lowering of the threshold differential pressure.

Other parameters such as high air flow or pressure pulses define the filter differential pressure. Filter clogging by aerosols and water also contribute to an increased differential pressure by reducing the filter permeability in addition to lowering of the threshold differential pressure.

The effect of the various parameters on the threshold differential pressure for causing structural damage is estimated from the literature data in Table 2. From these values it is possible to generate Table 5 relating the threshold differential pressure for each environmental exposure that can structurally damage the filter. The data in Table 5 is applicable to the standard HEPA filter used in DOE facilities: a deep pleated filter with aluminum separators, and an organic sealant. Although other filter designs are available and periodically used in DOE facilities, they have lower threshold values for differential pressure.

Conservative values for the different parameters have been included in Table 5 to simplify the determination of structural damage. In most cases, the conservative value is the lowest experimental or computed value believed to cause structural damage. However for moisture exposure, the lowest values were not used because they seemed unrealistically low. Ricketts et al [34] found three filters out of 29 tested that had structural failures when wet and exposed to less than 10 inches of water: one failed at 3.6 inches and two at 7 inches. Although the authors did not state the extent of the damage at 3.6 and 7 inches, they were most likely tears in the media pleats based on the photographs shown in the paper. The authors did state they measured the "differential pressure at which the first visible structural damage to the filter medium appeared.": This damage would correspond to the initial damage shown in Table 4. Note that the differential pressure at which medium blow out occurs is more than 4 times the value at the initial damage. If a similar ratio applies for the wet filter, then the lowest pressure drop for blowing out the wet filter is 14.4 inches. The conservative value for the threshold differential pressure for wet filters was therefore set at 10 inches of water.

Table 5 Threshold Values* of Differential Pressure Required to Structurally Damage the Standard HEPA Filter

Parameter	ΔP Threshold*, inches w.g.
Baseline (new filter, normal conditions)	37
Age (15 years or older)	13
Radiation (6×10^7 Rad)	18
Chemical (HNO_3, HF)	0-37
Temperature	
less than 200°C, (392°F)	37
200-300°C, (192-572°F)	
10 minutes	33
1 hour	30
10 hours	22
300-400°C, (572-752°F)	15
400-500°C, (752-932°F)	10
Moisture	
wet filter, (greater than 95% relative humidity)	10
dry filter, previously wet	22
Air pulse from explosion	29

* These values represent the most conservative values (except for moisture) taken from an analysis of experimental studies reviewed in this report and summarized in Table 2

We also did not select the lowest value for structural damage at 500 C because 8 inches only produced tears in the media, but did not cause total filter blow-out [32]. In a second test, Pratt [32] observed a total filter collapse at 20 inches after exposure to 500 C. We selected 10 inches of water as a compromise between the conservative value based on partial filter damage in one of the two tests conducted by Pratt [32] and the wide range in values observed in Table 2 for HEPA structural damage.

It is important to note that the parameters in Table 5 represent exposures to a HEPA filter during its life, not just during the DBA. All of the parameters must be taken into account throughout the life of the filter in addition to the parameters applicable to the specific DBA. The damage caused by the different parameters is not reversible except for water, and that is only partially reversible. A previously wet HEPA filter will have a 40% reduction in its tensile strength [34].

A major concern with the use of Table 5 for determining filter survivability is the question of whether multiple stresses act independently and are additive. Unfortunately there are not sufficient data available to answer this question definitively. Nearly all previous studies on HEPA stress were done with single stresses. However, it is possible to make general observations. Age, radiation and temperature

all reduce the tensile strength of the filter medium. If a combination of these stresses were applied to the medium, the tensile strength of the medium would decrease up to the limiting value where the binder that holds the glass fibers together is no longer effective. Thus the three parameters can be viewed as acting independently and can be added up to the limiting strength of no binder. The three stresses also cause a loss of water repellency, which makes the filter absorb water and loose strength. Since all of the stresses in Table 5 degrade the medium strength by attacking the binder, there is a lower strength limit for these parameters. An approximate value is 10 inches of water.

In contrast, the attack by chemicals such as HNO_3 and HF attack the glass fibers directly and can continuously degrade the media strength to the point where it collapses under its own weight. Chemical attack must be treated as a separate case from the other stresses.

The effect of temperature on the structural damage to the HEPA filter depends on both the temperature value and the exposure time. Figure 6 shows the percent of the initial tensile strength and burst strength for HEPA filter media samples after ten minute exposures at the indicated temperatures [30]. The burst strength and tensile strength follow a common curve because the filter media are held together with similar acrylic binders [30]. Breschi et al [26] found that at 200 C, the filter medium becomes

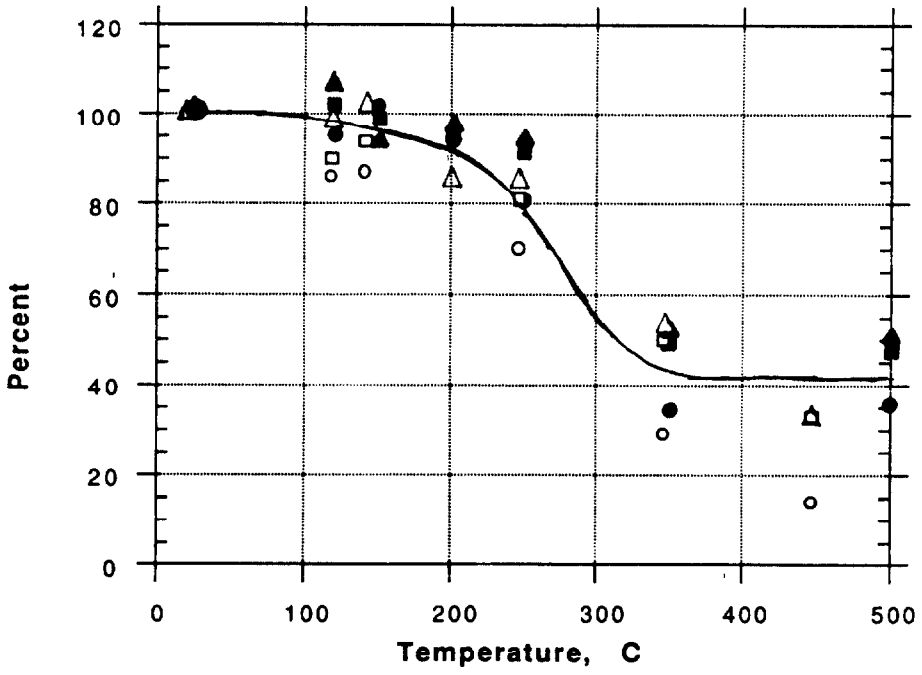

Figure 6. Percent of initial tensile strength and burst strength for three different HEPA media as a function of temperature. Open points represent tensile strength and solid points represent burst strength. Data replotted from Hamblin and Goodchild [30].

brown, and electron micrographs show the microfibers are covered with small lumps and deposits due to melting of the binder. Raising the temperature to 300-400 C cleans the microfibers from all deposits [26]. Gilbert et al [41] also found that the acrylic weight loss occurs between 300-400 C.

Figure 7 shows the percent of the initial tensile strength and burst strength as a function of time for HEPA filter media samples exposed to 120 C and 250 C [30]. At 120 C, the media show a negligible decrease in strength over time. However, at 250 C, the media show a gradual, but significant, loss in strength. Hamblin and Goodchild [30] also found that all the binder is lost in less than 10 minutes at 400 C.

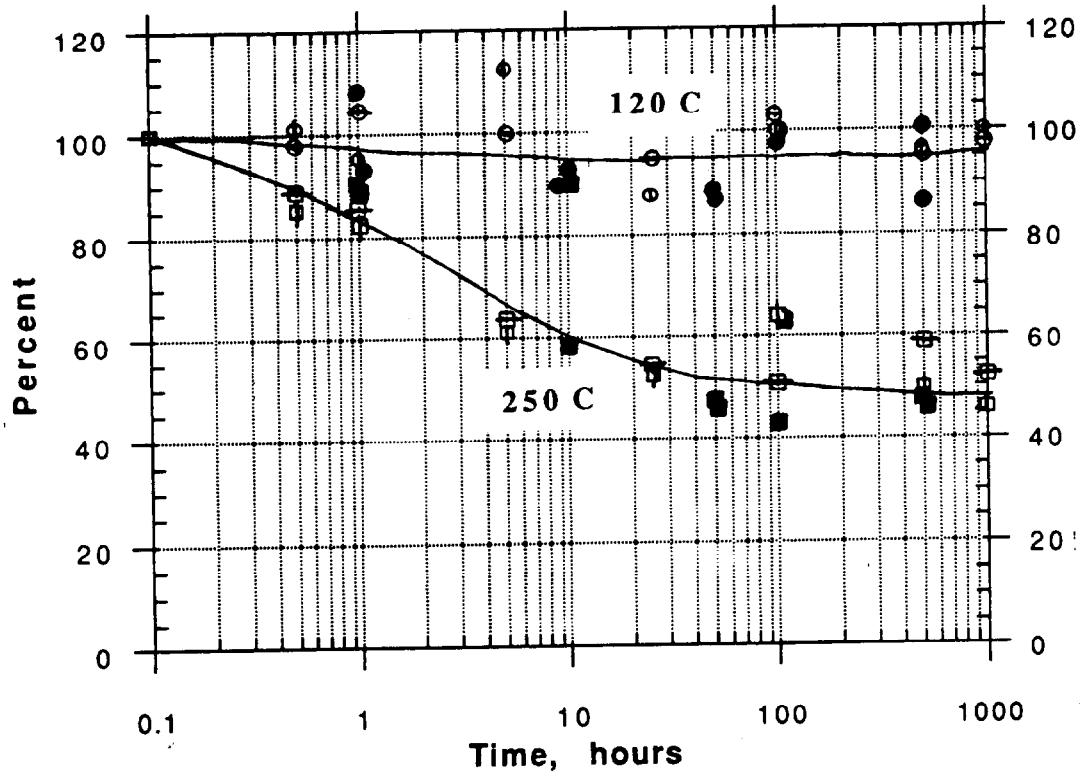

Figure 7. Percent of initial tensile strength and burst strength for three different HEPA media as a function of time after exposure to 120 C or 250 C. Open points represent tensile strength and solid points represent burst strength. Data replotted from Hamblin and Goodchild [30].

We have used these studies to generate the temperature and time data in Table 5. Since there is no significant deterioration at temperatures below 200 C, the threshold value of differential pressure will be the same as the baseline filter. For temperatures between 200-300 C, we used the curve for 250 C in Figure 7. The estimated percent of initial strength at 10 minutes, 1 hour, and 10 hours are approximately 90%, 80%, and 60% respectively. These percent values were multiplied by the baseline differential pressure of 37 inches and yield 33, 30, and 22 inches respectively. For temperatures above 300 C the deterioration in medium strength is essentially complete within ten minutes as seen in Figure 6. Thus, the differential pressure for temperature exposures between 300-400 C is computed from 40% residual strength and the baseline 37 inches to yield 15 inches. Since the deterioration occurs in less then 10 minutes, there is no time associated with this exposure.

The temperature can also cause the sealant that holds the media pack in the frame to char and sometimes burn and break loose from the filter frame. High temperature can also cause the filter medium to develop tears, especially when using steel frames due to the difference in thermal expansion between the steel frame and the medium pack. The additional failure modes lower the differential pressure for structural failure. These type of failure modes are not significantly affected by the other parameters in Table 5

Thus for determining the threshold differential pressure for structural damage, we can use the following prescription: For single stresses, the threshold differential pressure is read from the applicable entries in Table 5. For multiple stresses, whether sequential or simultaneous, the lowest differential pressure threshold is selected. If the environmental parameters are not well defined for a given DBA then the threshold value of 10 inches is used.

In order to use Table 5 for estimating structural damage, the pressure drop for a particular filter must first be determined for the environmental exposure in the DBA. The driving force for the filter differential pressure may be a fan, a tornado, an explosion, a pressurized gas release, or other sources of negative or positive pressures. For a plugged filter, the differential pressure can be approximated by the source pressure since nearly the full load will be applied across the filter. Cases were the filter may approach full plugging are during high smoke concentrations from oxygen starved fires [42] and water exposure on clogged filters [33,34].

For a clean or partially plugged filter, the differential pressure will be less than the source pressure and must be estimated. The most common source of partial filter plugging is particle deposits from atmospheric dust or plant operations. The data compiled by First and Price [43] and Novick [44] can be used to approximate the particle loading on HEPA filters. All new HEPA filters must have a pressure

drop less than one inch of water at 1,000 cfm. At higher air flows the pressure drop increases as shown in Figure 8. This figure can be used directly to determine the pressure drop across a clean filter if the air flow is known. Figure 8 can also be used for computing the pressure drop of partially plugged filters at a second flow if the filter pressure drop is known at one flow.

$$\Delta P_2 = \Delta P_1 \times \Delta P_{C2}/\Delta P_{C1}, \quad (1)$$

where ΔP_2 is the pressure drop of the partially plugged filter at the second flow

ΔP_1 is the pressure drop of the partially plugged filter at the first flow

ΔP_{C1} is the pressure drop of the clean filter at the first flow from Figure 8

ΔP_{C2} is the pressure drop of the clean filter at the second flow from Figure 8

For an illustration, assume that a HEPA filter is loaded with particles and has a pressure drop of 4 inches at the standard flow of 1,000 cfm. If the flow suddenly increases to 10,000 cfm, the resulting pressure drop would be 48 inches (4 X 12/1). We obtained the 12 inches and 1 inch from Figure 8.

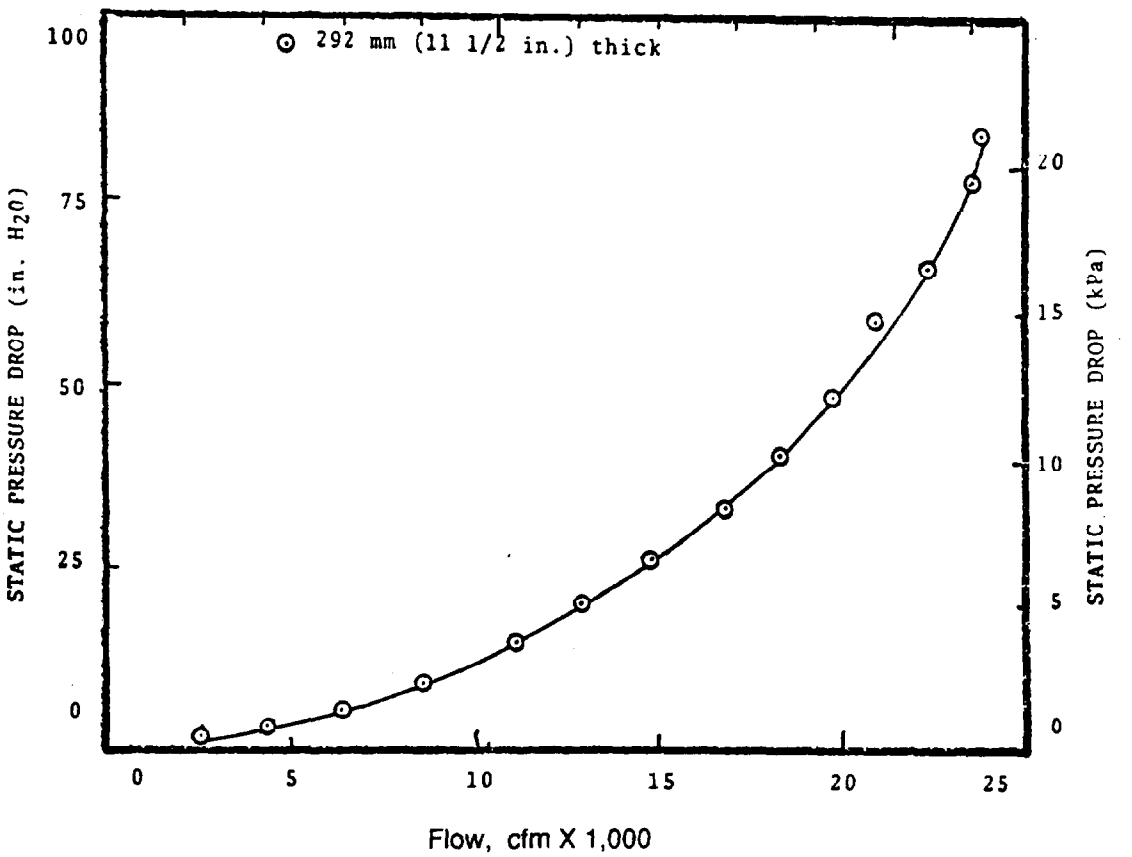

Figure 8. Pressure drop as a function of flow rate for a clean HEPA filter from Gregory et al [45].

Once the appropriate pressure drop is determined for the HEPA filter under DBA conditions, the value can be compared to the applicable threshold values listed in Table 5. If the estimated differential pressure is less than the threshold value, then the HEPA filter will not be structurally damaged, and the filter efficiency can be determined in the next section. However, if the differential pressure exceeds the threshold values, then the filter will be structurally damaged and will be assigned a 0% efficiency under DBA conditions.

We can also use Figure 8 and Equation 1 to compute the air flow through a partially plugged filter if we know the initial pressure drop and flow rate and the final pressure drop. This computation is made easier by rearranging Equation 1 as follows:

$$\Delta P_{C2} = \Delta P_{C1} X \Delta P_2 / \Delta P_1 , \qquad (2)$$

For example, if the partially plugged HEPA filter has a pressure drop of 4 inches at 1,000 cfm and is then subjected to a pressure drop of 48 inches, the pressure drop for the clean filter will be 12 inches (1 x 48/4). The corresponding air flow is then read from Figure 8 to be 10,000 cfm.

Once the appropriate pressure drop is determined for the HEPA filter under DBA conditions, the value can be compared to the applicable threshold values listed in Table 5. If the estimated differential pressure is less than the threshold value, then the HEPA filter will not be structurally damaged, and the filter efficiency can be determined in the next section. However, if the differential pressure exceeds the threshold values, then the filter may be structurally damaged and will be assigned a 0% efficiency under DBA conditions.

Determination of HEPA Filter Efficiency Under DBA. If the HEPA filter is not structurally damaged, then the filter efficiency can be estimated from the filter efficiency tables and from the conditions during the DBA. Table 3 summarizes the effect of various parameters on the penetration of HEPA filters obtained from our literature review. However, before the data can be used for determining filter efficiency under DBA conditions it must be consolidated and simplified.

One consolidation of Table 3 is to treat the air flow and air pulse as one parameter since they are not independent. This is possible because the particle capture mechanism is the same for both processes. In our combined air flow and pulse, the air pulse is viewed as a higher flow for a short time. We were also able to derive an empirical equation for the maximum filter penetration as a function of air flow based on the data from VanOsdell et al [15]. The maximum penetration point for velocities of 0.5, 1,

2, 5, 10, and 20 cm/s were taken from Figure 3 and regraphed in Figure 9. The straight line through the data points fit the following equation:

$$P = 3.65 \times 10^{-4} V^{2.58} \ \%, \qquad (3)$$

where P is the penetration in percent and V is the velocity in cm/s.

Since air flow is a more practical unit of measure than air velocity through the medium, we can substitute air flow/filter area for velocity in Equation 3. If we assume the average deep-pleated HEPA filter has 200 square feet of media then Equation 3 becomes

$$P = 3.65 \times 10^{-4} (\text{flow}/400)^{2.58} \ \%, \qquad (4)$$

where flow is in cfm.

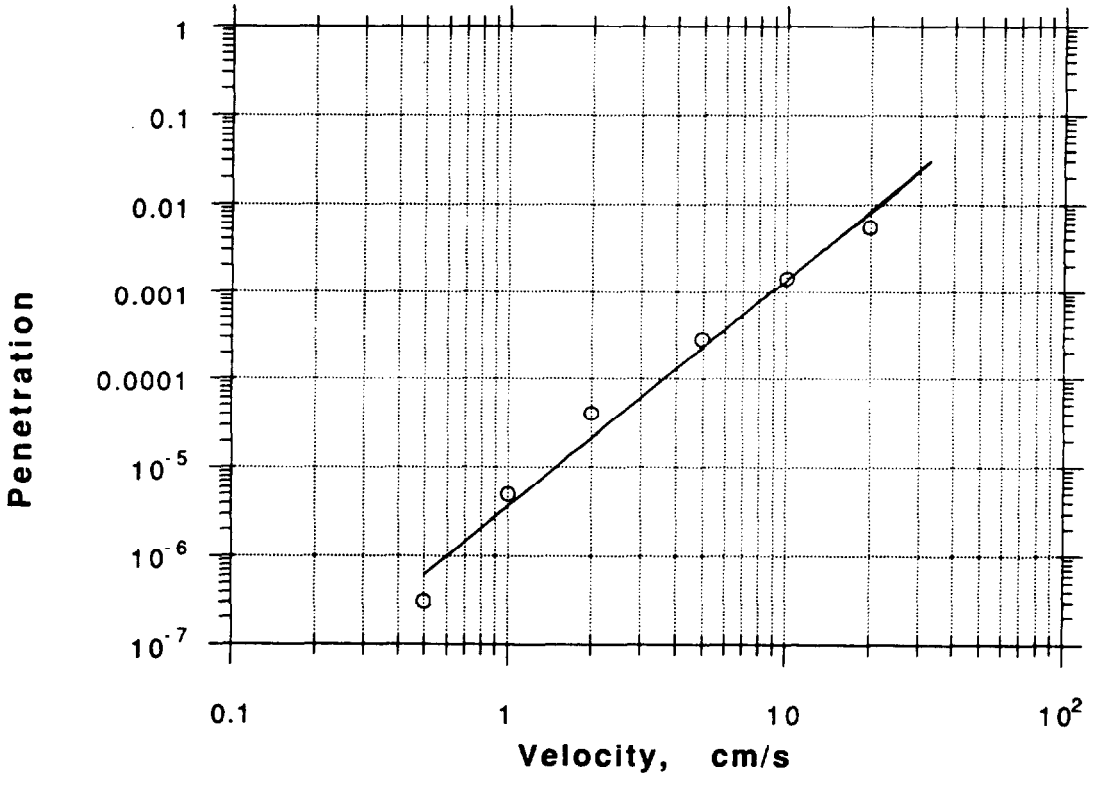

Figure 9. Maximum filter penetration as a function of air velocity replotted from Figure 3

Equation 4 also applies to an air pulse. However, in order to obtain filter penetration from the equation, it is necessary to determine the air flow through the filter that corresponds to the applied differential pressure. For example, a 1 psi (27.7 inches) air pulse applied to a clean filter corresponds to

an air flow of 15,000 cfm as determined from Figure 8. Computing the penetration at 15,000 cfm with Equation 4 yields a penetration of 4.2%. Gregory measured 0.1% penetration for 0.46 μm latex particles in a 1 psi pulse simulating a tornado [25]. He also measured 0.9% penetration for previously deposited 0.46 μm latex particles in a simulated explosion shock (1 psi estimated). Since the penetration for 0.1 μm particles is more than ten times the penetration for 0.46 μm particles (see Figure 5), Equation 4 is in general agreement with experiment.

We should point out that the increasing penetration with increasing air flow is not in disagreement with previous studies that show an initial increase and then a decrease in penetration with increasing air velocity [18]. In the previous studies, the particle size remained constant as the air flow increased. The penetration initially increased because of decreasing time for diffusional capture. With increasing air flow, the particle inertia increased and resulted in decreasing penetration. The observed penetration increased and then decreased as the dominant capture mechanism switched from diffusion to inertia. However, for the maximum penetration, the particle size decreases with increasing air velocity and therefore extends the range where diffusion dominates and results in increasing penetration with increasing air flow. The increasing contribution due to inertia is also seen in Figure 9 by a small deviation from the straight line to lower penetration levels.

We then prepared Table 6 for computing filter efficiencies under DBA conditions by consolidating the data from Table 3 and making simplifying assumptions. The primary assumption was to use the most conservative penetration value for each parameter. We also combined the penetration increase due to water accumulation and oil accumulation into a single liquid accumulation term. All of the entries in Table 6 represent penetration values to be added to the baseline 0.1% penetration. Equation 4 was used in place of the data for air flow and air pulses. Although the entry for HF corrosion shows only a single data, the penetration increases continuously with increasing HF exposure. Unfortunately there were no additional data available. For the temperature parameter, we reduced the number of temperatures and used the highest penetration value. No credit was given for the initial decrease in penetration from 25 to 200 C, as shown in Figure 1, because the change in penetration was small compared to 0.1%. We also used the maximum allowed penetration of 3% for exposure to 371 C (700 F) for 5 minutes as specified in MIL-F-51068 [39].

The final entries to complete Table 6 were solid and liquid loading. For solid loading we indicated -0.05% since it improves filter efficiency. For liquid aerosols, the penetration increases by 1.3 times the product of the initial penetration and the ratio of the final pressure drop to the initial pressure drop. The increased penetration is due to liquid build-up that blinds portions of the medium and hence increases the

air flow through the remaining unblocked portions of the medium. The higher air flow causes the increased particle penetration.

Table 6 Effect of Environmental and Filter Parameters on the Aerosol Penetration through HEPA filters.

Parameter	Filter Penetration*
Baseline	0.1%
HF corrosion	
1,500 ppm-hr.	0.1%
Temperature	
less than 200°C (392°F)	0.0%
200-300°C (392-572°F)	0.1%
300-350°C (572-662°F)	0.4%
350-500°C (662-932°F)	3.0%
Particle Deposits	
Solids	-0.05%
Liquids	$1.3\ P_i\Delta P/\Delta P_i$ %
Air Flow (Air Pulse)	$3.65 \times 10^{-4}(\text{flow}/400)^{2.58}$ %

* These values represent the most conservative values taken from an analysis of experimental studies reviewed in this report and summarized in Table 3.

Table 6 can be used to estimate the aerosol penetration of a HEPA filter under the conditions expected in a given DBA. Once the parameter values that apply for a given DBA are established, the corresponding penetrations can be used for determining the HEPA filter penetration. As we have previously discussed, since the penetrations due to the different parameters are independent of each other, then the filter penetration for a combination of parameters will equal the sum of the penetrations for the individual parameters.

Thus for determining the aerosol penetration from the data in Table 6, we use the following prescription: For single stresses, the penetration is read from the applicable entries or computed from the flow. For multiple stresses, the penetration from each of the stresses are added to yield a total filter penetration.

V. Computing the Efficiency of HEPA Filters Under DBA Conditions

General Procedure

The determination of the efficiency of the HEPA filters under DBA conditions is a three step process.

(1) Determine the values of the temperature, moisture, radiation, and chemicals to which the final exhaust HEPA filters are exposed during normal operations and during and after the DBA. Standard engineering practices should be used in determining these parameter values. Also assume a filter age that represents the maximum age of filters in the facility. The most important parameter to be determined is the filter pressure drop during and after the DBA. Guides for estimating the pressure drop are presented in this paper.

(2) Compare the environmental and filter parameters listed in step (1) to the corresponding values in Table 5 that show the threshold value of differential pressures that would cause structural damage to the HEPA filter. For multiple parameters, use the lowest differential pressure. Compute the differential pressure for the HEPA filter under the DBA conditions assuming maximum particle loading. If the filter differential pressure under DBA conditions is greater than the threshold value shown in Table 5, then the HEPA filter is assumed to be damaged, and the allowed efficiency credit is 0%.

(3) If the differential pressure is less than the threshold value shown in Table 5, then the filter is considered to be undamaged, and the filter penetration is determined from the filter penetration values shown in Table 6 that correspond to the environmental conditions in the DBA. For a DBA challenge with multiple environmental parameters, the total HEPA penetration is obtained by adding the penetrations from the individual environmental parameters.

Examples

Example 1: Assume a two-stage HEPA filter system with a demister system, a blower with a 15 inch w.g. vacuum and a DBA that consists of a hot fire followed by activation of a fire protection water deluge system to protect the first stage HEPA filter. The temperature at the first filter is determined to be 250°C and the second 200°C. In this scenario, the first filter would be partially loaded, but not completely plugged, due to the smoke. Using the data in Table 5, each filter has a maximum differential pressure threshold of 33 inches, beyond which value the filters will rupture. Since the fan can only pull 15 inches w.g., there is no damage to the filters at this point. However, once the water deluge is turned on, the first filter becomes wet and becomes plugged. The threshold value for filter rupture is now reduced to 10

inches w.g. because the filter is wet. Since the blower vacuum exceeds the minimum value of differential pressure required to damage the filter, the first filter will be structurally damaged. This follows because the full vacuum of the blower will be applied across the first stage HEPA filter. If the smoke from the fire and the water spray continues, then the second filter will soon plug and also rupture. The assumed efficiency for each ruptured filter is 0%, thus resulting in 0% efficiency for the two filters.

Example 2: Assume the same conditions as in example 1, but the blower can only pull a 10 inch w.g. vacuum. In this case the threshold value for the differential pressure is still 33 inches w.g. for each of the two filters during the high temperature exposure. After the water spray is turned on, the differential pressure threshold for the first filter is 10 inches w.g. Since the fan can only pull 10 inches w.g., neither filter is damaged, but the first filter is plugged and the air flow is reduced to a very low flow. The first HEPA filter has a penetration of 1.4% according to Table 6 because 1.3% penetration due to moisture accumulation is computed from the liquid particle deposits and added to the baseline penetration of 0.1%. Since the second HEPA filter has the baseline 0.1% penetration, the total penetration for the two filters is 0.0014%, or an efficiency of 99.9986%. However, the process air ventilation system is effectively shut down, and contaminants may leak out into the building rooms from the containment structure, ducts and housings.

Example 3: A two-stage HEPA filter that has a flow of 1,000 cfm and an initial pressure drop of 4 inches w.g. for the first stage and 1 inch w.g. for the second stage is subjected to a negative 75 inch w.g. tornado condition. Assume that the calculations from the EVENT code [45] predict a pressure drop of 50 inches w.g. across both filters and a flow of 10,000 cfm. Under these conditions the first filter will have a pressure drop of 40 inches and the second filter 10 inches w.g. According to the data in Table 5, the first filter will exceed the threshold differential pressure of 37 inches w.g. and will be structurally damaged. After the first filter is destroyed, it will no longer impose a restriction on the air flow and a new flow computation is required. Assume that the new computations using EVENT show the remaining HEPA filter has a pressure drop of 25 inches w.g. and a flow rate of 15,000 cfm. Under these conditions, the second HEPA filter will remain undamaged. The damaged filter will be assigned 0% efficiency, and the efficiency of the second filter determined from Table 6. Assuming the relationship between air flow and penetration in Table 6, we estimate that 15,000 cfm air flow will result in a penetration of 4.2%. After the tornado pulse has passed, the filter penetration will return to the baseline value 0.1% (99.9% efficiency). Thus the efficiency of the HEPA filter system is 95.8% during the tornado and 99.9% after.

VI. Conclusion

We have established criteria for calculating the efficiency of HEPA filters in a DOE nonreactor nuclear facility during and after a Design Basis Accident (DBA). Previous efforts of selecting a single efficiency value for all accidents were unsatisfactory because the potential DBAs vary significantly among different facilities and operations and result in large variations in computed filter efficiencies, primarily due to the deterioration of the HEPA filter. The deterioration of the filter efficiency depends on the exposure parameters; in severe exposure conditions the filter will be structurally damaged and have a residual efficiency of 0%. The large variation in filter performance makes it necessary to determine filter efficiency on a case-by-case basis. It also prevents the use of a limited number of tests to estimate the efficiency for a given DBA.

Despite a significant amount of data in the literature on the performance of HEPA filters under off-normal conditions, it is not sufficient to cover the full matrix of different values and combinations of the following parameters that weaken the filter or cause structural damage: age, moisture, chemical attack, high temperature, overpressure, seismic and rough handling, liquid and solid particle loading, and radiation. The primary reason for the large number of combinations of parameters is that the parameters are highly dependent and cannot be separated. Because of the large number of possible DBA conditions, the preferred method for determining the efficiency of HEPA filters under DBA conditions is to conduct experiments in a test stand that can simulate the DBA conditions. Unfortunately since this test stand is not available, a secondary method is required

The method for computing filter efficiencies that we selected was chosen to be consistent with the limited data available. We approximated the performance of HEPA filters under DBA conditions by separating the effect of filter structural damage from filter efficiency. In this fashion, we were able to significantly reduce the number of required test parameters to match the available literature data. Even with this approximation, there are large gaps and limitations in the data that introduce significant error in the estimates of HEPA filter efficiencies under DBA conditions. Because of this limitation, conservative values of filter efficiency were chosen when there was insufficient data.

The method we selected for estimating the efficiency of the HEPA filters under DBA conditions involves three steps. In the first step, the filter pressure drop and environmental parameters such as temperature and moisture are determined during and after the DBA.. The second step consists of comparing the filter pressure drop to a set of threshold values above which the filter is structurally damaged. If the filter pressure drop is greater than the threshold value, the filter is structurally damaged and is assigned 0% efficiency. If the pressure drop is less, then the filter efficiency is determined in a third

step where the efficiency is determined from literature data that matches the same exposure conditions. The efficiency of the HEPA filters within DOE facilities should be determined on a case-by-case basis.

VII. Acknowledgement

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DISCUSSION

WEIDLER: I heard you say it is going to be a DOE proposed standard. Is the standard proposed only for DOE, or would it be for the rest of the industry?

BERGMAN: I believe it could be for whomever feels it is applicable, but I will let Jim Leonard respond further.

LEONARD: The intent is that it would apply to DOE.

MISHIMA: I noticed that you have a value for air pulse, and you also have a value for failure. Am I to infer that the failure pressure, e.g., 37 in.w., is a static load and the air pulse is over some time duration?

BERGMAN: What Joe Mishima has just referred to is air flow and air pulse. Professor First was very gentle with me in pointing out that I am counting too many marbles at the same time; all of these things are the same phenomenon. What you have is air that creates a force that is identical whether it is over a few milliseconds or over a longer period of time. I have not made the point in this presentation because of time, but the equation applies over a millisecond. There is only one penetration episode reported in the literature. The calculation came up with 30% penetration across the HEPA filter during a tornado pulse. Another, reported by the Las Cruces people, reported 32-35%. Therefore, the damage applies to both pressure types.

MISHIMA: I have seen the data you are talking about by Paul Smith at Las Cruces. They seem to indicate that there is a difference between the failure mechanism from a pulse, essentially a shock, and one from a deflected blast.

BERGMAN: I understand that you are saying that I left out the air pulse and you are suggesting I should put it in. I am not quite sure that is correct. I will have to look at the details. Let's compare, for example, a shock pulse that gives a pressure differential of 30 in.w. and a static flow that gives a differential of 30 in.w. I am not sure that the shock flow will have a different result with respect to rupturing the filter than the steady flow of 30 in.w. Logically, you could figure you have to account for inertia, and you may have some other factors. We are at such a crude stage in the study that I did not see any difference. That is to say it is within the same order of magnitude. Refinements are called for. I will make sure I include that in the final paper.

JENKINS: I am sure this is interesting from a theoretical point of view, but I am trying to think of practical applications for our plant, given some accident scenario that we might be in. By that I mean, I am not sure what degree of accuracy you might achieve. You are looking to predict off-site doses under accident conditions. Since we generally have actual post-filter radiation levels, what is the application of this theoretical approach?

BERGMAN: The application of the paper is for computing the efficiencies of HEPA filters in nonreactor nuclear facilities during and after a design basis accident. The purpose

of the method described in this paper is to make the computations before an accident occurs. You are correct in implying that the method has no purpose after an actual accident occurs. Actual measurements are always better than calculations. Of course, it would be instructive to compare the predicted and actual efficiencies in order to improve the predictions. The method was intended for nonreactor applications where there are many different DBAs, in contrast to reactors that have a single DBA defined by Nuclear Regulatory Guide 1.52.

WEBER: Is there a cumulative effect of certain excessive exposure parameters, such as temperature or moisture, that might accelerate aging?

BERGMAN: Concerning cumulative effects, one of the most common events is when people repeatedly wet the filter and dry it. They think no detrimental effect occurs. I should acknowledge that 90% of the data on this comes from Mr. Wilhelm's group at KfK. The U.S. does not have appropriate facilities for conducting these experiments. I am sad to learn the facilities in Germany have been dismantled. But Mr. Wilhelm pointed out many years ago that after you wet a filter, dry it, wet it again, it will retain only half its strength.

WILHELM: There is a very strong effect of operational time on the behavior of HEPA filters under wet conditions. We found that the binder starts to get soft and dissolves at high differential pressures. For longer times, there is also a time dependency, but it may not be very much. There is a very strange time dependency on the influence of water on HEPA filters. After I heard what you said, I would be very much interested to assist you. If you would send me your papers, I think I could send results that are not published. We worked for years and years on that project with one American scientist, Dr. C. I. Rickerts, who is now at Las Cruces.

BERGMAN: Thank you for that input. We have incorporated many of your outstanding research findings in our analysis. Water exposure is unquestionably an important factor leading to the deterioration of HEPA filters and their degradation to 0% efficiency when coupled with higher pressure drops. Unfortunately, this condition is precisely what may occur during accidental fires when the water fire-suppression system is used on the filters. The filters become weak and plug with water. The full vacuum of the blower is then applied across the HEPA medium which may then blow out. I recall a fire at Rocky Flats in 1980 where an entire bank of filters was blown out in such a fashion.

WEBER: Is there a cumulative effect of transient conditions such as excessive temperature or moisture which could accelerate aging and affect pressure drop thresholds? In applying your results to filters in service, is the existing detection equipment adequate to monitor and record transients significant to pressure drop and other thresholds?

BERGMAN: Regarding the first question, there are indications that there may be cumulative effects, but the data is insufficient to make definitive statements. For example, studies have shown that a dry filter medium that was previously wet has 40% lower tensile strength. We do not know what a sequence of repeated applications would do. For

temperature, the effects appear to be both time and temperature dependent. It takes a given exposure time at a given temperature to have a complete effect. For example, applying 350° C for a short time would show less damage than the same temperature applied for a long time. In this case, multiple applications of the same temperature would appear to be cumulative, at least until the complete damage is reached. After the complete damage is reached, there will be no further effect. As the temperature is raised, there is a new level of damage. The greater the damage to the filter, the lower will be the differential pressure for medium blow out.

Regarding the second question, the existing detection equipment generally consists of radiation detection equipment that can alarm quickly and temperature sensors that activate fire suppression systems quickly. Although HEPA filters generally have a Magnehelic differential pressure sensor, they are generally not instrumented for alarm or other emergency responses. The temperature sensors have a strong effect on the HEPA performance by activating the water suppression system that makes the HEPA filters wet. Some facilities do not have the water suppression automatically turned on because of the concern with HEPA filter damage.

TARTAGLIA: An example was given on how to apply the results of the paper. The example examined the estimated filter efficiency drop following a fire and subsequent water inundation of the filter. Nuclear power plants do not consider a fire as a design basis accident (DBA), nor is a fire considered to occur concurrent with a DBA. Can you provide an example where this paper applies to nuclear power plants?

BERGMAN: The paper is intended for non-reactor facilities. Nuclear Regulatory Guide 1.52 applies to nuclear power plants. It is not our intention to compete with or supplant the R. G. 1.52.

PERFORMANCE OF HEPA FILTERS UNDER HOT DYNAMIC CONDITIONS

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ABSTRACT

Accidents in nuclear facilities involving fires may have implications upon the ventilation systems where high efficiency particulate air (HEPA) filters are used to minimise the airborne release of radioactive or toxic particles.

The Filter Development Section at Harwell Laboratory has been investigating the effect of temperature on the performance of HEPA filters under hot dynamic conditions [1] for a number of years. The test rig is capable of delivering air flows of 1000l/s (at ambient conditions) at temperatures up to 500°C, where measurements of the penetration and pressure drop across the filter are obtained.

This paper reports the experiments on different constructions of HEPA filters; rectangular and circular. The filters were tested at an air temperature of 200°C for up to 48 hours at the rated airflow to assess their performance. The penetration measurements for rectangular filters were observed to be below 0.02% after prolonged operation. In a number of cases, holes appeared along the pleat creases of circular filters although the penetration remained below 1%. The sealing gasket for these filters was noted to deform with temperature, permitting a leakage path. A prototype high strength circular filter was evaluated at temperatures of up to 400°C with a penetration less than 0.65%.

1. INTRODUCTION

High Efficiency Particulate Air (HEPA) filters are used in Nuclear plants to minimise the airborne release of radioactive or toxic particulate to the environment. Most applications involve the filtration of air at ambient temperature. Fires may occur either in the plant or the ventilation system and, under these circumstances, the filters may be subjected to high air temperatures.

The Atomic Energy Standard Specification (AESS) [2,3,4] for rectangular and circular filters requires a static oven test, where, for a high temperature (Type II) filter, the penetration measured using the sodium flame test, [5] must be no greater than 2% after being heated to 500°C for 10 minutes. The filter is then subjected to a burst strength test, in which it is dust loaded to a pressure drop of 3kPa at the rated flow. However, this test does not accurately simulate the type of accident condition likely to occur in practice, where a filter may be subjected to hot gas containing a significant amount of smoke.

Investigations of the mechanisms of filter failure [6] with dry air have revealed failures due to either buckling of the filter pack or swelling of individual pleat channels leading to splitting. However, at elevated temperatures, degradation of the paper binder [7] can lead to dramatic reductions in the tensile strength of the medium and therefore failure may occur at reduced pressure drops.

The performance of HEPA filters under hot dynamic conditions have been experimentally studied by a number of workers [8,9] who noted that the filters performance deteriorated with increasing temperature, due primarily to cracks in the sealant between the pack and casing.

This report describes the series of tests performed on clean HEPA filters under hot dynamic conditions for operation at prolonged periods. The results are also presented for a prototype filter using a high strength medium, derived from the addition of a glass fibre scrim.

2. APPARATUS AND TEST PROCEDURE

2.1 Apparatus

A flow diagram of the Hot Dynamic Test Rig is shown in Figure 1. The rig has been designed as a "once-through" system where air, after passing through the filter, is exhausted to the environment. Air is drawn through an inlet leg which incorporates an orifice plate for measuring the air flow. The air then passes through a 750 kW direct heating gas burner and then via a thermally insulated 35cm duct to the filter housing. This duct section contains an aerosol injection point just after the gas burner, and a Stairmand disc to aid mixing of the test aerosol at the sampling point before the filter housing. The filter housing may be either rectangular, or circular and these were uninsulated to enable realistic temperature gradients to be established in the filter housing. Instrumentation is provided to measure the inlet air temperature to the filter housing and pressure drop.

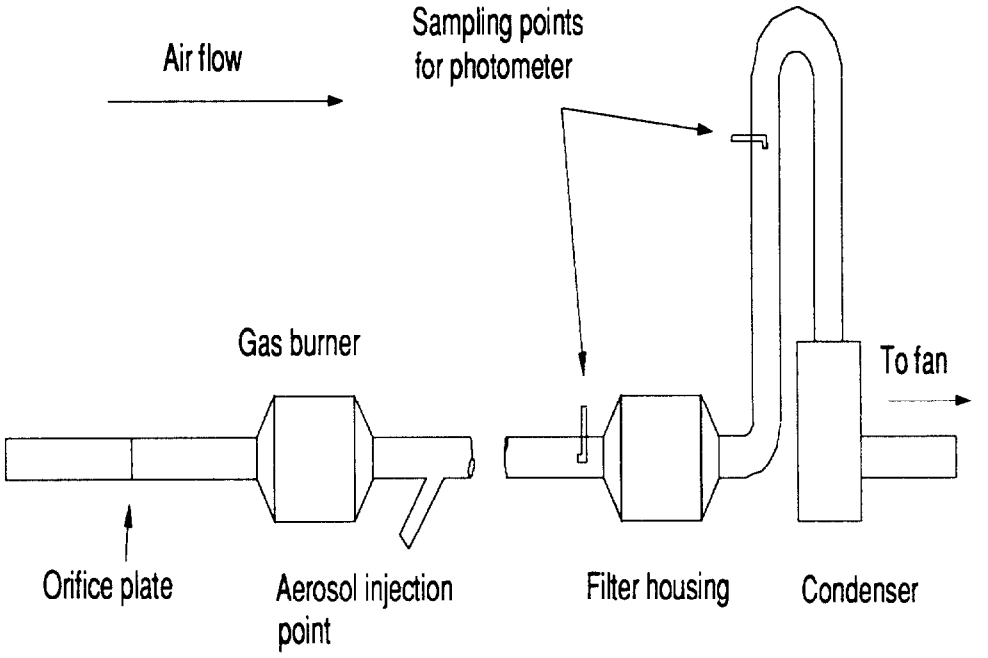
The hot air then passes through a vertical section of duct which includes a Stairmand disc to aid mixing of any test aerosol passing through defects in the filter before reaching the downstream sampling port. The hot air then passes through a water cooled finned tube heat exchanger to reduce the air temperature to 50°C or less before being expelled to the atmosphere. Between the heat exchanger and the fan, additional instrumentation permits the measurement of volumetric flow rate and air temperature.

A programmable microprocessor unit provided three term control for both the fan speed and gas burner. This allowed flow rates of up to 3400m^3/hr with temperature not exceeding 500°C to pass through the filter under test, where the pressure drop and penetration were recorded.

The penetration of the filter was measured using a modified sodium chloride technique. A Harwell design sodium flame photometer was used to measure the sodium aerosol concentration, which was generated using a sodium chloride stick thermal generator. The generator is designed for in-situ testing and provides an aerosol of 0.35μm mass mean diameter by vaporising a stick of sodium chloride in an oxy-propane flame. The concentration of the aerosol cloud could be altered by varying the feed rate of the salt stick, which for the tests performed was 1.9mm/min. The penetration was determined from the ratio of the downstream to upstream concentration as

$$Penetration(\%) = \left(\frac{downstream concentration}{upstream concentration} \right) \times 100 \quad (1)$$

Figure 1. Test Apparatus



2.2 Test procedure

The filters were tested at the rated volumetric flow rate, which was measured before the gas heater using an orifice plate as shown in Figure 1. The flow rate was maintained constant, such that after the gas burner, the reduction in density of the air (due to change in temperature) caused the volumetric flow rate through the filter to increase while the mass flow rate remained constant. The high temperature filters, were operated at 200°C for up to 48 hours. During this time the penetration and pressure drops were recorded, when at temperature and after the system had returned to ambient conditions.

For the tests performed with rectangular filters, a constant fan speed was used to give the rated flow at ambient conditions. Consequently, when the air was heated, the increased volumetric flow rate after the gas burner caused increased frictional pressure drop in the pipe work and across the filter and housing, thus reducing the flow rate.

3. RESULTS AND DISCUSSION

3.1 Mini-pleat filters

The value of the penetration and pressure drop measurements are shown in Figure 2. Figure 2(a) shows the penetration value for the filter at different temperatures. The penetration values are shown for ambient temperature and for an air temperature of 200°C, against the time that the

filter has been operated at temperature. The initial penetration was below 0.01% and was observed to steadily increase with time to a final penetration value of just below 0.02%, with very little difference between the value recorded at ambient or elevated temperature conditions.

At the same time the penetration was measured, the flow rate and pressure drop across the filter were recorded, as shown in Figure 2(b). The operation procedure for rectangular filters, at a constant fan speed, resulted in the flow rate through the filter dropping in response to an increase in pressure drop due to the increased local velocity and deformation of the packing. The initial pressure drop of the filter at ambient conditions was 280Pa which remained constant throughout the test, but the volumetric flow rate through the filter, after 48 hours at temperature, decreased by 10%. The pressure drop when operating at elevated temperature was greater than that at ambient temperature due to the reduced air density and increased local velocity. The pressure drop remained steady with time, but the flow rate was observed to decrease from 500 to 450l/s during this period. Closure of the medium pleats was observed, which may account for the lower volumetric flow rate.

3.2 Deep pleat filters

The penetration and pressure drop values for the deep pleat type filters are shown in Figure 3. From Figure 3(a) it may be observed that over the first four hours of operation the penetration rose sharply and thereafter slightly increased. In all cases the penetration remained below 0.02%, with little difference between the penetration values recorded at ambient or elevated temperature.

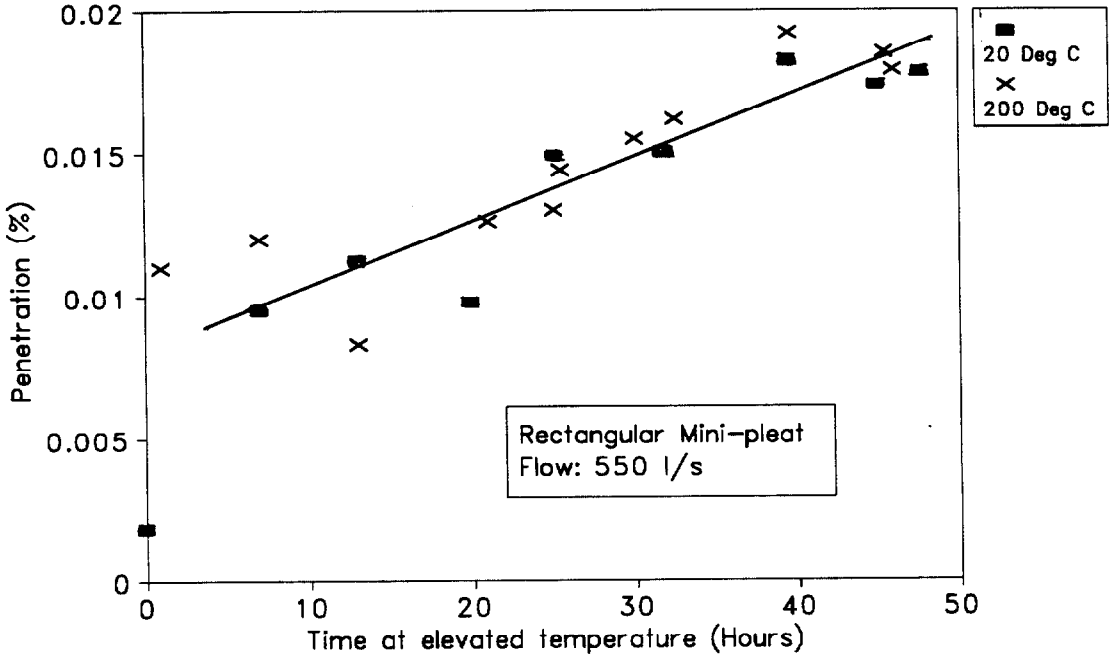
The pressure drop and flow rate data are shown in Figure 3(b), where in the first couple of hours of operation at temperature there was an increase in the pressure drop which was attributed to shifting of the packing and closure of individual flow channels. This was noted in the pressure drop measurements at ambient conditions, where from an initial value of 210Pa at 500l/s the final pressure drop was 600Pa at a flow rate of 470l/s.

3.3 Internal seal circular filters

The tests on the cirqular filters were performed under constant mass flow rate conditions. The results are shown in Figure 4, with the penetration values shown in Figure 4(a). The initial penetration value recorded at an air temperature of 200°C was about three times the initial ambient value suggesting that the dwell time of the test aerosol through the filter matrix was sufficiently reduced such that the collection by the diffusion mechanism was diminished. Thereafter, the penetration values at temperature remained relatively constant. However, after 10 hours at temperature the penetration measured at ambient conditions exceeded those at temperature. Examination of the sealing ring [10] after the tests revealed deformation that was believed to allow a seal leakage path when cool and was reduced at temperature due to thermal expansion of the locating spigot. The filter was replaced in the hot dynamic rig 22 days after the test had ceased. The penetration value at ambient conditions was measured at 0.0176%, indicating that the sealing ring did not retain its original shape.

Figure 2. Mini pleat test results (AESS 30/93401)

(a) Penetration measurements



(b) Pressure drop and volumetric flow rate measurements

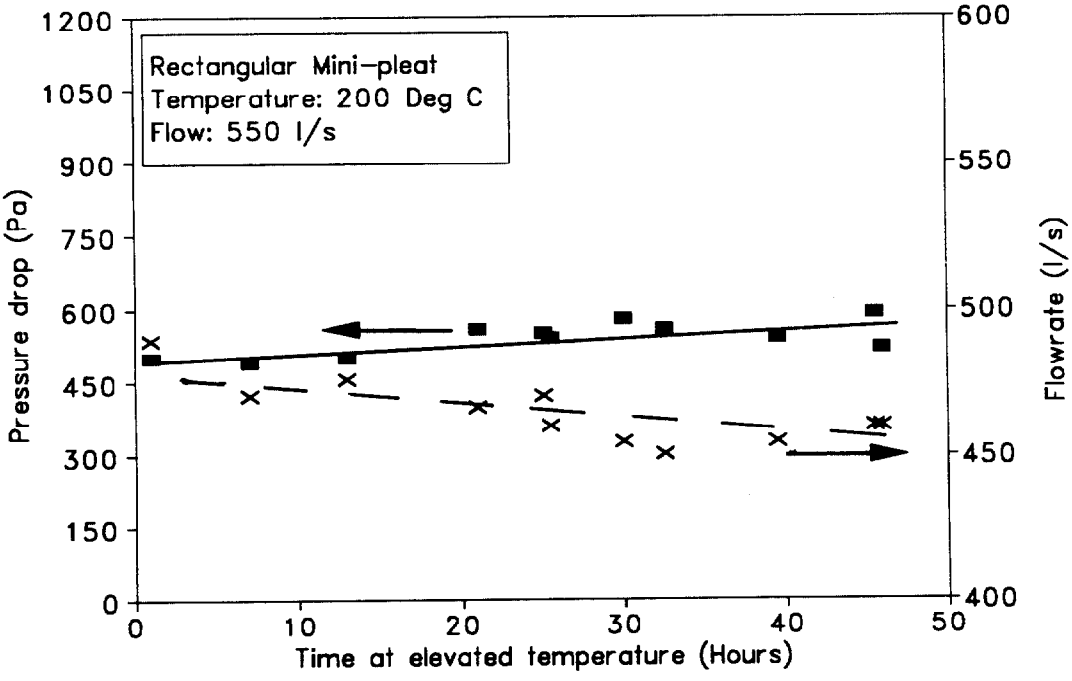
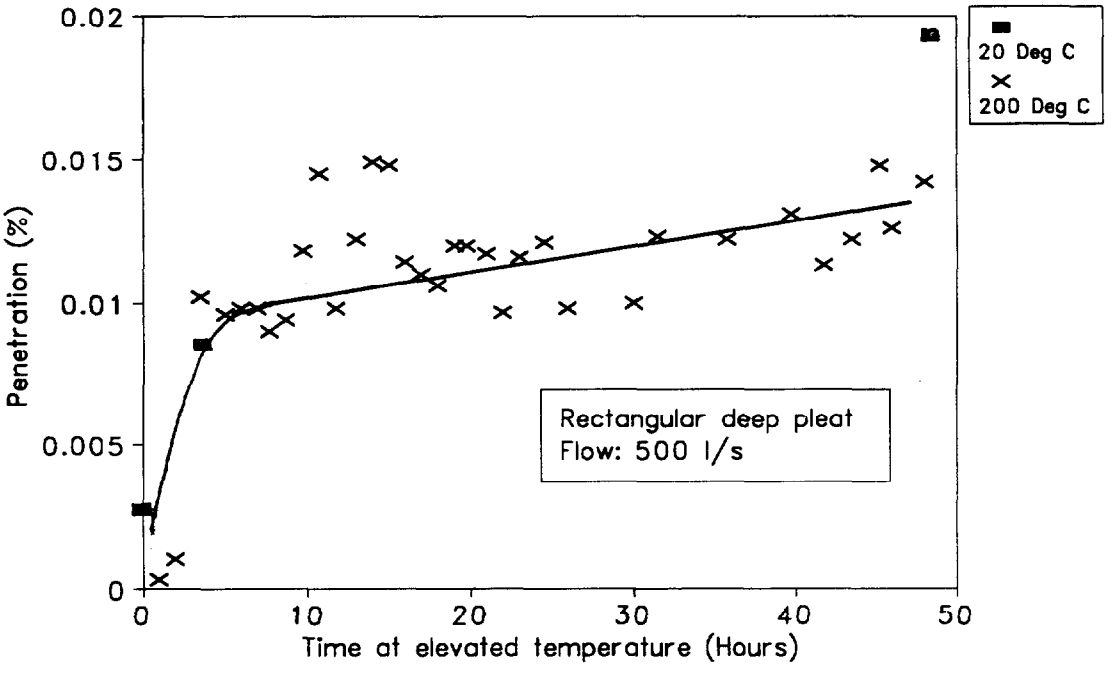


Figure 3. Deep pleat test results (AESS 30/93402)

(a) Penetration measurements



(b) Pressure drop and volumetric flow rate measurements

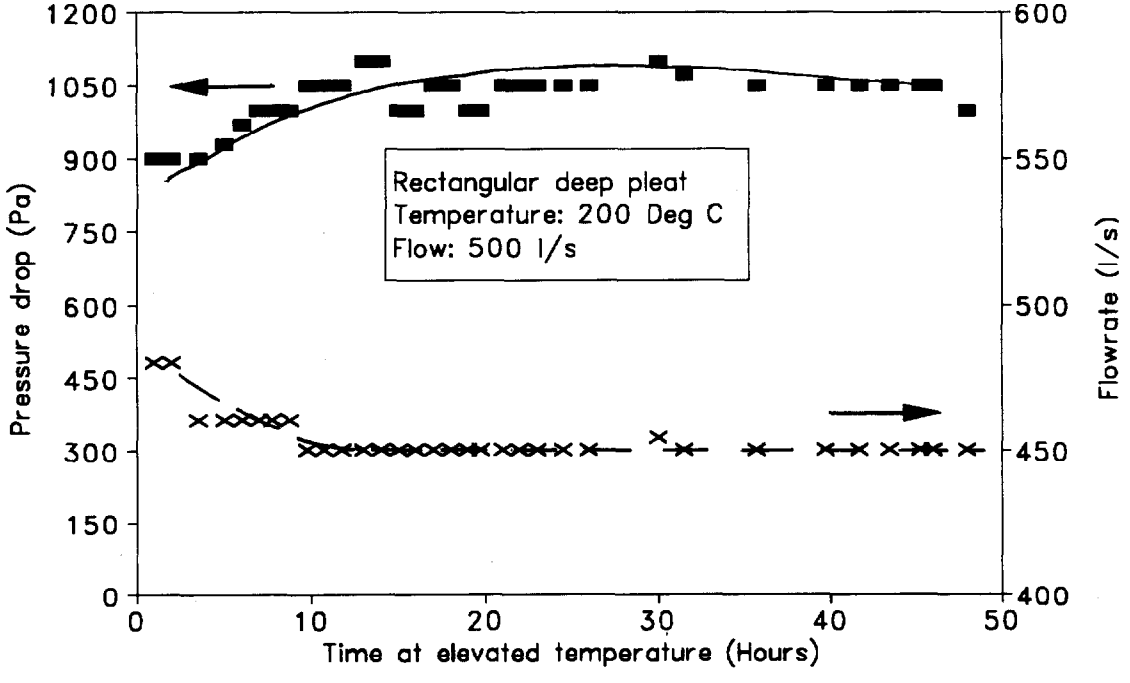
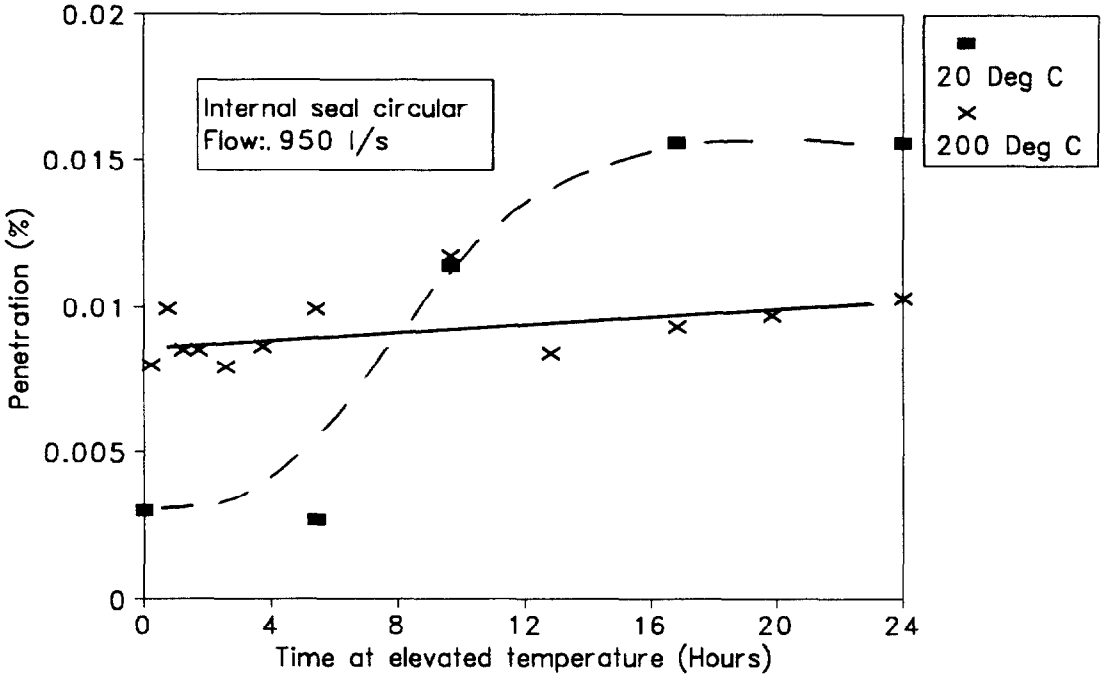
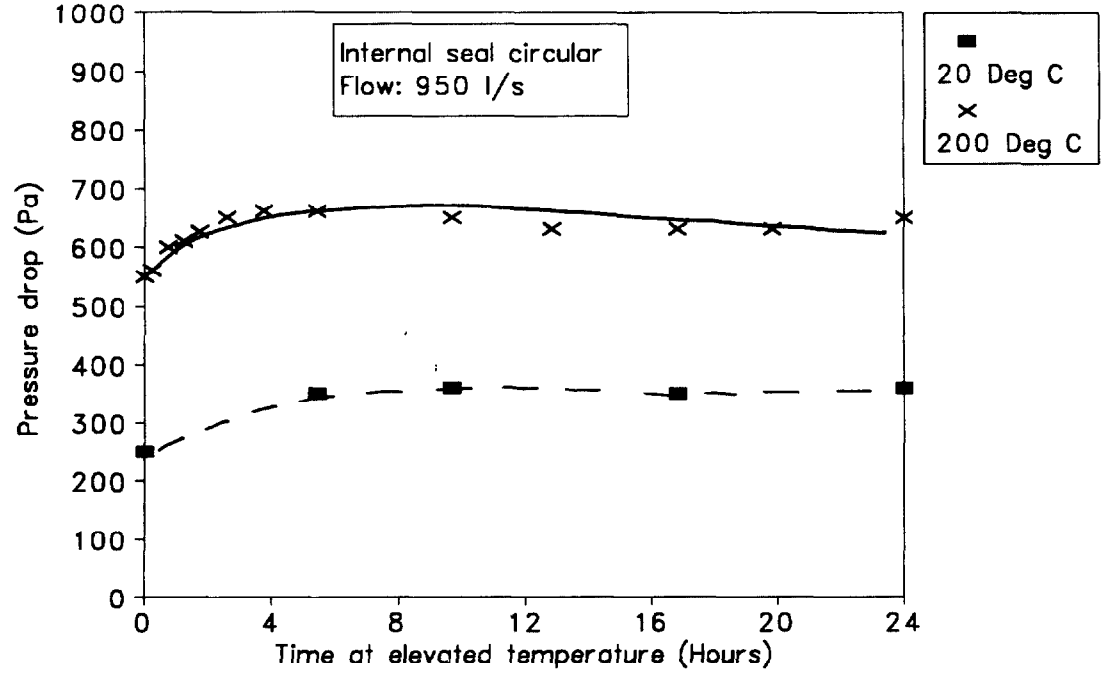


Figure 4. Internal seal circular test results (AESS 30/95100)

(a) Penetration measurements



(b) Pressure drop measurements



The pressure drop values, given in Figure 4(b), indicates that they increase in the first few hours of operation at temperature, and thereafter remain relatively constant. The reduction in the density of air between the temperatures of 20 to 200°C is of the order of 40%, which with the mass flow rate remaining constant will result in an equivalent increase in the air velocity through the filter. Previous experience has indicated that the pressure drop across the filter, ΔP, is proportional to the volumetric flow rate, Q, to a small power, n,

$$\Delta P \alpha Q^n \tag{2}$$

where a typical value for n is 1.2. The volumetric flow rate may be expressed in terms of the mass flow rate, $\dot{m}$, and the density, ρ, such that,

$$\Delta P \alpha \left(\frac{\dot{m}}{\rho} \right)^n \tag{3}$$

Hence for a reduction of 40% in the density of air due to the temperature change, the pressure drop should increase by 85%, which is close to the increase observed in Figure 4(b).

The pressure drop increased during the first 6 hours of operation and thereafter decreased slightly with time. This reduction in the pressure drop may be due to the degradation of the paper binder.

A number of failure points were observed in circular filters, where in particular cases the penetration rose dramatically in the first few minutes of operation, but was less than 1%. It was observed that holes appeared randomly along the pleated medium crease. A possible explanation of the cause of these holes may be due to local melting of the glass fibre medium by incandescent particles [11]. The pressure drop for the filters steadily increased with time, even though holes appeared, indicating closure of the flow channels.

3.4 High strength prototype circular filter

A prototype circular internal seal filter was constructed using a high strength medium, Lydall 3255-LIW in which the filter medium was supported by a glass fibre scrim.

Experiments were carried out at the rated flow, but in this case they included operation at different temperatures and the penetration and pressure drop were recorded with time as shown in Figure 5. Referring to Figure 5(a), there was an initial increase in the penetration when operated at 250°C which thereafter remained relatively constant at 0.005%. After 24 hours the temperature was raised to 300°C for four hours. During this time the penetration remained at 0.005%. After the total time of 28 hours at temperature the air temperature was again raised, to 350°C, where the first penetration measurement increased to 0.024%. Penetration increased steadily to 0.028% over the next 6 hours of operation. The air temperature was then raised to 400°C and over the next 6 hours of operation the penetration increased to 0.65%.

Visual examination of the insert after operation at temperature for 38 hours revealed that the silicon gasket material was cracked, allowing a leakage path for the test aerosol. Similarly, the penetration measurements at ambient conditions were greater than those recorded at temperature due to deformation of the gasket. The penetration after testing was measured using the sodium flame technique [5] at 3.25%. The original gasket was brittle and disintegrated when touched, was replaced before the penetration was again measured and found to be 0.09% at a pressure drop of 1490 Pa under ambient conditions. Examination of the filter revealed cracks within the sealant between the end cap and the medium, with the medium touching the outer support grille.

The pressure drop measurements, shown in Figure 5(b), revealed an increase in the first few hours of operation at temperature but thereafter remained relatively constant. With each increase in temperature there was a step increase in the pressure drop due to the reduction in density of the air and an increase in the velocity of the air passing through the filter. The final pressure drop at ambient temperature was three times the initial value, indicating that considerable shifting of the packing medium had occurred. The pressure drop across the filter was sufficiently large that the flow rate dropped during testing from 950 to 750l/s, when at temperature, due to the limitations of the fan performance.

4. CONCLUSIONS

1. Rectangular mini-pleat filter when tested at an air temperature of 200°C for 48 hours was found be give penetration values of less than 0.02%. No deterioration was observed of the gasket material.

2. Similar observations were observed with the deep pleat filter. Swelling of individual pleat channels resulted in a significant pressure drop increase during the test period although physical damage of the medium was not observed.

3. The penetration value of the internal seal circular filter was observed to be higher when measured at ambient conditions than at temperature. Deformation of the silicone gasket was responsible.

4. A number of failures were observed with circular filters where holes appeared along the pleated crease, but the penetration remained below 1%. Damage to the filters occurred in the first few minutes of operation.

5. The high strength internal seal circular filter performed well at temperatures below 300°C. At 350°C the gasket material failed resulting in a final penetration of 0.65% when operated at 400°C. Replacing the gasket of the high strength filter revealed a final penetration of 0.09%, with no obvious damage to the filter medium, but cracking of the high temperature sealant between the filter pack and the casing was evident.

6. Further investigations are needed to determine an alternative circular gasket to withstand operation at high temperatures.

ACKNOWLEDGEMENTS

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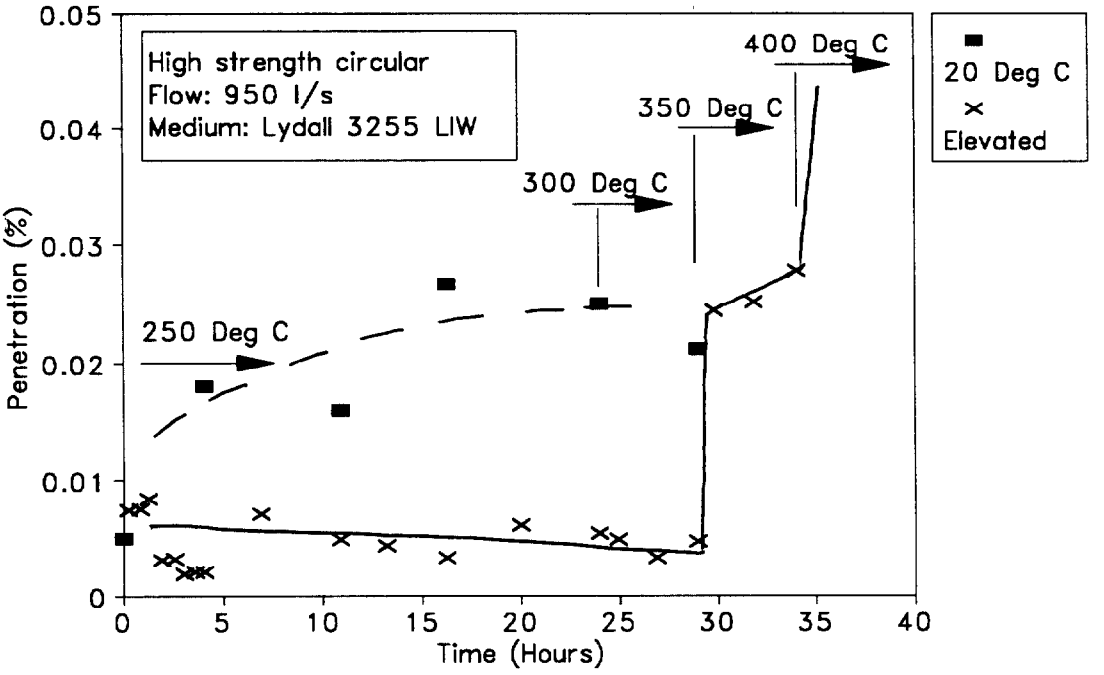
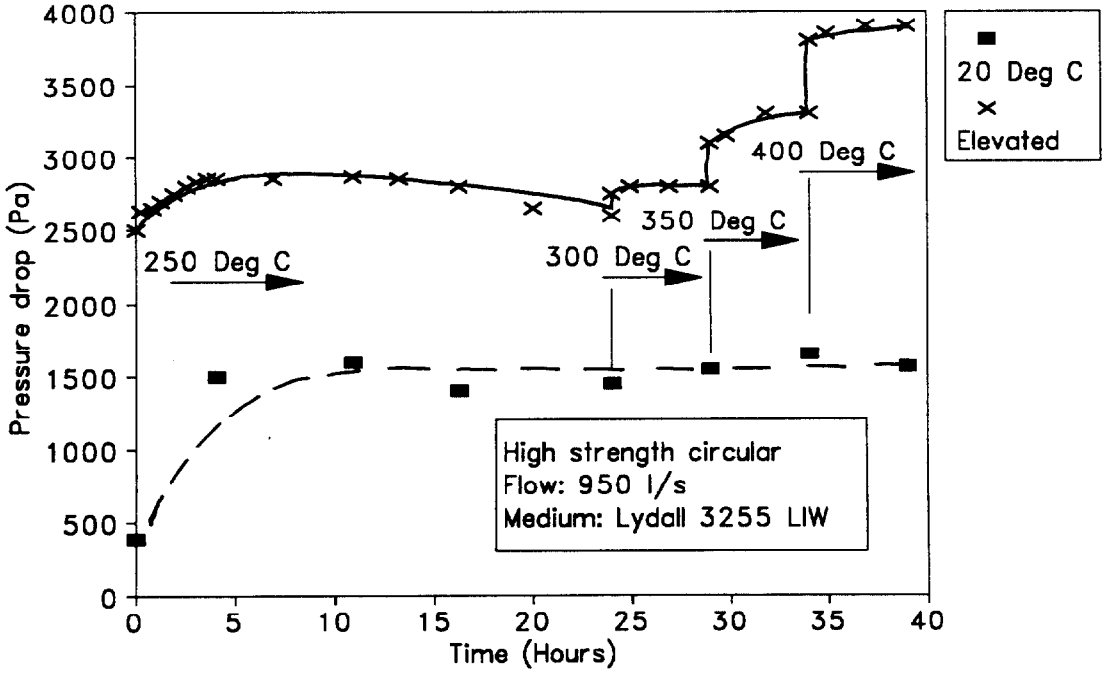
Figure 5. Internal seal circular test results (High strength)

(a) Penetration measurements



(b) Pressure drop measurements



DISCUSSION

FIRST: Were your efficiency measurements made at the temperature to which the filter was being heated, or were they done after the filter had been cooled down again?

FRANKUM: There were two temperatures shown on the graphs, one at 20° C, ambient conditions, and one at temperature. The ones at temperature were actually made at the temperature the filter was being operated at. And the ones at 20° C were made after the rig had been shut down.

PRELIMINARY STUDIES TO DETERMINE THE SHELF LIFE OF HEPA FILTERS

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Abstract

We have completed a preliminary study using filter media tests and filter qualification tests to investigate the effect of shelf-life on HEPA filter performance. Our media studies showed that the tensile strength decreased with age, but the data were not sufficient to establish a shelf-life. Thermogravimetric analyses demonstrated that one manufacturer had media with low tensile strength due to insufficient binder. The filter qualification tests (heated air and overpressure) conducted on different aged filters showed that filter age is not the primary factor affecting filter performance; materials and the construction design have a greater effect. An unexpected finding of our study was that sub-standard HEPA filters have been installed in DOE facilities despite existing regulations and filter qualification tests. We found that the filter with low tensile strength failed the overpressure test. The same filter had passed the heated air test, but left the filter so structurally weak, it was prone to blow-out. We recommend that DOE initiate a filter qualification program to prevent this occurrence.

I. Introduction

Although it is a widely held belief that HEPA filters degrade with age, there is little technical information on which to establish a shelf life. The components of a HEPA filter such as the organic

1. Consultant, McLean, VA 22101.
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binder that holds the glass fibers together in a sheet, the organic sealant that glues the filter pack into the frame and forms a seal, the organic gaskets, and even the glass fibers themselves are subject to ageing. An informal statement [1] made more than two decades ago that glass fibers, used in medium manufacture, start to age and weaken at the moment it emerges from the platinum orifice of the melting pot from which it is extruded. Further private information from a significant manufacturer of continuous - strand glass fiber, employed as the reinforcing agent in fiberglass and plastic lay-ups, indicates that his product is placed in a conditioned storage space after manufacture to inhibit loss of strength.

Previous studies on the related in-service ageing have shown significant reductions in filter strength [2,3]. Johnson et al [2] studied the effect of age on the structural integrity of HEPA filters. They conducted simulated tornado pulse and shock overpressure tests on HEPA filters that were in service for 13-14 years and found no loss in efficiency, but a significant decrease in filter strength. The HEPA media pack was blown out of the filter housing at a differential pressure as low as 13 inches of water. The HEPA filters used glass fiber media that was folded in a deep pleat configuration with asbestos separators and glued into the plywood frame with a urethane foam sealant. Tests on the filter media showed it was weak and brittle; 42% of the samples failed the tensile strength; and 100% of the samples failed the water repellent top test and 57% the water repellent bottom test. The media was so brittle that it was not possible to test the tensile strength across the bends.

Robinson et al [3] examined filters with a service life of up to ten years and observed significant reductions in the paper strength and severe corrosion of aluminum separators. They found that the corroded aluminum separators formed a strong bond to the HEPA paper and would therefore have an increased tendency to tear the filter media when subjected to pressure stresses. They also found the aged HEPA media had lost its water repellency.

These previous studies imply that ageing and weakening continue even after the fiber has been made into medium and the medium fabricated into a filter. Although the previous studies were conducted on in-service ageing, and not shelf-life ageing, they suggest the type of effects one can expect for shelf-life ageing. The

because the filters were second-stage filters that were effectively only exposed to clean air and were housed inside a building characterized by moderate temperature and humidity conditions.

II. Experimental Plan

The experimental plan that we selected for this study was to first accumulate unused HEPA filters that had been stored for various years in warehouses. We wanted a minimum of four filters from the same manufacturer for each filter age; one filter would be cut open and provide samples of filter media and other components, while the remaining three filters would be tested separately for resistance to overpressure, heated air and rough handling. After we accumulated the available filters, we would first conduct tests on the filter media to identify candidate parameters that show a relation to filter age. Following the media tests we would conduct the overpressure, heated air and rough handling tests on those filters for which a trend is established between a media parameter and the filter age. The experiments conducted in this study were limited in both scope and depth to keep the costs within the available budget. The study should therefore be viewed as a preliminary effort for a more in-depth investigation to follow.

III. Test Results

We were able to locate a number of size 5 (2 x 2 x 1 ft.) HEPA filters that had been stored at the Rocky Flats Plant (RFP) and at Lawrence Livermore National Laboratory (LLNL) The filters ranged in age from 0.2 to 18 years. All of the filters came from Rocky Flats except the June 1984 filter of Manufacturer A. In addition to the size 5 filters, we obtained media samples of Manufacturer A for 1976 and also cut media samples from a 1991, 50 cfm HEPA filter (Manufacturer A) found at LLNL. All of the size 5 filters were open-faced with the media folded in a deep pleat configuration and were made with organic sealant and plywood frame. Except for the January 1976 filter of Manufacturer B , all were equipped with aluminum alloy separators. The exception had crysotile asbestos separators.

Filter Media Tests

The laboratory tests on the filter media selected in this study consisted of measuring the tensile strength, quantity of binder and Nomex (du Pont trade name) fibers, media thickness and weight. We carefully cut open the filters and extracted several layers of media with the separators in-tact. The media was unfolded and appropriate samples cut for the different measurements. We used a thermogravimetric analyzer (TGA) for determining the amount of binder and Nomex fiber in the media and an Instron tester for measuring the tensile strength. We omitted many additional tests that would be included in a more comprehensive study. The primary tests omitted are air flow resistance and DOP penetration for newly cut samples and samples after flexing; tensile strength in across-machine direction, after heated air, and after wetting; and water repellency [4]. Since the previous studies [2,3] suggest that aged filters loose their water repellency treatment and become brittle, it is important that the additional tests be conducted in a more complete study.

The medium thickness was determined with a Scherr-Tumico micrometer having a 0.5 inch diameter anvil and foot and is designed for measuring the thickness of sheet stock like paper and rubber. The filter medium was compressed in the micrometer until the first click of the tension ratchet assembly.

To determine the amount of binder and Nomex, the TGA was used rather than the conventional TAPPI T-413 method of weighing the sample before and after heating in an oven at specific temperatures [5]. We found the TAPPI method prone to error, time consuming, and requiring modification to evaluate Nomex. Temperature settings are required @ 107 C. to drive off adsorbed water, at 400 C. to drive off the binder, and at 550 C. to drive off the Nomex. Preliminary tests with the oven method showed rapid weight gain, due to moisture adsorption, during the weighing operation after removing the filter medium from the oven.

We determined the medium tensile strength with an Instron tester in accordance to MIL-F-51979 [4]. We cut several 1 x 6 inch samples in the flat portion of the medium and additional samples with a pleat in the center. The 1 x 6 inch samples were cut with the length in the machine direction (the direction in which the medium moves forward during the paper manufacturing).

A TGA model 2950 from TA Instruments, New Castle, DE, was used to determine the percent by weight of binder and Nomex fiber in 1/4 inch disks punched from the media samples. Nomex was added to the filter media for RFP in the early 80's to make it more resistant to attack by nitric and hydrofluoric acid. Asbestos was formerly used to provide the acid resistance. Although other DOE facilities do not specify the addition of Nomex, it sometimes appears in the media.

After inserting the sample into the TGA, the instrument automatically measures the amount and rate of change in the sample weight as a function of temperature in a nitrogen atmosphere. The amount of weight loss in known temperature regions is used to determine the percentage of the acrylic binder and du Pont's Nomex in the filter medium. Figure 1 shows the TGA curve for the 17.5-year-old sample of Manufacturer A. The sample shows the weight loss begins at about 250 C and ends at about 420 C. The 4.5% weight loss is due to the binder. The derivative of the weight loss curve is also shown in Figure 1 as a single peak and is useful for identifying the beginning and end temperatures of the weight loss from a component. The sample in Figure 1 shows a single peak in the derivative curve and thus indicates only a single component, the binder, accounts for the lost weight.

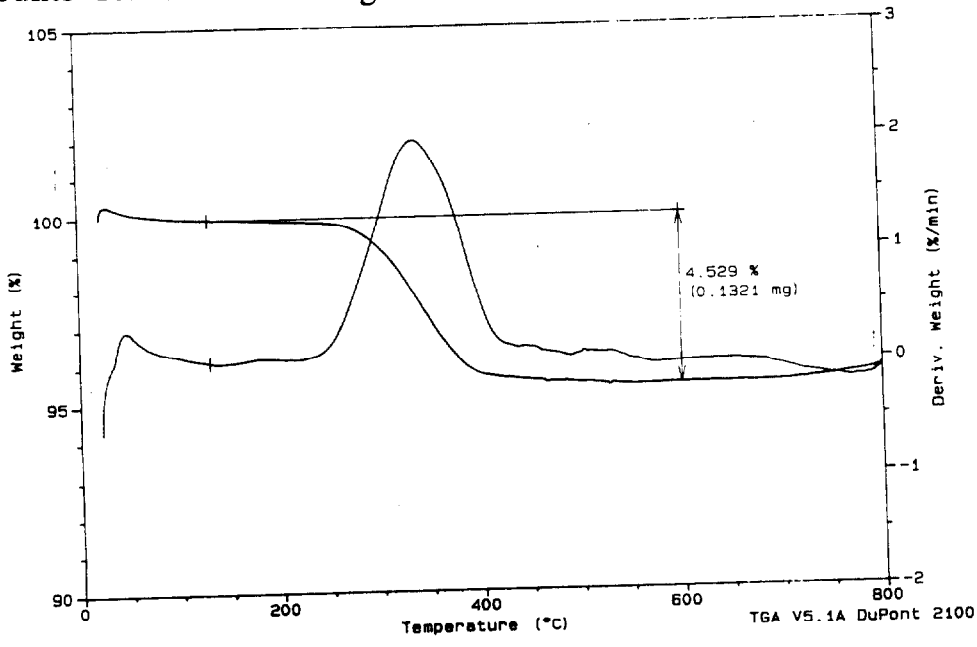

Figure 1. TGA results for filter media taken from 17.5-year-old filter (Manuf. A) showing binder loss.

Figure 2 shows the TGA curve for the 2.7-year-old sample of Manufacturer A. We see two peaks in the derivative curve, one for the binder and one for the Nomex. In this case the binder begins to loose weight at about 320 C and is completely vaporized at 429 C. The second peak for the Nomex begins at 429 C and is through at about 580 C. The weight loss for the binder and Nomex peaks are 1.5% and 1.6% respectively.

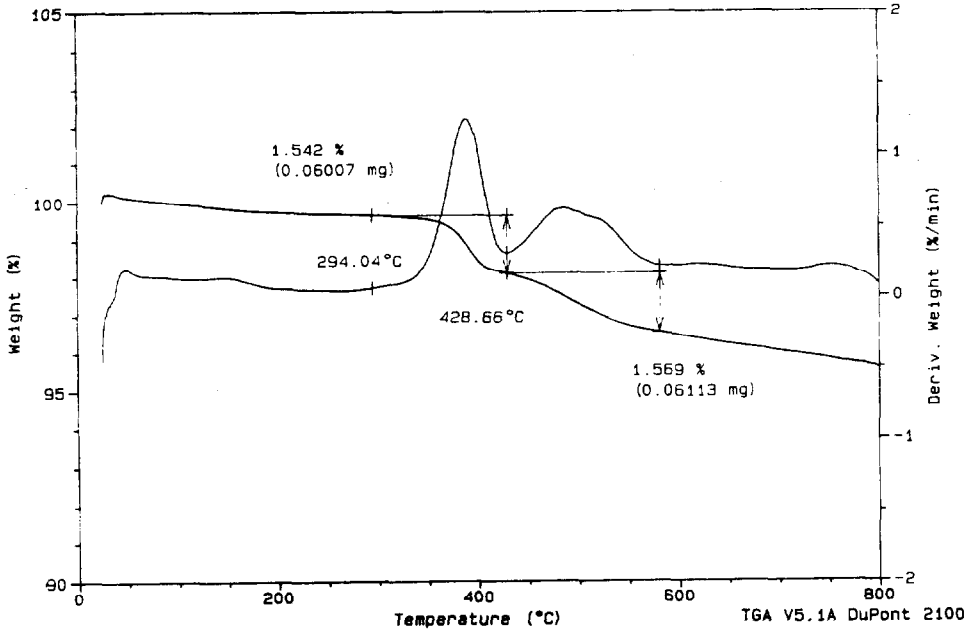

Figure 2. TGA results for filter media taken from 2.7-year-old filter (Manuf. A) showing loss of binder and Nomex.

We encountered more complicated TGA curves as shown in Figure 3, where four derivative peaks are seen for the sample taken from a 12.1-year-old filter (Manuf. D). The four derivative peaks indicate four components are present, although not necessarily independent. The first peak is due to adsorbed water removal. Water adsorption on the filter media suggests that the organic water-proofing has degraded. The second and third peaks are due to loss of binder and Nomex respectively. The weight loss due to binder is 1.6% beginning at 290 C and ending at 424 C. The weight loss due to Nomex is 1.8% beginning at 424 C and ending at 581 C. We do not know what the fourth peak is due to.

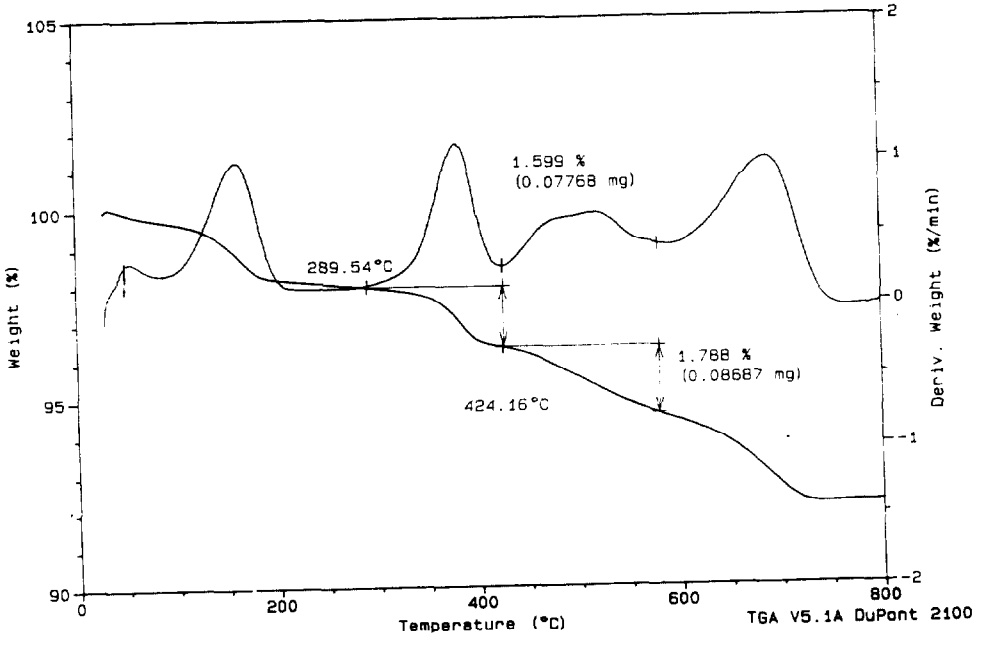

Figure 3. TGA results for filter media taken from 12.1-year-old filter (Manuf. D) showing loss of water, binder, Nomex and an unknown component.

In order to relate the weight loss in the TGA curves to the weight percent of binder and Nomex fibers in the filter media, we conducted baseline TGA tests using pure acrylic binder and Nomex fibers [6]. The results for the acrylic binder and Nomex fibers are shown in Figures 4 and 5 respectively. The baseline tests show the weight loss for acrylic binder is 81.2% in the temperature limits between 250 C and 420 C and 34.7% for Nomex fibers in the temperature limits between 420 C and 580 C. Since the pure samples do not show 100% weight loss in the temperature limits, the measured weight loss for binder and Nomex have to be corrected. For the acrylic binder, the measured weight loss has to be multiplied by 1.23 to obtain the percent of binder in the medium. For the Nomex fibers, an additional correction has to be made since a small portion of binder looses weight in the temperature region attributed to Nomex fibers. This overlap is corrected by subtracting 11% of the measured binder weight loss from the Nomex weight loss. The net measured weight loss for Nomex fibers is then multiplied by 2.67 to obtain the percent of Nomex fibers in the medium.

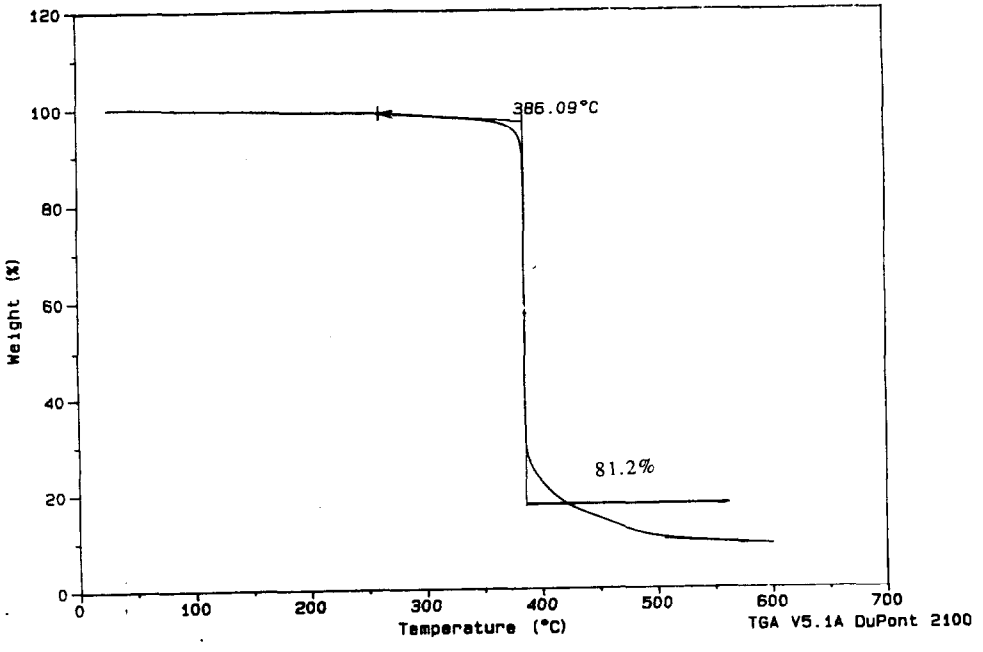

Figure 4. Baseline TGA curve for 100% acrylic binder.

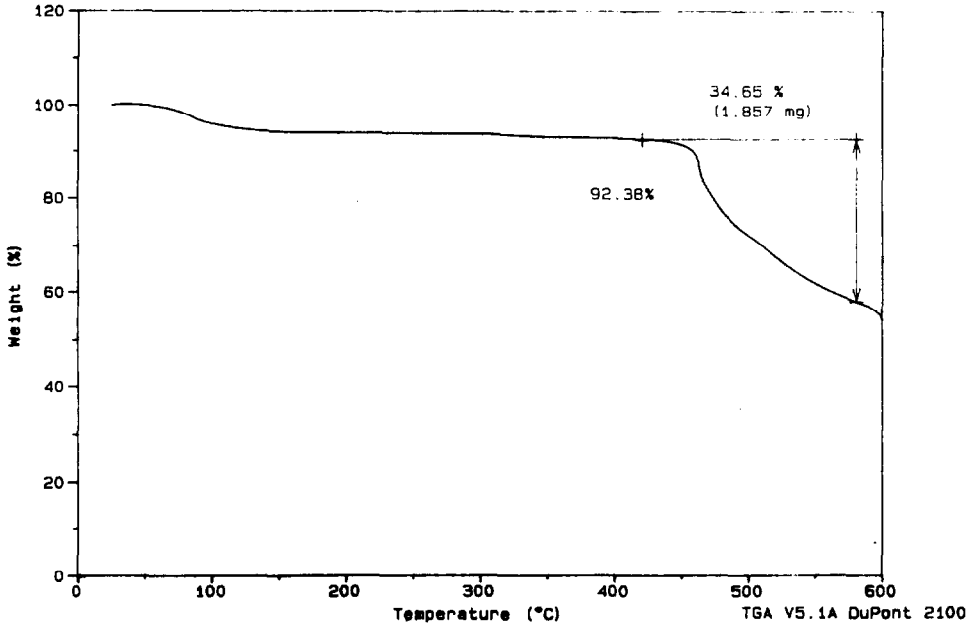

Figure 5. Baseline TGA curve for 100% Nomex fibers.

The results from the laboratory tests are summarized in Table 1, where we have tabulated the percent by weight of binder and Nomex, the tensile strength of the unfolded and folded samples, the thickness, and the weight of the media samples. We computed the correlation of filter age to the binder composition, tensile strength, thickness and ream weight, but did not find any significant correlation. Figure 6 shows the least squares fit between the tensile strength of the unfolded media and the filter age. We expected to see a strong correlation in tensile strength with age based on previous studies on in-service aging [2,3].

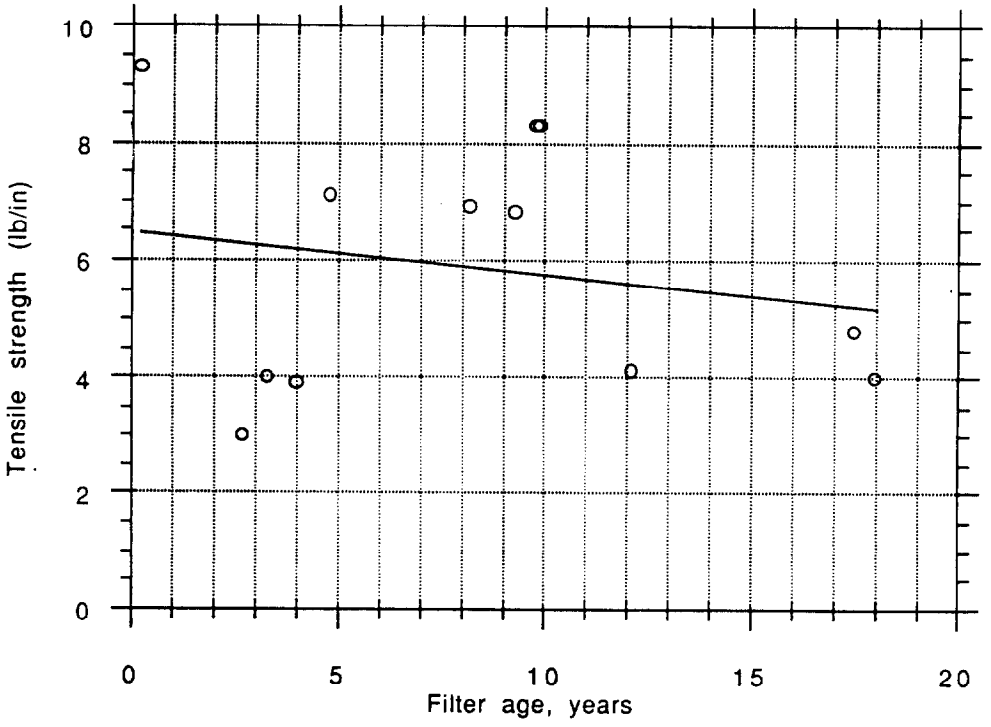

Figure 6. Correlation of media tensile strength to filter age.

During our shelf life study, we learned that the filter medium in the 1990 and 1991 filters of Manufacturer A currently was developing cracks during transportation and installation. Since the problem seemed to be related to manufacturing and not age, we examined the effect of removing the questionable data from our correlations. We removed the 1990 and 1991 data on Manufacturer A and replotted the data in Figure 7. The data now show a strong correlation of decreasing tensile strength with age. The regression coefficient of the linear least squares fit is R= 0.81. A similar trend is seen for the tensile strength of the folded media in Figure 8, although the values are much smaller.

Table 1 Media Test Data

Age (Years)	Manu-facturers	Purchase Date	Composition (% by wt.) Binder	Composition (% by wt.) Nomex	Tensile Strength (lb./in., Mach. dir.) Unfolded[1]	Tensile Strength (lb./in., Mach. dir.) Folded	Thickness (in.)	Weight lb/3000ft^2
18	A	1976	1.4	0.0	4.0	–	.019	42.7
17.5	B	Jan '76	5.5	0.0	4.8	1.1	.021	58.1
12.1	D	Aug '82	2.0	4.3	4.1	1.9	.022	59.3
9.8	C	Apr. '84	5.8	4.3	8.3	2.7	.024	58.6
9.9	A	Jun '84	3.0	2.4*	8.3	1.6	.023	48.0
9.3	E	Nov. '85	4.3	3.7	6.8	1.9	.020	53.8
8.2	A	Oct. '86	3.8	2.9	6.9	1.6	.025	56.6
4.8	E	May '89	4.7	4.0	7.1	2.7	.020	57.4
4	A	1990	2.0	2.9	3.9	–	.024	52.3
3.3	A	Mar '91	2.5	1.9*	4.0	0.9	.023	46.8
2.7	A	Oct '91	1.8	3.7	3.0	0.9	.020	43.7
0.2	A	May '94	3.0	3.2	9.3	2.3	.024	50.5

[1] Standard is 2.5 lbs. minimum
* Nomex not requested in LLNL purchase order

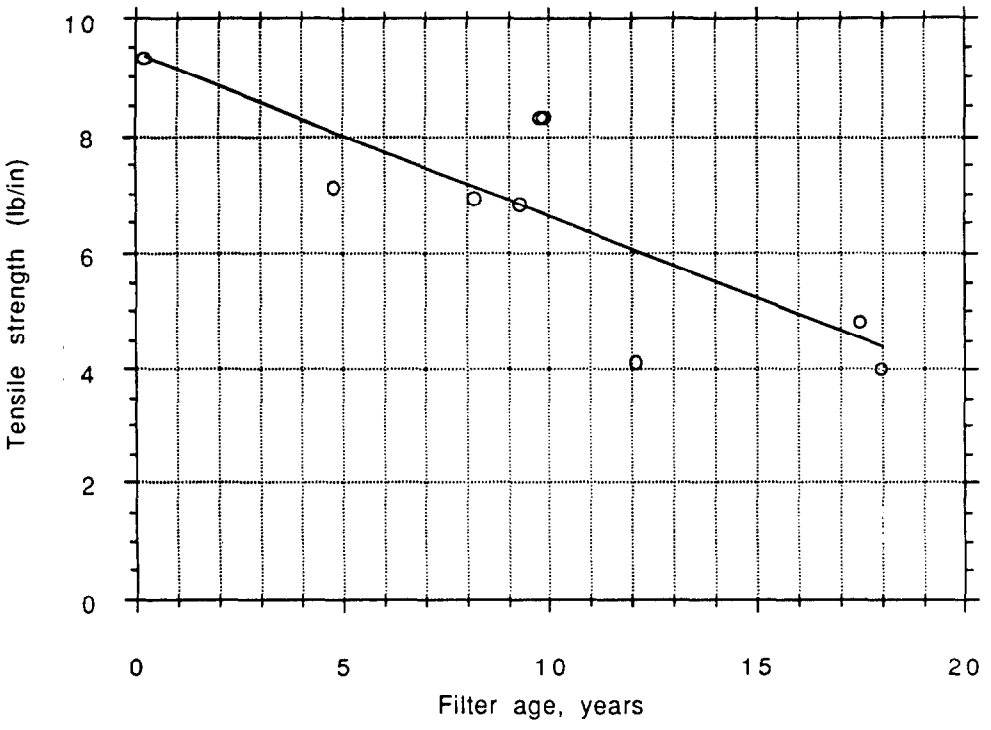

Figure 7. Correlation of media tensile strength to age with 1990 and 1991 data on Manufacturer A removed.

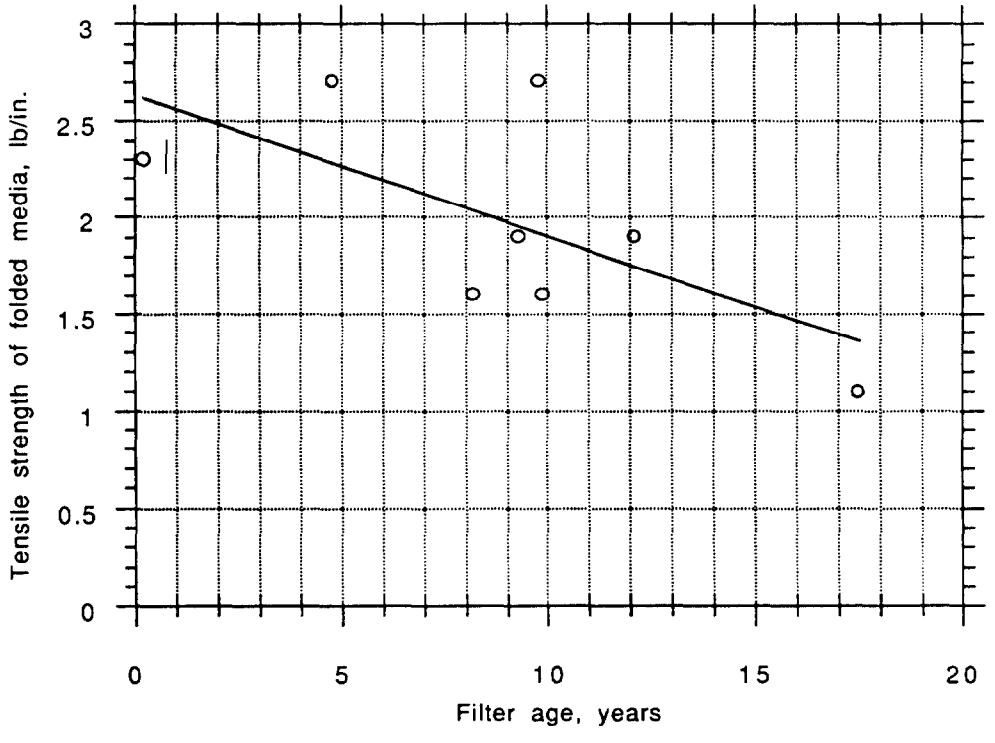

Figure 8. Correlation of tensile strength to age of folded media with 1990 and 1991 data on Manufacturer A removed.

The results from our media tests show that the tensile strength of the media decreases with age, but does not provide sufficient information to establish a shelf life for filters. All of the filter media tested in our study meet the requirements in MIL-F-51079 that specifies the tensile strength of unfolded media be greater than the minimum value of 2.5 lb./in.(4). There is no requirement for the tensile strength of the folded media, although that is the critical parameter determining media failure. Note that the average tensile strength of the folded media is about 1/3 the strength of the unfolded media.

The media tests do suggest that the low, although acceptable, tensile strengths of the 1990 and 1991 media of Manufacturer A is due to insufficient binder to hold the glass fibers together in a sheet. We have plotted the tensile strength versus the percent of binder for all of the media samples of Manufacturer A in Figure 9 and show good correlation. The straight line correlation was obtained by least squares analysis. The correlation is not as good when the data of all the manufacturers are combined. This is not surprising since the manufacturers do not use the identical materials and processes.

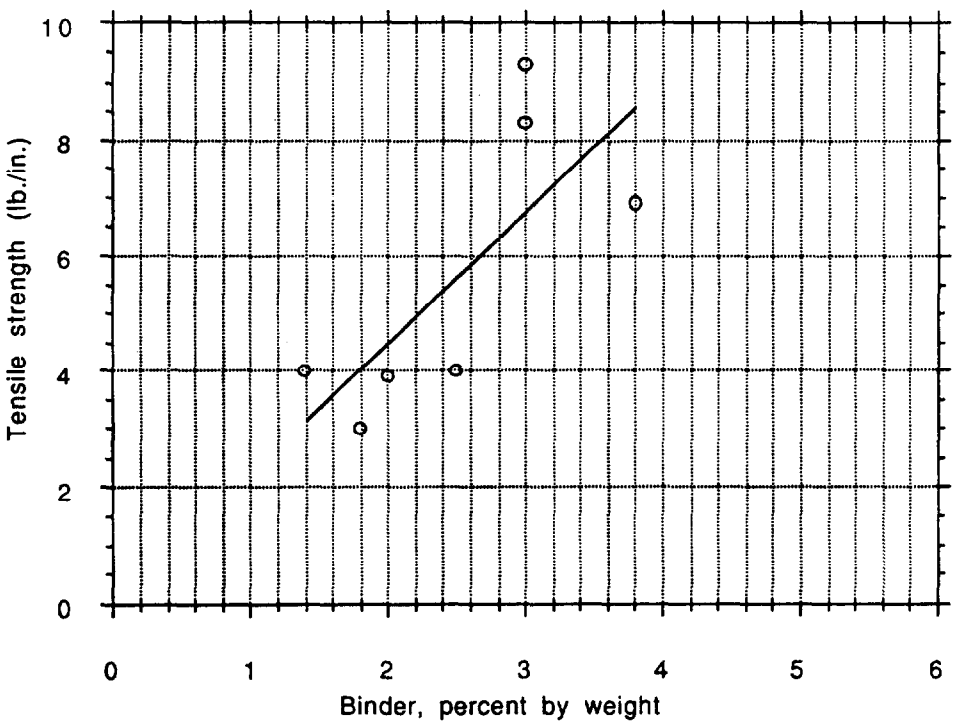

Figure 9. Correlation between the percent of binder and the media tensile strength for Manufacturer A.

Filter Tests

We conducted a limited number of non-destructive quality assurance (QA) tests and destructive qualification tests on three different aged filters we had available. These tests were selected because they specify the minimum acceptable performance for new filters. We reasoned that aged filters should also meet these requirements. A previous study on in-service filter life used simulations of tornado pulses and shock wave overpressures to evaluate aged filters.

The quality assurance tests on assembled filters consist of visual inspection for damage, penetration, and resistance [7]. Because all of the filters under study are Size 5, designated 24 by 24 by 11-1/2 inches, the latter two tests involve use of the Q107 penetrometer to measure penetration of dioctyl phthalate (DOP) particles through the filter and resistance to air flowing at 1000 cfm. A second penetration test is made with air flow reduced to 20% (200 cfm.) and is primarily targeted at identifying unwanted holes in the media and leakage at those seams where frame and gasket pieces are joined together. The upper limit for DOP penetration is 0.03% at either flow rate. The maximum allowed resistance (pressure drop) is 1.0 inch, water gauge, at the 1000-cfm. flow rate.

Qualification testing has reliability of the design of the assembled filter as its primary aim. Testing is abnormally severe and is so intended to ferret out any component weakness by which the filter might fail. This dictates that a filter not be used after a qualification test; therefore, qualification testing is classified as destructive. A detailed explanation of the tests was included in the Proceedings of the 22nd DOE-NRC Nuclear Air Cleaning conference [8] and listed below by function:

a. Q160 overpressure apparatus. A 60-minute test which subjects a previously humidified filter to steam droplets in air flowing at an elevated resistance of 10.0 inches, water gauge. Post-test penetration must not exceed 0.03% at 20% air flow.

b. Heated air device. Subjects a filter to air while heating to 700 degrees F. and operation at that temperature for five minutes. Post-test penetration must not exceed 3.0% at 100% flow.

c. Rough handling machine. The filter, in its shipping carton, is strapped to platform which subjects the packaged filter to an amplitude of 1/2 inch at a frequency of 200 cycles per minute. Post-test penetration must not exceed 0.03% at both 100% and 20% flow. No rough handling tests were conducted in this preliminary study.

We conducted QA and qualification tests on only three different ages filters in this preliminary study. The 0.2- and 2.7-year-old filters of Manufacturer A were selected to provide information on an immediate problem with filters used at RFP and other DOE facilities. The 9.8-year-old filter of Manufacturer C was selected at random. In a more comprehensive study, all of the filters we collected would be tested.

We conducted the heated air and pressure resistance tests using a different filter for each test as specified in MIL-F-51068 [7]. We also conducted tests using the same filter in a test sequence consisting of a heated air test followed by a pressure resistance test. The latter test sequence was previously used to evaluate a high-strength HEPA filter to better simulate the multiple stresses placed on HEPA filters during accident conditions[8]. Ruedinger et al (9) reported that nuclear reactors in Germany require filter qualification tests consisting of elevated temperature in still air, pressure resistance in high air flow, and humid air resistance.

Table 2 shows the test results for the pressure resistance tests. The 0.2-year-old filter of Manufacturer A and the 9.8-year-old filter of Manufacturer C passed the test and showed no structural damage. In contrast, the 2.7-year-old filter of Manufacturer A failed the test. Examination of the filter after the test showed a slit about 5 inches along a pleat (Figure 10) and small media tears near the housing (Figure 11), both defects on the downstream side.

Table 2. Pressure resistance tests.

			Before			After	
Age (Years)	Manufacturer	Purchase Date	ΔP in.	Penetration 100%	Penetration 20%	ΔP in.	Penetration 100%	Penetration 20%
9.8	C	April '84	.86	.030%	.033%	.86	.026	.032
2.7	A	Oct '91	.80	.01%	.01%	.74	.51%	.81%
0.2	A	May '94	.80	.016%	.018%	.78	.005%	.011%

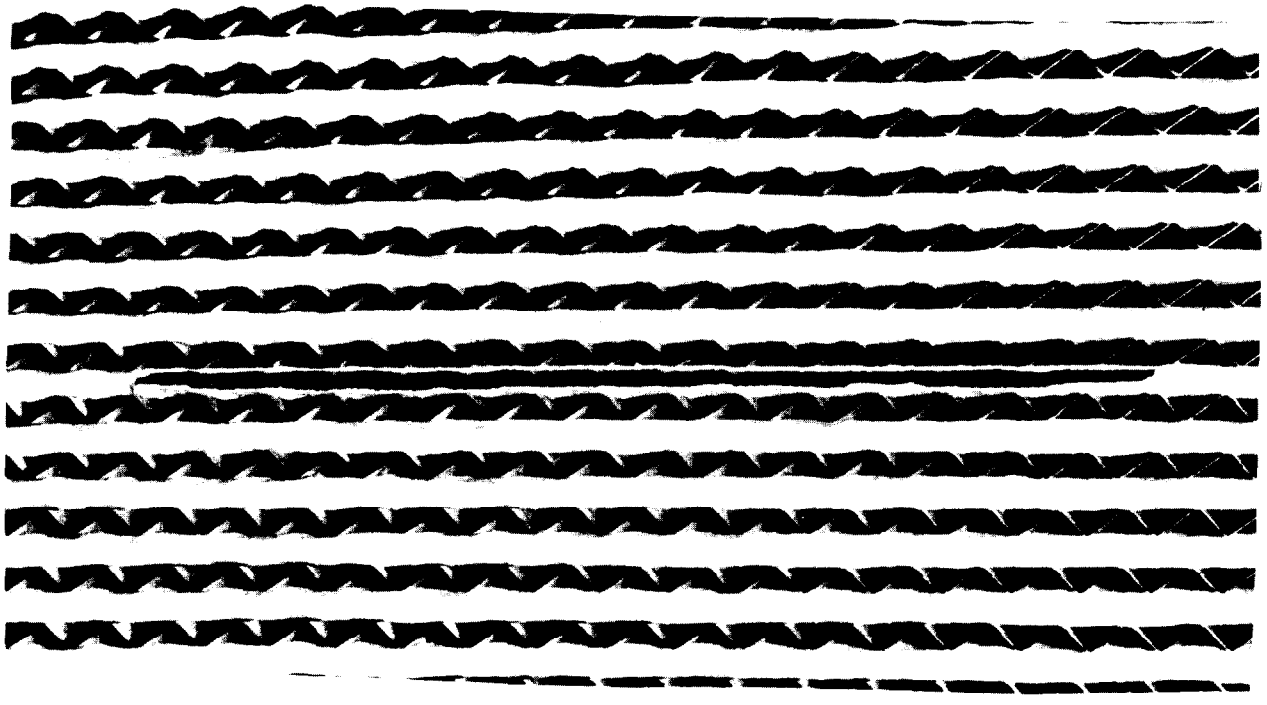

Figure 10. Slit in media pleat on the downstream side of a 2.7-year-old filter of Manufacturer A following the pressure test.

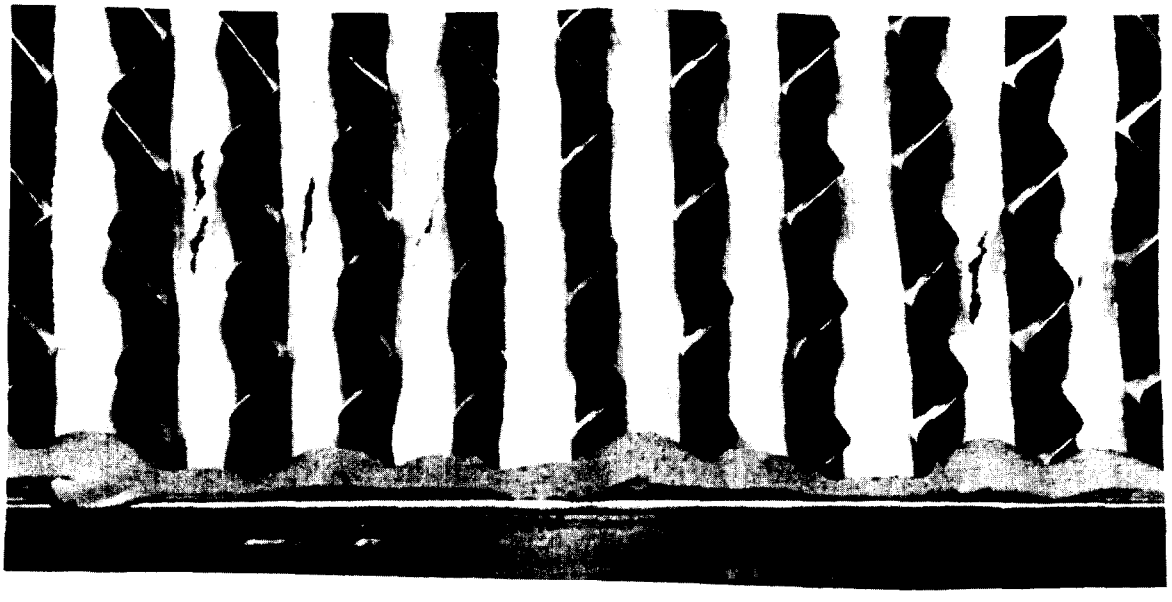

Figure 11. Small tears on downstream side of 2.7-year-old filter of Manufacturer A following the pressure test.

The failure of the 2.7-year-old filter in Table 2 can be attributed to the low tensile strength of the medium which resulted from insufficient binder. The other two filters show no deterioration after the pressure test despite the large age difference. Filter construction properties clearly have a much greater effect on resistance to pressure than filter age.

We then evaluated two additional filters in a test sequence consisting of a heated air test followed by a pressure test and a third filter in the heated air test only. Filter penetration measurements were made before and after each test. The test results are summarized in Table 3.

Table 3. Test results following heated air and pressure resistance.

			Before			After Heated Air			After Heated Air and Pressure		
Age (Years)	Manu-facturer	Purchase Date	ΔP in.	Penetration 100%	20%	ΔP in.	Penetration 100%	20%	ΔP in.	Penetration 100%	20%
9.8	C	April '84	.86	.012%	.013%	.90	.015%	.017%	–	–	
2.7	A	Oct '91	.76	.018%	.023%	.74	1.24%	4.52%	0.64	5.86%	7.51%
0.2	A	May '94	.74	.008%	.008%	.76	0.77%	1.91%	.80	2.05%	4.12%

The three filters meet the requirement of less than 3% penetration at 100% flow after the heated air test. Since there are no standards for a sequence of tests on the same filter, there is no established penetration level defined as a failure.

During the heated air test on the 2.7-year-old filter, the sealant was burning and continued to burn even when the heat was removed. Examination of the filter after test showed the sealant had burned through the entire depth of the filter, leaving the filter pack loose in the wooden frame. Figure 12 shows a close up of the sealant on the exit side of the filter after the heated air test. The gap between the wooden frame and the filter pack is visible in the photograph. The filter pack also showed a slight buckling of the separators and media pleats into an "s" shape near the bottom frame of the filter. This buckling was presumably due to the softening of the media and the weight of the filter pack. No tears or holes were found in the filter media. The penetration at 100% flow is 1.24% and

is within the allowed 3% limit. Note that the filter would have failed if the penetration at 20% flow were used as done in the overpressure test.

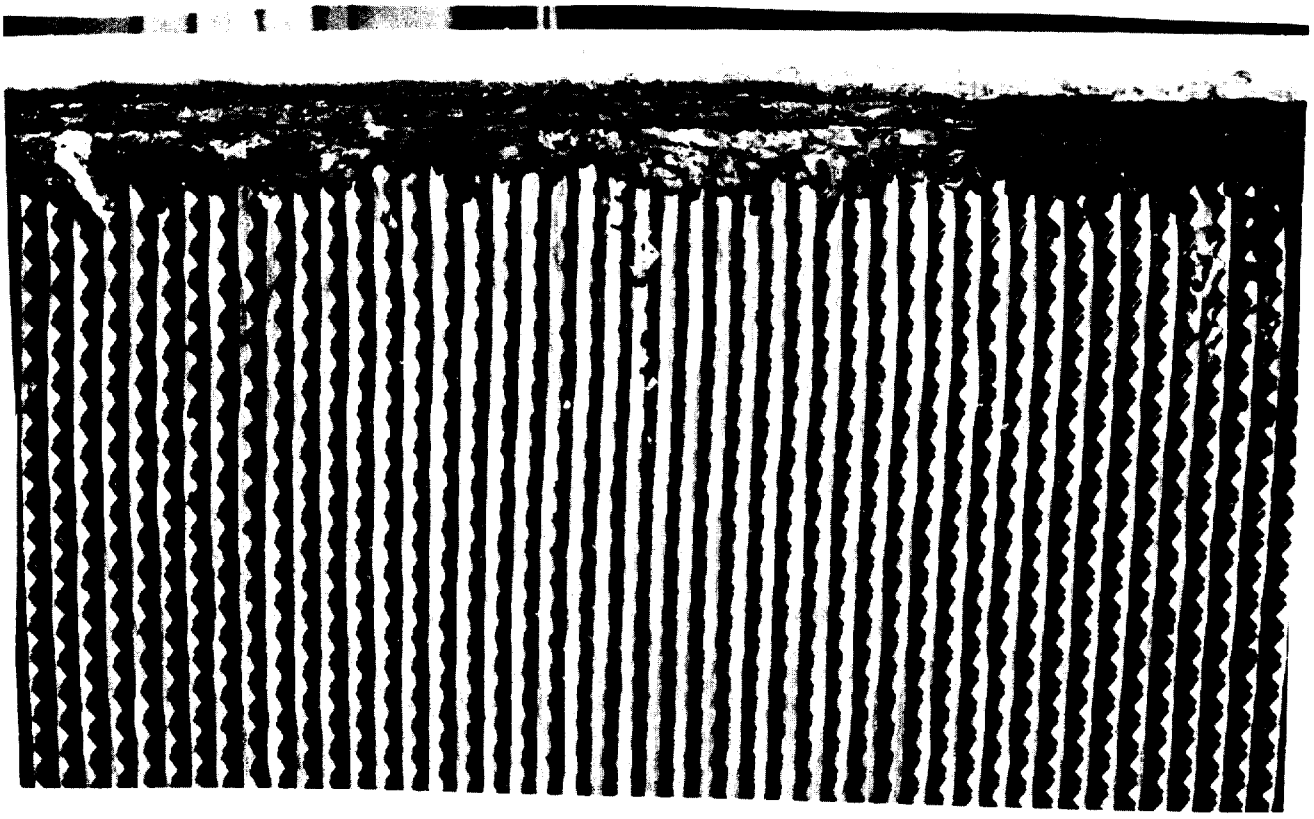

Figure 12. Photograph of 2.7-year-old filter of Manufacturer A showing the crack where the sealant had burned away.

The damaged 2.7-year-old filter of Manufacturer A was then subjected to the overpressure test. During the test, a major portion of the filter pack was pushed out of the frame about one inch, but was not blown out. Figure 13 shows the exit side of the filter with portions of the filter pack pushed out. (Note that the gasketed side of the single gasket filter must be faced upstream in the heated air test and reversed to face downstream in the overpressure test.) The displacement of the filter pack can be seen by the extension of the aluminum separators beyond the gasket in the right side of the photograph in Figure 13. The central portion of the filter pack was pushed out even farther after the seventh aluminum separator from

the right. The step dislocation is seen by the exposed filter medium separating the two portions of the filter pack. The filter also showed more extensive buckling near the bottom frame and had media tears in that region as seen in Figure 14.

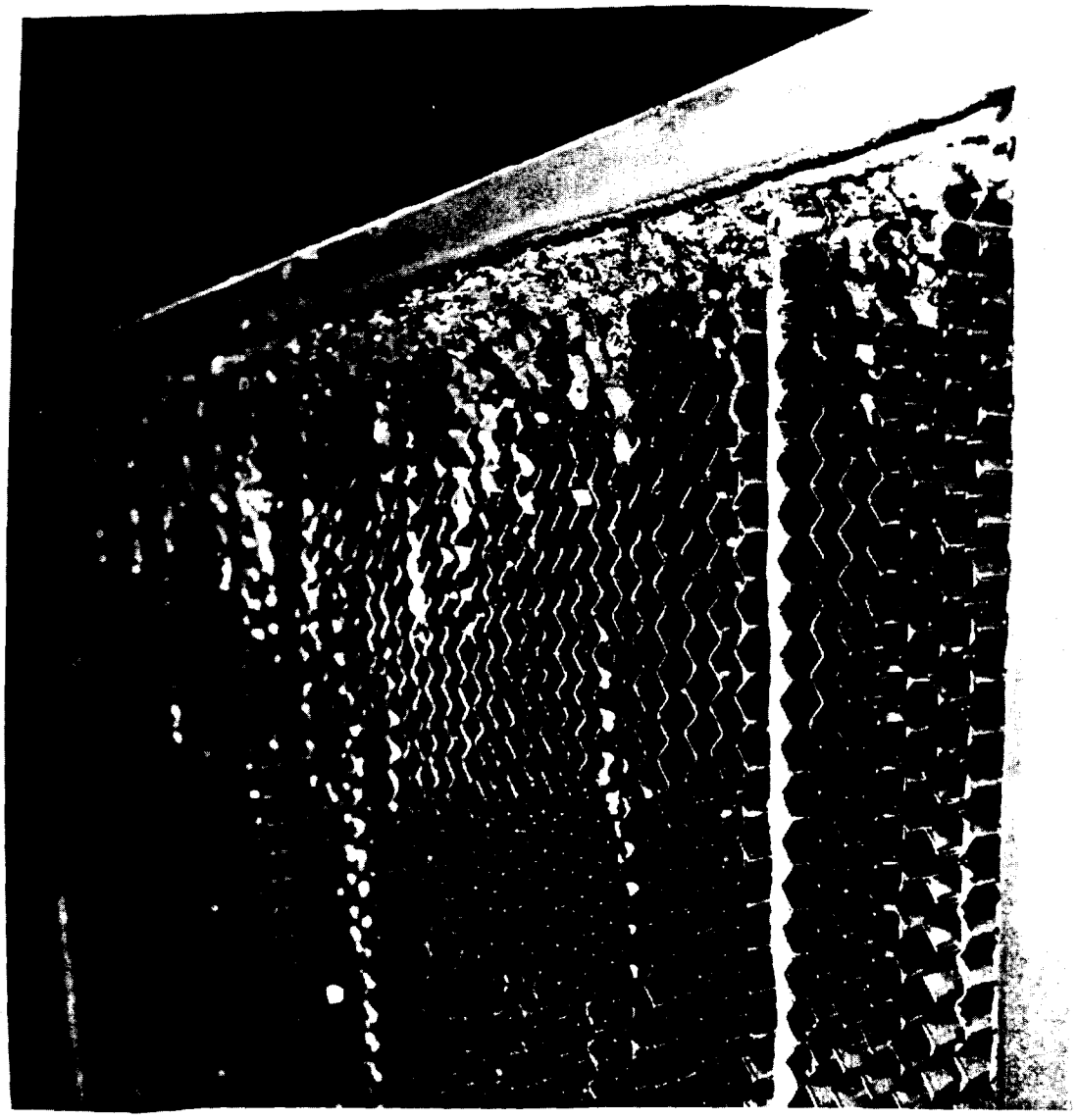

Figure 13. Photograph of the exit side of the 2.7-year-old filter of Manufacturer A showing filter pack pushed out of its frame after the overpressure test.

Penetration tests on the filter showed 5.86% and 7.51% at 100% and 20% flow respectively. Under slightly more severe conditions, the media pack would have completely blown out of its frame and resulted in 0% efficiency.

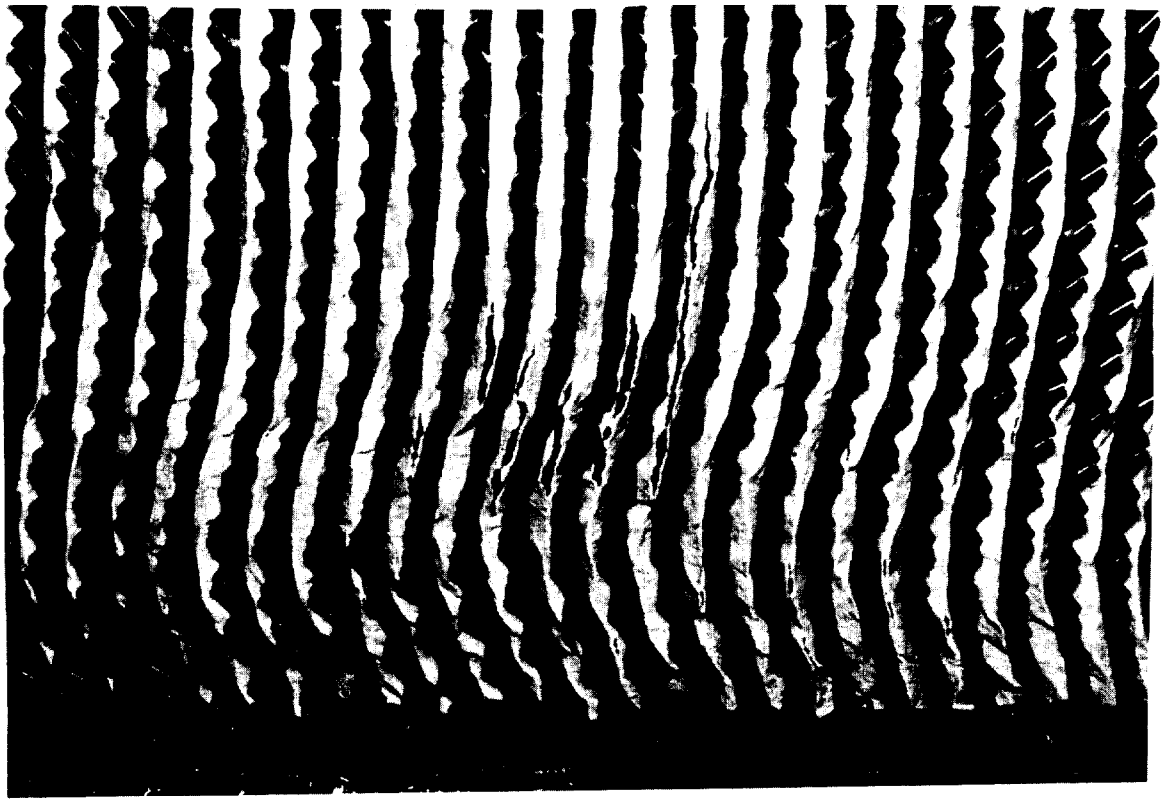

Figure 14. Photograph of the exit side of the 2.7-year-old filter of Manufacturer A showing media buckling and tearing after the overpressure test.

The 0.2-year-old filter of Manufacturer A had far less damage after the heated air and overpressure tests than the 2.7-year-old filter. The filter sealant had charred but held the media pack tight to the frame. There were four slits along the media pleats, about 3-4 inches long, on the exit side of the filter along with slight media buckling. During the heated air test, smoke was jetting out from the joints in the plywood frame. Bubbles were forming at the cracks indicating that the glue used to seal the frame was melting and burning.

The large difference in the fitler penetration measurements for the three filters in Table 3 after the heated air test is due to the type of material used to seal the filter pack into the filter frame. Table 4 shows the filter penetration data befofe and after the heated air test retabulated from Table 3 along with filter age, medium tensile strength and sealant type. Filter age and medium tensile strength do not correlate well with the penetration data. However there is a

strong correlation between the sealant type and the penetration. The filter using a flame inhibited rubber is unaffected by the heated air, while the filters using a urethane sealant show significant degredation to heated air.

Table 4. Effect of filter parameters on heated air test results

Parameter			Heated Air Test	
Age (years)	Medium Tensile Strength (lb/in)	Sealant	Penetration (%)	
			Before	After
9.8	8.3	inhib. rubber	.012	.015
2.7	3.0	urethane	.018	1.24
0.2	9.3	urethane	.008	.77

Based on the limited filter tests summarized in Tables 2-4, we can conclude that filter age is not the primary factor affecting filter performance in the heated air and overpressure qualification tests. The 2.7-year-old filter of Manufacturer A had failed the overpressure test due to tears in the filter media. We have shown this filter has poor tensile strength due to insufficient binder. The filter also had severe structural damage during the heated air test, although it met the maximum penetration requirements. The sealant was completely burned out around the filter pack, leaving it susceptible to blow-out. In contrast, the filter of Manufacturer C that used a sealant made from flame inhibited rubber showed no deterioration after the heated air test. Thus, our preliminary conclusion is that the type of materials and the construction design used in HEPA filters have a greater effect of HEPA performance than age.

IV. Rocky Flats HEPA Failures

Our study to determine the shelf-life of HEPA filters coincided with a problem encountered at the Rocky Flats Plant with aged HEPA filters of Manufacturer A. The volume of filters purchased by Rocky Flats during 1990 and 1991 exceeded the capacity of the local storage facility. The filters were found acceptable upon quality assurance tests following delivery and were stored in containers which were outside and exposed to weather changes. During 1993 and 1994 many of these filters were withdrawn from containers, re-certified with quality assurance tests, and issued for installation. Some filters at the installation site were found with damaged

medium; and following installation of others, in-place testing identified installed HEPAs with damage not prominently discernible to visual inspection.

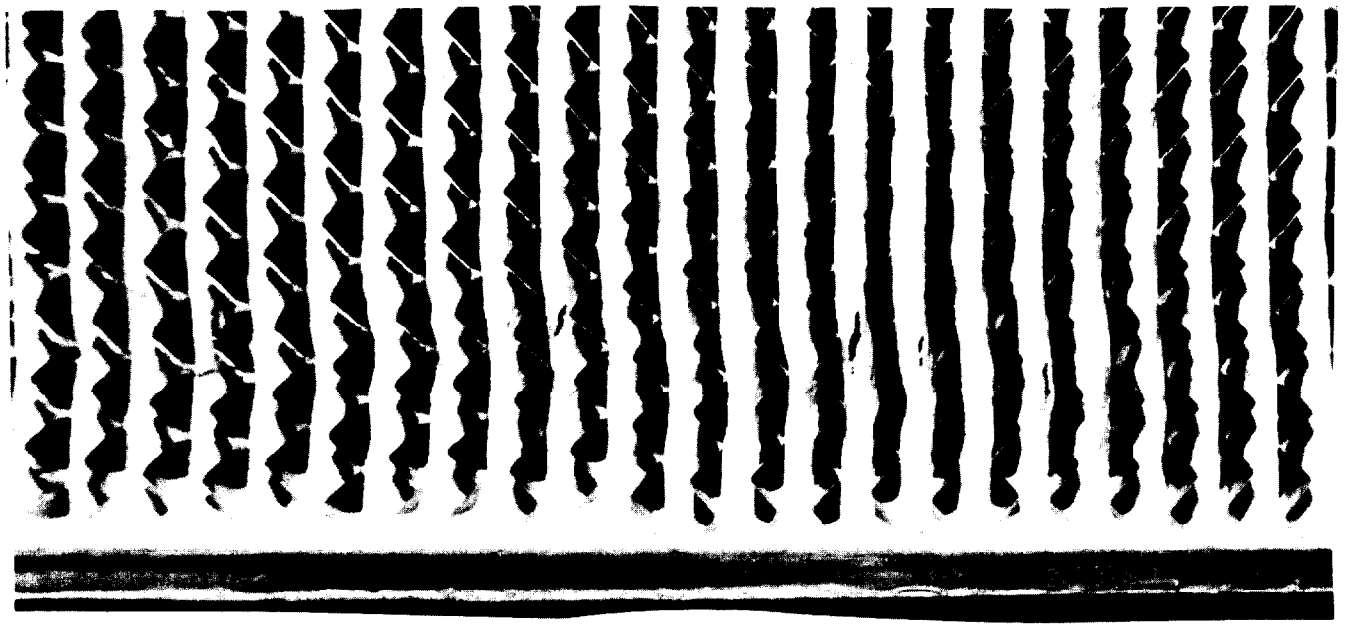

Figure 15. Photograph of filter media tears encountered at the Rocky Flats Plant during the installation of 2- to 3-year-old filters of Manufacturer A.

An independent study by some of us (J.K.F. and F.R.) showed that the filter failures were due to small tears in the media that occurred during the transportation and installation of the filters. The mechanical stresses placed on the filter were evidently sufficient to damage the media. Figure 15 shows the typical damage that was seen with these filters. Our present study showed the damage was due to low tensile strength as a result of insufficient binder.

V. Conclusions

We have completed a preliminary study using filter media tests and filter qualification tests to investigate the effect of shelf-life on HEPA filter performance. The filter media was extracted from filters stored up to 18 years. Our media studies showed that the tensile strength decreased with age, but the data was not sufficient to establish a shelf-life. The media was also analyzed for the percent of binder and Nomex fibers using a TGA. These analyses

demonstrated that the low tensile strength of the 1990 and 1991 media samples of Manufacturer A were due to insufficient binder.

The filter qualification tests (heated air and overpressure) conducted on different aged filters showed that filter age is not the primary factor affecting filter performance. The type of materials and the construction design have a greater effect on HEPA performance than age. We found that the 1991 filters of Manufacturer A had failed the overpressure test. The filter had passed the heated air test, but left the filter so structurally weak, it was prone to blow-out. The unsatisfactory performance of these filters is partially due to the lack of sufficient binder in the medium. The use of a combustible sealant that burns through the filter depth and leaves the filter pack loose inside the filter frame is also not acceptable.

This is a preliminary study of some of the factors involved in establishing a shelf-life for HEPA filters. The study was limited in both the type of parameters studied and the number of samples. Future studies should also include all of the filter components, e.g. sealants, gaskets, frame, in addition to the media. Other filter tests such as simulation of tornado pulses and smoke plugging should also be conducted in addition to the qualification tests to better differentiate the age effects.

The discovery that sub-standard HEPA filters have found their way into DOE facilities despite an existing system of regulations and quality control laboratories suggests that the present system must be improved. All HEPA filter manufacturers that sell their filters to DOE facilities must have every type of size 5 filter they sell pass the qualification tests (heated air, overpressure, and rough handling) every five years [7, 10]. The enforcement of the requirements is typically left to buyers in the DOE facilities. Some manufacturers do not requalify their filters every five years. Our present study has shown that even if a manufacturer qualifies their filters every five years as required, the manufacturing process or materials used may change and lead to sub-standard filters. We recommend that DOE initiate a filter qualification program to prevent this occurrence.

Our study also suggests that the Nuclear Regulatory Commission (NRC) should re-evaluate its policy of not requiring HEPA filter qualification tests at the DOE filter test stations [11]. The NRC study cited the low rejection rate (about 6%) at the filter test stations

and the cost of the certification tests as the basis for their decision to discontinue certification tests. Unfortunately, the study was incomplete because it did not address the risk from the low probability event of rejected filters. The study ignored the consequences of installing unqualified filters in radioactive facilities. Once installed, these filters have a high disposal cost (about $5K) and potential decreased performance [12]. Based only on the cost to test and dispose of contaminated HEPA filters, the filter certification test has a break-even cost at 0.7% HEPA failure rate. The NRC study also assumed that the low rejection rate was not related to the requirement for filter certification, an assumption strongly denied by filter manufacturers and HEPA experts. A classic risk analysis based on the product of the probability of failure (% failure) times the effect or consequence of the failure would justify having HEPA filters certified in the filter test stations.

VI. Acknowledgment

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DISCUSSION

FIRST: You and I have talked about this before, but I want to make sure that the point gets brought out for everyone. It is very troubling that manufacturers make unannounced changes in the composition of the materials that go into the filters, and change manufacturing methods. My question to you is, how do you account for changes in technology over time, as well as the aging effect? In other words, were filters just less strong 18 years ago than they are now, and are we now seeing deterioration effects that will no longer occur?

GILBERT: I do not think there is any one factor involved. In some cases, during paper making, a new binder is put in, but I do not think it results in any change in the aging effect. I hold to the opinion that everything about the filter does age. However, I do not think that great care is taken to avoid it. For example, the fiber is made from time to time and may be stored a long time before delivery to the paper maker. After the paper making process, paper may be stored for long periods by the filter manufacturer. Since each paper manufacturer seems to use a recipe which is unique, maybe somebody slipped. So, filter failures have a number of sources. Some aging effects merely aggravate what started out as a deficiency.

WEBER: Glass is a water soluble material, and I do not know whether aging, as seen in tensile degradation, could be accelerated by humidity. The solubility of glass is not that great in neutral or acidic water. In our laboratories, when we subject fresh resin-bonded glass fiber media to short-term wetting, there is an immediate very large loss of tensile strength that appears to be associated with the way the fibers are adhering to one another, rather than to some short-term degradation of the fiber. It could have something to do with a change in lubricity affecting the resin binder held on the glass fibers. I am curious to know if you are considering using microscopy or some other examination of failed media to find out which components are the most affected.

GILBERT: No, our study was very limited in scope. A variety of laboratory studies still are

needed to assess the response of the fibers and medium to age and various environmental conditions. However, your question illustrates the need for a cooperative endeavor involving filter users and the filter industry, including fiber and medium manufacturers. This, in turn, might lead to a voluntary agreement for controlled storage at the source to preserve the tensile strength of fibers after they are produced. Medium fabricators also will want to review their similar responsibility for the period before converting the fibers into HEPA and ULPA media. Such a cooperative effort would benefit both users and producers.

MALIK: I have a comment on the tensile strength of glass media. Glass fibers do not have natural hydrogen-bonding, like cellulose fibers do. The amount and type of binder in glass media is very important. Measuring internal bonding strength of glass paper may be more appropriate than testing tensile strength alone or performing both tests can give a better picture for the strength of glass media.

GILBERT: I am not sure that there is a floor that could be put on the amount of binder because each glass paper manufacturer makes a product that is slightly different.

BERGMAN: I want to make the point that the greatest effect on filter strength I have found is related to the type of materials used in construction. Aging has a much lower effect, overall. Even if this information came across earlier, I want to emphasize the point.

TARTAGLIA: What was the basis for the test temperature (200°-600° C) and test pressure, 10 in.w.? Most nuclear plants would challenge the filters design basis accident (DBA) only to 200° F maximum and 2½ in.w.!

GILBERT: The standard is not intended for nuclear power plants. The test temperature and pressure are specified in the military specification for the heated air and overpressure tests, respectively.

YETTER: HEPA filters are the main boundary of protection to keep both chemical and radiation particles from the air we breathe. I am troubled by what I heard in the talks, that the rules and regulations regarding the assembly of HEPA filters may not have the enforcement that at one time was in place. I sincerely hope that we maintain high standards for these products.

GILBERT: DOE has maintained strict requirements for DOP tests of every HEPA filter used in DOE facilities. A sample of filters also is required to pass qualification tests for exposure to heated air, overpressure and rough handling every five years or whenever new filter designs or filter materials are used. Although these requirements generally have insured that high quality filters are supplied to DOE, our study has shown that substandard filters can pass the DOE penetration and resistance tests but not meet the required qualification tests. The problem is that the existing qualification tests do not catch deficiencies due to production changes between the five-year intervals. In our paper we showed that the strength of the medium of Manufacturer A had decreased significantly in 1990 and 1991 due to insufficient binder. Filters fabricated with this medium were weak structurally and failed the overpressure test. The problem with the current qualification test requirements can be solved by adopting a standard practice of testing representative samples periodically, not just the testing of custom manufactured filters initially and every five years. The DOE facility at Rocky Flats has the capability to perform the required qualification tests.

EFFECTS ON THE EFFICIENCY OF ACTIVATED CARBON ON EXPOSURE TO WELDING FUMES

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1.0 Abstract

There exists in the nuclear power industry the belief that welding fumes have a detrimental effect on activated charcoal used for air cleaning and filtration processes. It is the intention of this paper to document that certain types of welding fumes have little or no effect on the effectiveness of the carbon filter air filtration efficiency when directly exposed to a controlled amount of welding fumes for a short-term period. No effort has been made to determine the effect of long-term welding fume exposure on activated carbon methyl iodide removal efficiency.

The welding processes studied were restricted to shielded metal arc welding (SMAW), flux cored arc welding (FCAW), gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) processes. These were some of the most common welding processes used at a nuclear site. Contrary to the SMAW and FCAW processes, the GTAW (or TIG) and the GMAW (or MIG) welding processes do not require the use of flux as part of the overall process. Credit was taken for these processes occurring in inert gas environments and producting minimal amount of smoke. It was concluded that a study involving the SMAW process would also envelop the effects of the TIG and MIG welding processes.

The quantity of welding fumes generated during the arc welding process is a function of the particular process, the size and type of electrode, welding machine amperage, and operator proficiency. For this study, the amount of welding for specific testing was equated to the amount of welding normally conducted during plant unit outages. Different welding electrodes were also evaluated, and the subsequent testing was limited to an E7018 electrode which was judged to be representative of all carbon and stainless steel electrodes commonly used at the site.

The effect of welding fumes on activated charcoal was tested using a filtration unit complete with prefilters, upstream and downstream high efficiency particulate air (HEPA) filters, and a carbon adsorber section. The complete system was field tested in accordance with ANSI N510 standards prior to exposing the filters and the adsorber bed to welding fumes. The carbon samples were tested at an established laboratory using ASTM D3803-1989 standards.

2.0 Introduction

The most common welding processes performed at the nuclear site are the SMAW, FCAW, GTAW, and GMAW processes (figure 1). Contrary to SMAW and FCAW processes, the GTAW (or TIG) process does not require the use of a flux as a part of the overall process. In this process an arc is established between a nonconsumable tungsten electrode and the piece being welded. Once the arc is established, bare filler metal is fed into the weld area where it coalesces with molten base metal to form the weld. Argon, helium, or a combination of the two is used as shielding gas and serves as current carrying plasma. Smoke and fumes produced are minimal since there is no metal to produce them and the gases used are inert. Smoke and fume generation during the GMAW process is also minimal since this process uses inert gas as the shield gas and consumable filler metal electrodes that leave no slag.

The SMAW process, commonly referred to as the "stick" welding process, is widely used and, at present, is the most dominant of various weld processes. This process uses an electric arc between a covered metal electrode and the base metal to obtain fusion. The electrode provides shielding and filler metal for the weld. This weld process generates the most smoke and fumes. It is assumed that a study involving the SMAW process will also envelop the FCAW process.

3.0 Purpose of the Study

This study was developed as a result of a statement in the Nuclear Regulatory Commission Regulatory Guide 1.52 which specified retesting of the filtration system following events of chemical release. The welding process was inferred as a form of chemical release and, consequently, it was understood that charcoal in a filtration system may be poisoned or contaminated following exposure to smoke and fumes generated during the welding process.

At the nuclear site, the standby gas treatment (SGT) system filter unit is normally operated twice a day for about an hour to purge the primary containment. The site configuration requires the SGT system to be operated during all refueling outages. This has required stoppage of all work involving welding for the duration of the purge. This restriction resulted in wasted manhours during outages. It was, therefore, desirable to establish the basis for the concern and investigate the most cost effective solution.

4.0 Analysis

The American Welding Society (AWS) has conducted numerous studies involving generation of smoke and fumes during various weld processes. All the

studies were restricted to concerns of health and the impact on the welders from short- and long-term exposure to the fumes. Table 1 lists the various welding contaminants and their effect on different parts of the human body. The welding process studies have concluded that the various gaseous byproducts do not constitute a major environmental problem.

The smoke and fumes generate particulate with average diameters from 0.3 to 0.7 microns. The particle behavior is influenced by the air movement in the immediate vicinity of the weld process. For a fume control ventilation design process, capture velocities in excess of 2000 ft/min are commonly used in order for the particle to generate sufficient momentum for transportation with the air stream. The building ventilation systems that normally exist in most plants are designed with terminal velocities less than 1500 ft/min and often do not provide enough momentum for transportation of the smoke/fume particles. It was concluded that any particulate that gains access to the plant exhaust system will eventually be trapped by either the prefilters or the upstream HEPA filters.

For the specific welding fume study, the type of welding processes commonly used in that plant were considered along with various electrodes. The predominant types of welding electrodes used were E7018, E308-16, E309-16, E316-16, and E71T-1. Excerpts from the AWS publication addressing E7018, E308-16, E70S-3, and E70T-1 are reproduced for reference, and a summary of results is presented in tables 2 through 6. The E7018 is a carbon steel low-alloy electrode. The E308-16 is considered to be representative of the E309-16 and E316-16 electrodes, with the major differences being the increase of chrome and nickel contents in the E309 and an increase in the molybdenum content in the case of the E316. The E70T-1 is basically the same as the E71T-1 electrode with the difference being that it is a consumable type of electrode. The E70S-3 is a consumable electrode used in the GTAW process.

Reviewing representative data from the AWS publication did not support any definitive conclusion regarding detrimental effects of welding fumes on activated charcoal; however, it was determined from the review that the possibility existed that activated charcoal may not be affected by short-term exposure to welding fumes for welding processes commonly performed at that plant site.

A test to determine the effect of welding fumes on activated charcoal was performed at Charcoal Service Corporation, Bath, North Carolina. The SMAW process was selected for the study since the fumes generated by this process are considered to be representative of the other weld processes. Welding electrode E7018-$\frac{3}{32}$ in. is commonly used at the nuclear site; therefore electrode type E7018 was selected for the test. The weld fume generated by the use of the carbon steel E7018 electrode was expected to be "dirtier" than stainless steel electrodes table 2. For the test, the largest diameter ($\frac{5}{32}$ in.) was selected. The test setup is shown in figure 2.

The number of electrodes for the prototype test was determined based on the air change per hour in the reactor building with SGT filtration train operating and the maximum number of electrode consumption rate per hour (i.e., during any given plant unit outage).

4.1 Test case

No. of electrodes= Building air change/hr (0.22) x 70 electrodes /hr $\simeq$ 15 electrodes.

4.2 Test Parameters

A filtration unit was utilized complete with a prefilter, a HEPA filter, carbon adsorber beds, dampers, necessary instrumentation, and a fan. The design features of the filtration unit are as follows:

- Two - 2 in. charcoal adsorber beds with sampling canisters.bed velocity: 40 fpm max; residence time >0.4 sec.
- One prefilter (45% efficiency based on ASHRAE 52-76).
- One 99.97% HEPA filter.
- One fan with provision for air flow adjustments: 0-2000 cfm.
- Flow control dampers.
- Differential Pressure gauges across each filter banks.
- Relative humidity indicator.

4.3 Test Setup

An air filtration system complete with an exhaust (capture) hood and ductwork was setup as shown in figure 2.

4.4 Test Conditions

The filtration system setup was functionally tested in accordance with ANSI N510-1989. The following tests were performed on the filter unit prior to testing the system with welding fumes:

- Visual inspection (check gaskets, etc.).
- Housing leak test (leak rate <3%/hr of housing volume at 10 in. wg).
- Air flow capacity and distribution test (verify that fan capacity is within $\pm$10% design flow; verify that airflow distribution through the HEPA filter and adsorber beds is fairly uniform at the designated flow rate).
- Air aerosol mixing uniformity test (verify proper mixing, e.g., max min readings do not vary more than $\pm$ 20%).

- In-place filter testing (verify HEPA efficiency >99.97%; adsorber bed efficiency >99.9%; the two 2-in. beds are tested as one 4-in. bed)

Two tests were conducted. Each test resulted in the complete consumption of 15 E7018 electrodes.

- Test No.1:"Protected Test". Setup is shown in figure 2

- Test No. 2:"Unprotected Test". Setup is shown in figure 2, but without the prefilter and the HEPA filter.

The two 2-in. charcoal banks were identified as banks "A" (upstream) and "B"(downstream). Nineteen samples were generated from this test: nine were from the "Protected Test", nine were from the "Unprotected Test", and one sample of new carbon was included from the original drum.

The sequence of sample removal during each test was as follows:

- Samples 1A and 1B after consumption of 5 electrodes.
- Samples 2A and 2B after consumption of 10 electrodes.
- Samples 3A and 3B after consumption of 15 electrodes.
- Samples 4A and 4B after consumption of 15 electrodes.
- Sample 5A was taken directly from the first adsorber bed after running the fan for 30 minutes to account for any offgas.

Test samples, including new carbon samples, were sent to Nuclear Consulting Services, Inc., (NUCON) for laboratory testing in accordance with ASTM D3803-1989. The carbon samples were tested for methyl iodide removal efficiency at test condition of 30°C/95% RH.

Samples from the "Protected" and "Unprotected" tests were tested as follows:

1. 1A + 1B - combined as a 4-in bed
2. 2A + 2B - combined as a 4-in bed
3. 3A + 3B - combined as a 4-in bed
4. 1A, 2A, 3A - tested separately as a 2-in bed
5. 4A - tested separately as a 2-in bed
6. 4B - tested separately as a 2-in bed
7. 5A - tested separately as a 2-in bed

It should be noted that the established test conditions were more severe than those experienced under real conditions because the charcoal was subjected to the total amount of welding fumes generated during the test period.

5. 0 Conclusion

Laboratory results are included in table 7. The results indicate that no detrimental effects were observed on the efficiencies of the charcoal test samples when exposed to a controlled amount of welding.

As a result of this test, credit was taken for not retesting the filtration unit when exposed to welding fumes. However, for added conservatism, charcoal in the filtration units were laboratory tested following plant outages for the next plant cycles. Charcoal test data following outages have shown no adverse impact on the charcoal efficiencies.

Acknowledgments

The author wishes to acknowledge the services of Mr. Latif Kaid and Mr. Al Dunbar of Charcoal Service Corporation Inc. who assisted with the tests. Further appreciation is extended to Mr. Mike Richards of Southern Company Services, Inc., for furnishing information on the various welding processes.

References

1. U.S. Regulatory Guide 1.52, Revision 2; "*Design, Testing, and Maintenance Criteria for Post Accident Engineered-Safety-Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Plants*".

2. ASME N510-1989; "*Testing of Nuclear Air Treatment Systems*", American Society of Mechanical Engineers.

3. *Charcoal Service Corporation Report,* 10-92-970.

4. Croker & King, *Piping Handbook*, McGraw-Hill.

5. American Welding Society, "*Characterization of Arc Welding Fumes*"; 1983.

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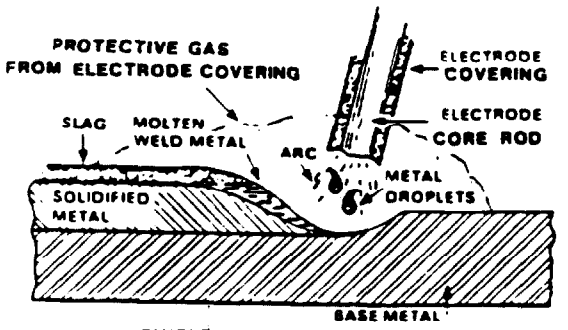
FIGURE 1

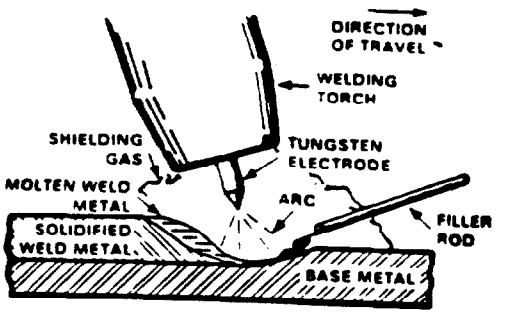
WELDING PROCESSES

Shielded Metal Arc Welding (SMAW)



SHIELDED METAL ARC WELDING

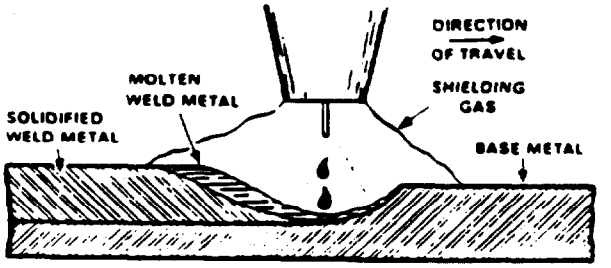
Gas Tungsten Arc Welding (GTAW)



GAS TUNGSTEN ARC WELDING

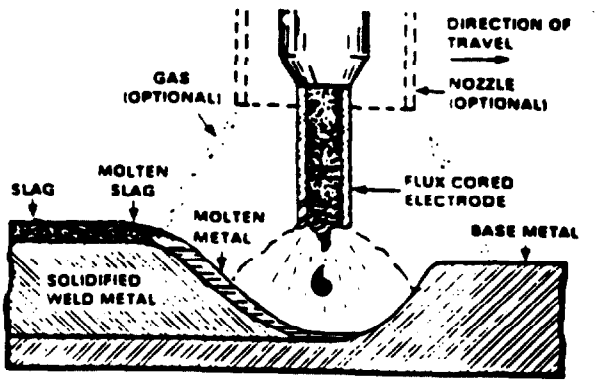
Gas Metal Arc Welding (GMAW)

Short circuiting, globular or spray transfer modes possible.



GAS METAL ARC WELDING

Flux Cored Arc Welding (FCAW)



FLUX CORED ARC WELDING

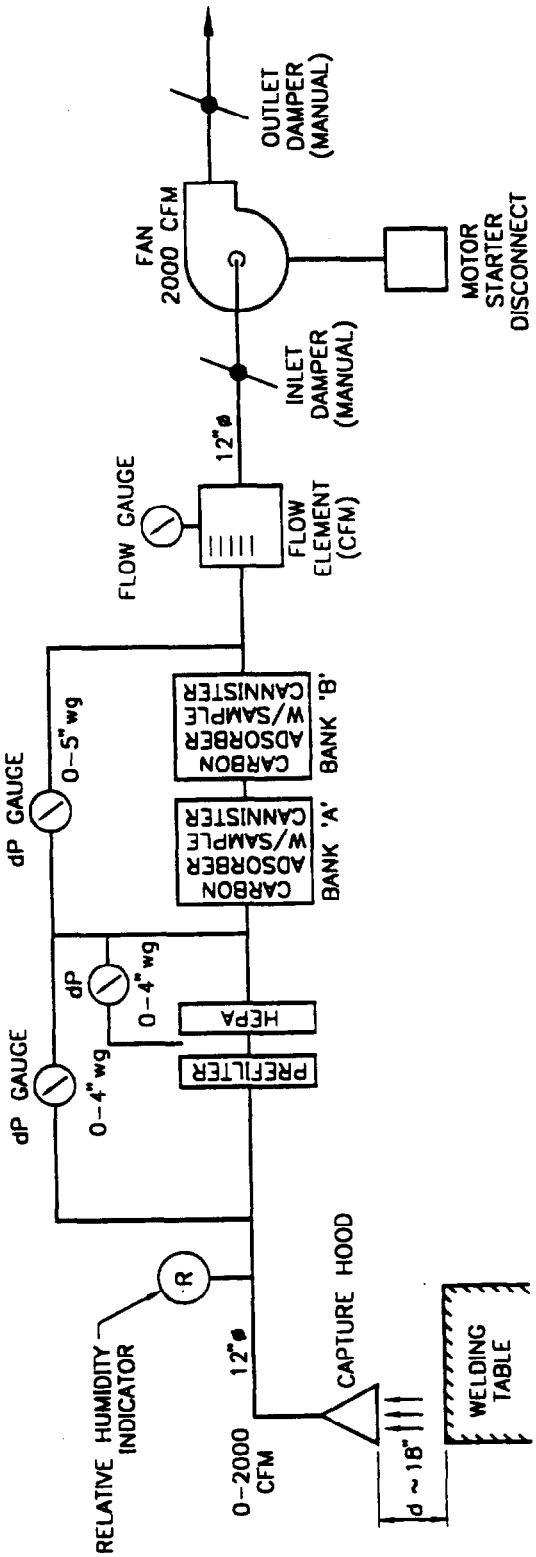


FIGURE 2

TEST SETUP

TABLE 1

TYPICAL WELDING CONTAMINANTS

MATERIAL	THRESHOLD LIMIT VALUES[a] Time-weighted averages (TWA), mg/m³ in 8 hours			Short-term exposure limits (STEL), mg/m³ in 15 min			POSSIBLE HEALTH HAZARD WHEN TLV IS EXCEEDED
FUMES	**ACGIH[b]**	**OSHA**	**NIOSH**	**ACGIH[b]**	**OSHA**	**NIOSH**	
Alundum (Al_2O_3)	10	–	–	20	–	–	Nuisance dust
Arsenic (As)	0.2	0.5	–	–		0.002	Lung & lymphatic cancer, respiratory irritant
Beryllium (Be)	0.002	0.002	–	–	0.005 (30 min)	0.005 (130 min)	Lung cancer, pneumonitis
Cadmium Oxide (Cd)	0.05	0.1	0.4	–	0.3	0.2	Lung and kidney effects, pulmonary edema
Chromium (Cr)	0.5	0.5	0.001[c]	–	–	0.05[c]	Lung cancer, skin ulcers, nasal perforation
	–	–	0.001[d]	–	–	–	
Cobalt (Co)	0.05	.05	–	–	–	–	Chemical pneumonitis
Copper Fume (Cu)	0.2	0.1	–	–	–	–	Irritant, fume fever
Fluoride (F)	2.5	2.5	2.5	–	–	–	Kidney and bone effects
Iron Oxide (Fe_2O_3)	5	10	–	–	–	–	Nuisance dust
Lead, Inorganic (Pb)	0.15	0.2	<0.05	–	–	–	Systemic poisoning
Magnesium Oxide (MgO)	10	10	–	–	–	–	Fume fever
Manganese (Mn)	5	–	–	–	5	–	Nervous system disorders
Molybdenum (Mo)	5[e]	5[e]	–	–	–	–	Respiratory Irritant
	10[f]	10[f]	–	–	–	–	
Nickel (Ni)	1	.007	0.015	–	–	–	Lung and nasal cancer, skin effects
Tin Oxide (SnO_2)	2	2	–	–	–	–	Nuisance dust
Titanium Dioxide (TiO_2)	10	10	–	–	–	–	Nuisance dust
Vanadium (V)	0.05	–	–	–	0.1	0.05	Eye, skin, and lung effects
Zinc Oxide (ZnO)	5	5	5	10	–	15	Fume fever
Welding fumes	5	5	–	–	–	–	Depends on constituents
GASES							
Carbon Dioxide (CO_2)	9,000	10,000	10,000	54,000	30,000	30,000 (10 min)	Respiratory effects
Carbon Monoxide (CO)	55	35	35	440	200	200	Asphyxiant
Hydrogen Fluoride (HF)	2.5	3	2.5[g]	–	6	5[g]	Skin, eye irritation, bone effects
Nitrogen Dioxide (NO_2)	6	5	–	–	1	1	Airway effects
Nitrogen Monoxide (NO)	–	25	25	–	–	–	Blood effects
Ozone (O_3)	0.2	0.1	–	0.6	0.3	–	Pulmonary edema
Phosgene ($CoCl_2$)	0.4	0.1	0.1	–	–	0.2	Airway effects

a. Threshold limit values for the measured elements and compounds, given in parentheses by their chemical symbols, are listed in mg/m³ (milligrams per cubic metre) for particular fumes and in ppm (parts per million) for gasses

b. ACGIH = American Conference of Governmental Industrial Hygienists.

c. Carcinogenic chromium.

d. Noncarcinogenic chromium.

e. Soluble molybdenum.

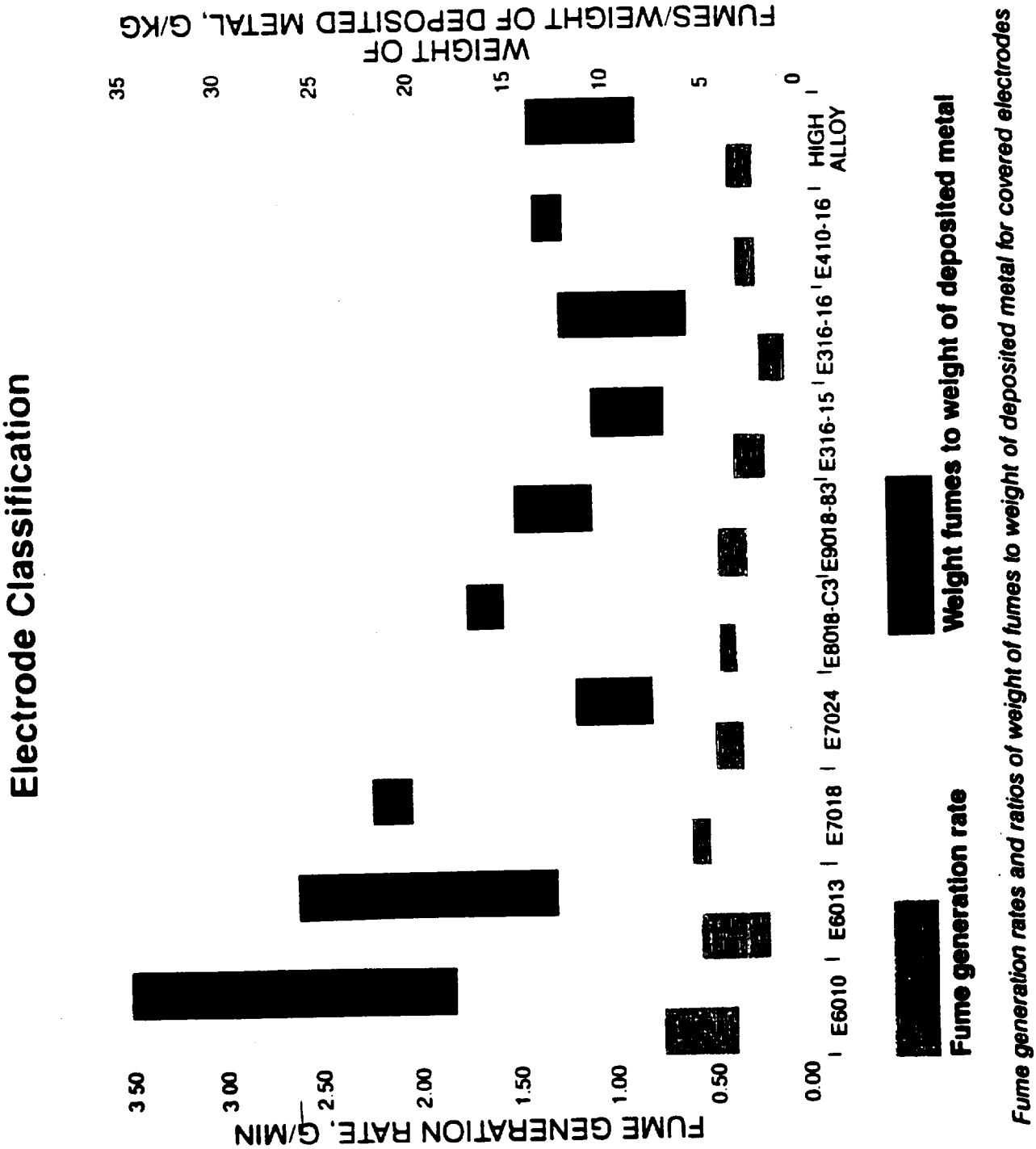
f. Insoluble molybdenum.

g. Reported as mg/m³, milligrams of fluorine per cubic metre.

Source: National Institute of Occupational Safety and Health (NIOSH)

Note: OSHA values are mandated; ACGIH and NIOSH values are recommendations only.

TABLE 2



Fume generation rates and ratios of weight of fumes to weight of deposited metal for covered electrodes

TABLE 3

Table 5b
E7018 — Percent Composition

	Percent by number	Percent by surface area	Percent by volume	Percent by mass
1 C/Organic	—	—	—	—
2 Fe	0.7	0.5	0.3	0.5
3 Fe/Low Si	1.0	0.4	0.1	0.2
4 Fe/High Si	0.2	0.0	0.0	0.0
5 Fe-Mn	0.9	0.4	0.2	0.5
6 Fe-Cr	0.1	0.0	0.0	0.0
7 Fe-Cr-Mn	—	—	—	—
8 Fe-Cu	0.4	0.9	0.6	1.3
9 Fe-V	0.6	0.2	0.1	0.1
10 Fe-Zn	—	—	—	—
11 Fe-Ti	0.2	0.4	0.5	0.5
12 Fe-Al	0.5	0.2	0.0	0.1
13 Fe-S	0.2	0.1	0.0	0.0
14 Fe-Cl	0.2	0.1	0.1	0.0
15 K-Cr	0.9	0.6	0.3	0.3
16 K-Fe	14.2	13.8	12.3	11.7
17 K-Cr-Fe	1.7	1.52	0.8	0.7
18 Ca-Fe	15.0	11.7	9.3	9.1
19 K-Ca-Fe	48.0	49.3	42.6	42.0
20 K-Mn	2.1	2.1	1.6	1.5
21 K-Ti	0.8	0.5	0.3	0.3
22 Ca-Cr	0.2	0.0	0.0	0.0
23 Ca-Mn	0.4	0.5	0.6	0.5
24 Ca-Ti	0.3	0.2	0.1	0.1
25 K-Ca	6.4	11.6	27.2	26.8
26 K-Rich	2.1	1.7	1.0	0.8
27 Ca-Rich	1.5	1.5	0.8	0.9
28 Pb-Rich	0.1	0.1	0.0	0.1
29 Cr-Rich	0.1	0.0	0.0	0.0
30 Mn-Rich	0.1	0.1	0.0	0.1
31 Cu-Rich	0.2	0.2	0.1	0.2
32 Ti-Rich	—	—	—	—
33 V-Rich	0.1	0.1	0.0	0.1
34 Fe-Rich	0.5	0.9	0.5	0.9
35 Na-Rich	—	—	—	—
36 Mg-Rich	—	—	—	—
37 Al-Rich	0.2	0.1	0.0	0.1
38 Si-Rich	0.2	0.4	0.6	0.5
39 Misc	0.4	0.1	0.1	0.0

TABLE 4

Table 5d
E70T-1 — Percent Composition

	Percent by number	Percent by surface area	Percent by volume	Percent by mass
1 C/Organic	0.8	0.5	0.2	0.1
2 Fe	14.4	9.2	2.7	2.5
3 Fe/Low Si	24.9	19.9	6.0	4.6
4 Fe/High Si	4.9	3.4	0.9	0.4
5 Fe-Mn	36.7	51.1	86.0	89.5
6 Fe-Cr	1.7	1.2	0.3	0.3
7 Fe-Cr-Mn	0.8	0.9	0.2	0.2
8 Fe-Cu	0.4	0.4	0.1	0.1
9 Fe-V	1.2	1.5	0.5	0.4
10 Fe-Zn	0.2	0.3	0.1	0.1
11 Fe-Ti	2.8	2.3	0.4	0.2
12 Fe-Al	0.1	0.0	0.0	0.0
13 Fe-S	0.2	0.2	0.0	0.0
14 Fe-Cl	0.5	0.4	0.1	0.0
15 K-Cr	—	—	—	—
16 K-Fe	1.3	1.0	0.4	0.2
17 K-Cr-Fe	0.1	0.1	0.0	0.0
18 Ca-Fe	2.5	3.0	1.0	0.5
19 K-Ca-Fe	0.2	0.5	0.1	0.1
20 K-Mn	—	—	—	—
21 K-Ti	—	—	—	—
22 Ca-Cr	—	—	—	—
23 Ca-Mn	0.1	0.2	0.1	0.0
24 Ca-Ti	0.1	0.0	0.0	0.0
25 K-Ca	—	—	—	—
26 K-Rich	—	—	—	—
27 Ca-Rich	—	—	—	—
28 Pb-Rich	0.1	0.0	0.0	0.0
29 Cr-Rich	0.1	0.0	0.0	0.0
30 Mn-Rich	2.8	1.8	0.5	0.4
31 Cu-Rich	—	—	—	—
32 Ti-Rich	—	—	—	—
33 V-Rich	—	—	—	—
34 Fe-Rich	1.0	0.8	0.2	0.2
35 Na-Rich	—	—	—	—
36 Mg-Rich	—	—	—	—
37 Al-Rich	—	—	—	—
38 Si-Rich	1.8	1.3	0.2	0.1
39 Misc	—	—	—	—

TABLE 5

Table 5c
E70S-3 — Percent Composition

	Percent by number	Percent by surface area	Percent by volume	Percent by mass
1 C/Organic	0.1	0.1	0.0	0.0
2 Fe	9.0	13.2	18.3	20.3
3 Fe/Low Si	14.4	32.9	58.9	56.7
4 Fe/High Si	0.3	0.2	0.1	0.0
5 Fe-Mn	16.9	12.5	6.0	7.7
6 Fe-Cr	5.1	3.9	1.2	1.8
7 Fe-Cr-Mn	0.9	0.9	0.3	0.4
8 Fe-Cu	4.2	2.4	0.7	0.9
9 Fe-V	3.7	3.4	1.7	1.5
10 Fe-Zn	2.6	1.9	0.7	0.8
11 Fe-Ti	3.0	2.2	0.8	0.4
12 Fe-Al	5.8	2.4	0.6	0.5
13 Fe-S	3.3	1.9	0.5	0.5
14 Fe-Cl	3.3	4.8	3.6	2.2
15 K-Cr	—	—	—	—
16 K-Fe	5.8	2.9	0.8	0.5
17 K-Cr-Fe	0.9	0.2	0.0	0.0
18 Ca-Fe	9.8	5.5	1.7	1.0
19 K-Ca-Fe	1.1	0.4	0.1	0.1
20 K-Mn	0.2	0.1	0.0	0.0
21 K-Ti	—	—	—	—
22 Ca-Cr	0.1	0.1	0.0	0.0
23 Ca-Mn	—	—	—	—
24 Ca-Ti	—	—	—	—
25 K-Ca	—	—	—	—
26 K-Rich	0.1	0.0	0.0	0.0
27 Ca-Rich	0.1	0.0	0.0	0.0
28 Pb-Rich	0.1	0.2	0.1	0.2
29 Cr-Rich	0.3	0.1	0.0	0.0
30 Mn-Rich	0.4	0.1	0.0	0.0
31 Cu-Rich	0.1	0.0	0.0	0.0
32 Ti-Rich	—	—	—	—
33 V-Rich	0.1	0.0	0.0	0.0
34 Fe-Rich	8.0	7.6	4.0	4.5
35 Na-Rich	—	—	—	—
36 Mg-Rich	—	—	—	—
37 Al-Rich	0.2	0.0	0.0	0.0
38 Si-Rich	0.3	0.1	0.0	0.0
39 Misc	0.3	0.1	0.0	0.0

TABLE 6

Table 5e
E308-16 — Percent Composition

	Percent by number	Percent by surface area	Percent by volume	Percent by mass
1 C/Organic	0.5	1.1	0.3	0.2
2 Fe	0.8	0.8	1.1	1.6
3 Fe/Low Si	1.2	0.5	0.2	0.2
4 Fe/High Si	1.2	1.0	0.7	0.5
5 Fe-Mn	5.1	5.2	4.2	7.0
6 Fe-Cr	1.5	1.8	1.4	2.7
7 Fe-Cr-Mn	1.4	0.8	0.5	0.8
8 Fe-Cu	0.6	0.5	0.3	0.5
9 Fe-V	0.9	0.8	0.6	0.7
10 Fe-Zn	0.8	0.6	0.5	0.8
11 Fe-Ti	1.0	0.4	0.2	0.1
12 Fe-Al	0.9	0.4	0.2	0.2
13 Fe-S	1.0	4.4	11.9	13.4
14 Fe-Cl	0.9	0.6	0.8	0.6
15 K-Cr	5.3	4.9	4.1	3.1
16 K-Fe	18.1	18.7	14.3	10.8
17 K-Cr-Fe	5.5	7.5	14.3	10.9
18 Ca-Fe	7.0	4.9	3.0	2.4
19 K-Ca-Fe	7.1	6.7	4.8	3.8
20 K-Mn	7.5	6.8	5.2	4.0
21 K-Ti	2.9	2.5	2.0	2.0
22 Ca-Cr	0.7	0.5	0.4	0.3
23 Ca-Mn	1.7	1.1	0.7	0.5
24 Ca-Ti	0.5	0.6	0.5	0.6
25 K-Ca	1.5	1.8	1.4	1.1
26 K-Rich	6.5	6.8	5.4	3.8
27 Ca-Rich	1.2	0.9	0.5	0.5
28 Pb-Rich	0.1	0.0	0.0	0.0
29 Cr-Rich	1.9	2.5	1.6	2.4
30 Mn-Rich	2.8	1.8	0.9	1.2
31 Cu-Rich	0.9	1.2	0.9	1.6
32 Ti-Rich	0.9	0.5	0.3	0.4
33 V-Rich	0.5	0.3	0.2	0.2
34 Fe-Rich	1.2	3.8	12.2	17.7
35 Na-Rich	—	—	—	—
36 Mg-Rich	0.1	0.2	0.1	0.1
37 Al-Rich	0.9	0.8	0.5	0.4
38 Si-Rich	6.2	6.2	3.9	2.8
39 Misc	1.3	0.5	0.2	0.1

TABLE 7

LABORATORY TEST RESULTS SUMMARY

Test Standard: ASTM D3803-1989

Test Condition: 30°C/95% RH

SAMPLE NO.	EFFICIENCY "PROTECTED" MODE	EFFICIENCY "UNPROTECTED" MODE
1A	98.627	98.827
1A +1B	99.983	99.977
2A	99.018	99.619
2A + 2B	99.970	99.982
3A	99.092	99.181
3A + 3B	99.982	99.971
4A	99.269	99.641
4B	99.461	99.222
5A "OFF GAS"	99.421	99.412
NEW CARBON	99.548	

DISCUSSION

JENKINS: You mentioned that your test results for "protected" charcoal (charcoal with installed upstream prefilters and HEPA filters) showed less impact than charcoal without upstream filters. I want to comment that my experience with TM1-Unit 2 cleanup supports your observation that upstream filters help. We noted that plasma-arc cutting of steel sections generated significant smoke that rapidly loaded up exhaust system prefilters. I noticed that the prefilters, which normally would operate for months at a time without having to be replaced or without showing any significant pressure increase, loaded up within weeks after we started doing extensive plasma arc cutting. Prefilters for HEPA filters make a big difference.

GHOSH: I agree with that.

WEIDLER: What is your charcoal impregnated within the system?

GHOSH: It was 2.5% TEDA.

ADAMS: What is the difference in length of duct run that you used in your test compared to the length of your normal standby gas system from containment?

GHOSH: The difference in the length? The plant that you are talking about is a two unit plant. Unit one uses the normal ventilation ducting system. Unit two has a separate duct, which takes direct suction from the secondary containment.

ADAMS: Do you have an estimate of the length?

GHOSH: I'd be guessing, but I would say unit two has about 200 ft., and unit one at least 300 ft.

ADAMS: In the test set-up that you had, was there ever a check to determine if any particulate was in the corrugated ducting that you used in your filter suction?

GHOSH: No. We did not look at the ducting, we were monitoring the smoke.

ZAVADOSKI: Were you successful in submitting a change in your technical specifications to the NRC to have welding fumes removed?

GHOSH: We did not go to NRC. We made a clarification to our technical specifications because we had a valid test to back it up. With that added assurance, we went back and did another test following a refueling outage. We did not see any degradation of the charcoal, and took that into consideration.

HOLTORP: What is the impregnant and impregnation level of the carbon in this system?

GHOSH: 2.5% TEDA.

GREENE: I have been debating for quite some time whether to make these points about the

effects of uncertainties in all aspects of the presentations that have been made at this conference and previous conferences. I believe that the attention given to errors in experiments, uncertainties in analyses and statistics, as well as the propagation and reflection of the uncertainties through regulations and enforcement is completely inadequate in this industry. Because it has been found to be unacceptable in all other fields of scientific research, product development, and government regulation, I have been reluctant to bring it up at this point. I am sure there are a lot of people who do not want to hear this, but I have been keeping a list while attending a lot of presentations and I have found that air filtration people apparently are unable to quantify uncertainties with respect to manufacturing standards and manufacturing practice, testing standards and testing practice, regulatory standards and regulatory guidance, compliance with performance standards with respect to trends in data for performance of filters as well as filter materials, uncertainties in the ranges of data and error bounds of data. Analysis of uncertainties is not propagated to consequences of risk, margins to performance limits apparently are not addressed. Thresholds for failure are portrayed as single point variables. Needs for risk- based regulation have not been recognized, and the statistics of historical performance are not adequately portrayed in order to evaluate trends.

Recently, we have recognized difficulties in predicting the performance of nuclear air filtration practice. I believe a lot of the difficulty in being able to forecast the performance of nuclear air filtration systems under projected harsh environmental conditions is due to a chronic failure to address the effects of uncertainties in all of these aspects. I believe that progress in filtration performance will continue to be hampered by such an approach. Most important, it is apparent that the people doing the research and making the regulations cannot tell the manufacturers, with any degree of certainty, what is causing degraded performance. A special difficulty that this field is going to have to address, not only DOE but NRC as well, is a lack of reliable and defensible estimates of expected performance, consequences, and risk in continuing operations in degraded facilities, especially under accident conditions and projected decommissioning and decontamination operations. I would like to hope that, in the future, people who do this work and who make presentations in this forum will give more attention to the effects of uncertainties on the extrapolation of their work so it can be more accurately put into practice.

CLOSING COMMENTS OF SESSION CO-CHAIRMAN BERGMAN

All five papers at this session have dealt with aging effects on air cleaning equipment. Mr. Winegardner discussed aging of HEPA filters and carbon adsorbers. He showed that stress factors such as heat, radiation, volatile compounds, and aerosols add to the aging effect. He specifically cited tensile strength and water repellency as two items that decrease with age. With regard to carbon, he attributes the loss of activity in adsorption sites to moisture and volatile organics. His conclusion is that degradation of HEPA filters and carbon adsorbers occurs.

A paper was presented that outlines a three step process to estimate the residual efficiency of HEPA filters during and after design basis accidents. The first step is determining what the environmental parameters are and what the pressure will be during the design basis accident. The next step compares the pressure drop under accident conditions to a threshold value. When the filter has a lower pressure drop than the threshold value, it survives and efficiency can be determined. When it does not survive because high pressure drop causes structural damage, it is assigned zero efficiency. When it survives, efficiency is determined from a tabulated summary of values that reflect efficiencies under different conditions.

Another paper described the performance of HEPA filters under dynamic conditions at temperatures up to 500° C. It was very interesting to learn that the rectangular filters, when heated up to 200° C for 48 hours showed less than 0.02% penetration, whereas circular filters showed 1% penetration. Slits and cracks were found in the medium plus deformation of the sealing gasket. The presentation was concluded with a description of a new prototype high-strength filter that showed 0.65% penetration at temperatures up to 400° C.

Preliminary studies made to determine the shelf life of HEPA filters found that media lost tensile strength with age, but the work was not yet sufficient to establish a shelf lifetime. The critical factors for determining filter performance are the type of materials used and construction methods. They are much more important than filter age. As an example, low media strength resulting in structural damage in a filter was due to insufficient binder, rather than age.

It was shown that short-term exposure to welding fumes had no effect on the effectiveness of activated carbon adsorbers. Long-term studies were not conducted. The welding fume exposures occurred in a complete system consisting of prefilters, upstream and downstream HEPA filters, and a carbon adsorber. The important finding was that HEPA filters prevent welding fumes from reaching the carbon adsorber.