*High Efficiency Filter Systems—General
Observations, 1992–1993*

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By

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ABSTRACT

Reviews of air emission control systems have been conducted at selected facilities supported by the Department of Energy (DOE) Office of Nuclear Energy (NE). Large high efficiency particulate air (HEPA) filtration systems and their testing received particular emphasis. Although significant differences between the sites were found, there were also several common issues. These are discussed under four general topic areas: policy development, testing multiple stage systems, guidance on in-place filter testing and system supervision, and uncertainty in in-place filter testing results. Two principal conclusions have emerged from these reviews. First, there is an immediate need to develop information on how filter mechanical integrity decreases with time and use this to establish limits on filter service life. Second, there is a general need to ensure the validity of in-place filter testing results and improve testing practices. A mathematical framework for describing the effects of nonideal system features on testing results is proposed as an aid in understanding the uncertainty in in-place filter testing results.

EXECUTIVE SUMMARY

This report summarizes general observations from two years of reviews of air emission control systems at selected facilities supported by NE at seven different DOE sites. The observations have been divided into four areas:

- Policy Development (filter shelf life, filter service life, role of HEPA acceptance and in-place filter testing, and system oversight)

- Testing Multiple Stage Systems (overall system testing, individual stage testing)
- Guidance on In-place Filter Testing and System Supervision (testing practices, test equipment maintenance and calibration, special concerns of older systems, measurement uncertainty and the pass/fail decision, frequency of routine testing, analysis and reporting of testing results, and technical support and training of testing personnel)
- Uncertainty in In-place Filter Testing Results

The performance of air emission control systems is enhanced by DOE requirements for the use of qualified HEPA filters, independent inspection and testing of the filters before installation, and routine in-place testing of filter installations. Air emission control programs would be improved by increased management oversight of the role, objectives, and performance testing of the systems, increased professional attention to technical aspects of system operation and testing, and more comprehensive support and training of in-place testing personnel.

Two primary technical concerns emerged. First, there are no generally accepted limits on how long filters can be stored or used. Although it is known that the mechanical integrity of filters decreases with time, the mechanisms governing this process have not been studied and applied in establishing maximum shelf and service lives for filters. An effort to develop this information should be initiated. Second, too little attention has been given to ensuring the validity of the in-place filter testing measurements used to establish whether system performance is acceptable. Recommended steps for improving the validity of tests results include changes in test procedures and equipment maintenance and calibration practices, immediate checking of all data during a test for consistency and reasonableness, and emphasizing consideration of measurements in the context of previous measurements rather than in isolation. In addition, the problems inherent in testing older systems that do not conform to current design and construction practices need to be considered. A mathematical framework for evaluating the influence of different system configurations on uncertainty has been developed but requires experimental validation.

I. BACKGROUND

The DOE Office of Nuclear Energy Self-Assessment (NE-80)* initiated a series of selected environment, safety, and health reviews in late FY1992. These reviews considered air emission control systems at sites and facilities supported by NE. The sites were:

Paducah Gaseous Diffusion Plant

Portsmouth Gaseous Diffusion Plant

Parts of both sites are now operated by the United States Enrichment Corporation. Facilities supported by NE are also located at sites supervised by other DOE offices. The facilities of this type included in these reviews were:

Area 200 of PF4, Technical Area 55 at Los Alamos National Laboratory (LANL)

Plutonium Fuel Fabrication Facility and Plutonium Experiment Facility at Savannah River Site (SRS)

High Flux Beam Reactor and Medical Research Reactor at Brookhaven National Laboratory (BNL)

Buildings 38 and 50 at Mound Plant (Mound)

High Flux Isotope Reactor, Radiochemical Engineering Development Center, and Isotope Enrichment Facility at Oak Ridge National Laboratory (ORNL)

One aspect of this effort was a survey of HEPA filter installations and testing procedures initiated as a DOE Safety and Health Issue (Lo92). A second aspect was on-site reviews of several specific HEPA filtration systems. The emphasis during these reviews was on the largest or most critical systems at each NE-supported facility. Associated charcoal adsorbent systems were considered when present. Consultants from LANL, Sandia National Laboratories, and The University of Michigan participated in those reviews concerned with air emission controls and associated monitoring. The reviews were not intended to be comprehensive audits of facilities or

* This Office is now part of NE-1.2, Quality Assurance Staff.

programs. Rather, they were intended to help describe program elements, bring attention to those that might benefit from changes or additional effort, and provide information to site personnel.

The reviews generally followed a similar course. Documents concerning the air emission control systems, especially those using HEPA filters, were requested from the facility for review before the consultants' arrival. The on-site portion of the review included presentations, tours, and discussions with site personnel responsible for various aspects of HEPA systems operations and testing. Additional documents and data were often obtained during the visit or in subsequent conversations to clarify points raised during the visit or report preparation. A report describing the observations and including suggestions for changes or further review was prepared after each visit. The reviews were intended to serve as the beginning of a continuing dialog with facility staff on approaches to improve the operation and testing of air emission control systems.

The types and designs of air emission control systems, the need for in-place HEPA filter testing, and testing practices varied widely between the sites. At each site, however, the same policies and practices were generally applied to all facilities regardless of the DOE office providing support and/or direct oversight for a specific facility. Some of the filter systems were designed and installed several decades ago and presumably reflected the design approaches and needs of the times. The concern during the reviews was how to best apply current testing methods and criteria. Similar observations at many of the facilities implied common problems concerning information or policy and technical aspects of in-place filter testing. This report summarizes these common observations and suggests areas that warrant consideration for further general study or decision making by DOE. To the extent the facilities and systems considered in these reviews are representative of those supported by other DOE offices, the observations discussed in this report may also apply to other DOE facilities.

II. DISCUSSION TOPICS

Air emission control systems were included in the design of each facility to prevent or mitigate potential releases of radioactive materials to the environment. Current environmental policy and practice place significant responsibilities on DOE and its contractors to verify the present acceptability of the performance of these systems, to periodically determine whether system performance is adequate to meet current requirements, and to ensure that program or process changes do not damage or defeat the installed emission control systems. Many older systems are still in use after being modified, but these changes have sometimes been made without a full understanding of the purpose and expected performance of the emission control systems. Some reactor facility personnel, for example, appear to have the perspective that significant incidents are of very low probability and, even if they happened, other systems would prevent major releases and human exposures regardless of the state of the emission control systems. Technical specifications, however, require that the system be maintained and periodically tested. Where this perception of the importance of emission control systems prevails, it is difficult for personnel to place much significance on filter performance, in-place testing, or professional involvement in system operation and evaluation.

The discussion topics have been grouped into four general areas. The areas are not totally independent, and there will be some repetition and reexpression as different aspects of similar problems are discussed. It should also be recognized that this discussion is intended to be general in nature. Specific situations may require special considerations, but the intent here is to provide a basis for establishing general policy and methods that should be appropriate in most situations.

A. Develop Policies Concerning HEPA Filter Use

This first general topic concerns areas in which we believe DOE should develop additional policies or guidelines to aid the different sites in developing more consistent and easily justified practices for managing HEPA-filter-equipped emission control systems. The first two

areas will require synthesis of existing data and experience and development of further information on HEPA filter aging. The other two topics are the role of HEPA filter quality assurance and in-place filter testing and practices for controlling the access to HEPA filtered exhaust systems.

1. Shelf Life

HEPA filter users presently have no basis for establishing how long new filters can be stored before being installed. It seems unlikely that filters would normally be warehoused for more than one or two years. We did not encounter any examples of extended storage before installation during these reviews. There are, however, two reported cases in which filters that had been held for several years were evaluated but not installed. The first case involves data obtained by the Oak Ridge Filter Test Facility (Br87). One hundred eighty two filters, originally purchased in 1976 by Arizona Public Service Company, were submitted to the test facility for recertification after nine years of storage. One hundred twenty five (69%) of the filters were rejected based on excessive penetration or storage damage. Details on the numbers rejected for either reason and the nature of the damage were not included in the report. If the filters were properly stored, the nature of the "storage damage" is especially interesting.

The second example has not yet been documented as thoroughly (Ra93). At the Rocky Flats plant, filters were found that had been stored for several years in transportainers outdoors. Inspection of the filters has shown cracks on the pleats of the filter medium and breaks in the adhesive sealing the medium into the filter frame. Additional evaluation of these filters is planned.

Both these cases suggest that one or more filter components deteriorate with time and may thus impair filter performance, mechanical integrity, and perhaps service life. It would be appropriate to determine whether other information is available on the integrity of filters stored for extended periods and establish whether the data are sufficient to provide guidance on how long after manufacture HEPA filters must be installed or discarded as no longer

suitable for use in air emission control systems. One of the difficulties in applying such information is the problem of controlling and documenting storage conditions, especially humidity and temperature, which are probably the most important factors affecting filter aging under normal storage conditions. Although the available data from filters stored for several years indicate deterioration during storage, these data may not be sufficient to describe the rate of deterioration. It may be necessary to conduct tests specifically designed to address this point and establish how storage conditions affect deterioration. These tests should address both filter performance and mechanical integrity.

2. Service Life

We found almost no restrictions on how long HEPA filters can remain in service at the facilities visited. It appears that filters are allowed to remain in service so long as their pressure drop does not increase beyond established values and the routine in-place filter testing results satisfy facility requirements. Thus, some currently installed in-use filters have been in service 20 years or more. In many cases, installation dates are not available, but we suspect this implies long rather than short service life. The only exception we found during the site visits was at BNL. There service lives are restricted to 10.5 years for the High Flux Beam Reactor system and 5.5 years for the Medical Research Reactor and other systems where filter failure could have potentially significant environmental impact. These restrictions were established in response to the April 1990 Tiger Team assessment in which a concern was expressed that the tensile strength of aged filters might no longer be sufficient to sustain accidental overpressures. Although we agree the service life of HEPA filters should be restricted, we know of no quantitative basis for establishing a specific limit.

We have reviewed one study demonstrating a decrease in filter medium strength with time (Jo89). The study, using filters that had been in service for approximately 14 years, was somewhat restricted in extent but demonstrated that the filter medium lost tensile strength and ability to survive transient overpressures. However, it was not possible to do more

than demonstrate the aging effect. One problem, as noted by the authors, was the inability to establish any relation between operating conditions, time, and loss of strength. As they indicate, it is likely that several factors other than service time will affect the aging process and fraction of the original strength lost. Corrosive atmospheres, for example, shorten the service life of a HEPA filter unless special acid-resistant filters are used (Te81).

Unfortunately, the relative contributions to the aging process of factors such as temperature, humidity, chemical nature of the filtered atmosphere, and amount of retained particles have not been quantified. There is an immediate need to obtain all available data and use them to design an experimental study to provide data for establishing service life limits under a defined set of operating conditions. These conditions should reflect common conditions and not extremes. The testing, given the concern about filter integrity, must encompass more than filtration and flow measurements. In particular, the degree to which aged filters retain their ability to survive overpressures when wet and to resist heated air and flames must be tested. Procedures for performing these tests are described in a military specification, MIL-F-51068. All models of HEPA filters used for environmental protection at DOE facilities are required to have passed these tests. If the tests are performed at the military test site, the Edgewood Research, Development and Engineering Center, the filter models are included on the military Qualified Products List (QPL).

3. Role of HEPA Acceptance and In-place Filter Testing

Several years after HEPA filters began to be used in air emission control systems at nuclear facilities, it was discovered that many of the filters did not meet the intended specifications (Gi60). This led to two major changes in the policy of the Atomic Energy Commission (predecessor to the DOE). First, filters were tested individually, independently of the manufacturer's testing, and second, filters were required to meet published construction and performance specifications. Filter test stations, now referred to as Filter Test Facilities (FTFs), were established at Richland, Washington and Oak Ridge, Tennessee in the 1960s and at Golden,

Colorado in 1974 to inspect and test each filter and verify that it met the purchase specifications. The specifications include the requirement that all filters be qualified according to the tests described in MIL-F-51068 and thus be suitable for inclusion on the QPL. This policy is spelled out in DOE Standard NE F3-45; the standard is presently undergoing editorial revision. Filters that DOE facility operators intend for critical uses are therefore shipped by the manufacturer to one of the test facilities where they are inspected and tested before being forwarded, if acceptable, to the purchaser. Although the manufacturer thus knows which filters will be subject to this testing, the failure rate is still approximately 2 percent. No information is available on the failure rate for filters included on the QPL but not subjected to acceptance testing because they are shipped directly to the user. It seems very likely, however, that the fraction of defective filters will not be lower than that found in filters submitted to the test facilities. Even a 2% failure rate seems unacceptably high for components of environmental protection systems.

In the early 1980s there was also a problem of some vendors making false claims about the nature and qualifications of their "HEPA" filters. A brief study was conducted by one of the major filter manufacturers to assess the quality of these filters (A183). Filters were purchased from seven manufacturers who responded to a purchase order for filters that conformed to the then-current version of MIL-F-51068. None of the supplied filter models was actually listed on the QPL. Five of the seven filters failed the acceptance test; the remaining two filters failed QPL tests of the filter medium taken from the filters. We believe the failure rate of filter models listed on the QPL but not designated for acceptance testing will be between that for acceptance-tested filters and that reported for the seven misrepresented filters. Although there are no published data available to support this view, we believe this observation is an indication of the need for independent inspection and testing of HEPA filters before their use in critical installations.

The present DOE policy, by requiring acceptance testing, helps ensure the quality of the HEPA filters installed in air emission control systems. The contribution of this policy to efficient operation of the control systems can be appreciated by considering the

process of replacing the filters in a large installation. After all filters have been replaced, an in-place filter test is conducted to determine whether the filters have been installed properly and the filter bank satisfies the required performance criteria. (A filter bank is a parallel arrangement of two or more filters on a common mounting frame enclosed within a single housing.) If the penetration is too high, the system must be reopened and the filter installation adjusted until a satisfactory test result is achieved. If high penetrations persist after adjustment, filter replacement may be necessary. Repeated testing and filter replacement will greatly increase the time and cost involved in bringing a newly installed filter bank up to its performance specifications. The likelihood of high penetrations being caused by defects in the filters is reduced by the acceptance testing procedure. Although an economic analysis is not available, it appears possible the added cost of quality assurance testing of HEPA filters is less than the increased costs that would result from using filters tested only by the manufacturer.

DOE policy (NE F3-45) states that "All HEPA filters designated for environmental protection purposes in DOE facilities..." must meet the quality assurance provisions of the standard. During these reviews, we observed that although all filters used in the final stages of air emission control systems conformed to this policy, some filters in systems that could contain airborne radioactive particles did not conform. Typically, these filters served glove boxes in one of two ways. First, they were intermediate filters in the box exhaust between the box outlet and the ducts leading to an emission control filter that served several boxes. Thus, this intermediate position could be considered, in the narrowest sense, as not designated for environmental protection. Second, the filters were on the glove-box-purge air inlets and filtered air entering the box. If an accident pressurized a box, these filters would also be required to prevent discharge of particles into the laboratory environment. Because the general exhaust from such laboratories passes through a HEPA-equipped emission control system, site personnel again considered that these glove box filters were not being used for environmental protection. In both cases, we do not believe this interpretation conforms to the intent of the DOE policy statement, especially if "environment" is considered to include the work environment of the laboratory or

plant as well as the more general surrounding environment. An additional concern about use of filters that have not been acceptance-tested at an FTF is that such filters might accidentally be installed in and possibly compromise the performance of a system requiring tested filters. Site operators need to have very clear policies and procedures to ensure that acceptance-tested filters are never replaced by untested ones in critical applications.

In-place filter testing, both when filters are installed and at regular intervals throughout their service life, provides an important assurance that a filter bank is capable of the filtration performance expected of it. Thus, no credit can be claimed in a system safety evaluation for a filter bank if the bank cannot be tested by itself. (The implicit assumption that testing provides an accurate indication of filtration performance will be addressed later.) Some filter installations, particularly those on glove box inlets, provide little if any possibility of testing, yet these filters may be required to protect the working environment under some accident conditions.

The administrative support of in-place filter testing programs varied widely between the sites visited. This was also true of the technical capabilities of the programs. Because in-place filter testing is often the only means of ensuring that HEPA filter systems are capable of meeting their operating requirements, we believe DOE should provide more active direction to the site operators in this area. The need for routine testing and valid measurements should be stressed.

4. Administrative Oversight of HEPA Systems

Exhaust and emission control systems equipped with HEPA filters involve more complexities than normal ventilation systems. This is true at all stages of their design, construction, operation, and maintenance. Facility management should therefore exercise more detailed oversight of HEPA-filter-equipped systems than is necessary for less complex exhaust systems. One example of the extra oversight needed is the emphasis on periodic system inspection and performance verification. While the need for regular testing of HEPA-filter-

equipped systems is generally recognized, there are other aspects of system oversight that often do not receive suitable emphasis.

Inclusion of HEPA filters in an exhaust system generally follows recognition of the need to reduce to the lowest level reasonably achievable particulate emissions from a process or source. Because operating requirements and conditions are usually well specified, it is comparatively simple to ensure that filter type and filter and fan capacities are appropriate when a system is designed and used for a single purpose as is the case with reactor building exhausts. The performance of such a system, however, may be compromised as its use changes and inlets and flow rates are changed in response to changing facility needs. Planned changes and their potential impact on the performance of the emission control system must therefore be analyzed carefully before actual changes are initiated.

The problem of changes is especially difficult for systems serving laboratory hoods in which the types and magnitudes of releases may change. One major concern is changes in the chemical nature of the aerosols and vapors entering an existing system. Regular HEPA filters and their hardware, for example, are damaged by acid aerosols, gases, and vapors. Although acid-resistant filters are available, because of their higher cost they are normally used only in systems expected to receive such material. Changes in a process or addition of a new, incompatible source in a system could thus lead to failures from unanticipated chemical attack on the filters. An example of this type of problem was observed at LANL. Visual inspection revealed corrosion of the screen face-guards on a bank of filters. Changes had been made in the laboratory processes so that corrosive aerosols were being generated and discharged, but those responsible for the filter system had not been informed of this. The problem will be corrected at the next filter replacement. Similar compatibility problems have been encountered at other facilities.

Exhaust systems that include HEPA filters are normally used to control a recognized potential hazard following an engineering and safety analysis. Although it was not an intended or anticipated part of these reviews, we encountered one example of inappropriate use

of HEPA filtration in a workplace exhaust system. We have no way of knowing how widespread such instances are but feel the observation must be noted as an example of the need for careful evaluation before HEPA filters are included in exhaust systems. A system was installed to draw exhaust from a canopy hood over a hot work area that was a potential source of fumes and vapors in a large room. (Industrial hygienists generally do not recommend canopy hoods to control worker exposures to fumes and vapors.) A decision was made to filter the exhaust even though the exposure of unprotected workers at the system inlet, which was within applicable occupational exposure limits, was likely to be much higher than any possible exposure to the discharged air outside the facility. In addition, one of the primary potential exposure materials was mercury, which would exist only as a vapor in the air exhausted from the workplace and would not be removed by any type of mechanical filtration. Because filters were being included in the system, it was decided to use HEPA filters "just to be on the safe side." It is not clear that the need for and design of this relatively small system [about 2000 cubic feet per minute (CFM) capacity] were reviewed by health and safety personnel or others familiar with the use of HEPA filters. However, because the system includes HEPA filters, they are included in the routine testing program despite there being no demonstrated need for them or rational criteria for judging their performance.

Exhaust systems are often treated by users as an almost invisible part of the supporting services of a laboratory. We encountered a welcome exception at one site where building maintenance activities (painting, welding, etc.) were controlled to minimize their impact on the emission control system. More commonly, however, changes are made in the laboratory processes and reagents without considering how they might affect the exhaust system. Also, HEPA filtration sometimes is included in systems without verifying that such filters are appropriate but nevertheless increasing the burden on maintenance and testing personnel. Better communication is needed between those specifying and using the systems and those responsible for their operation and maintenance. This is especially important at old facilities at which the original emission control systems have continued to be used even though there were changes in

the type of work, equipment, and processes being used. These changes have often involved modifications of the exhaust system ductwork that affect the ability to perform in-place tests. This points to the need for coordination between technical program, maintenance, air cleaning, ventilation, and in-place testing personnel. The extent of this problem and the availability and coordination of different types of expertise appear to vary widely between facilities. Guidance in recognizing possible problem situations is probably more appropriate than any effort to establish a general standard.

B. In-place Filter Testing of Multiple-Stage HEPA Filter Systems

A multiple-stage HEPA filter system is a series arrangement of filters that enhances air cleaning by filtering air more than once. Such systems are often the most critical component of the overall strategy for control of airborne hazards and for preventing environmental releases. Multiple stage systems are used in situations where challenge concentrations are potentially high enough to require more than a single stage of HEPA filtration to clean process air to safe levels. These systems are often the final air cleaning control prior to release to the environment. Failure of these systems can potentially result in significant airborne release of hazardous materials.

A number of the HEPA filter systems that were reviewed were constructed prior to issuance of the American National Standards Institute (ANSI) standards pertaining to nuclear air cleaning systems (ANSI75, ANSI76). References to these standards have been incorporated into facility safety analysis reports, reactor technical specifications, and in-place filter test procedures at several of the facilities. Because of the age of some of these systems, strict compliance with the ANSI testing standards is questionable. The gap between practice and requirements may be the widest for multiple stage systems where constrained test geometries make testing of individual stages difficult and limits on detection make overall system tests ineffectual.

Because of rigorous construction criteria for nuclear facilities, space allocated to air cleaning systems is severely scrutinized. Consequently, individual stages of multiple-stage HEPA filter systems are frequently constructed close to one another, constraining the geometry of in-place filter tests. This type of constraint was observed at NE-supported facilities at LANL, SRS, Mound, and ORNL. Each of these facilities has devised its own individual procedures for in-place filter testing of such systems.

An important design criterion of HEPA filter systems is the decontamination they provide. Each stage of filtration can provide a specific level of decontamination. The number of filtration stages is determined from the required decontamination needed to reduce the highest anticipated challenge concentration to levels below safe release limits. In this design approach, each stage is credited with a specific amount of decontamination. Typically, air cleaning facility designers assume that each stage of HEPA filtration reduces air-contaminant concentration by a factor of no more than 2000. This decontamination factor translates into a maximum penetration of 5×10^{-4} for each stage. The job of in-place filter tests is to assess whether air cleaning systems are performing to the decontamination design criterion. Consequently, the tests must be sensitive enough to reliably determine penetration to levels below the maximum penetration.

1. Overall System Tests of Multiple Stage Systems

Los Alamos personnel have used a laser spectrometer system method (ASTM93) to provide an overall test of multiple stage systems. The spectrometer is sensitive enough to determine penetration to levels below 2.5×10^{-7} and can be used to perform overall system tests on two stage systems. Recently, test procedures for the NE-supported facility at LANL have been changed to provide individual stage testing in addition to the overall tests. Injection and sampling manifolds have been installed to improve test aerosol concentration uniformity for each system stage (Or93). The individual stage tests supplement overall system test results by providing information on each stage.

Mound personnel use an overall system test on their multiple stage systems. Their safety and operating requirements allow them to take credit for only one stage of HEPA filtration in these multiple stage systems. The overall system tests at Mound are made with a photometer. The sensitivity of the photometer does not allow testing of multiple stage systems when credit is being taken for more than one stage of HEPA filtration. The minimum detection limit of modern photometers is on the order of 10^{-5} penetration. For a single stage of HEPA filtration, this photometer sensitivity is sufficient to determine that penetration does not exceed the typical maximum penetration of 5×10^{-4} . For two stages of filtration, the penetration limit would be the single stage limit squared or 2.5×10^{-7} penetration. This penetration limit is far below the photometer detection limit.

The photometer approach to testing multiple stage systems restricts the interpretation of test results. For example, overall system penetration can be well below the photometer detection limit even when the penetration of each stage is well above the penetration maximum of 5×10^{-4} . Test results between the detection limit and the penetration maximum indicate that at least one stage is severely compromised. Test results above the leakage limit indicate severe degradation of the performance of each stage.

These tests results are indicators of system performance under normal operation conditions. The test provides little information pertinent to the system's ability to withstand design-basis off-normal operating conditions. The system's ability to withstand such off-normal conditions could be significantly compromised even though test results indicate system performance is adequate.

The approach of testing several stages of a multiple stage system as a unit should be accompanied by administrative controls to assure adequate system performance. To limit degradation of system performance for withstanding off-normal operation, a limit on service life might be considered. The service-life limit would have to be balanced against costs of replacing filters. Filter change-out is often difficult, time consuming, and costly in terms of facility downtime.

Another possible administrative control is an action level set at detectable penetrations less than an allowable penetration limit. The action level might trigger such activities as a detailed visual inspection of the filter stages. Information from this type of visual inspection is potentially useful in deciding whether filter change-out is necessary.

The need for such administrative controls can be reduced by consideration of alternative testing approaches. One alternative approach is to use a laser spectrometer method for two stage systems. A second alternative is shroud testing of individual filters. If this alternative is used, the increase in potentially hazardous exposures of the test personnel should be weighed against the potential for reducing air emissions. A third alternative is the use of injection and sampling manifolds; this is discussed in the next section.

2. Individual Stage Testing

Individual stages of multiple stage systems are tested at LANL, SRS, and ORNL. The proximity of system stages leads to potential errors in test results. For tests conducted on the initial stage of a system, errors may come from inadequate mixing of penetrant aerosol prior to downstream sample collection. Error in tests on the final system stage may come from inadequate mixing of the challenge aerosol. Tests of intervening stages suffer from both of these problems.

Characterization and correction of these errors is difficult. The test provides no information regarding whether sample concentration overestimates or underestimates the integrated concentration required for determining stage leakage. Heterogeneity in the challenge concentration profile can misrepresent portions of the filter bank. For example, if regions of high leakage coincide with areas of low challenge concentration, test results can overestimate stage efficiency.

Overall system tests could be considered to augment or replace individual stage testing. In situations where a valid overall system test can be performed, such tests give a view of system performance unencumbered by the problems of individual stage testing.

Interpretation of results from these tests is subject to the restrictions discussed in the preceding section.

Overall system tests do not provide information on performance of individual stages. This information may be important in situations where redundancy of air cleaning components is required. Managers of facilities with such requirements have to balance potentially inaccurate information on performance of individual stages with valid information on the overall system. In some cases the extra costs of performing both types of tests may be justified.

Measurement of the differential pressure across each stage along with measurements of total system flow rate can augment overall system test data to a limited degree. Differential pressure across individual stages, when referenced to system flow rate measurements, can indicate gross problems with individual stages. Pressure measurements far below measurements across adjacent stages may indicate severe degradation of the stage. Differential pressure measurements distinctly greater than measurements on adjacent stages can indicate flow restrictions.

One solution to the problems of individual stage testing was observed at ORNL. Certain non-NE facilities at ORNL have upgraded their air cleaning systems with modern filter housings that have provisions for testing individual filters. Aerosol dispersion and static mixing devices are used in these housings to enhance aerosol mixing upstream and downstream of the filters. The static mixing devices can be moved out of the way of flow in periods between tests. We are not aware of any published evaluation of these housings. The costs of such upgrades may be prohibitive. Facility managers must weigh such factors as the risks of air emissions against these costs. A number of DOE nuclear facilities are approaching the end of their service lives. In such situations, resources for upgrading filter systems and facilitating in-place filter testing programs may best be directed towards less costly efforts to assure health and environmental protection.

Another solution that ORNL is pursuing is the use of injection and sampling manifolds. These manifolds, when designed and operated properly, can mitigate effects of poor mixing. Evaluation of in-house designs is under way at ORNL. Manifolds are ineffective in situations where mixing lengths are exceedingly short. The required spread ratios (lateral transport distance/convective transport distance) for these devices must be less than one.

C. Guidance on In-place Filter Testing and System Supervision

1. Testing Practices

The majority of the facilities visited use the same basic method of in-place filter testing, but there are considerable variations in the actual test procedures. (One laboratory, LANL, uses a different measurement method than the photometer approach used by the others.) Facility operators do not presently have guidance on how to conduct their in-place tests beyond the very general information in ANSI N510. An effort was begun recently within several DOE facilities to develop a written standard for in-place filter testing of HEPA filter systems. Progress was made and then interrupted, but the effort has recently begun again with the support of the Defense Programs Office.

Although most of the in-place filter testing practices observed or described during these reviews approximate those outlined in ANSI N510, there was one general exception. Visual inspection of the filters, which is included in the ANSI standard, was often omitted. Many systems did not have provision for this without entering the filter plenum.

Based on our observations during these reviews, several points not covered in the ANSI standard should be included in any standard or guidance on good practice for in-place filter testing using the photometer method. Among these are

a) Challenge aerosol concentrations should be in the range of 20–100 micrograms per liter ($\mu\text{g/l}$). The upper bound is approximately the upper end of the linear response range of the photometer. The lower bound is approximately the minimum concentration that can be used without requiring excessive gain in the photometer electronics if the photometer is adjusted so the

challenge concentration gives a 100% of full-scale reading. Excessive gain leads to high noise levels that interfere with the measurement of penetrations in the range of typical acceptance limits.

b) Testing personnel should be encouraged to use the photometer's internal reference light to set the gain instead of using the older practice, described above, of setting the gain so the challenge concentration corresponds to a 100% reading.

c) Operating conditions of the filtration system, the aerosol generator, and the photometer should be evaluated for reasonableness and self consistency before proceeding with a test. The expected challenge concentration, calculated from the system flow rate and generator aerosol output rate, should be approximately the same as that indicated by the photometer when its gain is set using the internal reference light.

d) Concentration measurement records, both upstream and downstream of the filter bank, should include a measure of variability, such as the standard deviation of the measured concentrations, to help assess the uncertainty of the final calculated penetration value. The variability information will be useful as an indicator of the inherent precision of the measurement process. Changes in variability will be related to changes in instrument or system performance and may indicate a need for corrective actions.

e) The design and construction of each system being tested should be reviewed for conditions that might interfere with testing. The results of the review should be retained in a permanent file that also includes as-built information and expected and actual operating conditions. This file should also include data from the system acceptance test.

2. Test Equipment Maintenance and Calibration

Greater emphasis should be placed on regular maintenance of test equipment to ensure its proper functioning. Although this in part means following the manufacturer's recommendations more closely than is sometimes done, there are several other aspects. Also, it may not be necessary or possible to send equipment off-site for service if it has

become contaminated. We believe there are several levels of maintenance and equipment performance verification that should be used. These include

- a) Check photometer electronic linearity before starting a filter test as is generally recommended by the instrument manufacturers.
- b) Verify the self consistency of system and instrument operating conditions during each test using a material balance calculation as described above in part 1.c.
- c) Perform periodic side-by-side comparisons of in-place filter testing instruments to verify that all are performing similarly. This will probably be more convenient if a small (order of 1000 CFM) flow system is available so that all available photometers, for example, can simultaneously sample the diluted output of one generator.
- d) Perform an electronic verification of photometer amplifier operation and linearity on an approximately annual basis.
- e) Calibrate photometer performance at one or more points by correlation of instrument readings with gravimetrically determined aerosol concentrations.

The different verification tests may be performed at frequencies ranging from every test (linearity and self consistency) to perhaps annually or somewhat less often. We are not aware of any data demonstrating how much time or use of a photometer is reasonable between either comparison to a reference instrument or true calibration. The photometer manufacturers recommend annual return for "calibration" and adjustment. We have not explored in detail the services performed by each manufacturer during the recommended service but believe it is a comparison to a reference instrument rather than a gravimetric calibration. There may also be site-specific quality assurance requirements concerning the frequency of instrument calibration. However, the distinction between verification of electronic function and actual calibration of photometer readings by an independent method must be recognized. It must also be remembered that the validity of measurements depends on both instrument performance and degree to which the measured sample is representative of the system being characterized.

The goal of ensuring that challenge concentrations are in the 20–100 $\mu\text{g/l}$ range will, at least until more data are available on instrument stability, place increased emphasis on regular photometer maintenance and calibration. Each photometer includes an internal reference light that can be used to adjust overall gain so that a full-scale reading on the 100% scale corresponds to 100 $\mu\text{g/l}$. Using this to adjust gain and then establishing that the air emission control system's volumetric flow rate and the aerosol generator output are consistent with the photometer reading places considerable emphasis on the stability of this part of the photometer.

3. Special Problems of Older Systems

Most of the air emission control systems at the NE-supported facilities visited during the past two years were designed and built before publication of the first editions (ANSI76, Bu70, ANSI75) of the current design and testing documents. Not surprisingly, these older systems often do not conform to current design and construction practices. They also, so far as present personnel at the sites can recall, were not subjected to the acceptance testing called for in the current design standard, ANSI N509-1989. In many instances it is not possible to perform many of the tests because of the way the systems were built. This is unfortunate because inspection or sampling ports, whether present initially or added later, are used without any demonstration that accurate testing can be performed. In addition, older systems have often been physically modified by changing filter plenum inlet geometry or system flow rate. These changes often exacerbate existing problems or introduce new ones that make it difficult to obtain representative aerosol samples during in-place filter testing.

Older systems should be reviewed and an effort made to perform—or at least approximate—the acceptance tests described in the standard. The procedures for this will probably need to be developed on a case-by-case basis and will require the efforts of facility and site personnel familiar with system design, construction, and in-place filter testing. These types of expertise and technical support are not always available or utilized at all DOE facilities, and it may be necessary to provide them from other sources. Contamination of these systems may be a

serious impediment to performing these tests. Similarly, testing geometries and procedures should be reviewed for the degree to which they conform to the current testing standard, ANSI N510-1989. Where uncorrectable differences exist, they should be documented and the magnitude of their effect on testing results estimated. In addition to providing a useful review of the systems, the information will also be needed in assessing the uncertainty of in-place filter testing results that is imposed by system design and construction. Only if the effects of system characteristics on test results are considered unacceptable should consideration be given to modifying the system. This would reduce the likelihood of making costly but sometimes unnecessary or ineffective changes to systems in response to criticisms that consider only an ideal situation rather than the realities of both old systems and the purpose of in-place testing measurements. Note that the problems of applying current testing methods and requirements to older systems have been discussed (We91). However, most of the facilities we reviewed that were faced with these problems did not appear to be making an effort to understand and overcome them.

Older multistage systems present a particular challenge in this respect. These systems often were built without adequate provision for injection and mixing of challenge aerosol and extraction of samples, especially for the second and later stages. The individual stage test results, if available, are probably quite unreliable. They are one of the reasons that overall system tests should be considered as discussed previously in section II.B.

4. Measurement Uncertainty and the System Pass/Fail Decision

In-place filter testing results are often treated as if they were accurate, absolutely precise measurements. Acceptance standards for the HEPA banks in air emission control systems are similarly stated as absolute values with no allowance for uncertainty in the measurements. These assumptions are invalid. The issue of measurement uncertainty should be addressed both by those making the measurements and by those responsible for establishing the pass/fail criterion.

Putting aside questions of inherent instrument performance, particularly linearity of the photometer detector and amplifiers, there are two main sources of uncertainty in the penetration measurements. The first and most easily determined is due to variations in photometer readings during the measurement periods. Unfortunately, the most common testing practice seems to be to adjust photometer gain so the challenge concentration reading "averages" full-scale on the 100% scale. There are two difficulties with this approach. First, if the aerosol concentration variability is too high, the concentration peaks are not only beyond the range of the meter scale but they may also peg the meter. Second, the averaging process is highly qualitative and entirely dependent on operator judgment. This latter difficulty is present even when the challenge concentration is simply read after adjusting instrument gain using the photometer's internal reference light. The difficulty applies to the downstream readings regardless of how the gain is set. From our observations, the variations are generally on the order of 5%– 10% of the central reading but are sometimes greater. More reliable average concentrations could be obtained using a true averaging process such as a strip chart recorder, data logger, or electronic integrator. The latter two methods also could easily provide a measurement of the concentration variability during testing.

The second major source of uncertainty is the filter system itself and the degree to which extracted samples provide a true average of the aerosol flux at the sampled cross sections. Problems such as multiple duct and plenum entries and mixing of the challenge aerosol and the aerosol penetrating the filter stage will need to be evaluated. As noted earlier, the quality of the mixing in older systems has generally not been considered so it is not known whether samples from these systems are true measures of the average aerosol concentrations. The uncertainty issue and the influence of mixing on penetration measurements are explored further in section D, Uncertainty in In-place Filter Testing Results. This aspect of ensuring the validity (quality) of the system performance measurements is at least as important as the more straightforward concern of most quality assurance programs with instrument calibration.

Just as the uncertainty in the calculated penetration needs to be associated with the results from each in-place test, it would also be appropriate to reevaluate the way in which the HEPA filter bank pass/fail criterion is expressed. Although it is convenient to use a general standard such as penetration less than 0.05%, this may not be applicable to all filter banks or systems. In particular, uncertainties in some systems may make it necessary to report that the maximum probable penetration is less than some acceptance limit. This should be recognized in standards and evaluations rather than continuing the assumption that all measurements are absolutely precise.

5. Frequency of Routine In-place Filter Testing

The majority of the systems considered during these reviews are supposed to be tested annually. (This discussion of testing frequency is not concerned with mandatory testing following filter replacement or other mechanical disruption of a filter bank.) Some systems, however, are tested more frequently. The selection of testing frequency appears to be based more on administrative concerns than engineering ones. It seems reasonable to consider annual testing as a minimum frequency for all systems, mainly to simplify record keeping and tracking. More frequent testing, however, would be appropriate under some circumstances. These might include, for example, systems handling aerosols or gases that degrade filtration performance, systems from which releases must be very stringently controlled, or systems operated under conditions that are likely to accelerate the normal aging of the filters and filter seals. An accelerated testing schedule might be reasonable if the likelihood of aerosol emissions increases due to progressive filter degradation. (It must be borne in mind that in-place filter testing addresses only the issue of system leakage and provides little if any information on mechanical integrity of the filters.) We do not presently have data on which to base a technical recommendation for filter testing frequency. A review of data from several systems might provide useful guidance. It would also be appropriate to consider how and whether to use discharge sampling or monitoring data, when available, in establishing testing frequency. It

appears reasonable, however, to consider increasing testing frequency to more than once per year as the filters in a system age.

6. Analysis and Reporting of In-place Filter Testing Results

In-place filter testing results appear to be considered only as indicators of the acceptability of the current performance of an emission control system. Although records of test results are maintained, we did not see any indication that new data are considered in the context of previous results. System users do not have data in a format that shows if system filtration performance is gradually deteriorating and when it might be necessary to replace the filters if a trend continues. Such trend information might be useful in characterizing system leakage and indicating modifications to reduce leakage.

While it seems appropriate to expect those relying on a filter system to control emissions from their facility to watch for trends in test data, we believe the responsibility, at least for preparing and formatting the data, should rest with the in-place filter testing group. There are three principal reasons for this. First, the testing group is specifically—and sometimes exclusively—concerned with HEPA filter system performance. Second, what appears to be a change in system performance may be the result of a change in test method or instrument performance. Comparison of current data to previous results provides a further check on test validity beyond that described as a recommended part of testing practice in the first two parts of this section. Third, in-place filter testing personnel should have a broader perspective on systems and their performance than those for whom HEPA filters and their performance are not a primary concern.

System test results should be reported to users in a format that shows both current acceptability and how the current results compare to previous ones. A statement about the current status and a graphical presentation of test data is one possible method that would not require elaborate data keeping or reporting procedures; in fact, such a report could be generated with standard personal computer spreadsheet software.

7. Technical Support and Training of In-place Filter Testing Personnel

The number and backgrounds of in-place filter testing personnel, as well as the continuity of their testing work, vary widely between the sites visited during these reviews. The range is from a group of several full-time testers to one or two people performing in-place filter testing less than 10% of the working year. The background of the testers varies from non-degreed maintenance and laboratory technicians to a Certified Industrial Hygienist. The testers generally learn the necessary skills through on-the-job training; this often has been augmented by attendance at specialized courses such as the Harvard In-place Filter Testing Workshop.

The variety of backgrounds and group sizes has also led to a wide range of capabilities to recognize and deal with unusual or nonideal conditions at the different sites. We feel this range points to one of the shortcomings of most in-place filter testing programs. Although test personnel generally followed test procedures (at least as they understood them) we found that testing was often done without consideration of the reasonableness of the data obtained. In part, we believe this reflects the tendency noted earlier to treat measurements as point values and evaluate them only in the comparison of the calculated penetration against a pass/fail criterion. Failure to consider the reasonableness of measurements in the context of system operation and previous measurements also reflects a general lack of engineering evaluation of the systems and testing data. This issue extends to the actual testing. Some of the systems being tested at the review sites cannot yield accurate performance measurements when tested by conventional procedures even though apparently reasonable data can be obtained. We have, in fact, serious questions whether some systems can be tested without extensive modification of both test procedures and the systems. These problems are not limited to the sites with the smaller in-place filter testing programs.

Training for in-place filter testing personnel should be expanded to help them develop a better understanding of test purpose, procedures, and ways in which system problems can affect test results. They should also receive additional technical support from engineers and other professionals with expertise in design, construction, operation, and evaluation

of air emission control systems. This support should go beyond discussions and data review and include participation in in-place filter tests and field observation of systems and their problems.

These observations lead us to recommend that DOE consider ways to provide additional technical support to the in-place filter testing groups. One step already under way is that the program under which this report was prepared will support the authors in providing consultation and assistance to in-place filter testing groups. (The authors can be reached by telephone at 505/667-7382 or by mail to LANL, ESH-5, Mail Stop K553, Los Alamos, NM 87545.) The nature and extent of this assistance will differ among the sites. We have noted that some groups are increasing the expertise of their engineering capabilities. The ability of different groups to cross compare and calibrate their instruments varies widely. Although technical support with this type of work would be useful, we believe the need to enhance the technical background of the in-place testing personnel and help ensure the validity of the measurements is more serious.

D. Uncertainty in In-place Filter Testing Results

An expression for the uncertainty in in-place filter testing results is developed in the Appendix. The expression, Equation 17 of the Appendix, describes the coefficient of variation for penetration CV_P in terms of the integrated upstream concentration X_U , the upstream and downstream mixing factors h_U and h_D , and penetration and flow rate heterogeneities, H_P and H_Q . The dimensionless upstream concentration can be written as

$$X_U = \frac{Q_{inj}}{Q}$$

where Q_{inj} is the aerosol injection flow rate and Q is the sum of the system and injection flow rates.

The expression of CV_P provides a rationale for estimating the uncertainty of in-place filter testing measurements. The uncertainty estimate permits interpretation of test results

in terms of a confidence interval and the relation of this interval to specified leakage limits. When the leakage limit is greater than the upper bound of the confidence interval, test results provide evidence the air cleaning system performance is acceptable. When the limit is between the upper bound and the point estimate $\hat{P}$ (see Equation 15 in the Appendix), the test results provide evidence that system performance is marginally acceptable. Such results could be defined as an action level that requires follow-up.

The uncertainty expression can also be used as an aid to assess the effect air-cleaning system modifications or test-procedure changes may have on the uncertainty of test results. This use can help evaluate the cost/benefit relation for potential system upgrades. System managers could use this tool to aid in making decisions on resource allocation. Use of the expression to estimate measurement uncertainty and to assess the effect of system modifications is explained in this section.

Inputs to the uncertainty expression are system parameters that are easily measured or can be approximated. The inputs include Q_{inj} , Q , h_U , h_D , H_P , and H_Q . The inputs Q_{inj} and Q are readily measurable system parameters. The input H_P can be estimated by substituting the corrected penetration point estimate $\hat{P}$ for "P" in Equation 5 of the Appendix. Values of h_U , h_D , and H_Q can be determined from detailed system measurements. These measurements may be time-consuming and difficult. In many situations, however, they can be estimated from the test geometry with sufficient accuracy. Examples of defining these values are given below.

For an air cleaning system within the range of systems observed in the reviews of NE facilities, Q_{inj} is typically about 1 CFM and Q is on the order of 10,000 CFM. ANSI N510 requires that the ranges of the measurements of flow rate and test aerosol concentration challenging a filter bank be no greater than $\pm 20\%$ of their averages. If the interval three standard deviations on each side of the mean is considered equal to the range of these parameters, this requirement implies the relative standard deviation of these parameters over the filter bank must be no greater than 0.067 of the average. For this system to meet these ANSI requirements, values

of h_U and h_D would have to be greater than 1500 and the value of H_Q no larger than 0.067. Using these values in Equation 17 of the Appendix yields estimates of CV_P for specific values of $\hat{P}$. Plots of these results are shown in Figure 1. For $\hat{P}$ at the typical limit of 0.0005 (or 0.05%), CV_P is equal to 0.073. The ANSI standard does not include a specific statement on the acceptable uncertainty of measured penetrations. Given the 0.067 value for the relative standard deviations of the flow rate and concentration measurements, it is reasonable to infer that an uncertainty of the same magnitude would be acceptable for the penetration. The value of CV_P calculated for a hypothetical system that meets the ANSI flow and concentration homogeneity requirements differs by approximately 10% from the inferred value. This agreement supports the formulation of the model and its calculated results.

The values of CV_P can be used to calculate the three-standard-deviation upper bound on penetration, $P_{+3\sigma}$. Values of this parameter are plotted against $\hat{P}$ in Figure 2. The value of $\hat{P}$ corresponding to $P_{+3\sigma}$ is the highest point estimate that assures system performance is at or below the leakage limit. At higher values of $\hat{P}$, system performance may be above the leakage limit. For the air cleaning system described above, a $P_{+3\sigma}$ of 0.0005 corresponds to $\hat{P}$ of approximately 0.00041. This result indicates that, in order for test results to provide clear evidence that system performance is at or below the specified leakage limit, the value of $\hat{P}$ must be no larger than 0.00041.

To illustrate the application of the uncertainty model with an actual system, the exhaust filtration system for Building 38 at Mound, one of those reviewed in this program, was considered. A diagram of the system showing air flow paths and sampling locations is shown in Figure 3. The system has two air flow entries into the plenum immediately upstream of the first HEPA filter bank. Aerosol is injected through one of the intakes from Room 140 which is connected to one of the entries. There is no aerosol injection in the other entry.

Figure 1. A plot of estimated CV_p versus the penetration point estimate $\hat{P}$ for a system meeting ANSI Standard N510.

Figure 2. A plot of estimated $P_{+3\sigma}$ versus $\hat{P}$ for a system meeting ANSI Standard N510.

Figure 3. Exhaust filtration system for Building 38 at the Mound Plant showing sampling locations ▲.

For this example, Q_{inj} will be 2 CFM and Q will be 30,000 CFM; both values are approximately those used when testing this system. The aerosol in the first entry is assumed to be well mixed in the flow as it enters the filter plenum. However, because no aerosol is injected in the second entry, the challenge concentration is almost certainly not the same for all the filters. Consequently, h_U is probably less than 1500; for this example, h_U will be 150. Because flow downstream of the HEPA filters passes through a fan prior to being sampled, h_D for this system is probably greater than h_U . So for this example, we will assume that h_D is 1500. Although the division of the total flow between the two entries is not known, we will assume that they are balanced and that H_Q is 0.067.

Results of evaluating Equation 17 using these values for the input parameters are plotted against $\hat{P}$ in Figure 4 and labeled "Injection in One Entry." At a $\hat{P}$ of 0.0005, CV_P for this system is approximately 0.82. The CV_P values were used to calculate $P_{+3\sigma}$ for this system. These results are plotted against $\hat{P}$ in Figure 5. From this plot, the value of $\hat{P}$ corresponding to $P_{+3\sigma}$ of 0.0005 is approximately 0.00014. This result indicates measurements of system leakage must be below 0.00014 to assure that system performance meets a leakage limit of 0.0005.

One potential method to reduce uncertainty in test results for this system is to inject aerosol into an intake of the second entry. If the aerosol injection rates were adjusted so that the average concentration was the same in both entries, the value of h_U for the system would be increased, thus reducing the estimated uncertainty. To illustrate this point, assume that aerosol injected in the second entry has the effect of increasing the estimate of h_U from 150 to 750, a five-fold increase. The CV_P values for this condition are plotted in Figure 4 and labeled "Injection in Both Entries." For $\hat{P}$ equal to 0.0005, CV_P is approximately 0.14, which is an almost six-fold decrease in CV_P relative to that for aerosol injection in one entry. Values of $P_{+3\sigma}$ for this test configuration are plotted in Figure 5. Under these conditions, system performance at or below a leakage limit of 0.0005 is assured when corrected test results of 0.00035 or lower are obtained.

Figure 4. Plots of estimated CV_p versus the penetration point estimate $\hat{P}$ for the Building 38 system.

Figure 5. Plots of estimated $P_{+3\sigma}$ versus penetration point estimate $\hat{P}$ for the Building 38 system.

III. RECOMMENDATIONS

Based on our observations and discussions during these reviews, we believe there are several ways in which DOE could improve the current use and testing of HEPA filters in air emission control systems.

First, DOE should initiate studies of the changes that take place in HEPA filters as they age. The goal of these studies should be to provide a technical basis for setting maximum storage and service times after which filters must be discarded or replaced.

Second, DOE should address several issues that presently have received significantly different interpretations. Among these are the use of acceptance-tested filters, the need to test intermediate stages of multiple stage systems, appropriate requirements for testing filters used with glove boxes, and the types and degree of administrative oversight and record keeping necessary when HEPA filters are part of exhaust and air emission control systems.

Third, in-place filter testing personnel should receive additional guidance, technical support, and training as part of a DOE program to ensure the validity of in-place filter testing measurements. Guidance should include the various aspects of recommended testing practices and the need for test equipment calibration and maintenance. Guidance should also be provided on improving the way test results are reported so that they will be viewed in context rather than as isolated pass/fail decisions. Technical support is essential to complete a general review of air emission control systems so that the most reliable in-place filter testing results are obtained and their limitations are understood. Training of in-place testing personnel should emphasize recommended procedures and how to recognize problems in the test equipment and the systems being tested. In-place filter testing personnel need to be better trained in proper procedures for performing tests and how to recognize problems in the test equipment and the systems they are testing.

Fourth, the uncertainties in in-place filter testing results and how they are affected by measurement methods, and system characteristics and nonidealities need to be studied. The

mathematical framework presented in this report represents a method for combining the different factors, but it needs to be extended to include errors in the measurement process. Experimental data from a variety of systems are needed to validate the mathematical description. The existence of these uncertainties needs to be included explicitly in setting standards for system performance acceptability.

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APPENDIX

Derivation of An Uncertainty Expression for In-place Filter Testing Penetration Determinations

The uncertainty in in-place filter testing results comes from propagation of uncertainties from the various components of the test. A diagram illustrating these components in a generic in-place filter testing setup is presented in Figure A-1. Test aerosol is injected into the system air flow a distance upstream of the bank of HEPA filters to be tested. The plane at which the aerosol is injected is called the injection plane. The test aerosol is transported to the filter bank by the system air flow. During this time test aerosol mixes with the system air flow through such mechanisms as turbulent diffusion.

At the upstream face of the filter bank the test aerosol concentration profile combines with the flow rate profile to determine the filter bank challenge. This face of the filter bank is called the challenge plane. The upstream aerosol sample is collected in this plane.

The number of particles per unit time penetrating at a point in the filter bank is determined by the local challenge concentration, flow rate, and penetration at that point. Over the entire bank these particle fluxes combine to produce the concentration profile at the downstream face of the filter bank. This filter bank face is called the downstream plane, and the profile is the downstream concentration profile. Just as the injected aerosol was mixed, the downstream concentration profile is modified as aerosol penetrating the filter bank moves with the system flow to the plane in which the downstream sample is collected. This plane is called the downstream sample plane.

Figure A-1. Generic in-place filter testing setup for a HEPA Filter installation.

At the injection plane, the initial degree of mixing of the test aerosol with the total air flow can be described (Ta79) as

$$H_{U0} = \frac{\sigma_{U0}}{X_U} = \frac{[X_U(1 - X_U)]^{1/2}}{X_U} = \left[\frac{1}{X_U} - 1 \right]^{1/2} \quad \{1\}$$

where

H_{U0} = concentration heterogeneity of the test aerosol challenge at the injection plane,

σ_{U0} = standard deviation of test aerosol challenge concentration over injection plane

$$= [X_U(1 - X_U)]^{1/2},$$

X_U = the dimensionless test aerosol challenge concentration

$$= \frac{Q_{inj}}{Q},$$

Q_{inj} = injection volume flow rate, and

Q = total HEPA filter system volume flow rate.

As injected aerosol approaches the filter bank, it mixes with the total system flow. The mixing reduces heterogeneity from its value of H_{U0} at the injection plane. By the time the aerosol reaches the challenge plane, concentration heterogeneity has been reduced to

$$H_{Uf} = \frac{H_{U0}}{h_U} \quad \{2\}$$

where

H_{Uf} = concentration heterogeneity of test aerosol challenge at the challenge plane and

h_U = the mixing factor by which H_{U0} is reduced at the challenge plane.

Features such as intervening entries can cause local increases in concentration heterogeneity between the injection and challenge planes.

At the challenge plane the challenge concentration profile, the flow rate profile, and the profile of penetration combine to give the resultant concentration profile immediately downstream of the bank. The heterogeneity of the flow rate profile in the challenge plane H_Q is

given by

$$H_Q = \frac{\sigma_Q}{Q} \quad \{3\}$$

where

σ_Q = standard deviation of flow rate over the challenge plane face of the filter bank.

Likewise, the heterogeneity of the penetration profile of the filter bank H_P is given by

$$H_P = \frac{\sigma_P}{P} \quad \{4\}$$

where

σ_P = standard deviation of penetration over the filter bank and

P = overall penetration of the filter bank.

A maximum value of H_P is obtained when H_{UF} and H_{UQ} equal zero, and P is the result of a single leak in the filter bank. Under these conditions H_P can be estimated as

$$H_P = \left[\frac{1}{P} - 1 \right]^{1/2} \quad \{5\}$$

The heterogeneity of the concentration profile in the downstream plane H_{D0} is given by

$$H_{D0} = \frac{\sigma_{D0}}{X_D} \quad \{6\}$$

where

σ_{D0} = standard deviation of penetrant test aerosol concentration over the downstream plane,

X_D = integrated downstream test aerosol concentration

$$= \frac{\sum_i X_{Ui} P_i Q_i}{Q},$$

X_{Ui} = local concentration at the i th position in the challenge plane,

P_i = local penetration at the i th position in the challenge plane, and

Q_i = local volume flow rate at the i th position in the challenge plane.

A closed form for H_{D0} does not exist. An approximation for H_{D0} can be written as

$$H_{D0} = \left[\left(\frac{H_{U0}}{h_U} \right)^2 + H_P^2 + H_{UQ}^2 \right]^{1/2} \quad \{7\}$$

As the penetrant aerosol moves from the downstream plane to the downstream sampling plane, the aerosol mixes with the system flow. The concentration heterogeneity at the downstream sampling plane H_{Df} is given by

$$H_{Df} = \frac{H_{D0}}{h_D} \quad \{8\}$$

where

h_D = the mixing factor by which downstream heterogeneity is reduced.

The overall filter bank penetration P is given by

$$P = \frac{X_D}{X_U} \quad \{9\}$$

These concentrations are determined from single- or multiple-point samples collected in the challenge and downstream sample planes. When concentration, penetration, and flow rate heterogeneities are zero, the sampled concentrations equal the integrated concentrations. When the heterogeneities are non-zero,

$$X_U = X_{US}K_U \quad \{10\}$$

and

$$X_D = X_{DS}K_D \quad \{11\}$$

where

X_{US} = the sample concentration in the challenge plane,

K_U = a correction factor for upstream concentration,

X_{DS} = the sample concentration in the downstream sampling plane, and

K_D = a correction factor for downstream concentration.

The correction factors depend on the relations between the integrated concentration and the sample concentration. This relation is affected by the concentration, flow rate, and

penetration profiles. For example, K_D is expected to change if one of the filter units in a bank develops a tear along a pleat (Jo89). The tear would affect the penetration profile which would, in turn, affect the concentration profile in the downstream plane and consequently in the downstream sampling plane. The correction factors can be approximated experimentally or numerically. Both of these approaches are prohibitively laborious and may only be valid for a single test.

Sample concentrations are those existing at inlets of the sample lines. These concentrations are drawn into an aerosol photometer for measurement through sample transport lines. The sample concentrations differ from the measured concentrations because of particle transport losses and photometer response. These losses and the photometer response are dependent on aerosol particle size. Recent reviews have characterized particle losses in sampling probes and transport lines (Br93, An92, and Fa92). Models of the processes determining these losses have been developed (An93, Ya89). These models can be used to account for differences between sampled and measured concentrations caused by particle losses.

Photometer response depends on scattered light intensities predicted by Mie theory. Tillery et al. (Ti83) have used a Mie theory code to determine photometer response as a function of particle size. This approach can be used to correct measured concentrations for photometer response changes caused by size-dependent particle losses.

An expression for upstream sample concentration that accounts for particle loss and photometer response is

$$X_{US} = X_{UM} \int_{d_p} f_u(d_g, \sigma_g) \cdot P_{USL}(d_p) \cdot P_{Ph}(d_p) \cdot dd_p \quad \{12\}$$

where

X_{UM} = upstream measured concentration,

d_p = aerosol particle size,

$f_U(d_g, \sigma_g)$ = upstream aerosol size distribution function,

d_g = size distribution count median diameter,

σ_g = size distribution geometric standard deviation,

$P_{USL}(d_p)$ = upstream sampling line penetration, and

$P_{Ph}(d_p)$ = relative photometer response.

A similar expression for the downstream sample concentration is

$$X_{DS} = X_{DM} \int_{d_p} f_D(d_g, \sigma_g) \cdot P_{DSL}(d_p) \cdot P_{Ph}(d_p) \cdot dd_p \quad \{13\}$$

where

X_{DM} = downstream measured concentration,

$f_D(d_g, \sigma_g)$ = downstream aerosol size distribution function, and

$P_{DSL}(d_p)$ = downstream sampling line penetration.

An expression for P that combines the point estimate of P , $\hat{P}$, and the uncertainty in P ,

CV_P , is

$$P = \hat{P}(1 \pm CV_P) \quad \{14\}$$

where

CV_P = the coefficient of variation for P .

The point estimate of P can be approximated by

$$\hat{P} = \frac{X_{DS}}{X_{US}} = \frac{X_{DM}}{X_{UM}} \cdot \frac{\int_{d_p} f_d(d_g, \sigma_g) \cdot P_{DSL}(d_p) \cdot P_{Ph}(d_p) \cdot dd_p}{\int_{d_p} f_u(d_g, \sigma_g) \cdot P_{USL}(d_p) \cdot P_{Ph}(d_p) \cdot dd_p} \quad \{15\}$$

This formulation of $\hat{P}$ corrects the measured concentrations for particle loss in sample transport lines and for photometer response.

Using the Taylor expansion and ignoring interaction and higher order terms, an expression can be written for CV_P

$$CV_P = [CV_{X_D}^2 + CV_{X_U}^2]^{1/2} \quad \{16\}$$

where

CV_{X_D} = the coefficient of variation for the integrated downstream concentration, and

CV_{x_u} = the coefficient of variation for the integrated upstream concentration.

Setting $CV_{x_D} = H_{Df}$ and $CV_{x_u} = H_{Uf}$, and using Equations 1, 2, 7, and 8 yields

$$CV_P = \left[\frac{\left(\frac{1}{x_u} \right) - 1}{h_u^2} \left(\frac{1}{h_D^2} + 1 \right) + \frac{H_P^2}{H_D^2} + \frac{H_Q^2}{H_D^2} \right]^{1/2} \quad \{17\}$$

This expression gives CV_P in terms of concentration, penetration, and flow rate heterogeneities.

This approach for estimating P approximates $\hat{P}$ using the measured concentrations corrected for particle loss and photometer response. Effects of concentration, penetration, and flow rate profiles on $\hat{P}$ are not considered.

The error component of P is estimated using concentration, penetration, and flow rate heterogeneities. Contributions of particle loss and photometer response to this error term are neglected. Statistical methods have been developed to analyze such error expressions in terms of confidence bounds and parameter sensitivities (Mc93). Confidence intervals developed from this analysis can be used to interpret in-place filter test results in terms of HEPA filter system acceptance criteria. Sensitivity analysis of the error term can help evaluate the cost/benefit of test system upgrades.

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