

COMPARISON OF HIGH EFFICIENCY PARTICULATE FILTER TESTING METHODS

FINAL REPORT
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1. INTRODUCTION

High Efficiency Particulate Air (HEPA) filters are used for the removal of submicron size particulates from air streams. In nuclear industry they are used as an important engineering safeguard to prevent the release of air borne radioactive particulates to the environment. HEPA filters used in the nuclear industry should therefore be manufactured and operated under strict quality control. There are three levels of testing HEPA filters:

- i testing of the filter media;
- ii testing of the assembled filter including filter media and filter housing; and
- iii on site testing of the complete filter installation before putting into operation and later for the purpose of periodic control.

The need for a co-ordinated research programme has arisen from the multiplicity of test methods used in the assessment of the efficiency of filters employed in the nuclear industry, both in testing filter media, testing assembled filters and filter installations. Based on the development works in various countries presently different methods of testing HEPA filters have been standardized and are followed. These methods differ from each other not only in the analytical technique employed but also in such basic parameters like size distribution of test aerosol, mass median diameter, concentration, etc. On the other hand, it is obvious that manufacturers and users should be able to compare the quality of the products which they make, buy and use, with the products of other firms. This problem - the multiplicity of testing methods on the one hand and the need of comparable results on the other hand - can not be solved on a very simple way. There are theoretical and practical difficulties to find for example general conversion factors by the help of which the results obtained by different methods under different experimental conditions could be made comparable.

However, having a collection of the description of different test methods, the experimental conditions under which they were used and the comparison of their results makes possible to find out the range of applicability, to select the different methods from the point of view of the purpose they can be successfully used for, to be able to find out whether results obtained by different methods are comparable or not and which are the reasons of variations.

The investigations carried out by the participants of the present co-ordinated research programme include the results of the nowadays most frequently used HEPA filter testing methods both for filter medium test, rig test and in-situ test purposes. Most of the experiments were carried out at ambient temperature and humidity, but indications were given to extend the investigations to elevated temperature and humidity in the future for the purpose of testing the performance of HEPA filter under severe conditions.

2. GENERAL SCIENTIFIC BACKGROUND

The need for a Coordinated Research Programme arose from the multiplicity of testing methods used in the assessment of the efficiency of filters employed in the nuclear industry. The differences between the test methods are concerned with the different methods of aerosol generation, detection and the nature of application of the tests (tests of filter medium, filter module or filtration system).

2.1 Survey of Different Aerosol Test Methods

The actual nuclear plant aerosol may have a very broad range of characteristics, depending on the process(es) by which it is produced. The aim of the test methods should be not to duplicate the nuclear plant aerosol, but to give information in accordance with the test performed. From this point of view it is important to look at the physical and chemical properties when proceeding to the intercomparison of different test methods.

Both aerosol generation and detection rely on specific aerosol properties. The particle size distribution being of particular importance; indeed intercomparison of test methods without considering particle size distributions is meaningless [2.1].

In high efficiency filter tests one is concerned with quantifying that fraction or percentage of the challenge aerosol which penetrates the filter or filtration system for a given test aerosol can be defined as (1):

$$E = \frac{\text{weight of particles collected by HEPA system}}{\text{weight of particles presented to the system}} \times 100 \quad (1)$$

This is the gravimetric efficiency. An alternative definition is the number efficiency, defined in terms of the number of particles rather than their weight. Depending on which detection method is used one or other of these definitions will apply. The penetration (%) is (100-E) and the decontamination factor is

$$\frac{100}{100 - E}$$

Aerosol generation methods can be divided into two specific groups:

A liquid aerosol may be obtained through the nebulization of low vapour pressure liquids such as DOP [2.2] or paraffin oil [2.3]; a solid aerosol is obtained from atomization of salt solutions and drying of the aerosol [2.4, 2.5]. The resulting aerosol size distributions are polydisperse* and depend on the characteristics of the liquid used as well as the design of the generator including any baffles, cascade impactors [2.5] etc. incorporated.

In addition to polydisperse aerosols, however, an atomization method can be used to generate monodisperse latex particles which are important for the determination of the fundamental penetration particle size curve [2.7].

Aerosol generation is also obtained through vaporization of liquids (DOP) [2.2] or solids (NaCl) [2.8], by manual or electrical discharge methods (see also chapter 3) and subsequent condensation. Again a polydisperse aerosol is obtained with a size distribution dependent on the physical process, employed.

The aerosol thus generated is diluted with the air-stream flowing through the unit under test (medium or filter system) allowing quantitative measurements upstream and downstream of the unit. Depending on the detection method used, the measurement may represent the number of particles or their mass and may be over a specific particle size range or, in the case of a monodisperse aerosol, for a specific particle size.

The most important detection methods can in fact be divided into two specific categories:

- detection in terms of weight.

The aerosol in the air stream is sampled and collected on a filter medium prior to determination of its mass by, for example, fluorimetry [2.5] or radioactivity measurements. (see chapter 3).

* We define an aerosol as polydisperse in the sense given by Fuchs [2.6].

In the case of NaCl the aerosol sample is fed to a flame spectrometer which determines the total salt concentration [2.4] or the mass of single NaCl particles (see Ullmann chapter 3).

All these detection methods give mass related values, and thus the measured penetration will be a mass penetration.

- detection through the light scattering properties of the aerosol.

The total concentration can be obtained through a forward light scattering photometer [2.2] or determination of the number distribution using a single particle aerosol spectrometer (see chapter 3).

The response of a light scattering photometer is strongly dependent on the particle size. The ratio of the upstream and downstream concentration is not directly mass-related. In the case of a single particle counter one obtains a number figure for the penetration [2.9].

For tests using aerosols with different physical and chemical characteristics, it is very difficult to obtain a unique correlation between test results and methods. Indeed the filtration capture mechanism varies with size distribution, shape, specific gravity, velocity, electric charge and influence of the ambient conditions on the particle clouds.

2.2 Survey of the Different Levels of Testing

The goal of the tests may be totally different for tests on filter mediums, filter units, or the filtration systems.

2.2.1 Filter medium test

This test may have two different aims. The first one can be that of obtaining information about the actual filtration characteristic of the filtermedium under consideration. Such information involves other parameters such as pressure drop as a function of face velocity, strength etc... as well as the penetration vs. particle size curve. The latter can be obtained by nebulization of monodisperse latex particles of different sizes and

measurement of the upstream and downstream concentrations with a single particle counter [2.14]. Moreover, it is very important that this curve be obtained not only for ambient conditions of temperature and humidity but also for more severe conditions and for various flowrates. In the context of the coordinated research programme the importance of the research performed by Hirling (Ch. 3) and Ullmann must be emphasized. Once this curve has been established, the quality of the filtermedium has to be controlled by checks on the fabricated paper. This can be done with an effectively monodisperse aerosol like DOP of 0.3 micrometer with a light scattering photometer or using polydisperse aerosol as in the French uranine methodology or the British sodium chloride flame photometer method. The figure for the efficiency is ill chosen and for that reason it would be rather better to use more "a figure of merit" for the test aerosol and the velocity under test condition.

The conclusion of Dorman was that all of the test methods were useful. Nevertheless, one should emphasize that once a test method is selected, it should be used at all levels of testing. At the present time testing at a particle size of 0.12 μm seems more realistic [2.15].

2.2.2 Rig Tests

Such tests concern not only the filtermedium but also other aspects such as the gasket sealing system and the sealing of the pleated filter paper against the frame. The rig has to be constructed such a way that there is no leakage between the filter and its mounting in the rig.

In the USA the manufactures of HEPA filters for nuclear service are required to submit filters for testing to the specification M.I.L.-F 51068; this implies testing a monodisperse DOP aerosol of 0.3 micrometer. Nevertheless it appears that the test aerosol produced by the Q 107 penetrometer is polydisperse with a geometric standard deviation greater than 1.35 [2.10]. In Europe aerosols used for rig testing tend to be polydisperse. Nevertheless the same "figure of merit" of 99.97% used in the USA is often cited as a European criterion. Here again a test at a 0.12 μm particle size seems a better criterium.

Dorman concluded [2.8] that there is little difference between the different methods when leakage is present since this dominates the size selective effects of the filtration. Nevertheless even with intact filter

units and with the same test method, agreement between testings was often poor, for example, due to inadequate mixing of the aerosol, errors in sampling and different operational conditions for the aerosol generators.

The sodium flame test and DOP Q 107 penetrometer are sensitive and relatively rapid but the capital costs are high for the latter. For uranine, high sensitivity can be obtained but requires longer test runs and very high standards cleanliness.

Whatever the method of generation and detection is, it is necessary to ensure good mixing of the aerosol with the airflow upstream and downstream of the filter under test to allow a representative sampling of the aerosol; it is essential that the characteristics of the challenge aerosol, i.e. particle size distribution and concentration, are homogeneous across the duct on the upstream side of the filter otherwise a part of the filter or filter seals and gaskets may be subjected to more or less challenge than the remainder. This is also a requirement for the downstream sample seals. [2.11].

2.2.3 In Situ Test

The problem is totally different since such tests are quality assurance tests for the whole filtration system. The aim is not to quantify the efficiency of the filter but to check the integrity of the filtration system, damage to the filters (pin holes, cracks, damage to gaskets...), leakage caused by bad positioning of the filter on its seat, by-pass leakage through insufficiently leaktight dampers.

Once again the utilization of the same test aerosol as was used for the filter media and rig tests is recommended and in this case the quantitative result should certainly be named "the figure of merit of the filtration system".

In the USA a polydisperse DOP aerosol with a MMD, of 0.5 micrometer, using a pneumatic generator, or 0.7 micrometer, using an evaporation/-condensation cycle is used for in situ tests. The figure of merit is 99.95% which can be compared with the 99.97% value required for the monodisperse aerosol tests needed at the time of manufacture. In Europe a wide range of granulometrics is used; Dorman [2.8] has concluded that for in situ tests the granulometry is not of great importance. On the other hand the reliability of the test depends more on the skill of the operators in identifying leak paths.

During these tests there are some other problems e.g. the difficulties of access to the filtration systems, inadequate mixing of the test aerosol and the difficulty of ensuring isokinetic sampling. Liaison between the designer and quality assurance test group should be established at the design stage.

When leakage is present most of the conventional test methods will give similar numerical results, because the filtration effects of leakage paths are largely independent of particle size.

System tests fall in three categories:

- (1) commissioning tests before start-up of the nuclear plant (acceptance tests). These tests verify that the different components are properly installed and can operate as intended.
- (2) routine surveillance tests by every 6 months or 12 months, after the system has been brought into operation to demonstrate its continuing ability to perform its air cleaning function.
- (3) replacement tests made after replacement of the system in whole or in part to demonstrate in particular the proper installation of the filter unit.

2.3 New Trends in Testing

There is a trend to transform the in situ leakage test into an actual efficiency test which is valid for the overall system (filtermedium, filter medium sealing, gaskets, separators, filter housing). As a manifestation of this trend use of single particle spectrometers were proposed [2.12] [2.13]. These instruments are able to measure the filter penetration as a function of particle size. If the actual particle size distribution of the nuclear plant aerosol is known, the equivalent penetration can be calculated from the measured penetration curve. In connection with the trend toward the use of more economical filter systems, for example in order to obtain larger decontamination factors, there is a need to increase the sensitivity of the applied HEPA filter testing methods. Such methods will be necessary for testing HEPA filters arranged in series configuration as a complete unit.

In this sense the research of De Worm (chapter 3) and Ullmann (chapter 3) is important.

2.4 Conclusions

From the different points treated in previous paragraphs one can state that, in the case of comparing different test methods, different requirements should be taken into account.

The first requirement is the reproducibility, it is very closely related to the characteristics of the aerosol generation method, in such a way, that the parameters determining the particle size distribution and concentration are of primary importance. The sensitivity of a test method is determined through the detector, and the selectivity rather through the aerosol generator. This selectivity has different meaning depending on the test under consideration (filter medium, filter, filtration system). It is of primary concern for the first two tests but less important for in situ measurements. The useability is important for the in situ measurements.

The adaptability of the test method may have a different meaning from one country to another. Some countries use different test methods for their filter medium and rig tests in comparison to their in situ testing. The ease and speed are important factors for in situ testing of a great number of filter systems. The same can be said about the economy which is important for in situ test but less important for the rig tests.

The problem of toxicity is important, but it should be emphasized that the operators are not working in the aerosol clouds. A detailed review of these different requirements is given by Dorman [2.8] in tables 14 and 15 of his report.

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3. SCOPE AND OUTLINE OF THE CO-ORDINATED PROGRAMME

A co-ordinated research programme on particulate filter testing methods was taken up by the Agency and contracts were awarded to the Member Countries, Belgium, German Democratic Republic, India and Hungary. The scope and outline of the programme undertaken by the participant countries are as follows:

Belgium:

To assess the laser spectrometer methodology for in-situ measurement of the filtration system in the nuclear industry.

To compare the two international standards: the French Standard AFNOR NFX 44011 (Uranine Test) and the American Standard ANSI - ASME - N510 - 1980 in which an in-situ test method using DOP aerosol is described, in regard to the method based on the laser spectrometer.

To study both single and composite (two stage) filtration systems.

To investigate other operational parameters like simulated leak paths, varied temperature and humidity conditions and the combination of both the parameters, etc.

German Democratic Republic

To obtain the initial data required for a systematic interpretation of filter test results and to draw the corresponding conclusions. Under laboratory conditions the following experimental investigations for four different test methods were made:

- determination of the particle size distribution of polydisperse test aerosols (NaCl, short-lived radon daughter products attached on NaCl, paraffin oil);
- determination of penetration of filters as a function of particle size;
- determination of total penetration.

India

To carry out detailed studies for the comparison of the test methods of HEPA filters under controlled conditions by testing a set of standard 1000 cfm HEPA filters using the aerosols of DOP, uranine and sodium chloride, all produced by compressed air atomisation.

To investigate the causes of variation in the test results determined by the above methods.

Hungary

To carry out detailed studies by testing various types of filters by the Radioactive Tracer Method, the Mono-disperse DOP Method and the Potassium-flamephotometric Method and compare the results obtained under the same air flow conditions to present an international guidance for filter testing in future.

From the data collected by the participants on the various aspects of the programme undertaken and based on the available literature on the subject of investigation, the participants have identified areas requiring further investigation.

4. CONTRIBUTIONS BY THE INDIVIDUAL SCIENTISTS

FEASIBILITY OF THE LASER PARTICLE SPECTROMETRY TECHNOLOGY FOR IN-SITU TESTING OF HEPA-FILTRATION SYSTEMS IN THE NUCLEAR INDUSTRY*

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Abstract

The application of the laser spectrometer as detector for rig testing of HEPA filters was investigated and compared to the uranine and DOP methodology. These rig tests were performed at different volumetric flow rates (350 - 3000 m³/hr) and for single and double HEPA filters.

The sensitivity of the laser detector on this test rig was at least 10³ higher as the two conventional methods. Penetrations down to 10⁻⁸ (confidence level of 99.7%), over the whole light scattering range (0.09 - 3 µm), were measured. Leakpaths of more than 1 mm² could be observed, working at three different flow rates through influence on the relation by $p = a v^{-b}$. The influence on the "a" parameter was important.

The influence of the particle size distribution of the test aerosol was established, giving rise to different penetration values depending on the considered size control. A particle size distribution can be established over the range 0.09 - 3 µm.

For the DOP aerosol the ratio of penetrations for the size range (0.09 - 0.195 µm) and (0.09 - 3 µm) was about 2. For the French uranine method this ratio was 1 indicating that this aerosol gives only information about the maximum penetration size range. Nevertheless a comparison in the range 0.09 - 0.176 µm gave a same figure for both aerosols, indicating that the influence of the physical state of the aerosol was beyond the errors on the determinations.

The laser detector has the great advantage that particles with different physical characteristics can be measured. The application of the laser detector to develop an inter-laboratory test method is well promising.

The American Standard methodology using DOP particles as test aerosol and the light scattering photometer is merely a leak testing method. It provides a reasonable and often conservative measure of the "true" performance for the test aerosols. The French Standard methodology with a very challenging aerosol, enables only to examine the maximum penetration range and gives also a conservative value.

Rig tests under more severe conditions indicated that the DOP and uranine aerosols are still good test aerosols for temperature up to 80°C and higher humidity.

* IAEA Agreement 2101 for the Research period 1979-1982.

The feasibility to transform the in-situ test into a more economical kind of total filtration system efficiency test was assessed. This in-situ test, using laser detector, replaces the manufacturers' rig test and the in-situ leak test through one test. With the present single particle spectrometer it was possible to assess penetrations less than 10^{-6} for the 0.09 - 3 μm light scattering size range.

INTRODUCTION

The study concerned the feasibility of a laser particle counter as a detector for in-situ testing of high efficiency particulate air filters in the nuclear industry.

During this study the conventional aerosol generation methods as described in the French Standard AFNOR NFX 44011 and the American Standard ANSI/ASME N510-1980 were used to compare the laser spectrometer with the respective conventional detectors (for penetrations higher than 10^{-5}).

The filtration system to be tested consisted of both single and composite (two-stage) absolute filters.

The use of the laser spectrometer for in-situ measurements of the efficiency of filtration systems in the nuclear industry has been assessed. Indeed the trends for using more than one safety barrier in nuclear power plants imply the measurement of much smaller penetration factors as mentioned. In addition, for economic reasons, the air cleaning systems are now being designed as compact units for which the testing of each single unit becomes an impossible task.

FEASIBILITY TEST DESIGN

The conventional in-place test methods consist in the determination of upstream and downstream particle concentrations. A laboratory scale loop was constructed to simulate a tandem filtration system with flow rates similar to those found in the nuclear installation ventilation systems, "see Figure 1". The loop was provided with sampling ports up- and downstream the filtration units and an injection port for the challenge aerosol. The duct velocity is regulated by adjusting the fan-motor speed and measured using a vane anemometer. To calculate the filtration velocity a filtration surface of 23 m^2 was assumed. The temperature of the air can be preset in the range 20-80°C with a heating battery. The humidity of the air can be varied between 20 and 100% at 25°C.

The test aerosols (DOP, uranine and NaCl) are generated with the help of air-operated atomizing-nozzle type generators as described in their respective standards (see references 1 and 2). The upstream number concentration ranged from $3 \cdot 10^6$ to 10^6 particles/ cm^3 for flow rates between 350 to 2500 m^3/h for the dioctyl phthalate aerosol (DOP), for the uranine aerosol $10^4 - 2.5 \cdot 10^3$ particles/ cm^3 and for a 1 % NaCl-solution $10^4 - 10^3$ particles/ cm^3 .

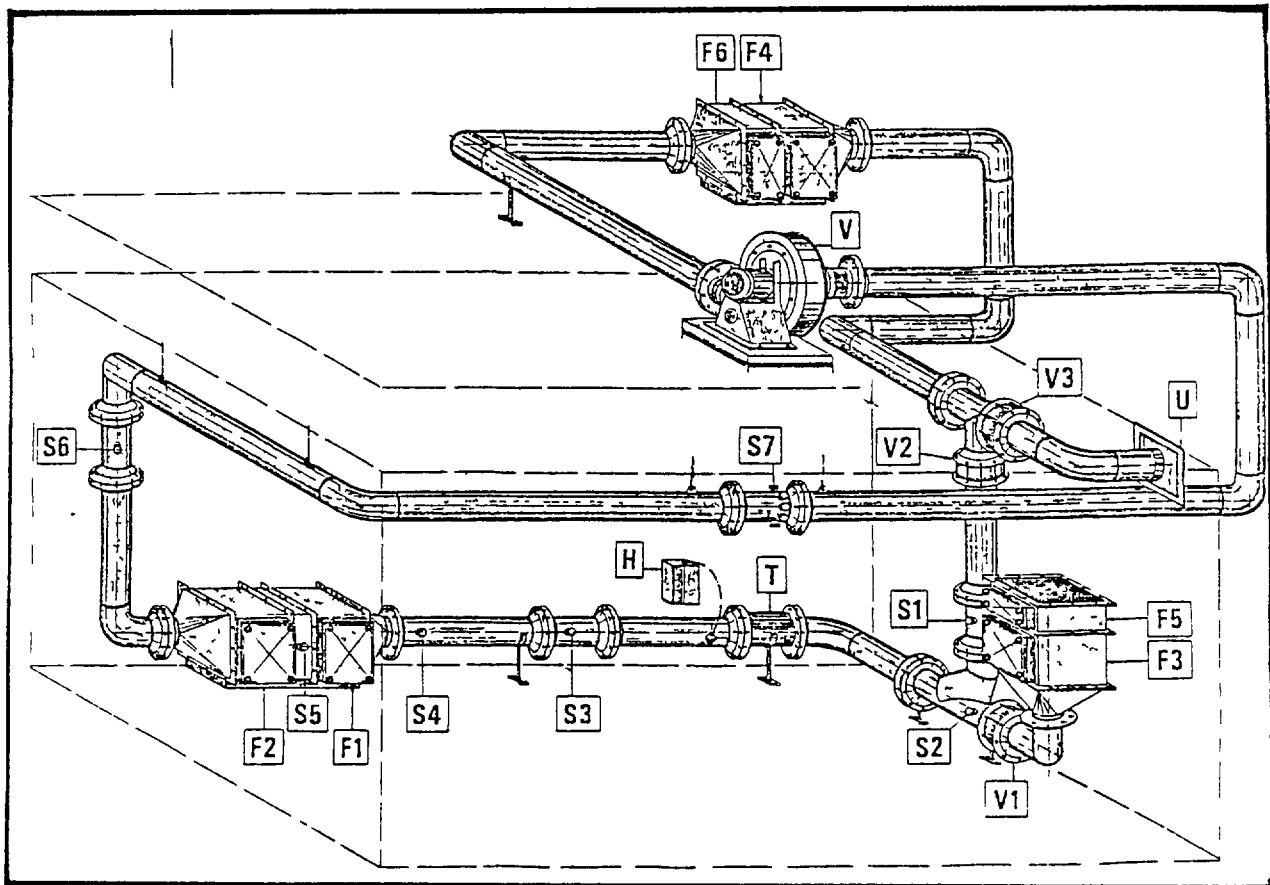


Figure 1 Schematic diagram of the research rig

F_1, F_2 Test section filters F_3, F_5 prefilters F_6, F_4 air cleaning filters
 S_1, S_2 injection ports S_3, S_4 upstream sampling ports S_5, S_6 downstream sampling ports
 V : regulated ventilator V_1, V_2, V_3 : dampers for working conditions in open or closed circuit
 H : system for humidification T : heating coil

METHODOLOGY WITH THE LASER SPECTROMETRY TECHNOLOGY

THE LASER SINGLE PARTICLE COUNTER AS DETECTOR

In the case of tandem filtration systems penetration factors as low as 10^{-8} are achievable. This means downstream concentrations as low as 0.01 particles/cm² for upstream concentration of 10^6 . The required downstream sensitivity dictated a device capable of detecting and counting single particles. The overwhelming argument in favour of light-scattering techniques vs other methods is that in light-scattering measurements direct physical contact with the particles measured is avoided.

The Knollenberg "see reference 3" light-scattering aerosol counter, known as the active scattering spectrometer was chosen as detector (ASAS-X, Particle Measuring Systems Inc. Boulder Colorado). The primary method of aspiration of the aerosol consists of a miniature wind tunnel "see Figure 2". The aerosol sample cross section includes only the central region of the He-Ne laser beam ($\lambda = 632,8 \text{ nm}$, $\phi = 200 \mu\text{m}$), operating in TEM₀₀ mode. The sample flow (0.5 - 1.5 cm³/s) is joined in the sample inlet by an air filtered sheath^{oo} air flow (20 cm³/s). The aerosol passes through the laser beam in the focal point of a parabolic mirror. The scattered light is collimated by this mirror and after reflecting by a flat mirror, refocussed by an aspheric lens and collected on a photodiode detector. A pulse high selector classifies the pulses into 60 channels divided in 4 overlapping ranges of 15 channels (R_0 : 0.60 - 3.00 μm , R_1 : 0.24 - 0.85 μm , R_2 : 0.15 - 0.30 μm , R_3 : 0.090 - 0.195 μm). The data are treated with a HP-85 desk computer. At the end of a measurement cycle (each cycle consists of five successive measurement periods), the results of each size range are printed, together with a plot of the size distribution and the total number of particles per second over the total measuring range (R_4 : 0.090 - 3.00 μm).

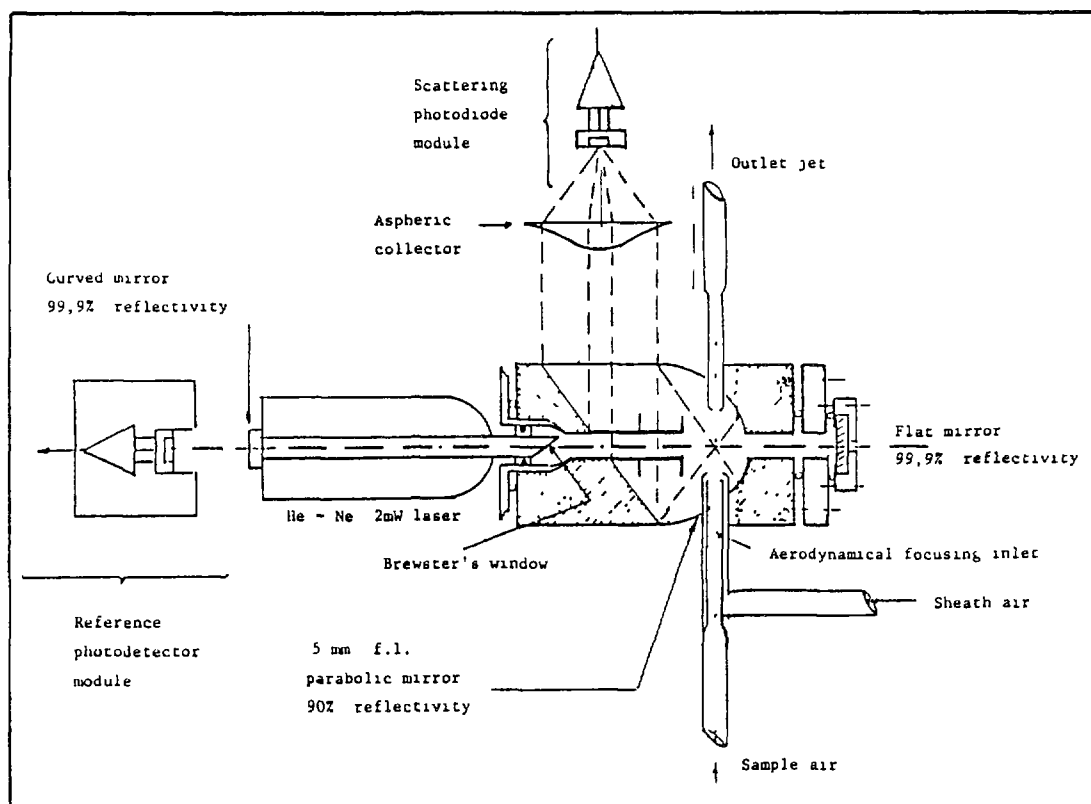


Figure 2 Optical system diagram ASAS-X

DILUTION SYSTEM FOR MEASUREMENT OF UPSTREAM CONCENTRATION

The aerosol concentration admitted to the laser spectrometer is limited by coincidence counting of particles in the sensitive volume. This volume formed at the intersection of the laser beam and the aerosol flow is about $6 \cdot 10^{-6} \text{ cm}^3$, the aerosol flow being $1.5 \text{ cm}^3/\text{s}$. So coincidence losses up to 10 percent in concentration can be tolerated, for the ASAS spectrometer this means a concentration of about $2.5 \cdot 10^4$ particles/s. These considerations led us to the conclusion that coincidence error may become significant at concentrations above 10^4 particles/s. The high concentrations encountered upstream the filtration unit necessitate dilution of the aerosol flow. Dilution ratios of 10^{-3} and less are to be obtained, which impose to dilute a small quantity of aerosol in a large volume of clean air. A pump diluter system was constructed, consisting of a small wind tunnel of 90 cm length and 7 cm diameter equipped with a variable speed blower "see Figure 3".

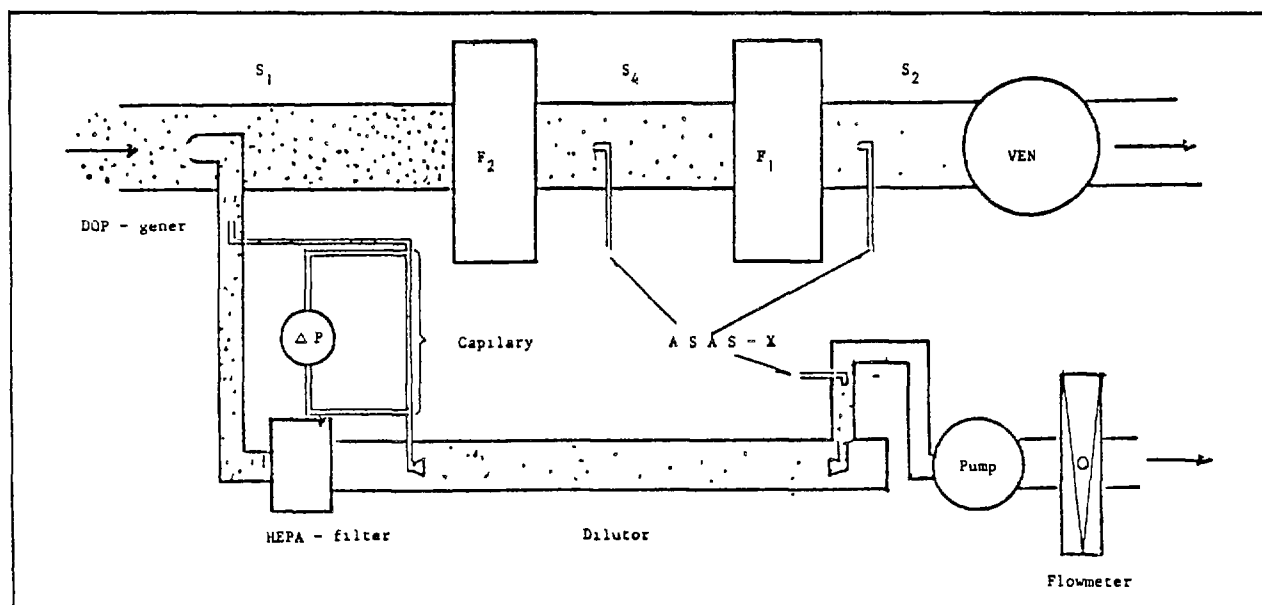


Figure 3 Dilution system for the laser spectrometer

An air sample is drawn upstream the filter units, a small portion (through a capillair Ø 1.2 mm and 410 mm length) is mixed in the wind tunnel with the major portion, which consists of clean air obtained through double HEPA-filtration of the sampled air. The pressure difference over the capillair airmeter provides an indication of the dilution ratio. The dilution ratio is established from the air flows and verified with a tyndallometer, which measures the initial challenge aerosol and that after the dilution.

DETERMINATION OF THE PENETRATION

The performance of a filter system can be calculated from the equations

$$P = \text{penetration} = \frac{\text{number particles/s (downstream filter)}}{\text{number particles/s (upstream filter)}} \times D \quad (1)$$

$$D = \text{dilution ratio} = \frac{\text{concentration after dilution}}{\text{concentration before dilution}} \quad (2)$$

thus

$$P = \frac{(C_{ds}/t_{C\ ds} - B_{ds}/t_{B\ ds}) \times D}{C_D / t_D} \quad (3)$$

The fractional error can be calculated from :

$$\frac{\Delta P}{P}^2 = \frac{\Delta D}{D}^2 + \left[\frac{\sqrt{C_D}}{C_D} \right]^2 + \left[\frac{\sqrt{C_{ds} + B_{ds}}}{C_{ds} - B_{ds}} \right]^2 \quad (4)$$

assuming that the random counting process of the spectrometer follows a Poisson-distribution. The second term in the preceeding equation can be neglected. The value of $\Delta D/D$ was experimentally determined, the fractional error was 0.10. The minimum counting rate and standard deviation of the background are 0.02 ± 0.02 particles. Defining the detection limit level as 4.65 times the standard deviation, means that about 0.1 particles/s (confidence level 95 %) are to be obtained downstream. The fractional error $\frac{\Delta P}{P}$ of the penetration can be maintained below 50 % by counting downstream more than 7 counts during a 100 sec counting interval. The minimum detectable penetration that could be obtained on the test rig ($1.700 \text{ m}^3/\text{h}$) was 5.10^{-9} (confidence level 95 %). In current in-place tests (flow rates of $36000 \text{ m}^3/\text{h}$ and more) backgrounds, owing to extraneous particles, amount up to 1 particles/s (for a 100 sec counting interval). These conditions limit the minimum detectable penetration to about 10^{-6} . For this reason a new single-particle spectrometer is under investigation.

The laser fluorescent particle size spectrometer (ASAS-XF, PMS Inc., Boulder USA) is an aerosol spectrometer designed to identify tagged (fluorescent) particles over a size range of 0.125 to $3.1 \mu\text{m}$ diameter.

Using the dilution system for upstream sampling, and working in the fluorescence mode it should be possible to obtain minimum detectable penetrations of 10^{-8} . Indeed the background count rates are not significant, because particles with the same fluorescent properties are below detectable ranges.

COMPARISON OF DIFFERENT TESTING METHODS

HEPA-filters with a penetration less than 5.10^{-4} (sodium flame test) were used. These HEPA-filters had a wooden frame with aluminium spacers and gaskets in neoprene, with standard dimensions ($609 \times 605 \times 298 \text{ mm}$).

The laser spectrometer methodology enables the determination of the filter efficiency by number. Different aerosol distributions were used for intercomparison. A liquid aerosol of DOP with number median diameter of $2 \mu\text{m}$ and standard deviation of 1.6, was obtained with an air operated atomizing nozzle type generator. The same pneumatic generator was used for the nebulization of 1 % NaCl in water.

The uranine generator from the French Standard was the second type of solid aerosol with a mass median diameter less than $0.25 \mu\text{m}$ and a standard deviation of 1.6.

This last aerosol permitted the determination of the filter efficiency by mass through determination of the mass collected up- and downstream the filter unit through fluorimetry.

The laser detector has been calibrated with latex particles, the refractive index for DOP is not substantially different from the latex and the generated DOP particles are spherical,

the light scattering diameters as obtained with the spectrometer are comparable. The other solid aerosols uranine and sodium chloride have a different refractive index, nevertheless as the active scattering method is not very dependant of this index, their influence is supposed to be very small.

The results of this intercomparison study are summarized in function of the flow rate "see Figure 4".

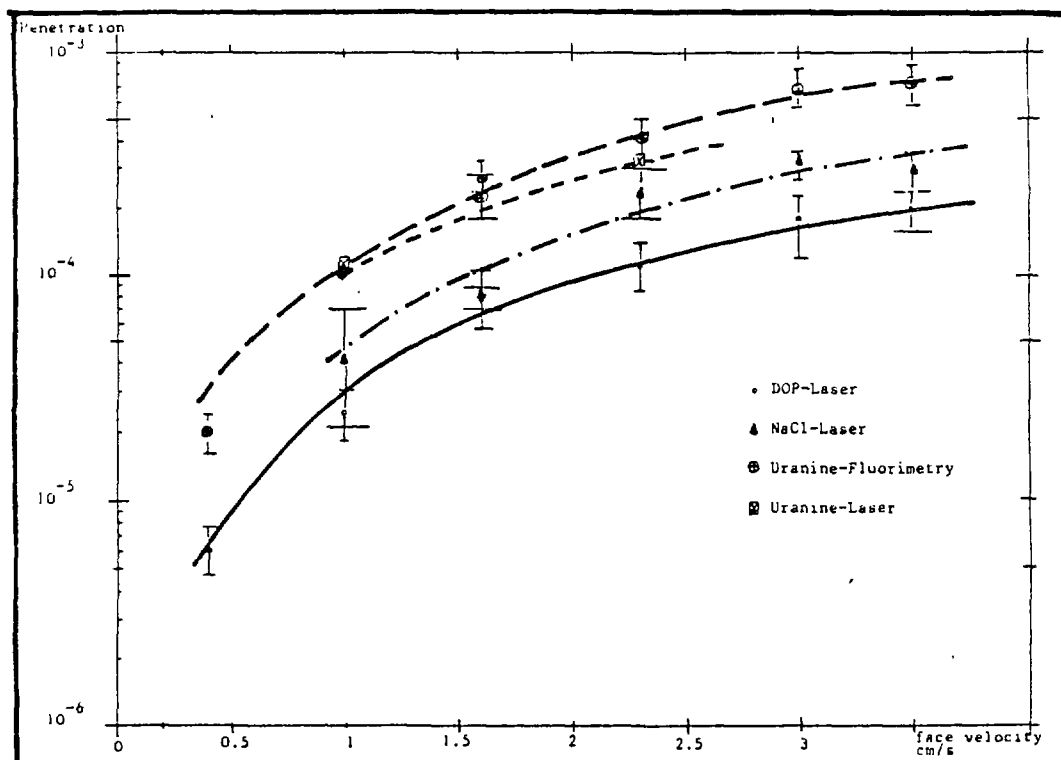


Figure 4 Penetration in function of the face velocity
 — DOP-laser detector — . — NaCl-laser detector
 — — uranine-fluorimetry — — — — uranine-laser detector

The penetration (1 - efficiency) is given over the sensible range of the laser detector (0.09 - 3 μm). The values obtained with the photometer are not reported in the figure 4, as these values were beyond the detection level of the photometer method (less than 10^{-4}). The measured values were adjusted with a least squares method to a power function, expressed as :

$$- \log P = a v^{-b} \quad (5)$$

In this expression P is the penetration over the range 0.09 - 3 μm , the values a and b are constants ranging from 4 - 4.5 and 0.16 - 0.19 respectively. Comparison of the penetration at a filtration velocity of 2 cm/s, brought us to the conclusion that the values obtained with DOP are about 3 times less than with the uranine, indicating that the penetration over the sensible measuring range (0.09 - 3 μm) is attenuated through the presence of particles of less penetrating diameter. Calculations of the overall penetration in the range 0.09 - 0.195 μm to the overall penetration in the range 0.09 - 3 μm indicate that this ratio had a value of 1,8 for the DOP-aerosol, 1,2 for the NaCl-aerosol and about 1 for the uranine-aerosol. The overall penetration in range 0.09 - 0.195 μm is less for the DOP-aerosol in comparison to the uranine, indicating that also the physical properties of the challenge aerosol are important.

The methodology of the laser detector together with a DOP-aerosol, with his broader spectrum, permits to obtain the penetration in function of the light scattering diameter in the range 0.09 - 0.23 μm with sufficient precision, indeed the number of DOP-particles downstream the filter unit is too low above 0.23 μm .

The figures 5 and 6 represent the shape of the upstream size distribution of a DOP-aerosol and the penetration curve. The overall penetration over the range 0.09 - 0.195 μm was 8.10^{-4} and 5.10^{-4} for the whole measuring range 0.09 - 3 μm . The curves were obtained through a polynomial regression model of the form $Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \dots + \beta_6 X^6$ and the β 's are computed via the

Cholesky method ($q \leq 6$). They are only valid within the sensitivity range of the laser detector.

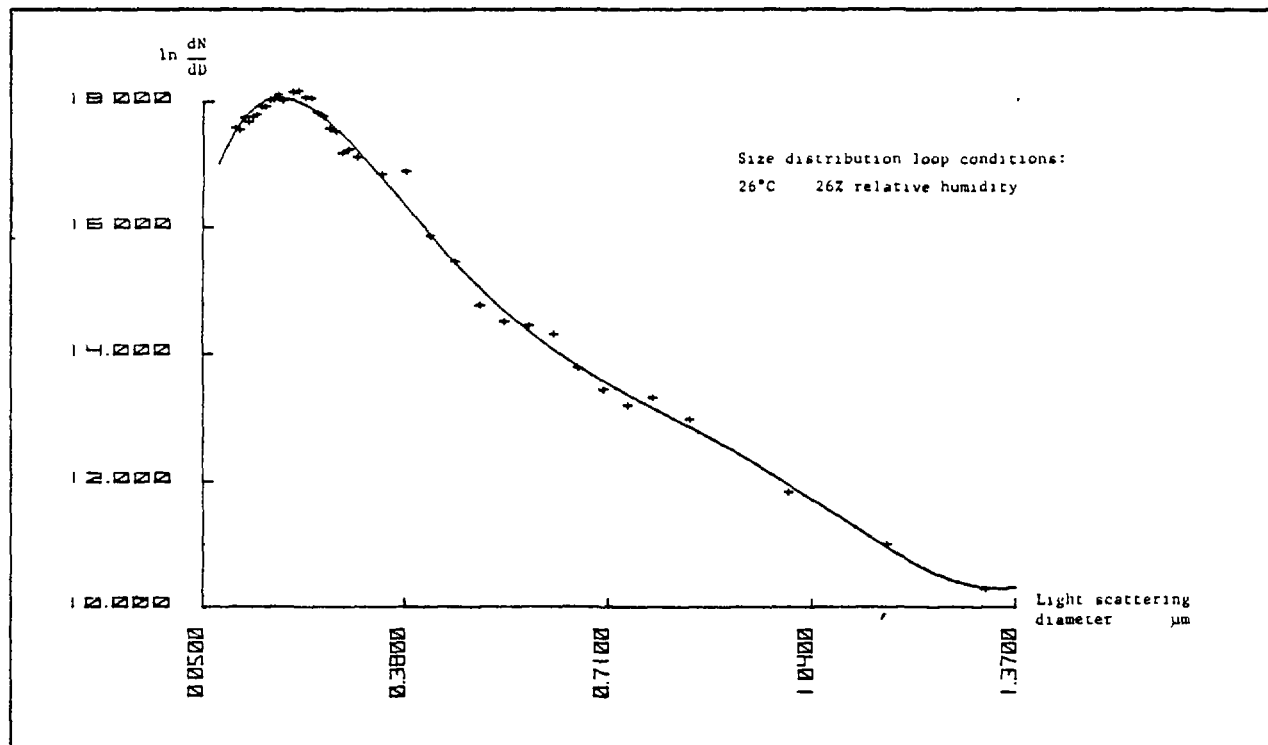


Figure 5 Particle size distribution of the challenge aerosol (upstream)

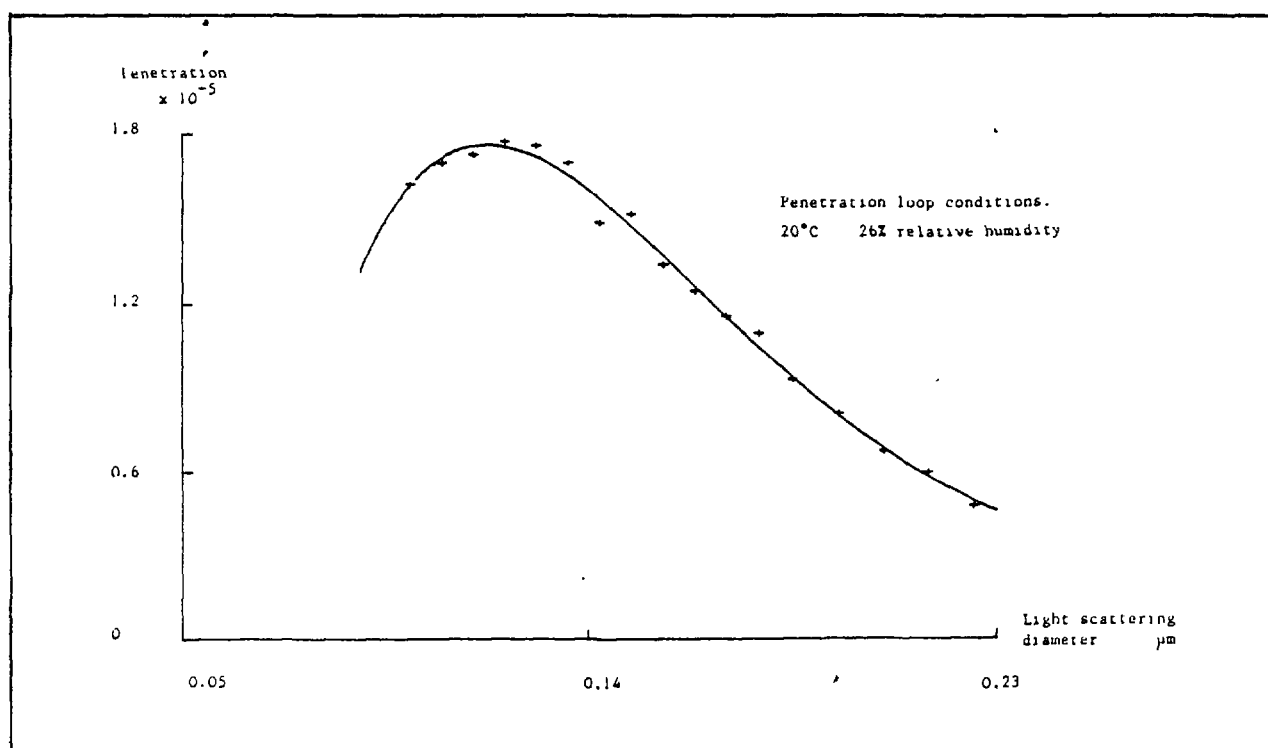


Figure 6 Penetration - particle size curve

INFLUENCE OF TEMPERATURE AND HUMIDITY

The influence of the temperature on the penetration was investigated for the different test aerosols. At higher temperature Brownian motion is more active so that diffusive deposition of aerosol should increase. The viscosity of air increases with temperature, however, so that inertial deposition would be expected to fall. Pich and Binck (see ref. 4) concluded that captive efficiency would increase with temperature for particles of about $0.1 \mu\text{m}$ but would fall for coarser particles. However the effect of the temperature on the adhesion may influence the overall efficiency. The different test aerosols were intercompared at different temperature (humidity constant at 26 %). The results are summarized in figure 7. Multiple linear regression on the data set for the temperature range under considerations indicates that the values in the lower range (P_3 : $0.09 - 0.195 \mu\text{m}$) are correlated (see table I) and that there exists a negative correlation for the temperature. The decrease of the overall penetration in the range $0.09 - 3 \mu\text{m}$ with temperature for the DOP-aerosol is less pronounced. This investigation goes into the sense of the mentioned theoretical approach.

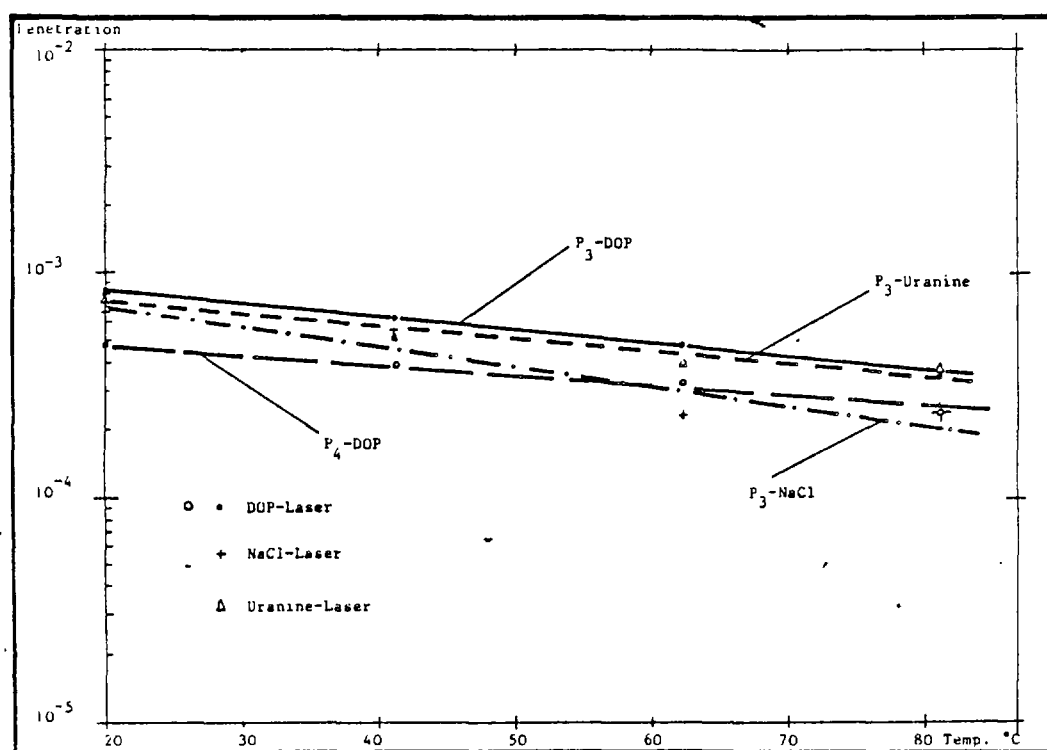


Figure 7 Influence of the penetration in function of the temperature for the different test methods. P_3 : penetration $0.09 - 0.195 \mu\text{m}$ P_4 : penetration $0.09 - 3 \mu\text{m}$

TABLE 1 - Correlation matrix of the values in figure 7

	NaCl	Uranine	Temperature
DOP	0.959	0.960	- 0.993
NaCl	-	0.917	- 0.941
Uranine	-	-	- 0.923

Dorman (see ref. 5) reported that information was leaking concerning the effect of humidity on penetration. Hirling (see ref. 6) reported data of his experimental work on filter paper, in which he concludes that penetration increased through the effect of higher humidity, probably owing to the wetting of the filter fibres. During the course of our experiments, it appeared to be very hard to obtain 100 % humidity at higher temperatures. It was only possible to obtain higher humidity conditions at 20 and 40°C . These experiments indicate rather a decrease with higher humidity at a constant temperature of 20°C . The results obtained are summarized in table 2.

TABLE 2 - Influence of humidity on penetration for different test aerosols at temperature of 20°C

Humidity %	Penetration x 10 ⁻⁴ Laser					
	DOP		NaCl		Uranine	
	P ₃	P ₄	P ₃	P ₄	P ₃	P ₄
26	7.9	4.7	6.6	5.9	7.9	7.5
100	4.8	3.2	1.4	1.6	5.9	6.1
ratio 26/100	1.6	1.5	4.7	3.7	1.3	1.2

IN SITU-TESTING OF HEPA-FILTERS

SINGLE FILTER SYSTEMS

Using a DOP-aerosol, obtained through an air-operated or an evaporation-condensation generator, depending on the flow rate of the ventilation system and a forward scattering photometer enables the determination of the penetration through single filter units with sufficient precision. Only in the case of very high efficient filters testing with the laser spectrometer should be proposed.

On the test rig different micro leak paths in a single filter unit, obtained in the pleats of the filter paper with sealed glass microtubes (dimension 0.86 mm²), were investigated. Within the relative error on the measurements (20 % at a confidence level of 95 %), the influence between 2, 3, 4 or 5 pinholes of 0.86 mm² was insignificant. However the advantage of the laser detector was threefold, consisting in the possibility of obtaining a penetration curve, the determination of the test aerosol particle distribution and in the comparison of different measuring ranges, giving information of possible leak paths.

TANDEM FILTER INSTALLATION

The methodology for testing tandem HEPA-filter installations with the laser spectrometer was developed by the group of B. Schuster et al. (see ref. 7). The concentration of the downstream extraneous particles limits the sensitivity of the methodology with the ASAS-X spectrometer. Since 1982 different in-situ tests with the laser detector were performed in Nuclear Power Plants in Belgium, on compact filtration systems, "see Figure 8".

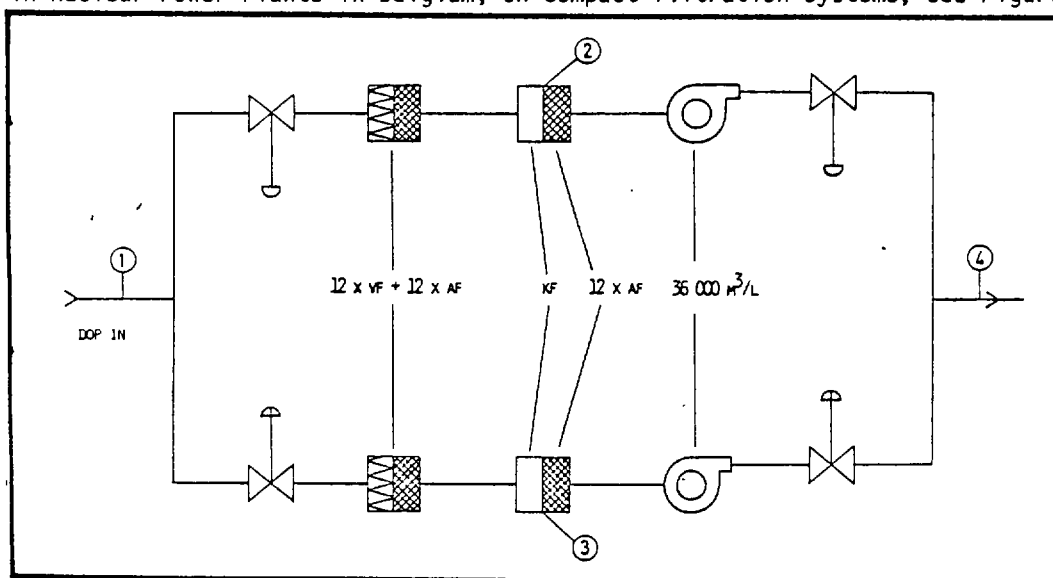


Figure 8 Diagram of a filtration unit in a nuclear power plant, consisting of two parallel systems (AF HEPA-filters, VF prefilters, KF carbon absorber units not filled during the testing, 1-2-3-4 sampling points).

For these compact units only values "less than" were calculated at a confidence level of 95 % (see table 3). A fluorescent laser detector is under investigation to overcome this problem.

TABLE 3 - Penetration obtained for conditions encountered in nuclear power plants.
DOP-aerosol with mass median diameter of 0.8 μm and geometric standard deviation 1.8
Flow rate through the whole system 36.000 m^3/h
Filtration unit consists of 12 parallel filters

Penetration for	Range		Range	
	0.09 - 0.195 μm	Fractional error	0.09 - 3 μm	Fractional error
2/1	$4 \cdot 10^{-5}$	10 %	$3.5 \cdot 10^{-5}$	10 %
3/1	$2 \cdot 10^{-4}$	10 %	$2 \cdot 10^{-4}$	10 %
4/1 through 2	$(3 \cdot 10^{-7})$	95 % confidence level	$(3 \cdot 10^{-7})$	95 % confidence level
through 3	$(6 \cdot 10^{-7})$	95 % confidence level	$(6 \cdot 10^{-7})$	95 % confidence level

The feasibility of the laser detector for in-situ testing of tandem filter systems was carried out in our test rig. This test rig enables working in ideal conditions in which the particle background is very low (below 0.01 particles/s). The penetration was first determined for the single unit (F_1 or F_2) and afterwards with the two filters in serie ($F_1 + F_2$). The results were evaluated at 2 cm/s face velocity (nominal flow rate in the filter unit 1700 m^3/h) and for different types of leak paths (see table 4).

TABLE 4 - Penetration for intact filters, single or tandem system, and influence of simulated leaks (1.5 mm^2 , microtube sealed in the medium).
Face velocity 2 cm/s (standard errors indicated)

Filtration condition	Penetration		Ratio P_3 / P_4
	P_3 Range 0.09 - 0.195 μm	P_4 0.09 - 3 μm	
single filter F_1	$(1.6 \pm 0.2) \cdot 10^{-4}$	$(0.86 \pm 0.09) \cdot 10^{-4}$	1.9
single filter F_2	$(2.9 \pm 0.3) \cdot 10^{-4}$	$(1.5 \pm 0.2) \cdot 10^{-4}$	1.9
tandem $F_1 + F_2$	$(5.8 \pm 1.9) \cdot 10^{-8}$	$(3.4 \pm 1.2) \cdot 10^{-8}$	1.7
intact $F_1 + F_2$ 1 hole of 1.5 mm^2	$(9.1 \pm 1.0) \cdot 10^{-8}$	$(3.8 \pm 0.4) \cdot 10^{-8}$	2.4
F_1 1 hole of 1.5 mm^2 + F_2 1 hole of 1.5 mm^2	$(16 \pm 2) \cdot 10^{-8}$	$(8.3 \pm 0.8) \cdot 10^{-8}$	1.9

CONCLUSIONS

The laser detector according to its present design can be applied in complex HEPA-filtration systems and provides reliable indications for penetration down to 10^{-6} . This methodology provides more than a single figure but gives the penetration particle size curve over the range 0.09 - 3 μm .

The drawbacks of the laser detector are the high investment costs, requirement on the qualifications of the operators, fragility of the laser tube and the influence of extraneous particles downstream the filtration system. This problem can however be solved by using a tagged aerosol and the fluorescent laser detector.

SYMBOLS

R_i = range of the classifier of the spectrometer

P_i = overall penetration in the range R_i , overall efficiency is equal to $1 - P_i$

D = dilution ratio of the diluter

C_D = total counts after diluter

t_D = upstream sampling time

C_{ds} = downstream total counts

$t_{C ds}$ = downstream sampling time

B_{ds} = downstream background counts

$t_{B ds}$ = downstream background sampling time in most cases $t_{B ds} = t_{C ds}$

v = filtration face velocity

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COMPARISON OF TESTING METHODS FOR PARTICULATE FILTERS*

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Abstract

The report is the result of investigations during the last 3 years (1980-1982) in the frame of the IAEA Co-ordinated Programme on "Comparison of Existing Testing Methods for Particulate Filters".

By means of experimental investigations of testing aerosol filters conclusions are drawn with respect to the initial data required for a comparison of methods and to the interpretation of test results. The penetration of a filter can be relative to the number, mass, activity or scattered light intensity of particles. For the interpretation of test results the knowledge of the so-called relevant particle size distributions of test aerosols, corresponding to these reference values, is of decisive importance.

A method to determine penetration as a function of particle size and several methods to determine total penetration for test aerosols with different relevant particle size distribution are included in the comparison of methods. This makes possible an analysis of the correlation between penetration and as a function of particle size, total penetration and relevant particle size distribution of test aerosols and thus an assessment of the evidence of different testing methods.

The results demonstrated:

- the feasibility for measuring penetration for any filter as a function of particle size with sufficient accuracy, to calculate the total penetration for any test aerosol, given the relevant particle size distribution;
- that universally-applicable values for conversion factors are not possible, because these factors for relating different standardized test methods depend on the quality of the aerosol filter in question;
- the sensitivity of total penetration to particle size distribution, thus emphasizing the need for any standardised test method to ensure a precisely reproducible size distribution for the test aerosol.

* IAEA Agreement No. 2483/CF for the research period 1979-1982.

1. Introduction

At present numerous different methods are used for testing of aerosol filters. A standardization on the international level has not yet been successful although, to growing extent, a comparison of test results has become necessary. The present paper is meant to be a contribution to the interpretation of measuring results obtained with different test methods.

Dorman /1/ described extensive investigations of the comparison of filter test methods. Total penetration was measured for 5 different glass fibre papers each graded in quality as a function of velocity. For filter material 3, Fig. 1 shows the results of the tests made with 6 different test aerosols. Their interpretation is difficult, since particularly data on the particle size distribution of the test aerosols used are missing.

To obtain the initial data required for a systematic interpretation of test results, under laboratory conditions the following own experimental investigations were performed with different test methods:

- determination of the particle size distributions of test aerosols (see 3.) underlying the various methods (see 2.),
- determination of penetration as a function of particle size (see 4.1.) and
- determination of total penetration with different methods (see 4.2. to 4.4.).

The tests were made at velocities of 2, 5 and 10 cm/s for the same 5 different filter materials as in the investigations described by Dorman.

From the measuring results obtained conclusions were drawn for the interpretation of filter test results (see 5.). Here, the connection between total penetration; penetration as a function of particle size and particle size distribution of test aerosols was in the centre of study.

Included in considerations were also comparisons of methods based both on own measuring results and on those described by Dorman.

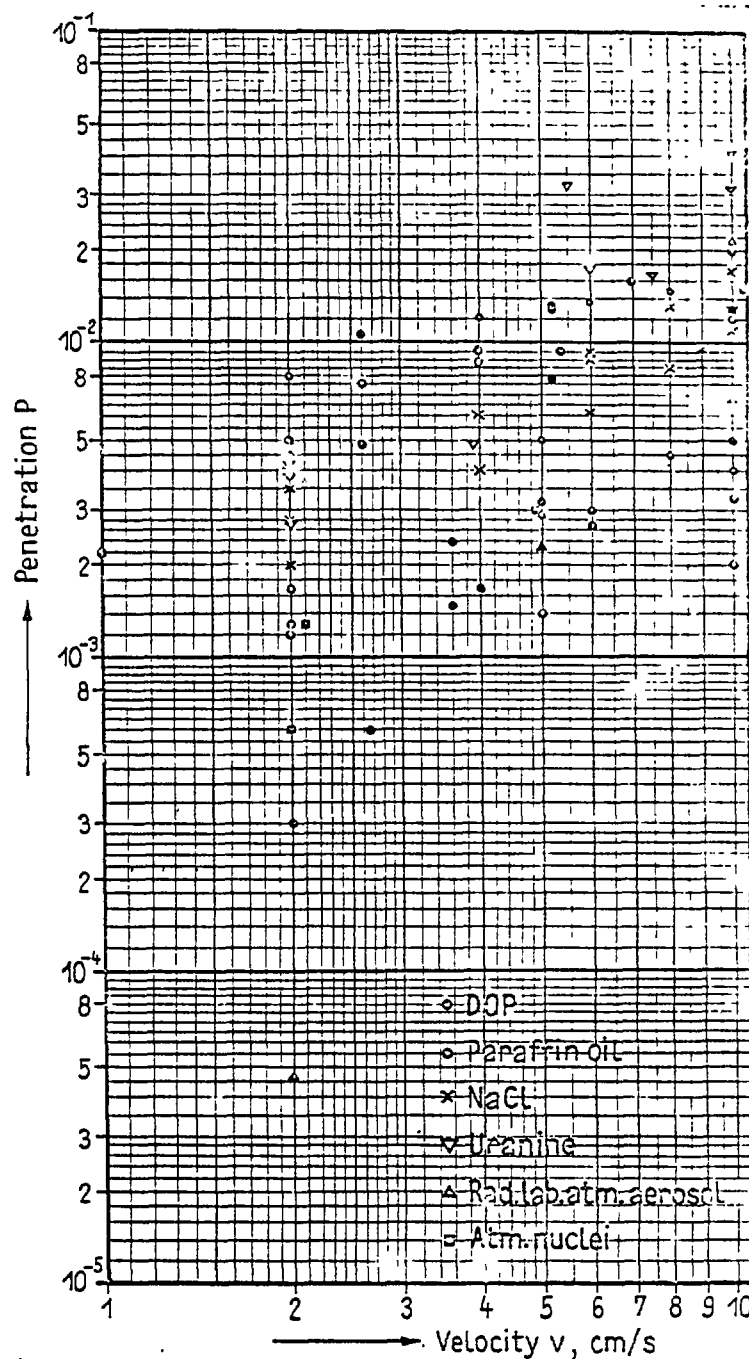


Fig.1 Results of comparison of various testing methods [1]

Finally, the assessment of test methods is discussed, taken into account the different aims of filter testing (see 6.).

2. Survey of the test methods used

To characterize the test methods used for comparative investigations, test aerosol, measured quantity and procedure of measurement are briefly described below.

Method A

- polydisperse NaCl test aerosol
- determination of penetration relative to particle number as a function of particle size and determination of total penetration relative to particle number, respectively,
- measurement of particle size distribution (relative to particle number) and of total particle number, respectively, in aerosol samples taken before and after the filter material to be tested.

This method is routinely used for radiation protection type testing of aerosol filters at the National Board of Nuclear Safety and Radiation Protection of the GDR /2/.

Methods B-1 and B-2

- polydisperse NaCl test aerosol (of different particle size distribution for B-1 and B-2),
- determination of total penetration relative to particle mass,
- measurement of mass concentration of aerosol samples taken before and after the filter material to be tested.

In principle, this method corresponds to the so-called sodium flame test in accordance with the British Standard B.S. 3928 /3/.

Method C

- short lived radon daughters attached on polydisperse NaCl aerosol,
- determination of total penetration relative to particle activity,
- measurement of the activity deposited on two connected in series specimens of filter material to be tested.

In principle, this method corresponds to the test method in accordance with DIN 24184 /4/, for which thoron daughters attached on atmospheric aerosol as test aerosol are used.

Method D

- polydisperse paraffin oil test aerosol,

- determination of total penetration relative to the intensity of total scattered light,
- measurement of the intensity of total scattered light of aerosol samples taken before and after the filter material to be tested.

This corresponds to the test method in accordance with DIN 24184 /4/ and DIN 3181 /5/ (paraffin oil test aerosol).

3. Test aerosol

3.1. NaCl test aerosols

For methods A, B-1, B-2 and C NaCl is used as test aerosol. In all cases the aerosol is generated by atomizing 2.5% aqueous NaCl solution with compressed air. The liquid drops developing are mixed with the testing air flow. The water evaporates. The filters are tested with NaCl crystals.

To generate aerosols, two different types of aerosol generators are used: Type I consists of a cylindrical vessel partly filled with an aqueous NaCl solution (see Fig. 2 a). The compressed air fed in at the bottom bubbles through the NaCl solution.

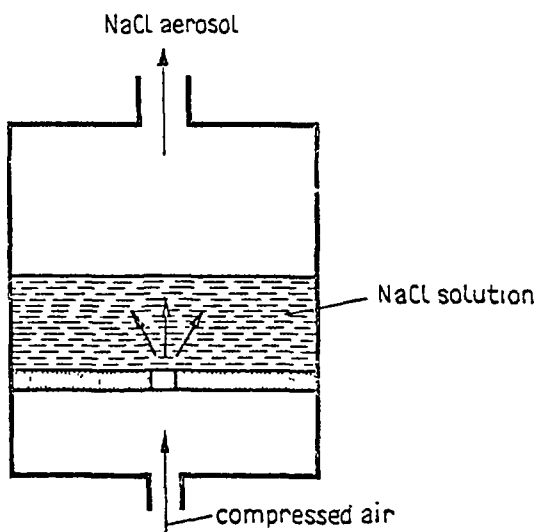


Fig. 2a Bubble generator

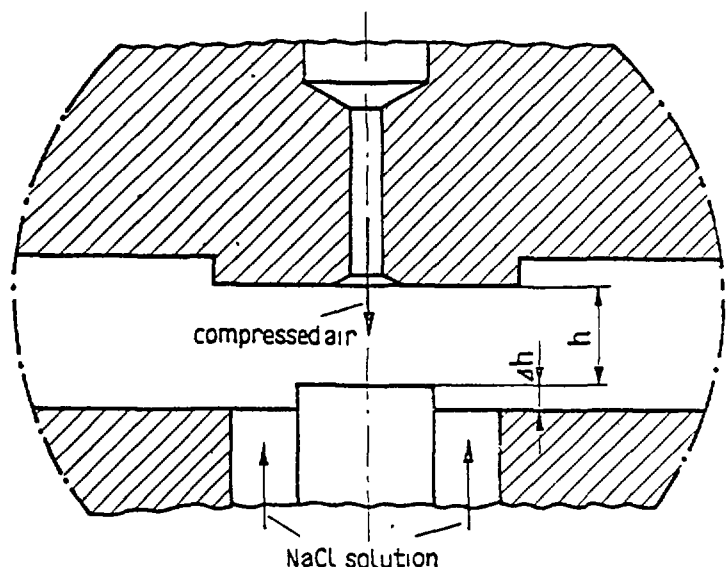


Fig. 2b Adjustable atomizer nozzle

The liquid drops developing are partly precipitated at the walls and the lid of the vessel and partly taken along with the air flow out of the generator. Both with respect to concentration and to particle size distribution the test aerosol exhibits a good long-time constancy. The aerosol parameters mainly depend on the geometric dimensions of the vessel and the liquid level in the vessel, the diameter of the compressed air inlet and the operating pressure. Type II is a so-called binary nozzle (see Fig. 2b). The NaCl solution is sucked by compressed air through a cylindrical tube and a ringlike slot by means of injector effect from the supply vessel and atomized by the compressed air. Larger liquid particles are separated in the nozzle interior by impaction. Here as well, the aerosol parameters depend on the geometric dimensions of the aerosol generator and the operating pressure.

The particle size distribution of NaCl aerosols relative to particle number was determined with the SARTORIUS scintillation particle counter (SST). The measurement is based on the principle of light emission of atomic Na vapour which is excited in an air-hydrogen flame. In contrast with the flame-photometric determination of the concentration of NaCl aerosols, the NaCl particles are individually and successively introduced into the excitation space of the flame. This makes the measurement of particle size distributions possible, since there is a definite relation between light intensity and particle size /6/. The lower detection limit corresponds to a particle size^{+) of 0.032 μm . The measurement is made in 10 channels. In a certain channel all particles are indicated which are larger than the particle size corresponding to this channel. Thus, declining cumulative distribution curves are obtained in graphical representation.}

Test methods A, B-1, B-2 and C require different concentrations and particle size distributions (mean value and scattering) of test aerosols. Optimal aerosol properties were obtained with Type I and II aerosol generators by choosing appropriate operating conditions and adjustment parameters. The particle size distributions measured with the SST can be approximated by logarithmic normal distributions. Thus the distributions

^{+) In the present Report the term particle size in case of NaCl aerosols refers to the edge length of NaCl crystals.}

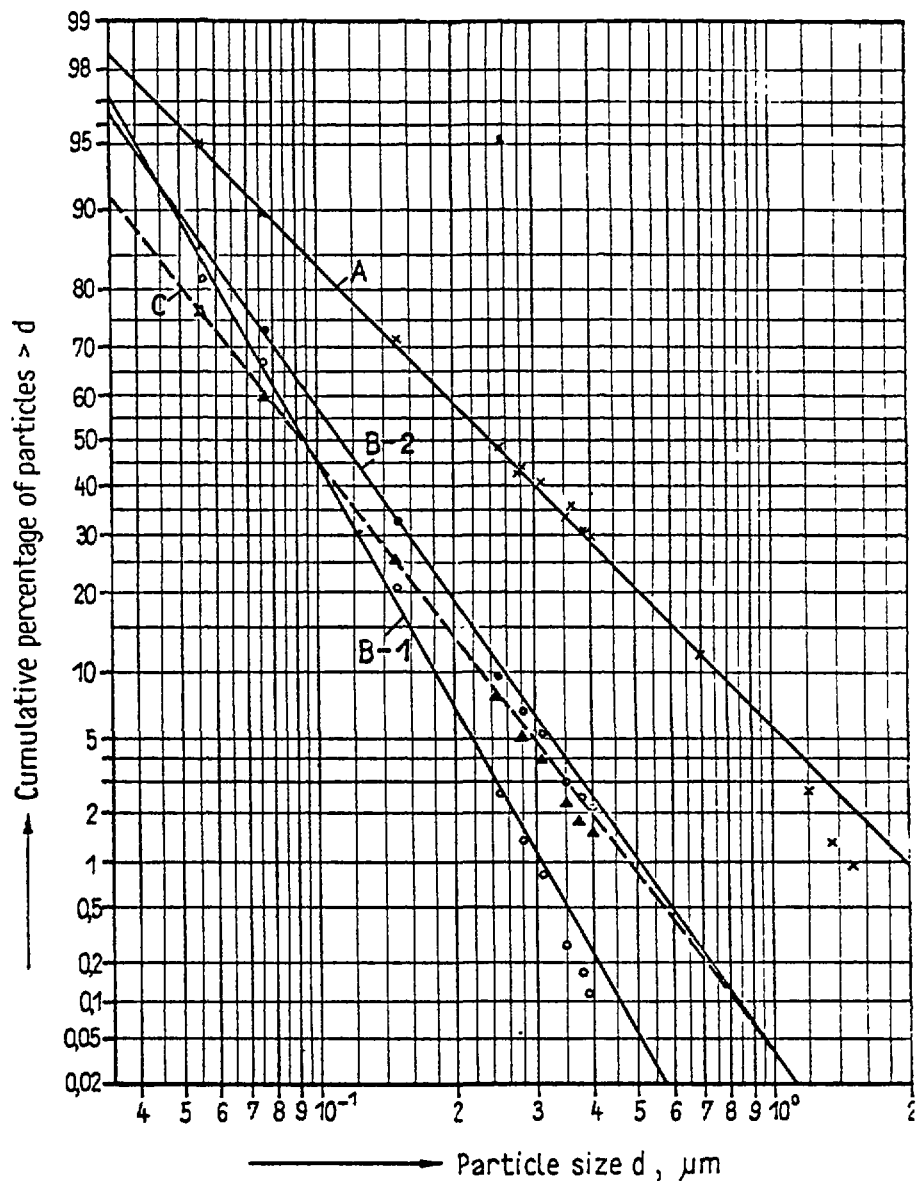


Fig. 3 Measured cumulative distribution of the used NaCl test aerosols (methods A, B-1, C), relative to the number of particles

relative to particle number are definitely characterized by the median value (50%-value) CMD (Count Median Diameter) and the geometric standard deviation σ_g . In case of a mass or activity distribution, the CMD is to be replaced by the MMD (Mass Median Diameter) or the AMD (Activity Median Diameter).

Fig. 3 shows the experimentally determined cumulative distributions of the particle size distribution relative to particle number for methods A, B-1, B-2 and C in the logarithmic probability paper. Fig. 4 shows the corresponding cumulative frequency distributions relevant for the measured quantity to be determined.

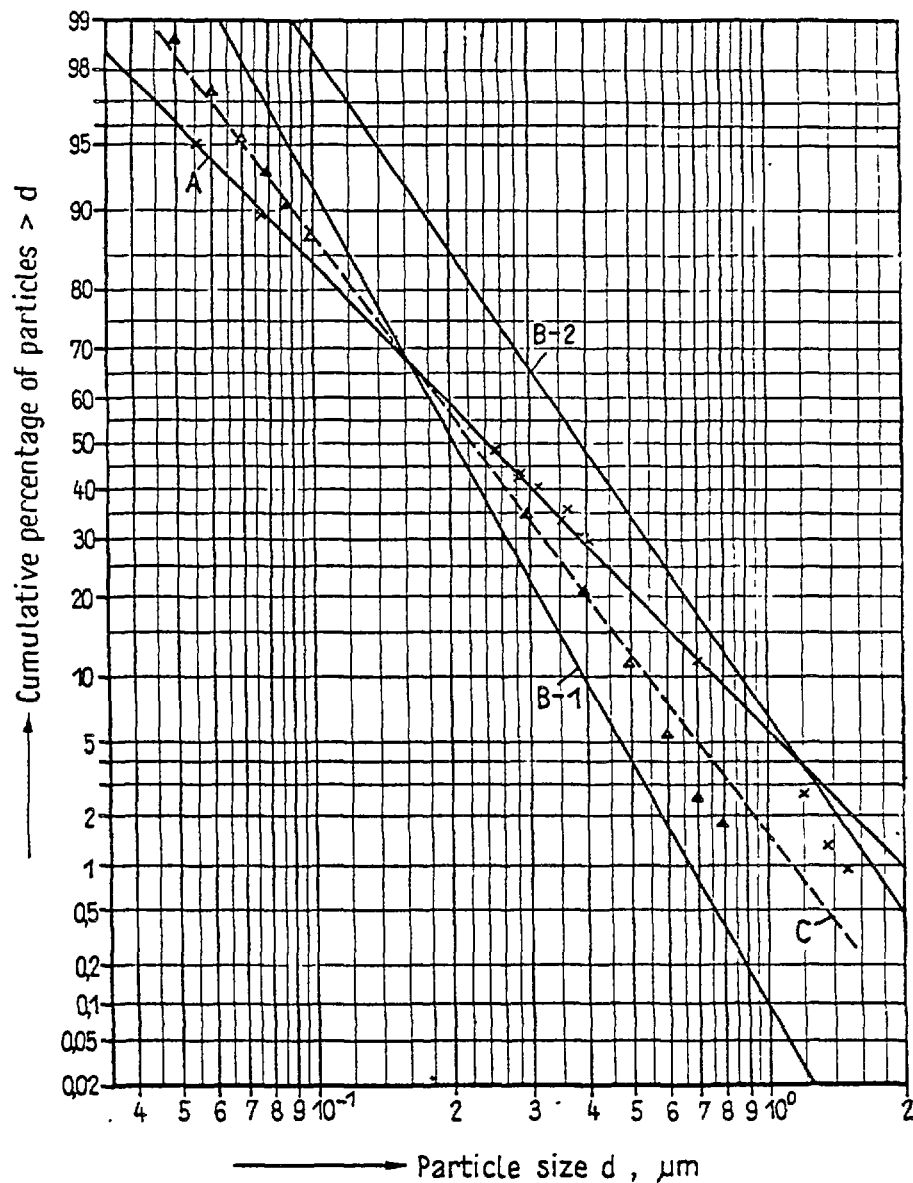


Fig.4 Relevant cumulative distribution of the used NaCl test aerosols relative to
 - number of particles (method A)
 - mass of particles (methods B-1, B-2)
 - activity of particles (method C)

Method A

To be able to determine penetrations with sufficient accuracy for the entire range of particle size of interest, a test aerosol is required distributed as equally as possible over this range. However, due to unavoidable particle losses in the testing apparatus, this can hardly be realized.

For the test aerosol used for method A (see Fig. 3 and 4, curves A) one obtains:

$$CMD = 0.24 \mu m, \sigma_g = 2.5$$

Methods B-1 and B-2

For these methods the mass distribution of the test aerosol is relevant. A finely dispersed test aerosol should be used, so that the influence of large particles on total penetration is not overrated. To make possible, within the frame of the present investigations, a qualitative comparison between the various methods, mass distribution should lie within the particle size range covered by method A. To study the influence of mass distribution on total penetration relative to particle mass, for methods B-1 and B-2 test aerosols of different particle size distribution were used.

To reduce the fraction of large particles in the test aerosol, for method B-1 a fibre filter used by a high velocity was located after the aerosol generator.

The test aerosols used are characterized by the following parameters:

	CMD in μm	MMD in μm	σ_g
Method B-1	0.093	0.20	1.7
Method B-2	0.11	0.39	1.9

For logarithmic normal distributions the MMD can be derived from the CMD /7/:

$$\ln \text{MMD} = \ln \text{CMD} + 3 \ln^2 \sigma_g$$

At transition to mass distribution, the standard deviation σ_g remains unchanged.

Fig. 4 (curves B-1 and B-2) shows the mass distributions calculated as mentioned above from the experimentally determined particle size distributions relative to particle number (see Fig. 3, curves B-1 and B-2).

Method C

For this method the activity distribution of the test aerosol is relevant. A NaCl aerosol with the following parameters (see Fig. 3, curve C) serves as carrier aerosol for the attached short-lived radon daughters:

$$\text{CMD} = 0.093 \mu\text{m}, \sigma_g = 2.1$$

The activity distribution was calculated from the measured particle size distribution relative to particle number according to the attachment theory by Lassen /8/+). For the particle size range of interest, the attached activity is proportional $R^2/(1 + hR)$ (R = particle diameter in cm, $h = 7 \cdot 10^4 \text{ cm}^{-1}$ for radon daughters).

The values calculated for the activity distribution of the test aerosol can be approximated by a logarithmic normal distribution. One obtains (see Fig. 4, curve C):

$$\text{AMD} \approx 0.22 \mu\text{m}, \quad \sigma_g \approx 2.1$$

3.2. Paraffin oil test aerosol (method D)

The paraffin oil test aerosol is generated by the aerosol generator (Type VI of Dräger) described in DIN 24184 /4/ and DIN 3181 /5/. The technically pure, non-resinous and non-alkaline paraffin oil (density = 0.843 g/cm^3 at 20°C) is heated in a thermostat to 100°C and atomized by filtered compressed air. The paraffin aerosol is then fed into a mixing vessel and here diluted with filtered air.

Fig. 5 shows the cumulative distribution of the test aerosol relative to particle number in the logarithmic probability paper as a function of Stokes diameter /5/. The median value (50% value) of the paraffin oil test aerosol is $0.40 \mu\text{m}$, the geometric standard deviation 1.8.

4. Test procedure and measuring results

4.1. Method A

Method A has been described in /2, 9, 10/. To determine the penetration relative to particle number as a function of particle size, the particle size distribution is measured before and after the filter material to be tested. From this, the penetrations of the respective particle size intervals are calculated.

+) The theory valid for spherical particles is used here as an approximation

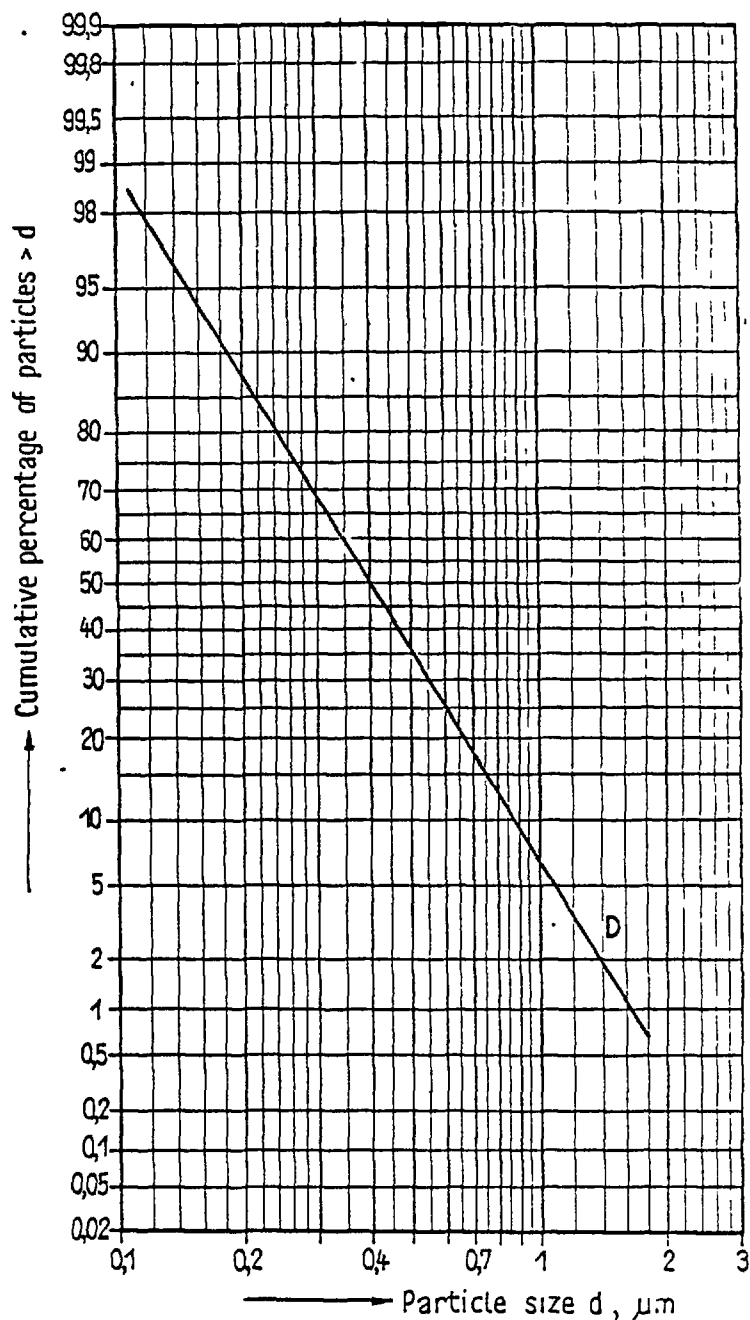


Fig.5 Cumulative frequency distribution of the used paraffin oil test aerosol relative to the number of particles[5]

These are represented by way of columns to make the interval division given by the SST visible. With the chosen test aerosol (see Fig. 3 and 4, curves A) a particle size range of nearly two orders of magnitude is covered.

Fig. 6 shows the experimentally determined penetrations P_i as a function of particle size for filter materials 1 to 5 and a velocity of 2 cm/s. Figs. 7 and 8 show the respective results

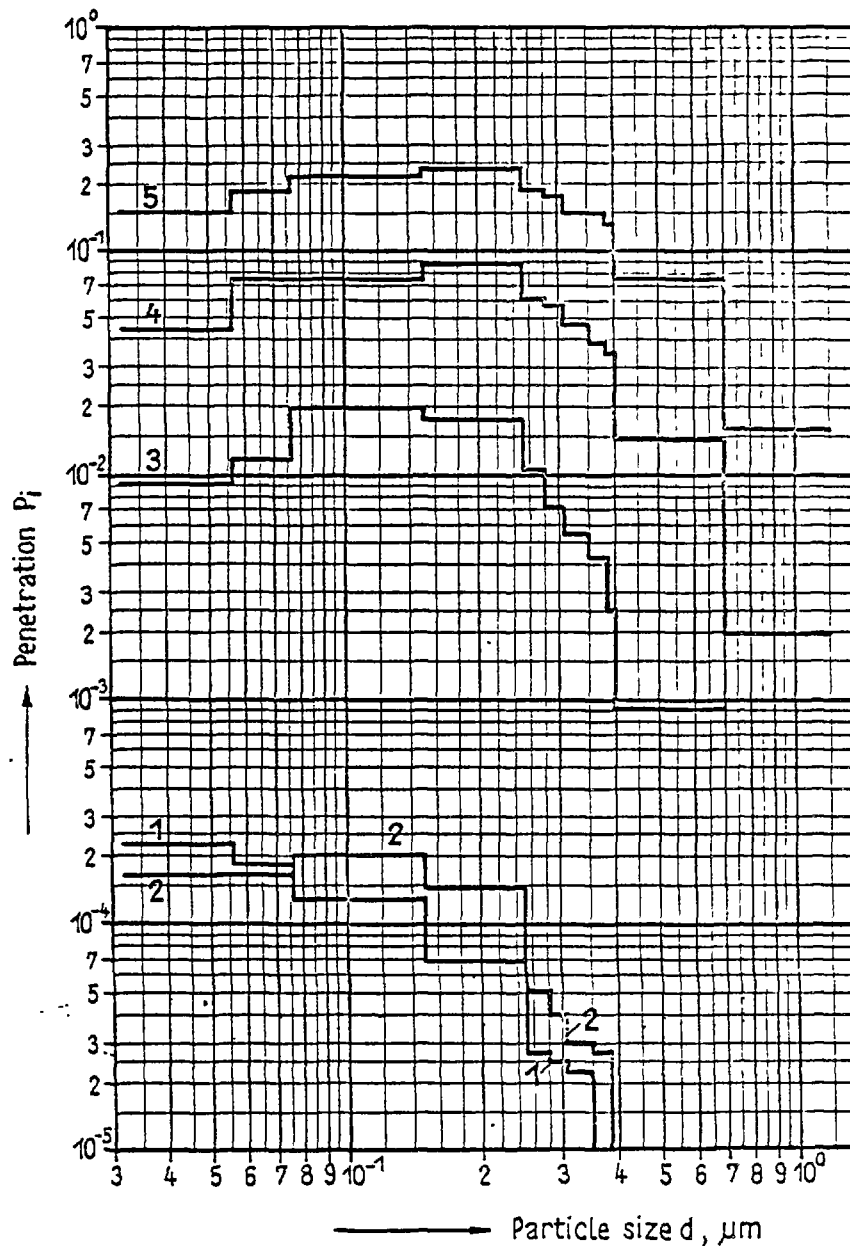


Fig.6 Results of method A : Penetration (relative to the number of particles) versus particle size (velocity $v = 2 \text{ cm/s}$, filter materials 1-5)

for velocities of 5 and 10 cm/s. In the present paper, all penetrations are given in absolute values. For filter materials 3, 4 and 5 the maximum penetration lies within the particle size range investigated and for filter materials 1 and 2 below the SST detection limit. For larger particles, penetration values strongly decrease. This occurs at particle sizes equal to or smaller than $0.3 \mu m$ and depends on filter material and velocity. From this it follows that, for the filter materials studied, the critical range of filtration lies below $0.3 \mu m$.

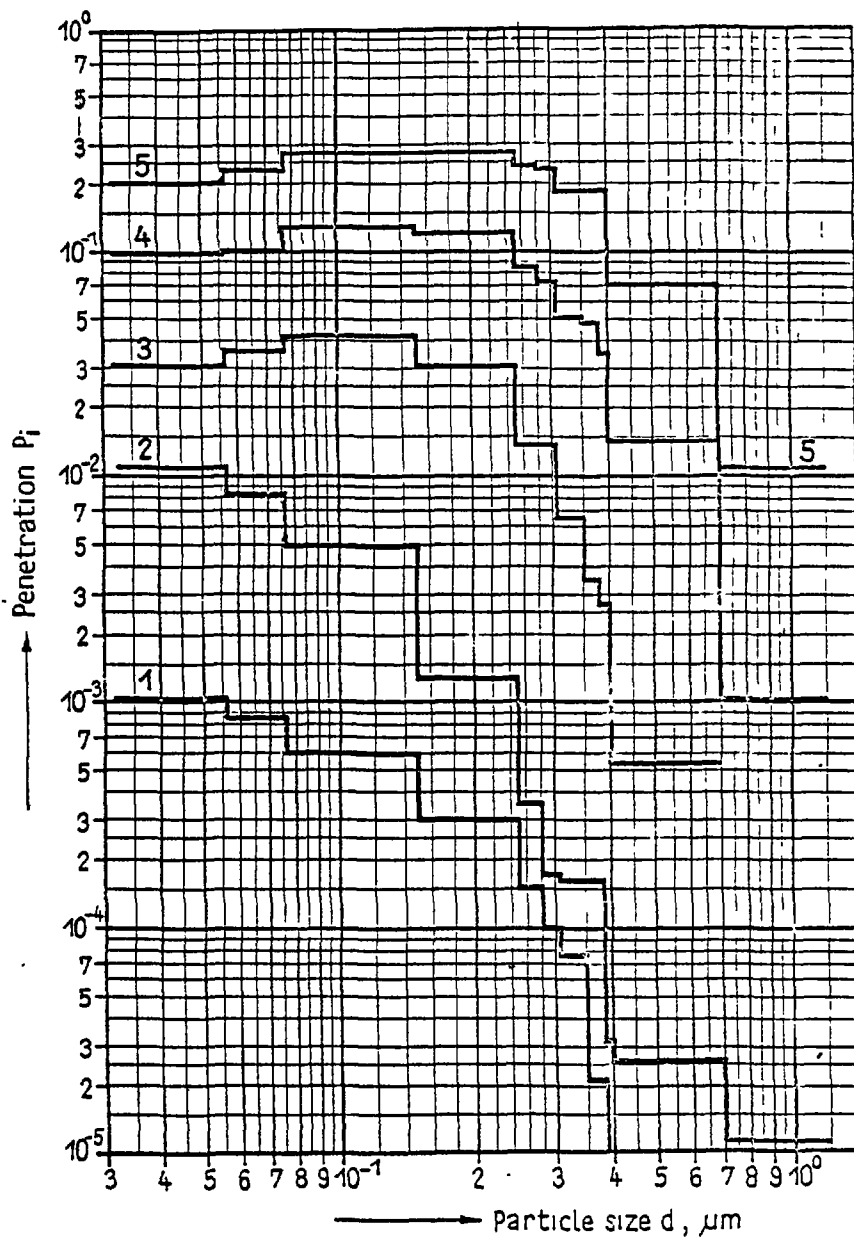


Fig.7 Results of method A: Penetration (relative to the number of particles) versus particle size (velocity $v = 5\text{cm/s}$, filter materials 1-5)

Additional, using method A one obtains the total penetration relative to particle number. Fig. 9 shows the results as a function of velocity for filter materials 1 to 5. The dependence on velocity is more strongly pronounced for high-quality filter materials.

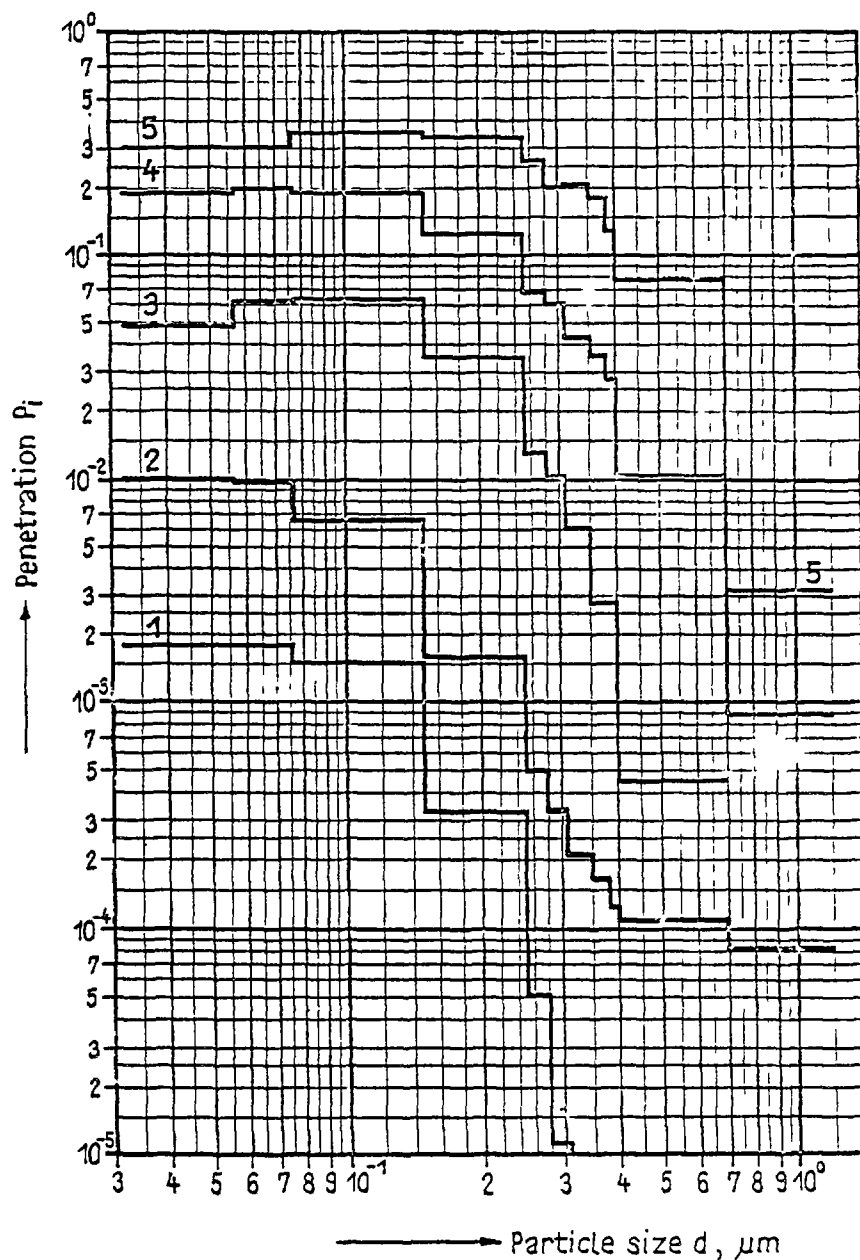


Fig.8 Results of method A: Penetration (relative to the number of particles) versus particle size (velocity $v = 10 \text{ cm/s}$, filter materials 1-5)

4.2. Methods B-1 and B-2

The mass concentration of the aerosol before and after the filter material to be tested is measured as by a flame photometer by the unit for mass concentration determination installed in the SST. However, due to the microflame used, lower concentrations can be detected. The measuring range is $0.1 \mu\text{g/m}^3$ to 20 mg/m^3 . To detect higher concentrations, a definite dilution with aerosol-free air is necessary.

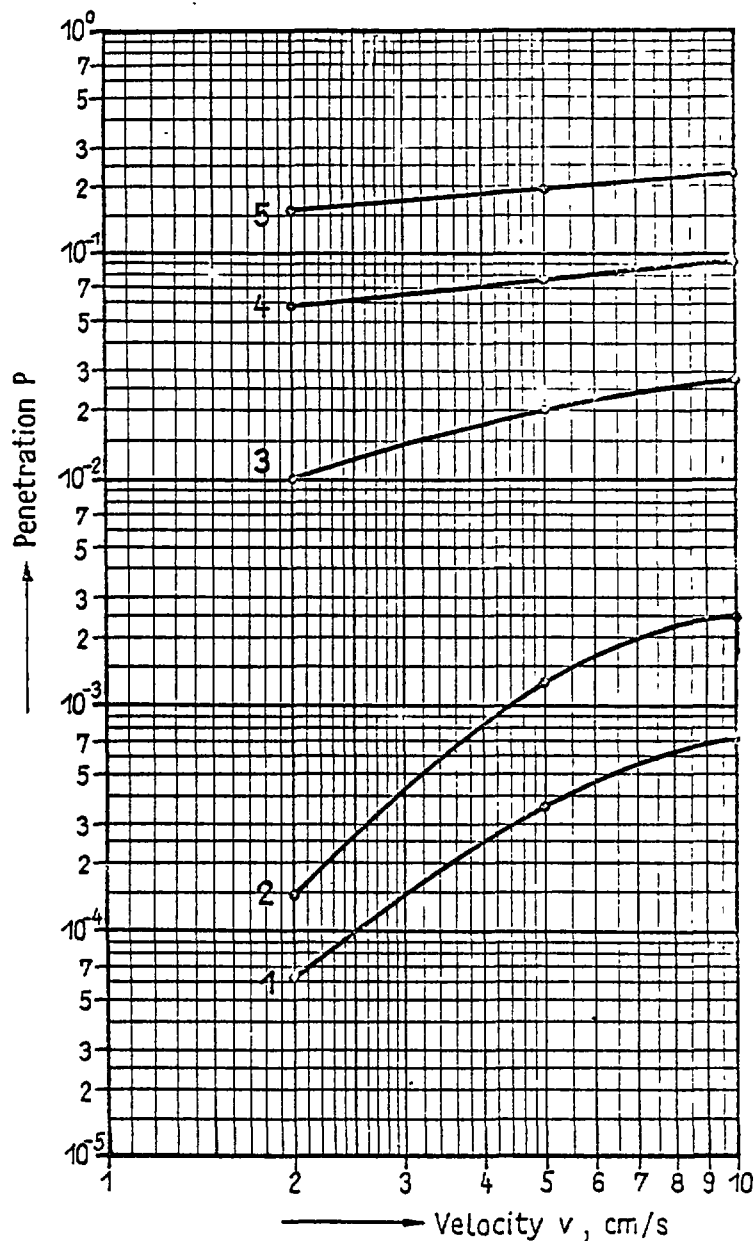


Fig.9 Results of method A : Total penetration (relative to the number of particles) versus velocity (filter materials 1-5)

To determine the total penetration relative to particle mass as a function of velocity, investigations with two different test aerosols were performed. With the more finely dispersed aerosol (see Fig. 3 and 4, curves B-1) filter materials 1 to 5 were investigated and with the less finely dispersed aerosol (see Fig. 3 and 4, curves B-2)- filter materials 3, 4 and 5. The results have been represented in Fig. 10. For methods B-1 and B-2 significant differences result for total penetrations. Thus it becomes clear that already

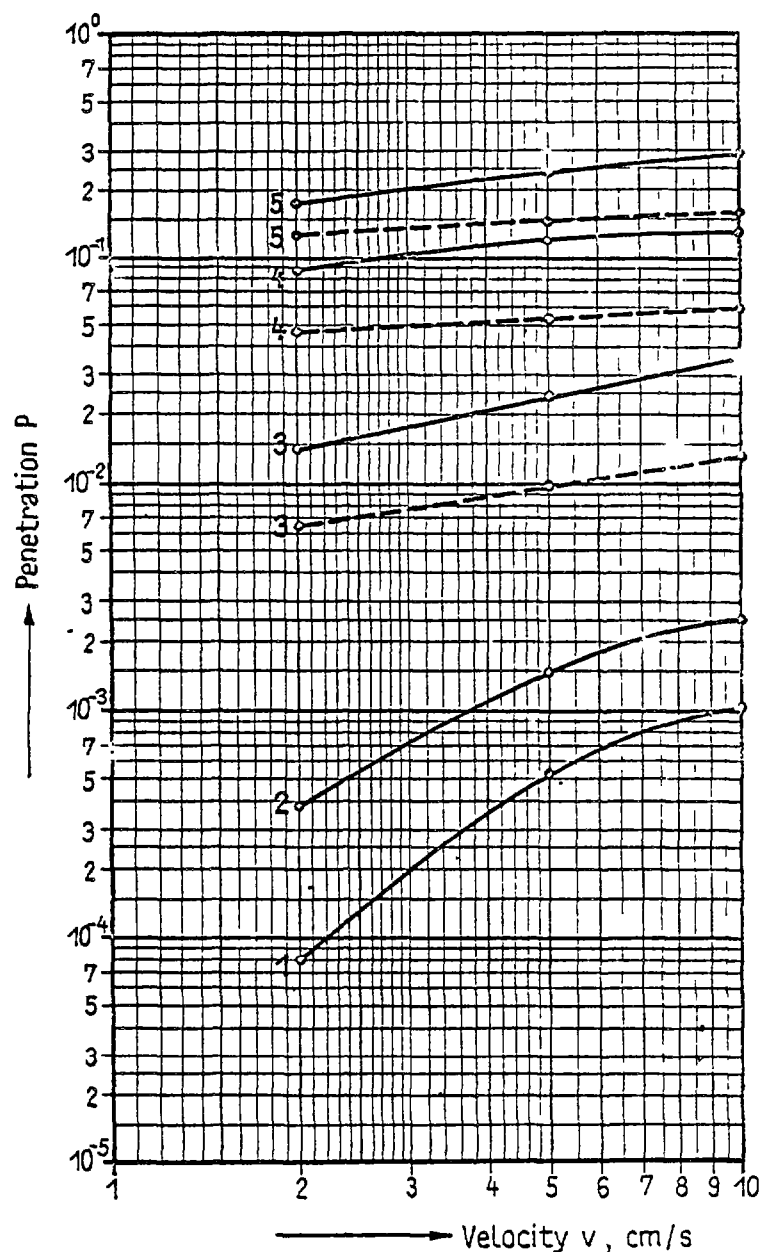


Fig.10 Results of methods B-1 (—) and B-2(---):
Total penetration (relative to the mass of particles)
versus velocity
(filter materials 1-5/B-1/ and 1-3/B-2/)

small changes in the size distribution of the test aerosol
 $((\text{CMD})_{\text{B-2}}/(\text{CMD})_{\text{B-1}} = 1.18; (\text{MMD})_{\text{B-2}}/(\text{MMD})_{\text{B-1}} = 1.95;$
 $(\sigma_g)_{\text{B-2}}/(\sigma_g)_{\text{B-1}} = 1.12)$ considerably influence the values
of total penetration.

4.3. Method C

The setup of the test apparatus has been described in /11/.
The NaCl aerosol (see Fig. 3, curve C) is in a testing chamber
of 12 m³ content equipped with a mixing fan. The radioactive

noble gas Rn-222 (half life: 3.8 days) is fed into this chamber. The short-lived radon daughters Po-218, Pb-214, Bi-214 and Po-214 attach to the NaCl aerosol. The activity distribution of the test aerosol relevant for the method is represented in Fig. 4 (curve C). In measurements, the so-called free fraction, i.e. the fraction of short-lived radon daughters not attached to aerosols lay below 3% in order to avoid falsifications of measuring results (low penetration for free radon daughters due to their great diffusion coefficient).

The total penetration relative to particle activity was determined according to the method of Hasenclever /12/. Here the test aerosol is deposited on two connected in series specimens of the filter material to be tested. Then alpha activity (Po-218, Po-214) is simultaneously measured for each of the two specimens. The total penetration follows from the ratio of pulse rates (N_1 for the first specimen, N_2 for the second one):

$$P = \frac{N_2}{N_1}$$

Fig. 11 shows the measured values as a function of velocity for filter materials 1 to 5.

4.4. Method D

To determine total penetration, the concentration of the paraffin oil aerosol is measured before and after the filter material to be tested as the intensity of total scattered light with the SARTORIUS aerosol photometer. The aerosol is fed through a measuring chamber where it hits a light beam at an angle of 45° . The scattered light is measured by a photomultiplier located at an angle of 45° to the forward direction of the beam. The measurable particle concentration relative to a mean particle size of the oil fog of 0.3 to $0.5 \mu\text{m}$ is about $5 \cdot 10^2$ to 10^8 particles/cm³ (about 10^{-12} to 10^{-6} g/cm³).

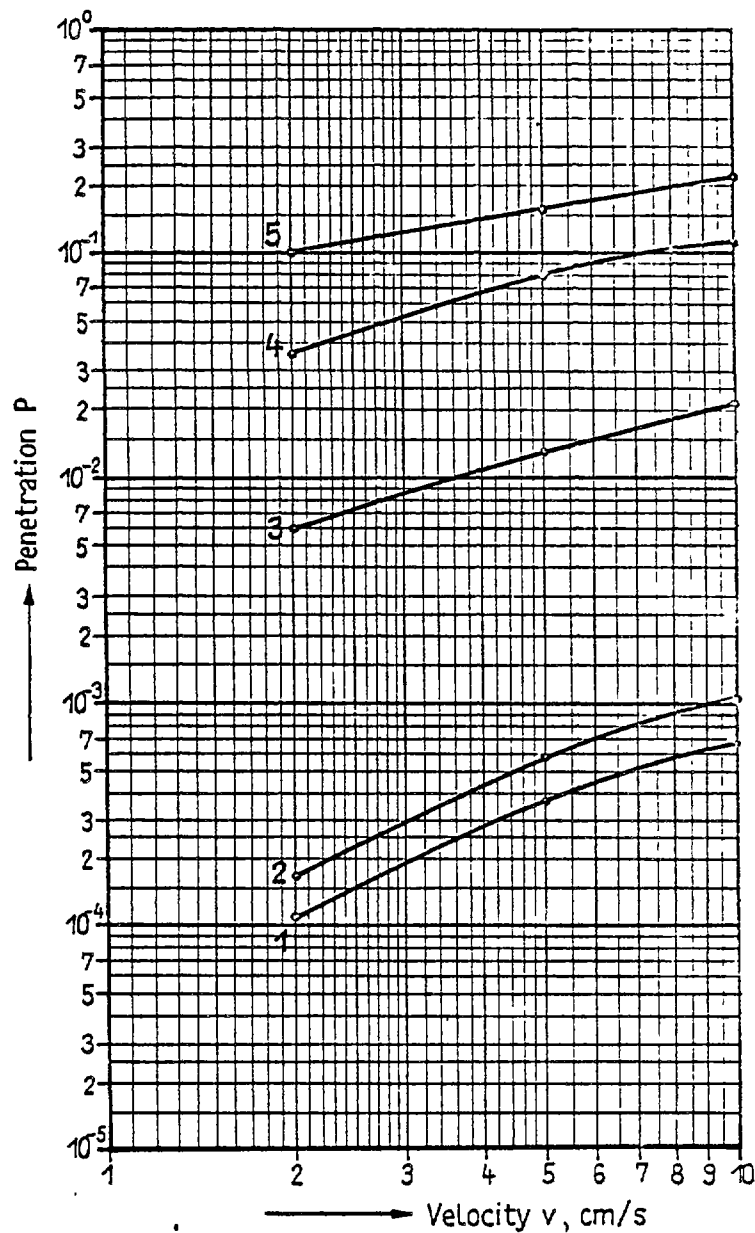


Fig.11 Results of method C : Total penetration (relative to the activity of particles) versus velocity (filter materials 1-5)

The measuring results obtained with the paraffin oil test aerosol (see Fig. 11) for the total penetration relative to the intensity of the total scattered light are represented in Fig 12 for filter materials 1 to 5 as a function of velocity.

5. Interpretation of the results of filter testing

5.1. Fundamentals

For each particle size or each particle size interval d_i there exists a specific penetration P_i . At sufficiently small particle

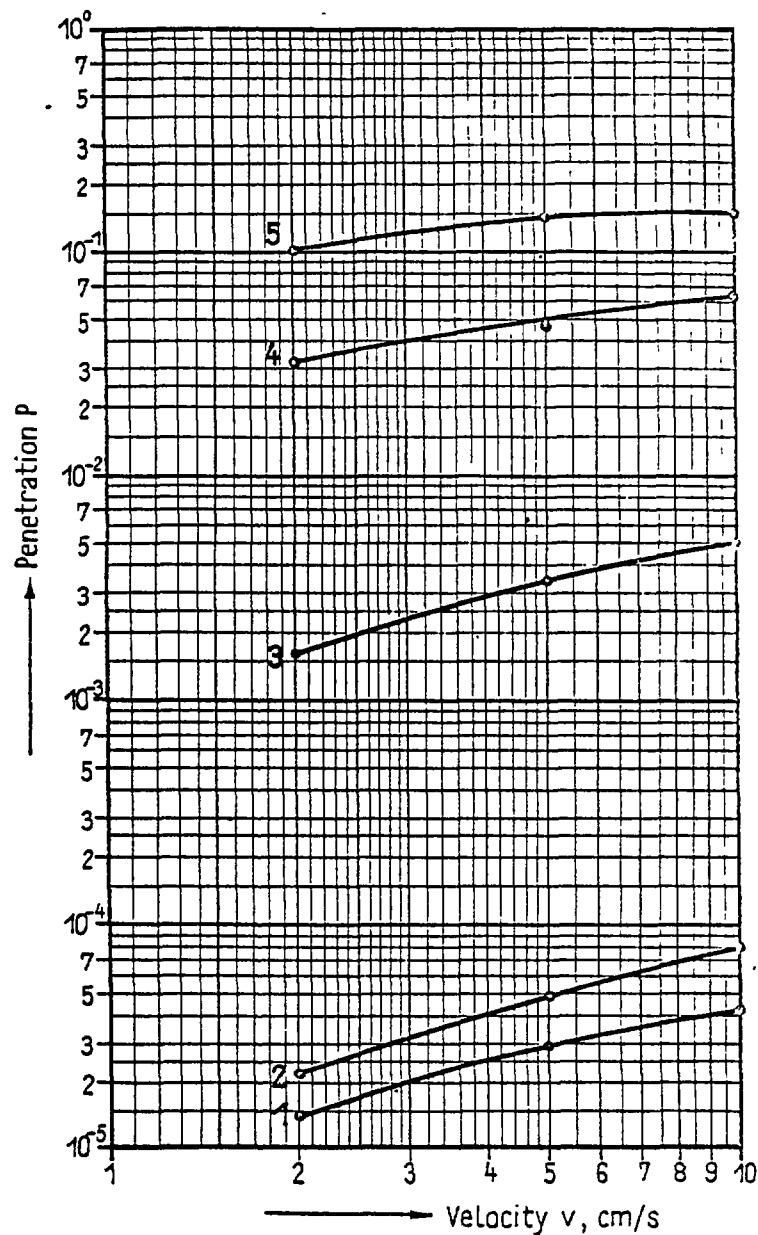


Fig. 12 Results of method D: Total penetration (relative to the intensity of total scattered light) versus velocity (filter materials 1-5)

size intervals, this is independent of the particle size distribution of the test aerosol. By the shape of penetration as a function of particle size the quality of a filter is characterized definitely. Therefore, test methods to determine this function exceed test methods to determine total penetration with respect to evidence. They are fundamental methods for filter testing.

Total penetration P summarily reflects the dependence on particle size. It is considerably influenced by the particle size distribution of the test aerosol used. Therefore, total

penetration can definitely characterize filter quality only if the test conditions are standardized and maintained accurately.

Mathematically, total penetration can be expressed as weighted sum:

$$P = \sum_{i=1}^n f_i P_i$$

- i = running index for particle size intervals
- n = number of particle size intervals considered
- P_i = penetration for i th particle size interval
- f_i = frequencies of relevant particle size distribution for i th particle size interval (fractions of particle number, mass and activity of i th particle size interval of total particle number, total mass and total activity).

If the P_i -values have been obtained with a fundamental method, the following estimations can be made:

- statement of the minimum value of the filter effect (maximum of penetration) reachable in practice if the relevant particle size distribution of the aerosol to be separated is unknown.
- assessment of the filter effect really reachable in practice for the aerosol to be separated if the f_i -values of the relevant particle size distribution are known (e.g. the activity distribution of an aerosol occurring at a Nuclear Power Plant).
- calculation of the total penetration to be expected when applying a specific test method if the f_i -values of the relevant particle size distribution of the test aerosol are known.

Following this procedure, total penetrations were determined using the experimentally determined P_i -values (see Fig. 6, 7 and 8) and the f_i -values of the relevant particle size distributions of the test aerosols used (see Fig. 4). These calculated values were related to the respective total penetrations experimentally determined with methods A, B-1, B-2 and C. By way of example these ratios are given for filter materials 3 and 5:

Method	Filter material 3			Filter material 5		
	Velocity v in cm/s					
	2	5	10	2	5	10
A	0.99	1.00	1.01	1.02	0.98	1.00
B-1	1.27	1.07	0.93	1.16	1.00	1.02
B-2	1.02	1.14	0.96	1.01	1.02	0.99
C	1.92	1.71	1.34	1.74	1.30	1.12

The agreement of the total penetrations derived from P_i - and f_i -values and determined directly is smaller for the method relative to activity than for the methods relative to particle number and mass. This can be explained by the errors occurring at the approximative transition from the distribution relative to particle number to activity distribution. When judging the degree of agreement, it should be considered that both the errors in experimental determination of P_i - and f_i -values and the errors in direct determination of total penetration will influence the ratio.

With respect to the assessment of total penetration values the following conclusions can be drawn:

- From the relevant median values (CMD, MED, AMD) of test aerosols qualitative statements on the relation between the total penetrations to be expected using different methods can be derived.
 - . If the relevant median values lie above the particle size corresponding to maximum penetration, total penetration is the lower, the greater the respective median value.
 - . If the relevant median values lie below the particle size corresponding to maximum penetration, total penetration is the lower, the smaller the respective median value.
- Statements on the above-mentioned relation become more reliable if, instead of relevant median values, the products of relevant median value and geometric standard deviation are compared for the respective test aerosols. In this way 84% of the relevant aerosol parameter (particle number, mass, activity) are included in the comparison.
- The more pronounced the dependence of penetration on particle size, the stronger the dependence of total penetration on the

relevant particle size distribution of the respective test aerosol. Thus, in the filter material investigated, the greater difference in the total penetrations obtained with different methods should be expected for the more efficient filter materials.

- Prerequisite to standardizing a test method to determine total penetration is the exact specification of relevant particle size distribution for the test aerosol.

5.2. Comparison of methods to determine total penetration

The measuring results are to be evaluated by means of the conclusions drawn in 5.1. For this purpose, both methods A, B-1, B-2 C and D and the investigations described by Dorman /1/ are included. The evaluation comprises:

- a comparison of different methods to determine total penetration by means of our own measuring results,
- a comparison of similar methods to determine total penetration by means of own measuring results and those described by Dorman for corresponding methods.

The results of comparisons are demonstrated by way of filter materials 3 and 5.

Comparison of different methods

Fig. 13 shows total penetrations for methods A, B-1, B-2, C and D as a function of velocity. As expected, the difference of values for filter material 5 is considerably smaller (smaller than factor 2) than for filter material 3 (up to factor 10).

Total penetrations for the investigations made with NaCl aerosols should decrease in the following series:

Method B-1:	MMD = 0.20	MMD · ϕ_g = 0.34
Method C :	AMD = 0.22	AMD · ϕ_g = 0.46
Method A :	CMD = 0.24	CMD · ϕ_g = 0.60
Method B-2:	MMD = 0.39	MMD · ϕ_g = 0.74

This is the case for the total penetration relative to particle number (Method A) and mass (methods B-1 and B-2). However, the total penetration relative to activity (method C) is lower than expected. Possible causes are mentioned in 5.1.

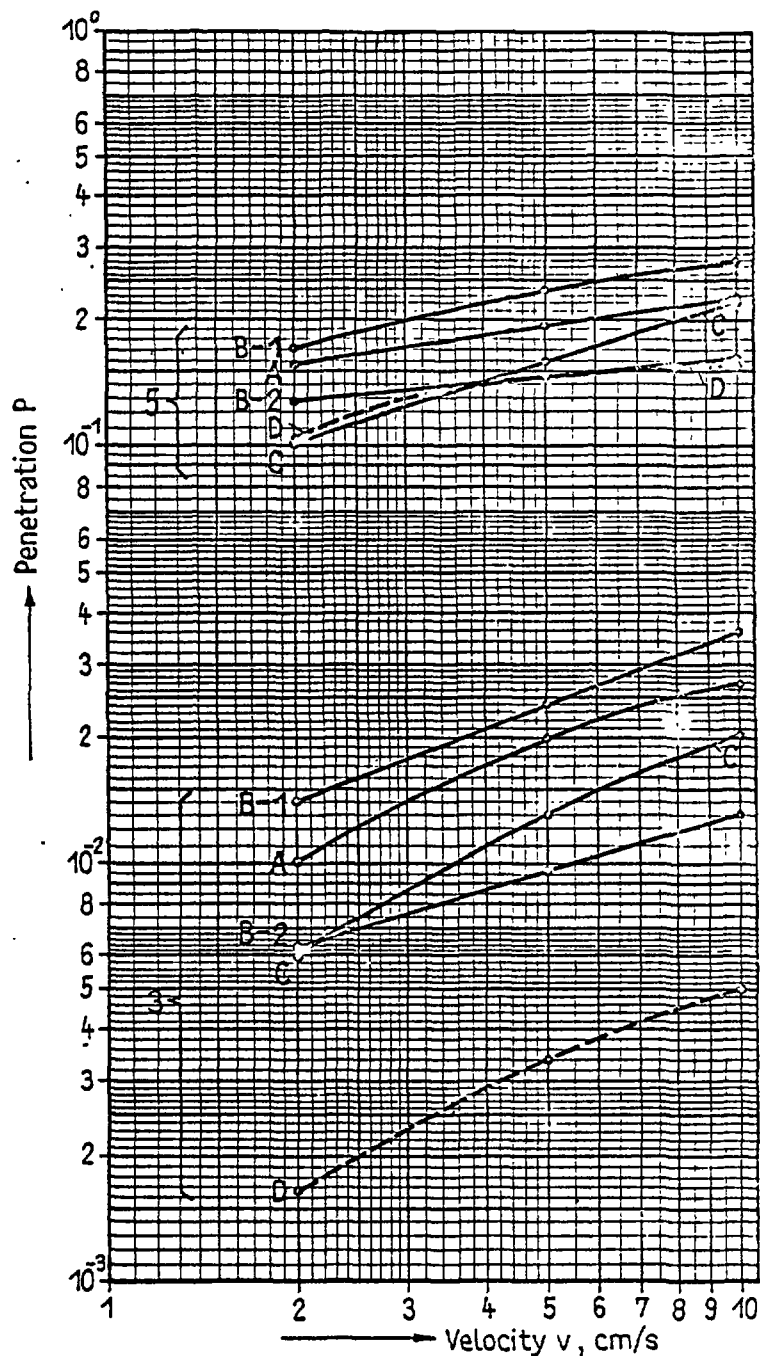


Fig. 13 Comparison of the results of methods A-D: Total penetration versus velocity (filter materials 3 and 5)

For method D only the particle size distribution relative to particle number as a function of Stokes diameter is known. The CMD value is $0.40 \mu\text{m}$. The relevant median value relative to the intensity of total scattered light and necessary for comparison is unknown. However, it is greater than the median values of methods A, B-1, B-2 and C. So it can be expected that the lowest values of total penetration will occur using method D. This becomes particularly evident for the more efficient filter material 3 (see Fig. 13).

Comparison of similar methods

The methods a.II and a.III described by Dorman correspond to methods B-1 and B-2. Likewise the methods a.IX and C as well as the methods a.VIII and D are comparable. For method A there is no possibility of comparison.

- NaCl test aerosols

The total penetration relative to particle mass is shown in Fig. 14 for methods B-1, B-2, a.II and a.III as a function of velocity. Methods a.II and a.III correspond to the NaCl flame test in accordance with the British Standard B.S. 3928 /3/.

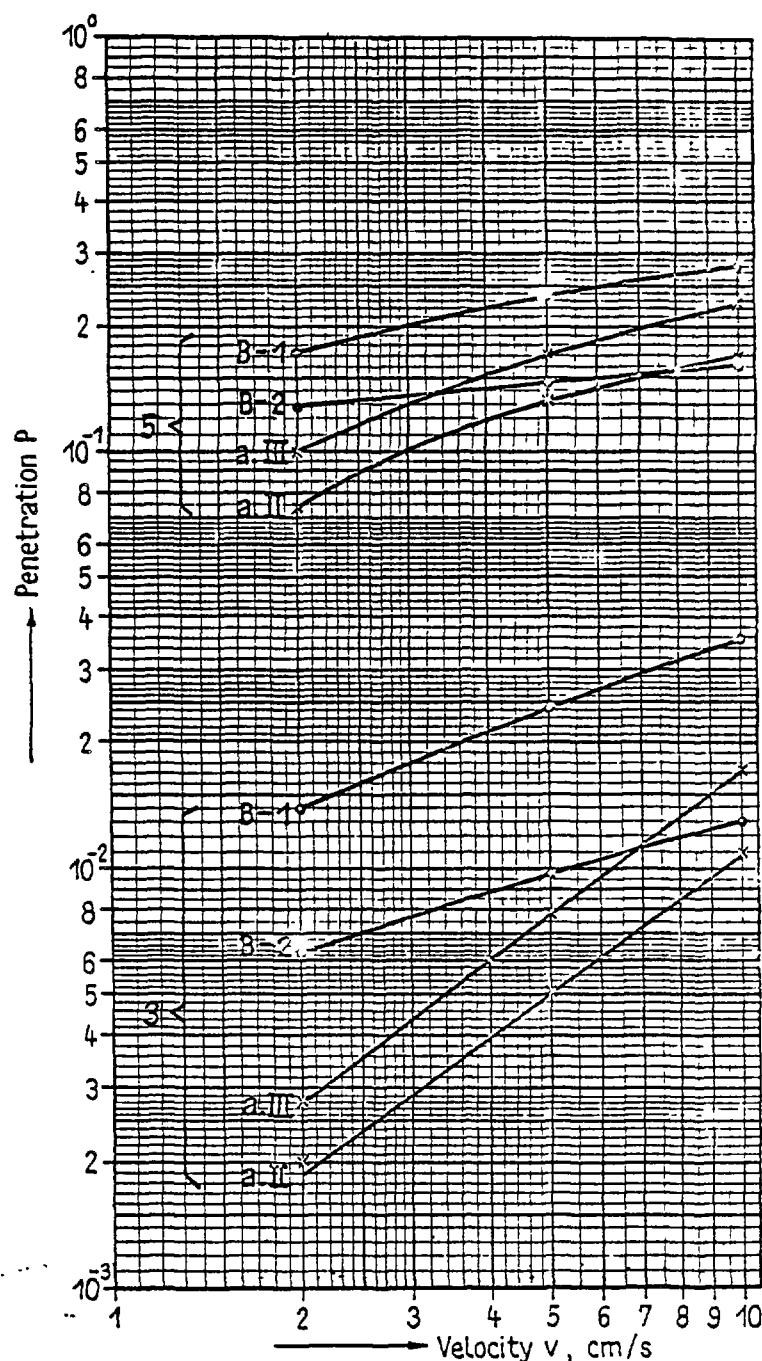


Fig.14 Comparison of the results of methods B-1 and B-2 with results described in [1] (filter materials 3 and 5)

They differ of each other in the manner of aerosol generation: Collison atomizer (a.II) and Dautrebande atomizer (a.III), respectively. For the NaCl aerosols used one obtains the following MMD-values:

Method	B-1	B-2	a.III	a.II
MMD in μm	0.20	0.39	0.40-0.45 /1/	0.65 /1/

As expected, method B-1 yields the highest and method a.II the lowest values for total penetration, the differences for the efficient filter material 3 being particularly evident. As the MMD-values do not differ considerably for methods B-1 and a.III, the σ_g -values should be included in the consideration. For method a.III, however, no σ_g -value was given.

- aerosols with attached thoron- and radon daughters

Method a.IX is the test method described in DIN 24184 /4/. Thoron daughters attached on atmospheric aerosol are used as test aerosol, the free fraction of thoron daughters not being limited. Fig. 15 shows the total penetrations relative to activity as a function of velocity. Method a.IX yields lower values than method C. The cause could be a higher value for the free fraction of thoron daughters in method a.IX (low penetration for free thoron daughters due to their high diffusion coefficient).

As expected, the difference of measuring results is more clearly pronounced for the more efficient filter material 3 and particularly great for low velocities. This is supported by the fact that the relevant median value for the extremely finely dispersed aerosol in method a.IX lies below the particle size corresponding to the maximum of penetration.

- paraffin oil test aerosol

Methods D and a.VIII correspond to the test method standardized in DIN 18124. As expected, the measuring results show good agreement, since in both cases standardized equipment was used for generating and measuring the aerosol. For the ratio of the total penetrations determined with methods a.VIII and D the following values are obtained:

Velocity in cm/s	2	5	10
Filter material 3	1.05	0.86	0.80
Filter material 5	1.02	1.00	1.07

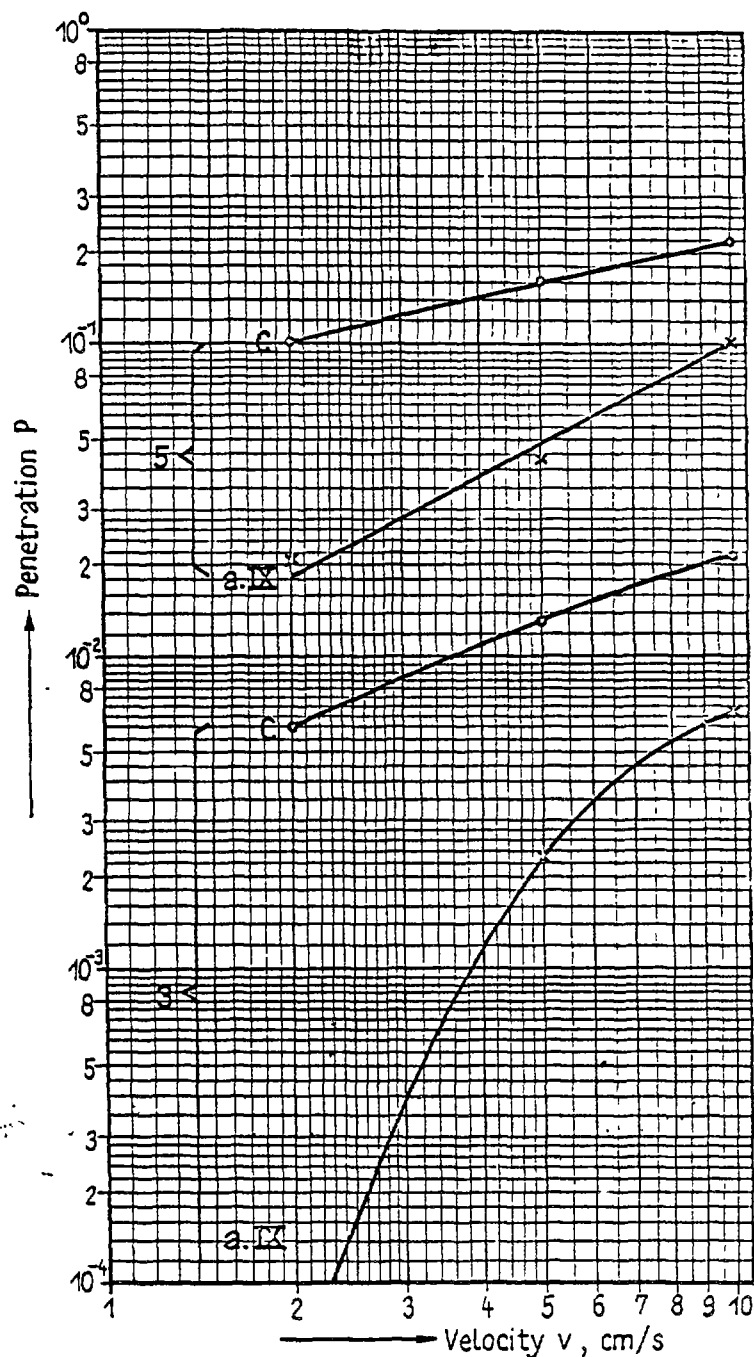


Fig. 15 Comparison of the results of method C with results described in [1] (filter materials 3 and 5)

6. Final consideration

The results of different test methods can differ considerably, e.g. for filter material 3 (see Fig. 1 and 13) by about one order of magnitude. The present paper shows that these deviations are mainly due to the different relevant particle size distributions of test aerosols.

The judging of filter test methods must base on the two different aims of filter testing:

- determination of characteristic filter properties (e.g. for filter development, type testing and testing for special purposes),
- control of the maintenance of specified filter properties (e.g. for production control and in-situ testing (commissioning- and repetitive test)).

In the first case general statements on penetration independent of the test aerosol are required. For this purpose methods to determine penetration as a function of particle size are suitable. If a method to determine total penetration is chosen, the relevant particle size distribution of the test aerosol should be adapted to the provided aim. If necessary, several methods should be used to cover all operating conditions of interest. This has been considered in DIN 24184 (3 test methods). At a too great relevant median value of the test aerosol e.g. a too low total penetration of the filter is simulated.

In the second case only relative values have to be determined for penetration. These can relate to filter penetration at the time of commissioning, e.g. in case of repetitive tests. Here, the test method should be chosen in a way that a relative value of sufficient evidence will be obtained for the provided aim. Then, the above-mentioned demands for adapting the test aerosol can be omitted.

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COMPARISON OF EXISTING METHODS OF HIGH EFFICIENCY PARTICULATE AIR FILTER TESTING*

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Abstract

With a view to carry out detailed studies for the comparison of different HEPA filter test methods, a set of twenty HEPA filters of 1000 cfm capacity with the same materials of construction were tested by the polydisperse DOP method, uranine method and the sodium chloride method. The test rig used for the test methods was the same and was fabricated based on British Standard BS 3928.

The polydisperse DOP method employs an aerosol generator consisting of laskin type atomizer nozzles to give an aerosol of DOP in submicron size range with 0.3 micron MMD. A size selective single particle counter set to count particles between 0.3 to 0.35 micron was used for measuring the concentration.

The test aerosol of uranine method is a di-sodium salt of fluorescein with 0.54 micron MMD and is generated by atomization of 1% uranine solution using collision type nozzles. The concentration of aerosol collected on the membrane filter is measured by fluorimetry.

The test aerosol of sodium chloride is generated by atomization of 2% solution of CaCl_2 using collision type atomiser nozzles. The mass median diameter of the aerosol was 0.4 micron. The concentration of NaCl is measured using flame photometry.

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A comparison of the penetration results determined by the three methods indicates that the values of uranine method are always higher than that of polydisperse DOP and sodium chloride methods. This can be attributed to the possible cross contamination during downstream sampling and analysis in the uranine method. The values determined by DOP and sodium chloride method can be of the same order.

Considering the quickness, reproducibility of the test results and the quick response and the portability of the particle counter, the polydisperse DOP method is very much suitable for large scale rig tests of HEPA filters and the in-situ test of filter installation. However, this cannot be a quantitative test of a filter medium because of the lower detecting limit of the counter. The uranine method is more suited only for the laboratory investigations of filter media because of its main disadvantage of longer duration of testing. Though the sodium chloride test is fast and reproducible to adapt for large scale evaluation of filters and as an accurate laboratory test, the method is difficult to adapt as an in situ test method because of the limitation of using flame photometry at the site.

1. INTRODUCTION

High Efficiency Particulate Air Filters are used as the ultimate means for the removal of air borne particulates from air streams. In nuclear industry they are used as an important engineering safeguard to prevent the release of air borne particulates to the environment. HEPA filters are therefore manufactured under strict quality control and are subject to stringent tests before being accepted for use in the system. Based on purely theoretical considerations it has been established that in the absence of any damage or manufacturing defect these filters should have a minimum collection efficiency for a particular size of particulate for the velocity normally encountered in practice. The basic principle of testing of HEPA filters consists in measuring the trace quantity of test aerosol of specific size characteristics penetrating the filter. The primary requirements of a filter testing method to evaluate the particulate removal effectiveness of a HEPA filter are given in Table-1.

TABLE - 1

PRIMARY REQUIREMENTS OF HEPA FILTER TEST METHODS

Reproducibility	size characteristics of aerosol, concentration levels, test results.
Sensitivity	analytical instrument
Selectivity	particle size
Useability	humidity and temperature
Adaptability	in-situ leak tests
Ease and speed	mass-scale evaluation of filters
Economy	cost of installation and operation
Toxicity	health hazards

Based on the development works in various countries presently different methods of testing of HEPA filters have been standardised and are followed in different countries to evaluate particulate removal efficiency of these filters (1-9). New methods are also being investigated for implementation (10-15). These methods differ from each other not only in the analytical technique employed but also in such basic parameters like size distribution of test aerosol, mass median diameter, concentration of test aerosol, etc. Table-2 summarises the type of aerosols employed and detection and measurement system.

A need for comparison of filter testing methods has arisen from the multiplicity of tests used, hence an attempt to correlate the results of the different methods requires priority consideration. Correlation of the test results of different methods will enable the manufacturers and users to compare the products which they make, buy and use, with products of other firms.

TABLE - 2

TYPE OF AEROSOLS AND ANALYTICAL METHOD

<u>Aerosol</u>	<u>Detection and measurement</u>
Monodisperse DOP liquid droplets of 0.3 micron generated by condensation of vapour	Forward light scattering photometer
Hetero-disperse DOP liquid droplets of 0.3 micron MMD generated by pneumatic atomization of liquid DOP	Forward light scattering size selective single particle counter.
Hetero-disperse, cubical NaCl particles generated by pneumatic atomization of solution of NaCl with subsequent evaporation to solid particles	Flame photometer
Hetero-disperse particles of Uranine generated by pneumatic atomization of solution of uranine with subsequent evaporation to solid particles	Photo fluorimeter
Hetero-disperse particles of Methylene Blue generated by atomization of solution of Methylene Blue with subsequent evaporation to solid particles	Staining-Densitometer
Natural atmospheric dust	Condensation Nucleimeter
Hetero-disperse paraffin liquid droplets generated by pneumatic atomization of liquid paraffin oil	45° forward angle light scattering photometer
Radioactive aerosol/Radioactive tagged aerosol	Nuclear Counting instrument

2. SCOPE AND OUTLINE OF THE RESEARCH PROGRAMME

A coordinated research programme on the comparison of filter testing methods was undertaken by the Air Cleaning Engineering Research Section of Bhabha Atomic Research Centre. The objective of the project was to carry out detailed studies for the comparison of the different test methods of HEPA filters under controlled conditions by testing a set of standard 1000 cfm HEPA filters using the aerosols of DOP, uranine and sodium chloride, all produced by compressed air atomization and to investigate the causes for any variations in the test results.

3. FILTERS FOR EVALUATION

A set of twenty HEPA filters of $1700 \text{ M}^3/\text{hr}$ (1000 cfm) capacity of size 610 x 610 x 305 mm size with soft gaskets on both faces were fabricated specially for this work. The filter medium used in all the filters composed of 100% micro glass fibre (16). The other materials of construction were also maintained the same for all the twenty filters (17).

4. TEST RIG

A filter testing rig based on British Standard BS 3928 was set up. The test rig was suitable for testing HEPA filters against DOP, uranine and sodium chloride aerosols. The details of the filter testing unit are shown in Figure-1. The test rig consists of a centrifugal blower to maintain necessary air flow through the filter;

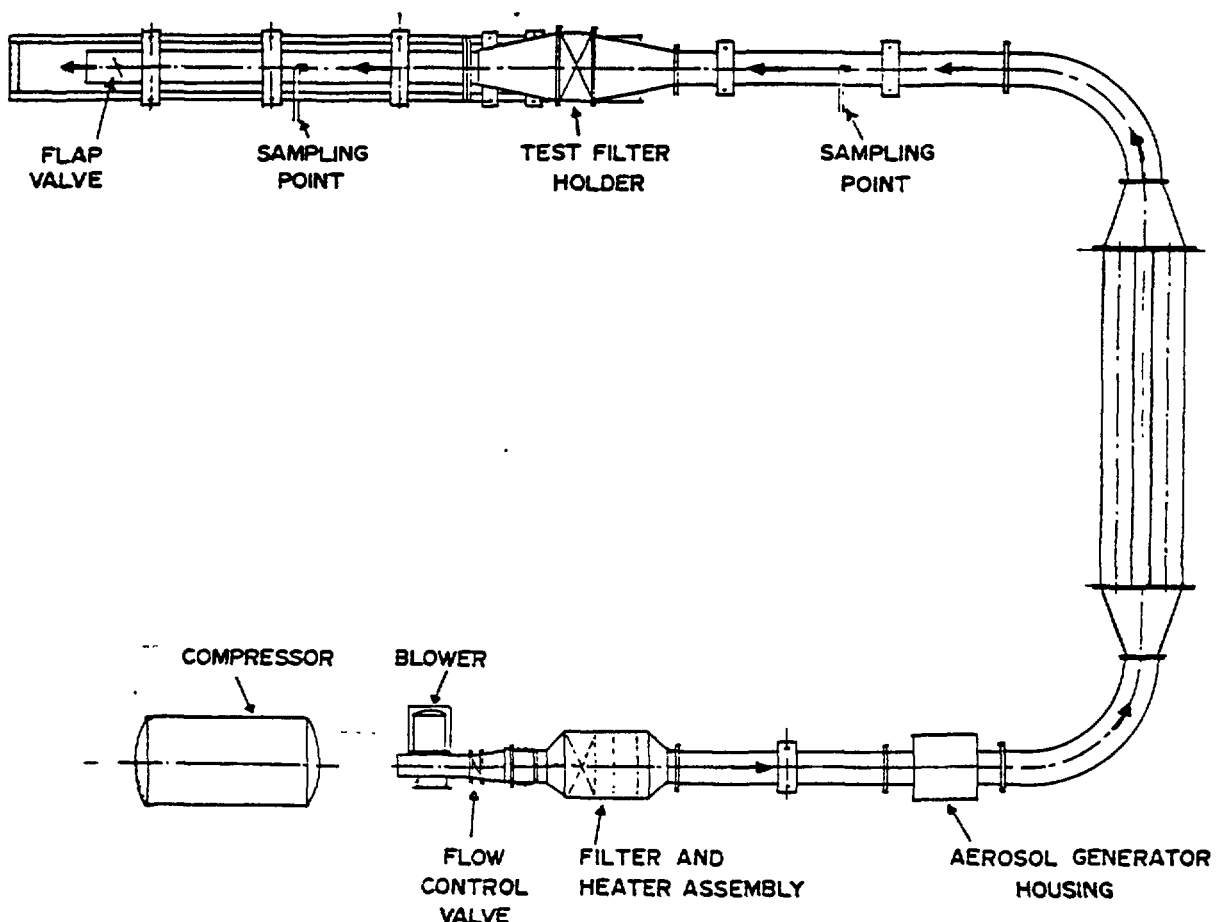


FIG.1 HEPA FILTER TEST RIG

an air heater assembly to control relative humidity; a long length of ducting before the filter to ensure thorough mixing and drying of aerosols; a pneumatically operated test filter holder and effluent ducting with arrangements for sampling and flow measurement. An electrical interlock between the air heater and blower is provided so that the air heaters are deenergised whenever the blower is off. The pneumatically operated test filter holder enabled quick installation and removal of test filter and also ensured uniform filter gasket compression.

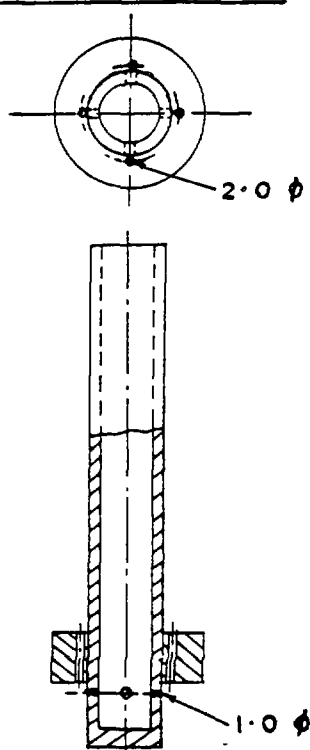
5. EXPERIMENTAL WORK

A set of twenty filters already fabricated were first tested by polydisperse DOP method, then by uranine method and then by the sodium chloride method at the flow rate of 1000 cfm.

5.1 Polydisperse DOP Method

The method employs a pneumatically operated aerosol generator and a size selective single particle counter for measurement of concentrations.

LASKIN TYPE FOR DOP



COLLISON TYPE FOR URANINE AND NaCl

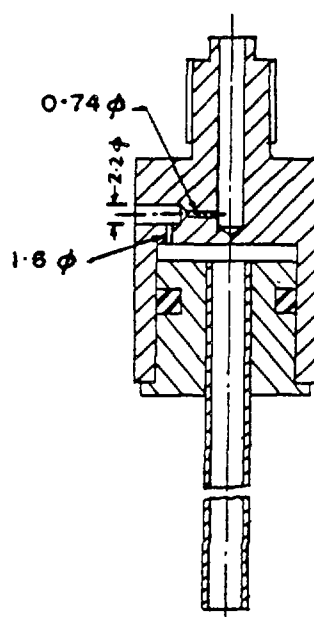


FIG.2 TYPICAL ATOMISER NOZZLES

DIMENSIONS ARE IN mm

The aerosol generator (18) consists of six standard dispersion jets immersed in liquid DOP, each jet having four air delivery holes and four fluid feed holes. For the purpose of these studies only one jet was operated at a pressure of 25 psi. The design of the nozzle is shown in Figure-2. The typical size distribution of the test aerosol after mixing with the total air flow of 1000cfm is given in Table-3.

TABLE - 3

SIZE DISTRIBUTION OF DOP AEROSOL

Generator : Royco Model 258 smoke generator
 Atomising Pressure : 25 psi
 Number of nozzle : One

Size range (Microns)	Number of particles per 0.1 cft	Percentage of total
0.30 - 0.35	2.60×10^6	56.0
0.35 - 0.50	6.51×10^5	14.0
0.50 - 1.40	9.06×10^5	19.5
1.40 - 3.00	4.83×10^5	10.4
3.00 and above	2.81×10^3	0.1

The operating conditions of the generator were optimised after detailed studies on the generation characteristics. The size analysis was carried out using a Royco Particle Counter - Model 225 (19). The threshold levels of the five channel particle counter were adjusted so as to count particles in the following size ranges:

Channel No. 1 : 0.30 to 0.35 micron
 Channel No. 2 : 0.35 to 0.50 micron
 Channel No. 3 : 0.50 to 1.40 micron
 Channel No. 4 : 1.40 to 3.00 micron
 Channel No. 5 : 3.00 micron and above

With one nozzle, operated at a pressure of 25 psi and 32 litres per minute air flow, the aerosol generated satisfied the test requirement with respect to particle size and concentration. The number concentration of the test aerosol of size between 0.3 micron and 0.35 micron was of the order of 2×10^7 particles per cubic foot, constituting about 56% of the total concentration, sufficient enough to accurately evaluate the filter penetration down to 0.001 percent. The accuracy of measurement could be enhanced by increasing the sampling time for downstream concentration.

5.2 Uranine Method

The test aerosol of uranine, i.e., disodium salt of fluorescein was generated using a collision type atomiser fabricated as per B.S. 3928. The design of the nozzle is shown in Figure-2. Two atomisers, each with three holes were used for generating the test aerosol by atomising 1% solution of uranine. The atomisers were operated at a compressed air pressure of 60 psi. The relative humidity of the air stream in the duct was maintained at 60% RH. The size analysis of the aerosol was carried out using a cascade impactor (20). The size distribution of the aerosol after mixing with the total air flow of 1000 cfm is given in Table-4. The test aerosol had a mass median diameter of 0.54 micron.

The filter penetrations for uranine aerosol were evaluated by taking upstream and downstream samples through membrane filters. (Millipore G.S. 0.22 micron was used for sampling). The membranes were thoroughly washed, in distilled water and the uranine concentration in the solutions were analysed using a photo-fluorimeter (21). The method followed for determining filter penetrations was

1. Two minutes upstream sample at 30 lpm was collected on the membrane filter and washed and made to 25 ml; with distilled water.
2. Downstream sample for 10 minutes at the identical sample flow rate of 30 lpm was

collected on the membrane filter, washed and made to 25 ml.

3. The upstream sample was diluted in steps to correspond to filter penetrations of 0.10%, 0.08%, 0.06%, 0.04%, 0.02% and 0.01%.
4. The fluorimeter reading was set to 100 divisions for diluted upstream corresponding to 0.01% filter penetration. Meter readings were then noted for all other samples corresponding to various filter penetrations and also for distilled water. A graph was drawn between the meter readings and penetration.
5. The downstream sample was tested in the fluorimeter and the meter reading was noted. The corresponding filter penetration was obtained from the graph.

TABLE - 4

SIZE DISTRIBUTION OF URANINE AEROSOL

Generator	: Collision type nozzles as per BS 3928
Atomising Pressure	: 60 psi
Number of nozzles	: Two

Size	Percentage cumulative mass concentration
6 micron & below	100%
2 micron & below	96%
0.7 micron & below	70%
0.5 micron & below	36%

5.3 Sodium Chloride Method

The test aerosol of sodium chloride was generated by an aerosol generator using collision type atomiser. The generator consists of four such atomisers contained in a PVC box. The whole generator was kept within the duct of the test rig between the fan and the main ducting. The atomisers were connected by separate feed pipes from a compressor incorporating suitable flowmeters and valves.

The size analysis of the aerosol was carried out using a cascade impactor and the size distribution of the test aerosol after mixing with the total airflow of 1000 cfm, is shown in Table-5. The mass median diameter of the test aerosol was about 0.4 micron. The atomisers were operated at a pressure of 70 psi. The relative humidity of the air stream in the duct was maintained at 60% RH.

A flame photometer, as shown in Figure-3, was fabricated, assembled and mounted on a panel board.

TABLE - 5

SIZE DISTRIBUTION OF SODIUM CHLORIDE AEROSOL

Generator	: Collision type nozzle as per BS 3928
Atomising Pressure	: 70 psi
Number of nozzles	: Four
<hr/>	
Size	Percentage cumulative mass concentration
<hr/>	
6 micron & below	100%
2 micron & below	94%
0.7 micron & below	78%
0.5 micron & below	56%
<hr/>	

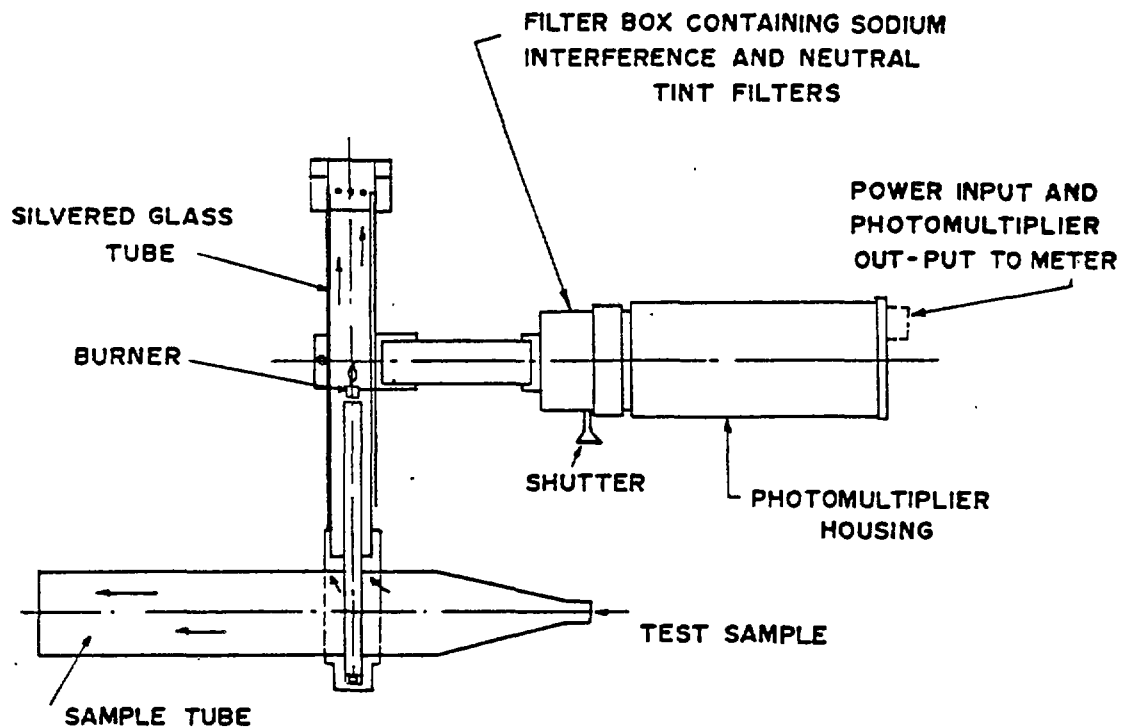
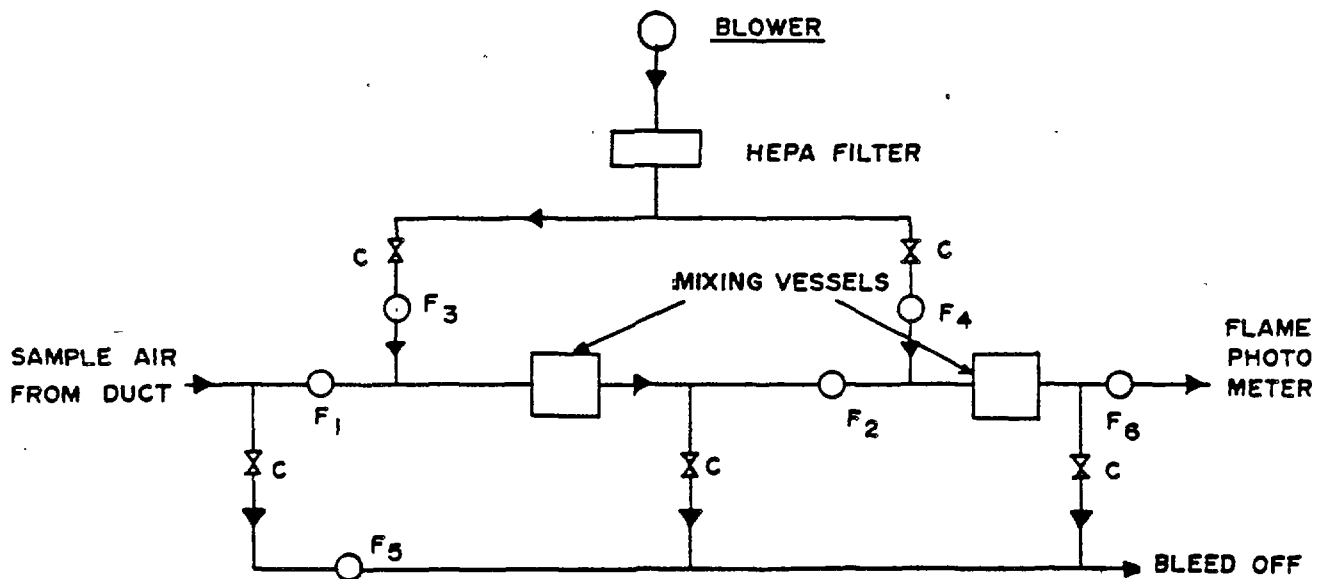


FIG.3 DIAGRAM OF PHOTOMETER FOR SODIUM
FLAME TEST EQUIPMENT

The photometer consists of a flame tube assembly to which a portion of the sample air from the test rig is directed. Inside the flame tube a steady flame can be maintained by a hydrogen burner. A photomultiplier views the flame through a tube fitted with a rotating optical shutter and a filter box. The filter box contains an optical interference filter permanently installed to isolate sodium yellow lines. After passing through the optical filters the light from the flame is allowed to fall on the cathode of the photomultiplier cell and the resulting photocurrent is measured by a sensitive galvanometer. By using neutral density filters of known values in the filter box the intensity of the light can be reduced to a convenient level. A high voltage unit provides a steady negative voltage of 900 V for the photomultiplier. A highly sensitive digital piccometer is used for measuring the photomultiplier tube output.

A dilution set up, as shown in Figure-4, for the main calibration was designed and was built as a permanent part of the test rig. The dilution set up consists of two



F₁, F₂ FLOW METERS 0 - 10. lpm

F₃, F₄ " " 20 - 200. "

F₅, " " 5 - 50 "

F₆, " " 0 - 80 "

C - CONTROL VALVES

DILUTION SET UP FOR SODIUM
CHLORIDE TEST METHOD

FIG. 4

chambers for obtaining two stage dilution. By varying the proportions of clean filtered air and salt laden air from the test rig concentrations from 0.005% to 100% of the original concentration could be obtained after two stages.

The following method was followed for determining filter penetrations.

1. Clean filtered air with a good quality filter in line was directed at a constant flow of 35 lpm to the photometer tube with necessary adjustments for zero reading. A clean flame background of nearly 50 was obtained in the piccometer.
2. The upstream sample was diluted in steps by mixing varying proportions of clean filtered air and piccometer readings were obtained for each dilution using known calibrated values of neutral density filters in the filter box.

3. A graph was drawn between the meter reading and the corresponding percentage penetration values based on dilution factors.
4. The downstream samples were directed to the photometer and piccometer readings were obtained. From the meter readings the percentage penetration values were obtained.

6. RESULTS OF FILTER EVALUATION

The percentage penetration through the HEPA filters tested by the above three methods are tabulated in Table-6.

TABLE - 6

<u>HEPA FILTER PENETRATION BY DIFFERENT METHODS</u>			
Sl. No. of filter	Percent penetration		
	DOP	Uranine	NaCl
1	0.058	0.120	*
2	0.093	0.140	0.013
3	0.019	0.031	0.007
4	0.013	0.044	0.009
5	0.007	0.017	0.011
6	0.006	0.015	0.009
7	0.011	0.022	0.011
8	0.003	0.010	0.007
9	0.005	0.075	0.007
10	0.025	0.073	0.024
11	0.015	0.023	0.020
12	0.009	0.015	0.009
13	0.107	0.185	0.057
14	0.028	0.055	0.013
15	0.042	0.071	*
16	0.014	0.027	0.009
17	0.023	0.037	*
18	0.014	0.046	0.007
19	0.013	0.044	0.007
20	0.013	0.043	0.007

* Filter damaged during handling and storage
Results of NaCl test not evaluated.

There was a time lag of more than a year between the uranine tests and sodium chloride tests and a few filters damaged during this period could not be tested by the sodium chloride method.

7. DISCUSSION AND COMMENTS

Before commenting on the numerical values of filter penetrations obtained by the three methods the relative merits and demerits of the individual methods should be understood.

The polydisperse DOP method is fast and the evaluation of a filter takes hardly a few minutes because of the quick response of the counter. The upstream concentration of DOP is very low and hence the loading on the filter during the test is minimum. The results are reproducible to the third decimal. In view of the above the test is quite suitable for large scale evaluation of filters. The method is easily adaptable for in-situ leak tests of filter installations and also during high humidity conditions. However the size selective single particle counter used in this test is a costly equipment and needs primary calibration very often. The lowest size of the particle that can be measured by this instrument is 0.3 micron and the particles of lower sizes are not accounted.

The uranine method is simple, less costly, and does not need elaborate arrangements for testing. However the main disadvantage is the longer duration of the testing of a filter to get a penetration value to the third decimal. Further this results in substantial loading of the aerosol on the filter. Cross contamination during sampling and analysis and the errors in the use of flow measuring equipment for sampling limits the accuracy and reproducibility of evaluation. The test is very difficult to adapt for in-situ leak tests of filter installations. The test may find limited application for large scale evaluation of filters because of the longer time taken for evaluation.

Like the poly disperse DOP method the sodium chloride method is also fast, accurate and reproducible. The test is suitable for large scale evaluation of filters. However the main calibration relating the concentration levels of sodium chloride with the piccometer readings using the dilution set up involves certain errors. The fluctuations in the flame height and the variation of piccometer readings over a longer period are some of the problems faced during the testing. The method is not adaptable for in-situ leak tests.

A comparison of the numerical values of percentage penetration determined by the three methods indicates that the values of uranine method are always higher than that of polydisperse DOP and sodium chloride methods. However no such correlation of results of DOP and sodium chloride methods is possible. The values determined by DOP and sodium chloride method can be taken as of the same order with as many as ten filters showing higher DOP penetrations, five filters showing higher sodium chloride penetration and two filters showing identical values.

The higher order penetration values obtained by uranine method may be attributed to the possible cross contamination during downstream sampling and analysis, which involves concentrations of very low order. No possible explanation can be given for the variation of results determined by the DOP and sodium chloride methods.

8. CONCLUSIONS

The results of the evaluation of various tests are only quantitative, in so far as they give figure of merit towards the particular type of test aerosol and the system of detection adopted for its evaluation. Further some of the studies carried out elsewhere have shown that efficiency results obtained by different methods do vary and sometimes even results of the evaluation carried out by the investigators using the same method are different.

In view of this it may not be appropriate at this stage, to single out a method as "absolute". Further any such conclusion may inhibit further developmental efforts in the systems improvements.

In making an appraisal regarding adopting a testing method, careful attention must be given to the assessment of many of the advantages and disadvantages outlined above, giving weightage to each of the factors depending on the site situation.

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COMPARISON OF SOME EXISTING TESTING METHODS FOR PARTICULATE FILTERS WITH SPECIAL REGARD TO RADIOACTIVE TRACER MEASURES*

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Abstract

In Hungary, samples of 17 different filter media were examined using monodisperse DOP Method (according to ANSI N 510 - 1975 US patent), a modified flame photometric method working with nozzle type aerosol generator and potassium chloride aerosol (particle size distribution and medium size were the same as that for sodium chloride according to British Standard 2831, 1957) and radioactive tracer method developed in Hungary using a spark-excited aerosol generator producing an aerosol of radioactive metal (^{192}Ir particles of $0.32 \mu\text{m}$ mass medium size, and conventional radiometric measurement as analytical method. The laboratory scale experiments were carried out under the same air flow conditions in all the three cases for all the filter samples. The results were compared and advantages and disadvantages of the different methods were given. The DOP and potassium flame photometric method was applied in rig tests for examination of industrial-scale HEPA filters made for nuclear power station purposes.

The laboratory scale experiments using the above mentioned radioactive tracer method were extended on the reference filter samples received from UK (filter sheet grade No. 1) and these results were compared to results obtained by other methods on the same filter media.

1. Introduction:

The determination of the efficiency of particulate filters is a very important task of the air pollution control. There are different filter testing methods, but the obtained results are also different.

* IAEA Contract No. 2270/RI/RB for the research period 1979-1982.

In the last three years our Institute had a research program of the International Atomic Energy Agency in the field of the investigation of HEPA filters.

In the last two parts of the progress report a new radioisotopic tracer method developed by our Institute and the DOP measurements were presented.

Our experiments were carried out using different types of filters. The applied testing methods were the following:

- 1./ Radioisotopic tracer method
- 2./ DOP-test
- 3./ Potassium-flamephotometric test

Each filter was investigated by all the above mentioned methods.

On the basis of the obtained experimental data we are ready to present an international guidance for filter testing in the future. The knowledge of the effect of temperature and the humidity of the air is necessary for the preparing a correct guidance in the selection of filter testing methods. We plan to carry out these experiments.

The research work of our Department was carried out as a part of research coordinated program of the International Atomic Energy Agency on the developing of international guidance of the filter testing.

The research work also belongs to the research program of our Institute and the National Energy Commission of Hungary. The list of papers, lectures presented on the research work can be seen at the end of the final report.

2. Existing filter testing methods

There are different filter testing methods in the international practice. The most frequently used are the following:

- a./ DOP-test
- b./ Sodium-flamephotometric test
- c./ Methylene-blue method
- d./ Radioisotopic test
- e./ Others, as uranine test, gravimetric method, etc.

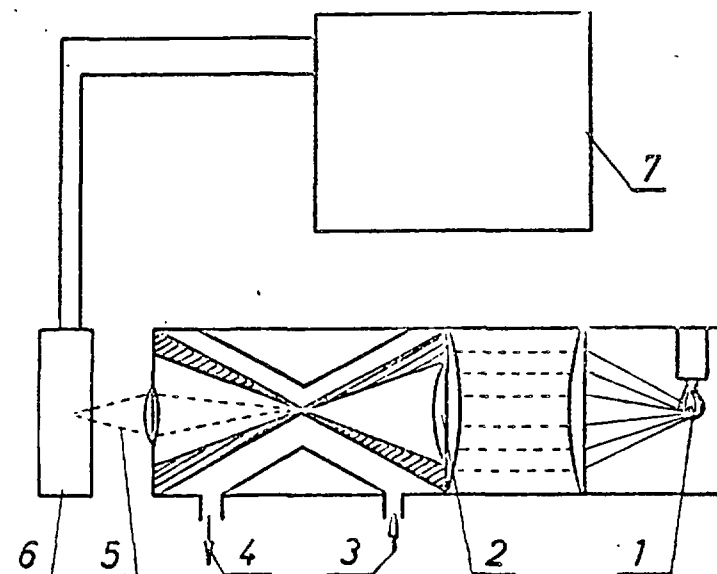


Fig. 2. DOP detector

1 - light source, 2 - lens, 3 - DOP aerosol inlet jet, 4 - DOP aerosol outlet jet, 5 - ray of light to photoelectron-multiplier, 6 - photoelectron multiplier, 7 - signal of evaluation

The test aerosol is formed by vaporization from DOP. The concentration of DOP aerosol is regulated by the temperature, the vapour pressure and the DOP flow-rate. The optimal concentration of the DOP aerosol is about $100 \mu\text{g/l}$.

Using the DOP equipment the rapid determination of filter efficiency is possible. The linear range of the DOP detector system is 10^5 . It is suitable for the investigation of high efficiency filters. In the U.S.A a basic standard [3] contains the application of DOP equipment for the filter investigation.

2.2 Flame-photometric test

The method is based on the flame-photometric determination of different alkaline-, and alkaline-earth metals as sodium, potassium, lithium, etc.

During the flame-photometric measurements the solution of the determined compound is pulverized into a suitable temperature flame, where vapour is formed and the compound dissociates to atoms. If the flame has high energy, the atoms are induced and the ground level atoms are emitted.

The wavelength of the emitted light characterizes the quality of the atom, and there is a tight relationship between the intensity of the emitted light and the concentration /the intensity is in direct ratio to concentration/.

The atomization and combustion processes are affected by the same disturbing processes; so we have to work using the same experimental conditions.

The advantage of the flame-photometric method is that it is very sensitive to small concentration of alkaline and alkaline earth metals, so it is possible to determine the concentration between the wide concentration ranges. The method based on the use of sodium-chloride as test aerosol was standardized in Great Britain [4]. In our modified method potassium-chloride aerosol is used instead of sodium-chloride.

The cause of the changing is the following:

- 1./ There are different sodium-compounds in the air, and these form the natural background of the determinations /sometimes it means a high value/. Using potassium-chloride aerosol the background has a very low value.
- 2./ The Hungarian flame-photometer has a higher sensitivity to potassium-than to sodium-atoms.

For the preparation of potassium-chloride test-aerosol the following assembly was used /Fig.3/.

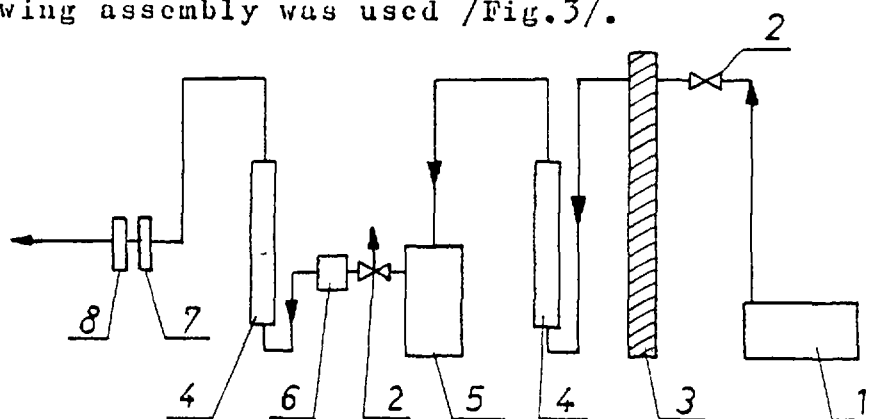


Fig.3. Preparation of potassium-chloride aerosol [4]
 1 - rotation pump, 2 - regulating cock, 3 - oil filter,
 4 - rotameter, 5 - aerosol generator, 6 - spray
 catcher, 7 - filter, 8 - filter

* /At the filter testing the first Millipore filter-house contains the investigated filter, the second one contains the absolute filter/.

For the preparation of potassium-chloride aerosol an aerosol-generator planned by us was used /Fig. 4/.

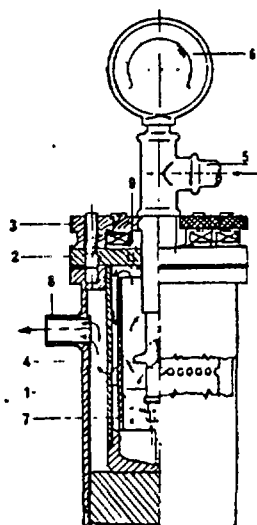


Fig. 4. Nozzle type atomizer aerosol-generator [5]

- 1 - steel reservoir, 2 - cover, 3 - screw caps,
4 - polyvinyl-chloride cup, 5 - air inlet jet,
6 - manometer, 7 - nozzle, 8 - aerosol outlet jet,
9 - screw cap for solution inlet

The aerosol-generator is suitable for pulverization of aqueous solution of inorganic salts. It works with medium pressure air. The equipment consists of a steel reservoir 1 to which a cover 2 is closed by screw caps 3. The equipment is pressure-tight. Inside of the reservoir there is a labyrinth formation, double wall polyvinyl-chloride cup 4 which is suitable for receiving 100 ml of salt solution and for separation of larger droplets and agglomerates which form during pulverization. In the axis of polyvinyl-chloride cup the air inlet jet 5, manometer 6 and nozzle 7 are placed. The filtered air, which enters through the 5 mm diameter duct of the nozzle sucks the salt solution from a central capillary, which has six "T" forms 0,5 mm diameter slits. The salt solution is pulverized in six radial, 1,5 mm diameter tubes, and it leaves the equipment after multiple impacts and inversion in the mentioned labyrinth system through the outlet jet 8. The salt solution is replaced through the sealed screw place 9 which is on the cover of the atomizer. The aerosol generator pulverizes 0,7-1,0 ml of solution per minute depending on the pressure ratios. In our experiments 5% of aqueous potassium-chloride solution was used.

As it can be seen on fig.5, two filters /7,8/ were used: the first was the investigated filter and the second one a so-called "absolute" filter. The retained amount of test-aerosol on these two filters were determined and from the obtained data the efficiency of the investigated filter could be calculated.

2.5 Radioisotopic tracing method

When testing the removal efficiency of HEPA /High Efficiency Particulate Air/ filters synthetically produced, submicron sized and practically monodispersed particle size distribution radioactive aerosols can be used as test aerosols either for examination of the efficiency of filter devices or to compare its results of high sensitivity with the results of other existing filter testing methods.

In this program a spark excited aerosol-generator, a filter test bench and radiometric evaluation method were developed and used with proper results as follows:

2.3.1 Preparation of radioactive test-aerosol

For preparation of radioactive test-aerosols a spark-excited generator was developed. The equipment prepares finely dispersed, submicron size aerosol from the neutron activated materials of high specific activity. Because of their construction, the radiation safety manipulator shielded against radiation. The spark-excited aerosol-generator prepares vapour-condensated aerosols by the help of low intensity and high voltage Tesla-current, which regularly serves as an arc ignition of an emission spectrum analyser instrument.

For the satisfactory sensitivity of detection of submicron size radioactive particles the increasing of specific activity of electrode metals is necessary, however it means radiation safety problems. Because of it an aerosol-generator was developed which can work by remote controlled manipulator in hot cell /Fig. 5/.

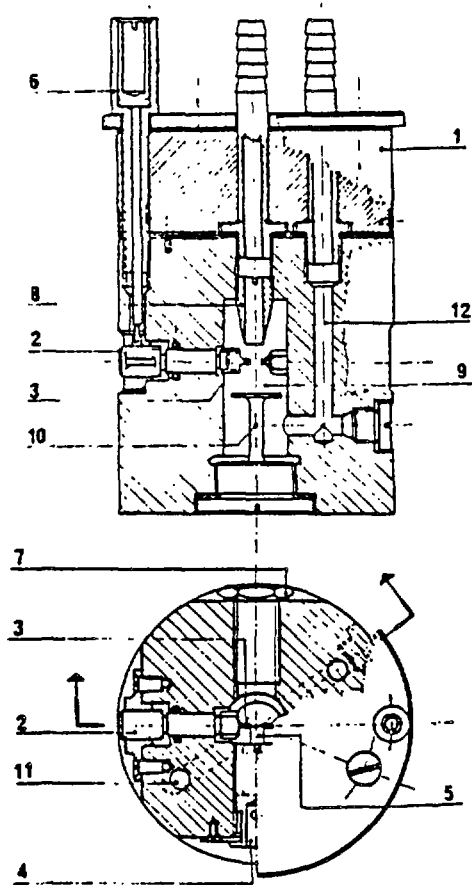


Fig.5. The spark-excited aerosol generator
 1 - box, 2 - electrode holder, 3 - radioactive electrode, 4 - spacer strip, 5 - variable spacer strip screw, 6 - high-voltage jointing, 7 - window, 8 - nozzle, 9 - condensation space, 10 - mixing baffle, 11 - input of dilution air, 12 - output of aerosol

During operation the aerosol-generator is put into a lead-castle, it's mass is 120 kg and it's wall thickness is 5 cm. The box 1 of spark excitation is connected to the removable lead plug of the lead castle with suitable passages. /The removal of the lead plug is carried out also in hot cell/. Two, electrode holders 2 fixed by screws are connected to the central hole of plastic house on both sides. To the electrode holders mushroom-shaped, radioactive electrodes 3 about 200 Ci g^{-1} specific activity are fitted with flare nuts by helping of manipulator. After that we have to screw the electrode holders with slotted manipulator 4 and so the exact adjustment of the spark gap is possible by variable diameter plastic plugs 5. During working the spacer strip plug is in back drawn position. Since it was made from insulant material, it does not disturb the formation of bridge of spark.

The spacer-strip plug is moved also by manipulator.

The power supply of the high-voltage Tesla current was connected by plug-in jointing sleeves 6. The form of the bridge of sparks can be perceptible through the plexiglass window 7 at inactive experiments. The electrode metal evaporated in the bridge of sparks is removed from the spark gap by the gas stream of changeable bore diameter nozzles 8. From the blowed out metal vapour of different particle size and relatively monodispersed aerosol is condensated depending on the flow-rate of gas in the D diameter condensation channel. The large size or coagulated particles are inertially separated by the \sqrt{D} diameter mixing baffle 10 put to the way of air flow. The coagulation can be decreased by the conducting of dilution gas into the condensation space 11. The gas containing aerosol removes from the generator through the 12 exit hole.

Since in the spark-excited generator the adjusting air flow determines the particle size, we have to choose the air flow of preparation and application separately. For this purpose 2-100 litres buffer tanks were used. At first they were evacuated and then the aerosol prepared by discrete flow-rate, was blown out by the necessary air flow of filtering experiment

2.5.2 Investigation of aerosol filters by radioisotopic test method

The radioisotopic filter-test apparatus and method is useful for highly exact determination both of fluid mechanical data of different forms and different bound filter materials and for highly sensitive determination of their efficiency.

In the following the test-method and its filter-test apparatus is described. The essence of the test-method, the degree of partition of radioactive test aerosol is measured both on the experimental filter and on the absolute filter-laid after the experimental filter-by scintillation counter instrument.

In the filter-test apparatus /Fig. 6./ the gas flow is kept with 600 kPa /6 atm/ compressed air system A or inert gas /nitrogen, argon/ vessel 1 or suction air B by vacuum-pump 15.

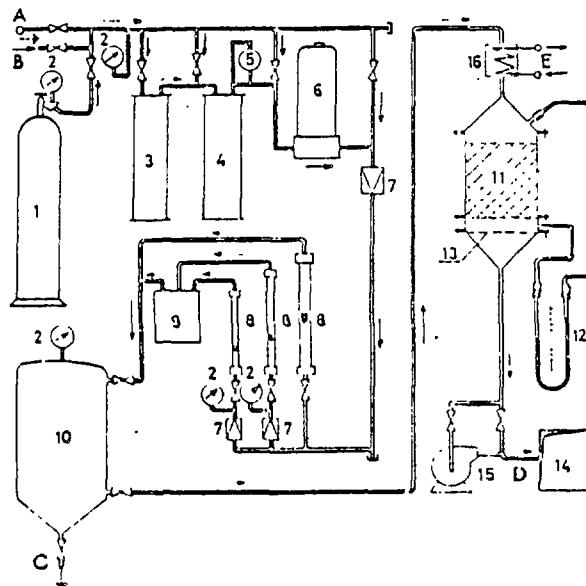


Fig. 6. The radioisotopic filter-test apparatus

- 1 - gas vessel, 2 - manometer, 3 - charcoal filter,
- 4 - silica gel filter, 5 - humidity indicator,
- 6 - ceramic filter, 7 - pressure reducer,
- 8 - rotameter, 9 - aerosol-generator, 10 - buffer tank,
- 11 - investigated filter, 12 - micro-manometer,
- 13 - absolute filter, 14 - air suction channel,
- 15 - vacuum pump, 16 - heater-cooler heat exchanger,
- A - compressed air, B - suctioned air, C - discharge,
- D - blowing off, E - joint of heater-cooler medium

The input air is purified by oil trap filter containing charcoal 3 and ceramic filter 6. For the decreasing of vapour content, specially when using generators working with carburation by spraying, dried silica gel column 4 was used for purpose of decreasing of vapour excess. The colour change of silica gel impregnated with CoCl_2 /cobalt-chloride/ 5 indicates the saturation of silica gel column. For the adjusting and checking of pressure and air flow-rate of pretreated air pressure regulators 7, manometers 2 and rotameters 8 are used. The constant pressure and flow-rate gas enters into the aerosol-generator 9 /sometimes for disturbing the coagulation together with dilution air/. From the generator the air enters into an evacuated, 100 litres buffer tank 10, from where it passes into a heat exchanger 16. The heat exchanger contains heating or cooling medium for the purpose of temperature control. After that

the aerosol reaches the filters in the experimental filter-box 11. The air-resistance of experimental filter is measured by differential-manometer 12. The aerosol which penetrates to the experimental filter gets to the Soviet absolute filters type PFP-15-5. The absolute filter works on the principle basis of idea of total flow air-sampling because of the two filters - experimental and absolute - are arranged in cascade system. This kind of arrangement of experimental and absolute filter meets the requirements of isokinetic sampling /the mass rate of air flow is the same on both filters/. The activity distribution between the two filters characterizes the efficiency of the experimental filter. The pneumatic working, filter house results in a quick closing. The D filtered air leaves through the offtake air channel 15 of the 84 m high chimney to the atmosphere /in the case of suctioned operating with the help of vacuum-pump/. The draining of buffer tank 10 the blowing off C is carried out on the underside of the tank. For the measuring of radioactivity /exactly the count number, which is rational to it/ of aerosol kept by the investigated filter, a specific, high cross-sectional $/2,5 \cdot 10^{-2} \text{ m}^2/$ lead castle was made /Fig. 7/.

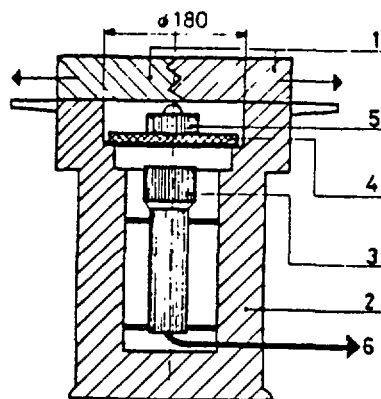


Fig. 7: Special high cross-sectional lead castle
 1 - cover, 2 - lead column, 3 - scintillation counter, 4 - filter sampling, 5 - ballast, 6 - cable to scaler

The experimental filters 4 were placed about 5 cm above the scintillation counter. Compressing the filter with ballast the difference of the count-rate of two sides of it becomes negligible. The scintillation counter is connected to a scaler 6. The cover 1 of the lead castle 2 is openable, its inner diameter is 180 mm.

2.3.5 Determination of filter efficiency

The total-flow air sampling /Fig.8 / is based on the cascade arrangement of the same diameter experimental and absolute filter in a common filter house.

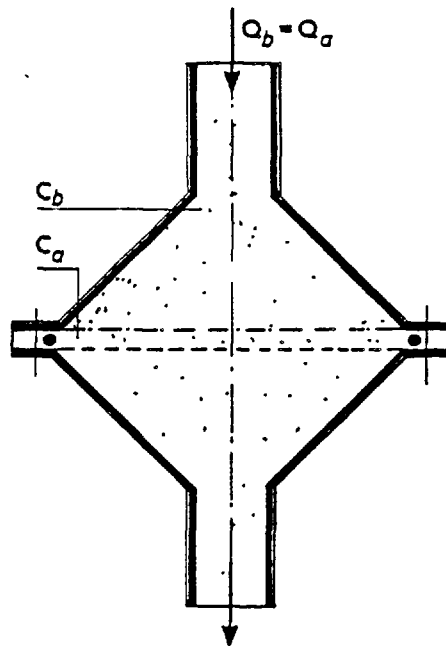


Fig. 8: Total-flow air sampling method

It is characteristic, that the same quantity of air flows through 3 both filters with the same mass rate, so the sampling is isokinetic.

The count rate of aerosol deposited on the experimental filter / I_b / can be measured directly on the filter and to compare to the count-rate of penetrated aerosol separated by the following, so called absolute filter / I_a /.

The count-rate / I_b , I_a / is proportional to the concentration ratio before and after the experimental filter so it means the changing of the aerosol concentration before and after the filter / C_b , C_a /. Using the total flow method we get the value of removal efficiency /retention/ of experimental filter / R / in the following way:

$$R = \frac{C_b - C_a}{C_b} = 1 - \frac{C_a}{C_b} = 1 - \frac{I_a}{I_b}$$

From the next equation we can get the penetration of the investigated filter /D/.

$$D = 1 - R = \frac{I_a}{I_b}$$

As we had a great number of experimental data, the calculations were made by computer. Certainly, the removal efficiency of used absolute filter is smaller than one, so we can correct the measured results with the following loss factor:

$$\gamma = \frac{1}{1 - D_{af}} = \frac{1}{R_{af}}$$

By our measurement in the case of two layers of absolute type filter FPP-15-3 the deficit is less than 0,0025%, so it is negligible.

5. Comparison of the results obtained by the three test methods /DOP, potassium-flame-photometry and radioisotopic tracing/

The results of the experiments using the above mentioned three testing methods were given in details in our previous report /see ref. 2 /. In Table 1. these results are summarized.

From the data of Table 1 it can be seen that the filter efficiencies determined by different methods are in agreement within the experimental error. The most accurate results were obtained by the DOP test and the radioisotopic method. Using the mentioned methods the determination of a small amount of the test aerosol was carried out with high accuracy. Summarizing the application of the three filter test methods we can establish the following:

- a./ The DOP test is a traditional method and it is useful for fast and accurate determination of filter efficiency. The applied test aerosol is a cheap commercial product. The cost of the DOP generator, the optical unit and the service is relatively high. The operation of the equipment is very simple. The equipment is applicable for determination of the efficiency of different filter equipments and to carry out leakage measurements too.

Table 1:
Comparison of filter efficiencies determined by different methods

	DH	80 m ³ m ⁻² h ⁻¹			160 m ³ m ⁻² h ⁻¹			240 m ³ m ⁻² h ⁻¹			320 m ³ m ⁻² h ⁻¹			400 m ³ m ⁻² h ⁻¹		
		DOP	FP	RT	DOP	FP	RT	DOP	FP	RT	DOP	FP	RT	DOP	FP	RT
Dexiglass 3737	10% (min)	84,011	82,410	83,416	82,054	80,347	81,319	80,310	77,942	79,537	75,301	74,317	74,315	73,410	71,410	70,009
Dexiglass 3903	35% (min)	98,543	97,013	98,113	96,917	95,792	96,452	94,927	93,790	94,265	92,994	92,430	92,313	91,990	91,372	91,456
Dexiglass 3938	60% (min)	99,100	98,091	98,649	98,642	97,709	98,013	98,131	97,631	97,384	97,221	97,212	97,039	96,989	96,840	96,649
Dexiglass 3939	15% (min)	86,417	84,142	85,419	84,317	82,070	83,984	82,093	79,752	81,421	81,120	78,310	80,316	79,710	77,007	78,069
Dexiglass 3937	92% (min)	99,893	99,477	99,842	99,843	99,271	99,713	99,720	99,152	99,609	99,650	98,853	99,403	99,317	98,614	99,104
Dexter C 1236	99.99%	99,997	99,993	99,995	99,997	99,990	99,993	99,646	99,950	99,416	99,454	99,917	99,223	99,242	98,897	99,001
Dexter C 1506	99.996%	99,998	99,994	99,996	99,899	99,899	99,844	99,713	99,642	99,645	99,598	99,433	99,511	99,530	99,193	99,430
Dexter 2080	99.995%	99,997	99,993	99,996	99,717	99,990	99,643	99,550	99,405	99,447	99,380	99,197	99,221	99,100	99,002	98,999
Dexiglass 3913	99.97% (max)	99,983	99,971	99,975	99,907	99,874	99,813	99,754	99,710	99,621	99,613	99,571	99,459	99,472	99,310	99,300
Dexiglass 3905	99.97% (max)	99,980	99,965	99,978	99,873	99,842	99,811	99,743	99,711	99,700	99,680	99,540	99,600	99,468	99,316	99,015

Table 1 (Contd.....)

	DM	80 m ³ m ⁻² h ⁻¹			160 m ³ m ⁻² h ⁻¹			240 m ³ m ⁻² h ⁻¹			320 m ³ m ⁻² h ⁻¹			400 m ³ m ⁻² h ⁻¹		
		DOP	FP	RT	DOP	FP	RT	DOP	FP	RT	DOP	FP	RT	DOP	FP	RT
Dexiglass 3907	99,97% (max)	99,982	99,944	99,963	99,846	99,791	99,659	99,635	99,616	99,442	99,546	99,432	99,370	99,411	99,190	98,917
Dexiglass 1397	99,98%	99,985	99,970	99,975	99,837	99,907	99,714	99,704	99,864	99,547	99,503	99,641	99,199	99,307	99,312	98,614
GDR I ^x	-	99,810	99,635	99,715	99,710	99,483	99,543	99,481	99,194	99,280	99,297	98,732	99,009	98,997	98,431	98,632
GDR II ^x	-	99,963	99,944	99,975	99,835	99,817	99,714	99,726	99,584	99,529	99,584	99,278	99,316	99,294	99,013	99,042
RA ₂ ^{xx}	-	99,742	99,574	99,852	99,691	99,254	99,613	99,537	99,035	99,469	99,405	98,714	99,311	99,230	98,341	99,005
Delbag Multiglass 60	-	94,743	94,313	94,516	94,033	94,001	93,205	92,873	93,547	91,017	90,327	-	90,016	87,882	-	89,836
Delbag Multiglass 95	-	99,947	99,872	99,937	99,925	99,732	98,916	99,536	99,505	98,728	99,270	-	98,342	99,012	-	98,216

DM values given by manufacturers
 FP flame-photometric method
 RT radioisotopic tracer method
 DOP DOP method
 x filter made in GDR
 xx filter made in Czechoslovakia

b./ The flame-photometric method is also a traditional filter test technique. It is useful for investigation of filter layers. The potassium-chloride test aerosol is dissolved from the surface of the filter and the solution is analysed flame-photometrically. This procedure has the longest sampling time, about 10-15 minutes. The cost of the flame-photometer is average. Maintenance of the equipments is necessary only occasionally. The disadvantage of this laboratory method is, that it is not suitable to test the efficiency of large scale filter equipments.

c./ The applied radioisotopic tracing method was developed in our Department. The equipments /spark-excited aerosol generator, centrifugal aerosol-spectrometer etc/ were made by us. The cost of the equipment is relatively low. The sampling time is short. The obtained result is very exact because the method by which this small amount of test aerosol is detected is very sensitive. The method is useful for exact determination of the efficiency of filter layers. As the method is highly sensitive, it is well applicable for investigation of HEPA filters. The disadvantage of the method is that the test is based on the use of radioactive aerosol, it is not useful for investigation of filter equipments and for leakage measurements.

4. Experiments carried out during the extended period of the research contract /1982/

The filter tests were extended for comparison to the unified air-velocity on the reference filter samples received from UK as a participant of the Coordinated Research Program /according to the decision of the 2nd Research Coordination Meeting held in Vienna, 8-10 December 1980/.

The use of the previously applied DOP, flame-photometric and radioisotopic filter test methods were extended to the scale of rig tests on various HEPA filters.

4.1 Efficiency test on UK filter No.1. using radioactive tracing method

The filter samples were received from the United Kingdom. These types of filters were earlier distributed in various European and U.S.A laboratories to be tested by different particulate test methods in the frame of a C.E.C organized comparison study /Ref. 5 /.

Thus our filter named UK No.1.corresponds to the filter sheet grade No.1.in Ref. 5

According to the decision of the 2nd Research Coordination Meeting /Vienna, 8-10 December 1980/ the experiments were made at linear air velocities between 2 - 10 cm/s. The pressure characteristics of the tested filter determined parallel to the efficiency tests are shown in Table 2.

Table 2 : Pressure characteristics of the UK.No.1. filter sample

linear air-velocity		pressure drop /Pa/
m/h	cm/s	
80	2,22	108
160	4,44	216
240	6,66	355
320	8,88	490
400	11,11	865

The efficiency test were completed by the radioisotopic tracing method described earlier in this report. The results of the experiments are shown in Table 3.

Table 3 : Removal efficiency values determined on UK No.1 filter sample by radioactive tracing method

linear air-velocity		Efficiency
m/h	cm/s	%
80	2,22	99,985
160	4,44	99,987
240	6,66	99,991
320	8,88	99,990
400	11,11	99,990

The efficiency values seem to be independt of the linear air velocity within the experimental error and show a sufficient good agreement with DOP values for the same filter sheet in Ref. 5.

4.2 Rig tests using DOP, potassiumflame-photometric and radioactive tracer methods

There are three levels of testing HEPA filters: a./ testing of small samples of the filter medium in laboratory scale, b./ testing of the whole filter these are the so-called "rig tests" and c./ on site or in situ testing of the complete filter installation before putting into operation and later for the purpose of periodic control.

The aim of rig test is to determine the efficiency of the complete filter including the efficiency of the filter medium and the effects of possible damage of the medium while manufacturing, transporting, gasket leaks or inadequate tightening inside of the filter housing. Three different filters produced for nuclear power station were investigated in a rig test installation. All the three filters were tested by potassium-flame-photometric method, and radioisotopic tracer method using ^{42}K radioisotope as tracer. The DOP method was applicable for one of the filters only, having a filter media of glass fibre, while the synthetic media of the two other filters became damaged by di-octyl-phtalate.

4.2.1 The tested filters

All the three tested filters were constructed for the nuclear power station with reactors type VVER 440. The filter media in the filter No.1 was glass fiber at No.2. and No.3. perchlorvinyl type synthetic fiber, type FPP 15-45. The nominal value of air flow for filter No.1 was $500 \text{ m}^3/\text{h}$, for No.2. $1000 \text{ m}^3/\text{h}$ and for No.3. $3000 \text{ m}^3/\text{h}$.

4.2.2 Rig test equipment

The scheme of the rig test equipment is shown on Fig.9. In the case of potassium-flame-photometric method and DOP samples were taken from upstream and downstream ducts by the help of pump. The distances between the sampling points and filter housing were $10D$ in the upstream duct and $5D$ in the downstream duct, wher D is the duct diameter.

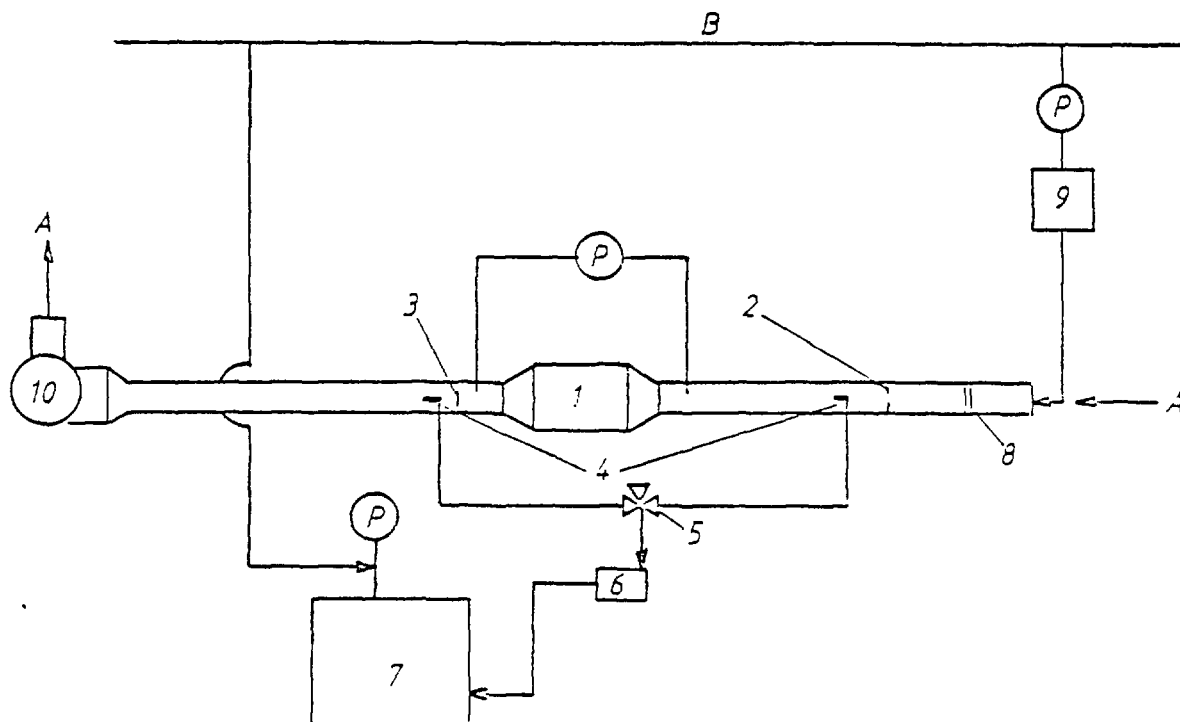


Fig. 9.:

Schematic diagram of particulate filter test rig

1 - filter to be tested; 2-3 - upstream and downstream mixing baffles
4 - sampling points; 5 - change-over valve; 6 - air pump type Millipore;
7 - digital flame-photometer or DOP detection system; 8 - adjustment of
air flow; 9 - potassium-chloride - or DOP-aerosol generator; 10 - ventilator;
A - pathway of test aerosol; B - compressed air duct; P - pressure gauges

The upstream and downstream air samples were then directly analyzed either by flame-photometric or DOP detector. Both potassium-chloride and DOP aerosol generators were the same as described earlier /chapter 2./

In the case of radioactive tracer method the 5% solution of KCl labelled with 0,2 GBq/ml ^{42}K was put into the aerosol generator. Upstream and downstream samples were collected in calibrated absolute filters and measured by conventional radiometric method /NaI scintillation detector and scaler/. The reason of using this method instead of the spark-excited aerosol generator was that the filter to be tested should not be contaminated with long-lived radioisotopes as ^{192}Ir . On the other hand the use of ^{42}K / $T_{1/2} = 12,4\text{h}$ / in the same aerosol generator provided the opportunity to control the accuracy of the potassium-flame-photometric method. However, some preliminary experiments were carried out using neutron activated ^{64}Cu as electrode metal in spark-excited aerosol generator. Since ^{64}Cu has relatively short decay time / $T_{1/2} = 12,8\text{ h}$ /, in the case of positive results this method can be applicable for rig tests too.

4.2.5 Results of the rig tests

The results of the rig tests are summarized in Table 4.

Table 4: Efficiency values determined in rig tests by potassium-flame-photometric, DOP and radioactive tracer methods.

filter	flame-photometry		DOP		radioactive tracer	
	air-flow m^3/h	efficiency %	air-flow m^3/h	efficiency %	air-flow m^3/h	efficiency %
No.1. /glass fiber/	276,2	99,940	306,0	99,918	500	99,936
	396,5	99,938	372,5	99,877		
	460,7	99,927	475,6	99,855		
	606,5	99,895	587,9	99,852		
	764,4	99,862	688,8	99,870		
No.2. /synthetic/	362,2	99,817			362,2	99,991
	508,7	99,767			625,1	99,987
	625,1	99,722				
	778,7	99,702			778,7	99,971
	1050,9	99,559			1196,7	99,952
No.3. /synthetic/	1196,7	99,640				
	372,5	99,807			400,0	99,982
	1060,0	99,786			1046,0	99,965
	1517,8	99,715				
	2561,2	99,745				
	2972,8	99,685			2972,8	99,954

5. Some problems of selecting the most proper filter-testing method

Selecting a proper testing method from the view point of a filter we have to take into consideration the following:

- a./ Properties of the filter /size, pore size, material of the matrix, etc/
- b./ Properties of the test aerosol /diameter, effect on the filter, etc/
- c./ Reproducibility of preparation of test aerosol
- d./ The time of sampling and the analyses; the type of the obtained result /direct or indirect/; accuracy and reproducibility of the result
- e./ The cost of the equipment and the maintenance.

At first we have to know the pore size of the filter. In the case of HEPA filters it is very small, only monodisperse, small diameter test aerosol can be used. To achieve acceptable results the correct analysis of the test aerosol /particle size distribution, average diameter/ is necessary.

Consequently for investigation of HEPA filters only the DOP aerosol and the radioactive iridium-192 aerosol are suitable. The other test aerosols are heterodisperse ones, and their medium diameter is variable /e.g uranine

$D_{\max} = 0,15 \mu\text{m}$, methylene blue $D_{\max} = 0,6 \mu\text{m}$ etc/. The aerosols which have larger diameter can be used for investigation of other types of air filters, prefilters.

For the investigation of filters the reproducible preparation of the test aerosol is very important. So we have to know those experimental conditions which have affect on the properties of the formed aerosol. Usually the air pressure is the most important of them, but we have to take into consideration the special requirements by aerosols, as in the case of iridium-192 aerosol the distance between the electrodes of the spark-excited generator, in the case of potassium-chloride, sodium-chloride and methylene blue aerosol the concentration of the solution etc.

In practice often a series of filter-testing is necessary.

In this case the sampling time and the time of the analyses are very important factors. The DOP equipment requires the longest warming-up period /45 minutes/, the others require the usual warming up period of an electrical instrument /15-20 minutes/. The sampling time and the analysis time are 1-2 minutes when using DOP test or radioactive tracing method. In the case of other methods the sampling time and especially the analysis time are much longer except for the radioisotopic tracing method.

The cost and the necessary service of the filter-testing equipment were described in Ref.2.

We propose to give the following data of the tested filter:

- a./ Material description /material, binder content, tickness, pore size, basis weight/
- b./ Filtration efficiency /determination method and the size of the used aerosol, efficiency with the filter-load/
- c./ Pressure drop /changing the air-resistance via filter-load/
- d./ Others: water repellency, /sometimes resistance to chemical gases/

For investigation of HEPA filters we have to make laboratory test and plant control /so called "in situ" measurement/.

- a./ laboratory test: At the determination of filter efficiency we use only a sample material. We can propose the application of the radioactive tracing method /application of iridium-192 isotopes/ because of the high accuracy of the test. /Certainly at the beginning of the measurements we determine the pressure drop of the filter sample/.
- b./ "In situ" test: In the case of "in situ" test usually the DOP test is used. By the DOP test the total efficiency of the filter system is measured. We have to take into consideration the possible loss due to the leakages, the condition of the gasket scales etc. Sometimes the sampling on the optimal place is difficult. So the obtained efficiency characterises the filter system but not the filter itself. We have to investigate the

leakage of the filter system separately. Taking into account the above mentioned problems the method provides correct results.

In the future we want to give a proposal for the selecting the suitable filter testing method. It was shown earlier / Ref. 2/ that the filter efficiency depends on the humidity of the air and the temperature in a lot of cases. We plan to carry out these experiments using the described method in the progress report.

6. Summary

Our Department had a research program coordinated by the International Atomic Energy Agency in the field of testing particulate filters. The program had three periods. At first a radioisotopic tracing method was developed by the Department. The equipment of the method was designed and made by us. The analyses of the radioactive iridium-192 test aerosol were also carried out. The efficiency of different filters was determined using radioisotopic tracing method. This part of the research work was reported in 1980. In the second part of the research program two traditional filter test methods were compared to the radioisotopic tracing method.

The received DOP equipment and the potassium-flame-photometer were set up and calibrated.

Determination of efficiency of 17 filters was carried out using the radioisotopic tracing method, DOP test and potassium-flame-photometric method. /The experimental conditions were the same/.

In the third period the filter tests were extended on the reference filter samples received from UK for comparison to the unified air velocities, and the DOP, flame-photometric and radioisotopic filter test methods were applied in rig test of industrial scale HEPA filters.

The results of the three methods were compared. The cost, the service and the accuracy of the methods were also compared.

Some problems of the selecting of suitable filter test method were summarized.

References

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5. DISCUSSIONS AND COMMENTS

In the considerations in introduction we have broken down the test of the HEPA filters in three categories. The same considerations may be used for the general discussion of the research carried out by the investigators.

5.1 Filtermedium Tests

Two groups of the investigators carried out research in this field. It was stated that capture mechanisms during filtration are influenced through physical properties e.g., particle size and shape, specific gravity, the velocity of the particles, their electric charge and also their chemical properties.

The penetration of a filtermedium can be relative to the number or mass or radioactivity (if the mass is not proportional to activity). Values of penetration are strongly dependent on the test method and characteristics of that method (aerosol generation and detection). Research to discover conversion factors that would make possible conversion of filter penetration measurements made by one method to equivalent values when measured by the other is only possible after investigation of the characteristics of the aerosol and its detection method.

Determination of the particle size distribution is important from this point of view. Two of the research projects were concerned with that problem. In the investigations of the group of Mr. Ullmann, particle size distributions were determined for the test aerosol. This group stated that the results of different test methods may differ considerably. This was also investigated by Dormann [5.1]. Nevertheless the work of Ullmann shows that the deviations between different methods are mainly due to the different relevant particle size distributions. The aims of the filtermedium testing are:

- determination of characteristic filter properties. The knowledge of this penetration vs. particle size curve can lead to a better understanding of the filtration process and development of new filter media;
- determination of the penetration vs. particle size curve also allows the calculation of the total penetration for a selected method for filter medium production control purposes.

The use of particle size dependent detection methods allows to determine the penetration vs. particle size curve. One of these instruments is the scintillation particle counter [5.2] (Ch. 4), the lower limit for particle size is 0.03 μm , nevertheless this instrument can only evaluate sodium containing particles. (NaCl , or uranine $\text{C}_{20}\text{H}_{10}\text{Na}_2$).

Another instrument used for the evaluation of particle size was the laser particle spectrometer (De Worm ch. 4). Although this instrument was not used in filtermedium test it enables obtaining the particle size distribution over the size range 0.09 - 3 μm (calibrated with latex particles, the liquid DOP particles have very similar response due to the little differences in refractive index). Particles with other refractive indices can be used. Nevertheless one should be aware that for this particles the obtained size is the "equivalent diameter" i.e. the size of a sphere of pre-determined refractive index (latex particles $n = 1.5905$) which gives the same pulse light as that for the actual particles (for DOP or DEHP $n = 1.4850$ the index does not deviated so much in comparison to latex [5.3]). Calibration of the instrument is possible with a mono-disperse aerosol with the same characteristics as the actual one but this is a rather intensive work.

Once this penetration curve is obtained one can use every test aerosol with measured size distribution and this allows the determination of the total penetration with the specific detector. In this way one can determine the quality during production of the filtermedium. Nevertheless every test method will supply other figures. We refer to the research of Hirling and Ullmann. The method used for medium testing should be well standardized as to obtain reproducible results. Comparison between different laboratories may give different values but this is mostly due to differences in the particle size distribution of the test aerosol or some differences in other physical characteristics like electric charges.

Adjustment with a least square method to a power function of the results of penetration in function of face velocity of the filter medium permitted to obtain the relation $-\log p = a v^{-b}$ (p = penetration value, v = face velocity in cm/s , a and b are constant) (De Worm Ch. 4).

As conclusion of the filtermedia tests one can state that it is important to determine on a regular base during the production the penetration vs. particle size curve. A standardized method using an aerosol with determined

size characteristics should be used for quality assurance programme. All the developed methods are equivalent to each other for that purpose (see Hirling, Ullmann, Ch. 4, Dorman [5.1]).

5.2 Rig Test Methods

The purposes of the rig test were necessary to assure the quality of the filter as a unit, (filter medium, sealing method, frame, gaskets). The method to be used by the investigators for that quality assurance programme may be different from that of the manufacturer for the filter medium.

Nevertheless one should again emphasize the importance of the determination of the particle size distribution of the test aerosol. The different researchers in the co-ordinated programme developed to some extent the determination of this particle size distribution and the influence of the working parameters on this distribution (see De Worm Ch. 4). Special care has to be given to the lay out and construction of the test rig, in order to obtain a good mixed aerosol cloud. Sampling has to be performed in the sense to obtain a representative sample of the aerosol cloud. (we refer to the research of De Worm, Hirling and Khan).

The determination of the penetration vs. particle size curve is important. The capture mechanism still depend on particle size, shape, specific gravity, electric charge, and physical state (liquid or solid).

There is little difference between all the test methods when there are known leakages. Nevertheless when there is a particle size depending separation (filtration, very small leakpaths) one obtains different results depending on the aerosol size distribution. The size distribution of the aerosol may be different depending on the goals. If this goal is to obtain a penetration-particle size curve then one should have a poly-disperse aerosol over the size range below 0.1 and up to 1 μm . If the goal is rather obtaining the total penetration then a more challenging aerosol should be used with the majority of particles in the range 0.05 μm and less than 0.3 μm size.

In case of laboratory testing the feasibility of the method depends on:

- reproducibility: This implies especially the aerosol and thus the parameters governing this generation e.g. air supplies pressure, salt concentrations, nominal volumetric air flow through the filter unit;
- no changes in the filtration characteristics through clogging. This feature may have a different sense for liquid or solid aerosols;
- The selectivity is more important for the total penetration methods, where the use of a more challenging aerosol is important (French uranine test method De Worm, HCl or NaCl Hirling and Khan, and a metal evaporated condensated aerosol with very special characteristics Hirling);
- Sensitivity, this property depend rather on the detection method and can be very high for certain methods like laser spectrometer 10^3 or radioactivity measurements (De Worm and Hirling);
- Limitations of test conditions: Both aerosol and detector are important. More severe conditions of temperature and humidity are needed (It was observed that DOP was still useful at 80°C , the uranine at higher humidity as 80% (De Worm)).

One can conclude from the experience obtained in this co-ordinated programme that all methods are equivalent (see the different investigations). The polydisperse DOP used with the forward light scattering photometer nevertheless is not a suitable methodology. It is merely a leak testing method, and provides a reasonable and often conservative measure of the true performance for the test aerosols. The American Standard Q107 penetrometer is more convenient; the laser spectrometer seemed also more suitable for the assurance of the monodisperse aerosol as the Owl. in this methodology [5.4].

One has nevertheless some advantage taking the same aerosol for the in-situ tests otherwise it will be very difficult to compare the figures obtained from the rig tests with those of the in-situ tests.

5.3 In-Situ Test Methods

Particle size distribution is perhaps a less stringent condition because one is looking for leaks (leaks in the seating of the gaskets, leaks through damage of the filter medium, gaskets or filter frame, leaks through by-passing through the dampers). The in-situ method is the quality assurance for the

filtration system at the commissioning of the nuclear plant or after periodical intervals.

For in-situ tests, the supplementary features are:

- each of use: some methods have draw backs; the more complicated the methodology is, the more skilled operator is needed;
- speed in obtaining the results is concerned mostly with the detector, light scattering methods and flame photometer were anyhow very suitable;
- minimum cost: we can refer to the review given by Dorman for the different methodologies [5.1].

At present the designers of the gas treatment units are constructing very compact units for economical reasons. This filtration system consists of a HEPA-charcoal absorber - HEPA-assembly, sometimes preceded by prefilters and demister units. A further trend is to replace the rig and the in-situ leak test through one test at the nuclear plant. With the present single laser particle spectrometer it was possible to assess penetrations less than 10^{-6} for the 0.09 - 3 μm light scattering size range. The draw-backs of the laser detector methodology, as investigated by the group of De Worm (ch. 4) were: the very high investment costs, fragility of the instrumentation, requirements on the qualification of the operators. The problem of extraneous particles downstream can be overcome by using a fluorescent tagged aerosol together with a fluorescent laser detector.

The general conclusion that can be drawn from this co-ordinated research programme is the difficulty to have one standard method. Nevertheless one should use the same methodology for rig and in-situ testing. In this way one relies always on the same reference method. The parameters of this reference method are to be established. The reasons not to recommend one standard method are:

- economical, most groups have already established their test methods;
- incompatibility with material properties specific for the nuclear plant or prohibition through the authorities e.g. incompatibility of DOP and synthetic filter media, sodium chloride and stainless steel or the hydrogenflame burner in exhausted gas streams containing hydrogen;
- impossibility to change through national regulatory guidance.

The present conventional test methods are adequate for nearly all requirements, but in the case of extremely high efficiency systems or compact systems the laser spectrometer methodology seems promising.

References

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6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

One of the major conclusions of the co-ordinated research programme was that it was not possible to recommend one method as a reference method for in situ testing of high efficiency particulate air filters. Most of present conventional methods are adequate for current requirements. The reasons why no method is to be recommended were multiple, ranging from economical aspects, through incompatibility of materials to national regulations.

It was concluded that national authorities should be dissuaded from presenting a specific test method; regulations should be limited to presenting the air cleaning units. Indeed introduction of specific methods into regulations may discourage scientific research. This would be an unwelcome effect, as the field of testing and monitoring of off-gas cleaning systems at nuclear facilities is still in full development.

The participants in the co-ordinated programme agreed that a training course should be promoted to assist in the development of expertise in developing nations. This training course with a duration of fourteen days, should cover all commonly used filter test methods presented by experts; the course should include experimental work allowing the participants to compare for themselves the practical as well as the theoretical differences between the various methods.

In the field of aerosol filtration there is an insufficient knowledge of the filtration and retention of particles in the size range below 0.1 micron. More scientific research has to be performed. Sponsoring basic filtration research is one of the keys to the development of more effective and more reliable filters for accident conditions.

The retention of filtered alpha-active particles is a problem of concern for the high efficiency particulate air filtration for some types of nuclear plants (plutonium fuel plants, alpha waste incineration, reprocessing plants). For these nuclear plants, the most radio-toxic challenge offered to the air cleaning units are plutonium or other transuranic materials in a finely divided state. Research should be initiated to clarify the mechanism of filter penetration by such nuclides. A number of filters mounted in series is an inadequate remedy, because a particle which has been penetrated the first barrier, may easily penetrate the second one.

More effort should be given to the assessment of the behaviour and formation of aerosols and iodine forms during abnormal (accident) conditions at all nuclear facilities and more precisely to the combined effects of accidents.

It was the wish of all participants that further scientific investigations on the general theoretical and experimental basis of filtration and adsorption, under normal and accident conditions should be performed.

The problem of ageing of the air cleaning units is important enough to promote further research both as regards HEPA filtration and iodine adsorption.

Currently tests are mostly performed on new units; there exists little or no information for aged HEPA-filters under normal or accident conditions and there is a lack of information on combinations of severe conditions (high humidity, chemical, particulate loading etc...). These tests should be performed both on the filter medium and on active filters.

The same problems of ageing exist for iodine adsorbers; the long term behaviour of iodine adsorbed on charcoal has to be established. Because of such practical difficulties a number of methods will continue to be used in the foreseeable future and it is therefore important that in order to be able to compare the standards as defined in terms of one test method with those applied with reference to other methods. Although not all participants in the intercomparison programme had a means of establishing the granulometry of the test aerosols or of deriving the filter media penetration curves - two forms of information essential to a quantified explanation of results obtained by different test methods - nevertheless all were able to benefit from a qualitative understanding of the differences found.