Fig 10

The paint on the filter housing began to blister in some areas at approximately 10 minutes and started to peel away from the steel of the housing in some areas at approximately 13 minutes. One isolated area of peeled paint ignited for approximately 3 seconds at 18 minutes.

At 24 minutes the bottom area of the filter housing was glowing red and the paint of the housing was badly blistered and peeled. The neoprene seal on the bottom removable door was, at this stage, melting and flowing out from the bottom of the door.

At 25 minutes molten aluminium was falling from the filter unit to the floor of the furnace.

At 31 minutes flames broke through the centre of the filter unit.

After the furnace had been turned off the filter unit burst into flames and the remaining paint on the outside of the filter unit ignited.

Fig 11

Summary of Inspection of Filter Unit after Test

The filter media had fused together and some had fallen away (the remaining filter media was partially supported by the thermocouples). The timber casing was glowing and flaming in places but the case appeared to have been protected from greater damage by the paper around the internal edge of the casing. The PVC sheet material, which had been positioned between the filter unit and the removable cover of the housing, had been completely destroyed.

It was difficult to estimate the effectiveness of the EPDM seal or the condition of the timber casing at the end of the test as the filter unit had continued to burn for some time after the test had been terminated. Fig 11 is a view of the filter housing and filter unit with the cover removed after test.

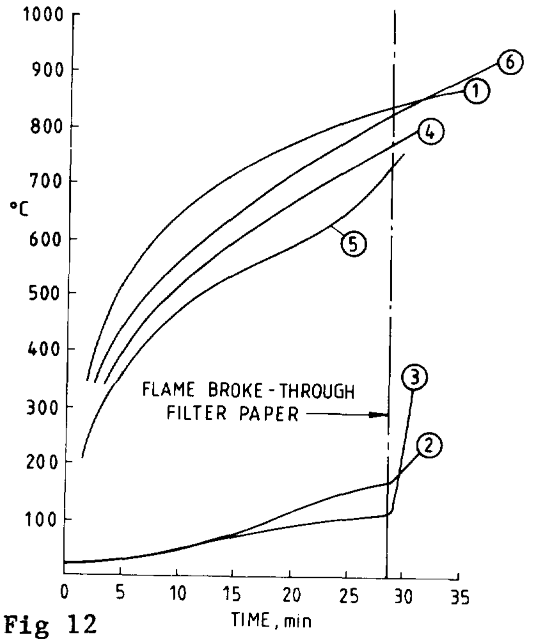
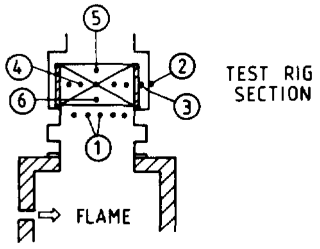


Fig 12

Temp Log during Test

Fig 10 shows temp details during test. Temp 1 indicates the time-temp relationship of the BS476 test procedure. The max temp before the flame broke through was 825°C after 28 minutes. Temp 5 again shows the large proportion of the heat that passes through the filter. Temp 3 is not the max temp the casing reached but shows a sharp increase in temp at that point when the flame broke through. The low temp for temp 2 and 3, as stated previously result from the method of construction of the filter pack where glass-wool and paper is used to line the inside of the casing.



Test No 6 "Ozonair" housing 500°C for 45 mins

Summary of Observations during Test

Light white smoke was given off from the upper surface of the filter during the test. The smoke production reached a maximum at approximately 6 minutes and then reduced to a negligible amount at approximately 25 minutes.

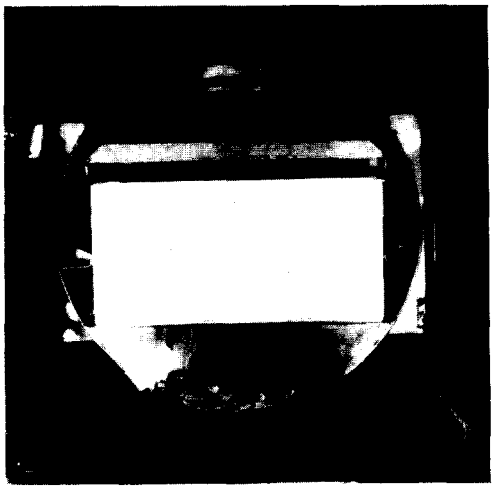


Fig 13

Summary of Inspection of Filter Unit after Test

The paper of the filter unit was slightly discoloured on the exposed face but aluminium foil protruding through both faces appeared to be completely unaffected.

The timber casing of the filter unit was much more damaged in the area of the filter which was adjacent to the bottom section of the front of the filter housing (ie immediately behind the removable protective cover) than in any other area. This appeared to be due to heat being conducted through the housing to this area faster than to other areas.

The timber beading on the exposed face of the filter unit was charred all around the perimeter of the unit and had fallen away in the area of maximum damage, as outlined above. The plywood casing was unaffected apart from the area of maximum damage, where an area measuring approximately 150mm by 40mm of the casing was discoloured and distorted.

The silicone seal was, in the main, undamaged and retained its resilience. In the area of damage previously described the seal had lost some of its resilience and was damaged slightly on removal of the unit from the housing. Small cracks had formed along the 'front' length of seal. The adhesive used to bond the seal to the plywood had broken down in the damaged area, causing the seal to become detached from the casing in this area. The seal between the filter unit and the housing appeared to be maintained throughout the test.

The PVC sheet material, which had been stretched over the front of the filter access aperture before the protective cover was positioned, had melted in the area which was in contact with the lower metal section of the housing, again indicating that relatively high temperatures had been reached in this area. The PVC sheet was undamaged above this area, apart from slight softening.

The filter housing did not appear to suffer any damage during the test. (See fig 13).

Test No 7 "Ozonair" housing to BS 476 (pt 8) 1972)

This filter unit had previously been tested at 500°C by 45 minutes when mounted in the "Unipak".

Summary of Observations during Test

Light white smoke was given off from the upper surface of the filter throughout the test but the volume was less than in previous tests, probably because the filter had previously been tested.

At 17 minutes the aluminium foil protruding through the exposed face of the filter began to melt and the neoprene bellows material appeared to be softening slightly.

At 22½ minutes a red glowing was observed on the upper face of the filter media and at 23 minutes a second area of glowing was observed. At 24 minutes flames broke through the filter unit.

After the furnace had been turned off the filter unit burst into flames and ignited the neoprene bellows at the top of the housing. Dense, black smoke was given off from the neoprene bellows.

Fig 14

Summary of Inspection of Filter Unit after Test

The filter media had not fused together as in some previous tests, the paper and aluminium foil separated easily from each other. The timber casing was glowing and flaming in places but was undamaged in other areas.

The silicone seal had been destroyed in some areas but remained intact in other areas, retaining some of its resilience.

The housing did not appear to be seriously damaged or distorted, apart from the neoprene bellows at the top of the housing, which had been completely destroyed.

It was difficult to estimate the effectiveness of the seal or the condition of the timber casing at the end of the test as the filter unit had continued to burn for some time after the test had been terminated.

Fig 14 shows a view of filter housing and filter unit, with the protecting cover e removed after test.

Test No 8 500°C for 45 minutes

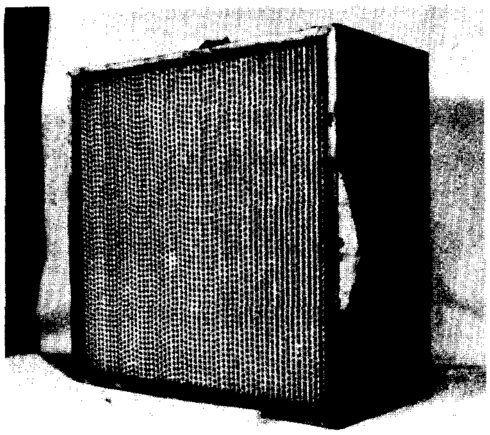


Fig 15

Summary of Inspection of Filter Unit after Test

Plywood Case

The untreated plywood case had charred away, adjacent to the silicone gasket, over an area measuring approximately 240mm long by 80mm high on the right-hand side (as viewed from the removable cover of the filter housing) of the case. The remaining three sides of the case were discoloured adjacent to the silicone gasket but remained intact.

Note. The filter unit was not removed from the filter housing until approximately 60 minutes after the test had been completed and it is possible, therefore, that further decomposition had occurred after the test had been completed. The timber bead around the edge of the exposed face was badly charred and had fallen away in the area of damage to the plywood case.

Silicone Gasket

The gasket was generally unaffected, apart from some discolouration, and appeared to have retained its resilience. The adhesive had failed in some areas and the gasket had become detached from the casing in those areas. Small cracks had formed on the inner edges of the gasket. (See fig 15).

Test No 9 500°C for 45 minutes

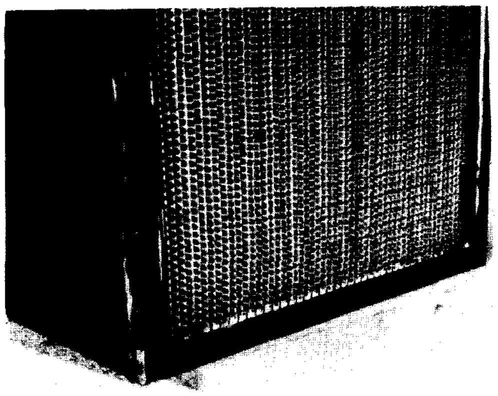


Fig 16

Summary of Inspection of Filter Unit after Test

Steel Case

The steel case was visually unaffected.

Glassfibre Gasket

The glassfibre cover material of the gasket had discoloured over its whole surface and had delaminated at all edges. The gasket was otherwise visually unaffected and did not appear to have suffered any damage which would reduce its sealing properties. The adhesion of the main body of the gasket to the steel case was unaffected. (See fig 16).

Test No 11 500°C for 45 minutes

This was a repeat test of test no 8 to confirm results.

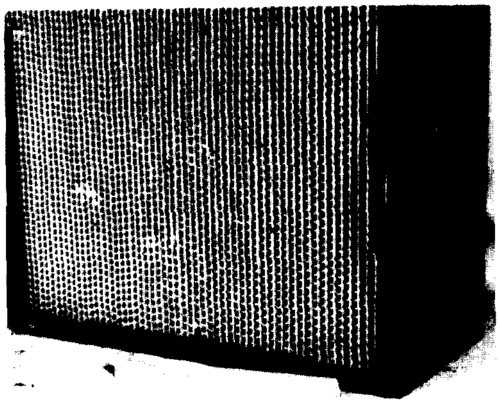


Fig 17

Summary of Inspection of Filter Unit after Test

Plywood Case

The plywood case was discoloured on all four sides of the filter unit but none of the areas had charred away. The timber bead around the edge of the exposed face was badly charred and had fallen away in some areas. The timber bead was glowing red in the area on the right-hand side of the case which had charred away during Test No 8.

Silicone Gasket

The gasket was generally unaffected, apart from some discolouration, and appeared to have retained its resilience. Small cracks had formed on the inner edges of the gasket. The adhesive bonding the gasket to the plywood case had failed in some areas, causing delamination of the gasket in places. The gasket was damaged in one area on removal of the filter unit from the housing, caused by the gasket sticking to the housing. (See Fig 17).

Test No 16 500°C for 10 minutes - ABS Filter Unit in "Unipak" housing

Fig 18

Summary of Observations during Test

After 1½ minutes light white smoke was given off from the top face of the filter unit. Smoke production increased steadily and at 2¼ minutes considerable amounts of yellow/white smoke was being given off. Pungent smoke continued to be given off and at 4 minutes flames appeared through the top of the filter housing. The test was immediately discontinued. (See fig 18).

Summary of Inspection of Filter Unit after Test

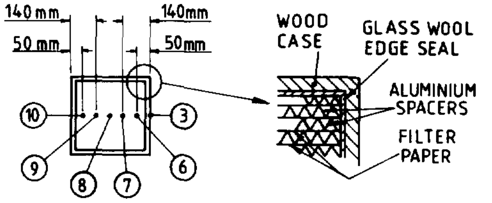
It was not possible to safely extinguish the flames from the filter unit immediately after completion of the test and significant decomposition of the unit continued, which which was restricted as far as possible by covering the top of the filter unit with a non-combustible board material. When some degree of control had been achieved the filter unit was sprayed with water.

On removal of the filter unit from the housing most of the filter media had fallen away and the aluminium 'straps' across the face of the media had melted away on the exposed face of the unit. The case was distorted but had not been damaged in any other way. The 'seal' between the case and the edge of the filter media had been almost completely consumed and it appeared to be this material which had been flaming during the test. The silicone gasket was visually unaffected and had retained its resilience. (See fig 19).

Fig 19

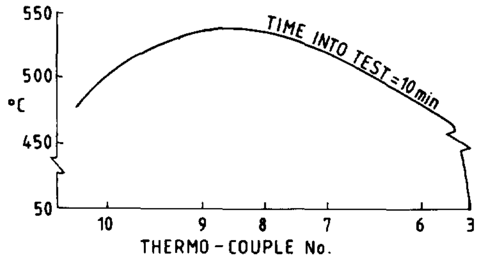
9. Temperature Profile across the Filter Pack

Taking the test results from test no 5 a limited assessment can be made on the edge conditions of the filter pack. Test no 5 was a test to destruction using a treated wooden case filter with the filter paper edge seal of glass-wool giving a measure of insulation to the wooden case. Fig 20 shows the temp profile across the mid-point in the filter pack and also the details of the edge seal to the paper.



SECTION THROUGH FILTER SHOWING DISPOSITION OF THERMO-COUPLES

SECTION THROUGH CORNER SHOWING GLASS WOOL EDGE SEAL



AIR TEMP. ACROSS MID POINT IN FILTER

Fig 20

10. Filter Performance Tests

The UK acceptance tests

The performance of a filter shall be such that at rated air flow (1000 cfm) the penetration measured shall not exceed .05%.

The filter must remain intact, have acceptable penetration and not contribute to combustion up to 500°C and test to verify this will be required. The acceptance limit for penetration is 2% of rated flow.

Results of tests

Table 3 lists the results of penetration performance tests which were conducted by Vokes Air Filters Ltd, on some of the filter packs which were included in the test series. The test results tabled are for before fire testing and after. The duration of the fire test is also indicated.

Table 3

Test No	Duration of fire test (minutes)	Performance test before fire test		Performance test after fire test	
		Penetration %	Pressure Drop ins wg	Penetration %	Pressure Drop ins wg
Not reported	10	.003	0.94	0.3	0.9
NR	10	.03	0.99	0.4	1.00
9	45	.007	0.95	0.4	0.95
11	45	.014	0.90	0.7	0.90
NR	10	.014	1.09	0.1	1.06
12	45	.010	0.99	0.2	0.98
13	45	.003	0.88	0.3	0.87
NR	10	.014	0.97	0.3	0.95
NR	10	.027	1.00	0.9	1.00
14	45	.015	0.99	0.4	0.96
15	45	.031	1.02	0.6	0.98

11. Discussion of Results

11.1 Apart from test no 16 all other material combinations and housings listed in table 2 withstood the 500°C temp test for 10 minutes without ill effect and with the filters passing the penetration test requirements.

11.2 The wood bead which charred in all the tests was a small (3mm x 3mm) square section piece of untreated wood used to retain the paper assembly within the case. This beading should be treated in all future applications to remove this hot spot.

11.3 Should however it be contemplated to subject installations to longer periods at 500°C then all low temp rubber seals and diaphragms should be replaced with silicone rubber and wooden cases should be subjected to a flame retardant treatment.

11.4 The "dry-seal", (see fig 20) treated wood case filter pack arrangement gave the best results from the extended period testing at 500°C. This arrangement is also the most suitable for breakdown and compaction on waste treatment. There was some concern however that during the filters operating life, the wood may creep resulting in the loss of the necessary pressure to maintain the edge seal on the paper. If this should prove to be the case, the next best arrangement would be to use a silicone rubber edge seal as tested in tests nos 8, 11 and 13.

11.5 In the tests to destruction of the filters in the three housings, (tests 3, 5 and 7) there was very little difference in the temp and time relationship for the flame to break through. It is therefore concluded that the housing design is not a critical factor. Test no 3 however showed that the subsequent damage after flame-breakthrough was less than in the other two cases.

11.6 From fig 17 it is clear that the narrow channels formed by the aluminium spacers helps considerably to keep the case temp much lower than the centre air stream temp. The convection conduction resistances set up are such as to allow the cases to radiate the heat flux to which they are subjected to, adequately. This point needs further substantiating by more tests with more thermocouples in the outer edge channels.

11.7 Test 16 demonstrated the geometry effect where the "high flow" filter which does not have the narrow channels, the low temp resistant edge seal material was subjected to the continuous flow of the max temp air in the centre. Further development of this type of filter for high temp applications is necessary, possibly a silicone rubber edge seal to replace the low temp resistant material used in the test is worth considering.

11.8 It was not possible to have forced flow circulation in these tests, the effect of this however may not have influenced the results greatly. The max temp where ignition and charring occurred were at the entry to the filter which would not be influenced very much by the higher flow. The temp that would be effected however would be the case temp further along the filter ie temp 5 and 7 in fig 9. The effect would be to bring them nearer to temp 8, a max increase of approx 75°C.

11.9 The large amount of heat that escapes through the filter as demonstrated in test no 4 suggests that any fire dampers are best located up-stream of the filters to allow the heat to escape under these low flow conditions leaving the filters intact for use after the incident.

11.10 No plugging effects of the filter were possible to assess in these tests, this would be difficult to control and in any case is dependent upon the materials of combustion.

11.11 The materials used for the gasket seal showed EPDM RA25, glass-fibre and silicone rubber to be satisfactory. The max gasket temp on extended period testing was 300°C. The glass-fibre high temp resistant seal on the steel case (test no 14) delaminated when subjected to 500°C for 45 minutes with the bond to the steel being broken.

11.12 In the filter performance tests as shown in table 3 the penetration figures after the fire test are well within the acceptance limit of 2%. The increase in penetration due to the high temp test is approx the same for both 10 minutes and 45 minutes test period. This implies that the change takes place in the first few minutes and then remain constant. Also the pressure drop is little affected by this particular series of fire tests as there was no attempt to generate high flows and dusty environments.

11.13 The test have demonstrated that filters installed in their housings will resist most categories of fires from the temp aspects. In order to overcome the problems associated with fume and smoke it is suggested that the damper be replaced with a suitable filter which like the damper is only brought into use when there is a fire. This would take the dust load off the in-line filters and would eliminate pressurisation of the system resulting from isolation by using dampers.

12. Conclusions

12.1 The tests have shown that more realistic high temp filter test method would allow a greater flexibility in the designs of filter packs, would reduce the subsequent waste packaging costs and make handling easier.

12.2 Wooden case filters adopting high temp sealing methods would make acceptable filters for high temperature applications. This would alleviate some of the waste disposal problems associated with steel cases.

12.3 Further consideration should be given to the filter performance test results where the pressure drop was unaffected by the fire test but the penetration increased by a factor between 7 and 100.

12.4 Further tests are necessary to establish more firmly the geometry effect and the plugging of filters. Such tests as comparing a standard low temp resistant wooden case filter with the high flow geometry one used in test 16 and to consider using silicone rubber as the paper edge seal in the high flow filters. Also to test used filters which are sufficiently blocked by use on plants to simulate combustion effects.

12.5 Further consideration should be given to replacing the dampers in the ventilation system by a filter to take the dust load off the in-line filters at the onset of a fire.

13. Acknowledgements

The author wishes to thank the fire testing officer, Mr Ralph Shaw of the Warrington Research Centre for carrying out the test programme, and Mr Ian Galemore of Vokes Air Filters Ltd, for his cooperation in the filter pack development work. Also Mr Alan Bateson of the UKAEA for the preparation of the data.

The test programme was carried out in collaboration with British Nuclear Fuels Ltd.

DISCUSSION

MURROW: Did you try any temperature-flow combinations that would permit the filter to retain some major portion of its filtration ability?

HACKNEY: There was no attempt made to establish temp-flow combinations as this would be affected by the rate of filter plugging, which we had no control over. We found that the change in filtration efficiency took place very quickly (within the first ten minutes) because there is no difference between filters that had been at 500° C for ten minutes and filters that had been at 500° C for forty-five minutes. We think the changes that take place in penetration take place early on.

MURROW: Some years ago I did considerable work on a similar program where we were working at 375° C and trying to maintain filter efficiency at least in excess of 95% efficiency after 5 minutes. Many of the filters would withstand that temperature excursion for that period. I wonder if you worked towards identifying a filter that would maintain a major portion of its efficiency under some preselected temperature change?

HACKNEY: We are saying that although the filters pass an efficiency test after a fire, they are no longer the same as before the test. But they are still considered adequate to rely on after a fire.

DYMENT: This is in response to Mr. Murrow's question. A test program in which HEPA filters were subjected to temperature cycling and penetration testing was carried out at Aldermaston in the late 1960s. The results showed that penetration was unaffected by temperature up to 200° C. At 300° C and above, acceptable performance lasted progressively fewer cycles. The results were reported in Filtration and Separation in 1970.

BURCHSTED: Air flow might substantially reduce any adverse effects on the filter case and gasket. Was there are flow through the filter during the test?

HACKNEY: The total air flow was that due to natural convection only and was not measured. We considered it important to maintain a constant inlet face temperature. These were quick tests to demonstrate whether or not wooden cases had a chance and to formulate a program for tests at design flow. At design flow, you need quite a lot of fire to use a once-through system.

BURCHSTED: We had a fire several years ago in which airflow was maintained through a combustible filter throughout the fire and the core was pretty well burned out but the wood cases had no damage. The filter pack, in this case, disappeared because it was combustible.

HACKNEY: I don't know whether there was much difference for non-air flow conditions because ignition obviously started at the front face. It is the front face temperature that is critical. That is the temperature we were measuring. If you have airflow during these tests, the only thing you will do is reduce the convection resistance to sideways flow into the filter. But you won't affect the face inlet temperature of the filter; that will be the same.

BURCHSTED: This is true, but airflow will considerably reduce damage to the case and to the gaskets. The gaskets compressed between the steel mounting frame and the filter case may become damaged but are unlikely to lose their seal.

HACKNEY: We were rather surprised at the enormous amount of heat that passed straight through the filter. One of the comments in the paper that I didn't get around to mentioning was that it probably would be better if we placed the dampers before the filters so that we do not surround the filter with the hot gases. Rather than that, we should allow the hot gases to race through and go up the stack.

GALLEMORE: The only comment I wish to make is that the final acceptance test made with sodium chloride aerosol calls for an efficiency greater than 98% for those that weren't damaged by the thermal cables.

RESPONSE OF HEPA FILTERS TO SIMULATED ACCIDENT CONDITIONS

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Abstract

High-efficiency particulate air (HEPA) filters have been subjected to simulated accident conditions to determine their response to abnormal operating events. Both domestic and European standard and high-capacity filters have been evaluated to determine their response to simulated fire, explosion, and tornado conditions.

The HEPA filter structural limitations for tornado and explosive loadings are discussed. In addition, filtration efficiencies during these accident conditions are reported for the first time. Our data indicate efficiencies between 80% and 90% for shock loadings below the structural limit level. We describe two types of testing for ineffective filtration--clean filters exposed to pulse-entrained aerosol and dirty filters exposed to tornado and shock pulses. Efficiency and material loss data are described. Also, the response of standard HEPA filters to simulated fire conditions is presented. We describe a unique method of measuring accumulated combustion products on the filter. Additionally, data relating to pressure drop vs accumulated mass during plugging are reported for simulated combustion aerosols. The effects of concentration and moisture levels on filter plugging were evaluated. We are obtaining all of the above data so that mathematical models can be developed for fire, explosion, and tornado accident analysis computer codes. These computer codes can be used to assess the response of nuclear air cleaning systems to accident conditions.

I. Introduction

Most nuclear facilities depend on ventilation systems to bring air into, through, and out of the facility. Because the air passes through contaminated areas, most ventilation systems also contain air cleaning systems; the high-efficiency particulate air (HEPA) filter is a critical component in the air cleaning system. The system may consist of a series arrangement of these filters or banks containing several hundred filters. These filters typically exhibit cleaning efficiencies of 99.97% or better. They operate very effectively in most noncorrosive atmospheres at normal airflow conditions. However, there is concern about the degradation of performance or destruction of these units when they are subjected to accident conditions. The areas of concern are (1) the structural integrity of the HEPA filter media, (2) the influence of design and construction on structural integrity, (3) the filtration effectiveness, and (4) plugging or clogging by combustion products.

A standard HEPA filter consists of pleated filter material enclosed by a plywood or metal frame. The filter material (which is made up of a thin mat of fine, intertwined glass fibers) is folded back and forth around thin sheets of asbestos or aluminum materials, called separators. The nominal airflow capacity of this type of filter is 0.47 m^3/s. High-capacity HEPA filters usually do not contain separators, have a reduced folding depth, and are arranged in a V-type pattern within the frame. These filters have a normal operating airflow capacity of 0.85 m^3/s.

Under accident conditions, HEPA filters may have to respond to high airflows and pressure surges resulting from tornado depressurization or from internal explosions. In the case of fire, the filter may be exposed to high temperatures and large quantities of smoke (solid and liquid aerosol). In this investigation, we have simulated the effects of tornado, explosion, and fire accident conditions and evaluated the response of both standard and high-capacity filters.

We examine the structural limits of these units and also discuss their filtration efficiencies when they are subjected to simulated tornado and explosion transients. A unique device to evaluate the response of HEPA filters to fire conditions is described, and preliminary filter plugging data are presented. Finally, we discuss how and where these data may be used by an analyst in evaluating the response of nuclear facility air cleaning systems to accident conditions.

II. HEPA Filter Response to Simulated Tornado Transients

The response of HEPA filters to simulated tornado transients has been reported in several places.(1)-(3) In this paper, we wish to summarize the structural limit data reported elsewhere and report for the first time on the efficiency of HEPA filters subjected to simulated tornado transients.

Structural Limits

Structural limits are defined here as the pressure differential across the filter needed to just break the filter medium. We have determined the structural limits for standard HEPA filters (American or British design) and for high-capacity designs, including both European and American models.

Standard HEPA Filters. Table I summarizes the structural limit data we obtained for four manufacturers' filters. The highest limit we found was 20.1 kPa (2.91 psi), and the lowest limit was 9.1 kPa (1.32 psi). The mean break pressure was 16.4 kPa (2.37 psi).

Table I. Standard HEPA filter structural limits for simulated tornado transients.

	Structural Limits	
Manufacturer	kPa	psi
A	17.3	2.50
B	20.1	2.91
C	9.1	1.32
D	18.4	2.66
Average	16.4	2.37

Table II. High-capacity HEPA filter structural limits for simulated tornado transients.

	Structural Limits	
Manufacturer	kPa	psi
E	11.0	1.6
F	9.0	1.3
G	15.9	2.3
H	9.0	1.3
Average	11.2	1.6

High-Capacity Filters. The structural limits for high-capacity HEPA filters were found to be lower than those for standard HEPA filters; that is, 11.2 kPa (1.6 psi) compared with 16.4 kPa (2.37 psi). The results of these tests are shown in Table II.

Filtration Response

Determining the structural limits of HEPA filters is important, but questions about the filter's capability to perform its function during tornado transients remain. Therefore, we subjected HEPA filters to two types of filtration tests: (1) entraining aerosol in the pulse upstream of a clean filter and determining its efficiency during a transient by measuring the amount of aerosol up and downstream of the filters and (2) preloading filters with aerosol and measuring the amount of aerosol dislodged when the filters were subjected to a simulated tornado transient. A description of the test method and other details can be found in Ref. (4).

Efficiency of Clean Filters. Polystyrene latex aerosol with a mean diameter of 0.46 µm was injected upstream of the test HEPA filter and downstream of the prefilters as shown in Fig. 1. After this operation, the tornado transient was

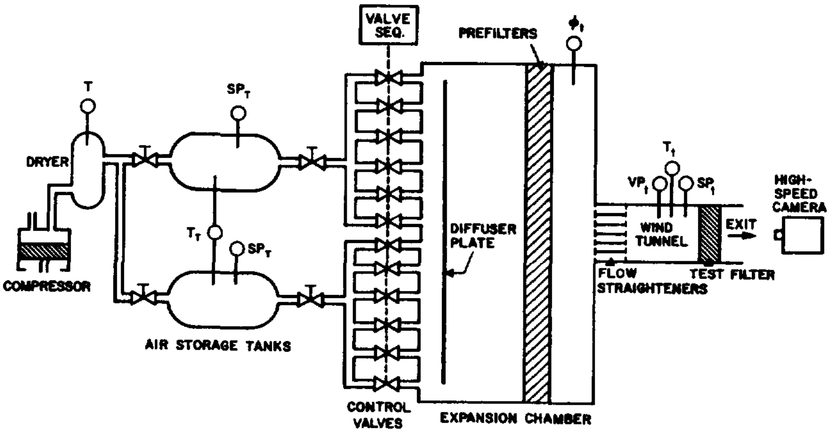

Figure 1. Schematic of apparatus used to determine the structural limits and efficiency of clean HEPA filters subjected to simulated tornado transients.

Table III. Efficiency of standard HEPA filters subjected to simulated tornado transients.

Manufacturer		Efficiency (%)
A		99.0
B		98.9
C		98.4
D		99.1
	Average	98.9

initiated, and upstream and downstream samples of particulate were collected on nuclepore filters. The particulate counts on the nuclepore filters were determined using an electron microscope. Table III shows the results of subjecting four manufacturers' standard HEPA filters to simulated tornado transients. The pressure transient was at a level below that required to cause structural failure. As shown in Table III, the filtration efficiency is degraded from 99.97% during normal operation to approximately 98.9%. No attempt has been made in our program to determine the effectiveness of high-capacity filters in this type of test.

Material Loss from Preloaded Filters. Standard HEPA filters were preloaded with 0.46-µm-mean-diam polystyrene latex aerosol using a Laskin-type generator at a normal operating condition airflow rate. The filters were loaded to a normal pressure drop of 38.1 cm w.g. At this pressure drop, approximately 1 kg of material was deposited on a filter. The amount of material released from the test filters was determined by placing nuclepore filters downstream of the filter and applying a vacuum of 12 cm w.g. to the back of the nuclepore filters to assure that the released aerosol would collect on them. As in previous tests, the test filter was subjected to only one simulated tornado transient, which was at a pressure level below that required to cause structural failure. The results of this type of test for standard HEPA filters are listed in Table IV.

Only two filters (from the same manufacturer) were evaluated. Table IV shows that the amount released in the two tests differed considerably. Although the amount released is significant, the analyst should be cautious when using these results because of the limited amount of data.

Table IV. Material released from preloaded standard HEPA filters during a simulated tornado transient.

Manufacturer		Particulate Mass Released (g)
A		14.6
A		7.1
	Average	9.35

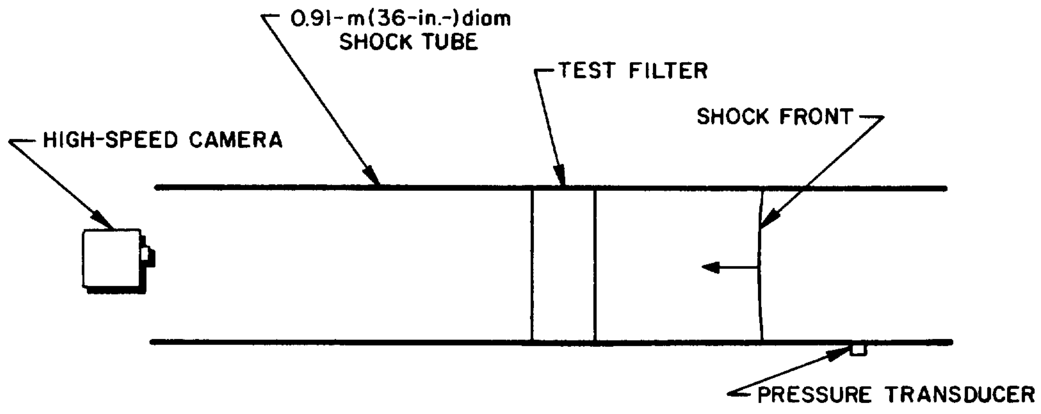

Figure 2. Test configuration used to determine structural limits and efficiencies of HEPA filters subjected to simulated explosive transients.

III. HEPA Filter Response to Simulated Explosion Transients

Data on HEPA filter response to simulated explosion transients can be found in several reports.(2),(5),(6) Here, we wish to summarize the data for structural limits, filtration efficiency, and material release that was obtained by subjecting HEPA filters to simulated explosion transients. These data contain values for both standard and high-capacity HEPA filters.

Structural Limits

The configuration used to determine structural limits is shown in Fig. 2. As discussed in the reports listed above, the break point or structural limit was determined photographically using the high-speed camera shown in Fig. 2. In the area of structural limits, we wish to compare our data with that obtained earlier by Anderson and Anderson and also determine structural limit data for high-capacity filters.(7) Our data for 47-ms-long simulated explosion waves are listed in Tables V and VI.

Table V. Structural limits of standard HEPA filters subjected to simulated explosion transients 47 ms long.

	Structural Limits	
Manufacturer	kPa	psi
A	17.2	2.50
B	17.4	2.53
C	7.2	1.04
D	9.5	1.86
Average	12.8	1.86

Table VI. Structural limits of high-capacity HEPA filters subjected to simulated explosion transients 47 ms long.

Manufacturer	Structural Limits	
	kPa	psi
E	5.5	0.8
F	5.5	0.8
G	9.7	1.4
H	6.9	1.0
Average	6.9	1.0

The structural limits of high-capacity filters are lower than those found for standard HEPA filters (6.9 kPa or 1.0psi compared with 12.8 kPa or 1.86 psi). Both of these values are lower than those reported earlier by Anderson and Anderson (22.0 kPa or 3.2 psi) for explosive waves of a 50-ms duration. We also noted that standard HEPA filters have different structural limits for tornado and explosive transients.

In our investigation of the structural limits of HEPA filters, we believed that identifying structural limits based on peak pressure alone was not sufficient. Therefore, we also evaluated the total impulse applied during the explosive transient. The impulse (I/A) was evaluated using Eq. 1 by including both peak pressure (p) at the structural limit and the time until the filter fails (Δt).

$$\frac{I}{A} = \int p \quad t \quad . \qquad (1)$$

We used Fig. 3 to study the supposition that impulse causes structural failure in the filters. Figure 3 is a plot of impulse per unit area; $I/A = \int p \, \Delta t$ as a function of shock wave duration. If the impulse resulting from the shock overpressure is the cause of failure, then the plots in Fig. 3 would be horizontal. Obviously, this is not entirely true. At the longer shock wave duration, impulse seems to be the controlling parameter, but this does not seem to be true for the shorter durations (5 ms--20 ms). This caused us to examine our test data more thoroughly as outlined below.

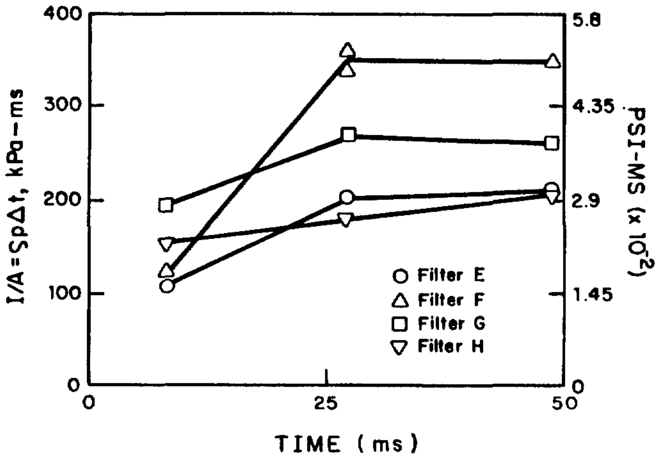

Figure 3. Plot of impulse vs shock wave duration for four manufacturers' HEPA filters.

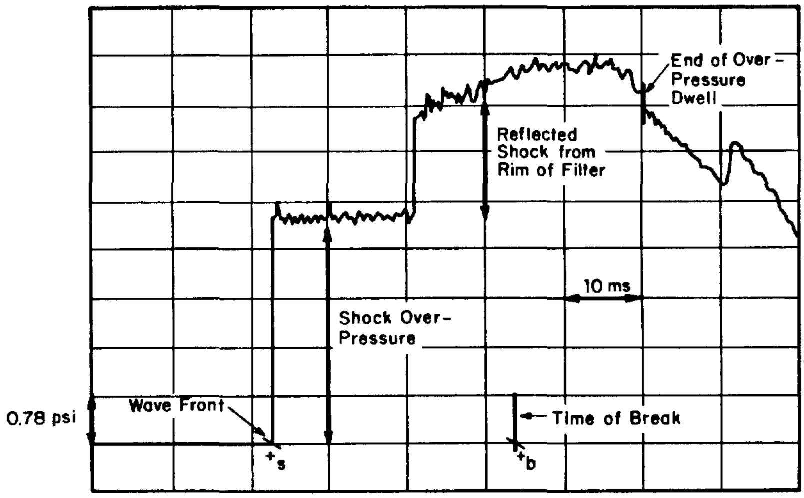

Figure 4. Typical pressure for a 47-ms shock wave duration.

Figures 4 and 5 show typical pressures for 47-ms and 5-ms shock wave durations. Previous studies have shown that the reflected wave from the rim of the filter case that appears at the pressure transducer located about 20 ms after shock passage is not experienced on the face. Careful examination of the pressure records reveals that for all of the short shock waves, filter failure occurred after the shock impulse had passed through (or more probably, had been absorbed by) the filter. Compare the shock wave shown in Fig. 5 with the long-duration shock wave shown in Fig. 4. This result seems to imply that some other mechanism contributes to the failure of the filter at short shock wave durations; airflow rate could be the cause of this phenomenon. The passage of the shock wave through the air by the tube causes the air to move in the same direction as the shock wave.

The structural limit of the E-type filter at the 5-ms shock wave duration was 10 kPa (1.45 psi). The air velocity behind the shock wave with the overpressure was 28.77 m/s or a flow rate through the filter of 10.69 m^3/s. Our tornado testing of this filter showed that flow rates through this filter reached a maximum value of 10.38 m^3/s and that most filter failures occurred at flow rates below this value. Thus, because high residual airflow rates persist after passage of the shock impulse, it is probably the high flow rate with its attendant high stagnation pressure that causes filter failure at short shock wave durations.

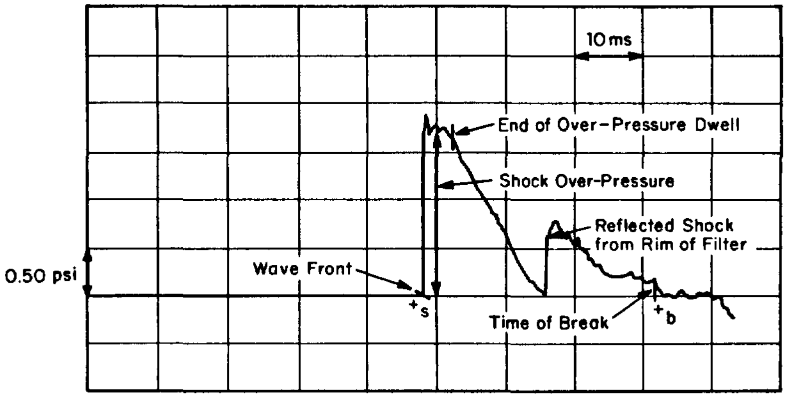

Figure 5. Typical pressure for a 5-ms shock wave duration.

Filtration Response. As in the response when filters are subjected to simulated tornado transients, we also are concerned about the response of the HEPA filters to simulated explosion transients. In these tests, only high-capacity HEPA filters were tested. Both efficiency testing of clean filters to shock-entrained aerosol and material loss testing were performed. The tests were very limited in number so the results should be viewed as somewhat qualitative and should be used with caution.

Efficiency of Clean Filters. The efficiency of high-capacity HEPA filters in simulated explosion transients was examined by first loading the driver section of the shock tube with polystyrene latex aersol like that used in the tornado testing. Our use of nuclepore filters to make the measurement was similar to that described above for the tornado tests. A single high-capacity filter (type E) was chosen for this test. The maximum pressure was 6.89 kPa (1 psi), which was below the structural limit found in earlier testing. Our measurement of upstream and downstream particles for the test indicated an efficiency of 70%.

Material Loss From Preloaded Filters. To determine the material release from high-capacity HEPA filters, we preloaded several filters with polystyrene aerosol in the same manner as for the tornado testing. In these tests, two manufacturers' filters were tested at simulated explosive pressures below break values found in the structural limit tests. The results of the material loss tests are given in Table VII. The large amount of mass loss for the first filter listed in the table (341 g) apparently occurred because the filter medium was slightly creased during the test. Again, the analyst should view these results with caution because of the limited amount and variability of the data.

IV. HEPA Filter Response to Simulated Fire Accidents

Background

In this section we will describe the Los Alamos National Laboratory filter plugging program and present some preliminary experimental results. This program was initiated in 1981 when we realized that there were no known data for simultaneous measurements of pressure drop, flow rate, and combustion product mass accumulation on HEPA filters for realistic fire conditions. These data are needed to calculate the empirical coefficients in expressions relating filter pressure

Table VII. Material released from preloaded high-capacity HEPA filters subjected to simulated explosive transients.

Manufacturer	Material Released (g)
E	341.3
E	0.001
F	0.002

drop to volumetric flow rate in the Los Alamos FIRAC accident analysis computer code.(8) An example of a typical semi-empirical expression of this kind is(9)

$$\Delta p = \Delta p_o (1 + \alpha m_p) \quad , \tag{2}$$

where

$$\Delta p_o = K_L \mu \frac{Q}{A^{3/2}} + K_T \rho \frac{Q^2}{A^2} \quad . \tag{3}$$

In Eqs. (2) and (3), Δp_o represents the clean filter pressure drop resulting from both laminar friction and turbulent dissipation in pascals, and

α = filter plugging coefficient dependent on filter and material properties (kg^{-1}),
m_p = accumulated mass of material on filter (kg),
$Q = V_A$ = volumetric flow rate (m^3/s),
Q_o = $V_o A$ = clean filter volumetric flow rate
A = filter cross-sectional flow area (m^2),
K_L, K_T = dimensionless laminar and turbulent coefficients, respectively,
μ = air dynamic viscosity (Pa•s,) and
ρ = air density (kg/m^3).

Equation (2) assumes that a linear relationship exists between $\Delta p/Q$ and m_p.

Other more complicated theoretical models of filter plugging are available in the literature, such as the the dendrite model(10) and the increasing fiber model.(10) The models quantitatively predict filter plugging as idealized cases in which the loading particles either form fiber-like dendrite chains or increase the fiber diameter, respectively. (In actuality, both effects are probably occurring in the case of smoke.) These models are extensions of existing pressure drop theories for clean filters.

The dendrite model states that the loaded filter pressure drop may be predicted using

$$\Delta p = \Delta p_o \left(1 + \frac{R\alpha_p}{r\alpha_F}\right)\left(1 + \frac{R^2\alpha_p}{r^2\alpha_F}\right)^{1/2}\left(\frac{Q}{Q_o}\right) \quad , \tag{4}$$

when the volumetric flow rate Q is a variable.

In Eq. (4),

α_p = particle volume fraction = vol. particles/vol. media,

α_F = fiber volume fraction = vol./fibers/vol. media,

r = particle radius (m), and

R = fiber radius (m).

Because α_F can be derived from measurable quantities and the uniform fiber (media) density, the fiber radius R may be estimated using the clean filter pressure drop equation.

$$\Delta p_0 = \mu Q_0 \, T \, \frac{16 \, \alpha_F^{3/2}}{R^2} , \qquad (5)$$

where T is the filter thickness (m).

Filter Plugging Facility,

To supply the needed filter plugging data, Los Alamos and New Mexico State University have constructed a unique filter plugging test facility. The purpose of this facility is to supply experimental data for 0.61- by 0.61-m HEPA filters under conditions simulating those postulated as credible for fires in nuclear facilities. Industrial fires such as these are expected to differ from other kinds of fires in the types of materials involved and the ventilation conditions (availability of oxygen). A typical fuel mixture may be composed of the materials listed in Table VIII. These materials are likely to burn under both oxygen-rich and oxygen-starved conditions (over- and under-ventilated conditions) to produce particulate material, water vapor, and gaseous combustion products.

Thus, some unique capabilities were required of the new facility. First, we needed the capability to determine the accumulated mass gain of a clean 16-kg HEPA filter because of smoke and moisture clogging. Previous tests using polystyrene latex spheres lead us to expect plugging (arbitrarily defined to be a 50% flow rate reduction from the design value) to occur from an accumulation of under 500 g of dry solid material. To resolve 2- to 3-g smoke accumulations out of 16 000 g, we designed and constructed a special null-balance filter-weighing apparatus. Second, we needed the capability to burn mixtures of materials selected from the

Table VIII. Typical fuel mixture composition.

	Component	Composition (%)
1.	Polymethylmethacrylate	45
2.	Cellulosic	26
3.	Elastomer	18
4.	Polyvinyl Chloride	8
5.	Hydraulic Fluids	2
6.	Polystyrene	1

above list with variable burning efficiencies. To do this, Pacific Northwest Laboratory designed and constructed a special combustor for Los Alamos. Finally, we needed the capability of adding varying amounts of heat and moisture to the airflow. Heat will be supplied by a commercial air heater, and water is sprayed into the air through a commercially available nozzle.

Idealized Tests Using Stearic Acid

A preliminary series of 19 plugging tests were conducted during the winter of 1981 to (1) prove out the null-balance filter-weighing system and (2) determine the effects of concentration and moisture addition. In these tests, dry stearic acid particles with a mean diameter of 0.488 μm were generated using a commerical condensation-type generator. Stearic acid was chosen because a fairly monodisperse, spherical, nontoxic, control aerosol could be generated for the approximate size and concentrations desired to simulate a fire. (We were able to generate stearic acid aerosol loadings of about 60 to 120 mg/m^3; full-scale forced ventilation fire tests at Lawrence Livermore National Laboratory have produced concentrations of real smoke in excess of 5 g/m^3 while burning porous cribs of solid fuels.) A spray nozzle was used to inject water at selected flow rates up to fully saturated conditions. The 19 tests, including dry particulate only, water only, and mixed conditions, are summaried in Table IX.

Reviewing Table IX, we observe that increasing the stearic acid concentration by increasing the generation rate from 0.105 to 2.05 cm^3/min in the absence of water spray successively reduced plugging times from 32.2 to 4.87 h. Adding water spray at the higher flow rates (200 and 400 g/min) resulted in faster plugging (about 3--6 h) with higher mass loadings (about 5.5--8 kg). Dry stearic acid plugged the filters with significantly less mass loading (about 0.40--0.55 kg).

Table IX. Summary of idealized filter plugging tests using stearic acid and water spray.

Test	Stearic Acid Volumetric Flow Rate (cm^3/min)	Water Mass Flow Rate (g/min)	Plugged Mass (kg)	Time to Plug (h)
17	0.0	100.0	3.447	27.0
18	0.0	200.0	7.729	9.52
19	0.0	400.0	6.996	5.27
4	0.105	0.0	0.415	32.2
7	0.105	100.0	6.481	32.9
6	0.105	200.0	8.060	5.787
5	0.105	400.0	6.583	4.93
1	0.241	0.0	0.401	20.7
10	0.241	100.0	6.179	31.5
9	0.241	200.0	6.941	4.53
8	0.241	400.0	6.336	4.13
2	0.941	0.0	0.550	13.4
13	0.941	100.0	3.796	6.22
12	0.941	200.0	5.429	6.23
11	0.941	400.0	5.450	3.90
3	2.05	0.0	0.454	4.87
16	2.05	100.0	4.251	5.97
15	2.05	200.0	5.345	6.05
14	2.05	400.0	6.449	3.00

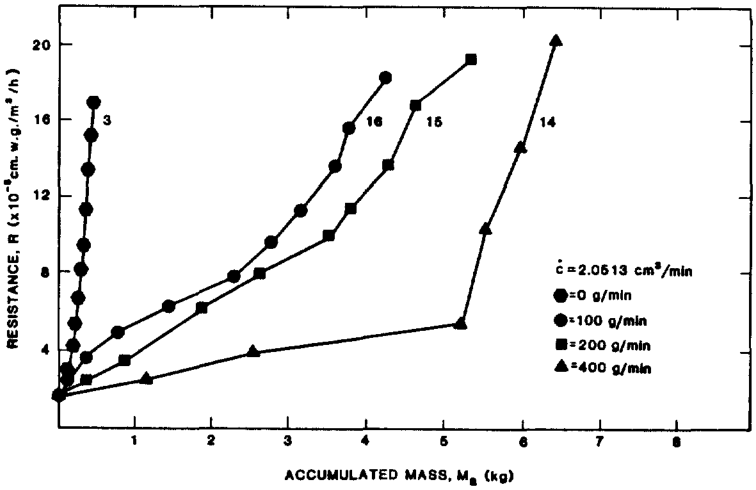

Figure 6. HEPA filter plugging by simulated smoke aerosols showing the effect of moisture addition.

Figure 6 presents the results of the four filter tests conducted at the highest stearic acid mass generation rate with three water spray injection rates. These curves can be fitted with polynomials of the form $\Delta p/Q = f(m_p)$, where f is a polynomial and includes the linear form of Eq. (2). In this way the data could be used in a computer code to estimate pressure drops during filter plugging under fire conditions.

A comparison of the dendrite model prediction of Eq. (4) and the experimental data of test 2 has been made in Fig. 7. For Test 2, the pertinent parameters used in Eq. (4) were ΔP_o = 2.3 cm. w.g., R = 1.428 µm, α_F = 0.4292, volume of filter media = 0.007267 m^3, and ρ_p = 0.9846 g/cm^3. The parameter p varied from 0 to 0.0767 as the filter was plugged with dry stearic acid. The flow rate Q dropped from 1695 to 878 m^3/h. Two values of particle (or dendrite) radius r were

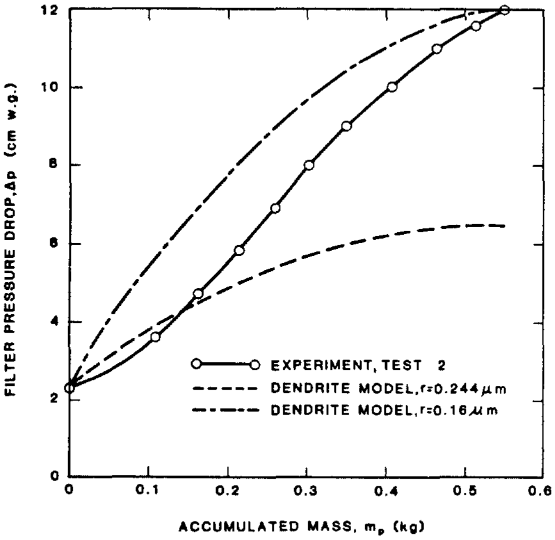

Figure 7. Comparison of dendrite model and experimental data.

used in Eq. (4) to produce the model curves shown in Fig. 7. The first value of $r = 0.244\ \mu m$ was determined as an arithmetic average of stearic acid aerosol particle sizes measured using a Royco Model 225 Aerosol Particle Counter. The second value of $r = 0.16\ \mu m$ was obtained by back-calculating with Eq. (4) to match the last or plugged data point shown. Figure 7 illustrates the sensitivity of the dendrite model to dendrite geometry and aging, that is, to the selection of r. However, the $r = 0.16\ \mu m$ curve presents a conservative estimate of filter plugging for this case.

Future Testing

A more complicated series of filter plugging tests will be conducted during the fall of 1982. This series will use the same weighing technique but will also use the special combustors to burn two materials, polystyrene (PS) and polymethylmethacrylate (PMMA), at two mass-burning (or smoke-generation) rates, high and low. The mass-burning rates will be controlled by adjusting the inlet air supply rate. Each of these conditions will be repeated 3 times for a total of 12 tests. The repetitions are intended to allow us to assess the reproducibility of our test results. Because PS and PMMA represent extremes of smoke-producing materials, we should be able to derive filter plugging coefficients that bracket those expected in nuclear fuel cycle facility fires. Additional experiments are planned for 1983, and these will include using typical fuel mixtures, adding heat and moisture to the flow, and using improved gas analysis and particle-size measuring instrumentation. These tests are intended to simulate and measure more complex and more realistic filter plugging conditions.

The current filter plugging test series are part of a Los Alamos fire test plan to support development and verification of the FIRAC Computer code. Ultimately, we wish to model and predict transient combustion product generation and transport in nuclear fuel cycle facilities using FIRAC. To do this, we need to develop experimental fire simulation and measurement capabilities in the following areas.

1. Fire simulation and classification
2. Compartment fire behavior
3. Combustion product behavior during transport (deposition and modification by aerosol dynamic changes)
4. Filter plugging behavior
5. FIRAC code verification

The testing in these areas will include release rate oven, compartment fire, filter plugging, and ventilation system facility experiments.

V. Application of HEPA Filter Data to Accident Analysis

Experimental results from subjecting HEPA filters to simulated accident conditions are needed by analysts concerned with the design and safety of nuclear facilities.(11) Typically, safety analyses require predicting the consequences of accidents occurring within nuclear facilities. In addition, the accident-induced challenge to the air cleaning system must be predicted. The analyst must know the structural limits, filtration efficiency, plugging effect, and possible material release from critical HEPA filters. We have obtained supportive HEPA filter experimental data that, when coupled with computer codes that can predict accident-induced loadings, will allow the analyst to determine the response of fuel cycle facilities to fire, explosion, and tornado accident conditions. In this section, we illustrate how and where HEPA filter experimental data can be used.

Evaluation of the effects of tornado depressurization on a nuclear facility air cleaning system an be accomplished using the Los Alamos computer code TORAC to predict the pressure and flow rates at all filter locations within the facility.(12) Knowing the predicted pressures and flows, the analyst then can turn to the structural limit data to see if structural failure can occur. If structural failure occurs during the transient, the analyst has the capability to restart the problem with new flow conditions that simulate the failure mode when using the TORAC code. If the analyst has no knowledge of the type of filter used in the facility, the lowest structural limit of 9.0 kPa (1.3 psi) should give the most conservative analysis.

The structural limit data for explosive transients can be used in the same manner as discussed for tornado transients. However, in this case the analyst would use the Los Alamos computer code EXPAC to simulate the explosive wave propagation.(13) Our data indicate that shock pressures should be less than 13.8 kPa (2 psi) for standard HEPA filters and less than 6.9 kPa (1 psi) for high-capacity HEPA filters to preclude HEPA filter destruction.

From our studies of high-capacity HEPA filters, we found that shock impulse per unit area (I/A) was related to structural failure. The filters seem to have a property that causes them to fail at a particular value of I/A. If this or a higher value of I/A is contained in an impinging shock pulse, the filters will fail during the shock over-pressure. The impulse present in any pressure wave can be calculated using the EXPAC computer program. If there is not sufficient I/A contained within the shock pulse, then the filter may still fail because of the magnitude of the airflow rate following the shock wave. Thus, the analyst must take great care when using I/A as a criterion. The safest approach would appear to be using the lowest I/A from Fig. 3 (that is, 100 kPa/ms) as the limiting I/A.

We believe that our material loss data from loaded filters (that is, filters that have seen significant service conditions) can be used by a safety analyst to estimate possible release when filters are subjected to tornado or explosive transients. However, we offer rather qualitative guidance because of the limited number of tests. Experiments show that at the inital point of failure, large amounts of particulate can be released. Further, even if structural failure does not occur and the peak pressure is 50% below the failure point, significant amounts of particulate will be released under explosive transients. In estimating possible releases from HEPA filter units, the safety analyst should consider using a pressure limit that is 50% below the structural limit. This area needs further investigation because of the limited amount of data.

The current generation of accident analysis codes also can predict transport and movement of particulate though a nuclear facility's ventilation system. If the analyst couples the experimental data for efficiency into the filter modules of these codes, an estimate of material release through the filter system can be made. If the analyst uses the results from our preliminary shock pulse study, he should allow 30% of the material to pass through the protective HEPA filter even if the impinging shock wave is below the filter's structural limit. However, the data in this area are limited and should be used carefully.

The filter plugging data being obtained by subjecting filters to simulated fire conditions are essential supportive data for a computer code to predict fire spread in a nuclear facility. The HEPA filter is very effective in trapping all smoke particulate generated from a nuclear facility fire. As smoke particulate accumulates on the filter, the pressure drop increases and the flow through the filter decreases. Therefore, a computer code that simulates smoke movement through a facility must have the capability to alter the flow dynamics in accordance with material accumulation on the filter. The FIRAC computer code discussed above will be capable of predicting temperature and smoke distribution throughout a nuclear facility ventilation system. As illustrated in Sec. IV, the data developed in this program will be transformed into a filter plugging relationship for the FIRAC code, which will automatically adjust the flow conditions in accordance with the mass of material on the filter. This simulation capability is essential if the analyst is to predict flow reversals and the effect of the changing ventilation conditions on the character of the fire. That is, the reduced airflow may create greater smoke production and flow reversals sending backflow to less less contaminated zones within the plant.

VI. Summary

Los Alamos is conducting multifaceted experimental studies funded by the U.S. Nuclear Regulatory Commission in which HEPA filters are being subjected to simulated accident conditions. The purpose of these studies is to obtain experimental data on filter performance and structural integrity during simulated accident conditions. The data will be used by analysts to formulate new or improve existing mathematical models of HEPA filter performance. Such models currently are being used, for example, in the Los Alamos family of nuclear fuel cycle facility accident analysis computer codes, FIRAC, EXPAC, and TORAC.

This paper presented test results for both domestic and European style HEPA filters of both standard and high-capacity design. These filters were exposed to simulated fire, explosion, and tornado conditions. Results showing filter explosion and tornado accident structural limitations and, for the first time, filtration efficiency were presented. Our HEPA filter plugging program and test facility are also reviewed. This program is yielding useful experimental data on HEPA filter performance during controlled loading with simulated combustion products. The effects of smoke concentration and moisture level were investigated.

Acknowledgment

The authors wish to recognize the contributions made by C. I. Ricketts and J. J. Dallman in the investigations described in this paper. The support of the U.S. Nuclear Regulatory Commission has made these investigations possible.

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DISCUSSION

BERGMAN: The experimental tests on filter plugging suggest that water greatly accelerates HEPA filter plugging. This effect poses a serious question about the advisability of using water sprays before HEPA filter banks. Would you please comment on this?

MARTIN: Our data show this. There is another source of water vapor besides the engineered safety spray systems. In general, combustion processes generate a considerable amount of water as a combustion product. A question here is whether the moisture can be transported to the HEPA filter. If the spray droplets are sufficiently large and properly directed, HEPA filter wetting can be minimized. The purpose of our tests was to determine HEPA filter behavior with and without moisture for modeling purposes. The code, FIRAC, can be used to determine the transport of combustion products throughout a facility, including their impact on filtration systems. Something that could have been done, but was not done in these tests, was to determine the quantity of solid particulate matter on the filters. The curves that I showed you represented the cumulative water and particulate additions. I think you pointed out that wetting filters is an important matter because of the reduced filtration effectiveness of the filters.

RUEDINGER: At KFK, we are investigating the response of HEPA filters to high humidities. In the case of condensing humidity, our experience, as well as the results of other authors, are in accordance with Dr. Bergman's statement. There are some indications, however, that between 70 and less than 100% RH, the dust loading capacity may be increased. I, therefore, would like to ask Mr. Martin to give more information about the levels of relative humidity that existed during the experiments he reported.

MARTIN: As I mentioned, the airflow was saturated, so the relative humidity was 100% in the case of the 200 g/min. and 400 g/min. tests. The point of these tests was to obtain data for the users which we could interpret and incorporate in our computer codes for accident conditions. The point of adding moisture is because, if the water spray system comes on in real facilities and fully saturates the air, the tests will show how the filters are going to respond in terms of pressure drop and flowrate characteristics. I think that is a good point and something we should be measuring for tests that introduce water sprays at somewhat less than 100% relative humidity. We will be making such measurments.

KRAUSE: In compartment fires, the combustion of hydrogen to water often is sufficient to produce relative humidity of 90% or above in the exhaust flow.

FREIBERG: A question on tornados, you indicated that even when you got up to 1.9 or 1.6 PSI, the structure survived. If that is correct, it indicates to me that HEPA filters will survive any tornado.

MARTIN: The maximum critical tornado is about 3 PSI external to the facility. The facility geometry, and components within the facility, will have a bearing on damage to filters. I presented the average structural breaking pressures so you can look in the paper and see the range of values that were obtained from four different manufacturers. I believe, one manufacturer had filter breakage at about 1.3 PSI. Others were higher.

FREIBERG: I am under the impression that 1.7 PSI is the maximum tornado. If that is correct, we can save a lot of money throughout the industry because that HEPA filters will survive the tornado impact; even though the ductwork may not.

MARTIN: That is certainly an important point. The data I cited is for a Region III tornado at 3 PSI overpressure.

FREIBERG: That surprises me because the same tornado study for us came up with 1.7 PSI.

GREGORY: I think for the Rocky Flats region, as in Region III, the specified tornado is 1.7 PSI but the maximum for the East and all other regions is specified in an interim NRC publication at 3 PSI.

HEPA FILTER RESPONSE TO HIGH AIR FLOW VELOCITIES *

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Abstract

High air velocities and high differential pressures across HEPA filters may occur in accident situations e. g. TORNADOS, LOCAs in nuclear power stations, fires.

Structural testing of new HEPA filters showed that under the favorable conditions of ambient temperature and low relative humidity commercial filters fail between 4 and about 20 kPa. The lower values are obtained with metal frame filters, usually being considered as potential filters for accident conditions, and with mini-pleat filters. With dust loading the break pressures measured were reduced, by up to 40 %. This is partly due to the fact that with the release of a cloud of dust the real point of first failure was recognized. Failure mechanisms were investigated and subsequent first modifications of the filter pack and paper tensile strength led to an increase to 24 kPa of the structural integrity of wood frame filters.

Since the filter resistance characteristic is also safety relevant, this property was investigated too. Filters of the mini-pleat design showed a less good performance at high air velocities than the conventionally pleated filters. Comparison with theory revealed that with improved filter design the resistance curves could be shifted towards lower values, thus reducing high differential pressures and the risk of failure.

I. Introduction

Ventilation systems make part of the outermost safety barrier of nuclear installations which in case of light water reactors consists of the containment and the steel concrete shell surrounding it (1). Should this barrier fail in case of an accident the contamination of the environment could be considerable, depending on the sequence of events considered (2). In order to protect the environment also in such unlikely situations, the HEPA filter elements, too, must remain efficient under accident conditions.

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II. The Challenge to HEPA Filters by High Air Velocities and High Differential Pressure, respectively

The challenges HEPA filters may become exposed to will depend on the accident scenario and on the design and geometry of the plant considered. Since hardly any reliable data on the operating conditions in accident situations are available, we depend on rough estimations.

In general, elevated temperatures can be expected to occur as a result of the release of enthalpy in the course of the accident and due to the decay heat of the radionuclides deposited in the filter elements. If coolant ducts rupture, the relative humidity of the air to be filtered will be high; even condensing steam can be anticipated.

Furthermore, elevated differential pressures may develop across the filter trains, leading to high mechanical loads on the filter elements. Such challenges may result from a TORNADO depressurization, which is a design base accident according to U.S. regulations. The maximum differential pressure at the intake or exhaust of an air cleaning system postulated for a region I TORNADO (3) is 20.7 kPa. The consequences of a TORNADO on air cleaning systems and their components have been investigated by Gregory et al. (4,5). Their analyses demonstrated that a significant attenuation of depressurization takes place inside the filter system so that the real stress on the filter elements will be lower.

The filter trains may become exposed to considerable stresses in internal accidents occurring in light-water reactors. The following estimates will illustrate this situation. The simplified ventilation scheme of a modern nuclear power station of German design is shown in Fig. 1. The annular space in the accident is ventilated via the filter system indicated in the figure. If we assume that a duct of the residual heat removal system in the annulus ruptures, which is a design basis accident, then an overpressure between 0.04 and 0.1 bar may develop in the annular room. The gas temperatures to be expected will be low but the relative humidity of the air will exceed 100 %.

The second example relates to a postulated hypothetical accident. A loss-of-coolant accident is assumed and it is postulated that isolation of the containment at the penetration of the ventilation system does not work, i. e., that the dampers D1 and D2 do not close. This is equivalent to a leak of 300 mm diameter. It can be assumed that ventilation ducts of relatively light design will quickly fail under the impact of the rising containment pressure. Therefore, humid air flows into the annular space through the leak in the containment. At the same time, air escapes from the annular space via the open filter trains of the negative pressure system and the annular room exhaust air handling system. The resulting plot of the pressure building up inside the annulus versus time was calculated with the COCMEL code (6) and is represented in Fig. 2. After approximately 300 s the maximum value of about 0.6 bar is attained. The temperature of the atmosphere would rise to about 75 °C, the relative humidity would be 100 % or higher.

Elevated differential pressures may build up not only in nuclear power stations but also in fuel cycle facilities. Examples are fires.

Hence in case of accidents, major mechanical stresses of HEPA filter elements in ventilation systems by elevated differential pressures must be expected. Moreover, challenges may occur at the same time which are due to increased humidities and temperatures.

It is not sure that the HEPA filters available now will withstand the challenges occurring in all postulated accidents. Therefore, it is one goal of our work to develop upgraded filters in the interest of nuclear safety. For this reason, structural tests are being performed as a first step at a test facility of the Los Alamos National Laboratory. The objective will be to determine the structural limits, study the failure mechanisms and investigate first modifications. The major results will be reported here.

III. Experimental

Test Facility

The only installation for realizing high air velocities through HEPA filters and, at the same time elevated differential pressures, is operated by the Los Alamos National Laboratory. It was used for two extensive test programs.

A schematic of the test facility with its main components is shown in Fig. 3. In principle, it consists of two large storage tanks for compressed air and a test duct, which is about 6 m long and has a cross section of 610 x 610 mm. The test filter is mounted at the end of the test duct. The pressurization rate and the air flow and, hence, the pressure differential across the filter are controlled by 12 solenoid valves in parallel. For more details see e. g. Ref. 7, 8.

Structural Testing

The tests were designed to determine the structural strength of the filters. This property is quantified within the framework of these tests as the differential pressure at which the first visible failure occurs. The response of the test filters to the challenge of increasing air velocity and differential pressure, respectively, is recorded with a high speed camera. Analysis of the films allows the times of failure to be indentified which, when correlated with the differential pressure record, indicates the failure pressure.

In Fig. 4, a typical record is reproduced of the variation of the differential pressure during a test, which usually lasts no longer than a few seconds. The second curve represents the variation in velocity upstream of the filter. The record also shows the timing marks allowing the frames of the high speed film to be related to the chart. For every test a new filter element was used.

Resistance Testing

The resistance characteristics of the test filters must be known in order to permit control of the rate of pressurization. Furthermore these data are needed as input data for codes like TVENT (4). Finally, the steepness of the resistance curve is a property of HEPA filters which is of importance in view of their possible damage in an accident,as themechanical load at a given air velocity will decrease with decreasing filter resistance.

Resistance characteristics were also measured with the blowdown facility: Starting with low values,the air flow is increased stepwise as soon as steady-state flow conditions are obtained. The manner in which a resistance test was performed is demonstrated in Fig. 5, which shows a typical chart of the increase in static differential pressure together with the simultaneous increase in the air velocity upstream of the test filter.

Preloading with Polystyrene Latex

In practice, HEPA filters are loaded with dust and are usually replaced, when the pressure drop at rated flow has increased to approx. 1000 Pa. Therefore, the consequences of dust loading on failure pressure have also been investigated.

The test filters were preloaded with polystyrene latex particles of some 0.3 µm aerodynamic diameter. This was done in a separate filter channel where an aqueous dispersion of latex was sprayed into the air flow. The water evaporates and the particles are collected on the filter paper. For the actual tests preloading was done with the dispersion sprayed at a considerably increased rate compared with the procedure described in Ref. 8. As a consequence, evaporation is not comlete, and droplets reach the filter. The remaining humidity evaporates from the fibers. This is demonstrated by SEM. In Fig. 6 a scanning electron micrograph is reproduced with dried droplets surrounding the fibers.

Therefore, as a result of the preloading conditions, the adhesion of the particles to the fiber is especially strong, which is advantageous for the tests performed.

Test Filters

The filters tested within the framework of this program were selected from the current production of major manufacturers worldwide, so that it was possible to determine the state of the art with respect to physical strength at high air velocities. Additionally, in order to avoid duplication, makes other than those tested by Gregory and co-workers were selected.

Twelve types of commercial filters were tested. They can be broken down into three different design categories:

- conventionally pleated filters with wooden frames for temperatures up to 120 °C, supplied by European manufacturers,
- conventionally pleated filters with metal frames for temperatures up to 250 °C,
- mini-pleat filters (multi-panel design) with wooden frames for temperatures up to 120 °C.

In addition, a series of 6 filter types with simple modifications in design were tested. The details of their design will be described in Chapter IV.

IV. Structural Limits of HEPA Filters

Results of Structural Testing

The results of the tests of new filters are summarized in Table I which is subdivided into conventionally pleated filters with wooden and metal frames and mini-pleat filters with wooden frames. The rated flow was 1700 m^3/h and 1800 m^3/h, respectively, with the exception of the DV type filter. The standard deviation was in the range between 3 % and 11 % which proved that the test procedure can be repeated in an excellent way. There were only two exceptions where one filter of each type was an outlier. A little greater scatter of the test results measured over a period of about two years was reported by Ricketts (9). The spread of the results is due to the sum total of variations of the experiments and to the tolerances of production, since a new filter is used for every test. Thus, these figures also demonstrate that, in general, the filter elements can be manufactured so as to show little variance in physical strength. This is of importance in view of the safety margin which needs to be specified.

The break pressure data indicated are mean values of tests repeated three to five times. The conventionally pleated filters with wooden frames proved to be the most stable design. DN type filters were a modification of the DH type. With this modification, an increase to a rather high value of 22.5 kPa was achieved. However, the useful temperature range of these filters is limited to some 120 °C. The metal frame filters, which are designed to withstand elevated temperatures and are therefore considered as accident filters, furnished only poor results. The filters of the mini-pleat design neither showed better performance.

In Table II the failure pressures of unloaded and preloaded filters are compared with each other. There is no obvious change for one filter type. In the other cases the first failure was observed at lower differential pressures, in the worst case the difference was as high as 40 %. However, the analysis of the high speed movies demonstrated that only part of this reduction is caused by preloading itself. Another part of it is due to the fact that first failure is clearly indicated by release of a cloud of dust

Table I Structural limits of commercial HEPA filter elements with respect to high differential pressure, filter size 610 x 610 x 292 mm

filter design		type rated flow		No. of tests	break pressure	standard deviation
pack	frame		m^3h^{-1}		kPa	%
conv. deep pleat	wood	DH	1 700	5	11.6	9
		VN	1 700	3	13.9	7
		S3	1 800	3	17.4	28
		DN	1 800	3	22.5	9
conv. deep pleat	metal	C1	1 700	4	4.2	11
		VM	1 700	4	7.0	8
		AM	1 700	4	8.4	6
		C2	1 700	3	9.3	6
		DM	1 700	6	10.5	3
mini-pleat	wood	L	1 700	3	5.9	5
		DR	1 700	5	5.9	6
		DV	3 000	3	11.1	30

Table II Effect of preloading on the structural limits of HEPA filters preloaded with PSL up to 1000 Pa pressure drop at rated flow, filter size 610 x 610 x 292

filter design		filter type	break pressure		
pack	frame		unloaded kPa	preloaded kPa	reduction %
conv. deep pleat	wood	DN	22.5	22.5	0
conv. deep pleat	metal	AM	8.4	8.0	5
		VM	7.0	6.2	11
		DM	10.5	7.7	27
mini-pleat	wood	DV	11.1	6.7	40

easily detectable on the high speed movie. In contrast, without preloading the real first break cannot be traced sometimes. This is especially true in the case of the 3000 m^3/h DV type filter, which is of the mini-pleat design with the panels very close together and extremely difficult ot observe.

The tests demonstrate that the structural strength of HEPA filters currently available is relatively low. The results obtained are in agreement with those Gregory and co-workers have published (7-9). Investigations into the response of HEPA filters to shock waves lead to figures which, on the average, are about 50 % higher (10-13). Furthermore, many authors reported filter damage found in various investigations, particularly for operation at high humidity (14-22,27). It has also been confirmed that the so-called mini-pleat design generally fails very early (11,19,21). There is only one exception for a LUWA filter of 3000 m^3/h rated flow recently tested together with other brands by Gregory and Smith (10). Until now there has been no explanation for the high break pressure of 15.9 kPa.

In his recent paper (10) Gregory confirmed the overall findings about the influence of preloading on failure pressure. The part which is due to the determination of the first break cannot yet be distinguished from the influence of preloading itself.

Analysis of Failure Modes

Evaluation of the high speed films not only allows the break point and thus the break pressure to be identified, but also furnishes wealth of data about the modes and courses of failure, thus providing the basis of successful development work. The three most important failure categories will be discussed below.

The weakest point in metal frame filters proved to be the attachment of the filter paper pack to the frame. The prefabricated filter cores were fastened throughout by stuffing the voids between the frame with glass wool. Consequently, the filter core is mainly held by friction forces. As soon as they are exceeded, the entire paper pack is pushed out, leaving the case empty (see Fig. 7).

The filters of the mini-pleat design fail as a result of shearing of the panels at the vertical bars where they are sealed. The filter element in Fig. 8 demonstrates this failure mode which has also been observed by other authors (10,19,21). In this case, sealing to the frame and the bar was strong enough, but the stability of the small packs (panels) was insufficient. This behavior can be explained on the basis of the results by Anderson (13), who showed that the strength of the filter pack decreases with decreasing depth of the pleats. This was confirmed by Burchsted (23) and represented graphically. The pleats of conventional filter packs are about six times deeper than those of the mini-pleat design. The high speed films revealed that the break of a single fold of the downstream face constitutes the typical first failure of conventional wooden frame filters (see Fig. 9).

With filter elements from one manufacturer Gregory (24) found that in 8 out of 11 tests the medium folds next to the frame were the points of initial breaks. Based on our test results and on those published by Ricketts (9) we can state that the first break of the conventionally pleated filters preferably occurs at a medium fold close to the sides of the frame. The analysis of the high speed films revealed that the break usually is preceded by ballooning of the same fold. Fig. 11 explains the tensile stresses in the lateral and in the circumferential directions. The tensile stress in the filter medium in the circumferential direction is approximately

$$\sigma_c \approx r \frac{\Delta p}{d}$$

with r being the radius of the fold, d the thickness of the filter paper and Δp the static differential pressure.

As a consequence of ballooning, the radius of the fold and thus the stress of the filter medium are increasing until the tensile strength is exceeded and the medium fails. The fact that the tensile stress in the longitudinal direction σ_l is only one eigth

$$\sigma_l \approx \frac{1}{8} r \frac{\Delta p}{d} = \frac{1}{8} \sigma_c$$

explains why transversal cracking of single folds never occurred.

Obviously, the tensile strength of the filter medium is of considerable importance for the structural limits of HEPA filters. Ricketts (9) found a good correlation between both properties. A closer look at the failed folds revealed that usually the edges of the folds had broken (see Figs. 12 and 13).

There is some evidence that the tensile strength of the medium is reduced along these edges. Analysis of the filter paper with the aid of scanning electron microscopy showed that the filter paper is partly damaged due to folding in the course of manufacture. In Fig. 14 a scanning electron micrograph is represented which shows an example of damaged filter paper. Damage may also be caused by the sharp edged aluminium separators.

With the differential pressure increasing beyond the first break pressure, the number of broken folds increases and likewise the extent of damage. Finally, after considerable increase above the first break pressure also the conventionally pleated wooden frame filters fail catastrophically (Fig. 10).

Summarizing the results of these analyses, it can be stated that there are three major points of weakness limiting the structural strength of HEPA filters:

- attachment of the filter pack inside the frame (filters for elevated temperatures),
- stability of the filter core,
- tensile strength of the filter paper.

In these points improvements have to be achieved in order to obtain HEPA filters fully applicable in accident situations.

First Improvements

Based on the results obtained so far, some modifications in filter design were tested with respect to the stability of the pack and the tensile strength of the paper. The basic version was a conventionally pleated filter with wooden frame and an elastomeric sealant for temperatures up to about 120 °C. This design ensures a relatively good fixation of the filter pack inside the frame. The modifications are characterized in Table III which, additionally, summarizes their effects on break pressure. The figures listed in the last column are mean values of four tests, with the exception of S1 type filters of which only one prototype was tested.

Table III Structural limits of modified HEPA filters, filter size 610 x 610 x 292 mm

filter type	rated flow m^3h^{-1}	characterization	break pressure kPa
DH	1 700	basic version	11.6
DN	1 800	U-shaped protective fabric strip between separators and paper	22.5
S5	1 600	typ DN with vertical web plate	18.0 (1)
S6	1 600	type DN with horizontal web plate	17.0 (1)
S4	1 700	type DN with long-fiber filter paper	24.0 (27.6) (2)
S7	1 700	protective glass fiber fabric pleated together with filter paper	23.1 (26.5) (3)
S1	≈ 40	metal fiber filter with reinforcing screens and grids	> 28.2

(1) low figures due to fabrication defects

(2) one filter remained undamaged at the maximum load of 27.6 kPa

(3) two filters remained undamaged at the maximum loads of 25.6 and 26.5 kPa, respectively.

In some cases the maximum static differential pressure obtained during the test was not sufficient to cause failure. Then the average break pressure was calculated using the maximum differential pressure realized. The best results are obtained with a combination of a long-fiber paper and a U-shaped fabric strip protecting the medium at the ends of the pleats from the separators, as suggested by White and Smith (25). One of these filters tested even withstood undamaged a differential pressure of 27.6 kPa. S7 type filters gave almost an equally good performance. Two filters of this type remained undamaged at differential pressures of 25.6 kPa and 26.5 kPa, respectively. With the web plates (the S5 and S6 versions) based on the results published by Anderson and Anderson (13) an increase in break pressure was expected because of the reduction in face dimensions by a factor of two. However, due to fabrication defects this result was not obtained.

A very special type of particulate filter was made from a series of stainless steel fiber mats, each of which clamped between reinforcing steel screens and grids (26). This filter, which can be used up to about 500 °C, withstood undamaged the highest differential pressure attainable of almost 0.3 bar. This caused only a slight reduction in filter efficiency measured at rated flow.

The tests of the modified HEPA filters demonstrated that for the low temperature version, for which the attachment of the filter core to the frame is sufficient, already a considerable improvement of the structural strength is achievable by simple means.

V. Resistance Characteristics of HEPA Filters at High Air Velocities

Resistance of New Unloaded Filters

The resistance characteristic of a filter element determines the mechanical load on the filter at a given air velocity. It is closely related to possible filter failure and therefore of safety relevance. This is the main reason for the investigations of the flow resistance of HEPA filters. Besides, knowledge of the pressure drop characteristics is necessary for the proper selection of the operating conditions for structural testing and as input data for codes like TVENT.

Fig. 15 shows two typical resistance curves of conventionally pleated HEPA filters. The DN type was tested three times, whereas two filter elements of the VN type were tested once. The small scatter of data points demonstrates that the LANL facility allows an excellent repeatability of the resistance measurements. Therefore, in the following diagrams data points are generally omitted.

The resistance curves of all new, unloaded filters tested are summarized in Fig. 16. There are three main categrories, the conventionally pleated filters, the mini-pleat filters, and metal fiber filter. Also with respect to flow resistance, the mini-pleat filters gave significantly less performance compared to the conventional design, because there is a steep increase already at air velocities between 12 and 15 ms^{-1}. Among the three mini-filters tested was also a so-called high-capacity filter with 3000 m^3/h^{-1} rated flow (DV type). At high air velocities it gave no better performance compared with the filters designed for 1700 m^3/h.

The S5 and S6 type filters were equipped with a web plate leading to a higher resistance compared with the other conventionally pleated filters. The resistance curves of these 10 filter types investigated so far are considered to be representative of the commercially available filters of this design. The S2 type filter approximately gives the average curve which can be written in the form

$$\Delta p = 0.026\ v + 0.014\ v^2$$

with Δp being the static differential pressure in kPa and v the average filter entrance air velocity in ms^{-1}; This is a reasonable assumption for analyses.

Resistance of New Filters Preloaded with PSL

Only three types of the conventionally designed filters were preloaded up to 1000 Pa pressure drop at rated flow and their resistance curves were determined. In Fig. 15 they are compared with those of the unloaded filters. The resistance of the AN type is approximated from Ref. 9 Table 5. With the limited number of data available it can be stated that at high air velocities too the increase in resistance at a given entrance air velocity is roughly 3-fold, as it is at rated flow.

The effect of preloading on the resistance characteristics of mini-pleat filters is demonstrated in Fig. 16. The most striking fact is that the air velocity at which the steep increase in resistance occurs is shifted to lower values.

Discussion of the Resistance Curves

It is well known that the interrelationship between pressure drop and air velocity depends upon the flow conditions. They are characterized by a Reynolds' number, which in case of a filter medium is defined using the fiber diameter D_f as the characteristic length

$$Re = \frac{D_f \cdot Vo}{\nu \cdot \varepsilon}$$

with Vo being the superficial velocity, ε the porosity and ν the kinematic viscosity. Viscous flow is prevailing at Reynolds' numbers below 1. In this case the air flow obeys Darcy's law so that there is a linear increase in resistance with growing air velocity. Equations describing the resistance characteristic, with a porous medium as the model concept were published for example by Davies(28), Clarenburg and co-workers (discussed in Ref. 28) and First (29). Based on the drag force model which represents in a more realistic way (30) the flow through a fiber medium with high fraction voids leads to a purely linear (28) or almost linear (31) relationship for viscous flow conditions. At Reynolds' numbers above unity the resistance follows a second order relationship with filtration velocity.

With a filter paper area of 20 m^2, an assumed mean fiber diameter of 1 µm and a porosity of 95 % the Reynolds' number amounts to only 0.04 at an entrance air velocity of 30 ms^{-1}. Therefore, laminar flow should be prevailing over the whole range of flow velocities investigated. Hence, the resistance characteristics should be straight lines. This is supported by the behavior of the metal fiber which is made of a series of mats consisting of 4 µm fibers. In this case the increase in resistance is linear up to the highest Reynolds' number of 0.4.

One reason for the deviation from theoretical behavior could be the compression of the filter medium possibly occurring with increasing differential pressure. As a consequence, porosity would be reduced and resistance would increase overproportionally. However, the glass fiber papers for HEPA filters are stabilized with binders. Therefore, they seem to be rigid enough to prevent the high compression which could be responsible for the deviation.

Another possible explanation starts from the assumption by Gregory and Smith (5,7) that the flow pattern is changing. With increasing velocity the air flow is believed to concentrate on the ends of the folds, leading to an uneven distribution of the velocity over the whole filter medium. However, there is no estimation yet about the order of magnitude of the increase in resistance caused by this phenomenon.

A very important effect is revealed by the high speed movies of the mini-pleat filters. It was observed that the steep increase in the slope of the resistance curve coincides with the swelling of the panels. This effect was also observed by Ricketts (Ref. 9 p. 71). As an example one frame of a high speed film is reproduced in Fig. 19. Since the panels are arranged in the form of V's they touch each other so that only a small part remains available for the passage of the air. Very likely this is the main reason for the specific resistance characteristic of the filters of the mini-pleat design. It is assumed that a similar effect of deformation is also partly responsible for the high resistance of conventionally pleated filters compared with theory.

Comparison of the shape of resistance curves with theory gave some evidence that the steep increase in pressure loss occuring at high air velocities might be avoided by design measures. This reduces the mechanical stress on the filters at a given air velocity, and increases, at the same time, the inherent safety of HEPA filters which constitutes a fourth way of particulate filter improvement with a view to accident situations.

VI. Conclusions

The tests performed on the structural limits of HEPA filters confirmed the statements of several authors (32-34) that they are rather fragile components of ventilation systems. They need further improvement in order to remain efficient also under accident conditions. The results of the investigations into the modes and courses of failures provide some guidelines for improvements.

The results on structural limits obtained so far can only be applied to conditions where high humidities and elevated temperatures are not encountered. The response of HEPA filters to the combined challenge of mechanical load, high humidity and elevated temperature still needs to be investigated.

The resistance characteristics of HEPA filters are also safety relevant. An additional way of filter improvement aims at the increase in the inherent safety by shifting the curves to lower resistance values.

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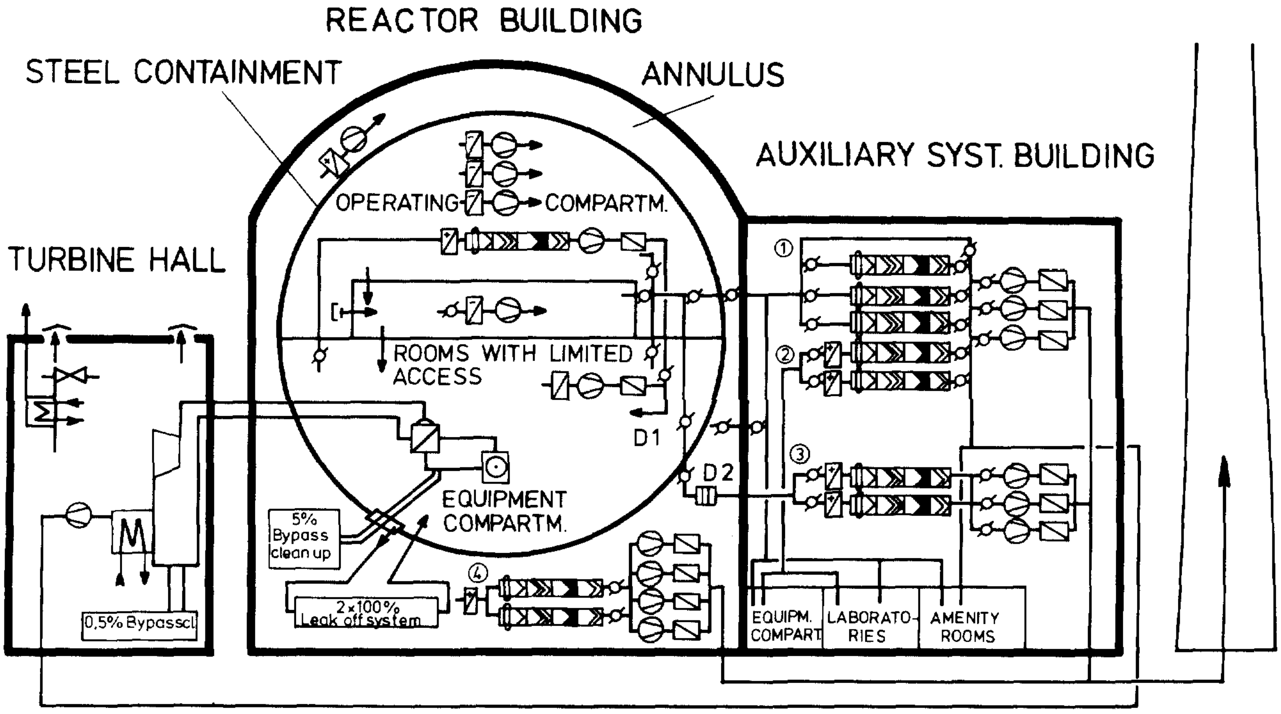


1 Vent air filter system
2 System exhaust air filter system
3 Subatmospheric pressure maintenance system
4 Annulus exhaust air filter system

Figure 1: Schematic of the ventilation system of a modern German PWR

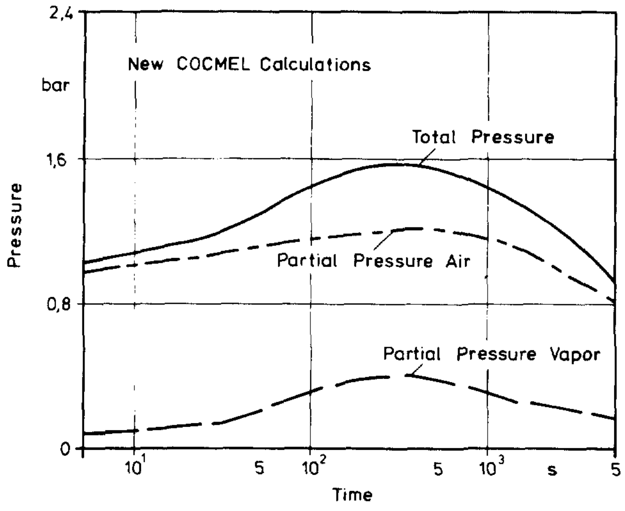


Figure 2: Pressures in the annulus, LOCA and 300 mm leak in the steel containment

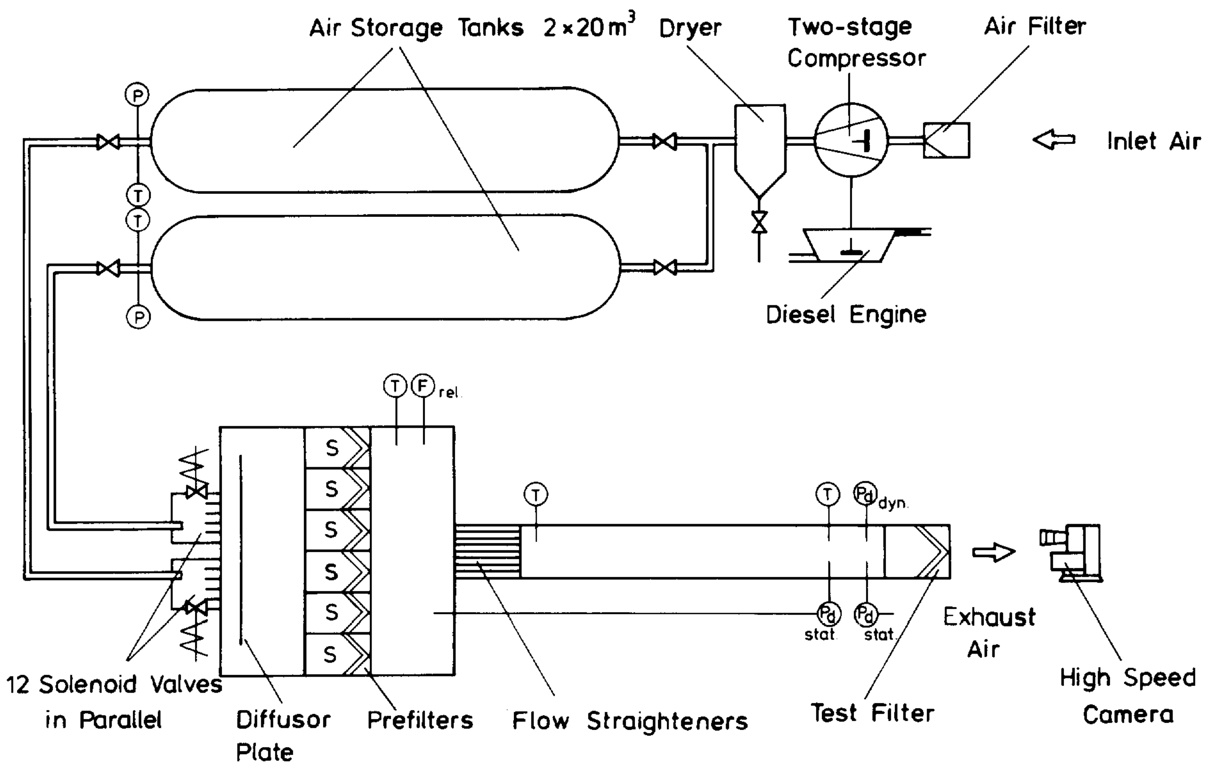


Figure 3: Schematic of the LANL-facility for structural testing of HEPA filters

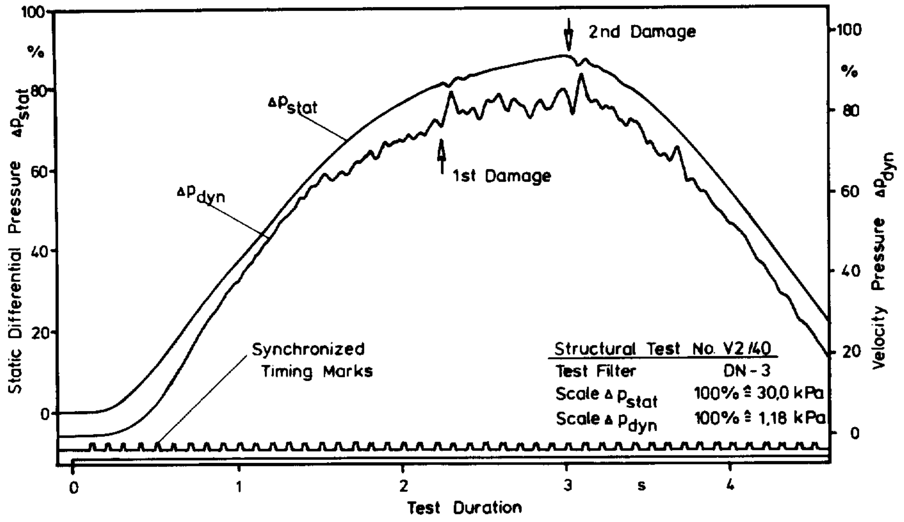


Figure 4: Pressure plot of a typical structural test

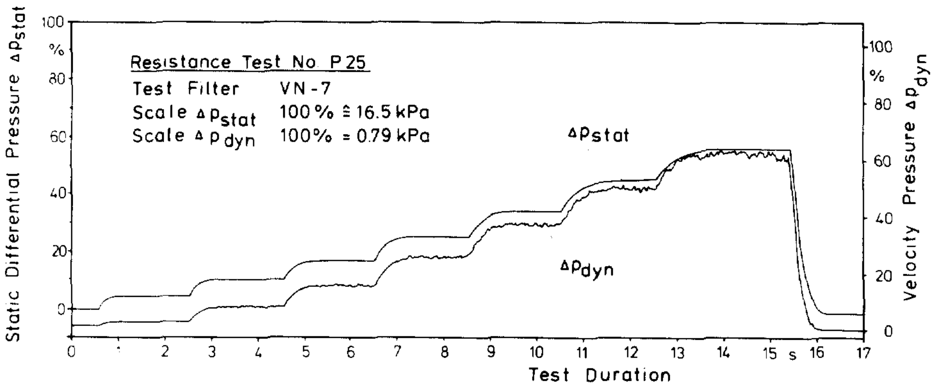


Figure 5: Plots of differential static pressure and velocity pressure in a typical resistance test

Figure 6: Scanning electron micrograph of a filter paper loaded with polystyrene latex aerosols

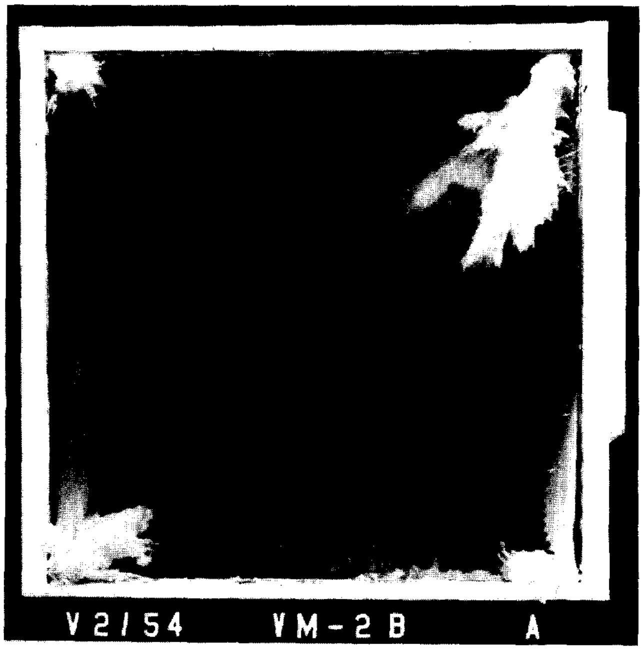


Figure 7: Typical failure of a metal frame filter

Figure 8: Typical failure of a filter of the mini-pleat design

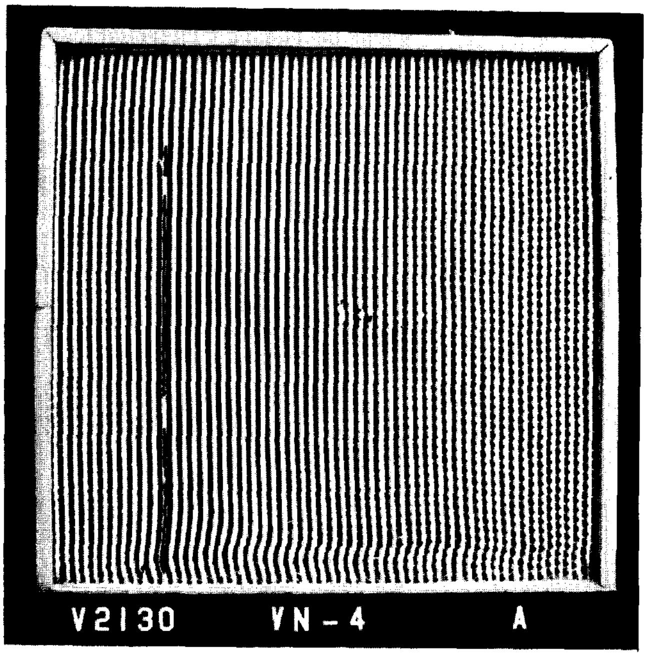


Figure 9: First failure of the deep pleat wooden frame filter

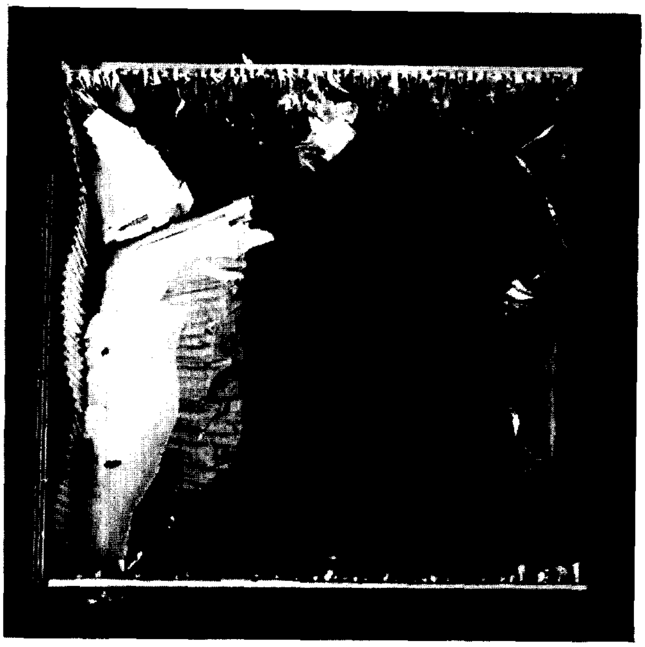


Figure 10: Totally damaged deep pleat wooden frame filter

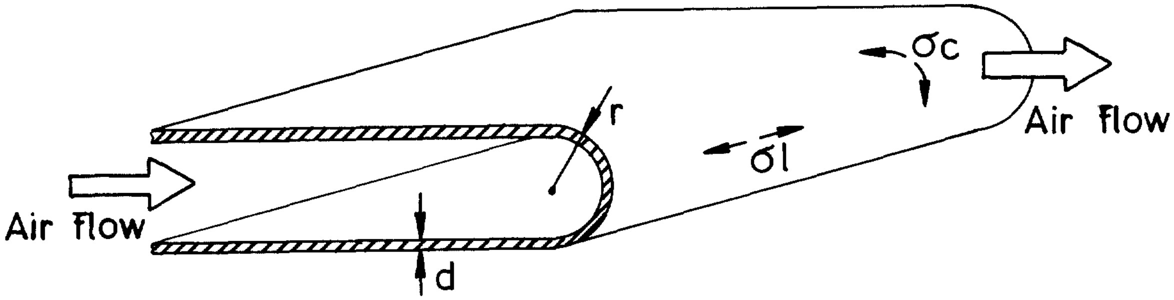
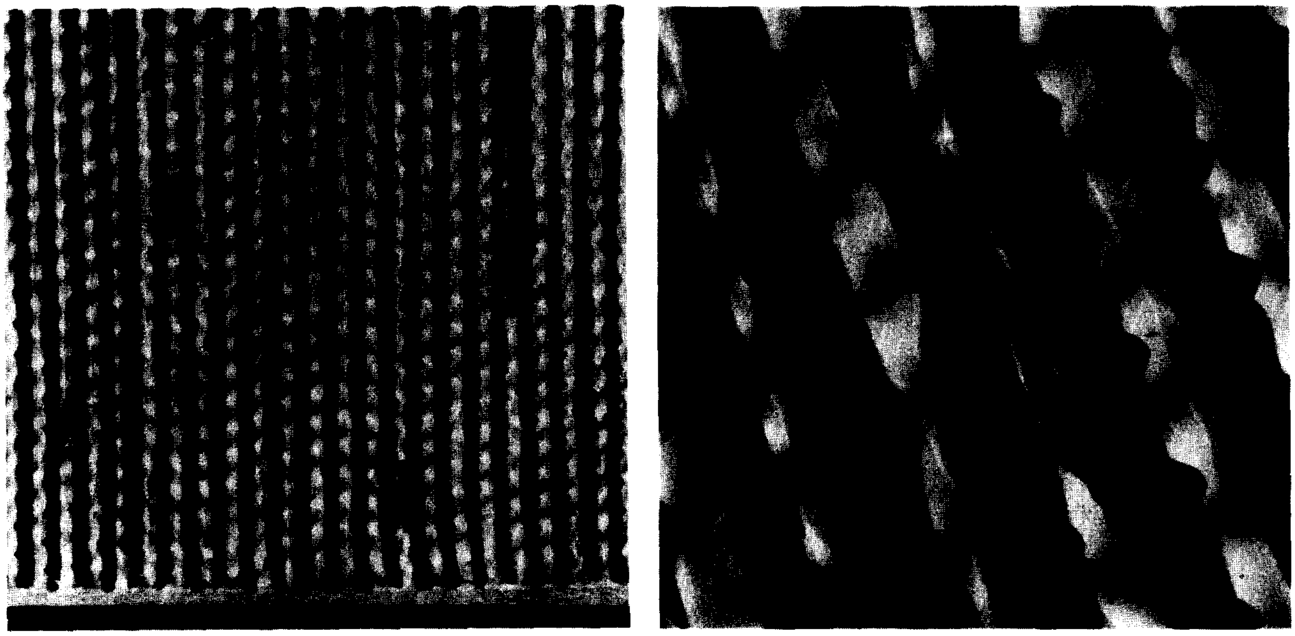


Figure 11: Tensile stresses in the filter medium of a downstream fold



Figures 12, 13: Failed folds of conventionally pleated filters

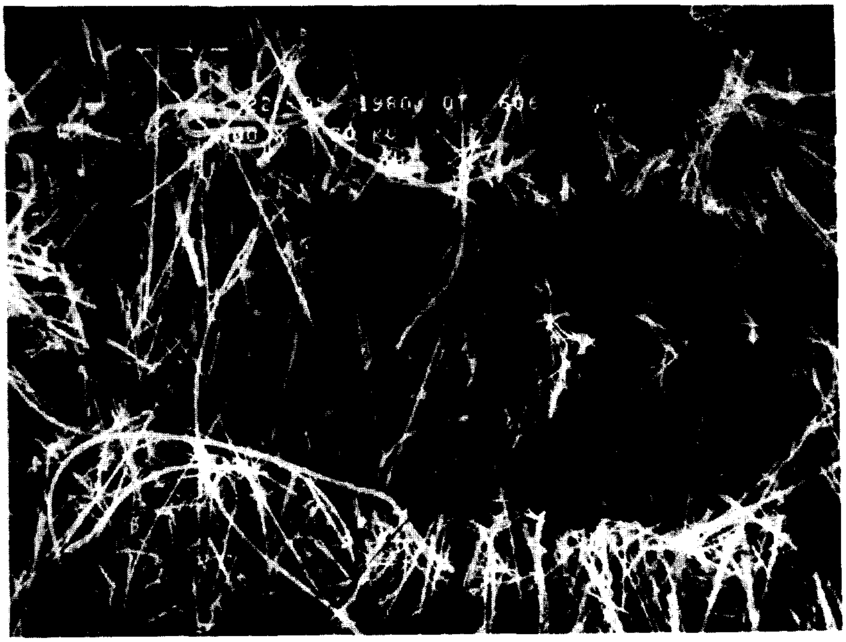


Figure 14: Scanning electron micrograph of a damaged filter paper

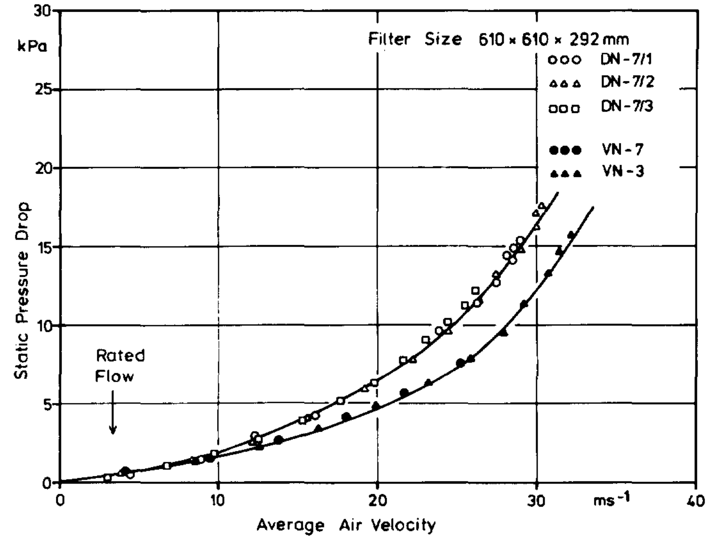


Figure 15: Repeatability of the flow resistance measurements

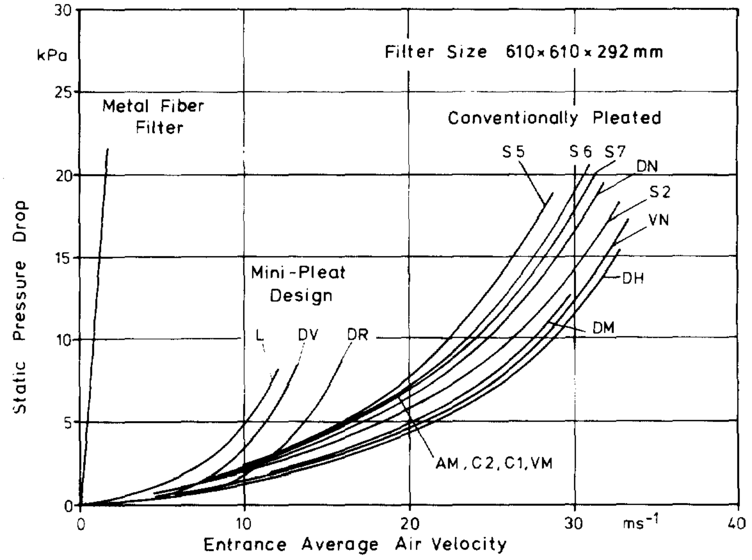


Figure 16: Resistance characteristics of standard size HEPA filters

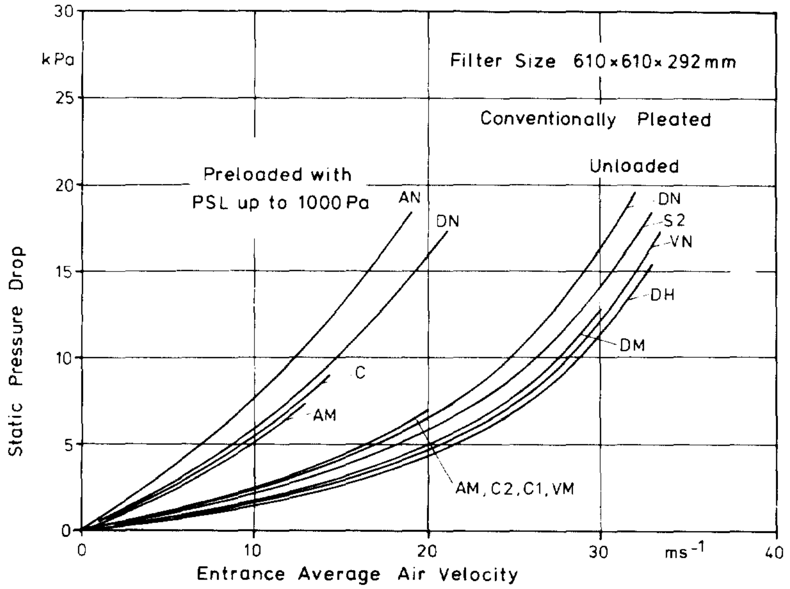


Figure 17: Increase in flow resistance of conventionally pleated HEPA filters due to preloading up to 1000 Pa at rated flow

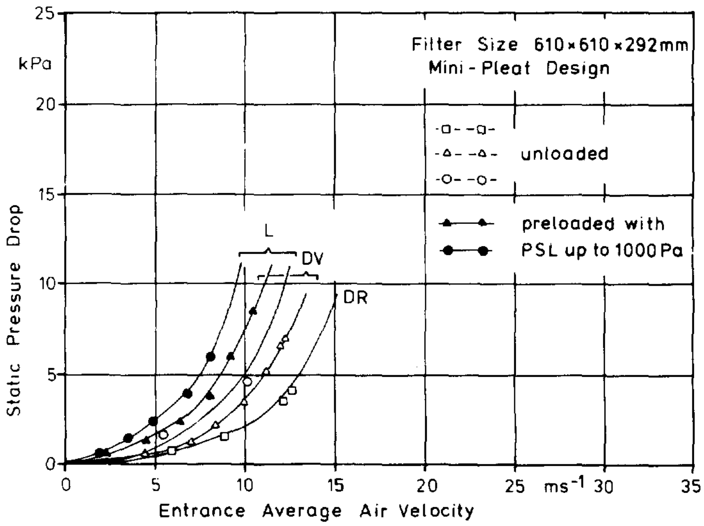


Figure 18: Increase in flow resistance of mini-pleat HEPA filters due to preloading up to 1000 Pa at rated flow

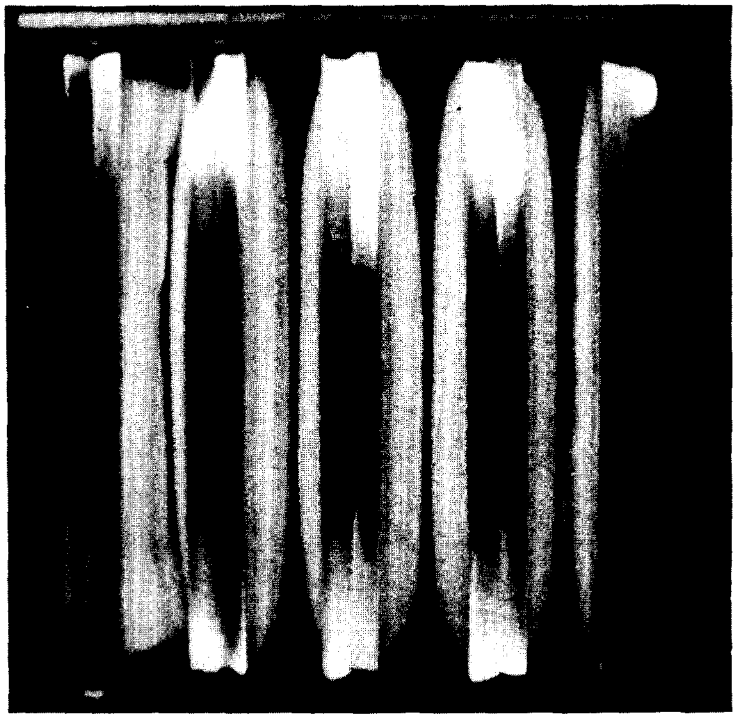


Figure 19: Mini-pleat filter with swollen panels at elevated differential pressure

DISCUSSION

BERGMAN: Is the increased pressure drop during high air velocities due to the turbulence within the conventional and mini-pleats of the HEPA filter? This is the most probable reason since there is no turbulence within the media and both mini-pleats and conventional pleats show the same behavior of increased pressure vs. velocity.

RUEDINGER: We agree that there will probably be turbulent flow conditions inside the triangular channels formed by the corrugated separators in the open folds. However, the total resistance is the sum of the resistance in the said channels plus the resistance of flow through the filter medium. Since the flow resistance through the fibrous medium is by far dominant, the flow conditions in the open folds can't determine the shape of the resistance curves.

WATSON: Did you test a UK-type deep pleat filter which has a grid on either side of the paper?

RUEDINGER: We did not test such filters from the UK. Modification of a deep pleat filter of another make gave no major improvement.

EFFECTS OF SHOCK WAVES ON HIGH EFFICIENCY FILTER UNITS

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ABSTRACT

Presented work was aimed at getting available an equipment by which comparative overpressure shock tests on components of commercial filtering units can be run.

In the paper problems encountered to arrange an existing shock tube, which is normally used to simulate open field explosions, in order to achieve significant and reproducible conditions of exposure to pressure waves of filtering units, are discussed and the selected arrangement of the equipment is described.

Shock tests on three different models of HEPA filters chosen among those commercially available in Italy, have been run measuring DOP efficiency of filters before and after each explosion.

Results showed importance of geometry of downstream ducts in determining the real pressure loading on the filtering pack; in fact equal blasts have caused different effects on filters, depending on the selected geometrical configuration.

Not negligible differences of behaviour were also found beetween standard and "diode" filters; the latter seemed to suffer overpressure transients more.

I. Introduction

Building ventilation and air cleaning are required either for occupational health and safety or for control and limitation of environmental pollution, whenever potentially harmful operations are involved.

Though for reasons different from the above, some delicate systems or operations need strictly controlled conditions of the room atmosphere, which are usually obtained by the same way.

These ventilation systems and specially filtration devices are designed for operation in a narrow range of flow conditions (temperature, flowrate, humidity, etc.).

However, both the same process and external, natural or human factors can originate abnormal situations which result in very much heavier conditions for these systems.

Therefore an important point to be investigated, is the behaviour of the whole filtering system and specially of its most delicate components (prefilters and filters), when they are called to operate in such abnormal conditions; at least to define threshold values of the operational and environmental parameters under which this system can be considered still correctly operating.

As it is well known, pressure transients lead the efficiency to drop or the filter to fail, and they can have a lot of causes: both natural (e.g. atmospherical events) man-originated (gas and fine-powder explosions, nuclear excursions, sonic booms, terroristic or war attacks).

Not many authors have run experiments, either with short(1,2) or long (3,4) duration transients, so new facilities are in preparation in various countries(5,6).

Up to now main results can be so summarized, in terms of drop of filter efficiency below the acceptance limit (named here resistance limit):

- resistance limit depends on size (low depth/breadth ratio causes lowering of resistance) conception and manufacture of the filter
- resistance limit depends on the time-law of the pressure transient
- dust preloading lowers resistance and a certain amount of deposed material is resuspended.

These above mentioned results are very interesting but certainly they don't exhaust all the aspects of the problem; in order to obtain further improvement of the knowledge in this field, the CAMEN and the Department of Nuclear and Mechanical Construction of the University of Pisa have planned a research program whose first steps are:

a) setting up an experimental facility which allows reproducible and conservative evaluation of filter resistance to short pressure transients;
b) comparative analysis of the performances of some types of HEPA filters, among the most commonly used ones, with particular reference to those manifactured in Italy;
c) modification of these filters to ameliorate their performances.

II. Experimental apparatus

II.1 The shock tube

The CAMEN simulator of openfield explosions consists of a cylindrical detonation chamber, an expansion tube and electronics for control and data recording.

The shock wave is generated by firing a charge, located at the center of the gun chamber and propagates through the tube; this is constituted by three cylindrical sections (diameters ϕ_1 = 915 mm; ϕ_2 = 1830 mm; ϕ_3 = 2440 mm and lenghts L_1 = 9144 mm; L_2 = 15546 mm; L_3 = 50030 mm) joined together by frusta of cone. Conical parts cause some perturbations in wave profile but they become minor more than seven diameters far off; positions of test stations (25, 44 and 62 m far from the charge) were chosen so as to minimize these effects. In these positions the shock wave has a satisfactory degree of planarity and normality to the axis of the tube.

Test stations are equipped by:

- piezoelectric transducers for low pressures (range 0 ÷ 2.1 MPa)
- " " " high " (" 0 ÷ 210 MPa)
- strain gauges.

Signals from transducers are amplified and recorded on a magnetic tape; simultaneous recording of up to 14 signals is possible.

Later on visualization was effected by an U.V. paper recorder; a timer controls the experiment step by step licensing in sequence:

- start of the tape recorder
- start of calibration signals
- fire of the charge
- stop of the recorder.

Fig. 1 shows a schematic of the shock tube and of the related equipment.

Performances, in terms of side-on overpressures and positive phase duration, are in Table I.

Table I: Shock tube performances.

TEST STATION NUMBER	DIAMETER (mm)	SIDE ON OVERPRESSURE PEAK RANGE (kPa)	POSITIVE PHASE DURATION (ms)
1	915	105-210	20-27
2	1830	42-90	50-65
3	2440	0-56	60-70

II.2 Pressure transient generation and evaluation

Data from Anderson(2) indicate that expected values for peak overpressures able to cause large HEPA filters to fail, can be obtained in test station n° 3. This station can be moved on rails and was placed 10 m far from the conical part (65 m from the charge). Peak overpressure was measured in four series of explosions to check both reproducibility of the pressure generation and stability of the signal transmission lines. The experiments were run in a period of 60 days.

Results reported in Table II and fig. 2 show:

- fine peak value reproducibility
- linear relation between charge weight and generated overpressure peak, in the range 100÷1200 g of TNT.

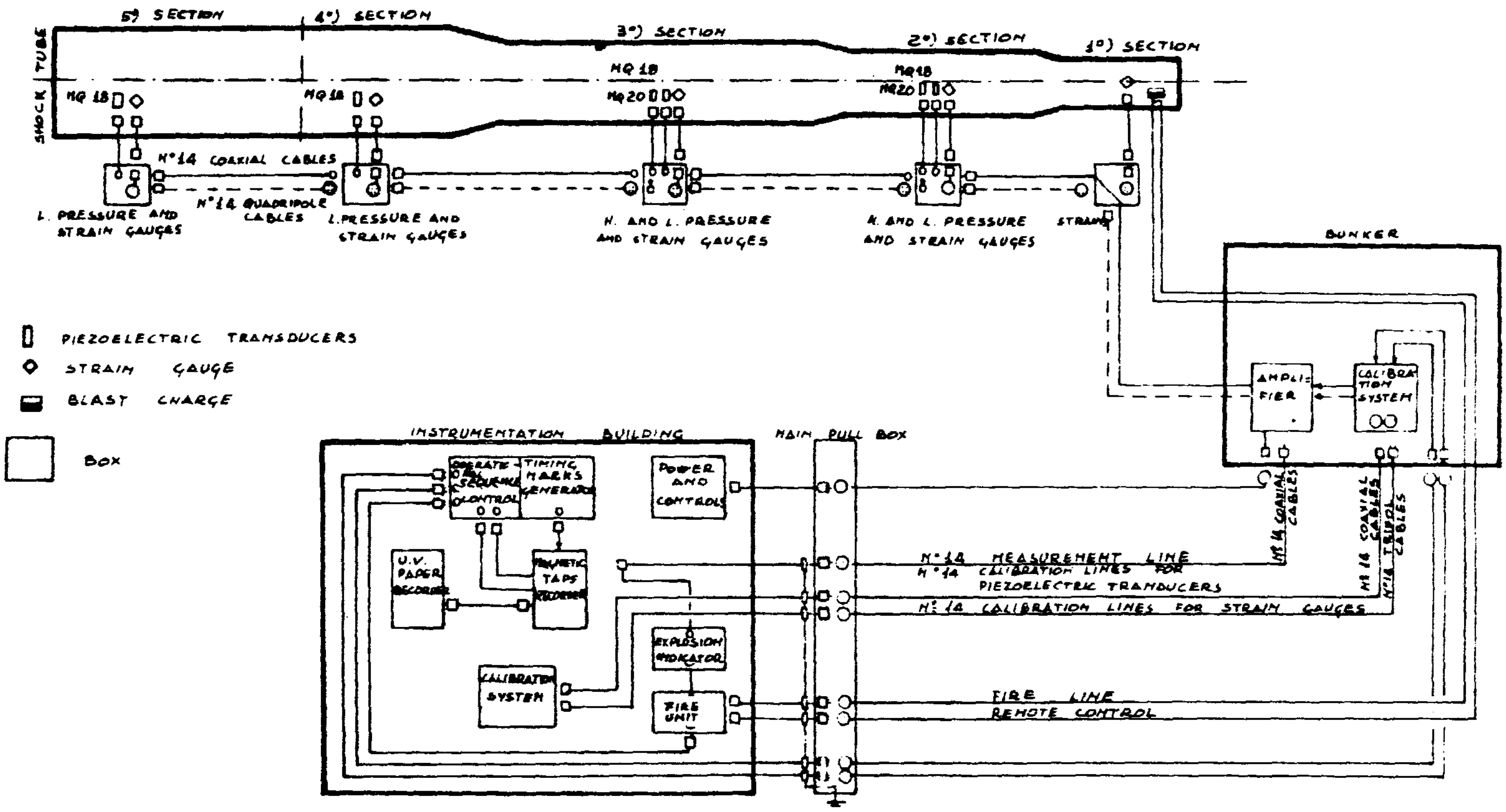

FIGURE 1
SCHEMATIC OF SHOCK TUBE AND RELATED EQUIPMENT

Table II: Reproducibility tests

Charge Weight gr	Overpressures (KPa)			
	1^series	2^series	3^series	4^series
100	7.1	7.1	7.1	7.0
200	9.9	-	-	9.6
300	11.2	11.6	11.6	11.2
400	13.3	13.5	13.4	13.5
500	15.4	15.8	15.7	15.4
600	16.2	-	16.5	16.2
800	21.7	22.4	22.4	21.8
1000	24.5	-	-	24.9
1200	26.9	27.5	27.6	-

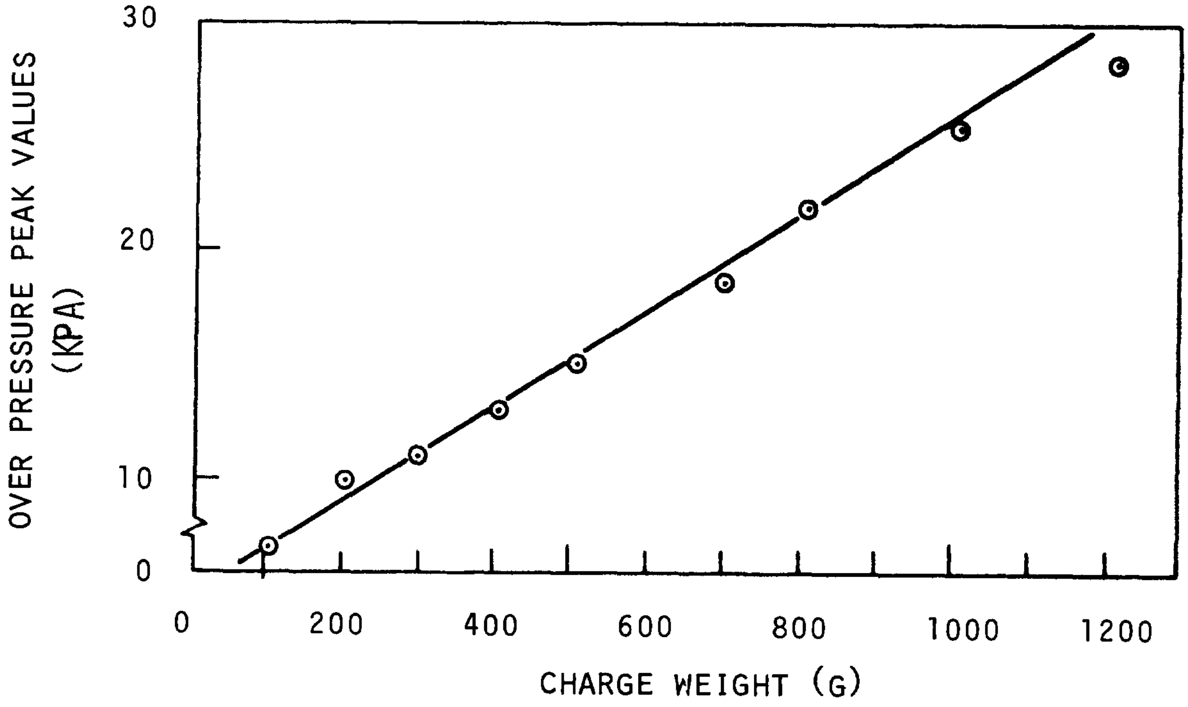

FIGURE 2
OVERPRESSURE PEAK VALUES VS CHARGE WEIGHT

Due to orientation of transducers, measured values are relative to stagnation over pressure.

Really, peak frontal load on an object is determined by the reflected overpressure. For a perfectly rigid object, the latter can be easily calculated; a simple relation in terms of side-on overpressure is:

$$p_r = 2pi \frac{7P_A + 4pi}{7P_A + pi}$$

where:

p_r = reflected overpressure

pi = side on overpressure

P_A = atmospheric pressure.

Since a filter is not rigid, the reflection coefficient becomes less than 2.

There are many difficulties in measuring the overpressure peak reflected by a filter, due to the impossibility that a transducer follows filter pack distortion adequately.

To get an order of magnitude, two different experiments were performed. In the first, two transducers were located at the sides of a rigid table (61x61 cm) and a third one was placed at the center of the table (see Fig. 3a).

In the second, the table was substituted by a standard HEPA filter of the same size (wooden case) and the central transducer was inserted in the filter pack, trying to damage it as less as possible (see Fig. 3b).

Results are reported in Table III and IV.

Measured values of the reflection coefficient were in a satisfactory agreement with theory and with Anderson's reported range (1.3÷1.5 for $0 < p_i < 5$ psi).

II.3 Filter arrangement and related diffraction effects

Effects of blasts on structures are especially related to impulse (area on force-time coordinates). In the shock tube, pulse height and duration are mainly affected by the position along the axis and by the characteristics of the charge; filter supports further modify pulse shape. Typical pressure graphs are in Fig. 5,6. A way to nullify diffractive effects due to supports is the mounting of the filter on a plate which completely covers the open end of the shock tube(4); this arrangement is certainly very simple in view of mathematical modelling and satisfactorily representative of some real situations (external explosions). Practical difficulties related to large diameter to be covered (2.44 m) and to the removal of explosion products had this solution rejected till now.

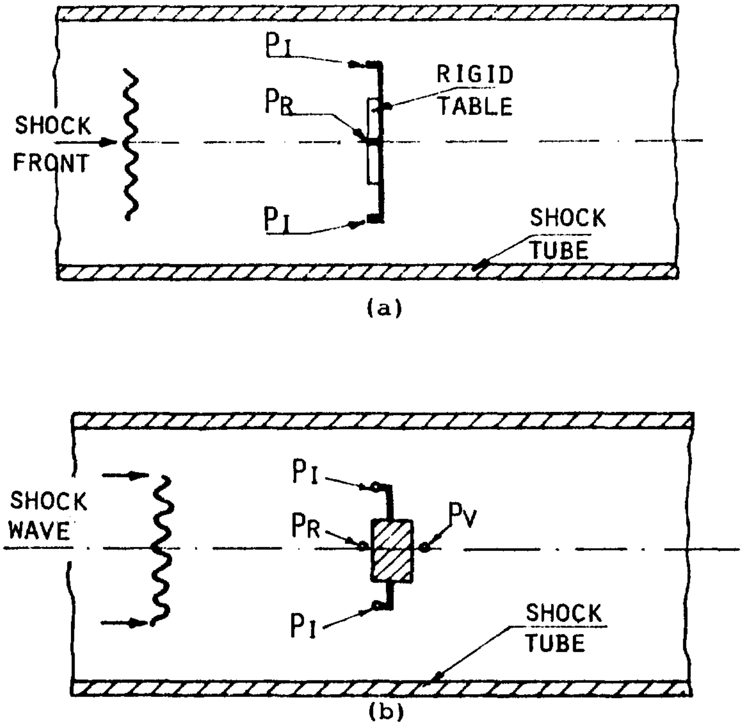

FIGURE 3
POSITION OF RIGID TABLE (a) OR FILTER (b) AND TRANSDUCERS IN TESTS FOR EVALUATION OF REFLECTION COEFFICIENT

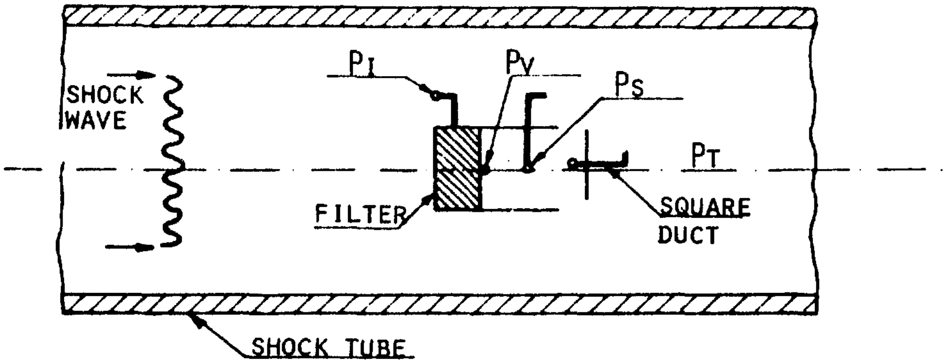

FIGURE 4
SCHEME OF EXPERIMENTAL APPARATUS (DUCT, FILTER, TRANSDUCERS)

Table III: Peak overpressures in tests for evaluations of reflection coefficient: rigid table

CHARGE WEIGHT (gr)	OVERPRESSURE kPa SIDES (average)	CENTER	REFLECTION COEFFICIENT
50	4.4	9.2	2.07
100	7.1	15.2	2.12
200	9.8	19.3	1.95
300	11.	22.8	2.05
400	12.5	27.6	2.20
500	15.	30.2	2.00
600	17.9	37.8	2.01
800	21.4	44.8	2.07
1000	22.7	50.3	2.19
1200	25.5	57.8	2.23

Table IV: Peak overpressures in tests for evaluation of reflection coefficient: standard HEPA filter (61x61x30.5 cm; wooden case)

CHARGE WEIGHT (gr)	OVERPRESSURE kPa SIDES (average)	CENTRE	REFLECTION COEFFICIENT
100	7.0	9.5	1.34
500	15.5	24.1	1.54
1200	25.1	34.4	1.35

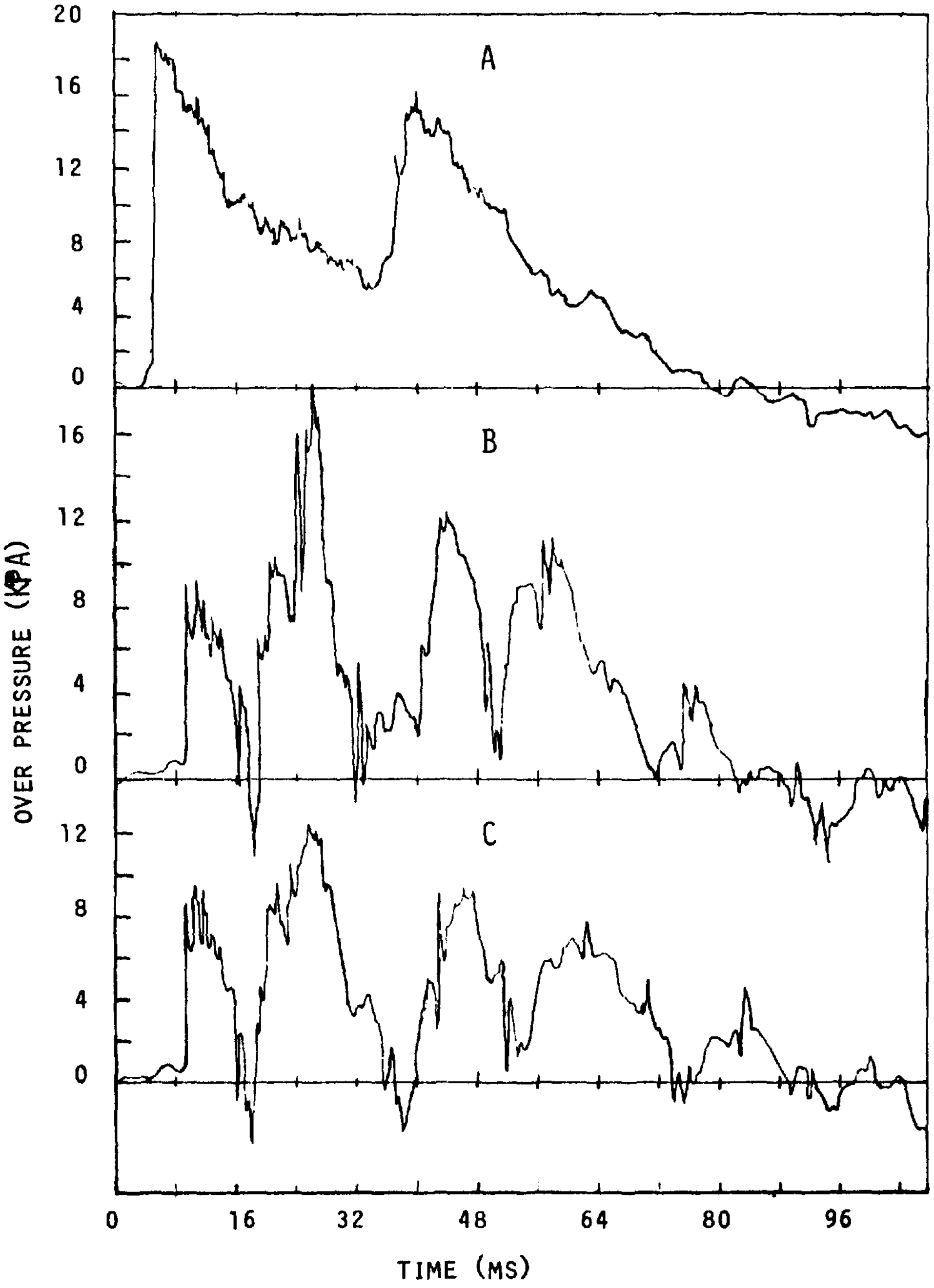

FIGURE 5
TYPICAL PRESSURE TRANSIENTS (700 gr TNT)

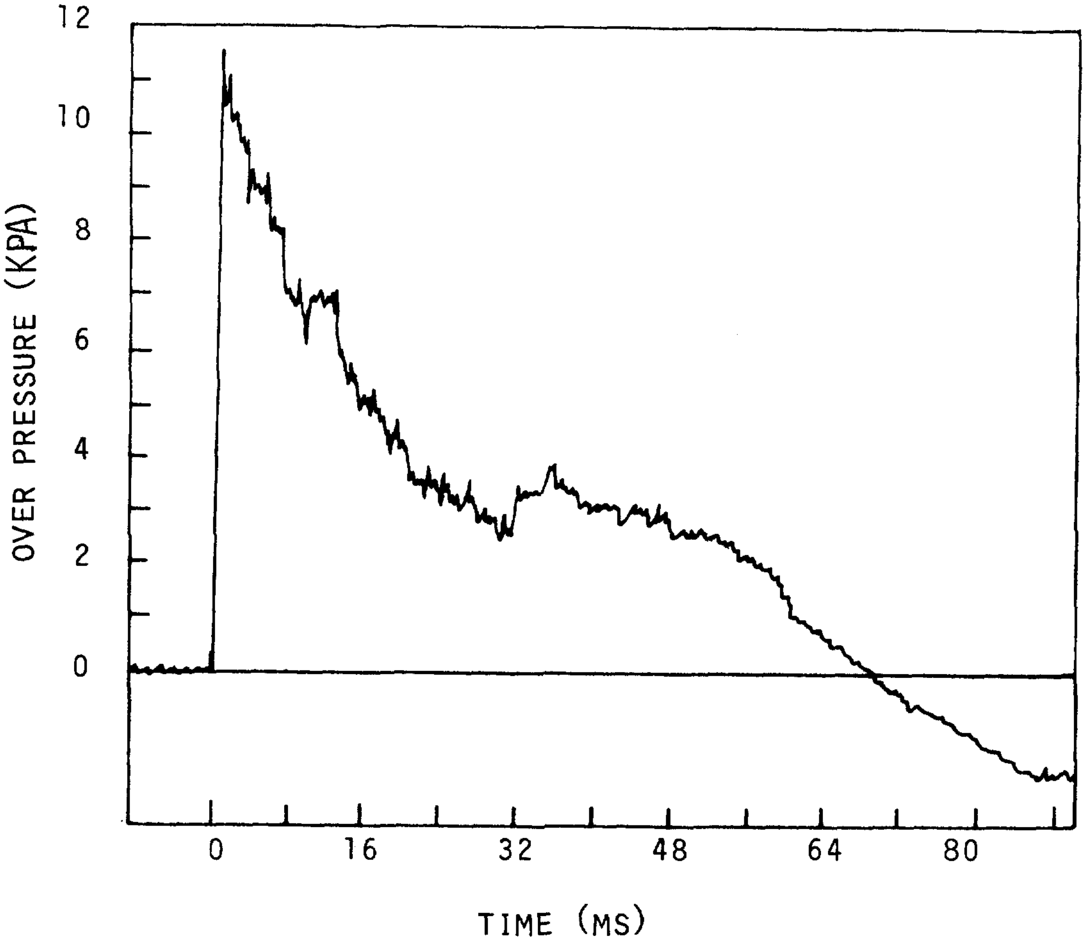

FIGURE 6 - WAVE SHAPE (300 gr TNT)

An alternative could be the connection of the filter to a long duct which gets out of the open end of the shock tube. Shorter ducts, completely contained in the shock tube, should be able to change the dynamic load configuration on the filter, from the case above to the extreme of free filter (duct lenght: zero).

In this preliminary phase of the research program a square duct (61x61 cm) 3 m long was constructed; its effect on a pressure transducer response can be seen in Fig. 5; the end of the duct can be covered to produce internal reflection effects.

Transducers are positioned to measure overpressure on the front face of the filter, and 50 cm far from its rear face: the latter records both pressure wave passed through the filter and that "reflected" or "diffracted" (according to whether duct is covered or not).

III. Tests on filters

III.1 Experimental procedure and description of the tested filters

Three new italian-made HEPA filters and one new V-type of foreign manifacture were tested. All the filters had standard sizes (61x61x30.5 cm).

In Table V filter main features are summarized. Filter A was

Table V: Filter characteristics

FILTER	CASE	PAPER	SEPARATOR	GASKET	MAX U.R.	MAX TEMP.	FLOWRATE m^3/h	INITIAL DROP PRESSURE
A	Wood	Glass fiber	Aluminum	Neoprene	100%	80 °C	1700	250 Pa
B	Galvanized Iron	" "	"	"	100%	80 °C	1700	250 "
C	Galvanized Iron	" "	"	"	100%	80 °C	2500	250 "
D	Galvanized Iron	" "	"	"	100%	70 °C	3000	250 "

tested in the open end configuration of the duct*; filters B and C were tested in the plugged end configuration; tests on filter D began in the open duct and went on with the plugged end till failure.

Filters were subjected to pressure transients of increasing intensity till failure. Before and after each shock, DOP penetration of the filter was determined.

A filter was said to fail when efficiency fell below 99.97%.

III.2 Results

Pressure peak data recorded during the tests are reported in Table VI e VII.

Table VI: Pressure data of the blast which made filters fail

FILTER	NOMINAL FLOWRATE	DUCT CONFIGURATION	Overpressure peak at failure (kPa)			
			P_i	P_v*	P_s*	P_i-P_v
A	1700	open	22.4	12.6	15.6	9.8
B	1700	covered	28.7	18.1	34.3	10.6
C**	2500	"	37.7	25.6	25.6	12.1
D	2500	open	14.3	9.3	11.9	5.0

(*) p_v = overpressure peak behind the filter
p_s = overpressure peak near the duct end
(**) a shock damper was placed on the cover

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* During the calibration tests an old, but still efficient filter of the same type was inserted in the shock tube without any duct behind; neither DOP efficiency drop nor damage was experienced up to a blast of 1800 gr of TNT, corrisponding to a peak overpressure of 35 kPa about.

Table VII: Difference between the peak values of front and back overpressures on the filter ($p_i - p_v$ (kPa))

FILTER P_i (kPa)	A	B	C	D*	D**
11.9	3.5	4.2	3.5	3.5	3.8
14.3	4.5	4.5	5.0	4.5	5.0†
15.3	5.6	4.3	6.1	5.4	
16.8	6.5	5.2	5.2		
17.6	7.3	6.7	6.1		
22.4	9.8†	9.2	8.6		
24.1		9.9	-		
25.9		10.1	9.4		
28.7		10.6†	11.2		
37.7			12.1†		

* covered end duct ** open end duct † failure of the filter

Fig . 5 shows typical pressure traces from front transducer (A) and from rear face transducer (B: open duct; C: covered end).

Graphs B and C present four main peaks: the first is caused by the passage wave through the filter, the second by its diffraction or reflection at the end of the duct; the other two peaks come from the second peak of the entering wave in the same way.

In figs. 7-8-9-10 are shown photographs of the failed filters.

Paper of the filters A and B presents transverse tears both on the front and on the back face; separators are partially crushed and twisted; the whole paper pack appears to be displaced in the direction of propagation of the shock wave.

Filter C shows a short transverse slit on the front face and small deformation of the separators, without visible, cracks of the paper, on the rear face: as a whole its structural damage appears minor in comparison with filters A and B.

In filter D damages are particularly evident on the laminae which support mini pleat pack; on both faces they are buckled in the direction of the wave; moreover in the back face they are pushed out of their housing and connected paper packs are cracked.

Experience acquired in calibration tests and results of filter testing suggest the following qualitative and provisional comments:

- V-type filters seem to be less resistant to rapid pressure transients then conventionally pleated filters;
- duct geometry, as it affects loading time-law acting on the filter, is important for evaluating resistance of an installed filter;
- filter C, which is standard, but able to operate at 2500 m^3/h seems to resist to shock better than the common type (flowrate 1700 m^3/h).

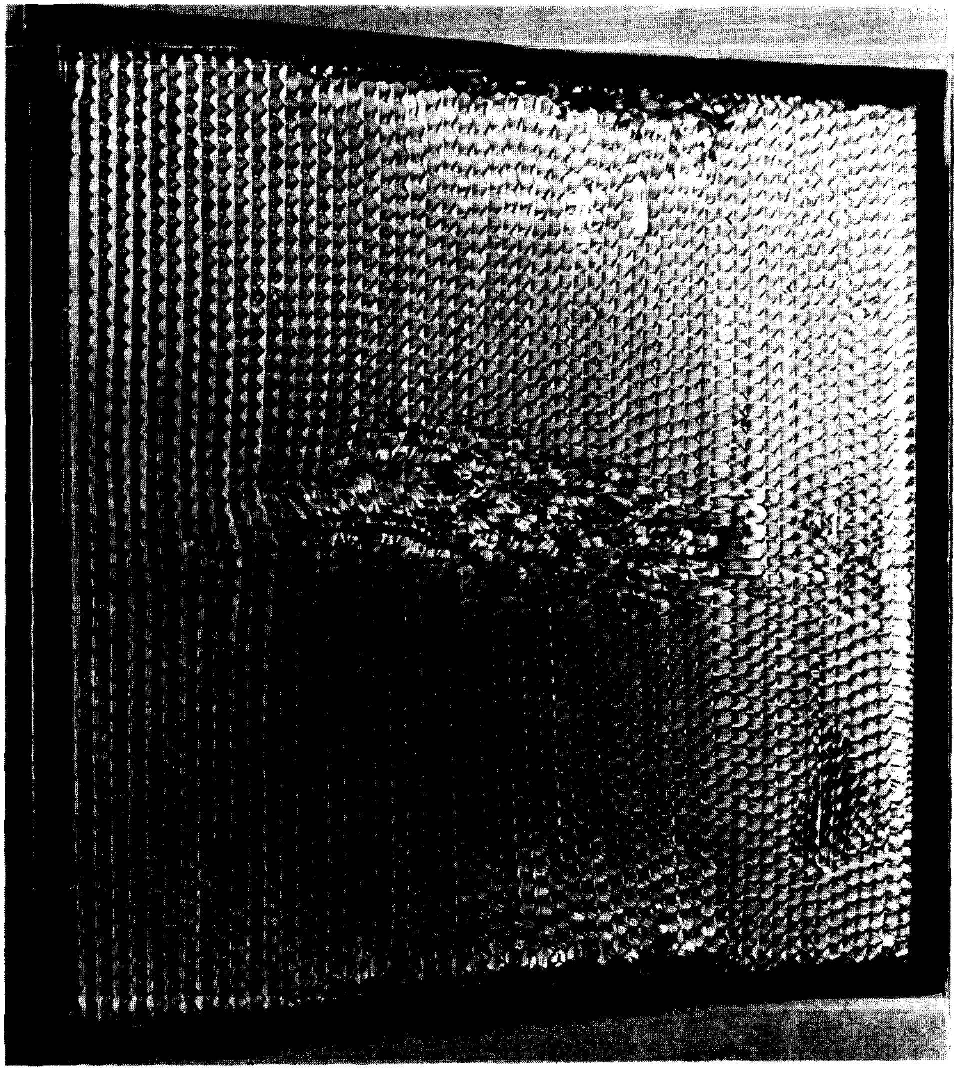

FIGURE 7

FAILURE OF METAL CASE FILTER (B)

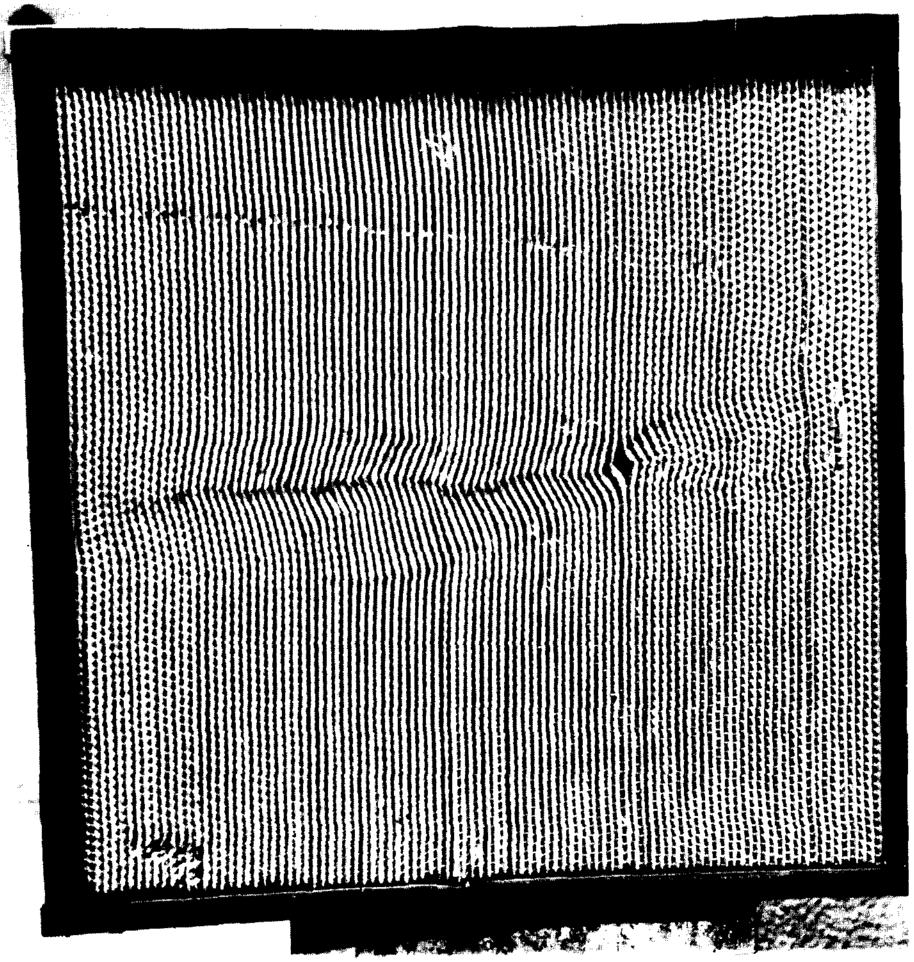

FIGURE 8

FAILURE OF METAL CASE FILTER (C)

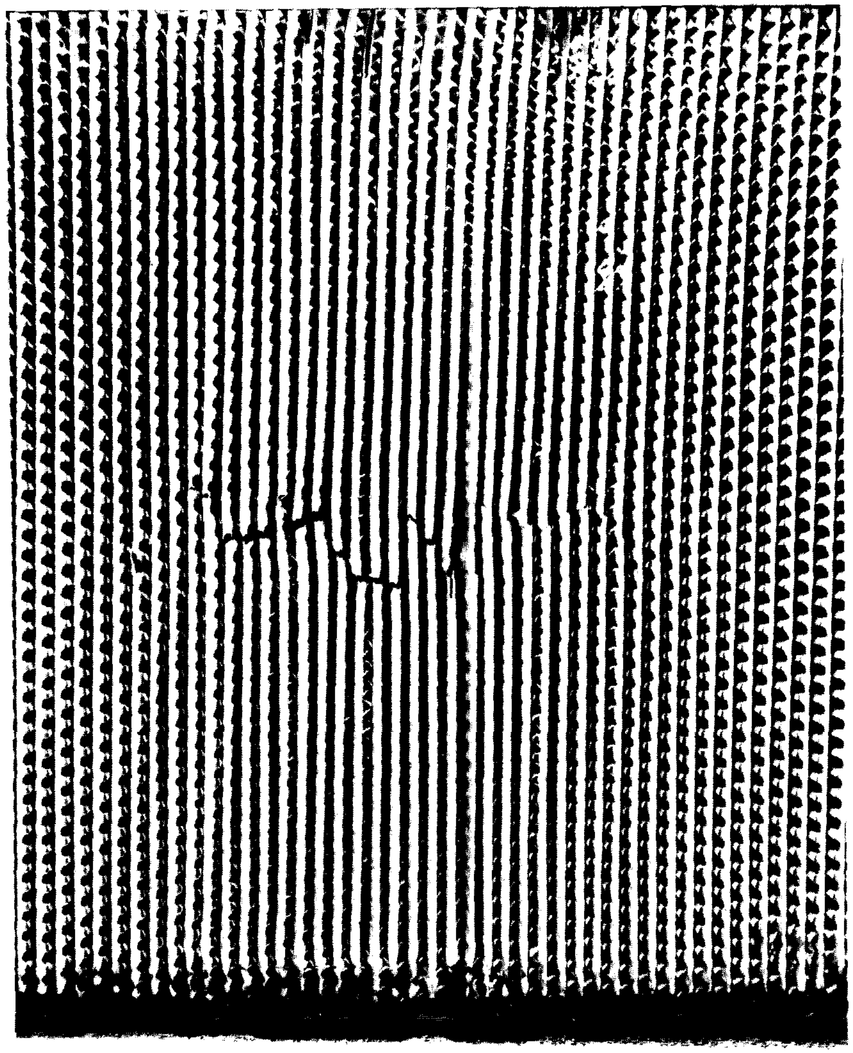

FIGURE 9

PARTICULAR OF SHORT SLIT (A)

FIGURE 10

FAILURE OF MINI PLEAT FILTER (D)

IV. Conclusions and future prospects

So far accomplished work had a limited and preliminary scope: to obtain direct experimental information on the possibility of using CAMEN shock tube for experiments on filters and / or other components of air cleaning systems. This possibility was satisfactorily demonstrated by the effected tests. Anyway much work is still to be done.

Conditions of these experiments are not quite representative of real situations a filter could have to withstand.

In particular diffraction or reflection back effects were delayed of only about 15 msec.

Last, present instrumentation did not allow to evaluate the impulse versus time and least of all to obtain a loading profile though approximate.

It must be remarked here that, even though it is important to know the effects of pressure transients on filters and prefilters, it is equally necessary to consider how other components (e.g.: valves, bends, restrictions, etc.) may affect the wave shape during its propagation through those so delicate components.

For these reasons: a new data acquisition system based on piezoresistive trasducers was purchased and computer processing of the tape-recorded data is in course of setting-up; a new duct, divided in flanged sections is under construction so as to be able to change the undisturbed period of the pulse.

When these new facilities are available immediate research objectives will be:

- study of the influence of duct lenght on the dynamic loading on the filter
- test of different blast charges to try to increase the duration of the pulse.

Afterwords an extensive analysis of italian-made filters and prefilters will be performed by testing their shock resistance with the aim at discovering weak points and suggesting possible ameliorations.

At the same time influence of the duct geometry will be investigated in order to find out the worst situations and possible remedies.

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