Nuclear Filtration and Ventilation 1980-2015 - a Personal Perspective.

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1.0 Situation in 1975-1995

I would like to begin by setting the scene in the UK nuclear ventilation and containment world when I became involved in the late 1970's. Co ordination of the various interests and requirements was carried out through a committee known as the Containment and Ventilation Treatment Working Party (CVTWP) The Working Party included representatives from all nuclear organisations operating Licensed Sites in the UK. Its objective was to identify and co-ordinate areas of research and development across the Nuclear Industry in the technical areas of containment, off gas treatment and filtration. There was a sub committee, the Filter Development and Standards Working Party, which concentrated of production, updating and publication of the various specifications and standards.

Funding of the work of these two committees was shared by participating members. The UKAEA had access to generic programme funding whilst other organisations contributed to research programmes. Some project specific work was also undertaken.

2.0 Filter test Facilities

Harwell expanded its filter test Laboratory in the early 1980's. By 1985 it had the following test facilities:

a) Test rigs for efficiency and dust loading of filter inserts up to 2000cfm (3400 cubic metres/hour) and 15 inches water gauge (3 KPa).
b) Air flow test facility for studying aerosol mixing and sampling arrangements associated with in-situ testing of HEPA filters.
c) A full range of test equipment for media testing and type approval.
d) A hot dynamic test rig for whole filter development work.

Harwell also had the capability for calibrating and testing of manufacturer's acceptance test rigs. This was done at 6 monthly intervals during the term of the BNFL running contracts.

Some other Sites had filter test rigs to BS3928 for acceptance, efficiency and pressure drop tests.

Respirator filters were tested at the DoE labs at Sheffield. The DoE also had some dust spot efficiency test rigs in Bedfordshire.

Work was ongoing to develop an alternative dynamic test to replace the static oven test for high temperature filters. I am not sure how far this got, but the hot dynamic test rig is no more.

Some other sites e.g. AWE, BNFL had a limited range of filter test facilities.

3.0 Review of Developments

3.1 Circular Filters

A test programme was carried out in 1981-2 on the then standard 1000 cfm 2x2x1 ft HEPA filters from the 4 major manufacturers for compliance. It revealed that the filters were far from compliant in issues such as case dimensions and flatness. There was also concern over quality of sealing gaskets, and in one case the quantity of paper used. Damage was also found in sample filters caused by the manual construction methods employed and the design of the filter pack to case seal employed.

At that time the gasket approved for the high temperature resistant filter was made from folded filter medium held in place by fibre glass scrim. This was a cause for concern as it was difficult to get a good seal of the filter into its housing. These findings focussed concern over the inherent design issues with rectangular filters, especially as consideration was being given to the development of remote change systems and re-enforced the view that it was time to look into alternative designs. (A paper presented to the 17^{th} DoE Nuclear Air Cleaning Conference comparing rectangular and circular filter systems is particularly relevant) Ref.1. Problems identified with the standard filters related to difficulties with seals between the filter insert and housing, handling, and disposal – the industry standard waste drum had been identified as the 200 litre drum, too small to accept the rectangular filter.
Some preliminary work had been done into circular filters. These promised to offer the following significant improvements:

> a) They would offer the potential of improved sealing into housings using lip or piston seal arrangements without the need for clamping.
> b) They could be constructed from machined pleated panels of media as used in the then current clean room panel filters eliminating the inconsistencies arising from manual pleating.
> c) Finally and of increasing importance, they could be disposed of into the existing waste stream without needing to be broken up.

It was considered important to develop both filter housings and inserts in parallel so that complete systems would be available.

It was decided to start from a known and established technical base, and so contracts were let to two established filter manufacturers. One was chosen for their interest in small volume specials whilst the second was chosen for its in house capability in mechanical pleating and production of clean room panel filters. Each company was tasked with producing prototype filter units for testing and evaluation at the Harwell Filter test labs. The initial aims were to produce a replacement for the ubiquitous 2 x 2 x 1 -1000 cfm plant room filter and to develop a range of smaller filters for glove box applications. Performance requirements would be as for the then current filter ranges.

We did spend time and money trying to develop an axial flow design. mimicking the deep pleat filter, for smaller glove box applications, but we were unsuccessful in that the design rely heavily on the use of adhesives to form the end of each flow channel, so the concept was dropped. Fig 1. Subsequently all of the applications were built round the use of radial flow circular filters, constructed by forming a panel of pleated filter media into an annulus and fixing it into appropriately designed end pieces.

As the project got under way, we were tasked with developing a remote filter change system for a state of the art alpha, beta, gamma facility being designed and constructed at Harwell. Each filter was rated at 150cfm. The filter had to be placed remotely into the wall of the shielded containment box and be posted out from the box using the designed disposal route. The final arrangement is fully described in Ref 1. This project specific requirement against imposed project timescales served to focus the development effort. More importantly its successful conclusion served to give publicity and impetus to the more generic development programme. Fig 2.

A second project specific requirement followed for hands on push –through filter and housing system for a new alpha glove box suite. Fig 3 This lead to a design of a simple lip seal arrangement and to the eventual range of filter units up to 300cfm for use in small cells and glove boxes. Ref 2

In parallel with this work, development of a 1000cfm filter and bag change housing system for plant room applications progressed. Joint development contracts continued with M C Filtration Ltd. This decision was based on the fact that from testing it emerged that their panels of media outperformed that of other manufacturers in terms of panel deformation and strength. This was due to the construction technique which employed fully glued spacer cords to maintain the flow channels in the pleated panels. The seal into the housing was a simple flexible silicon ring against a tapered spigot. Fig 4.
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This feature was exclusive to M C Filtration Ltd. (MCF), the panels being pleated on a machine developed in France by Sofiltra Poelman and subject to design and patent protection.

The only concession given to M C Filtration was to allow them to switch to a filter paper manufactured by Lydall Inc, after due type approval testing, as the UK sourced paper was not as amenable to machine pleating.

In order to expand the circular concept to the high temperature (500 degrees centigrade) requirement, it was necessary to develop an adhesive to seal the pleated panel into the filter case. Again this problem was solved by MCF, other manufacturers also tried but the MCF adhesive has proved successful and features in the type approved filter design. This adhesive was also used on the rectangular deep pleat filter and its high capacity variant.

The take up of the plant room designs was somewhat slow due to a slow down in new plant construction, but prototype units were tested at the UKAEA Site at Dounreay which demonstrated that the concept was sound and demonstrated significant advantages over the rectangular units.

Many other applications have since been developed and the promise of better sealing, easier handling and compatibility with disposal routes has been demonstrated and circular filters are established as the systems of choice in the UK.

Circular HEPA filters are currently available over a wide range of capacities up to 950 litres/sec (2000 cfm.) in both low temperature and high temperature rating. Type approval testing is currently under way by M C Air Filtration Ltd. Fig 5

3.2 High Capacity Filters

Whilst attention was focussed on using the machine pleated panels in circular filters, some consideration was given to the relatively new high capacity filters offered by several manufacturers. These offered the potential for smaller plant rooms having a rated flow of twice that of the deep pleat filter with the same physical sizes. This was achieved by reducing the air flow resistance in the flow channels of the filter, some 30-40% of the clean pressure drop in deep pleat filters, and at the same time increasing the area of media in the filter. This was achieved by arranging panels of pleated media into vee format within the filter case. Fig 6

Initial burst testing showed that the filters suffered from panel deformation and damage due to poor panel support. Filters modified to provide additional panel support were found to pass the hot dynamic rig test.

Subsequent testing showed that for sub micron challenges, the dust holding capacity of filters is directly proportional to the area of filter media. Therefore as long as the high capacity filters contained the equivalent media area, the promise of reduced plant room size was achievable without reducing the service life of the filters.

As far as I am aware, no high capacity filters have been type approved in the UK to date, although testing is planned for later this year.

3.3 In situ Testing

Another field of concern in the early years was in –situ testing of filters. It was established practice that after a new final extract filter was installed it would be tested to ensure that it had been correctly installed and had not been damaged in the process. The acceptance level was a df of 2000, or efficiency of 99.95% as per the filter as manufactured. This has now been increased to 99.99% mainly due to improved sealing between the filter and its housing and improved manufacturing techniques. Accurate measurement relied on good mixing of the test aerosol upstream of the filter face and also mixing of any aerosol through leaks or damage prior to the downstream sample point. Design guidance at the time was that 20-25 duct diameters of straight duct should separate upstream injection and sample point and filter face and downstream sample. This should ensure an aerosol concentration across the duct of within 10%. However this requirement impinged on the plant room layouts and so a programme to assess proprietary mixing devices and develop a range of multi point injectors and samplers to reduce the required straight duct lengths. The results were published in papers to the 20th DoE /NNC Nuclear Air Cleaning Conference and European Conference, Ref 3:4. and demonstrated that with the appropriate devices separation distances could be reduced to 10-12 duct diameters. Successful designs based on this work are available from established manufactures and the modified requirements are set out in the latest Design Guide. Ref 5.
This guide also requires that on commissioning new plant test facilities shall be “characterised” to ensure that the appropriate level of mixing is achieved.

In the early days , a team from Harwell was responsible for the annual in situ filter testing across all of the UKAEA sites. As improved filter test equipment became available, the later particle generators and photometers simplifying the test procedure, local dedicated test teams were set up on each Site, the Harwell team being available for support and back up should problems arise.

The instrument of choice in the UK for in-situ filter testing remains the light scattering photometer. This instrument , together with DOP aerosols has been demonstrated to have a maximum sensitivity of 100,000. Ref 6. Thus two stages of filters together exceed the sensitivity of the photometer so where the safety case analysis demands this degree of Df , it is necessary to fit the plant with inter stage injection and sampling points so each stage can be assessed separately. This is seldom the case , a Df of 100,000 being adequate for most facility discharges.

3.4 Hot Dynamic testing of Filters.

It was becoming apparent that more consideration was required regarding the high temperature performance of plant room filters under accident conditions

Historically, two versions of the standard filter were specified and available , Type 1 limited to a short exposure of 150 degrees and Type 2 which were required to withstand 500 degrees for 10 minutes. It is believed that this requirement came from treating the filter as a standard building component at the same fire resistant standard was adopted. The fire test was for the filter to be placed in a pre-heated oven for 10 minutes after which it would be efficiency tested to BS 3928 . The oven test would also demonstrate that the materials of construction would not support combustion

The filter was also then loaded with a test dust to a pressure drop of 12inches water gauge. The only concession was that the filter efficiency was allowed to fall from 99.95% to 98% after the fire test.

There were two inherent problems with the Type 2 filter. The seal between the filter pack and the case was affected by compaction of glass fibre matting and the gasket was constructed from folded filter paper held in place with a glass fibre scrim.

Problems with the compressed fibre matt lead to a reduction in overall efficiency of the filter to 99.5% compared with the media value of 99.995%. The paper seal was very hard and not compliant , leading to a higher requirement in flatness of the mating seal surface and higher seal loadings. This later point became more important when remote change systems were considered.

There was a lot of discussion over the appropriateness of the oven test. Many people considered that it did not model the actual conditions experienced in a fire incident, the principal one being that the filter will continue to collect dust/smoke whilst being subjected high temperature air. There was also a school of thought that predicted that due to the thermal mass of the housing and heat losses from the system the outer edges and sealing faces would not reach 500 degrees c. Thus the gaskets and filter seal arrangements would not be overly stressed.

It was therefore decided that a new test facility be built to enable research into the hot dynamics of filter performance to be evaluated. Fig 7 Ref 7

After an extensive period of testing the following conclusions were reached:

a) The high heat losses and thermal mass of the housings ensured that the sealing faces and gaskets did not reach the high test gas temperatures. It was demonstrated that silicon rubber exhibited adequate temperature resistance and could be used in place of the folded paper gaskets. One concession to the oven test would mean that the oven test could be carried out without the gasket in place.
b) The tensile strength of the filter media was reduced to some 70% of the pre test value due to loss of binder at temperatures above 350 degrees C
c)The oven test procedure was not representative of the actual operating conditions under high temperature excursions and does not predict the actual performance under accident conditions.
d) Consideration would be given to the development of a hot dynamic test as part of the type approval process

Unfortunately the Filter Test Facilities, including the hot dynamic test rig, were closed down before this last issue could be addressed. In my opinion this is still an outstanding issue.

3.5 Dust Loading of Filters

A substantial testing programme into the dust loading of filters was carried out at Harwell during the 1980's. Ref 8:9

The initial testing was done with the standard ASHRAE test dust, a blend of carbon black, cotton lint and quartz particles and BS No. 2 test dust of 3.5 and 7 micron fused alumina particles. This showed that there was a significant inertial separation effect within the filters which affected the dust holding pressure drop characteristics of the filters.

These early results also showed a significant variation in the dust holding between the ASHRAE and BS No.2 dusts. It was concluded that this was due to the presents of a sub micron , carbon black, component in the ASHRAE dust.

In order to eliminate the inertial effects and to more closely mirror the actual aerosol challenges to plant room filters, which would be essentially sub micron, further testing was carried out using only carbon black . Results showed that the increase in pressure drop equated to the quantity of carbon black present in the ASHRAE Dust. The quartz and cotton lint were collected as a surface cake and did little to contribute to the pressure drop increase.

However there were difficulties in ensuring that agglomeration of the carbon was avoided and a true submicron challenge was generated. Fig 8. To overcome this challenge aerosol was changed to a flame generated NaCl aerosol developed for in situ testing giving a near mono-dispersed aerosol of 0.15 microns.

The net result of these later tests was to demonstrate that for sub micron challenges where inertial effects are insignificant the dust holding versus pressure drop of a filter was directly proportional to the effective area of media in the filter and proportional to the air face velocity. Fig 9

For larger aerosol size distributions inertial effects are significant> For example the alumina and cotton lint elements of the ASHRAE dusts were found to bridge across the top of the mini pleated panels, leading to higher pressure drops.
There was a dust loading requirement added to the type approval test in later versions of the specification. The chosen test dust was carbon black. It could be argued that this was not typical of the challenge dust which would be found in practice.

4.0 Review of Codes and Specifications

4.1 Engineering Standards

AECP continued to be revised and updated as requirements changed and technical understanding of the issues evolved. During this period ownership and responsibility was held by UKAEA and the various documents were issued as AESS's , Atomic Energy Standards and Specifications, and AECP's Atomic Energy Codes of Practice. When the UKAEA was disbanded in the late 1980's, ownership was transferred to BNFL. The documents were withdrawn and re-issued as NF's. For example AECP became NF 166. When BNFL itself was privatised, and under pressure from the UK Nuclear Installation Inspectorate, ownership transferred to the NDA, (Nuclear Decommissioning Authority), and a new series of documents were re-issued as Engineering Standards. The wheel has now turned again and Sellafield Ltd, (SL) effectively the "rump" of BNFL has again assumed responsibility.

One fall out of the ownership by NDA was that licensed sites not owned by them did not have to follow the Codes and Standards issued by them, so other organisations began to publish their own versions. One example was AWE which began a programme of rewriting and publishing their own versions. Fortunately there weren't significant variations in the technical content, but at one stage there were at least 3 versions of the original AECP 1054, the basic design guidance document for ventilation of radioactive areas.

The NDA and ONR began pressing for industry wide consensus and discipline out of which the National Nuclear Ventilation Forum (NNVF) was born. Representatives from across the nuclear and filter industry are welcome to attend, and open access to its meetings and discussion forums are encouraged. Whilst SL author a new or revised document, it is put through the NNVF for consideration/comment and once agreed the SL will add it to the list of Engineering Standards is amended and becomes available to all.

The NNVF also authors documents but they are advisory only and are issued as good practice. They do not become Engineering Standards.

Thus in the UK situation , having gone through a bad period following changes in the organisation of the UK Nuclear industry , there is now accountability and structure over the control of Standards which form the basis of the UK regulated nuclear industry.

4.2 UK Industry Ventilation Design Guide

The original Code of practice AECP 1054 has been revised and updated many times. The Code is now published as NVF/DG001 with the title "An Aid to the ventilation of Radioactive areas," Ref 5

The principal significant change came in 1985 regarding recommended air change rates for classified areas. Until that time the air change rates quoted were treated as a basis for design regardless of actual requirements. Instead designers were encouraged to minimise air flows in and out from classified areas, depending upon need. Thus the required air change rates were calculated on the basis of occupancy, process requirements including process heat removal, dilution and most importantly ,maintaining containment air velocities between zones of differing classification. These changes lead to much reduced volumetric air flows in facilities leading to reductions in energy consumption and size of extract filter banks. Thus energy requirements and waste arisings are reduced.

5.0 Outstanding issues

5.1 Type approval testing

The last independent type approval testing of HEPA filters was carried out in the early 1990's, just before the Harwell Filter Test facilities were closed. Under the old pre 1990 rules the supply of plant room filters was as follows:

BNFL ran tender exercises and placed a running contract for HEPA filters which other UK nuclear users ordered against. The tender exercise required bidders to provide 4 filters for type approval by the Filter Test Labs at Harwell. When compliance with the spec. was confirmed a contract was placed for a 3 year period. During the contract period, BNFL carried out routine QA assessments to monitor the production process confirm that no changes were made and approved materials as used in the test filters were used. Any material or design/assembly method changes had to be submitted for approval.
Also at regular intervals during the contract period, Harwell would carry out checks on the performance of the manufacturers test rig .
h) The approval of the media used was subject to a separate type approval process and the approved media had to be used by all suppliers.

Harwell also required individual retest for efficiency for all HVAC filters on receipt from manufacturers before being place in store prior to use. This was because of the potential damage caused in transit due to construction weaknesses. An average failure rate was in the order of 1-2%

To my knowledge no independent type approval programme has been carried out since the closure of the Harwell Test Labs around 1990. Currently one major supplier is developing their own in house type approval process and facilities. The current Specification does not require separate type approval of the filter media used. The latest Type Approval Specification for filters was issued by Sellafield Ltd. in January of this year Ref 10

Currently, I understand that the U K Regulators are encouraging type approval of all filters used as the final stage between the plant and general public that is prior to discharge. In the absence of independent testing laboratories, one UK supplier, M C Air Filtration Ltd. is establishing type approval facilities to the latest specification at its own works. Testing is due to start imminently.

5.2 High strength filters

5.2.1 Glass fibre Media

The typical conventional glass fibre media filters are designed for a burst pressure of around 12 inches water gauge or 3Kpa. For some applications this is insufficient and a lot of work went into developing higher strength filters. Perhaps the most successful is described in a paper to the 20th DoE Conference .Ref 11. This paper describes a high strength media developed by Lydall Inc. The performance was enhanced by adding a glass fibre scrim to the conventional media. Changes were made to the detail design of the pleat spacers and the result was a commercial filter with a burst strength of around 50-60 KPa. This work was reported in an article in The Nuclear Technology Journal Ref 12 , where its adoption on German installations was reported. At Harwell we also carried out promising tests on a similar media, Lydall 255LWI but at the time our priority was circular filters and trials showed that it was not possible to fabricate machine pleated panels with this media.

5.2.2 Metal Filters

Metal filters have been of interest for quite some time, the first references appearing in the 16th DoE Nuclear Air Cleaning conferences of 1980. The main interest was in nuclear power plant applications where their considerable strength and self cleaning properties gave them a considerable advantage over conventional glass fibre products.

The main disadvantages were seen to be lower efficiencies to sub micron particles and higher pressure drops than conventional media.

A paper to the 20th DoE conference describing research and development by Pall Ltd. Reference 13 provides a good summary of how far development had progressed.

Around that time we carried out some test work into the back flow cleaning of metal cartridge filters. We were able to demonstrate that repeated back pulse cleaning was possible and that , although there was a slight increase in as-cleaned pressure drop, this was not significant over 10 plus cleaning cycles. The principal draw back to the wider application of metal filters was seen as cost, higher pressure drops per unit flow resulting in larger installations and greater fan powers and handling, the metal filters are considerably heavier than conventional ones.

As well as power plant applications, there is now wider interest in the metal filters where the twin properties of greater strength and back pulse cleaning are required.

Reactor Containment applications dominate this field but there are an increasing number of others. I understand that work is now ongoing to produce a US specification for these filters, AG1-FK, which should facilitate their adoption in the US and elsewhere.

5.3.3 Ageing of Filters

The question of life span of glass fibre filters has long been a cause for concern. If the filters are changed too frequently this potentially leads to an unnecessary increase in waste disposal costs and additional dose uptake to operators. If the filters are kept in service beyond their life span then there is the potential for failure under abnormal flow conditions and loss of containment.
Early research into aging effects was concentrated on dismantling the filter and carrying out tests on the recovered media. In a paper presented to the 20th DoE Conference, Ref 14, a significant reduction in the tensile strength of the paper in 15 year old filters led to a calculated 28% reduction in the burst strength of filters.

The real problem with these and other early published results is that there is very little detailed information of the working conditions of the filters examined. It is know that in environments with low but significant concentrations of acid fumes and or high humidity, deterioration of the filter is more rapid. However the circumstances where this is quantified are few and the relevance to other filter installations unsure. Perhaps it would be better if the gas treatment of these effluent streams was revisited to remove these contaminants rather than risk the integrity of the final discharge filters.

There were plans to build a test rig at Harwell in which radio actively contaminated filters could be subject to over pressure to determine the ageing effect on whole filter burst strength. Sadly this project was never brought on line due to interestingly, the failure of modelling to demonstrate that shock waved generated by the test filter would not be amplified in the rig and cause failure of the exhaust filters and contamination spread into the laboratory. Perhaps if high strength metal filters had been readily available at that time the test programme would have gone ahead.

In the UK there is a move to limit filter life to 5 years, though the evidence to support his is unclear. It must be remembered in most applications the filters are seeing clean filtered air for most of their working lives. The generation of more radioactive waste than is necessary should be resisted.
It can only be concluded at this stage that more work is required before any working life restrictions can be justified and introduced.

5.3.4 Modelling

The first modelling I was aware of was in 1982 and was a tenth scale model of a Glove box facility constructed in clear plastic with warm water- fed glass models of operatives(to simulate body heat losses) The gas used was selected to replicate the Reynolds Number of air at the tenth scale, and the objective of the model was to investigate the best location for laboratory ventilation extracts to minimise dose uptake to the operators.

Things have come a long way since then and computer based modelling is now an important tool in the ventilation systems designers’ s toolbox. In the UK ,whilst Regulators welcome the use of computer modelling to support Plant Safety Cases, it is not as yet a requirement. However, there is a requirement that any analytical models and associated design and fault analysis should be validated, One of the most commonly used packages is a steady state network analysis PIPENET, (copyright of Sunrise systems Ltd.) This package allows the performance characteristics of a ventilation system to be investigated for a wide variety of plant configurations including normal and fault conditions. Most applications I have personal experience of were on plant modifications or upgrades, where code validation was relatively straightforward as the models predictions could be verified against actual measurements made on the plant before modification.

Recently more extensive modelling has been developed to predict such parameters as temperature distribution and hot spots within facilities and dilution or build up of explosive gases. A recent paper presented at last years UK Nuclear Ventilation Conference described modelling to demonstrate hydrogen management in a proposed passive nuclear store. In this case a full scale model of a section of the Store had been constructed to support the development of the CFD model and its validation. Ref 15.

My personal belief is that whilst computer modelling is of great help in the design development stage , validation is much more difficult, but without it ,its value must be questionable.

6 Conclusions

The period covering the late 1970's and 1990's saw much research and development activity in the Nuclear Ventilation field not only in the UK but also in Europe and the USA. The value of the DoE Nuclear Air Cleaning Conference in disseminating the results of this work cannot be over emphasised.

Whilst it is true that in the UK the break up and privatisation of the UK Nuclear industry together with reduction in centralised generic R and D funding since then, there is evidence that the worst is over, certainly in terms of the quality and integrity of published Standards and Codes of Practice. This is largely due to the work of Sellafield Ltd. and the NNVF.
Some areas which in the views of the Author require further work have been identified. The listing is in no way meant to be complete. More work will be required as challenges and problem areas are identified. The need for well funded centres of R and D excellence is obvious if continuing progress is to be maintained.

Finally, this paper is very much a personal reflection by the author and in no way should be read as an indication of the views of other individuals and organisations from the UK Nuclear industry. However I would like to acknowledge the work of the many engineers and scientists who contributed to the developments reported in this presentation.

7 References

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8 Figures

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Fig 3 Glove Box Push Through Filter and Housing
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Fig 5 Range of Circular Filters (courtesy of M C Air Filtration Ltd)
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Fig 7 Hot Dynamic Filter Test Rig
Fig 8 Dust Loading of HEPA Filters with Carbon Black
Fig 9 Dust Loading of HEPA Filters with sub –micron NaCl Aerosol

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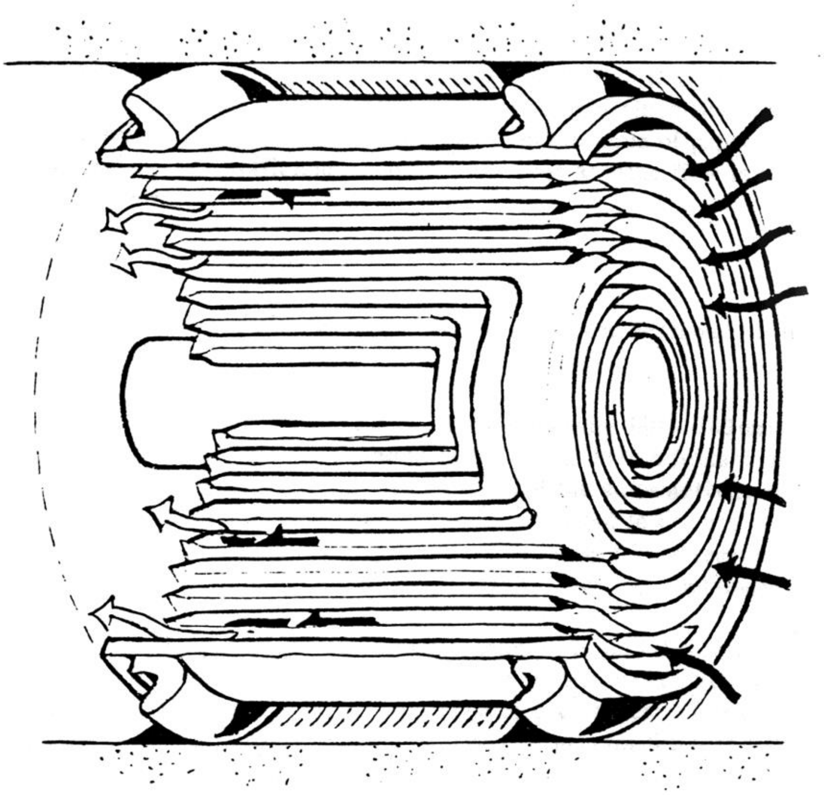

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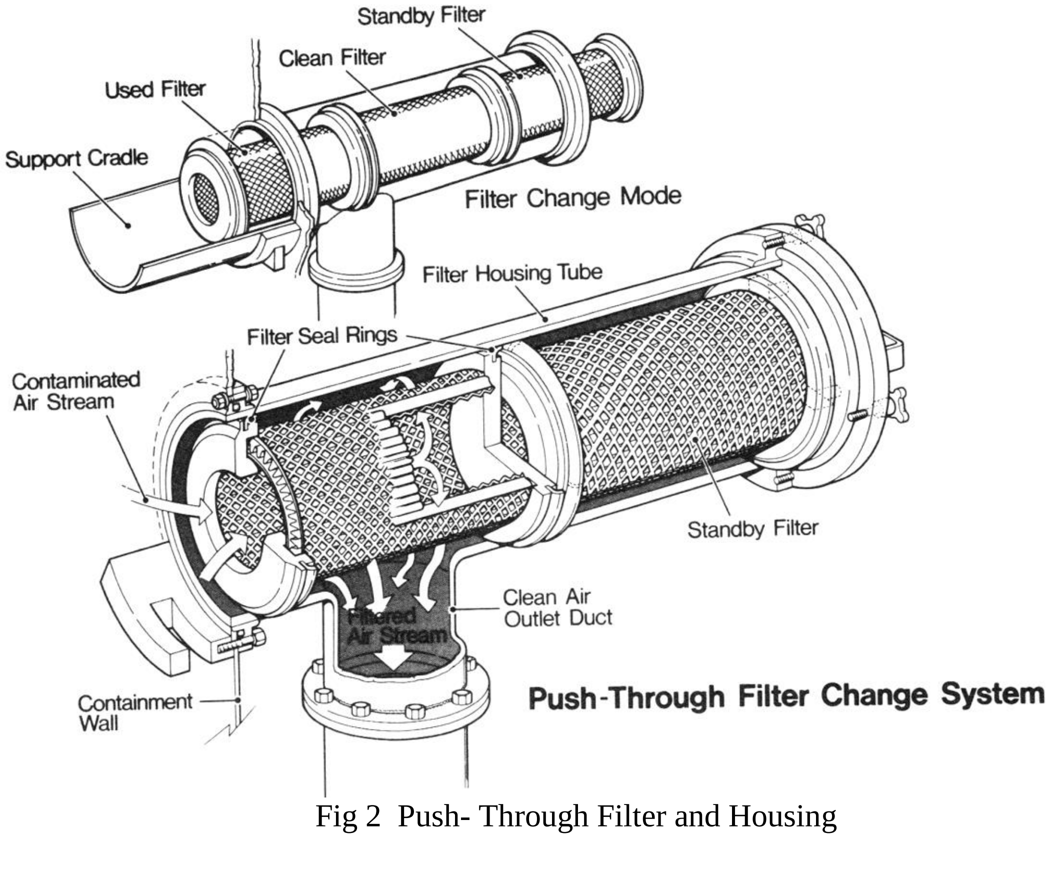

Fig 2 Push- Through Filter and Housing

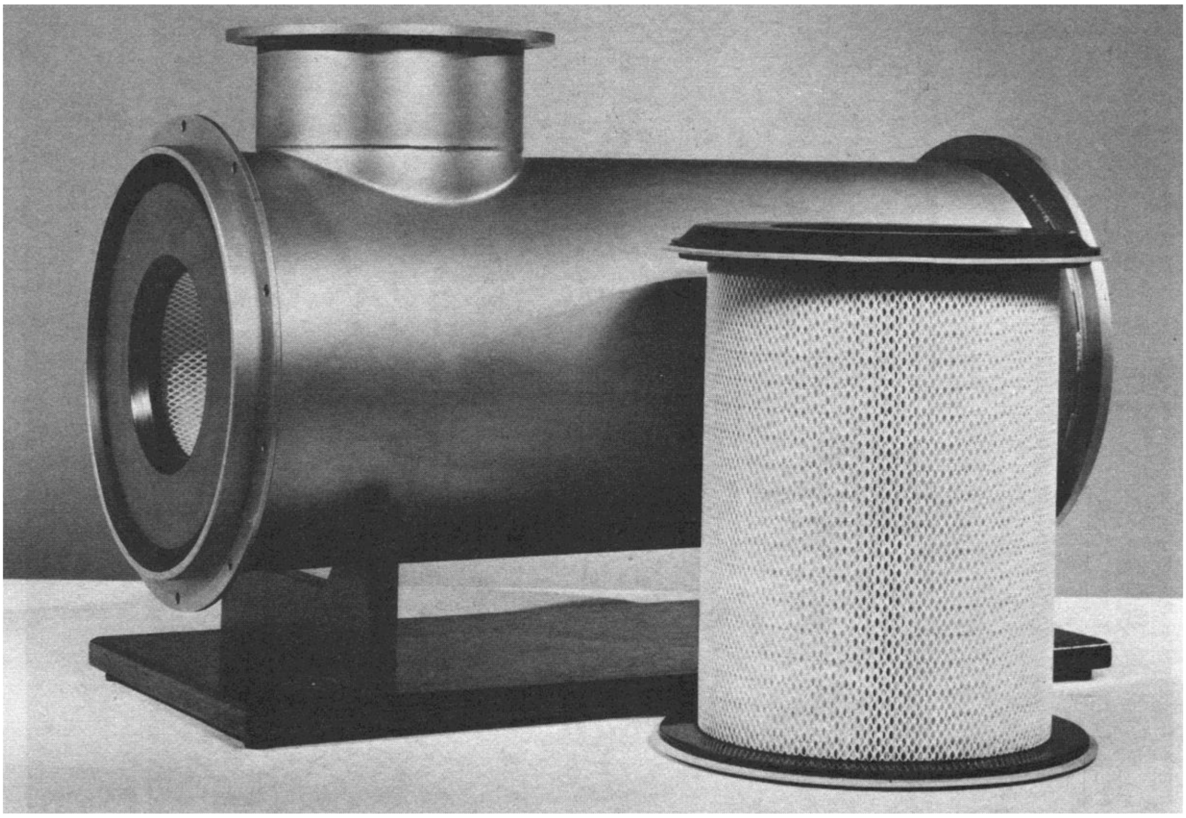

Fig 3 Glove Box Push Through Filter and Housing

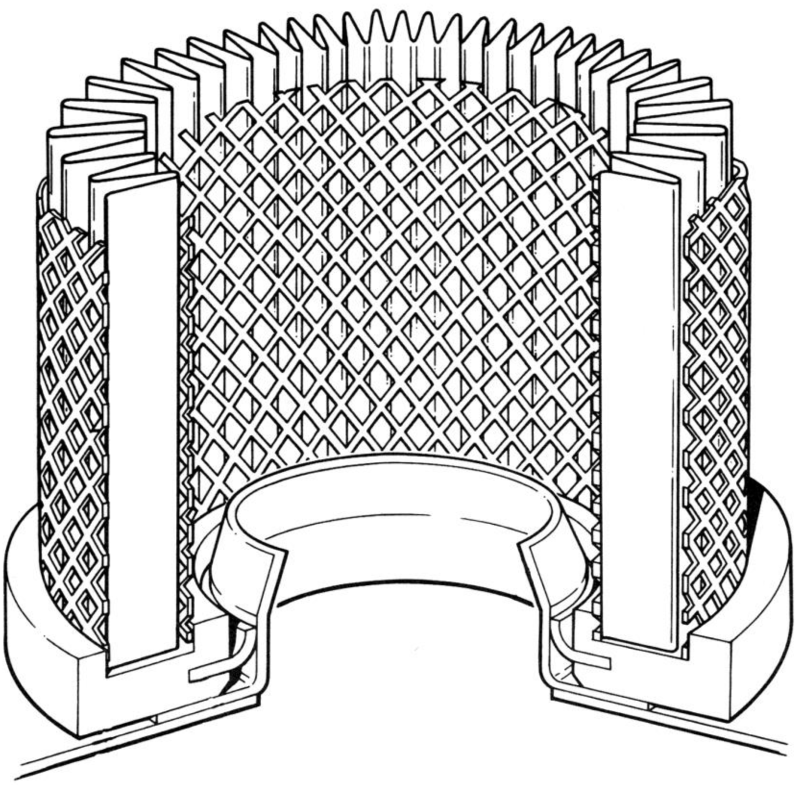

Fig 4 Internal Spigot Seal Arrangement

Fig 5   Range of Circular Filters (courtesy of M C Air Filtration Ltd)

Fig 6 High Capacity HEPA Filter (courtesy of M C Air Filtration Ltd)

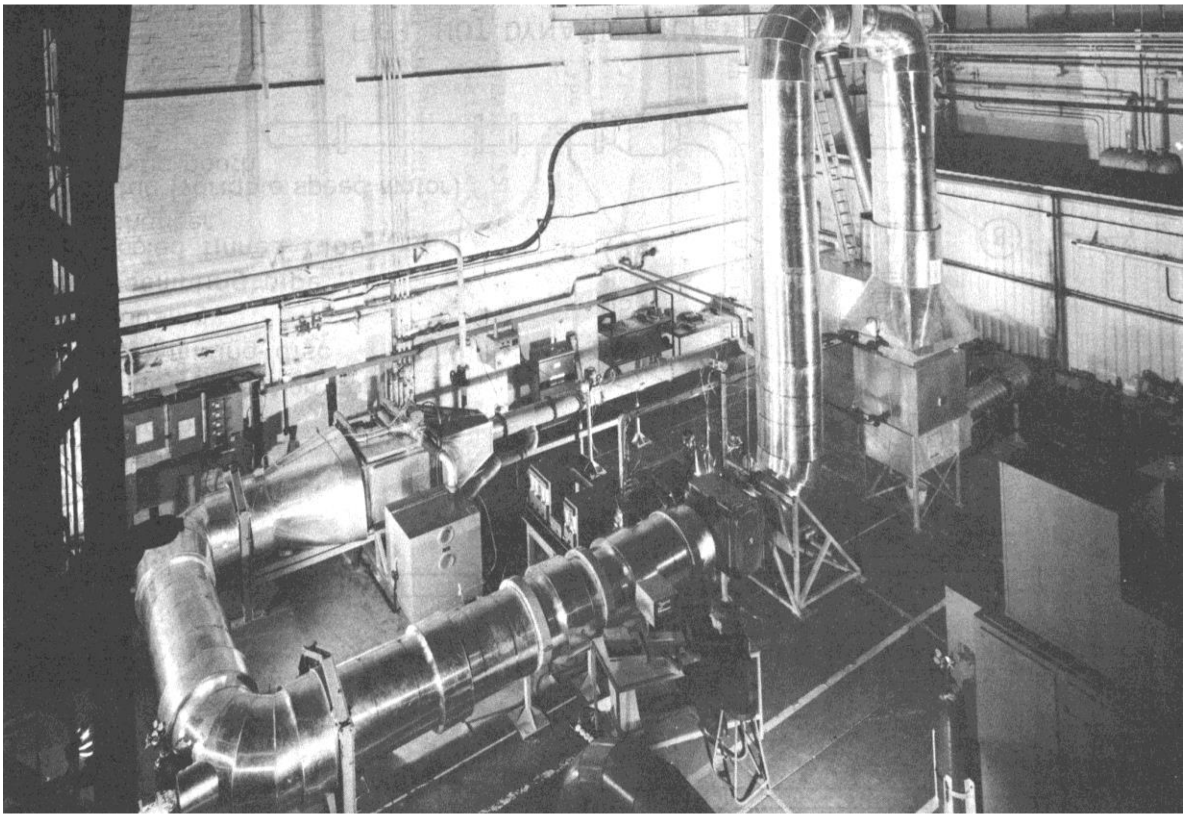

Fig 7 Hot Dynamic Filter Test Rig

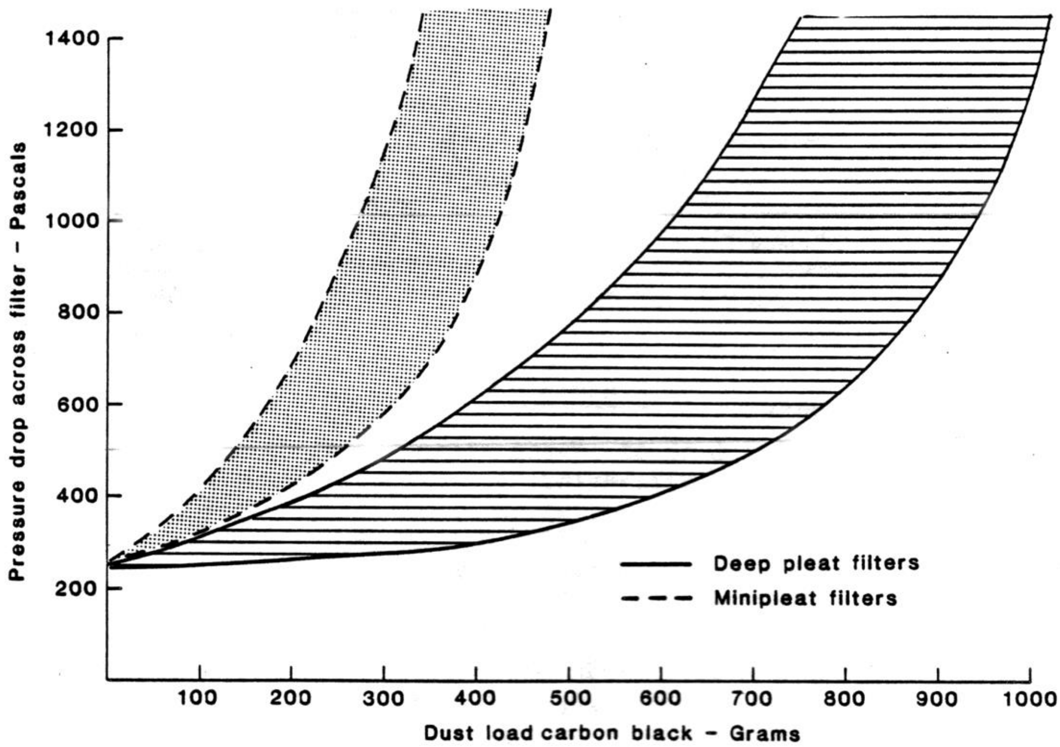

Fig 8 Dust Loading of HEPA Filters with Carbon Black.

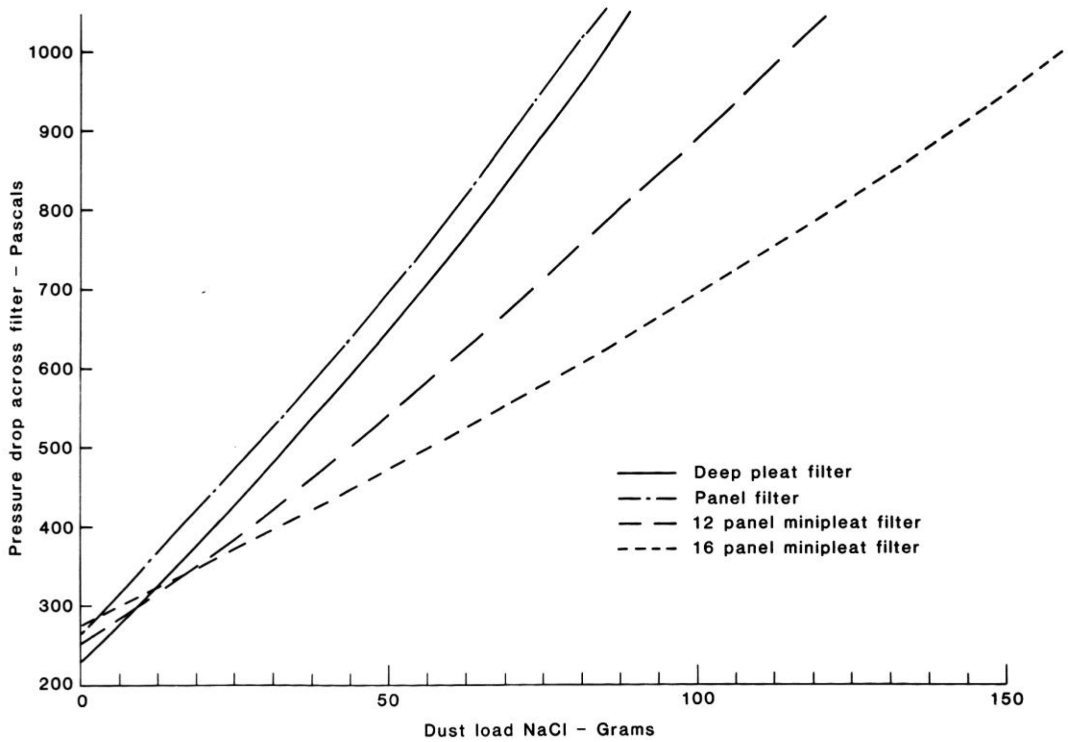

Fig 9 Dust Loading of HEPA Filters with sub –micron NaCl Aerosol