SESSION 3

A - DECOMMISSIONING AND DECONTAMINATION
B - RESPONSE OF HEPA FILTERS TO PHYSICAL STRESS

MONDAY: August 22, 1988
CHAIRMEN: R.T. Kratzke
            D.A. Huff

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M. Ammerich, A. Braind, J.C. Laborde, Ph. Mulcey, J. Savornin

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CLOSING COMMENTS OF SESSION CHAIRMAN HUFF

OPENING REMARKS OF SESSION CHAIRMAN KRATZKE

This session will cover two subjects. The first part of the session will cover decommissioning and decontamination. The second part will be concerned with the response of HEPA filters to physical stress. In the areas of decommissioning and decontamination we have three papers that address methods which measure and/or control aerosols that may be generated during R & D operations. We also have a paper on the increase in activity concentration as collected by supply air filters after the nuclear accident at Chernobyl.

During the second part of the session, we will be covering the response of HEPA filters to physical stress. We have five papers that look at a variety of stress factors. They include performance limitations and possible contamination releases related to high temperatures and high flows, effects of age on structural integrity, and on tests that measure the effects of these factors.

Both subjects are very challenging technically, and I look forward very much to this session.

MEASUREMENT AND REMOVAL OF STEEL FLAME CUTTING AEROSOLS
(0.01-1μm) IN WAGR DECOMMISSIONING

K.S. Robinson and C. Hamblin
(Chemical Engineering Division, AERE, Harwell)

ABSTRACT:

This paper gives details of work undertaken in
support of the AGR decommissioning programme at
Windscale Nuclear Laboratories using full-scale
inactive simulation of oxy/propane flame cutting
operations. Cutting fume aerosol size distributions
and concentrations were measured and tests were
undertaken to establish the performance of an
electrostatic precipitator and reverse pulse cleaned
cartridge filter as prefilters for the main
ventilation HEPA filters.

1.   INTRODUCTION

An extensive programme is under way at UKAEA Windscale Nuclear Laboratories
(WNL) to investigate and demonstrate flame cutting techniques for reactor
decommissioning aimed specifically at the dismantling of the Windscale AGR.
Throughout such activities it will be necessary to maintain large working areas at
sub-ambient pressure to prevent the release of radioactive dusts. The ventilation
air removed will inevitably contain significant quantities of aerosol produced by
the dismantling operations which will require filtration prior to exhaust to the
atmosphere. Although High Efficiency Particulate Air (HEPA) filters have the
required collection efficiency, the size and concentration of aerosols present in
the ventilation air are likely to cause rapid blinding of the filter media and a
high arising of used, active filters for disposal. In order to reduce the disposal
of these secondary arisings self-cleaning prefiltration techniques are being
investigated at both WNL and Harwell.

The work reported in this paper includes particle size measurements in the
range 0.01-1.0 μm carried out for flame cutting aerosols from the HERO facility at
WNL and efficiency measurements made on two prefiltration devices: a "Smoghog"
model SH10PEH manufactured by United Air Specialists (UK) Ltd. and a reverse
air-pulse clean cartridge filter system supplied by Donaldson Torit, Minnesota.

2.   EXPERIMENTAL
2.1   Aerosol Measurements

The HERO test rig is illustrated in Figure 1. This facility was originally
used for AGR coolant physics experiments and is therefore a good simulation of the
WAGR vault and air extract system. Figure 1 also shows the approximate distribution
of the 13600 m³/h (8000 cfm) exhaust between main cutting vault and outer annulus.
Cutting operations used an oxy/propane flame, with or without the addition of ~100
g/min 15% Al/85% Fe powder to the flame. Powder injection raises the flame
temperature to enable stainless steel and insulation-backed plate to be cut.

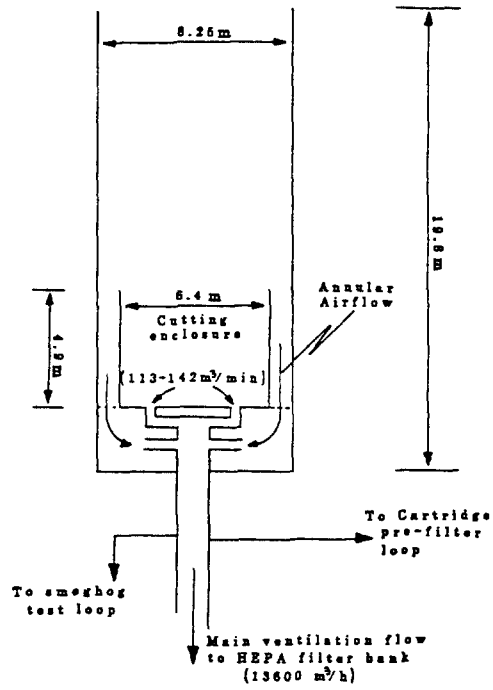Particle size distribution measurements were obtained using a TSI 3030
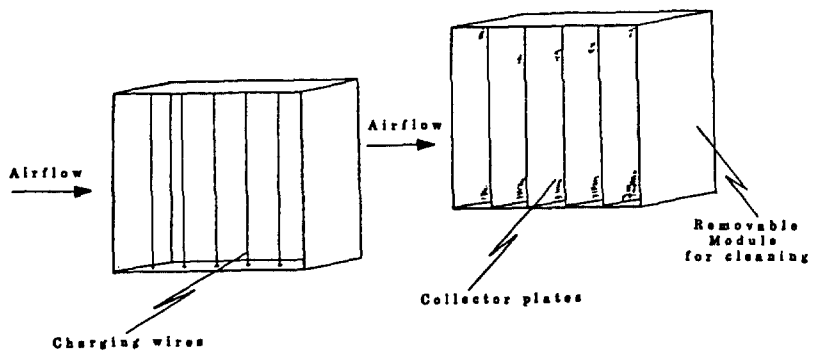
Figure 1

HERO Cutting Vault

Figure 2

Main Features of Smogbog Type Pre-filter.

Electrical Aerosol Analyser[1] (EAA). Aerosol laden sample was removed at 4 ℓ/min and size distribution histograms printed automatically every 2 minutes. The size bands used and the band mid-points are given in Table 1.

TABLE I
TSI 3030 EAA Size Bands

Particle Size Band (μm)	Mid Point Diameter (μm)
0.010 - 0.018	0.013
0.018 - 0.032	0.024
0.032 - 0.056	0.042
0.056 - 0.100	0.075
0.10 - 0.18	0.13
0.18 - 0.32	0.24
0.32 - 0.56	0.42
0.56 - 1.0	0.75

As measurements were in the 0.01-1.0 μm diameter range, isokinetic sampling was not used. To minimise errors a ^{85}Kr source was fitted in the sampling lines to equilibrate electrostatic charges on the cutting aerosols: charged particles may react differently to uncharged particulate within the TSI size analyser which relies on electrostatic separation. The results presented are typical of those gathered throughout the work. Some variation in distribution and concentration did occur, but in general results from the HERO rig were within ±10%.

2.2   The "Smoghog" Pre-filter

The range of "Smoghog" electrostatic precipitators supplied by United Air Specialists (UK) Ltd. are used primarily to remove welding/flame cutting aerosols from workshop environments. The main features of a typical precipitator are shown in Figure 2. A high voltage (6-8 kV) is applied to the corona charging wires. Aerosol particles are charged as they pass between the wires and then collected on downstream plates. Particulates captured on the collector plates usually form an agglomerated layer on the surface which must be periodically removed to maintain collection efficiency.

The "Smoghog" test loop at WNL is illustrated in Figure 3. Air from the cutting vault at a flowrate of ~1000 m³/h passed through a model SH1OPEH "Smoghog" (rated at 1700 m³/hr) mounted upstream of a 1700 m³/h (1000 cfm) deep pleat HEPA filter unit. Aerosol sampling points allowed efficiency measurements to be made during pre-filter operation, and the charger wire and collector plate voltages were continuously monitored. HEPA pressure drop measurement were also used as an indication of pre-filter collection efficiency.

2.3   The Pulse Clean Cartridge Filter

The reverse, air-pulse, clean cartridge filter and housing are shown in Figure 4. A Donaldson Torit Corporation type P14-5891 "Ultraweb" filter cartridge was used in the trials. The element (see Figure 5) comprises 322 pleats, each 49.5mm deep and 656mm long, giving a total area of filtration of ~20m². The operating gas velocity should ideally be in the range 0.7-1.5 m/min (840-1700 m³/h). The air channels between adjoining pleats are maintained by a combination of crimps

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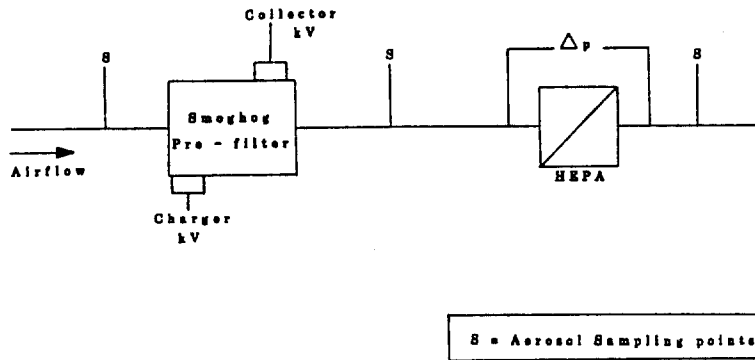
Figure 3

Smoghog Test Loop (schematic)

S = Aerosol Sampling points
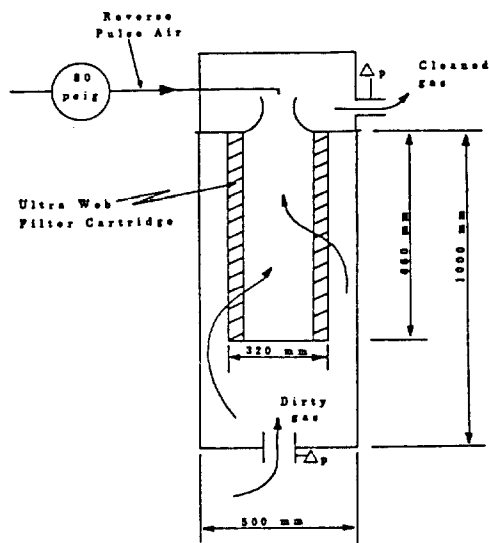
Figure 4 Reverse Pulse Clean
Cartridge Filter Installation
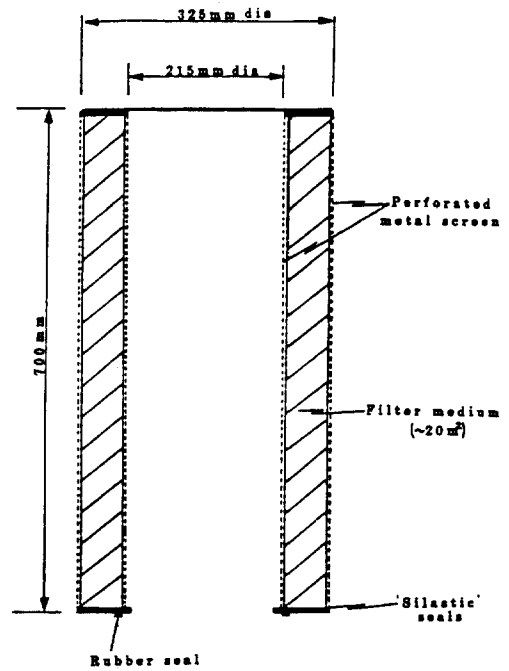
Figure 5 Cartridge Filter Design Details.

S = Aerosol Sampling points
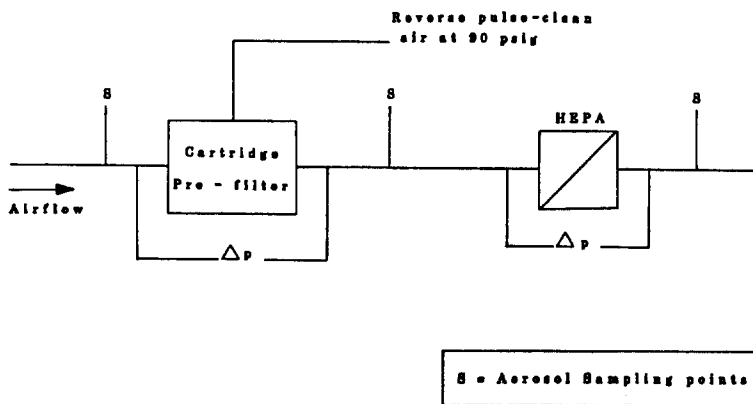
Figure 6

Cartridge filter Test Loop

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on the edges .of the pleats and the ribbed surface of the medium. The cartridge is protected during handling and installation by perforated metal screens fitted around the inner and outer faces. The screens and element are sealed into the cartridge end plates with a low temperature resistance sealant.

The cartridge medium is cellulose-based, and consequently has poor fire resistance, but the experiments at WNL were primarily intended to show whether the captured aerosols would produce a filter cake that could be removed by reverse pulse cleaning. The cartridge filter test loop at WNL is shown in Figure 6. Aerosol laden air from the cutting enclosure at a flowrate of ~1250 m³/h passed through a flow control valve to the cartridge filter unit and finally through a 1700 m³/h (1000 cfm) HEPA filter. To keep experimental timescales reasonably short the tests were carried out on the fume produced during the cutting of stainless steel: aerosol concentrations from the cutting of stainless steel are greater than produced during cutting mild steel.

Cartridge filter operating efficiency and pressure drop were continuously monitored. Pulse cleaning was carried out with the aerosol flow isolated as the pre-filter test housing was not fitted with a dust collection hopper. To avoid re-entrainment particulate removed from the cartridge was cleaned from the housing before re-starting the aerosol flow.

3.   RESULTS AND DISCUSSION
3.1   Aerosol Size Distributions

Typical size distributions (for the sub-micrometre fraction) of the aerosols produced during the cutting of 75mm thick mild steel, with and without uowder addition, and 25mm thick stainless steel with powder addition are given in Figures 7, 8 and 9 respectively. The total number and volume (expressed as μm^3 of particulate per cm^3 gas) and volume mean diameter data for each aerosol are summarised in Table II.

TABLE II
Cutting Aerosol Data

Cutting Details	Total Number of 0.01-1.0μm Particles (n/cm³)	Total Volume of 0.01-1.0μm Particles (μm^3/cm³)	Volume Mean Diameter (μm)
Mild Steel + Powder	~8.2 x 105	~ 7000	~0.35
Mild Steel no Powder	~1.5 x 105	~ 120	~0.24
Stainless Steel + Powder	~3.0 x 106	~15500	~0.50

The addition of powder to the mild steel cutting flame increases both aerosol size and concentration. Both mild steel aerosols are finer (and less concentrated) than that produced during stainless steel cutting operations. All aerosols, however, are in the size range and at a concentration that will cause rapid blinding of HEPA filters.

3.2   The "Smoghog" Prefilter

The "Smoghog" operating efficiency was measured using di-octyl-phthalate (DOP), naturally occurring atmospheric aerosols and the particulate produced during mild steel cutting (with and without powder addition) and stainless steel cutting (with powder addition to the flame). As would be expected, particle penetration values (calculated for the entire 0.01-1 μm range) were found to be dependent on collector plate operating potential as shown in Figures 10 and 11. The plate potential was rapidly reduced by collected aerosol, as illustrated in Figure 11.

For non-radioactive dusts plate cleaning is an easy operation. The plate module is removed from the housing and adhering particulate brushed from the surfaces. Remote cleaning in a nuclear environment would require development. Sharp edges on the rectangular plate module would pose serious problems during bagging operations which would be necessary to avoid re-entrainment of radioactive dusts. Moreover, the efficiency data suggest that only a relatively small saving in HEPA arisings would result from use of this type of filter for flame cutting aerosols. Higher efficiency, self-cleaning electrostatic precipitators are available. Capital costs are high and considerable development would be required to make them acceptable for use in a nuclear environment.

3.3   The Pulse Clean Cartridge Filter

The results from the cartridge filter test loop are given in Figure 12. The main ventilation system HEPA filters (a bank of 8) blinded and required change-out after cutting a 25mm thick stainless steel plate at ~100 mm/min for 300 minutes. No change in the pressure drop of the HEPA unit downstream of the cartridge filter was observed after 600 mins cutting. The overall DF (decontamination factor) of the cartridge filter during this period was found to be in the range 3000 to 4000. (Grade efficiency data could not be obtained due to difficulties found in downstream sample extraction.)

As the cartridge filter housing was not fitted with a dust collection hopper, pulse cleaning was timed to coincide with stops in the cutting operation. This may explain the gradual increase observed in the 'cleaned' cartridge pressure drop (see Figure 12). At the end of the cutting operation a large reduction in cartridge pressure drop was achieved by a long series of cleaning pulses (40-50). Although not normal operating procedure, this demonstrated that more efficient on-line cleaning could be obtained.

4.   CONCLUSIONS

1.   Measurements have shown that flame cutting decommissioning operations will lead to large numbers of HEPA filters requiring disposal.

2.   A "Smoghog" type pre-filter would lead to only moderate savings in HEPA arisings. Much work would be necessary to enable this form of prefiltration device to be used in nuclear environments.

3.   Reverse pulse-clean cartridge filters are available with an operating efficiency comparable to that of HEPA filters. Such systems have the potential to greatly reduce HEPA filter arisings.

5.   FUTURE WORK

(i) Long-term trials using a pulse clean cartridge filter with improved on-line cleaning triggered by a pre-set pressure drop.
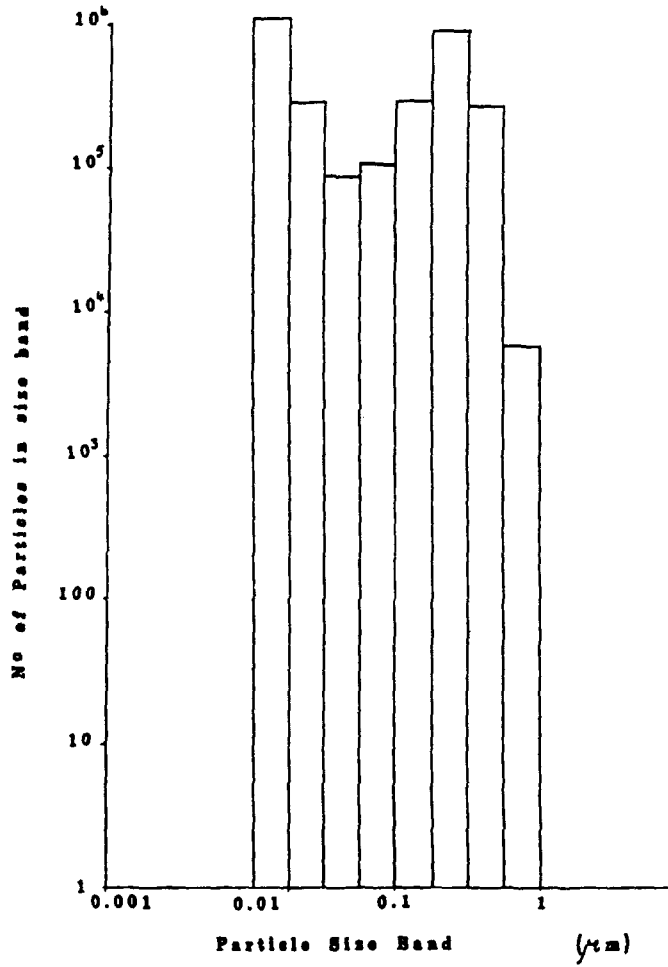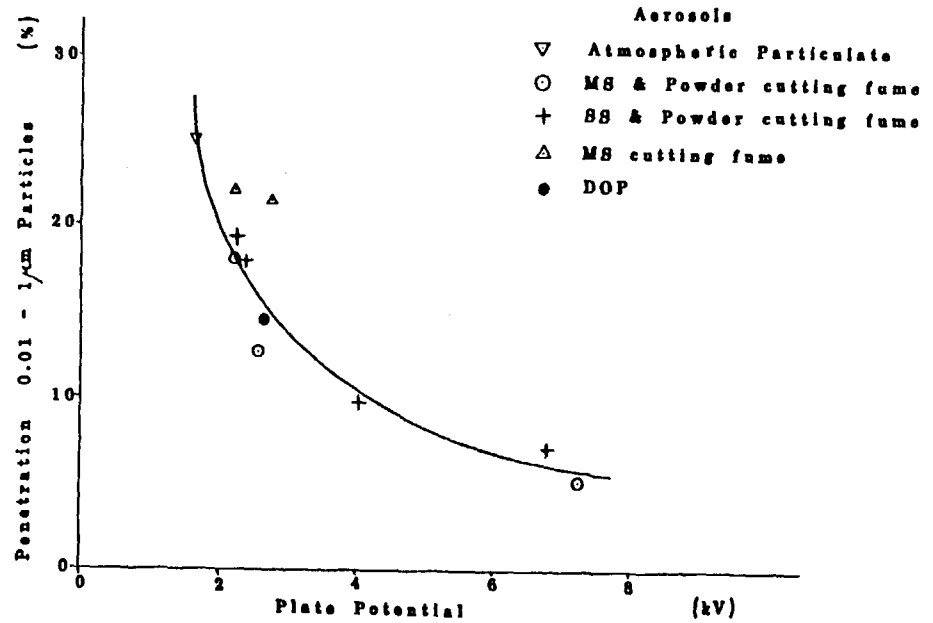
Figure 9

Number Size Distribution for Stainless Steel
with powder addition to flame

Figure 10

Smoghog Operating Efficiency as a Function of Plate Potential
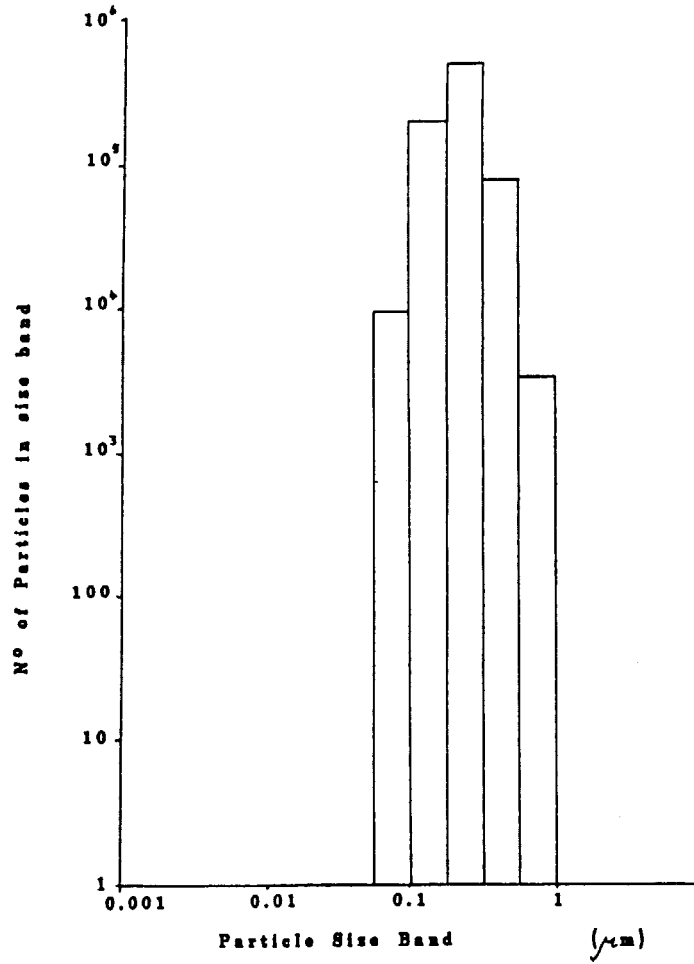
Figure 7

Number Size Distribution for Mild Steel

with powder addition to flame
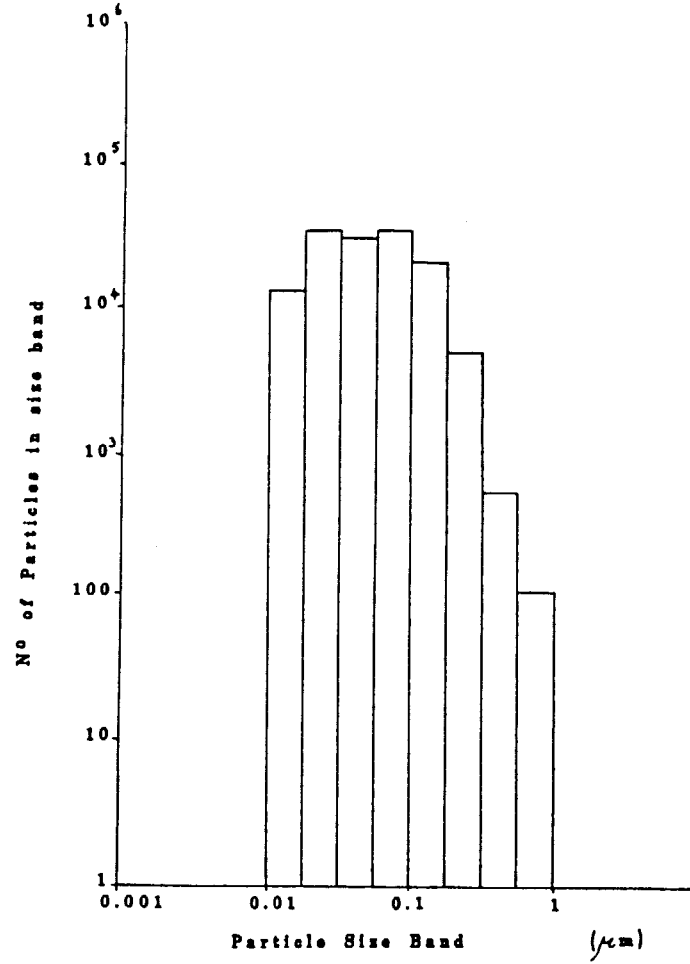
Figure 8

Number Size Distribution for Mild Steel

with no powder addition

(ii) Construction and evaluation of high strength glass-fibre filtration medium cartridge unit with improved resistance to high temperatures.

6.   REFERENCES

1.   Lin, Y.U. et al. Particle Technology Lab. Pub. N°. 303, Aerosol Measurement Workshop, Univ. Florida, Gainsville, March 1976.

Figure 11
Effect of Collected Stainless Steel Cutting Fume on Smoghog Operating Voltages

Figure 12
Variation in Filter Pressure Drops with Cutting Time

DISCUSSION

BERGMAN: Do you see any problems with using a pulse cleaning system for the prefilter in contaminating the environment? This may be a problem because of positive pressure in a negative system. Positive pressure pulses are a frequent problem in glove-box contamination. Do you feel there is a fire hazard from sparks in the electrostatic precipitator?
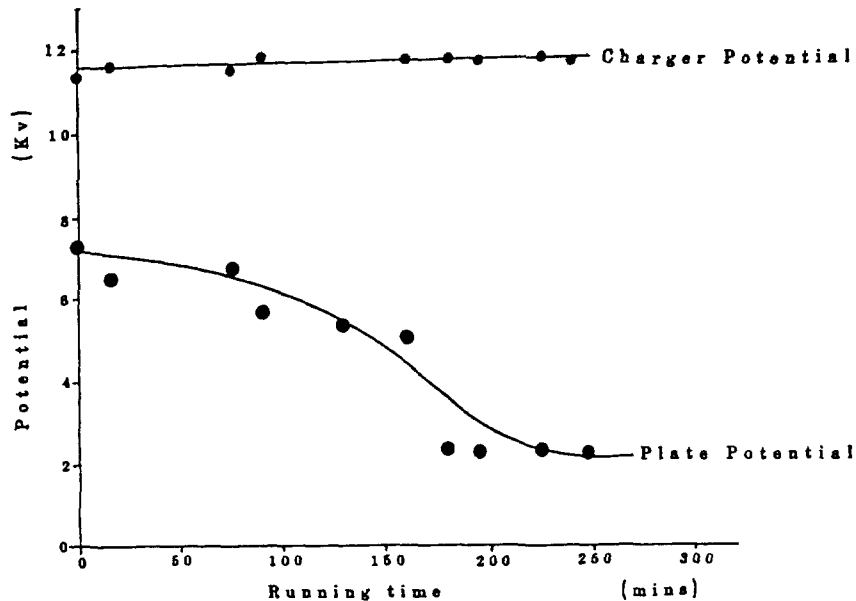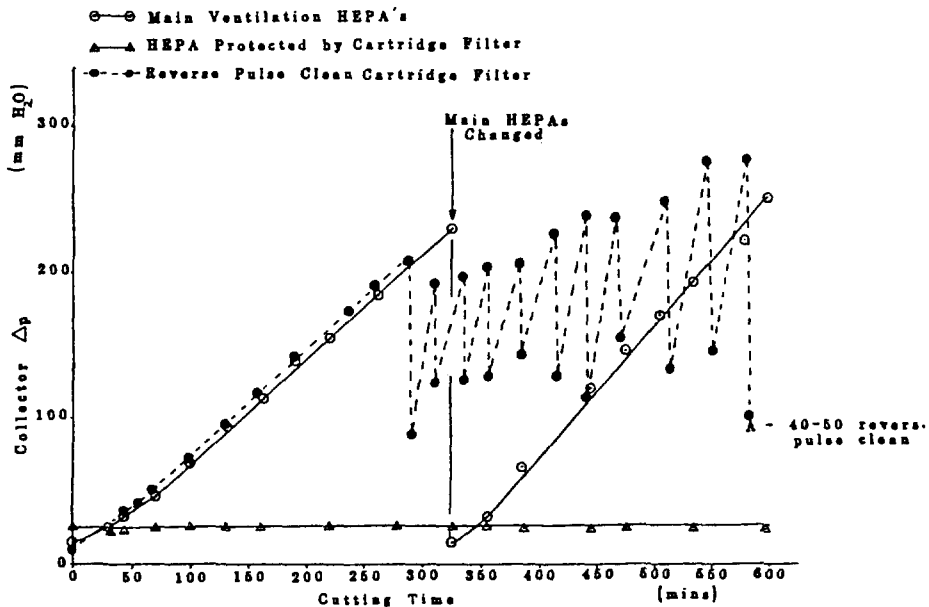
ROBINSON: The volume of the filter necessary will be very much larger than the filter cartridge and I doubt that overpressurization will occur. We plan to test a full scale multiple unit and will then have a better idea if any problems exist. Yes, I do feel that scrubbing could be a problem with electrostatic precipitators.

BERGMAN: Because of the potential for contaminating a negative pressure duct. The reason you have a negative pressure duct is to prevent leaks of radioactive materials to the outside. When you pulse something, you create a momentary positive pressure and from peoples' experiences with glove boxes that is one of the primary causes of releasing radioactive material to the surroundings.

LOUGHBOROUGH (for Robinson): I can only say that this has not been considered a problem by the people who carried out the tests. What I will do is take the question back to the authors of the paper and see what they have to say.

BONKA: Did you measure aerosol particles having a diameter larger than 1 μm? You know that the particle diameter is not a measure for activity over the entire particle size range.

LOUGHBOROUGH (for Robinson): We did not measure particles greater than 1 μm. The machine we used is only capable of measuring 0.1 to 1 μm. So, as far as I know, they did not measure above 1 μm.

SCHMIDT: My question is very much the same as the last speaker's. I was wondering why you arbitrarily stopped your measurements at 1 μm?

LOUGHBOROUGH (for Robinson): Having not carried out the work, I can not be definite. However, what I can say is that maybe they assumed that particles up to 5 or 10 μm would not reach the prefiltration device because the velocity in the duct would be inadequate. Now, that is only my guess at the moment.

SCHMIDT: I suspect that if you had made particle size distribution measurements with a cascade impactor, you would have found a mass median diameter of 3 - 5 μm, with some particles as large as 15 μm. It is important to know this size range for health and safety purposes, and monitoring purposes.

LOUGHBOROUGH (for Robinson): One of the reasons they chose that particular size is that they will generally block the HEPA filters quicker. In that case, is there any reason to worry about 5, 10, 30 μm particles when all they do is form a cake on the HEPA filters and not block it.

ROBINSON: We have used both a cascade impactor and light scattering instrument and the total distribution is bimodal as you suggest. We have concentrated on the subversion peaks in this work as these are the particulate that will blind a filter medium.

SCHMIDT: From a safety standpoint, if larger particles are soluble and reach the upper part of the respiratory system they can be very toxic and very important.

LOUGHBOROUGH (for Robinson): That is if they escape into the atmosphere as opposed to staying within the equipment.

SCHMIDT: Perhaps not if you have some kind of equipment leak, or a HEPA filter leak, or an explosion, or something of that sort.

THE DEVELOPMENT OF A MULTI-TUBE AXIAL FLOW CYCLONE SEPARATOR SYSTEM FOR USE IN NUCLEAR GAS CLEANING SYSTEMS

by

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ABSTRACT

Axial flow cyclone separators have been manufactured by Pall Corporation under its trade mark Centrisep for more than 20 years. They have been used typically to protect gas turbine and Diesel engines and control systems from abrasive airborne contaminants.

The axial flow cyclone system provides a permanent, high efficiency, non-clogging separator with no moving parts and minimum maintenance requirements. These attributes suggested its use as a particle separator in nuclear gas systems, and led to the initiation of a programme of test work by the Central Electricity Generating Board (CEGB) and Pall Europe Limited to develop a suitable system.[1]

In this paper the development, testing and application of separator panels using multiple 2-stage separators are described. Several nuclear application concepts are discussed, and details are given of a specific installation at Dungeness B nuclear power station.

The design objectives for the separator system were: (a) to develop the dust separation efficiency to a level above that of existing units and (b) to minimise dust hold-up within the separator assembly so as to minimise the exposure of maintenance personnel to radioactive debris.

The multi-tube separator assembly achieved an efficiency of separation of 98.5% and a dust hold-up of 162 g when tested with AC coarse test dust.

1.   Principle of Operation

The principle of the cyclone separator is the separation of particles from a gas stream by causing them to take different routes from the gas stream by virtue of their inertia. In the cyclone system described, the basic flow is axial and gas entering the vortex tube is forced into a spiral flow by the fixed blades of the vortex generator. The particulate is thrown outwards to the periphery of the vortex tube by centrifugal force, and is carried away through the annular gap between the vortex tube and outlet tube with a small proportion of the gas flow (the scavenge flow). The principle is illustrated in Figure 1 which shows a typical single-stage tube configuration.
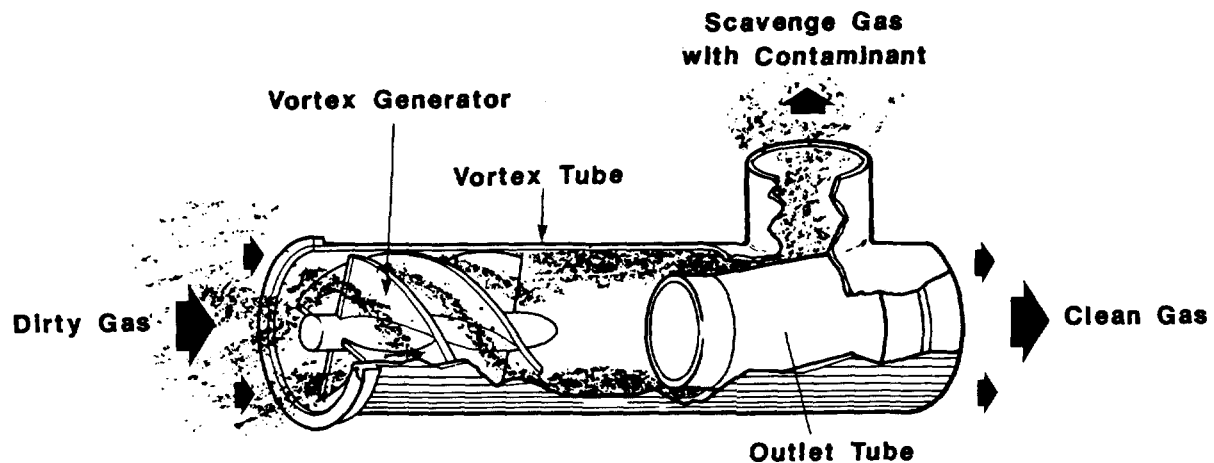
FIG. 1   PRINCIPLE OF OPERATION OF SINGLE-STAGE SEPARATOR

The bulk of the gas flow, from which the particulate has been separated, passes axially down the centre of the outlet tube. The separated contaminant is concentrated into the scavenge gas flow which is piped away for discharge, further concentration or filtration, depending on system requirements. There are no moving parts in this separator system.

To handle higher flow rates, a number of tubes can be mounted in parallel between tube plates or in blocks; the optimisation of tube quantity and layout can then provide the best efficiency of particulate separation in conjunction with pressure loss and space considerations. Separation efficiency is a function of particle size and density, gas conditions, volumetric flowrate and cyclone geometry. For a given particle size, an increase in separation efficiency is normally gained at the expense of energy loss in some form, usually as an increase in pressure drop.

2. Historical Background

The Centrisep separator system was developed 25 years ago and is described in patents[2-6]. Development followed two different but related product lines: (a) panels of multiple plastic tubes for helicopter and fighting vehicle engine protection and (b) metal single-tube separators for high pressure air applications such as gas turbine control systems and aircraft environmental control systems.

The separators are sometimes combined with other filtration or separation equipment to optimise system protection eg

(a) Two stages of axial cyclone separator.
(b) Axial cyclone separator and barrier filter.
(c) Axial cyclone separator and liquid droplet coalescer.
(d) Axial cyclone separator and miniature separator to further concentrate the scavenged contaminant into a smaller gas flow.

A high efficiency single-tube separator was developed for use in a critical air system on the Rolls-Royce RB-211 commercial aircraft gas turbine engine. The unit separates solid and liquid contaminants and increases the time between overhaul and recalibration of a compressed air guide vane control system.[7]

Because the aircraft unit was already developed to high performance, it was chosen as the starting point in the joint CEGB/ Pall development project; this programme culminated in the supply of assemblies with 264 2-stage separator tubes for use in the Irradiated Fuel Dismantling Facility (IFDF) at Dungeness B nuclear power station.

3. Conceptual Applications

Although scavenged axial flow cyclones function as concentrators rather than absolute separation devices they are ideally suited for use in some nuclear ventilation and off gas systems. In principle they can be used as a direct substitute for a conventional filter, the only difference being the requirement to have a system to process the scavenge flow containing the separated solids. For nuclear applications where the separated solids and sometimes the gas itself are radioactive it is often preferable to process a small volume of gas containing a higher concentration of particulate material, especially where expensive remote handling techniques are required. While any traditional gas cleaning method could be used to treat the scavenge flow, the use of high efficiency filters (disposable or regenerable) or scrubbing systems has been identified as being appropriate for nuclear installations.

The scavenged axial flow cyclone separator offers the following performance and radiological advantages when compared with alternative commercially developed techniques:-

(a)   The assemblies are passive, their performance being dependent only upon the flow of gas through the device.

(b)   The assembly can be designed and fabricated to operate for full facility life.

(c)   The performance should remain constant through its operating life.

(d)   No maintenance or special handling facilities are required.

(e)   The construction is mechanically robust.

(f)   The cyclone can handle a wide range of solids and concentrations.

(g)   The scavenge flow, being only a small percentage of the main flow, is more amenable to processing using sophisticated treatment technology.

(h)   The scavenged cyclone system can be incorporated into a fully integrated waste management process in which waste volumes are reduced and the active debris is treated as it arises.

(i)   The cyclone assemblies can be designed for minimum dust hold-up.

(j)   In general, the pressure loss of the axial flow cyclone is lower than that of the reverse flow cyclone or barrier filter.

(k)   The performance of the cyclone assembly is not affected by the orientation of installation and gas flow direction.

Axial flow cyclones can be used to advantage as a substitute for conventional filters, especially where multi-stage filtration is required or where gas is recycled. Two conceptual applications are shown in Figures 2 and 3. Typical applications would be as the primary device in nuclear cell ventilation systems, waste management off gas plants, or irradiated fuel handling and storage plant extract ventilation trains. It is also anticipated that the device could be used to reduce the quantity of secondary waste arising from nuclear decommissioning activities.
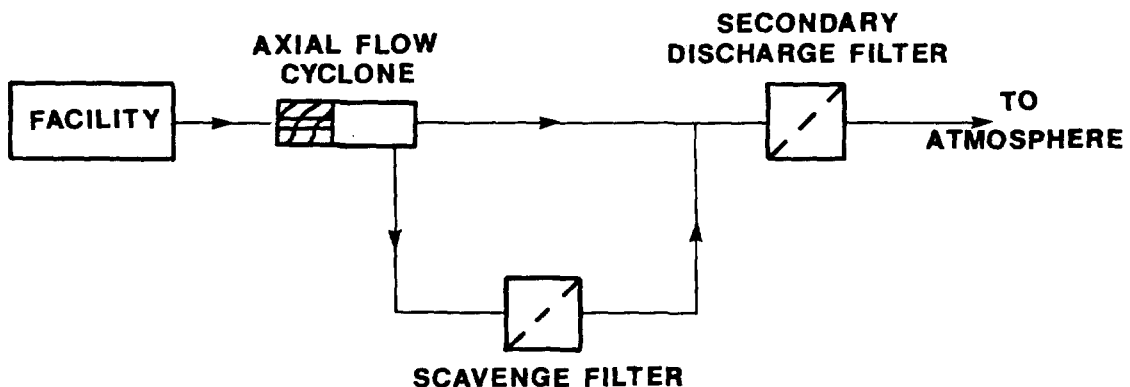
FIG.2 CONCEPTUAL VENTILATION EXTRACT SYSTEM
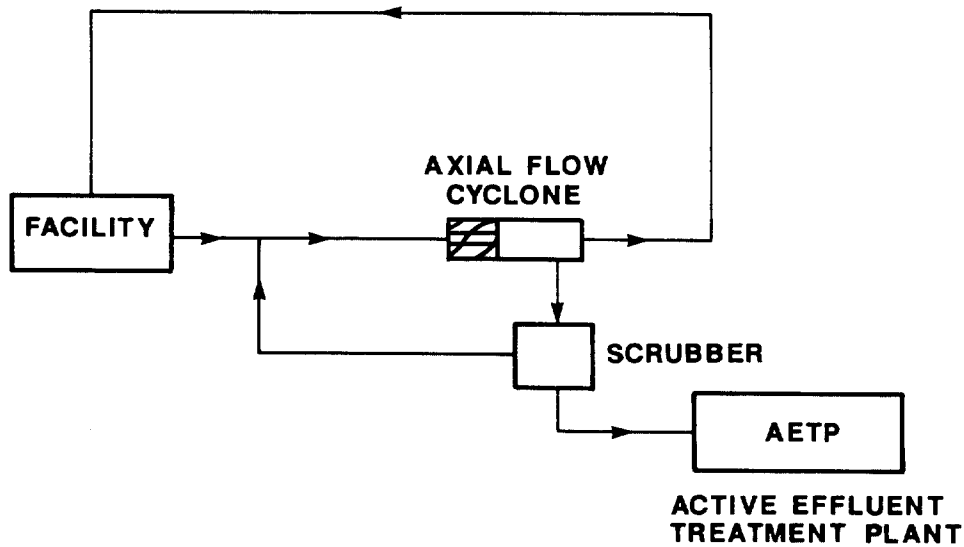
FIG.3 CONCEPTUAL RECIRCULATORY CLEAN-UP SYSTEM

4. Development of aircraft Separator

The aircraft single-tube assembly is shown in section in Figure 4. It is made of stainless steel and has inlet and outlet fittings which interface with the engine pipework.   The basic vortex generator is 13mm (.52") diameter.
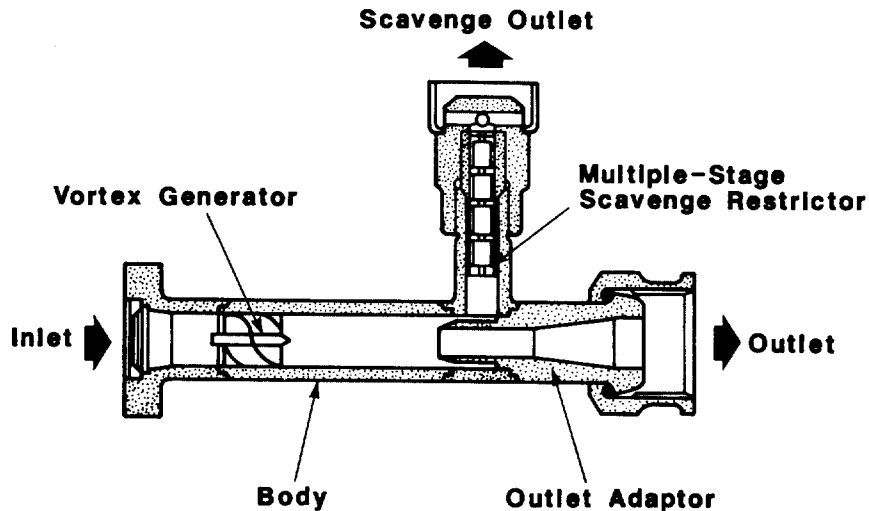
FIG.4 AIRCRAFT SEPARATOR

Primary development was concerned with the geometry of body, vortex generator and outlet to give high efficiency of dust separation over a range of flow, pressure and temperature conditions; this was achieved in conjunction with specified pressure loss and installation requirements. Secondary development was associated with the scavenge restrictor.[7]

To simulate aircraft conditions, a range of standard test dusts and special graded dusts were used in the development testing. The particle size distributions of some of these test dusts are shown in Table 1.

Test Dust	Percentage by weight below size							
AC coarse	–	–	8	12	24	70	94	100
AC fine	6	16	27	39	57	95	100	100
BS.2831. No 2	1	4	35	55	100	100	100	100
0-5 µm graded	20	59	76	88	100	100	100	100
Particle size µm	2	3	4	5	10	50	100	200

Table 1   Particle Size Distributions

The separation efficiencies achieved with four test dusts are shown as a function of flow in Figure 5. It can be seen that the efficiency of separation rises with flow, then reaches a plateau above which efficiency is essentially constant for further flow increases. It is important in systems with varying flow to ensure that the flow per tube is selected on the plateau region of the efficiency curve for all operating conditions.

The AC fine separation efficiency was 92%, whereas BS.2831 No. 2 dust yielded 97% at the plateau: This apparent anomaly can be explained by closer examination of the particle size distributions of the two dusts. AC fine and BS.2831 No. 2 dusts have mass median sizes of 8µm and 4.8µm respectively; the nature of the separation process in the cyclone ensures a higher separation efficiency for larger
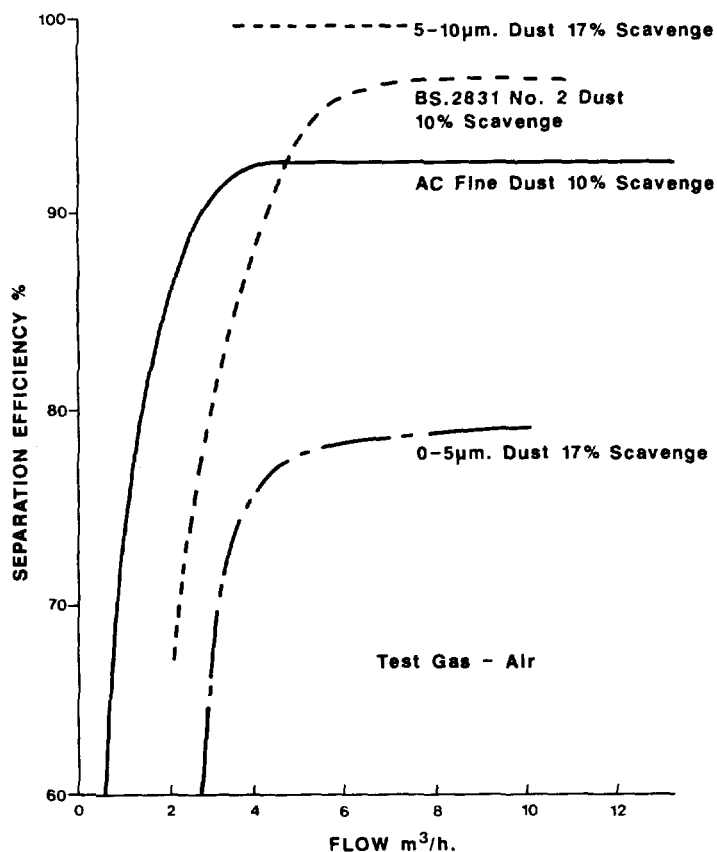

FIG. 5

EFFICIENCY/FLOW CHARACTERISTICS FOR
AIRCRAFT SINGLE-TUBE
SEPARATOR

particles, so a higher efficiency with AC fine dust might be expected. However the small particle distribution is more important in determining the efficiency of this cyclone separator; AC fine dust has a fairly wide size spectrum, with 6% by weight of its particles below 2μm, whereas No. 2 dust has a narrow spectrum with only 1% below 2μm. The lower efficiency with AC fine dust is explained by the higher proportion of fines present, which are less easily separated. This is supported by the data presented in Figure 10, showing that the efficiency falls only for particles below about 2-3μm. In a similar way the 5-10μm graded dust has very few particles below 2μm and demonstrates an efficiency greater than 99% in Figure 5.

5. 2-Stage Single-Tube Separator Development

To enhance further the separator performance, two stages of axial flow cyclones can be arranged in series. This configuration is shown diagramatically in Figure 6.
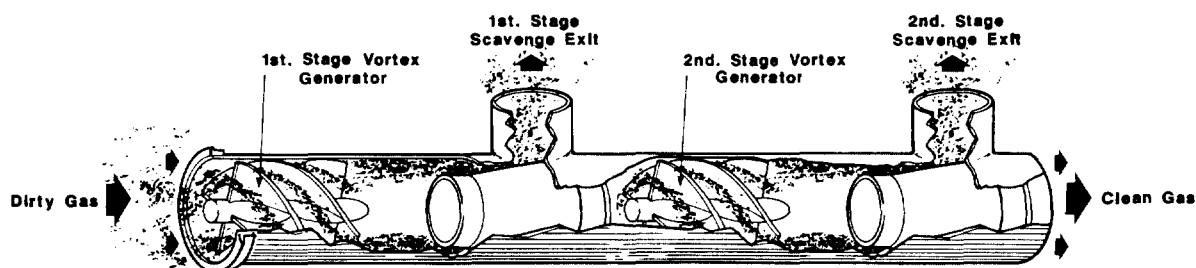
FIG.6 TWO-STAGE SEPARATOR

With this 2-stage configuration the efficiency of separation is increased, but in general pressure loss and scavenge flow are also increased. Where highest efficiency is required and sufficient space is available, the 2-stage separator with multiple tubes provides a good solution; this was the case with the Dungeness B IFDF installation, described later in section 6.

The initial 2-stage test assembly was produced by coupling together two aircraft units in series with a short length of pipe. The efficiency of dust separation was raised from 97% to 99% by the addition of the second unit, but, as would be expected, the pressure loss was almost doubled. Efficiency and pressure drop characteristics are shown in Figures 7 and 8 respectively. In this test work, the scavenge mass flows were adjusted to be equal from each separator stage, and the scavenge totals are expressed as a percentage of separator inlet flow. The performance test comparisons are derived from reports.[8&9]

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FIG. 7
EFFICIENCY/FLOW CHARACTERISTICS FOR
1-STAGE AND 2-STAGE
SINGLE-TUBE AXIAL FLOW CYCLONES
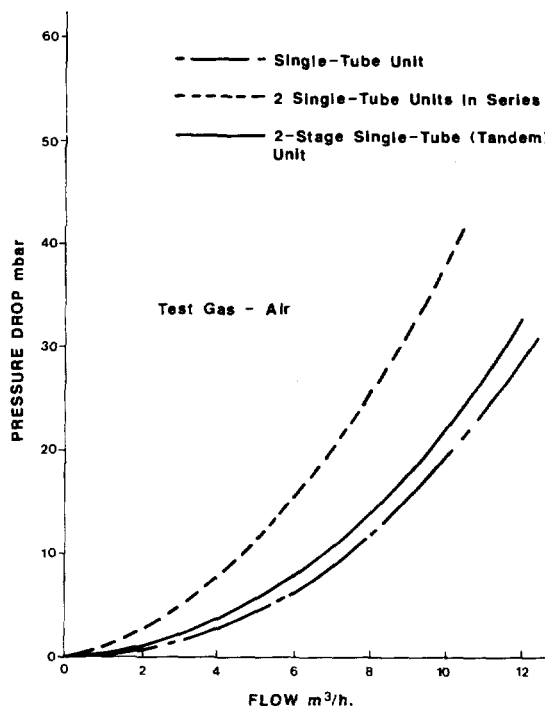
FIG. 8
PRESSURE DROP/FLOW CHARACTERISTICS FOR
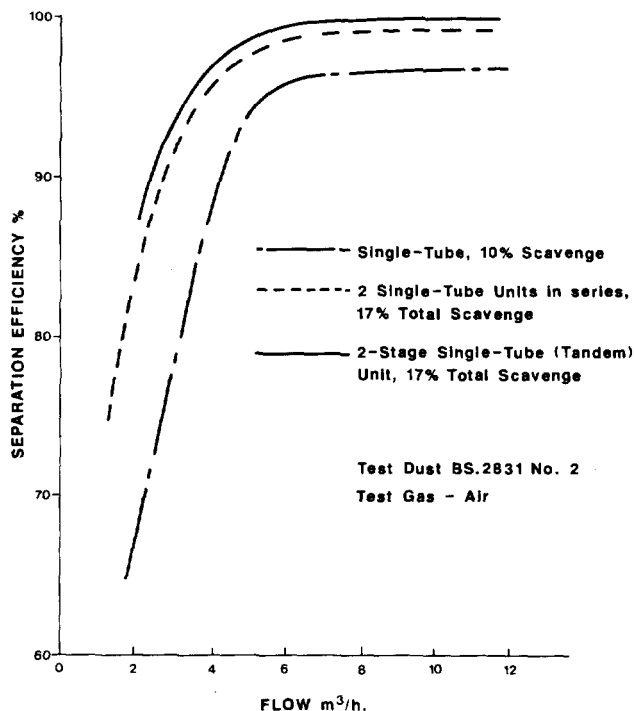1-STAGE AND 2-STAGE
SINGLE-TUBE AXIAL FLOW CYCLONES

The next hardware produced for test was a purpose-built 2-stage assembly using the same geometry as the aircraft separator, but with the outlet from the first stage directly connected by a short diffuser to the inlet of the second stage. This "tandem" 2-stage configuration is shown in Figure 6.

This configuration gave a further increase of efficiency of dust separation - see Figure 7. Also the pressure loss of the tandem unit was considerably less than that of the two separate assemblies coupled with a pipe, as shown in Figure 8. The reason for the reduced pressure drop is that the swirling vortex flow from the first stage is still quite strong when it reaches the second stage vortex generator of the tandem unit. With pre-swirl the second stage vortex generator exhibits a lower pressure loss. In the assembly with two coupled aircraft units, the connecting pipe allows the vortex from the first stage to die before it reaches the second stage vortex generator, resulting in the same high pressure loss at each vortex generator.

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Further tests were carried out to determine the way in which efficiency of separation with BS.2831 No. 2 test dust varied with inlet gas flow and percentage scavenge flow; the results are shown in Figure 9. High separation efficiency can be achieved with total scavenge flow as low as 5%, provided the inlet flow is set at the highest level.
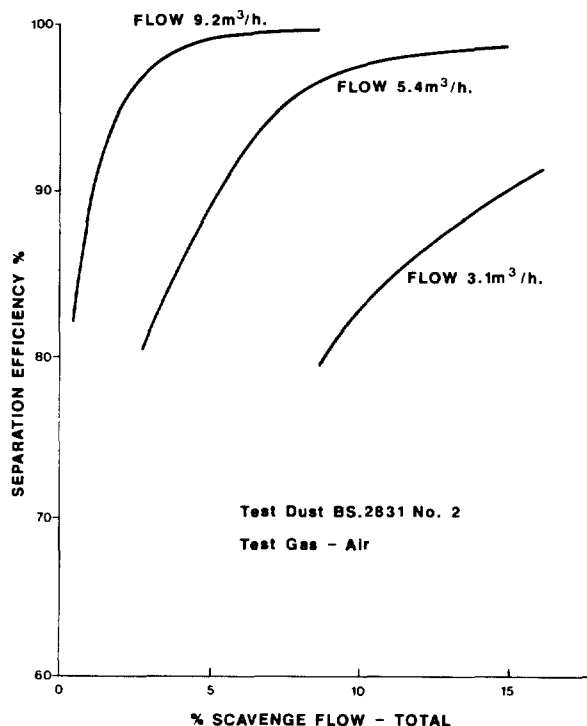
FIG. 9

EFFICIENCY/SCAVENGE FLOW CHARACTERISTICS FOR
2-STAGE SINGLE-TUBE (TANDEM)
AXIAL FLOW CYCLONE
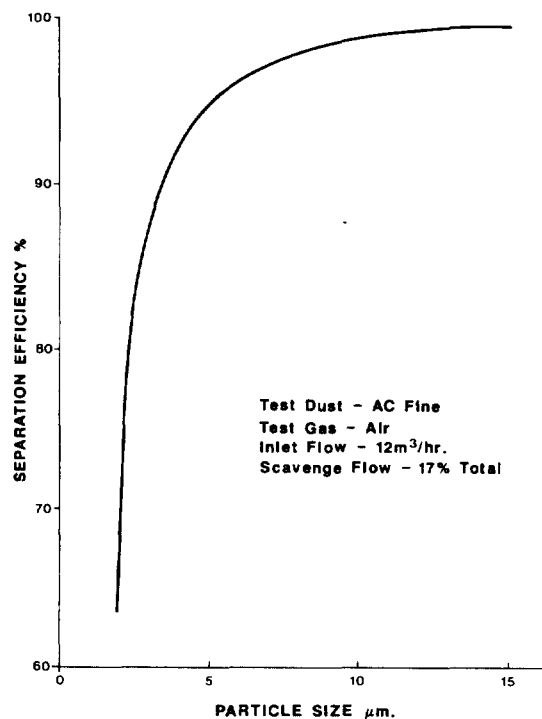
FIG. 10

EFFICIENCY/PARTICLE SIZE CHARACTERISTICS FOR
2-STAGE SINGLE-TUBE (TANDEM)
AXIAL FLOW CYCLONE

Efficiency tests with AC fine test dust were carried out to determine the way in which efficiency varies with particle size. The results are shown in figure 10. Upstream and downstream particle size analyses were carried out using the Andreasen pipette technique combined with the gravimetric efficiency measurement.

Final efficiency tests with three test dusts, showing the variation with inlet flow rate, are presented in Figure 11. Again it can be seen that the nominally finest dust, BS.2831 No. 2 gives the highest efficiency because it contains the smallest proportion of particles below 2μm.

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Recent development testing, outside the scope of this report, has indicated that higher efficiencies of separation can be achieved by further optimisation of the tube configuration.
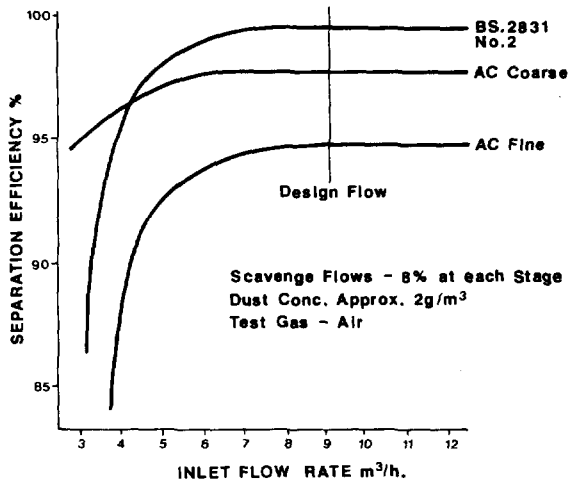
FIG. 11

EFFICIENCY/FLOW RATE CHARACTERISTICS FOR
2-STAGE SINGLE-TUBE (TANDEM)
AXIAL FLOW CYCLONE
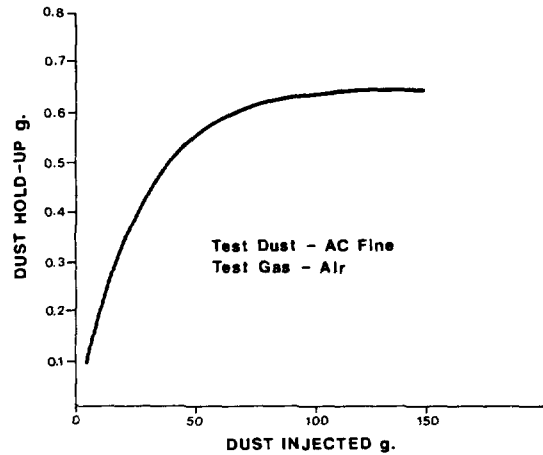
FIG. 12

DUST HOLD-UP CHARACTERISTIC FOR
2-STAGE SINGLE-TUBE (TANDEM)
AXIAL FLOW CYCLONE

Dust Hold-up

One of the advantages of a cyclone separator, as mentioned in Section 3, "Conceptual Applications", is that active debris can be treated as it arises. This reduces the end of station life hazard in general, but the local hazard at the cyclone installation can only be minimised if the amount of residual debris lodged in the separators is kept at a low level. Rig tests on a single-tube tandem unit were carried out to determine the likely dust build up, using a standard test dust (AC fine). The resultant curve (Figure 12) shows that for the test dust used a hold-up of approximately 0.65 g per tube could be expected. This quantity was later confirmed by tests of the full panel assembly, and is considered to pose an acceptable hazard in the installation at Dungeness B power station. This acceptance is based on the assumption that AC fine dust is approximately representative of the true IFDF contaminant.

6. Development of Multi-tube Separator

The two-stage single-tube separator performance had now been developed to a sufficiently high level, as indicated in Section 5. The basic cyclone tube was next designed into multi-tube panels for the Irradiated Fuel Dismantling Facility (IFDF) carbon dioxide cooling circuit of the Dungeness B nuclear power station.

The initial test build was a partial panel containing a total of 116 separator tubes. A dust separation efficiency of 98.5% with AC coarse test dust was achieved, and pressure losses, scavenge flows and flow distributions were found to be satisfactory.[10&11] These excellent partial panel test results gave confidence to proceed quickly to the full scale 264-tube assembly build and test programme.

Plates 1, 2 and 3 show the full assembly, the tubed sub-assembly and the scavenge manifold respectively of one of the large separators for the Dungeness B IFDF. The test programme and the test results[12&13] are discussed below.

The significant performance requirements and areas of technical difficulty were as follows:

(a) Pressure loss of 30 mbar from inlet to main flow outlet, and 42 mbar from inlet to scavenge flow outlet at a design flow of 1.13 kg/s of carbon dioxide.

(b) Dust separation efficiency of 96.5% minimum with AC coarse test dust.

(c) Choice of materials, balancing of scavenge flows and minimisation of dust hold-up.

(a) Pressure Loss

The flow and pressure loss requirements were met by the use of 264 tubes per assembly, based on air tests of single-tube units, calculated conversions to carbon dioxide conditions and calculated housing losses.

Pressure losses through the assembly are predominantly dynamic losses and are governed by the formula:

$$\Delta P = \frac{K\ B\ T\ W^2}{P\ A^2} \tag{1}$$

where
ΔP = pressure loss, mbar
K = constant for given assembly and tube configuration and system of units used in the equation
B = gas constant, J/g°K
P = inlet pressure, mbar absolute
W = mass flow at inlet, kg/s
T = temperature, °K
A = total flow cross-sectional area at vortex tubes, m² (= 264 x 0.000137 = 0.036m²)
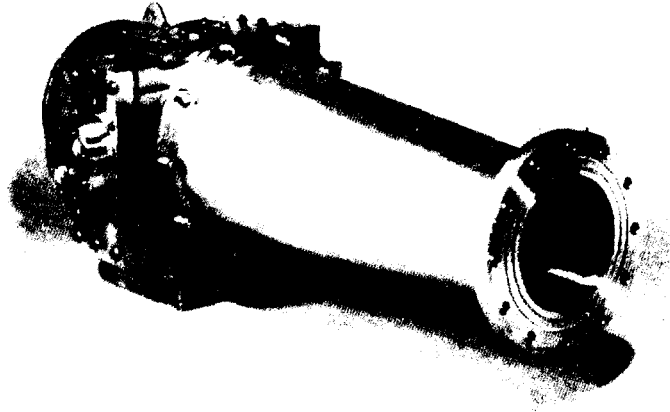
PLATE 1

**264-TUBE CYCLONE SEPARATOR ASSEMBLY
FOR DUNGENESS B IFDF**
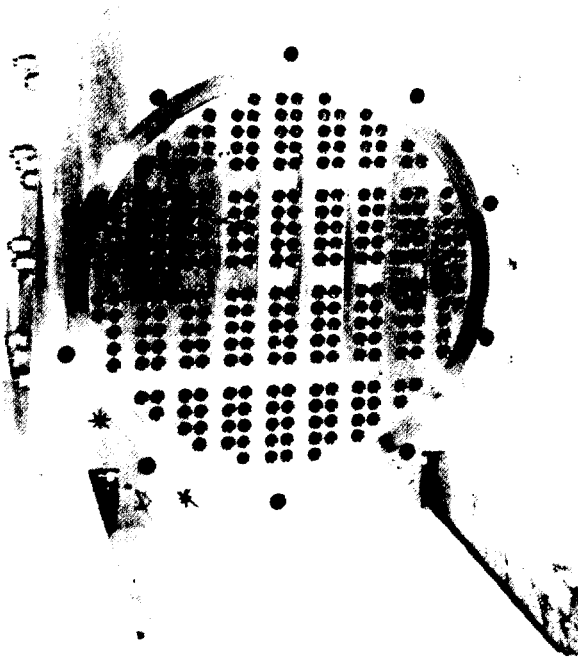
PLATE 2

**264-TUBE PANEL SUB-ASSEMBLY SHOWING
TUBE PATTERN AND BLOCK ARRANGEMENT**
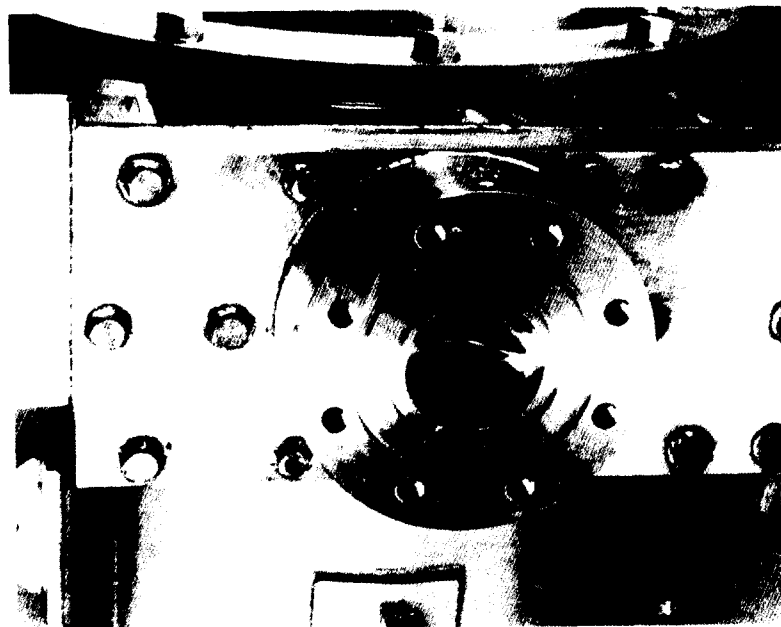
PLATE 3

SCAVENGE MANIFOLD FITTED TO
264-TUBE CYCLONE SEPARATOR ASSEMBLY

As a typical air test on the full 264-tube assembly, test 15 of report reference (12) is considered in the following analysis:

The air test conditions are:-

ΔP	=	21.3 mbar	B	=	0.287 J/g°K
P	=	1034 mbar abs.	W	=	0.810 kg/s
T	=	291.5°K	A	=	0.036 m²

Using Equation (1) and substituting these air test data we obtain a value of constant K = 0.522.

For the installed design condition using carbon dioxide, the known parameters are:-

P	=	997 mbar abs.	W	=	1.13 kg/s
T	=	320 °K	A	=	0.036 m² (264 tubes)
B	=	0.190 J/g°K			

Using Equation (1) and substituting the carbon dioxide data and K = 0.522 the installed pressure loss can be evaluated:-

$$\Delta P \ (CO_2) = 31 \text{ mbar},$$

which is acceptably close to the design aim of 30 mbar.

(b)   Efficiency of Dust Separation

As a check of dust accountability, the dust injected, dust scavenged, main outlet dust and deposited dust are all weighed for each test run or series of test runs. The efficiency of dust separation can be calculated in several ways and the values will differ, depending on the accountability. The two methods used in this analysis are: Efficiency (A) is calculated by comparing the scavenged dust with the dust injected; it assumes that the dust not accounted for passed through the outlet and was not separated, hence is the lower of the two efficiencies: Efficiency (B) is calculated by comparing the dust passing through the main outlet with the dust injected; it assumes that dust not accounted for was separated, and hence is the higher of the two efficiencies.

Dust not accounted for was typically 0.3% to 1% of the dust injected; thus efficiencies (A) and (B) do not normally differ by more than 1%. The test results for the final 264-tube assembly[12&13] using AC coarse test dust were:-

Efficiency (A)	97.7%
Efficiency (B)	98.5%

Both efficiency values exceed the 96.5% specification requirement.

The assembly was tested in both the horizontal and vertically upwards flow directions, to simulate initially proposed and final adopted installation orientations respectively. These tests showed the performance was not affected by installation orientation.

(c)   Materials, Scavenge Balancing and Dust Hold-up

Since these multi-tube panel assemblies are required to operate with minimum maintenance in a radioactive environment at temperatures up to 175°C, stainless steel was chosen as the material of construction. This represented a radical change from the plastic and aluminium alloy construction typically used for aircraft and other industrial applications. The development of this separator system in stainless steel required considerable ingenuity in the design and manufacturing techniques to maintain the performance characteristics and to minimise manufacturing costs.

Areas where particular development effort was required included:-

(a)   The restrictor orifices controlling the scavenge flows from the vortex tubes were sized and toleranced to achieve balanced flows from the two separator stages and good distribution over the tubed panel area.

(b)   The sizing of the annular gap between the vortex tube and the outlet tube was developed to optimise scavenge flow and dust hold-up. The scavenge gas flow passes through this annular gap and flow interactions with the scavenge restrictor are important in determining both scavenge percentage and dust deposition.

(c)   The design of the scavenge gas flow passages was such that constant velocities were maintained and "dead areas" were avoided throughout the panel and scavenge exhaust manifold. The velocities were chosen to minimise dust hold-up without exceeding the pressure loss limit for the system.

(d)   Overall attention was paid to the internal surface finishes and shaping of flow passages to minimise dust retention.

(e)   Each separator assembly includes a long diffuser on the inlet side of the tubed panel, and a radiused contraction on the outlet side; these provide the required interfaces with the system pipework whilst minimising pressure losses, dust deposition and flow distortion.

Performance Summary

The physical characteristics of the 264-tube assembly, the test performance using air, and the calculated carbon dioxide performance are given below:-

Physical characteristics:-

Number of tandem separator tubes per assembly		264
Thickness of panel of tubes	mm	210
Length of assembly (including diffuser and contraction)	mm	1650
Width of assembly	mm	550
Depth of assembly	mm	650
Weight of assembly	kg	600

Test performance using air:-

Inlet flow	m³/hr	2437
Total scavenge flow	m³/hr	415
Outlet (clean) flow	m³/hr	2022
Pressure loss, inlet to outlet	mbar	21
Efficiency of separation of AC coarse test dust calculated by method (B)	%	98.5
Dust hold-up from 8956 g. AC coarse fed	g	162
Dust hold-up as %	%	1.8

Estimated performance with carbon dioxide at 47°C and 997 mbar:

Inlet flow	kg/sec	1.13
Total scavenge flow	kg/sec	0.19
Outlet flow	kg/sec	0.94
Pressure loss, inlet to outlet	mbar	31
Pressure loss, inlet to scavenge outlet	mbar	44
Efficiency of separation of AC coarse test dust calculated by method (B)	%	98.5

Independent Tests

Independent tests were carried out at the British Hydromechanics Research Association (BHRA)[13]. The BHRA test set-up included a large section of the simulated IFDF pipework including the three branches in which three of the 264-tube assemblies were fitted. The tests included flow distribution development between the branches, and flow distortion measurements across the face of the cyclone panel assembly. Separation efficiency and dust hold-up tests were also included in the programme, and all the BHRA results were in close agreement with those presented in this paper.

7. Application of Separator at Dungeness B

Much of the development work already described was undertaken in support of the back fit of axial flow cyclones into the Irradiated Fuel Dismantling Facility (IFDF) coolant system at the Dungeness 'B' power station. Many of the points made above are reflected in the design of this system.

The original IFDF coolant system, shown schematically in Figure 13, was a closed loop through which carbon dioxide circulated to remove heat from the irradiated fuel. The system had two sub-circuits serving different parts of the main facility. Each sub-circuit included a filter system to minimise the spread of radioactive materials within the facility. The radioactive nature of the contaminant and the design of the coolant recirculation system required the clean up device to need little or no maintenance and to have a relatively low and stable flow resistance. The equipment initially installed was stainless steel filters fitted with reverse flow insitu cleaning provisions which failed to satisfy these requirements.

A revised coolant clean up system design has been developed (Figure 14) substituting the unsatisfactory stainless steel filters with scavenged cyclone assemblies. Since the coolant flow through the sub-circuits is unbalanced with approximately a 3:1 ratio between the IFD cell and Break Down Hole flows, a secondary cyclone assembly is included to further concentrate the scavenge debris from the IFD cell circuit, and thereby reduce the total

IFDF   Irradiated Fuel Dismantling Facility
c   Cooler
1   IFDF Cell Filters
2   Break Down Hole Filter
3   IFDF Blowdown Filter
4   IFDF Blowdown Iodine Adsorber
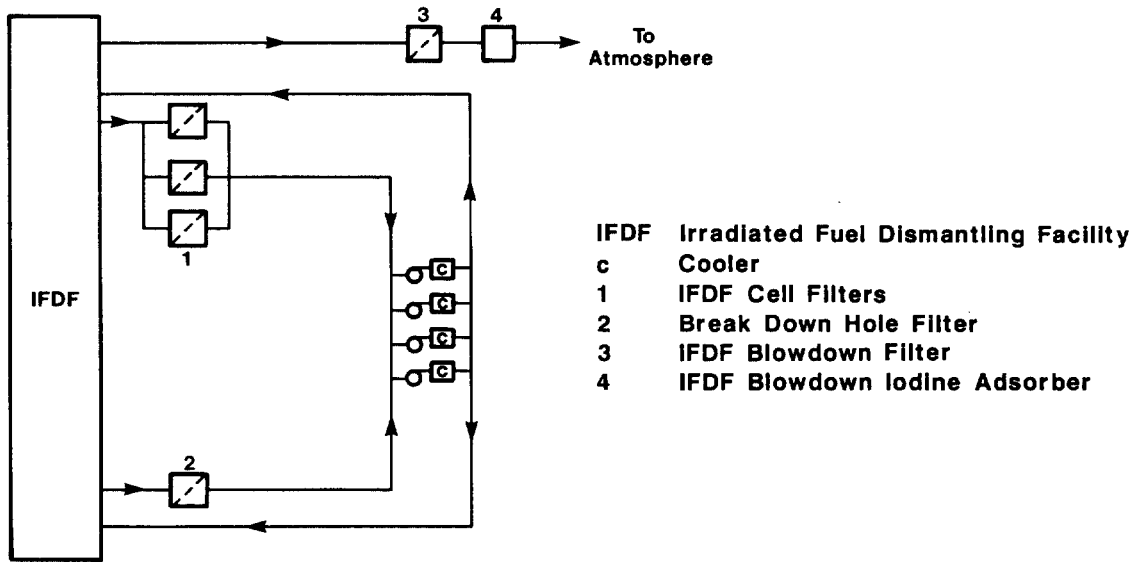
FIG.13 FLOW DIAGRAM SHOWING ORIGINAL DUNGENESS B IRRADIATED FUEL DISMANTLING FACILITY COOLANT CIRCUIT AND FILTERS

IFDF   Irradiated Fuel Dismantling Facility
c   Cooler
1   IFDF Cell Cyclone Units (3)
2   Break Down Hole Cyclone Unit
3   IFDF Cell Scavenge Cyclone Unit
4   IFDF Blowdown Filter
5   IFDF Blowdown Iodine Adsorber
6   Venturi Scrubber
7   Chiller/Drier
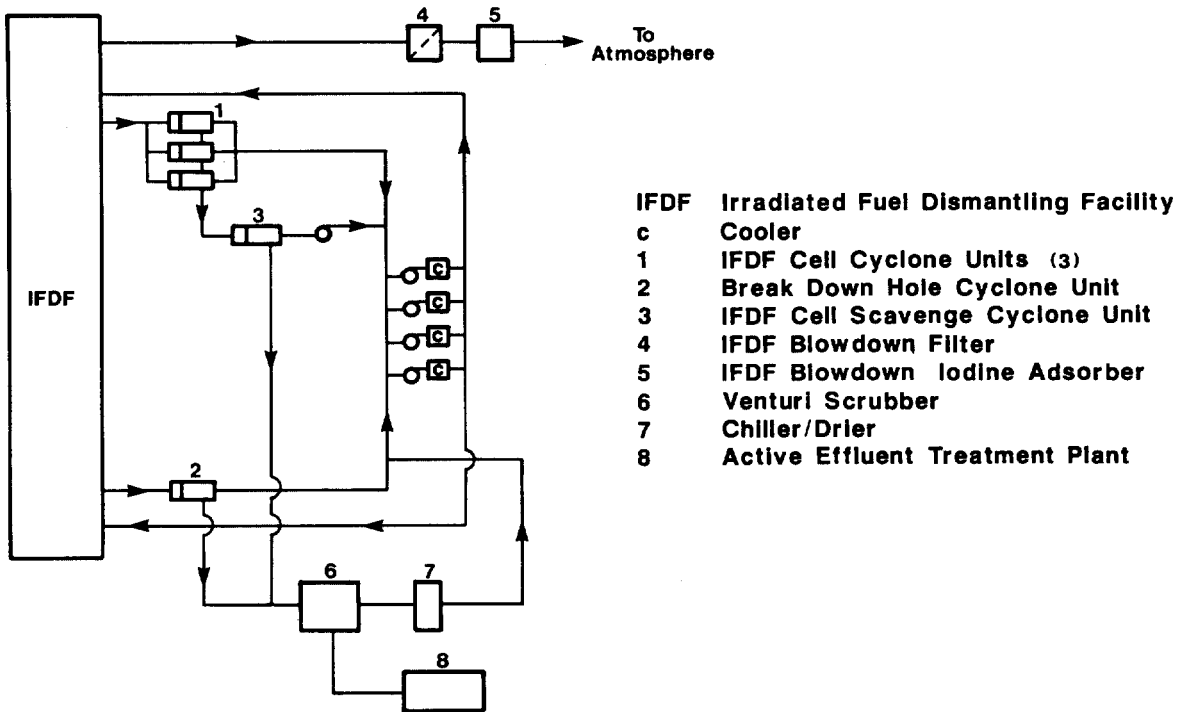8   Active Effluent Treatment Plant

FIG.14 FLOW DIAGRAM SHOWING NEW DUNGENESS B IRRADIATED FUEL DISMANTLING FACILITY COOLANT CIRCUIT, CYCLONES AND AETP

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lume of carbon dioxide requiring clean up. The balance of the
D Cell scavenge flow is returned to the main circuit. The
:avenge flows from the two sub-circuits are combined and routed
to a high efficiency venturi scrubber to transfer the separated
solids from the gaseous to the liquid phase. The venturi scrubber
liquor, containing the radioactive particulate, is treated using
the Power Station Active Effluent Treatment Plant (AETP). The
scrubbed carbon dioxide is dried using chiller plant before being
returned to the main circuit, thereby avoiding any unnecessary
discharge.

The system design has been developed to take advantage of the
characteristics listed in section 3 and is especially appropriate
at Dungeness B as the cyclone hardware is compatible with perfor-
mance and engineering constraints imposed by the existing gas
circuit. The recirculatory nature of the system allowed some
flexibility with respect to separation efficiency and the need for
high pressure driving heads has been confined to the new compo-
nents associated with the scavenge and venturi scrubber systems.
Routine maintenance requirements are confined to conventional
components of the system (fans, valves, pumps) which are located
in lower dose rate areas. Furthermore, the cyclone scheme will
avoid the accumulation of active IFD debris waste on site, which
would otherwise become a problem during decommissioning.

8. Conclusions

(a) The development of the 2-stage tandem model separator
achieved the expected high efficiencies of dust separation
with acceptable pressure losses.
(b) The 264-tube production units achieved a separation effic-
iency of 98.5% with AC coarse test dust.
(c) The pressure losses for the 264 tube units are low, constant
and acceptable for the system; see Performance Summary.
(d) The dust hold-up in the 264 tube panel is low and acceptable;
see Performance Summary.
(e) Based on current estimates of the size of active particulate
in the Dungeness B IFDF, the separators are suitable for its
removal.
(f) The axial-flow cyclone separators are capable of further
development to higher efficiencies of separation.
(g) The separators are suitable for many nuclear gas cleaning
applications, either alone or in conjunction with other
filtration equipment.

Acknowledgement

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2) British patent No. 1207028 filed 11 November 1968 entitled "Tubular vortex separator" by Pall Corporation.

3) British patent No. 1278488 filed 25 June 1969 entitled "Vortex air cleaner assembly having uniform particle removal efficiency throughout the array of air cleaners" by Pall Corporation.

4) British patent No. 1236941 filed 19 June 1968 entitled "Gas cleaner" by Pall Corporation.

5) British patent No. 1310792 filed 19 April 1971 entitled "Vortex separator" by Pall Corporation.

6) British Patent No. 1465915 filed 11 April 1974 entitled "Vortex air cleaner array" by Pall Corporation.

7) Aircraft Porous Media Europe Ltd internal test Report No. 2014 dated 28 February 1978 entitled "Results of type tests carried out on QB0190 single-tube Centrisep assembly for RB-211 Engine".

8) Pall Europe Ltd internal SLS test report No. LIR 20998 dated September 1984 entitled "Performance and dust hold-up testing of 2-stage single-tube Centrisep, DAF 16729".

9) Pall Europe Ltd internal SLS test report No. ETS 1036 dated 20 September 1985 entitled "Vertical flow tests of 2-stage single-tube Centrisep".

10) Pall Europe Ltd internal SLS test report No. ETS 1036 dated 20 September 1985 entitled "Horizontal flow tests of 3-block module assembly".

11) Pall Europe Ltd internal SLS test report No. LIR 27060/CT 1003/IP/1 dated 14 July 1986 entitled "Vertical flow tests of 3-block module assembly".

12) Pall Europe Ltd internal SLS test report No. LIR 27060/CT.1003/IP/2 dated 4 September 1987 entitled "Vertical flow tests of 264-tube module assembly".

13) Arato E G and Clarke A, "Flow investigations of the IFD cell and IFD scavenge cyclone assemblies and efficiency test of a production unit", BHRA report No. RR2867, January (1988).

IMPROVEMENTS OF DECOMMISSIONING GASEOUS WASTE HANDLING BY CLEANING DEVICES

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Abstract

The processes of thermal cutting, because they are efficient, are often recommended and used during nuclear installation dismantling operations. But these processes have the particularity of emitting large amounts of ultrafine aerosols which, if no precautions are taken, quickly clog HEPA filters in the ventilation networks.

This paper pinpoints the problem in its context and presents some of the technical devices that can be considered to limit the impact of these wastes. A few examples are given about the use of decloggable prefilters and their performance for particular applications is outlined.

I. General

The dismantling of nuclear installations implies a stage of disassembly of the structures and of a diversity of equipment. If the materials are radioactive, these structures and equipment have to be packed in containers for subsequent routing to a waste storage area.

Often, to reduce the dimensions of the waste disposal area, cutting operations have to be performed by mechanical tools (saws, grinders, ...) or thermal tools (oxyacetylene, oxy-propane or plasma torches, ...) which are in fact relatively conventional means, but which have the particularity of being used in radioactive environments. In other words, particular attention must be paid to how these cutting tools are used so that the protection of personnel and environment are guaranteed throughout the operations.

One of the problems encountered, in particular in the case of thermal cutting, is the production of metal oxide aerosols which are issued in relatively high concentrations with size distribution which is generally sub-micronic. These ultra fine aerosols are affected little by gravity and are easily conveyed by the extraction ventilation from the cell or the room in which cutting takes place.

One of the most undesirable effects, if no particular precautions are taken, is that the first very high efficiency particulate filtration stage (HEPA) rapidly becomes clogged. Other effects appear, often equally undesirable. These are :

- decreased visibility,

- deposit of aerosols on the tool, on the walls of the cell (windows) and in the ventilation network upstream of the HEPA filters (the deposits are essentially made by brownian diffusion and thermophoresis).

In addition to the previous effects, which do not affect the radioactive character of the aerosols, those related to the transfer of contamination by radionuclides themselves should be added with the accumulation by deposit inducing the gradual increase of the dose rates on the tools, on the walls of the cell, in the ventilation ducts up to the HEPA filters.

To limit the impact of these problems on the surrounding environment, a number of protection techniques may be recommended and that is the subject of this paper.

But before going into detail of the protection techniques that might be considered, let us give a few orders of magnitude on the basis of a typical example in which the nuisances produced by a thermal cutting tool are measured and whose impact upon HEPA filters in a ventilation network is evaluated.

II. Representative Experimentation of HEPA Filters Behavior in the Case of Thermal Cutting

This example, characteristic enough of several configurations, is taken from a study made in cooperation with UKAEA - Windscale, with the collaboration of UKAERE-Harwell within the framework of a contract with the European Communities (1).

Refer to figure 1 which describes the experimental set-up obtained. Essentially, it includes a containment enclosure of approximately 800 m³, ventilated by means of a main extraction network which includes an HEPA filter housing (8 filters in parallel). The extraction rate is around 13,000 m³/hour. A secondary network is mounted in derivation of the first network in order to perform tests which will be described subsequently in chapter 4.

The plate to be cut is put into the containment and positioned in front of the mechanism so that automatic cutting is possible with an oxy-propane torch. Note that the torch can operate with or without the injection of powder. The powder is a mixture of Al-Fe, making it possible to considerably increase the cutting thickness and stainless steel cutting.

If we refer to the increased pressure drop of the HEPA filters of the main circuit for the cutting conditions considered here, it will be found (cf. table 1) that the cutting of stainless steel with the injection of powder causes more particularly fast clogging of these filter elements.

Thus, a dismantling operation carried out under these conditions would require the changing of the 8 HEPA filters each time a cut of 10 to 15 m of steel has been made. Hence, the advantage of finding technical solutions to increase the lifetime of such filters.
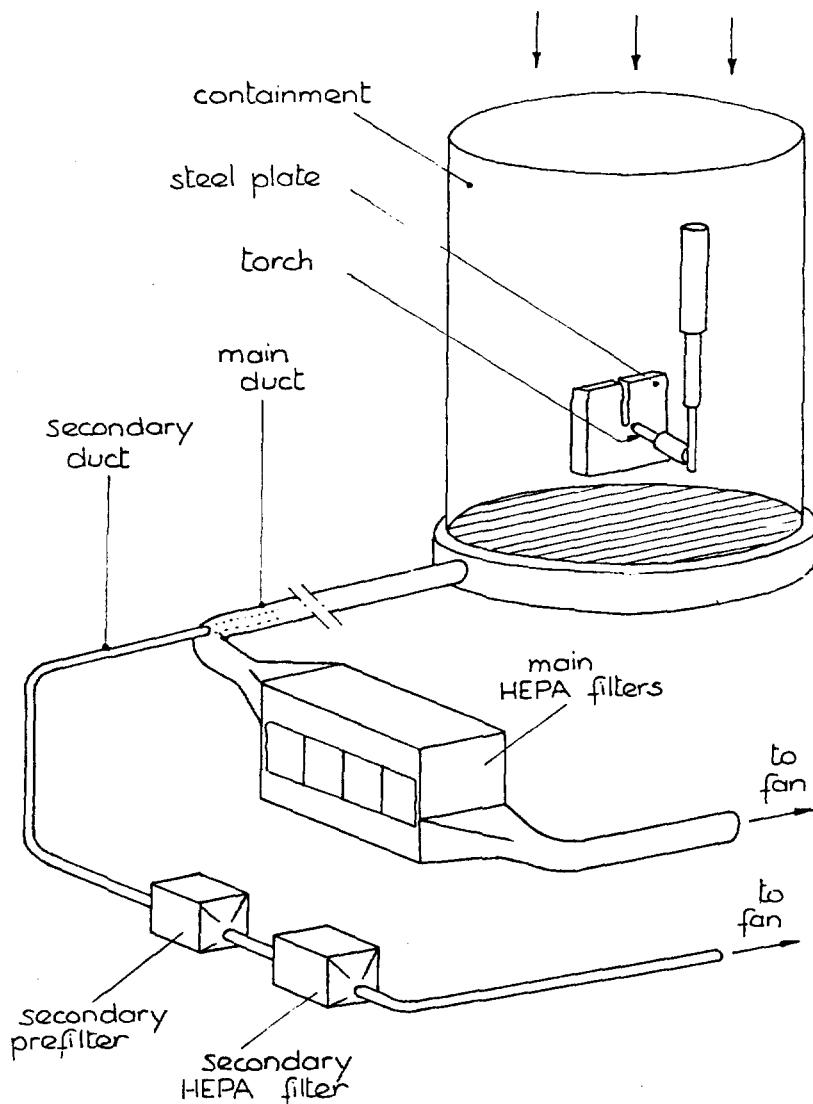
Figure 1
Experimental facility

Table 1. Evolution of HEPA filter pressure drop under
different conditions of cutting with oxy-proprane torch

Test N°	Type of plate to cut	Powder flow (g/min)	Increase pressure drop *HEPA filters for 10 m cut (daPa)
1	Mild steel 80 mm thick	0	13
2	Mild steel 80 mm thick	78.2	63
3	Stainless steel 25 mm thick	92.8	125

III. The Protection Techniques which can be Considered to Improve the Lifetime of HEPA Filters During Cutting Operations

Let us consider figure 2, which represents the most difficult case of thermal cutting in a ventilated cell.
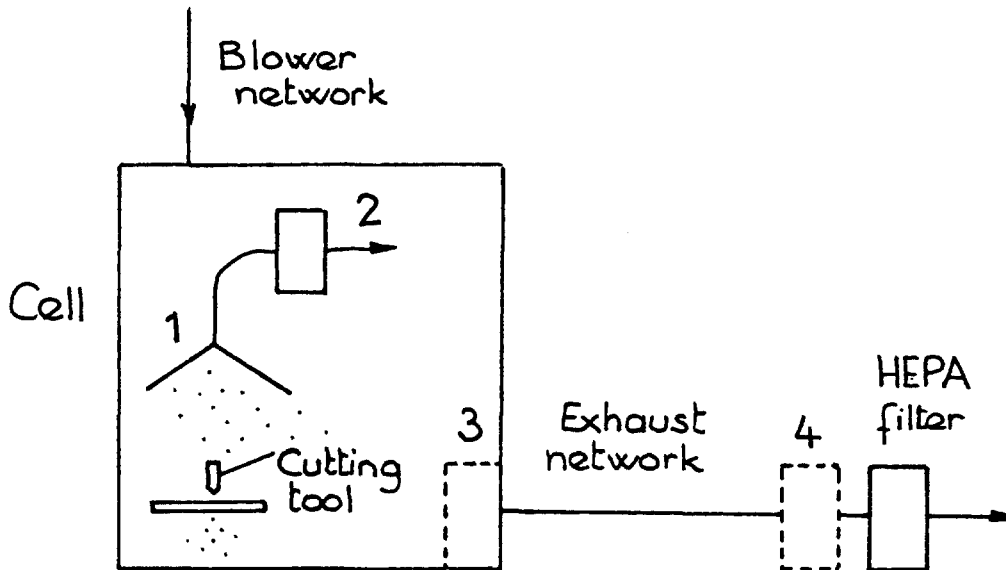
1 : capture at source

2, 3, 4 : prefilters

Figure 2
A few of the protection techniques which may be considered

To limit the effects due to the emission of aerosols, it is possible to schematically consider three levels of protection which will be graded A, B and C. Level A is that where protection is maximum.

. Level A

It is desirable to reduce the dispersion of contamination in the cell where cutting takes place and, all the more so, throughout the general ventilation system up to the HEPA filters. In practice, this corresponds to the implementation of a capture device at the source (1), associated with a secondary ventilation network comprising prefiltration (2) capable of connection or not to the general exhaust ventilation.

. Level B

If capture at the source is impossible, we accept the effects of cell pollution, but the general ventilation exhaust network is protected by the installation of a prefilter (3).

. <u>Level C</u>

The effects of cell pollution and that of the extraction network are accepted, but the HEPA filtration stage is protected by the installation of a prefilter (4).

Table 2 illustrates these different levels of protection and the expected consequences. On this point, the following remarks might be made :

- the protection techniques considered at levels A, B and C may be accumulated to improve the overall protection of the installation,

- the role of ventilation to maintain dynamic containment within the cell where cutting takes place is essential, but has not been dealt with here. We will simply consider the problem by stating that the exhaust flow should be as low as possible so as to avoid the need of overdimensioning the cleaning devices, but must be sufficiently high to satisfy safety needs, imposing the maintenance of dynamic containment, in particular for thermal cutting likely to cause overpressure by overheating the air.

Table 2. Levels of protection and expected consequences
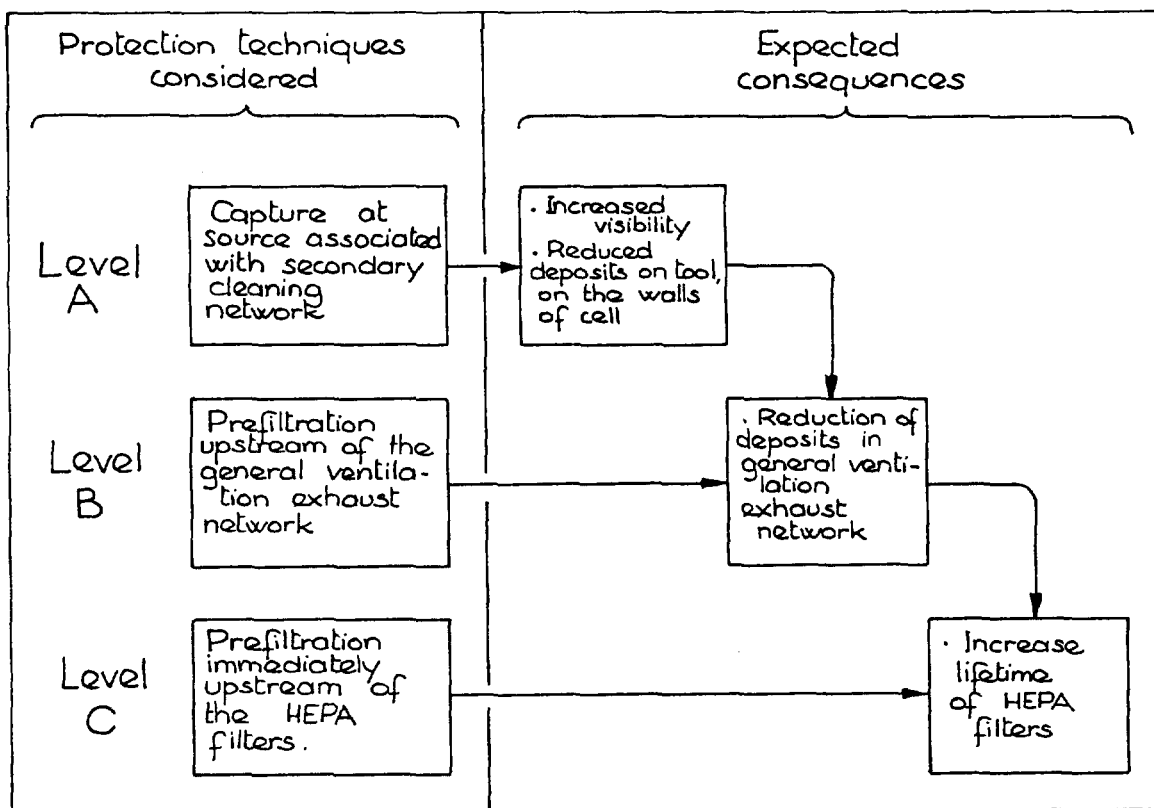
IV. Optimization of Prefiltration During Dismantling Operations

IV.1. General

Note that, for the three levels of protection considered above, there is a question of implementing cleaning devices or prefilters. But, if we consider the most difficult case (sub-micronic dusts in high concentrations), many of the prefilters currently on sale are inapt for this particular use. If, in addition, this cleaning device has to offer good efficiency (more than 90% to increase by a factor of approximately 10 the life of the HEPA filters), a low pressure drop, with compact dimensions, and if, finally it is required to be regenerable by declogging, the choice is even more limited.

Naturally enough, the choice will go to well known techniques like bag filters or electrostatic filters whose behavior should satisfy the criteria announced.

IV.2. Evaluation of comparative performance of electrostatic filters/bag filters during cutting operations

In order to gather together any data regarding efficiency, the increase pressure drop, the possibility of automatically cleaning the chosen prefilters, several series of experiments have been implemented during thermal cutting operations on metal structures.

VI.2.1. Oxy-propane torch cutting with and without powder injection

An experimental set-up was installed on the secondary circuit schematized in figure 1. The results obtained are summed up in table 3 for the electrostatic filter* and in table 4 for the bag filters**. Also, size distributions of the aerosols, measured upstream and downstream of the cleaning systems, have also been plotted.

These measurements were made by a differential mobility particle sizer, manufactured by TSI.

To recapitulate on the basis of these tests and under nominal operating conditions, it would appear that the efficiency of bag filters is always greater than that of electrostatic filters, in particular when the bag filter has already been preclogged.

Conversely, the drawback of the bag filter is a fast increase of the pressure drop, principally because of the submicronic size of the aerosols emitted by thermal cuts. This requires frequent cleaning, for instance by reverse compressed air. This principle has proved to be satisfactory during the experiments described above.

* Nominal flow 800 m³/h

** Nominal flow 500 m³/h

Table 3. Electrostatic precipitator experiments

experim. number	Mass efficiency of the electrostatic precipitator	SIZE DISTRIBUTIONS number concentration versus particle diameter	
		upstream	downstream
1	96,7 %		
2	98,3 %		
3	79,2 % (clogging)		

Table 4. Bag filter experiments

experim. number	Mass efficiency of the bag filter	SIZE DISTRIBUTIONS number concentration versus particle diameter	
		upstream	downstream
1	97,9 % (new bag)		
2	99,95 %		
3	> 99,98 %		

IV.2.2. Other tests

To evaluate the behavior of these prefilters in other situations, a multitude of tests has been undertaken during the thermal cutting operations, by means of the following processes :

- plasma torch in air,
- plasma torch under water,
- arc-air process,
- oxy-acetylene torch.

Finally, the overall behavior of these prefilters can be summed up in the various situations experimented by drawing up a balance as given in table 5.

Table 5. Performance of prefilters with respect to the criteria that apply

Criteria	Behavior of prefilters	
	bag filter	Electrostatic filter
Efficiency	very good > 99%	good > 95%
Pressure drop	Quick increase	very slow increase
Declogging	. Possible by blowing air (pulse or reverse) . Inefficient by mechanical shaking	. Possible by pneumatic vibration of electrodes

Note that, to complete the intercomparison of these devices, the purchase prices are similar enough for the same flow rate to be processed, but that the dimensions are two to three times smaller, to the benefit of the electrostatic filter (typically 0.1 m³ for 1000 m³/h processed).

Finally, although most of the results were obtained by cutting non-radioactive metal parts, some tests were nevertheless carried out actively.

This was the case of cutting underwater with a plasma torch for parts contamined (or activated) by isotopes 137 Cs, 60 Co and 54 Mn, where the characterization of the aerosols emitted and the electrostatic cleaning of these gas wastes were studied specially (2).

During these tests, the decontamination factors measured upstream and downstream of the device, calculated on the basis of activity, were included between 90 and 97%. These efficiency values are of the same order of magnitude as those measured in the inactive experiments.

V. Conclusion

To avoid the dispersion of contamination during cutting operations or during dismantling works, the advantage of capture at the source associated with prefiltration at medium efficiency has been clearly demonstrated. The use of decloggable prefilters (of the bag or electrostatic filter types) indeed reduces the concentration of aerosols upstream of the ventilation networks and of the HEPA filters, thus increasing the life of these filters, limiting the operating costs and reducing the overall volume of produced wastes. However, it is certain that improvements can yet be made to increase the interest of such prefilters, in particular by studying geometries which are even more compact, making it possible to easily install these devices within the cells, or by searching for new cleaning techniques which may offer even better performance.

What is more, although our choice at the present time goes more toward cleaning devices of the electrostatic filter or bag filter types, it must not be limitative. Indeed, tests underway on medium efficiency filter cartridges (of a type similar to the cylindrical pleated HEPA filters), cleaned by air pulse, demonstrate that other technical solutions are also promising. Thus, for dismantling operations, even if a cutting technique is considered as polluting, it must not be dismissed offhand, because sufficiently effective protection techniques can be proposed.

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DISCUSSION

PARTHASARATHY: Did you consider a roll type or a moving curtain type pre-filter?

POURPRIX: That is a good suggestion but, roll type or moving curtain type pre-filter, to my knowledge, require a lot of space and are mechanically elaborate. For dismantling operations, we need and we like compact and not complicated devices, especially to have a minimum of maintenance problems with potentially radioactive materials.

BERGMAN: Do you see a problem with using a pulse cleaning system for a prefilter that may cause radioactive contaminants to escape the ventilation ducts? Also, do you see a problem with sparks from electrostatic precipitators causing a fire?

POURPRIX: It is necessary, of course, to maintain an underpressure in the ventilation ducts, especially during the declogging phase if a pulse cleaning system is used. We have no experimental results on this subject in decommissioning operations, but similar investigations concerning air pulses in ventilation ducts have been solved in a reprocessing plant process. About the second question, the fire risk with electrostatic precipitators is probably negligible in this case because the particles collected are metallic oxides.

SUPPLY AIR FILTERS AFTER THE NUCLEAR REACTOR ACCIDENT AT CHERNOBYL

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Abstract

In the case of increased activity concentration in the air supply air filters are the facility compounds where enhanced activity is collected. Therefore, it was understandable that the people put questions about the doses caused by supply air filters after the nuclear reactor accident at Chernobyl. When comparing the local dose rate at a distance of 1 m in front of filters with the outdoor local dose rate due to dry deposited radionuclides, nearly the same local dose rate results assuming an air flow rate of approx. 60 m^3/h. Supposing a 10 hours stay at a distance of 1 m in front of filters and an air flow rate of approx. 5000 m^3/h the same dose is obtained after a 10 days delay as the dose due to outdoor inhalation. At Aachen, the local dose rate near to filters increased up to approx. 10 μSv/h. After a suitable time delay of one month filters could be rejected like normal waste. A review is given on individual measured values.

I. Introduction

After the Chernobyl nuclear reactor accident the people of the Federal Republic of Germany was confused about the contamination of skin, food and the external radiation exposure. Some people working in clean-air receivers, e.g. in hospitals, feared that the activity which had been deposited on the filters might be transferred. Technicians beeing charged with replacing filters were worried. Frightening impressions were caused by persons generally familiar with the subject when wearing protective suits while first replacing filters after the Chernobyl nuclear reactor accident.

The competent commission of the Federal Republic of Germany, the radiation protection commission of the Federal Minister of the Interiour, now the Federal Minister for the Environment, gave the following statement on May 7th, 1986 concerning the necessity of replacing air filters (1):

'The radiological situation does not demand a replacement of filters for air-conditioning plants etc. If filters have to be replaced for operational reasons, the following procedure is recommended:

The staff is supposed to wear dust masks. The direct contact of the body surface with the filter or the filter dust, respectively, is to be avoided. The filters have to be stored in plastic bags in a place where persons do not stay over a longer period. The final disposal can follow as usual up to now after approx. 2 months. Before having a meal and after finishing the work hands have to be washed and clothing which has been polluted by filter dust has to be taken off.
From the radiation protection point of view air filters of motor vehicles do not need to be replaced. Filters that have been disassembled in the course of usual maintainance can be treated like normal waste.'

II. Activity concentration in the air and aerosol particle size distribution at Aachen after the accident

We analyzed the activity concentration in the air at Aachen, the aerosol particle size distribution, the dry and wet deposition, and the transport of the radionuclides in the animate and inanimate nature in detail. Besides considering the radiation protection aspects we concentrated on acquiring radioecological parameters.

Fig. 1 and 2 show the measured I 131- and Cs 137-activity concentration in the air at ground level at the site of our institute at Aachen (2). The increase of the activity concentration in the air at the different sites of measuring stations in the Federal Republic of Germany can be explained referring to the course of two trajectories with their starting point at Chernobyl on April 27th 86 at 00 UTC and April 27th 86 at 12 UTC at the 850 hPa niveau, that means at approx. 1500 m height (3). Fig. 3 shows the approximate course of several 850 hPa trajectories basing on the weather maps of the German Weather Board (Deutscher Wetterdienst) (1), (3), (4).

Apart from Iodine all radionuclides that could be measured at Aachen were bound to aerosol particles. I 131 was bound to aerosol particles at a rate of approx. 35 %. Approx. 20 % of the total iodine has been elemental iodine (5), (6). The other gammaspectrometrically measurable radionuclides are shown in Tab. 1. The table shows the ratio of the activity of the different radionuclides to the activity of Cs 137 in a filter sample consisting of a membrane and a charcoal filter unit as well as that in a part of the main supply air filter of the clinic of the Aachen University. The composition of the aerosol bound radionuclides was not constant with respect to time as shown in Fig. 4. The last column in Tab. 1 shows the measured time-integrated activity concentration of the most important radionuclides in the air (7).

The aerosol size distribution has been measured with a 6 stage impactor of Sierra-Andersen Inc. (Type 236). Fig. 5 shows the cumulative frequency distribution of the most important aerosol bound radionuclides vs. the aerodynamic particle diameter. The curve has been calculated according to the activity deposited on each stage taking into account the collection efficiency of the individual stages and the wall losses. For comparison purposes the volume distribution function of the aerosol particle spectrum for continental aerosol according to Junge (8) is shown in Fig. 6, too.

III. Activity in the air supply filters at Aachen after the accident

After the activity concentration in the air at ground level at Aachen increased, enhanced local dose rates were measured at all air supply filters operating at higher flow rates. The activity in the filters could be estimated efficiently knowing the time-integrated activity concentration in the air, the flow rate and the penetration rate. The aerosol bound activity deposited could easily be made visible exposing an X-ray film to the filters for one day. A large amount of dark spots could be seen on the developed film similar to those occuring by exposing the film to the radiation due to aerosol particles deposited on vegetation or other surfaces.

Tables 2 to 4 show some measured values of filters of the air supply filter unit of the clinic of Aachen University. The air flow rate is approx. 2500 t/h, i.e. approx. $2 \cdot 10^6$ m^3/h. The air is purified from aerosol particles by prefilters and main filters. The supply air of e.g. the operation theatres is additionally purified with HEPA-filters. The 1056 prefilters, class EU 4, consisting of 16 units provide a filter surface area of 5280 m^2 (8). The air flow rate of each prefilter is approx. 2000 m^3/h. The main filters, class EU 9, are combined into two times 24 banks. 23 of these are constantly operating. Each bank consists of 24 full-sized and 6 half-sized filters or 12 full-sized and 6 half-sized filters, respectively. Each full-sized filter has a filter surface area of 9 m^2 (8). The air flow rate is approx. 2000 m^3/h. The HEPA-filters have a surface area of 4 m^2. The air flow rate is approx. 400 m^3/h (8).

Table 2 shows the measured specific activity of the most important radionuclides in a sample of a prefilter on June 4th 86. For comparison considerations the last column shows the activity in all filters on May 4th 86 basing on the values of June 4th 86. Table 3 shows the data for the main filter related to three samples. The last column again gives the exterpolated values on May 4th 86. Mean values have been calculated from the 3 measured values and are presented in the last line of the table. Table 4 shows the measured activity in a HEPA-filter. No total value for all HEPA-filters is given because the air was only partly purified by HEPA-filters.

As can be seen from the tables, most of the activity was deposited on the main filters. A penetration rate of approx. 92 % for the prefilters as well as a penetration rate of approx. 8 % for the main filters can be derived from the values in Tables 2 and 3.

Table 5 shows the activity in all filters on May 4th 86 calculated using the time-integrated concentration in the air (see table 1) and the air flow rate. 35 % of the I 131 were assumed to be aerosol bound, see Fig. 2. The results are in good agreement with the values given in Tab. 3. The decrease of the activity in the filters with time can be calculated according to the data given in the columns 3 to 5.

IV. Enhancement of the local dose rate due to radionuclides
retained in the air supply filters

The local dose rate near to large filter banks at Aachen increased up to approx. 10 μSv/h due to the radionuclides deposited in the air supply filters. As the increase of the local dose rate was essentially caused by the short-lived radionuclides Ru 103, Te 132/I 132, I 131 and La 140 it descended quickly with time, similar to the outdoor local dose rate at Aachen, see Fig. 7. The local dose rate at a distance of approx. 1.8 m from a vertical main filter bank (6 x 4 1/2 filters) was approx. 3 μSv/h on May 16th 86, see Tab. 3. The flow rate of this filter bank is approx. 55000 m^3/h.

The local dose rate near to different filters can be calculated rather sufficiently by the increase of the outdoor local dose rate due to the dry deposition of radionuclides using the data of the filter units. The calculations show whether precautionary measures are necessary. According to Fig. 7 the specific activity per unit area of the radionuclide r on the ground at the time t_1 is:

$$A_{g,r} = v_d \int_0^{t_1} C_r \exp[-\lambda_r \cdot (t_1 - t)] dt \tag{1}$$

C_r = concentration of the radionuclide r in the air
v_d = deposition velocity
λ_r = radioactive decay constant

Taking into account the dose rate factor for contaminated ground $g_{g,r}$ the local dose rate due to the deposited activity is:

$$\dot{H}_{g,r} = A_{g,r} \cdot g_{g,r} \tag{2}$$

The mean deposition velocity for aerosol bound radionuclides is approx. 0.001 m/s (9).

At the time t_1 the following activity is found in a filter bank with the air flow rate $\dot{V}_f$ and the penetration $\bar{D}$

$$A_{f,r} = \dot{V}_f \cdot (1-\bar{D}) \int_0^{t_1} C_r \exp[-\lambda_r (t_1 - t)] dt \tag{3}$$

Estimating the local dose rate one can consider a point source. This assumption yields sufficiently exact results. More exact solutions considering surface or volume sources are given in (10). According to the former method the local dose rate near to filter units is

$$\dot{H}_{f,r} = \frac{A_{f,r} \cdot \Gamma_r}{x^2} \tag{4}$$

Γ_r : specific gamma ray constant (10), (11)
x : distance from filter

Accordingly, the local dose rate at a distance x in front of a filter is equal to the outdoor local dose rate due to the dry deposition of radionuclides, if the flow rate of the filter unit is

$$\dot{V}_f = \frac{v_d \cdot g_{g,r} \cdot x^2}{(1-\bar{D}) \Gamma_r} \tag{5}$$

Basing on equation (5), and assuming a zero penetration as well as a distance of 1 m, calculated flow rates are given in Tab. 6. Assuming a flow rate of approx. 60 m^3/h, a local dose rate at a distance of 1 m in front of a filter unit results, which is equal to the outdoor local dose rate.

In the case of precipitation the contribution of the wet deposition must not be considered. At Aachen e.g. approx. 250 Bq/m^2 of Cs 137 have been deposited excluding the contribution due to rain and approx. 1750 Bq/m^2 of Cs 137 have been deposited by rain (2), (7). According to Fig. 7 the increase of the local dose rate due to dry deposition was approx. 0.0036 µSv/h on May 16th 86. By this, a local dose rate of approx. 3 µSv/h is achieved at a distance of 1 m in front of a filter bank assuming a flow rate of 55 000 m^3/h. At a distance of 1.8 m a local dose rate of 1.5 µSv/h is calculated assuming a deposition velocity of 0.0007 m/s which has been measured at Aachen after the accident (9). A value of approx. 3 µSv/h (see above) was measured at the rear side of the

filter. At the front side a value of 2 µSv/h was detected. The distance between front side and filter center has not been measured.

With the air flow rate of 60 m^3/h it is possible to evaluate the dose rate due to the deposited activity on motor-vehicle air filters, too. Assuming a rate of revolution of 4000 min^{-1} and a swept volume of 2 l, an air flow rate of 240 m^3/h results. Hardly any motor vehicle ran during all the time when the activity concentration in the air was enhanced. Considering a distance between the filter and the driver of more than 1 m, motor-vehicle filters were obviously of no problem.

In the case of temporary increase of activity concentration in the air equations (1) and (3) can also be used to derive the flow rate at which the specific activity deposited on the filters is equal to the dry deposited specific activity per unit area on the ground. According to

$$\dot{V}_f = \frac{v_d}{(1-\bar{D})} \tag{6}$$

assuming a zero penetration and a deposition velocity of 0.001 m/s, a value of this equivalent flow rate of 3.6 m^3/s is obtained. Applying this result and assuming a dry deposited specific activity of Cs 137 on the ground of 250 Bq/m^2, a Cs 137 activity of 1.4·10^8 Bq should have been deposited in all filters of the clinic. This value is in good agreement with the values for the main filters given in Table 3, see also Table 5.

The outdoor effective inhalation dose of the people allows another evaluation of the doses absorbed when staying near to the charged filters. It is convenient to use the outdoor effective inhalation dose because no distinction has to be made between dry and wet deposition. The outdoor inhalation dose due to the radionuclide r is

$$H_{h,r}^{eff} = \dot{V}_h \cdot g_{h,r}^{eff} \int_0^{t_1} C_r \, dt \tag{7}$$

The inhalation rate $\dot{V}_h$ is approx. 20 m^3/d. $g_{h,r}^{eff}$ is the inhalation dose factor for the calculation of the effective dose (12).·Assuming a short time of increased activity concentration in the air as well as the same dose due to outdoor inhalation and due to the exposure in front of the filters during the time period Δt, the following flow rate of the filters can be derived:

$$\dot{V}_f = \frac{\dot{V}_h \cdot g_{h,r}^{eff} x^2}{(1-\bar{D}) \cdot f_r \exp[-\lambda_r \cdot t_1] \cdot \Delta t} \tag{8}$$

Table 7 gives calculated flow rates for a time of stay $\Delta t = 10$ h and a distance of x = 1 m in front of the filters. After a time delay of $t_1 = 10$ d the mean value is approx. 5000 m^3/h. If, however, after a time delay of 10 days somebody stayed near to the main filters of the clinic of the University of Aachen for 10 h because he was charged with the replacement of filters, this person will have received a dose which is approx. 10 times higher than the dose due to inhalation in the beginning of May 86. The effective inhalation dose of an adult at Aachen was approx. 7 µSv and approx. 13 µSv for children (age 1 a) (7). This value sufficiently corresponds to the above mentioned measured local dose rate considering the radiological decay.

All these data prove that no special precautionary measures had to be taken for replacing filters after the accident at Chernobyl than those conventionally applied. Wearing dust masks was sensible as well as wearing protective gloves. Shortly after the beginning it was sensible to keep the disassembled filters in plastic bags for one month before final disposal in order to lower the dose rate.

V. Final disposal of the filters

Because of the low local dose rate near to the filters they could be deposited like normal waste about one month after the nuclear accident at Chernobyl.The dose received by workers on refuse dumps was negligible. The endangering of the subsoil water is impossible because of the migration velocity of the radionuclides of less than 1 cm/a. Two years after the accident at Chernobyl the activity has not migrated deeper than 4 cm into uncultivated ground.

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Table 1 Measured ratio of the activity of the different radionuclides to the Cs 137 activity on filters and time-integrated activity concentration in the air $\int C_r dt$ at Aachen

nuclide r	half-life	activity ratio $A_r/A_{Cs\ 137}$		$\int C_r dt$ $\left[\frac{Bq\ h}{m^3}\right]$
		membrane and charcoal filter unit May 1st, 6.45 pm to May 2nd, 8.15 am	main supply air filter of clinic May 14th 86	
Mo 99/Tc 99m	66h/6h	0.09	0.014	
Zr 95	64d	0.01	0.014	
Nb 95	35d	0.02	0.02	
Ru 103	39.4d	0.9	1	84
Ru 106	368d	0.2	0.34	22
Ag 110m	250d	0.02	0.03	
Sb 125	2.8a	n.d.	0.05	
Te 129m	33.6d	0.7	1.05	
Te 132	76h	2.4	0.3	180
I 132	2.3h	2.4	0.3	180
I 131	8.02d	4.7 *	0.61**	460 *
Cs 134	2.06a	0.48	0.51	36
Cs 136	13.2d	n.d.	0.07	
Cs 137/Ba 137m	30.2a/2.6m	1	1	72
Ba 140/La 140	12.8d/40.3h	0.9	0.27	30
Ce 141	32.5d	0.007	0.01	
Ce 144	285d	0.003	n.d.	

n.d.: not detected   * total iodine   ** aerosol bound iodine

Table 2 Measured activity on a prefilter (EU 4) of the supply air filters of the clinic at Aachen

sampling time	nuclide	activity at sampling time				activity in all filters on May 4th 1986 [MBq]
		activity per m² filter area [kBq]	specific activity of filter material [Bq/g]	activity per filter [kBq]	activity in all filters [MBq]	
June 4th 86	Ru 103	2.3	12	11	12	20
	I 131	0.8	4.5	4	4.5	60
	Cs 134	1.4	7.5	7	7.5	7.5
	Cs 137	2.8	15	14	15	15

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Table 3   Measured activity of a main filter (EU 9) of the supply air filters of the clinic at Aachen

sampling time	nuclide	activity at sampling time				activity in all filters May 4th 86 [MBq]
		activity per m² filter area [kBq]	specific activity of filter material [Bq/g]	activity per filter [kBq]	activity in all filters [MBq]	
May 14th 86	Ru 103	11	72	97	94	110
	Te 132/I 132	3.0	20	27	26	230
	I 131	6.5	43	59	57	135
	Cs 134	5.3	35	48	46	46
	Cs 137	11	70	95	91	91
May 16th 86	Ru 103	34	212	300	290	360
	Te 132/I 132	7	45	64	62	860
	I 131	16	98	140	135	380
	Cs 134	17	107	150	150	150
	Cs 137	33	205	290	280	280
June 4th 86	Ru 103	11	77	98	95	160
	I 131	1.4	10	13	12	160
	Cs 134	7.7	54	69	67	67
	Cs 137	15	108	140	130	130
mean value	Ru 103					210
	Te 132/I 132					500
	I 131					230
	Cs 134					88
	Cs 137					170

Table 4   Measured activity on a HEPA-filter of the supply air filters of the clinic at Aachen

sampling time	nuclide	activity at sampling time			activity per filter on May 4th 1986 [kBq]
		activity per m² filter area [kBq]	specific activity of filter material [Bq/g]	activity per filter [kBq]	
May 16th 86	Ru 103	0.74	9	3	3.7
	Te 132/I 132	0.11	1.4	0.46	6.4
	I 131	0.41	5	1.7	4.8
	Cs 134	0.4	4.8	1.6	1.6
	Cs 137	0.7	8.4	2.8	2.8

Table 5 Activity in all filters of the clinic at Aachen on May 4th 86 according to the measured time-integrated activity concentration in the air considering an air flow rate of $2 \cdot 10^6$ m³/h

nuclide	activity in all filters on May 4 th 1986 [MBq]	decrease of the activity with time				
		0d	10d	30d	100d	365d
Ru 103	170	1	0.84	0.59	0.17	1.6E-3
Te 132/I 132	360	1	0.11	1.4E-3	3.1E-10	2E-35
I 131	320	1	0.42	0.05	1.7E-4	2E-14
Cs 134	70	1	0.99	0.97	0.91	0.71
Cs 137	140	1	1	1	0.99	0.98
Ba 140/La 140	60	1	0.58	0.2	4.4E-3	2.6E-9

Table 6 Flow rate of supply air filters assuming a local dose rate at a distance of 1 m from a filter bank equal to the outdoor local dose rate due to dry deposited radionuclides

nuclide r	$g_{g,r}$ $\left[\frac{Sv \cdot m^2}{Bq \cdot s}\right]$	r_r $\left[\frac{Sv \cdot m^2}{Bq \cdot h}\right]$	air flow rate $\dot{V}_f$ (equ. (5)) $\left[m^3/h\right]$
Co 60	1.6E-15	3.5E-13	59
Ru 103	4.1E-16	7.6E-14	70
Ag 110m	1.9E-15	4.0E-13	62
Te 132/I 132	1.5E-15	3.4E-13	57
I 131	3.0E-16	5.7E-14	68
Cs 134	1.1E-15	2.4E-13	59
Cs 137	3.8E-16	8.7E-14	57
Ba 140	1.6E-16	3.1E-14	67
La 140	1.4E-15	3.2E-13	57

Table 7 Flow rates of supply air filters as a function of decay time t_1 assuming a local dose rate equal to the outdoor inhalation dose of an adult

distance : 1 m; exposure time: 10 h

nuclide r	$g_{h,r}^{eff}$ $\left[\frac{Sv}{Bq}\right]$	air flow rate $\dot{V}_f$ (equ. (8)) [m³/h]			
		$t_1 = 0d$	10d	30d	100d
Co 60	5.9E-8	1.4E4	1.4E4	1.4E4	1.4E4
Ru 103	2.4E-9	2.6E3	3.1E3	4.5E3	1.5E4
Ag 110m	2.2E-8	4.6E3	4.7E3	5.0E3	6.0E3
Te 132/I 132	2.4E-9	5.9E2	5.2E3	4.2E5	1.8E12
I 131	8.1E-9	1.2E4	2.8E4	1.6E5	6.7E7
Cs 134	1.3E-8	4.5E3	4.5E3	4.6E3	4.9E3
Cs 137	8.6E-9	8.2E3	8.2E3	8.2E3	8.3E3
Ba 140	1.0E-9	2.7E3	4.6E3	1.4E4	6.0E5
La 140	1.3E-9	3.4E2	2.1E4	8.1E7	2.8E20
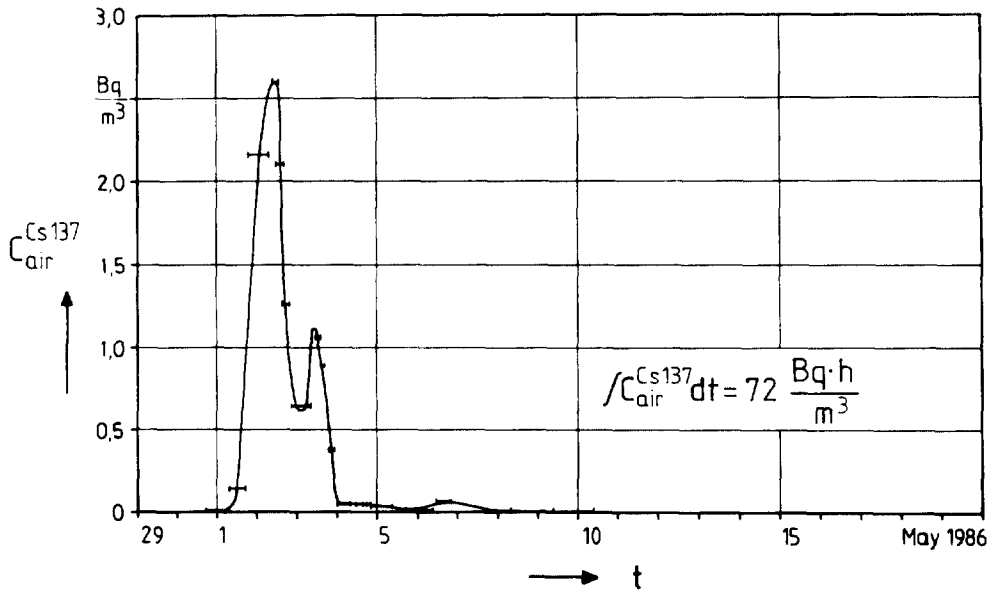
FIGURE 1
CS 137-ACTIVITY CONCENTRATION IN THE AIR AT AACHEN (2)
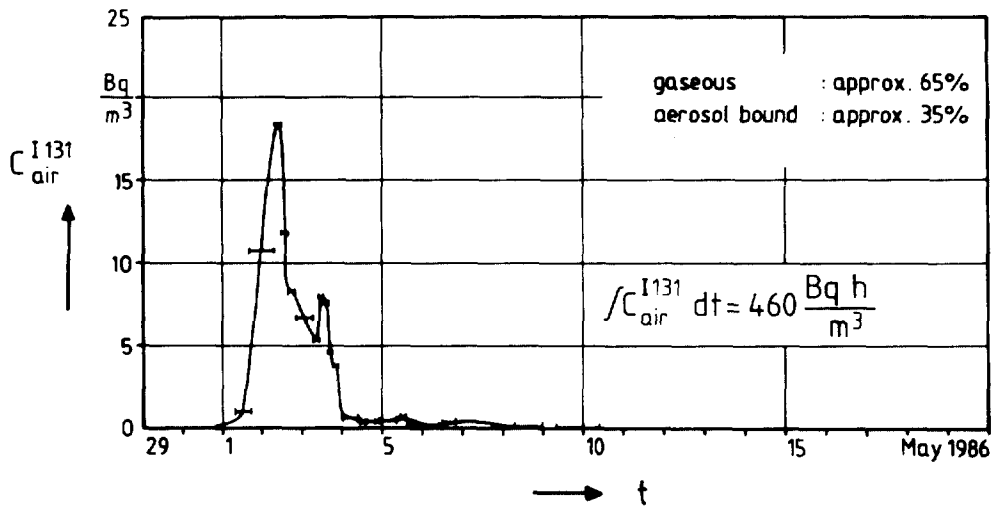
FIGURE 2
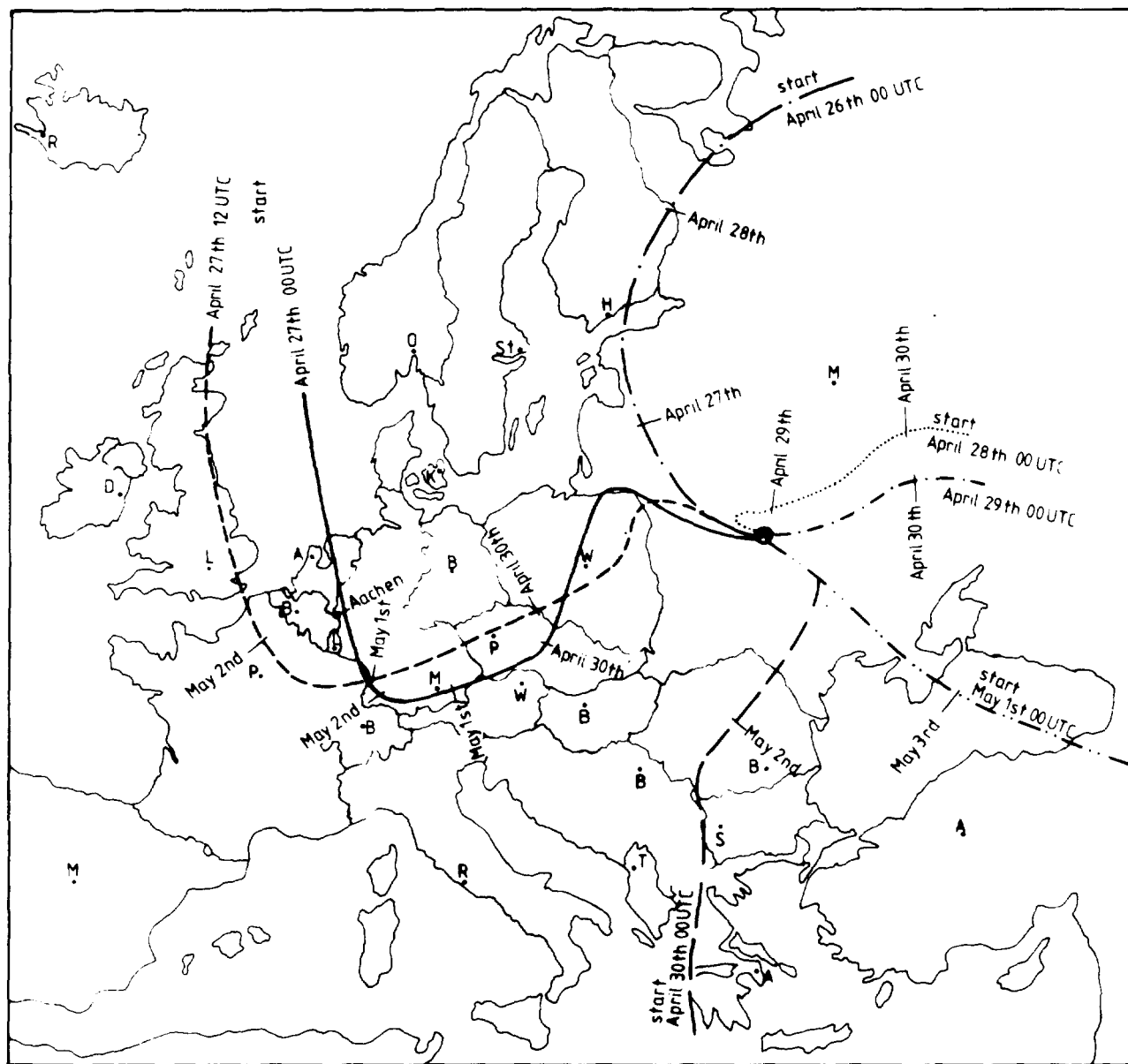I 131-ACTIVITY CONCENTRATION IN THE AIR AT AACHEN (2)

FIGURE 3
APPROXIMATE COURSE OF TRAJECTORIES WITH THEIR STARTING POINT AT CHERNOBYL
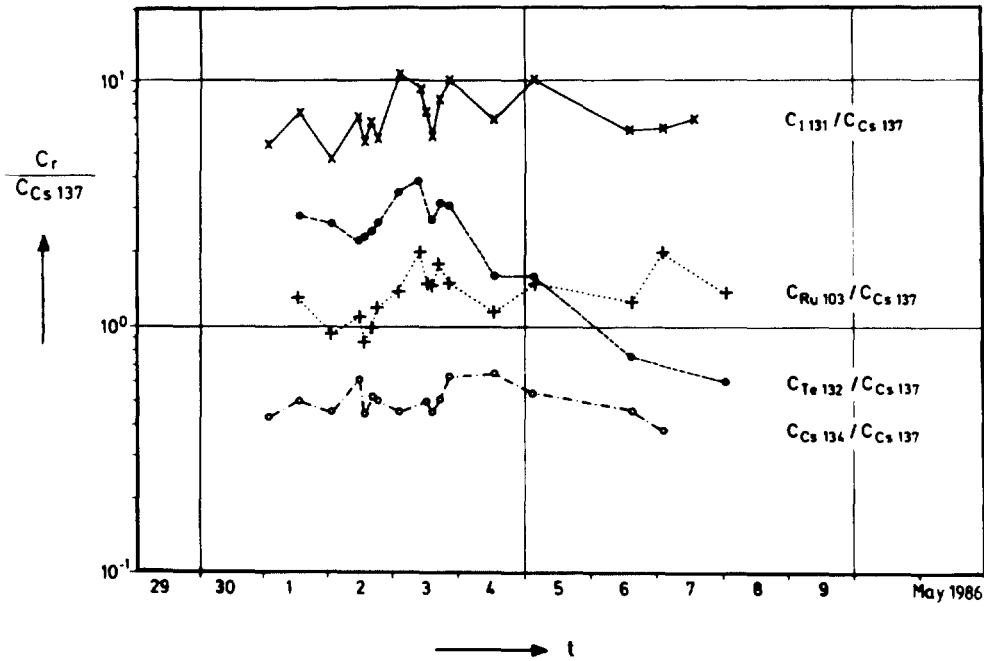AT THE 850 hPa NIVEAU AFTER THE NUCLEAR REACTOR ACCIDENT ON APRIL 26TH 86

FIGURE 4
ACTIVITY CONCENTRATION RATIO OF THE DIFFERENT RADIONUCLIDES TO THE
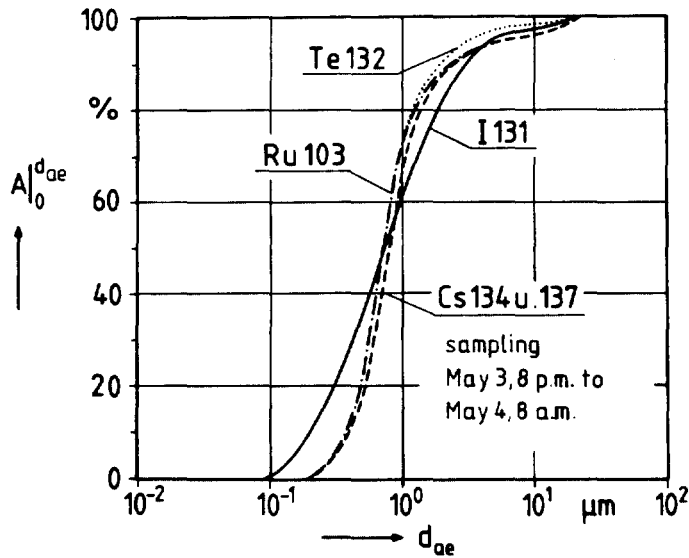CS 137-ACTIVITY CONCENTRATION IN THE AIR AT AACHEN (2)

FIGURE 5
CUMULATIVE FREQUENCY DISTRIBUTION OF THE MEASURED AEROSOL BOUND RADIONUCLIDES
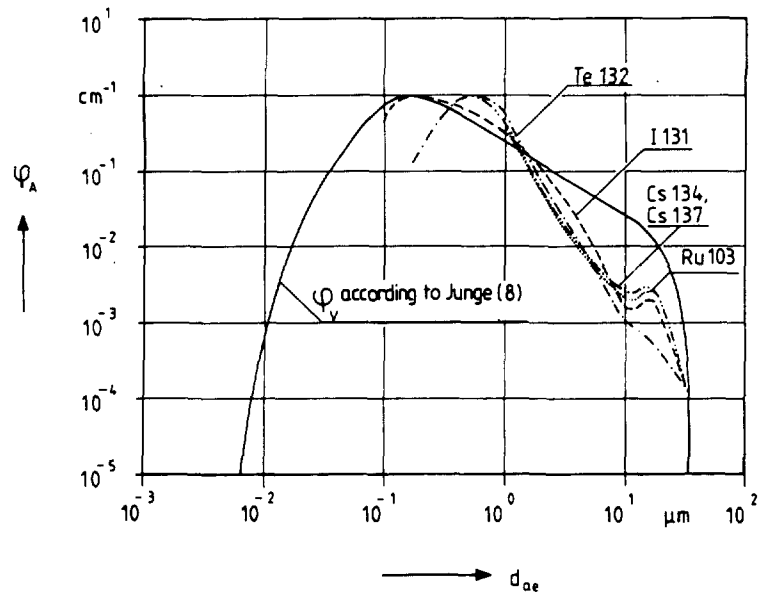VS. THE AERODYNAMIC PARTICLE DIAMETER IN THE AIR AT AACHEN (9)

FIGURE 6
ACTIVITY SIZE DISTRIBUTION (dA/dd_{ae}) OF THE MEASURED AEROSOL BOUND
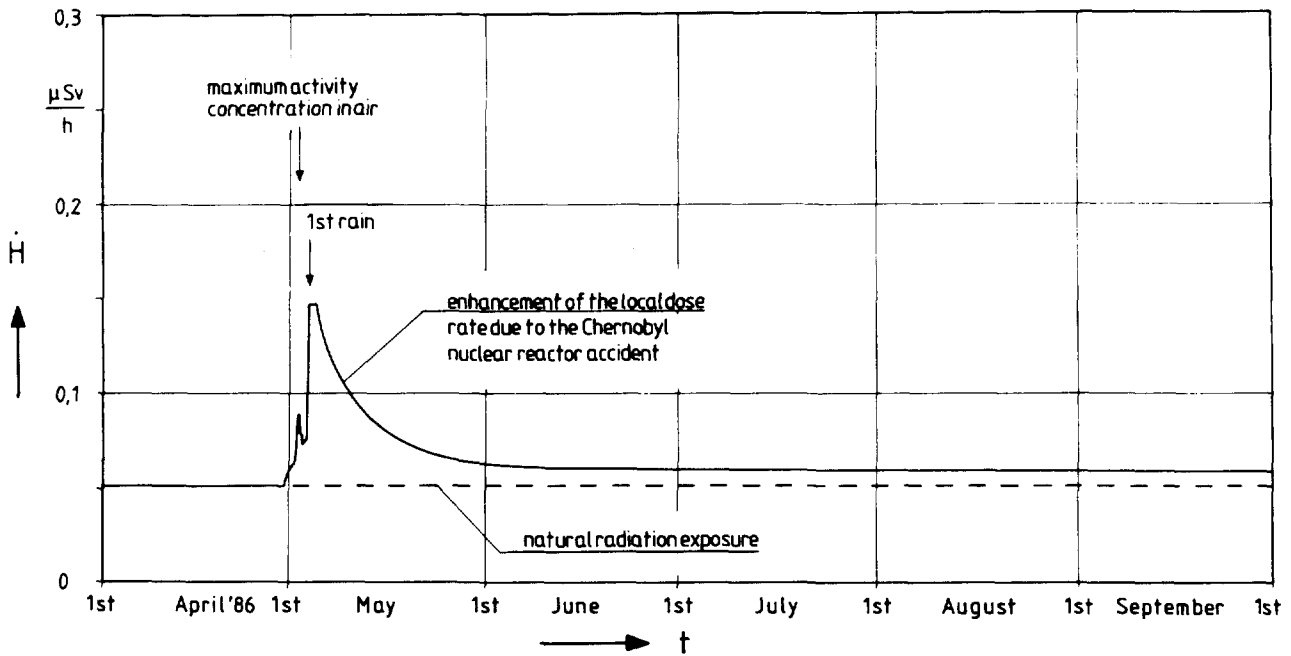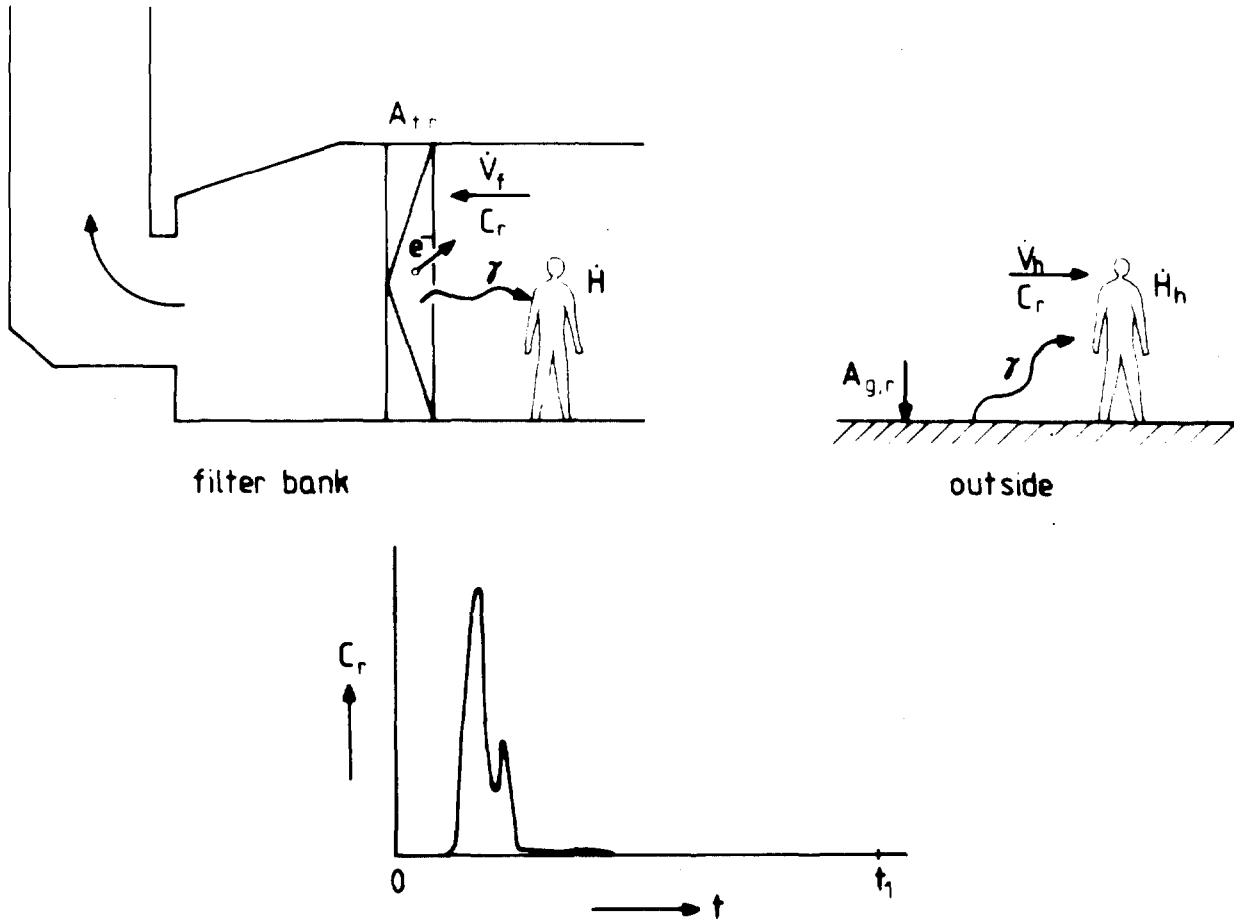RADIONUCLIDES VS. THE AERODYNAMIC DIAMETER IN THE AIR AT AACHEN (9)

FIGURE 7
MEASURED LOCAL DOSE RATE AT AACHEN (2)

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$$A_{f,r} = \dot{V}_f\,(1-\bar{D})\int_0^{t_1} C_r \cdot \exp[-\lambda_r\,(t_1-t)]\,dt$$

$$A_{g,r} = v_d \int_0^{t_1} C_r \cdot \exp[-\lambda_r\,(t_1-t)]\,dt$$

$$A_{h,r} = \dot{V}_h \int_0^{t_1} C_r\,dt$$

FIGURE 8
DEPOSITION OF RADIONUCLIDES ON GROUND AND FILTER BANKS AS WELL AS INHALATION
OF RADIONUCLIDES