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AN "ULTIMATE" CASCADE IMPACTOR FOR AEROSOL ASSESSMENT

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Abstract—A new cascade impactor is described which can sample the entire size range of air-borne particles. At 5 l/min the cut-off values of the eight stages are 30, 16, 8, 4, 2, 1, 0·5 μm with a final filter of selected efficiency. A single door gives immediate access to all sampling slides. Internal wall losses are negligible at all stages. The reasons for preferring slot jets to single or multiple circular jets are discussed.

1. INTRODUCTION

Cascade impactors are devices which classify aerosol samples into known size ranges by drawing the aerosol through a cascade of progressively finer nozzles. The air jets from these impact on plane sampling surfaces and each stage collects finer particles than its predecessor. The samples may be analysed under the microscope or by any method which may be suitable for estimating the mass of material on each stage. The latter process is attractive because an adequate approximation to the mass distribution curve may be drawn from the mass data, without the tedium of using the microscope, and the particles are classified according to their "aerodynamic size" to which the instrument is calibrated and which is nearly always the parameter of interest in aerosol assessment. This is the diameter of the sphere of unit density which has the same impaction characteristics as the particle. Several papers have appeared in recent years on methods of deriving size distributions from stage mass data and are separately listed in the references. At the time of writing it is not known which is to be preferred and the subject will not be pursued in this paper.

Apart from analysis methods, about twenty different designs of cascade impactor have been described since that in the original paper (May, 1945). This was a four stage system of simple construction, light weight and small frontal area which could be freely suspended on a gantry for field use. A tail vane directed the intake orifice into the wind to give an approximation to isokinetic sampling, so minimizing intake losses. (About 25% of 20–50μm diameter droplets fail to be sampled on the first stage in open air winds). For its designed purpose it does not seem to have been bettered and its withdrawal from manufacture by C. F. Casella & Co Ltd. in 1958 in favour of a design more suited to mass production but clumsier in use has been a matter of frequently expressed regret.

Most subsequent designs have more stages than the original (up to 10), are robustly built, are not intended for wind direction orientation, have poor intake efficiency or high internal losses for large particles and have to be dismantled completely to gain access to sampling surfaces. The justification for the additional design presented here is that it covers the total size range of aersol particles with extremely small internal losses and offers quick and easy access to all sampling surfaces. It does not compete with the 1945 model for use in open air winds.

2. DESIGN CONSIDERATIONS

Sampling surface

There is no doubt that the standard 3 × 1 in. microscope slide is superior to all other forms or materials on which to deposit samples in respect of ease of handling, examination or washing off of specimens, cleaning and availability. It was therefore decided to use standard slides throughout, except of course in the final filter. The only problem with slides is that the thickness is not standardized so that slides have to be selected to suit the clearances in the present instrument.

Reason for choice of slot jets

Systems currently in use are of three main types (a) single circular jet at each stage (e.g. Brink, 1958; Mitchell and Pilcher, 1959; May, 1966; Mercer *et al.*, 1970; Burkholz, 1973). (b) Multiple circular jets at each stage (e.g. Andersen, 1966; Cohen and Montan, 1967; Carson and Paulus, 1974). (c) Single slot jets at each stage (e.g. May, 1945; Mammarella, 1966; Lundgren, 1967; Jaenicke, 1971). Each system has its advantages and disadvantages. It has been pointed out (May, 1975) that a major advantage of a multi-hole aystem of N holes per stage over a single hole system is that the Reynolds' number (Re) of the flow through each hole is proportional to $N^{-2/3}$, the jet velocity to $N^{-1/3}$, the pressure drop across the stage to $N^{-2/3}$ and the total area available for impaction of particles to $N^{1/3}$. Hence by making N as large as possible consonant with practicality, the desirable result is that halo formation, impact velocity and blow-off, leakage, pump requirements and particle overloading are all reduced.

Similarly for a slot jet of length L, Re is proportional to L^{-1}, jet velocity to $L^{-1/2}$, pressure fall to L^{-1}, impaction area to $L^{1/2}$ (for a given flow rate and impaction efficiency) so that L should be as large as is practical. A further reason for using maximum L is that errors from end effects are minimized. The ribbon deposits from slot jets are very convenient for microscope examination and counting whereas it is difficult to obtain a representative fraction of a circular deposit.

In the present instrument it was particularly desired that wall losses for larger particles should be small so that an accurate sample of the upper end of coarse aerosols could be obtained. No way could be seen of achieving this with single or multiple round holes but wall losses can be reduced to a negligible amount by using slot jets and making the sampling slide itself act as one wall of the next jet in the first and second stages. Wall losses become less of a problem with particles smaller than say 8 μm dia. (free fall velocity $< 0{\cdot}2$ cm/sec) so that a 180° turn in the air passages between jets is acceptable. Having started with slot jets it seemed logical to continue with them throughout the impactor, though it is possible that multiple holes might be preferable for the final three stages. However it would be necessary to have at least 100 holes down to 0·18 mm to match the chosen slots in respect of air velocity, total area, etc. and drilling these accurately is certainly more costly and difficult than the simple method of accurately machining fine slots described below.

Number of stages

Probably the best series of cut-off (d_{50}) values for the stages is that chosen by Mitchell and Pilcher (1959) in which d_{50} decreased by a factor of 2 for each stage. This gives a clear size differentiation from stage to stage with little overlap and permits a wide size coverage by relatively few stages. In the present instrument the objective was to produce d_{50} values of 32, 16, 8, 4, 2, 1 and 0·5 μm for seven impaction stages. Although it is possible in theory to differentiate particles considerably smaller than 0·5 μm by decreasing jet dimensions and increasing the velocity up to that of sound the appearance of high velocity impact areas is chaotic under the microscope (except for ideal particles in otherwise perfectly clean air) so that visual analysis is usually impossible or of very doubtful value. The final stage is therefore a filter which may be used if required and can accommodate membrane or other filter material. The instrument will therefore cover the entire range of airborne particles, down to the penetration point of the filter.

3. DESCRIPTION OF INSTRUMENT

A vertical section normal to the long dimension of the slots is shown in Fig. 1 while Figs. 2 and 3 show photographs of the assembled and disassembled instrument.

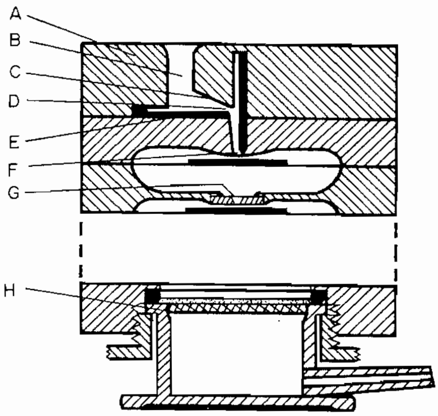


Fig. 1. Vertical section through impactor normal to the long dimension of the slots.

With the access door open as shown in Fig. 2 the ends of all seven slides are conveniently exposed for withdrawal and replacement, a process which takes only a few seconds. This door is held tightly shut by a single clip and seals off all the exposed faces of the impactor by means of its internal facing of 5 mm foam neoprene. Then, when air is drawn through the final filter, it is obliged to pass through all the stages in series (To preserve the resilience of the neoprene the door should never be left shut when not in use).

The first two stages, for capturing coarse particles, are embodied in the top block (A) in Fig. 1. For convenience in the prototype this was made in Perspex. The intake orifice (B) is a slot 7 × 50 mm with 3 mm radius outer lips. The internal walls are parallel and one side projects down very close to the first sampling slide (E) so that the whole of the air stream is forced to turn through 90° to the second jet (D). Thus one boundary of the air-channel between the first and second stages is the first slide itself. The upper boundary is the roof (C) which converges to encourage streamline flow and to form the jet (D). Particles are not deposited on the roof, partly because gravity keeps them away (the instrument is always operated in the vertical position) and partly because the impaction process on the first stage concentrates the escaping particles very close to the slide surface (May, 1975).

Leading to the third jet (F), the side of slide 2 again forms one side of the air channel. Particles are inertially impelled away from the other side of the channel after making the 90° turn at jet 2, which again avoids wall loss. The third impaction stage is a conventional bifurcating flow, after which the air stream is deflected through 180° before entering the next jet (G) by the rounded internal air channel. This has generous dimensions to reduce air velocities. The system repeats as far as the seventh stage, all the rectangular stage blocks being identical except for the jet dimension and the clearances between the underside of the jet and the upper surface of the slide. The lowest block into which the 8th stage filter holder (H) is screwed is of identical external dimensions to the others. Before the filter assembly is finally screwed tightly into place the suction connector tube can be rotated to the most convenient position in respect to the body of the instrument as a whole.

All the stage blocks are held together by the four corner tie rods which can be seen in Fig. 2 and are tightened up by the wing nuts at the bottom. To assemble the instrument after dismantling for cleaning, etc. (which is rarely necessary) each stage block is scrupulously cleaned and the flat mating faces are given a very thin film of grease. The tie rods are then passed through the corner holes, one of them acting as the door hinge also and the wing nuts lightly tightened. A check and adjustment if necessary is then made to ensure that the side of the assembled block, against which the door mates, is quite flat. The wing nuts are then done up tightly. While the assembly cannot be claimed to be vacuum tight a good seal is in fact obtained provided that the mating faces were perfectly clean before assembly. Any inward leaks are then entirely negligible in relation to the total throughput. The overall pressure fall across the stages, excluding the filter, is about 25 cm water gauge at 5 l/min, most of which is across the 7th stage.

When an aerosol passing through a tube is to be sampled an adaptor may be bolted on the upper block, to cover the intake slot. This smoothly fairs the intake opening to a 25 mm circular tube at its apex.

4. MACHINE DETAILS

The upper block (A), Fig. 1 was machined from a piece of perspex 20 mm thick and 82 × 76 mm. The entrance orifice (B), 50 mm × 7 mm, (parallel to the long sides of the block) was first milled from this followed by the sloping ceiling (E) to the channel leading to the second jet. The channel is 50 mm × 10 mm and the ceiling height starts at 6 mm from the first slide and ends at 1·1 mm distant from it to form the second jet. The slot for the second slide was cut right through the block with a circular slotting cutter. To avoid smearing any adhesive or detection preparation on the slides, all blocks are recessed on the jet side of the slides to a depth of 0·5 mm, the recesses having a width of 22 mm. These recesses were next cut in the upper block, using the slotting cutter for stage 2 and an end mill for stage 1. Finally the back of the upper block was sealed off by cementing in place a piece of perspex, 6 mm thick, 20 mm wide and 82 mm long, to make the final block 82 mm square to match all the succeeding ones.

The seven blocks which form the remaining stages were all cut from accurately flat duralumin sheet 12·7 mm thick, the external dimensions being 82 × 82 mm. The air channels and slide slots were milled out, though as stages 3–7 are basically identical simple forms they would be very suited to casting.

The third slot-jet (F) was cut into stage 3 by a fine end and side cutter. This slot has to be accurately located with respect to that in the upper block to form one continuous slot to hold the second slide.

The remaining slot jets are accurately formed by machining as indicated in Fig. 4. Two metal strips of brass or stainless steel 60 × 6 × 1·5 mm (these are convenient, not mandatory dimensions) are clamped side by side by side in a precision milling machine and a light cut is taken along the top of the strips to make them accurately level and flat. The recess to form the slot is then cut to half of the slot width and the entrance side of the slot is chamfered off as indicated, leaving a level portion of about 0·5 mm. The pieces are then removed, the flat unrecessed ends (A) are lightly tinned and the two faces (A) are forced together and heated to solder up. For the narrowest jets it may be preferable to cut one strip only to the full width of the slot. The jet plates may then be fixed in place in the stage blocks by epoxy resin or other suitable means. Finally each stage block is placed in the milling machine with the underside of these jet plates uppermost and lands at each corner of the slide, to maintain the clearance between slide and jet, are milled off to the required height.

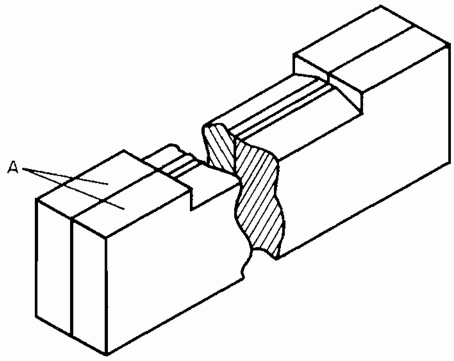
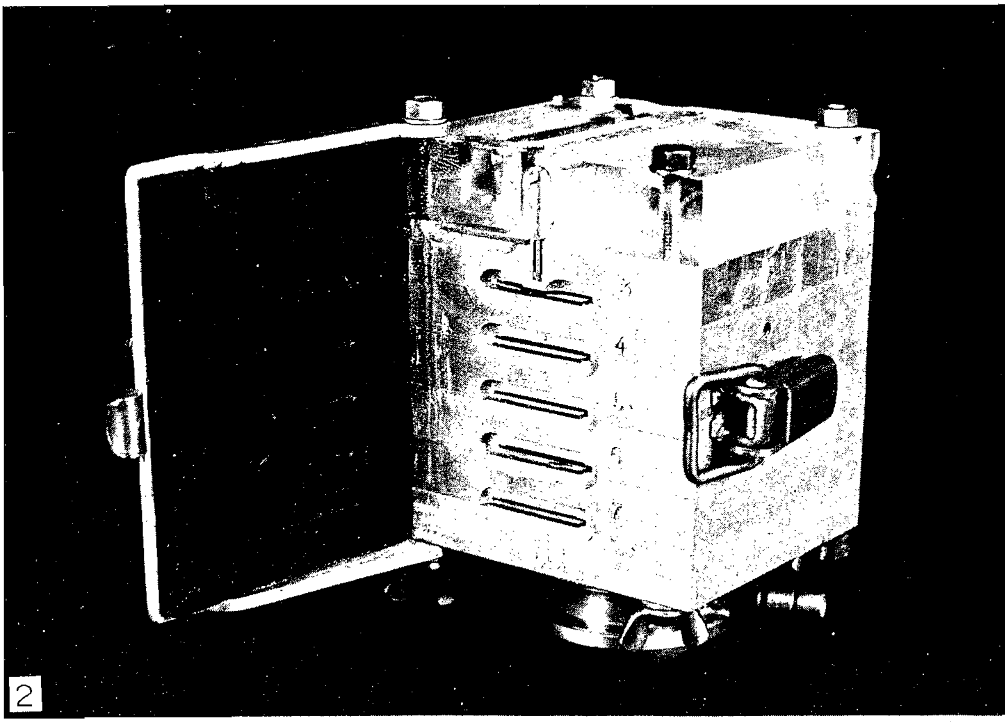


Fig. 4. Isometric sketch, not to scale, to explain the machining process for the slot jets.



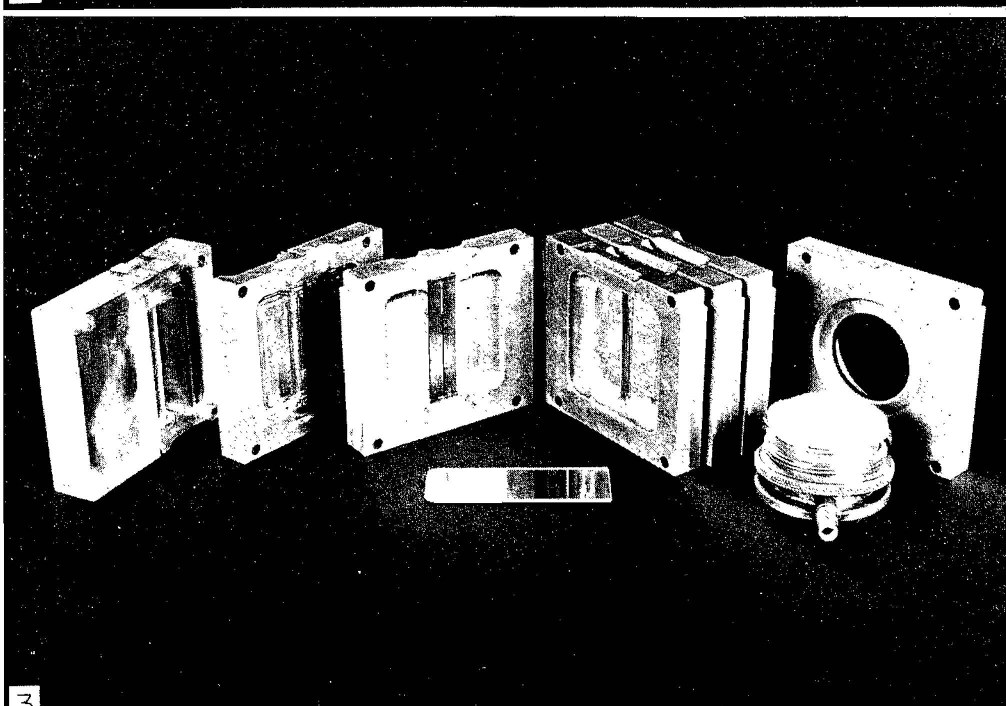


Fig. 2. Photograph of the complete instrument with door open to show access to the seven slides.

Fig. 3. The seven stage blocks disassembled to show slot jets and the final filter holder.

Table 1. Slot dimensions

Stage	Length L, mm	Width e, mm	Clearance, jet to slide, mm*
1	50	7	6
2	50	1·1	1
3	50	0·96	1
4	50	0·52	0·5
5	50	0·26	0·5
6	50	0·137	0·5
7	14·2	0·137	0·5

* Figures approximate because of small variations in slide thickness. Nominal slide thickness 1·25 mm.

The jet plate is given a skimming cut if necessary. Sharp edges and corners, on which slides might snag while being inserted, are rounded off. Similarly the corners of the glass slides should be rounded off (using a carborundum/water slurry) so that there are no sharp corners of glass within the instrument from which fragments might break off.

Clearances between the underside of the jet and the glass slide are given in Table 1. The construction of the holder for the 47 mm filter in the base will be clear from Fig. 1. The instrument stands on this filter holder, but the four tie rods may be extended downwards if preferred to form a leg at each corner.

5. CALIBRATION

Consideration of dimensions required to give a 50% cut in the region of 32 μm, as was desired for the top stage, showed that the sampling rate would have to be quite low, if slot dimensions were to be compatible with the standard microscope slide. The standard rate was therefore set at 5 l/min. It was soon found that the geometry chosen for the first three stages as shown in Fig. 1 was not amenable to the usual calculations for the efficiency of impaction of slot jets. In stage 1 this is because, at the essentially low air velocity obtaining, gravitational settlement plays a major part in determining the particle collection of the first slide. The centrifugal force of the 90° turn under the entrance slot is in the region of $1 \times g$ only and gravity acts along the remaining half of the slide before reaching the second jet. For this reason the instrument should always be operated in the vertical position. In jet 2 the particles are concentrated along the lower side so that a relatively thin film of aerosol has to penetrate most of the thickness of the air jet before striking the slide. This together with the single 90° turn demands a relatively narrow jet and high jet velocity but gives a fairly sharp cut-off. A rather similar situation prevails in stage 3 except that the post-impact flow bifurcates. The dimensions of the top three slots therefore had to be adjusted by trial and error after their original estimated settings. The remaining jet sizes were originally based on the recent experimental work of May (1975) who presented the simplified expression for the 50% cut-off diameter,

$$d_{50} = 75\, l\,(L/FC)^{1/2},$$

where L, l are the slot dimensions; F, the flow rate, l/min and C the Cunningham slip correction. In the present work however the value of the constant factor was found to be 80–85, the difference perhaps being due to the high value of L/l and the fairly high jet to slide clearances.

Calibration was performed with the fluorescent droplets of dioctyl sebacate as described by May (1975) for particles down to 3 μm and below this with highly monodisperse polystyrene latex spheres (prepared in bulk by Dr. M. C. Wilkinson, CDE, Porton).

Stage characteristics. The percentage retention E of unit density spheres with respect to diameter for each stage for a sampling rate of 5 l/min is given in Fig. 5, the slot dimensions being those in Table 1. Calibration was also performed at 20 l/min, at which rate the cut-off (d_{50}) values for each stage should be halved. This was found

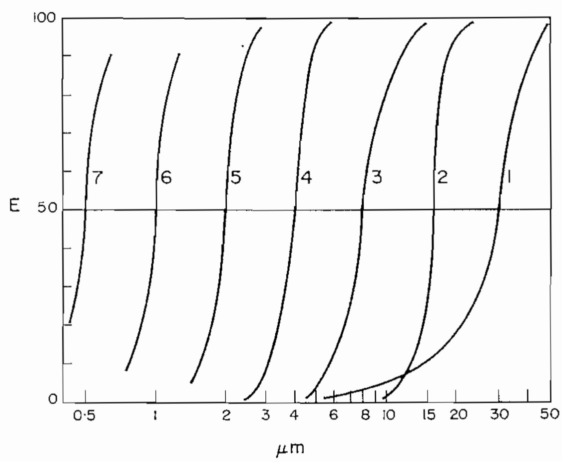


Fig. 5. Particle retention efficiency E, for each stage vs unit density sphere dia.

to be so, except for the first stage where the d_{50} was reduced from 30 μm at 5 l/min to 20 μm at 20 l/min. The seventh stage however was not calibrated because the sonic velocity obtaining here at 20 l/min gave blow-off and halo problems and other experimental difficulties in assay which could not be overcome in the limited time available. At 20 l/min it is probably better not to insert the 7th slide, so collecting the smallest particles on the filter.

Intake losses. Because of the very low air velocity into the intake slot and of its geometry, the sampling efficiency of the device for large particles is very poor in a crosswind so that as far as possible the device should be used in still air if large particles are to be assessed. The deposit on the first slide will represent "fall-out" particles (at 5 l/min) rather than true airborne particles. When the intake adaptor cone is used to withdraw aerosol from a pipe, etc. some loss inside the cone can be expected because of turbulence and this may need separate assessment, according to the circumstances.

Sharpness of cut-off. The ideal of a step-function cut-off for each stage can never be achieved with an aerosol-filled impaction jet, but the steeper the cut-off curve the better is the aerosol size distribution assessment. May (1975) shows that when the sharpness of cut-off of a given impaction system is defined as the ratio of particle sizes having efficiencies of impaction of 90% and 10% (i.e. d_{90}/d_{10}), the values for slot jets in recent publications vary from 2·4 to 1·14, his own value in carefully controlled laboratory conditions being 1·29. In Fig. 5 the values of d_{90}/d_{10} for the first six stages are 2·8, 1·4, 2·3, 1·5, 1·5, 1·5 respectively. The first stage is the least good because of the large effect of gravity. The third stage is also relatively poor in cut-off characteristics for reasons which are not clear but must be some consequence of bifurcating flow from non-uniform concentration in the slot. The overall picture from Fig. 5 is good with little size overlap between the top and bottom of adjoining curves. An effect of gravitational fall-out on the first slide is that the Stage 1 curve intersects the stage 2 curve at the bottom, so that at 10 μm for example there are more particles on stage 1 than stage 2. The quantities involved however are small relative to the whole sample. When the sampling rate is increased to 20 l/min, curves 1 and 2 do not intersect (because the gravity effect is relatively less at the higher velocities obtaining) and the d_{90}/d_{10} ratios for the first three stages were found to be 2·0, 1·5, 1·7 respectively.

Internal losses. Droplets over a wide size range were sampled so that a heavy deposit was obtained on each slide. Each was assessed and the instrument was disassembled as in Fig. 4 so that all internal airways could be washed off for assessment. All parts had previously been thoroughly rinsed before the test until blank results were obtained.

It is clear from Table 2 that the objective of negligible internal losses was fully attained.

Slide capacity. As with all impaction devices which collect aerosol particles on solid surfaces and which do not present continuously moving surfaces to the air jet there is a limit to the amount of aerosol particles which can be collected on each stage.

Table 2. Internal losses—amounts in ml × 10^{-6}

Slide	Amount	Part assessed	Amount	% loss
1 & 2	2110·4	Top (perspex) block, excluding lips of slot.	17·1	0·81
3	1300·3	Block No 3	8·7	0·70
4	1533·5	Block No 4	28·3	1·84
5	802·9	Block No 5	6·3	0·78
6	262·6	Block No 6	too small to measure	<0·2
7	77·1	Block No 7	,, ,,	<0·6
Filter	28·0	Filter holder	,, ,,	

The limit (for bulk assay of droplets) is when pools of collected liquid are blown off the slide by the air flow. This occurs at a few μl for stages 3, 4 and 5 and considerably less for the lower stages. For microscope counting, accuracy is severely limited when particle density is such that there is frequent overlap of individual particles. At these concentrations also dry aerosol particles may bounce off or be blown off previously impacted particles. Even with the most efficient adhesive films large particles can escape beyond their proper stage (i.e. 100% impaction efficiency is not achieved) and an examination of the deposit of the final stages of cascade impactors after taking a heterogeneous aerosol sample will confirm this. Clearly this limits the accuracy of bulk assessment of fine-particle impactor stages.

Flow rate control. To set the flow rate at 5 l/min the intake cone adaptor is fitted to the intake slot and connected to a flow meter. The most convenient way of limiting the flow is to insert a critical orifice between the impactor and the pump, provided that the pump can give 0·5 atm depression. Because of the resistance of the impactor the critical orifice will be one which gives about 5·5 l/min in free air.

For 20 l/min the seventh jet acts as a built-in critical orifice but the final filter must not have a high flow resistance. This instrument is the subject of a British Patent Application.

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