Measurement of the Performance of Air Cleaners Against the Particulate Element of Rosin-based Solder Flux Fume

A. E. JOHNSON and R. C. BROWN

Health and Safety Laboratory, Broad Lane, Sheffield S3 7HQ, U.K.

A number of commercially available air cleaners designed for use against solder fume have been examined. The fume capture efficiencies have been measured with a tracer gas comprising a neutrally buoyant mixture of sulphur hexafluoride and helium, and the filtration efficiencies have been measured using solder fume produced at a constant concentration, laboratory-generated monodisperse aerosols, and standard aerosols. The extractor volume flow rates of the simpler types of fume collection units, measured by us, differed from those reported by manufacturers. The capture efficiency of these units was good when the soldering iron was less than about 20 cm from the air intake, but the filtration efficiency against particulates and, therefore, the protection offered, was poor. More robust LEV units containing a HEPA filter had a similar capture efficiency, but a filtration efficiency that was well above the standard strictly necessary; such units will give good protection if properly used. The tip-extraction type of system was found to be very effective but the extraction nozzle rapidly became blocked with the rosin in the solder. Subsidiary measurements of vapour filtration efficiency were made. Activated carbon filters in the form of foams, used with the simpler type of cleaner, had negligible filtration efficiency against either particulates or vapours and would, therefore, offer no protection against any hazardous component of the fume. The granular carbon filter in the tip-extraction system was an effective vapour filter.

INTRODUCTION

The making of conductive connections is a common operation in the electrical and electronics industries, and it usually involves soft soldering with a 60/40 tin/lead alloy and a rosin-based flux. Rosin-based solder flux fume (RBSF fume), which is produced by the thermal decomposition of the flux during rosin-core soldering, is known to be a respiratory sensitizer (HSE, 1995). In the UK there are many small companies involved with the hand soldering of electrical components, and approximately 50,000 people are exposed to RBSF fume. Occupational asthma due to RBSF fume is a recognised disease, with 20–30 new cases per annum qualifying for Disablement Benefit (Employment Gazette, 1991).

The quantity of fume emitted during soldering will depend on a number of variables including the wire thickness, metal/flux ratio, flux composition and solder temperature. The fume, which has a small vapour component associated with it, rises slowly on the thermal currents created by the hot iron towards the breathing zone of the worker. Control is normally achieved by means of air cleaners in the form of local exhaust ventilation (LEV) units, which are available from a number of companies, but concern has been raised about the effectiveness of such systems, and suppliers have little data on their performance. This paper describes an assessment of the performance of commercially available air cleaners and of the factors influencing their capture efficiency and filtration efficiency.

METHODS AND MATERIALS

Air cleaners tested

Four units, considered to cover the range of those currently used, were tested:

Unit A

This is a relatively inexpensive bench mounted unit, incorporating a small fan and a foam-type activated carbon filter of thickness 5 mm with a porosity rating.
of about 45 pores per inch (p.p.i.) (18 pores per cm). The unit is described as a ‘Fume Displacement Purifier Unit’ and its technical specification states that ‘The unit, of open face area of 0.0121 m², is fitted with a high capacity fan which draws the fumes across an activated charcoal impregnated filter thereby significantly reducing the likelihood of eye and throat irritation, known to be caused by soldering flux fumes. The fan, of recirculating type, displaces 94 ft³ min⁻¹ (2662 l/min) and is relatively silent in operation’. The specification does not include quantitative information on filter efficiency.

**Unit B**

This unit is described as a ‘fume absorber’ and is in the middle price range. It comprises two axial fans which draw air through a foam type activated carbon filter, 2 cm thick, of porosity rating approximately 45 p.p.i. The unit, of open face area 0.0312 m², incorporates a light and is supported by a bench clamp stand and extending support arm to give adjustments for height and reach. Its technical specification states that ‘Two 120 mm 240 V axial fans within the unit generate a powerful airflow of 70 m³/hr⁻¹ (1167 l/min⁻¹) drawing fumes through an activated carbon filter and well away from working areas’. The specification did not include quantitative information on filter efficiency.

**Unit C**

This unit is a ‘top of the range’ extraction system able to handle up to 25 soldering operations simultaneously. It comprises an extraction unit with a variety of LEV cowls, and it has the facility for tip extraction by means of a small exhaust nozzle that fits close to the tip of the soldering iron, with flexible tubing to carry away the fume. When used in the tip extraction mode the unit operates as a low-volume high-velocity (LVHV) extraction system using relatively small volumes of air at high velocities to control contaminants. With a 5 mm diameter extraction nozzle, a flow rate of 301 min⁻¹ is used. In its alternative mode, with arm extraction via an LEV hood, duct velocities in the range 10–15 m s⁻¹ are set. The filter specification is ‘an environmental filter which removes all particulate debris down to 0.3 micron and 95% of particles down to 0.01 micron, at a guaranteed air purification factor of 99.997%’. The condition of the filter is continually monitored and displayed.

**Unit D**

This unit, smaller in size than the other units tested, is powered by compressed air and allows the fitting of one or two tip extraction nozzles using a system like that described for unit C, above. The technical specification supplied with the unit states ‘The compressed air supply should be dry and clean at 3.5 to 7 bar, which produces an airflow of 25–30 l min⁻¹. The unit came factory-set and included a certificate stating that it was tested at a compressed air pressure of 5.5 bar to give an extraction flowrate of 29 l min⁻¹. The specification also goes on to say that ‘The polluted air undergoes five filtration stages both physical for particles and activated carbon for gaseous chemical removal. The resultant exhaust air is 99.995% clean and can be vented into the workplace.’

The experimental work required: apparatus for the production of RBSF fume at a constant rate over an extended period; apparatus through which a suitable tracer gas (sulphur hexafluoride) could be produced in such a way as to mimic the behaviour of the RBSF fume produced during soldering; means of keeping the air issuing from the cleaners separate from atmospheric air, so that the concentration of fume passing through the filtration system could be measured; and means of quantifying the concentration of both the RBSF fume and the sulphur hexafluoride used in the experiments.

**Apparatus for the production of uniform rosin-based solder flux fume**

A common type of soldering iron, an electronically controlled Weller soldering iron incorporating a spade tip, operating at a temperature measured to be between 330 and 340°C, was used, along with general purpose multicore 60/40 tin/lead alloy of 18 SWG, as solder. Figure 1 shows a commercially available solder dispenser (A) fitted with a small motor (B), connected to a knurled wheel that pinched the solder wire against an adjustable tension spring. The complete unit measured approximately 20 cm x 20 cm x 20 cm, and it could be bench mounted. To minimise the effect of the unit on airflow patterns close to the iron tip, the solder was passed through a guide (C) consisting of a 5 cm long tube, between the dispenser and the soldering iron (D). The optimum solder delivery speed was obtained with a motor voltage of 8 V which delivered solder to the heated iron tip at approximately 25 cm min⁻¹.

**Containment**

It will be shown below that measurement of both capture efficiency and filtration efficiency requires that the filtered air, which is usually discharged into the workplace atmosphere, should be kept separate from the ambient air so that the analyses can be carried out. The containment system that achieves this is shown in Fig. 2. The outlet of the extractor is completely enclosed in ductwork, which forms a plenum chamber where the gas concentration can be measured, and which vents outside the laboratory, to prevent recirculation of the test gas in the laboratory air. At the outlet of the plenum chamber is situated an exhaust fan, the speed of which can be adjusted so that the pressure in the plenum chamber equals atmospheric pressure. In this situation the exhaust fan simply balances the resistance of the ducting and does not assist the ventilation provided by the internal fan of the cleaner. In order to control better the flowrate in units A and B, their internal fan was switched off after the flow rate had been measured and the flow, measured
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Fig. 1. Solder production system: A—solder dispenser; B—motor; C—guide; D—soldering iron.

Fig. 2. Schematic illustration of the apparatus used for measurement of the capture efficiency and filtration efficiency of air cleaners: (A) air cleaner under test. (B) plenum chamber for sampling captured and filtered gas. (C) manometer used to ensure that atmospheric pressure is maintained in test chamber. (D) manometer for monitoring pressure drop across. (E) orifice plate. (F) gate valve controlling (G) exhaust fan venting captured gas to atmosphere.

with a calibrated orifice plate, was provided entirely by the exhaust fan in the exhaust duct, which was controlled by a gate valve.

Use of a tracer gas for capture efficiency measurements

Resin acids in solder can be accurately measured (HSE, 1997) but a long time is required for sample collection and analysis, and so a tracer gas in the form of a neutrally buoyant mixture of sulphur hexafluoride (SF₆) and helium was used for measurement of fume capture efficiency. The mixture was released at a constant rate at points in front of the extract system (Hampl and Shulman, 1985) and its concentration was measured when it was well mixed in the exhaust of the system under test. SF₆ is non-toxic and easily detectable to parts per million (ppm) levels using a MIRAN infra-red detector.

Since the current work involves high temperatures and, therefore, convection currents, a comparison exercise was considered to be necessary to assess
whether the tracer moves in the same way as the solder fume. At a flowrate of approximately 330 cc min⁻¹ the tracer, which was passed through a smoke tube to make it visible and then released beneath the tip of a heated soldering iron, appeared to behave in the same way as the RBSF fume.

The smoke tube was then removed and solder was fed to the heated iron. The concentration of the particulates in the RBSF fume was then measured in the plenum chamber with a Dustrak (TSI Inc), a direct reading instrument, and the concentration of the tracer gas was measured with the MIRAN. The tests were carried out with the source at a number of positions in front of the extractor and the results are plotted in Fig. 3, which shows that the behaviour of the tracer and that of the RBSF fume are similar.

Finally the tracer gas concentrations and the concentration of the resin acids in the RBSF fume in the plenum chamber were compared. The fume was sampled for periods of between 10 and 25 minutes, longer times being necessary when the source was further from the extractor face. The concentration of resin acids, measured in the standard manner (HSE, 1997) was low, but the general behaviour, as shown in Fig. 3, was similar to that obtained from the tracer gas, thus validating the tracer gas method.

**Measurement of capture efficiency with tracer gas**

When the tracer is released immediately in front of the extractor unit, so that all of the gas enters, the concentration corresponding to 100% capture efficiency can be determined. Capture efficiency at any position of the source relative to the face of the extractor can then be calculated by dividing the concentration measured in the exhaust in those conditions by the concentration at 100% capture efficiency. This method clearly indicates when the capture efficiency is low, but since errors in measurement of one or two percent are common, the method is not very effective at making fine distinctions at high capture efficiency. For example it would not distinguish easily between 98% and 99% capture; two situations that result in exposures differing by a factor of two.

When the tracer gas concentration was measured in the tests to be reported below, the background concentration was allowed to return to zero and the gas was run to waste for a period of 3 minutes in between tests to allow conditions in the ductwork to stabilise. Gas concentrations at each measurement point were taken over a period of 10 minutes and the values recorded on a data logger at one second intervals.

**Measurement of filtration efficiency**

The efficiency of the filters in the four extraction systems was measured in three ways: using the resin acids in the RBSF fume, using monodisperse aerosols of a range of particle sizes and using standard aerosols.

**Filtration efficiency measurement using resin acids in the RBSF fume**

Solder fume was generated using the apparatus described above. The fume was released at such a position that it was all captured. In this situation the filtered air coming from the cleaners enters the plenum chamber, where the concentration of contaminant is measured; recirculation is prevented. The fume was collected on membrane filters and the resin acid content was measured by gas chromatography (HSE, 1997). For units A and B, the fume was collected in the exhaust ductwork, with and without the filters fitted, for a sampling time of 5 min and a sampling flowrate of 21 min⁻¹. For cleaners C and D, which had separate filtration units, the fume was sampled upstream and downstream of the filter.

**Filtration efficiency measurements with monodisperse aerosols**

Measurements with RBSF fume give a valuable indication of real performance, but the difficulty of analysis introduces random error, and the results do not give the performance of the filters as a function of particle size. Accurate measurement of efficiency requires monodisperse aerosols. Filters can be tested using aerosols in the size range 1.5–9 μm generated by an automated form of modified vibrating orifice generator system (Blackford et al., 1985). Mor-
odisperse aerosols are passed, in turn, through the filter under test and through an identical balanced empty unit. The airflow is kept constant by computer control, and the test particle size is varied automatically. The particles in the filtered and unfiltered aerosol are then counted optically and the penetration of the test aerosol is calculated by computer.

The tests on filters from air cleaners A, B and C were carried out at the same filtration velocity as achieved through the units when under normal operation. Since tests are much easier to perform on flat material, the pleated filter in unit C was opened out and an uncreased portion selected. The filter in unit D was in the form of an encapsulated cartridge which contained six filters in series, called in turn by the manufacturer: a roughing filter, prefilter, micro filter (HEPA), gas filter, particle filter and carbon filter. Owing to difficulty envisaged in separating the various components the cartridge was tested as a complete unit.

The HEPA filters were tested with submicrometre aerosols generated by an electrostatic classifier and detected, before and after filtration, by a condensation nucleus counter. In addition tests were carried on the filters to British Standard 4400 (1969) using a NaCl test aerosol of nominal mass median diameter 0.6 \( \mu \text{m} \).

**Filtration efficiency against vapours**

The measurements described above will quantify only the particulate element of the rosin-based solder flux fume. Three of the cleaners tested contained a vapour filter and in two of these it was the only filter. Just as activated carbon filters are ineffective in the capture of particulates, even high efficiency particulate type filters are ineffective in the control of vapour. Measurements of the vapour content in the solder fume were carried out in the plenum chamber using unit A both with and without the filter, and using unit D with upstream and downstream sampling.

### RESULTS

**Measurement of volume flowrate**

The extraction rates of units A and B were measured both with and without their filters, and the results are shown in Table 1. The manufacturer of unit A specified an extraction rate of 94 ft\(^3\) min\(^{-1}\); this figure is close to the results of our measurements made with the fan free running i.e. without the filter fitted. In the case of unit B, we measured a flowrate higher than that specified, even with the filter in situ. Unit C had an adjustable flowrate. This would normally be set by the engineer installing it, but we set it ourselves. The accuracy of setting of the flowrate would, in practice, depend on the skill of the engineer.

Tip-extraction unit D came with a certificate claiming that the unit was tested to give an extraction flowrate of 291 ft\(^3\) min\(^{-1}\). When the flowrate was measured by us it was found to be only 111 ft\(^3\) min\(^{-1}\). The fault was traced to a loose locking nut on a flow regulator which controlled the extraction rate. Correction of a fault of this type would require the use of a rotameter or bubble meter, equipment not readily available in the workplace.

**Measurement of fume capture efficiency**

Capture efficiencies of units A and B, and of unit C fitted with an extraction cowl were measured using the tracer gas. Figure 4 shows the capture efficiency of the units as a function of distance between the source and the extractor. Each of the units was in its normal working position i.e. units A and C were bench mounted, and unit B was operating at its mid-height position 17.5 cm above the bench. The soldering iron was positioned on the centreline 1.5 cm above the bench, this height being typical of many of the operations carried out in the industry e.g. soldering operations on printed circuit boards. The three units behaved in basically similar ways. Capture efficiency was high when the separation of the source and the extractor was less than about 20 cm, after which it fell off rapidly with increasing distance from the unit's face, a feature typical of all LEV systems.

**Effect of source height and extractor unit height on capture efficiencies**

In order to assess fume capture efficiencies during the soldering of components of different sizes, tracer gas concentration measurements were made with the source at heights of 1.5, 10, 15, and 25 cm above the bench, and at a range of distances from the extractor. The results for unit A, bench mounted, are shown in Fig. 5. In all instances the rapid fall-off of capture efficiency with distance is apparent. The capture efficiency is marginally reduced for source heights of up to 15 cm, but at a source height of 25 cm, where...
the source is 9 cm. above the top of the hood, it drops significantly.

Figure 6 shows the capture efficiency of unit B bench mounted, at the mid-height position (the base 17.5 cm above the bench) and at the maximum height (35 cm above bench height) with a source height of 1.5 cm. The capture efficiency in the bench mounted condition is consistently higher than the efficiency shown in Fig. 4. This is consistent with the observations of Fletcher and Johnson (1982) that the centreline air velocities on the bench for a unit resting there were the same as centreline air velocities of an extraction unit with twice the area, i.e., the real unit along with its mirror image reflected in the bench. This would be expected if the flow into the extractors were well-described by a potential flow approximation (Landau and Lifshitz, 1959).

**Capture efficiencies of tip extraction system**

Tracer gas measurements were carried out for tip extraction fitted to unit C and unit D, with three orientations of the soldering iron tip and the extraction nozzle: in the normal operating position with the extraction nozzle positioned above the iron tip, with the iron tip and the nozzle at the same level and with the extraction nozzle beneath the iron tip. In all cases the capture efficiency was 100%, within experimental error. This is consistent with results obtained by Dal-
rymple (1986), that capture was complete except for fume from ‘splutter’ and fume produced during very rapid movements of the soldering iron. However, in both Dalrymple’s tests and our own, it was observed that during extraction the nozzle rapidly became blocked. The resin in the solder flux appeared to condense a short distance inside the extraction tube.

Manufacturers of units C and D recommend respectively that the volume flowrate through the nozzles of the tip extraction tube should be set at 29 and 30 l min

−1. A flowrate of 29 l min

−1 would give a velocity of 24.6 m s

−1 at the nozzle face. As a rule of thumb, the velocity in front of an extraction system will fall to a tenth of the face velocity at one diameter from the face. As fume in both systems was extracted through a 5 mm diameter nozzle 5 mm from the iron tip this approximation gives a capture velocity at the soldering iron tip of approximately 2.5 m s

−1. A velocity of this magnitude should be very effective in removing the fume. For example, the recommended capture velocity for welding fume is between 0.5 and 1 m s

−1 (ACGIH, 1995).

Effect of filter blockage on capture efficiency

Filtration will be considered in detail below, but the effect of filter blockage, like that of extraction tube blockage, is to reduce the flowrate through the system. The effect of reduced volume flowrate on unit A was investigated with the soldering iron 1.5 cm above the bench. Capture efficiencies were measured as a function of the distance of the source from the face of the unit operating in its normal condition, i.e. the flow unrestricted, and then with the flowrate reduced by 10, 20, 30, 50 and 70%. Some of the data obtained are plotted in Fig. 7, where the reduction in capture efficiency with distance is apparent, as before. The distance at which capture efficiency is acceptable becomes smaller as the flowrate decreases.

Filtration efficiency

Because of the high efficiency of the filters in units C and D the filtered fume was sampled for 10 min at a flowrate of 30 l min

−1 in order to enable sufficient quantities of resin acid to be deposited onto the sampling filters for accurate analysis. Each of the tests was repeated and the results are shown in Table 2.

The foam filters fitted in units A and B were very inefficient against particulate. Although some deposit was seen on the filters, a penetration of over 80% was obtained for filter A and over 50% for filter B. The HEPA filters, from units C and D, performed well, with average penetrations of 0.034% and 0.096% respectively.

Solder fume analysed using an electron microscope had a particle size range of around 0.5–5 μm although some particles had agglomerated into small clusters or chains up to 20 μm in length (M. I. Pengelly, HSL, private communication). The data on monodisperse aerosols in Table 2 are consistent with 50–100% of particulates in the size range 0.5–5 μm penetrating through filters A and B. The HEPA filters were efficient against submicrometre particles, with penetrations of below 0.015%. The other filters were not tested with small particles because they performed so poorly with larger ones.

In order to compare like with like the filters from units A, B and C were tested with British Standard 4400 (1969) NaCl test aerosol at the same face velocity (10.2 cm s

−1) but as filter D was tested as a complete unit, a face velocity of only 7.9 cm s

−1 could be achieved. The results, shown in Table 2, are consistent with the results with submicrometre aerosols.

Analysis of vapour

No evidence of resin acids at the detection limit of the gas chromatograph (~ ng m

−3) was found in the vapour phase of the unfiltered fume. The only vapours of compounds known to be associated with the fume were a—pinene, b—pinene and liminene, all relatively harmless compounds present at low concentrations. The concentrations of these were virtually unaffected by the presence of the foam type activated carbon filter from unit A, indicating that the filter would not cope with any hazardous component in the vapour.

The measurements were repeated using the filter cartridge from unit D, which contained granular car-
bon material as one component, for the removal of gaseous chemicals, along with a potassium permanganate/aluminium oxide filter. Vapours were sampled upstream and downstream of the filter, but again no evidence of resin acids in vapour form was found. However, this cartridge filter did remove the other vapour constituents associated with the fume indicating that it was an effective filter against organic compounds of the type normally adsorbed by carbon filters.

DISCUSSION AND CONCLUSIONS

To be efficient a cleaner is required to capture fume effectively and to filter it efficiently before the filtered air is returned to the workplace. All the LEV systems captured the fume effectively provided that the soldering was carried out close to the capture inlet. However, the units with porous foam filters were ineffective in filtering the fume and so would not give adequate protection. If they could be fitted with an effective filter, whilst maintaining their airflow, they would work.

The extent of control of fume possible with all LEV hoods falls rapidly with increasing distance of the point of generation from the hood face, and it varies with the height of the soldering iron during use and the height of the extraction unit above the bench. It also depends on the airflow rate. The flow rates quoted by the manufacturers were not very reliable, but even accurate information of this sort has little relevance to the end user. Guidance on the maximum distance from the cleaner at which effective capture of the fume takes place would be of much more value. For the cleaners tested this distance was of the order of 20 cm, and the information might be supplied in the form of a ‘capture envelope’, printed onto a work mat on which soldering operations are carried out, indicating where, say, 95% efficiency is achieved.

Owing to the tendency of RBSF fume to drift a LVHV system in the form of tip extraction has special features. It collects fume from the iron when it is in use and also when it is at rest in its holder, but it will not collect fume from a smoking joint after the soldering iron has been removed from it. The extractor must be well maintained and the extraction flowrate must be set correctly. Too low a flowrate would result in poor capture whilst too high a flow rate could result in excessive cooling of the iron tip. A user confronted with the problem that we observed, a flow rate different from that quoted by the manufacturer, would not be directly aware of the problem nor able to correct it, though inefficient capture of fume by the tip extraction system might be apparent.

A major disadvantage of the system, however, is that the narrow bore tubing connecting the iron to the extraction unit is prone to blockage by the rosin in the solder so that frequent cleaning may be necessary. Better design might reduce the rate of build-up or allow it to be easily removed. Moreover, the addition
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of an extraction nozzle to the soldering iron affects the ‘balance’ of the iron and, along with the extraction pipework may make it unwieldy and uncomfortable to use for extended periods.

The HEPA filters fitted in units C and D performed extremely well, with efficiencies of up to 99.99%, but such filters tend to have a high resistance to the flow of air and require a powerful (and expensive) centrifugal fan to give an acceptable face velocity. It is unusual, in normal practice, to obtain capture efficiency greater than about 95% with LEV systems. Making the filtration efficiency more than say one order of magnitude better than this, i.e. 99.5% efficient, is well into the realms of diminishing returns. Moreover, high efficiency filters tend to be fragile and expensive and they tend to clog rapidly.

Coarse foam filters of the type used in units A and B were ineffective against either vapour or fine particulates. A low-resistance/high efficiency material might transform the performance of the units. Low resistance filters enable manufacturers to use axial fans, which are relatively inexpensive, to give an acceptable capture velocity in front of the units.

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REFERENCES
HSE (1995) Respiratory sensitisers and COSHH. Brent Creedy An Employers leaflet on preventing occupational asthma IND (G) 95 (L) (rev).