

# Visualisation and control of solder fume exposure

A quantitative assessment of LEV effectiveness

Prepared by the **Health and Safety Laboratory**  
for the Health and Safety Executive 2011

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A quantitative assessment of LEV effectiveness

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Colophony or Rosin Based Solder Flux Fume is a known cause of occupational asthma and as such exposure to it should be controlled. An effective method of engineering exposure control is to use local exhaust ventilation (LEV) to extract the fume at source. Personal exposure to solder fume was quantitatively measured in the breathing zone of a manikin, these exposures were then compared to those caused by uncontrolled soldering in order to assess five different LEV systems. The five LEV systems tested were a downdraught bench; an extracted bench top enclosure, a mobile capturing hood, an on-tip extraction system and a bench top fume absorber.

It was found that even a moderate amount of soldering when uncontrolled caused exposures over 50 times greater than the 8-hour Workplace Exposure Limit of  $0.05 \text{ mgm}^{-3}$  and over 30 times greater than the 15-minute Short Term Exposure Limit of  $0.15 \text{ mgm}^{-3}$ . It was found that all five LEV systems were capable of reducing exposure to zero if used correctly. Each system had distinct advantages and disadvantages that make their use more or less suitable in various situations.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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*First published 2011*

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# EXECUTIVE SUMMARY

## Objectives

The main objectives of the project were to quantitatively measure personal and background exposure to colophony fume generated by soldering with rosin flux cored solder. Exposures were measured for uncontrolled soldering and soldering with a variety of engineering local exhaust ventilation (LEV) controls. The engineering controls tested were: a downdraught bench, a mobile capturing hood, an enclosing hood, an air displacement box (or fume absorber) and an on-tip extraction or Low Volume High Velocity (LVHV) system. Then using this data to compare and contrast the available engineering controls and to determine whether it is possible to rank order them. Three soldering scenarios were considered in the project, moderate soldering was 1 s in 20 s, substantial soldering was 1 s in 10 s and extreme soldering was 2 s in every 10 s. The five LEV controls were all tested using the extreme soldering scenario in order to provide the highest emission rate and therefore the most stringent test of the system's ability to control exposure. Rosin based solder flux fume (colophony) has an 8-hour TWA Workplace Exposure Limit (W.E.L) of  $0.05 \text{ mgm}^{-3}$  and a Short Term Exposure Limit (S.T.E.L) of  $0.15 \text{ mgm}^{-3}$ . The majority of tests in this study were 15 minutes long allowing direct comparison with the S.T.E.L.

## Main Findings

- Soldering produces a narrow but expanding directional rising plume of fume with a high concentration gradient making it a high strength source. The plume of fumes is highly variable and prone to disturbance by ambient air movements.
- Uncontrolled soldering causes high personal exposures in the breathing zone; this can be 20 – 50 times the S.T.E.L dependant on the soldering scenario. This can equate to exposures exceeding the 8-hour TWA W.E.L after only 15 minutes of soldering.
- General ventilation at 5 air changes per hour (ach) per hour was not sufficient to control personal exposures, but was capable of reducing background exposures within the test room.
- Four of the five controls - on-tip extraction, downdraught bench, mobile capturing hood, and the enclosing hood – can all reduce personal exposure to zero if used and maintained correctly.
- The fifth control, the air displacement box or fume absorber was capable of extracting solder fume from the working zone if used correctly, but filtration of the exhausted air was ineffective causing secondary personal exposure by increasing the background concentration of solder fume within the test room.
- Rank ordering the controls was more complex than comparing their quantitative performance reducing exposure and required consideration of their usability, ease of maintenance and adaptability to different processes and tasks.
- Rather than rank ordering the controls it makes more sense to divide them into two groups, the first being the most effective includes the on-tip extraction system, the downdraught bench and the enclosing hood. The second includes the mobile capturing hood and the air displacement box.
- Each control has advantages and disadvantages, these are summarised below.

### **On-tip extraction**

- ✓ Is capable of reducing exposure to zero
- ✓ The extraction point is always close to the source eliminating the need to reposition the LEV when the soldering position moves
- ✓ The system is highly adaptable to changes of process and task
- ✓ Requires only a small volume air flow – approximately  $1.8 \text{ m}^3\text{h}^{-1}$
- ✗ The extra extraction tubing can cause a dragging effect making it slightly harder to use than a standard soldering iron. The presence of the extraction nozzle close to the tip can limit access in situations where space is restricted and may restrict visibility
- ✗ Solder fume tends to condense inside the narrow bore extraction nozzle and tubing causing blockages and restricted flow leading to a loss of control – this means that the system requires regular cleaning to function properly. During this study the system became blocked after approximately 1 – 2 hours of soldering

### **Downdraught bench**

- ✓ Is capable of reducing exposure to zero
- ✓ Because the surface of the bench is extracted the effective capturing zone encompasses the whole working area
- ✓ It is easy to use, does not require any repositioning of the extract when moving soldering position
- ✗ Requires a large volume air flow – approximately  $575 \text{ m}^3\text{h}^{-1}$  at maximum flow
- ✗ The size of objects that can be soldered is limited as blockages of more than 50 % of the extracted surface can compromise control
- ✗ It is unclear how the bench would perform when soldering objects that form cavities shielded from the downward flow of air such as the inside of televisions or tower PCs

### **Enclosing hood**

- ✓ Is capable of reducing exposure to zero
- ✓ It is highly resistant to disturbing draughts such as people moving around or the close presence of a cooling fan
- ✓ Provides a physical barrier between the source and the worker's breathing zone
- ✓ Requires a relatively small volume air flow – the enclosure maintained complete control of the fume emission operating at  $40 \text{ m}^3\text{h}^{-1}$
- ✓ Enclosures are ideally suited to production line work where identical or similar sized objects will be soldered

- × Enclosures are more difficult to use where objects of various sizes and shapes are encountered as they are only capable of controlling emissions that occur within the enclosed volume

### **Mobile capturing hood**

- ✓ Is capable of reducing exposure to zero if positioned correctly
- × Has a relatively small effective capturing zone which means that it needs to be repositioned when the soldering position moves to keep it within the working zone and maintain control
- × The model of mobile arm tested is difficult to move and reposition although other more flexible versions are available
- × If the hood is not positioned close enough to the source fume escapes capture and high exposures can occur

### **Air displacement box**

- ✓ It is simple and easy to use
- × Whilst it is capable of capturing fumes at source and preventing direct exposure, the filtration in the unit tested was ineffective. The exhausted air contained a high concentration of particulate phase fume, that, in the relatively small test room used (46.7 m<sup>3</sup>), caused the background concentration to increase rapidly, which in turn caused exposure that exceeded the S.T.E.L.
- × The integral filter in the unit is an activated carbon porous foam, which is very porous meaning that much of the fume passed straight through, unabsorbed
- × The air displacement box works on the same principle as the mobile capturing hood, which means it has a relatively small effective capturing zone. If the source is outside of this zone then control is ineffective and exposure occurs
- × The air displacement box tested would not be suitable for use where extensive and prolonged soldering will take place, such as a production line

### **Recommendations**

Of the five controls tested the enclosing hood, the downdraught bench and the on-tip extraction system are the most effective. Each has advantages and disadvantages in various situations and careful consideration of the processes and tasks to be controlled is required to select between the three.

The mobile capturing hood is capable of controlling exposure if used correctly, but like all capturing hoods requires repositioning if the source moves in order to keep it within the effective capturing zone. This means that the potential for worker misuse leading to exposure to solder fume is high, for this reason it should be considered secondary to the other forms of control in the opinion of the author.

Whilst it is capable of capturing solder fume the air displacement box does not adequately filter the exhaust causing background exposure, for this reason the air displacement box should not be considered suitable for use in industrial production.





# 1 INTRODUCTION

Due to concerns over exposure to lead, the soldering industry has moved toward the use of lead free solders; these tend to be a tin/copper alloy. In order to compensate for the removal of lead another flux substance has to be used to aid the flow of the solder. One of the most commonly used fluxes is rosin or colophony. When heated, rosin creates fumes (known as Rosin Based Solder Flux Fume - RBSFF). This fume is composed of two fractions, the particulate fraction contains rosin sublimates and thermal decomposition products, which are predominantly a mixture of diterpentine acids, this fraction makes up approximately 90 % of the total fume. The remaining gaseous phase of the fume is composed of low molecular weight organic compounds including acetone, methyl alcohol, aliphatic aldehydes and other hydrocarbons.

RBSFF is a known cause of occupational asthma[1, 2], it is also a cause of contact dermatitis[3]. Colophony is a hazardous substance and has a workplace exposure limit (W.E.L) of  $0.05 \text{ mgm}^{-3}$  over an 8-hour reference period and a short-term exposure limit (S.T.E.L) of  $0.15 \text{ mgm}^{-3}$  over a 15-minute reference period[4]. Furthermore, as a known asthmagen it is necessary to reduce exposure to solder fume as far below the W.E.L as is reasonably practicable as stated in Control of Substances Hazardous to Health (COSHH) Reg 7.7(c)(ii)[5]. Exposure should be reduced by following the principles of good control given in COSHH Schedule 2a[5].

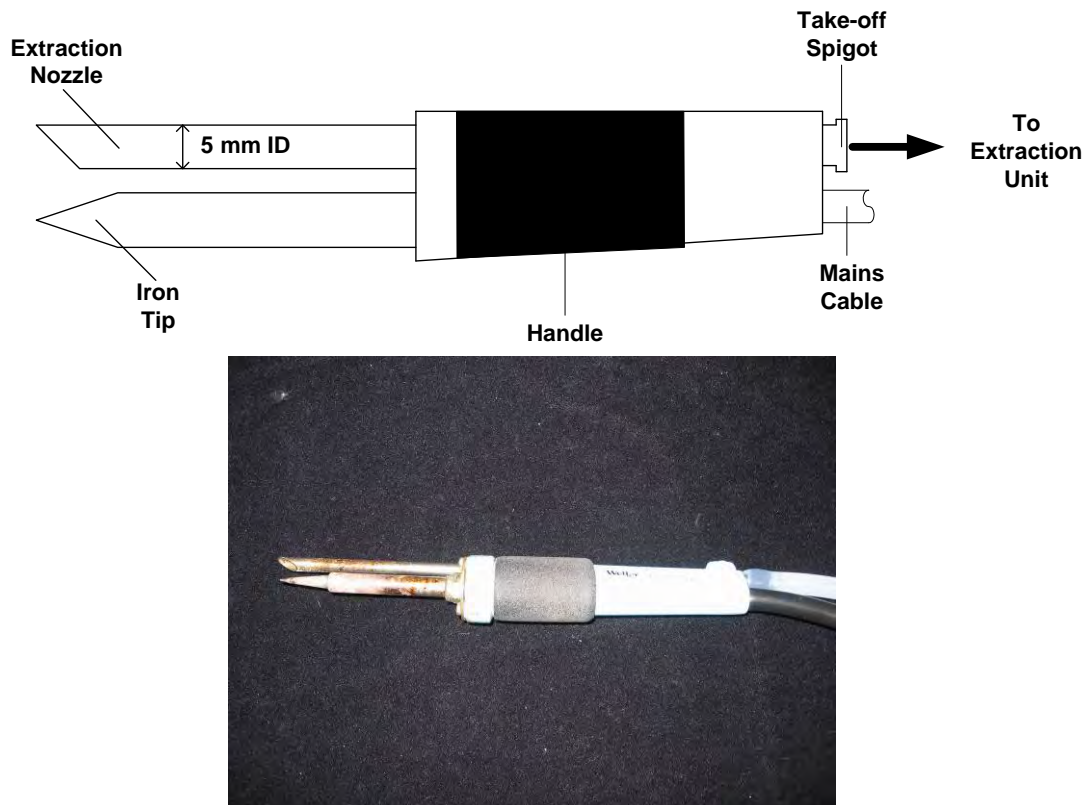
This research project was initiated by the Health and Safety Executive (HSE) to visualise the emission of colophony fume by hand soldering, produce a series of training aids and then quantitatively measure the effectiveness of a variety of LEV controls. The project was to be completed in two phases. This project was to quantitatively measure the effectiveness of the different controls by measuring a baseline exposure for uncontrolled soldering and compare this with exposure whilst controls were employed and to the workplace exposure limit (W.E.L). The results from phase 2 are detailed in this report.

## 2 LEV CONTROLS, EXPERIMENTAL PROTOCOL & SCHEDULE

### 2.1 LEV CONTROLS

#### 2.1.1 On-tip Extraction - Low Volume High Velocity (LVHV)

This system extracts air through a nozzle positioned very close to the iron, generally within 10 - 15 mm of the tip. The nozzle has a small diameter, and operates at a face velocity of the order of 20 – 25  $\text{ms}^{-1}$ ; this means that a relatively small volume of air has to be moved. This type of extract system is often referred to as Low Volume High Velocity (LVHV). Operating at full capacity drawing, air through the 5 mm diameter tube, the system moves  $28.8 \text{ lmin}^{-1}$  (approximately  $1.7 \text{ m}^3\text{h}^{-1}$ ) of air. Figure 2.1 below shows a schematic diagram and photograph of the soldering iron used throughout testing with the on-tip extract in position.



**Figure 2.1** Schematic diagram and photograph of the soldering iron with tip extraction nozzle in place

Most proprietary on-tip systems use an extraction nozzle of 5 mm diameter. A bespoke system designed and used by an electronics manufacturer was evaluated and compared to the standard commercially available 5 mm system in previous work carried out at HSL[6]. The use of a larger diameter extraction nozzle was not commercially available and required a special fitting to mount it to the soldering iron and a bespoke extraction system to provide airflow and was therefore not considered in this study.

### 2.1.2 Movable Capturing Hood

A proprietary solder fume extraction system composed of an articulated 54 mm internal diameter duct available with a variety of hood attachments. The most popular hood was selected; this is called a pen nib hood that is simply an un-flanged angled piece of the duct. The air extracted through the hood was filtered using a pleated glass fibre barrel type filter before being returned back into the test room so as not to impose any additional general ventilation. Volume flow rate through the system was measured using an orifice plate and a digital micromanometer and controlled using a valve on the fan exhaust. For controlling the emission of solder fume the manufacturer recommended an operating volume flow rate of  $80 \text{ m}^3\text{h}^{-1}$ , this gave an average face velocity at the pen nib of approximately  $6.6 \text{ ms}^{-1}$ . It was also tested at an arbitrarily selected reduced flow rate to simulate use when the filters are partially blocked; this was  $40 \text{ m}^3\text{h}^{-1}$ , which gave an average face velocity of approximately  $3.3 \text{ ms}^{-1}$ . Figure 2.2 below shows a photograph and schematic diagram of the moveable capturing hood.

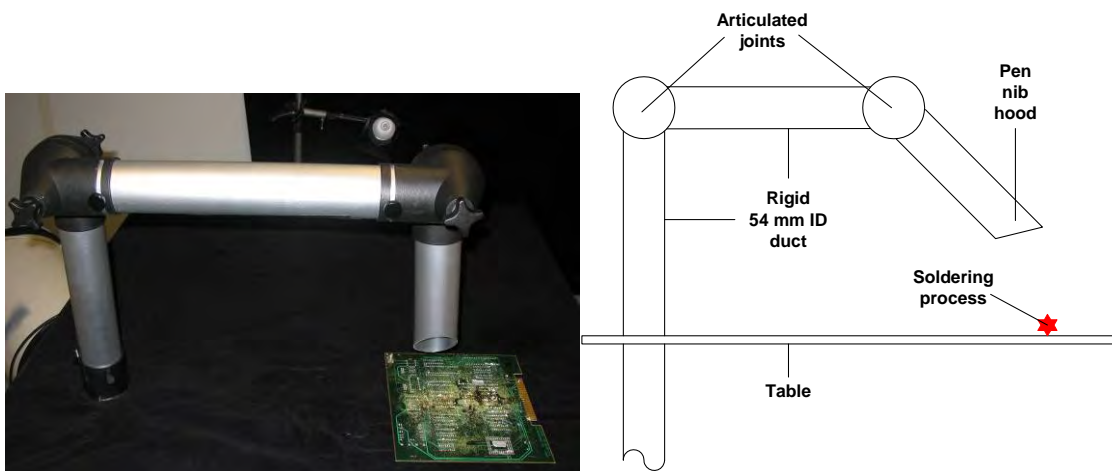
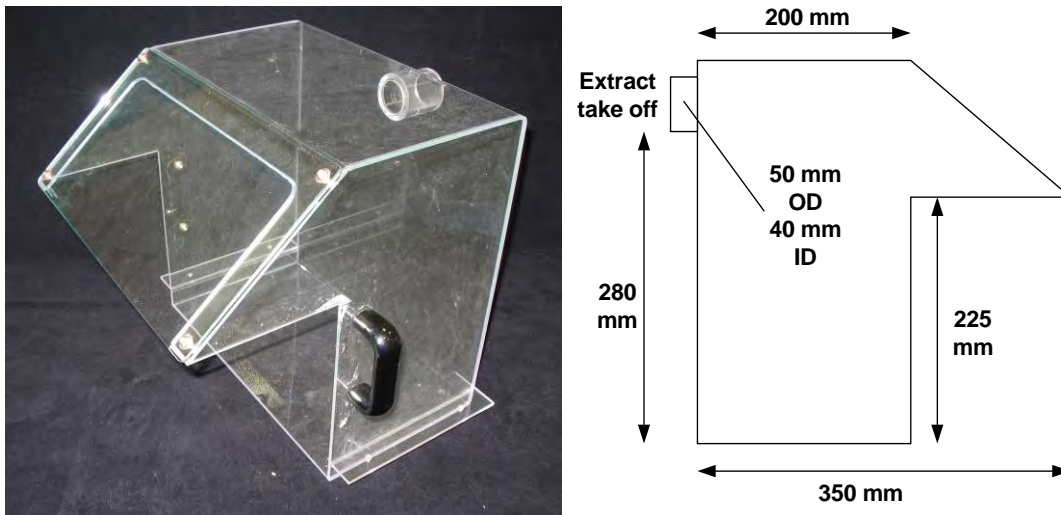


Figure 2.2 Photograph and schematic drawing of the moveable capturing hood

### 2.1.3 Enclosing Hood

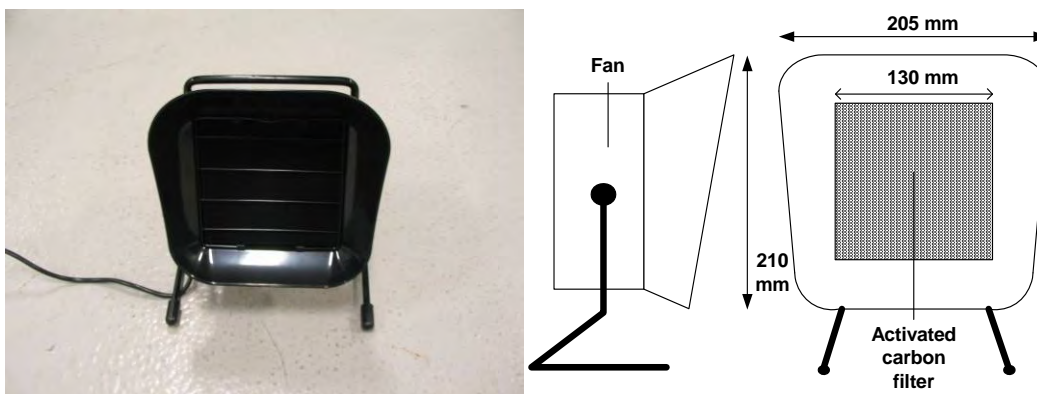
The enclosure was designed and built by an alarm company for use at their electronics assembly facility. They were designed to enclose the soldering process as much as possible. The enclosure was fitted to the same extraction system as the capturing hood. Like the capturing hood the extracted air was filtered and returned to the test room. The enclosure was tested at the same two operating volume flow rates as the capturing hood,  $40 \text{ m}^3\text{h}^{-1}$  and  $80 \text{ m}^3\text{h}^{-1}$ ; a photograph and schematic diagram are shown below in Figure 2.3.



**Figure 2.3** Photograph and schematic drawing of enclosing hood

#### 2.1.4 Air Displacement Box

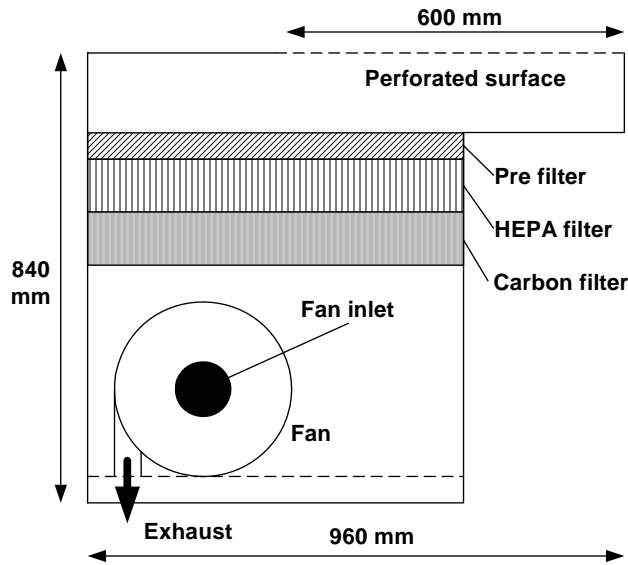
The air displacement box was an ‘off the shelf’ proprietary control measure sold as a solder fume extractor. It comprised a small axial fan, fitted with a small flange, which draws air through a porous activated carbon filter measuring 130 mm x 130 mm, the air is then exhausted out of the back of the unit. The average face velocity measured at the filter was approximately  $0.5\text{ms}^{-1}$ , this equates to a volume flow rate of approximately  $30\text{ m}^3\text{h}^{-1}$ . There was no speed control for the fan, it was either on or off; a photograph and schematic diagram are shown below in Figure 2.4.



**Figure 2.4** Photograph and schematic diagram of the air displacement box

#### 2.1.5 Downdraught bench

The final LEV control tested was a self-contained downdraught bench. This comprised a fan contained within a steel bench drawing air through the perforated surface of the bench. The exhausted air was passed through a pre-filter and HEPA filter to remove particles and then an activated carbon filter to remove the gaseous element of the fume before being discharged through the bottom of the bench and returned to the test room. A schematic diagram of the downdraught bench is shown below in Figure 2.5.



**Figure 2.5** Cutaway side view of the downdraught bench

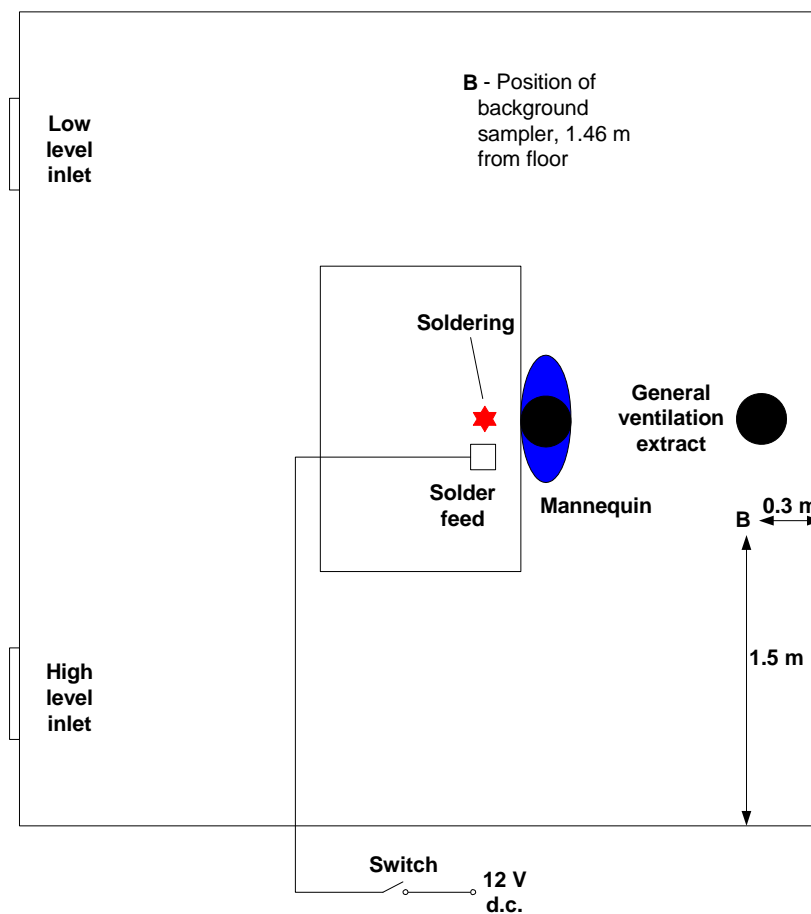
For controlling solder fume the manufacturers recommend that the fan speed controller be set to 75 %. This gave an average face velocity of  $0.44 \text{ ms}^{-1}$ , which equates to a volume flow rate of  $575 \text{ m}^3\text{h}^{-1}$ . This was measured by dividing the extracted portion of the downdraught bench into 16 equal squares and measuring the velocity at the centre of each square five times using a 100 mm vane anemometer, the velocities quoted are the mean of the five measurements. The distribution of velocities across the extracted section of the bench surface was very uneven due to the internal geometry of the bench and the position of the fan as shown in Figure 2.5 above. The velocity at the front edge of the extracted portion was approximately a third of that at the back edge. The velocity distribution from right to left was fairly even being slightly greater on the left, which was the side the fan inlet was positioned. Figure 2.6 below shows the velocity profile of the downdraught bench operating at the recommended volume flow rate for solder fume. Setting the fan control to maximum only increased the average face velocity to  $0.45 \text{ ms}^{-1}$ . The bench was also tested at a reduced volume flow rate of approximately  $430 \text{ m}^3\text{h}^{-1}$ , giving an average face velocity of  $0.34 \text{ ms}^{-1}$ .



**Figure 2.6** Velocity profile of downdraught bench operating at the recommended flow rate. Velocities quoted are in  $\text{ms}^{-1}$

## 2.2 TEST ROOM CONFIGURATION, SAMPLER LOCATIONS & CALIBRATION

Testing was conducted in a modular test chamber, which measured 4 m x 4 m x 2.92 m. The room air was extracted at a rate of 0.5 air changes per hour (ach) ( $23.4 \text{ m}^3\text{h}^{-1}$ ) to simulate a naturally ventilated space or 5 ach ( $234 \text{ m}^3\text{h}^{-1}$ ) to simulate a mechanically ventilated space. Air was extracted through a circular 250 mm diameter opening in the ceiling, positioned 300 mm from the wall behind the worker on the centreline of the room. Extracted air was discharged outside of the building to prevent re-entrainment of any solder fume into the room air. Make up air entered the room through two 400 mm square openings to ensure that air entered at low velocity. The inlets were positioned in the wall opposite the extract opening, one at high-level 2.2 m from the floor one at low-level 0.3 m from the floor. Figure 2.7 below shows a schematic of the test room as it was set up for testing during phase 2.

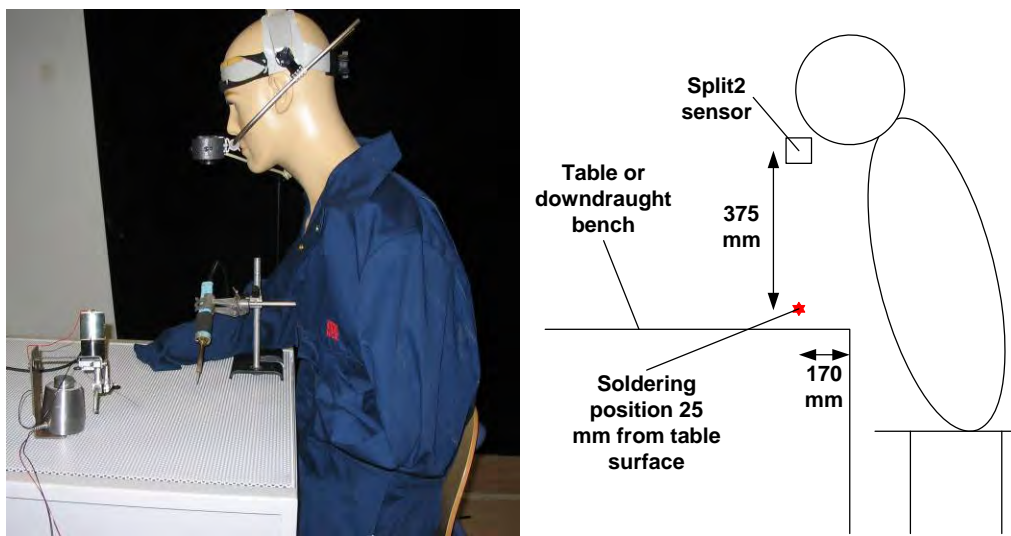


**Figure 2.7** Room set up

During phase 2 the human worker was replaced by a manikin and an automatic solder feed system. There were two reasons for this; firstly the nature of the testing during phase 2 presented a significant risk of repeated and prolonged high exposures to solder fume and secondly, the use of an automatic solder feed, coupled with a static manikin, allowed a higher degree of control and repeatability of the soldering. RPE alone was not considered adequate protection for a human operator especially as the first part of testing was to measure the exposure of uncontrolled soldering. A life size manikin in a sitting position was used with the breathing zone sampler mounted on the head. This had the advantage that it allowed the position of the sampler to be fixed relative to the position of the soldering iron making comparisons

between tests meaningful. By using an automatic solder feed it was possible to use a more precise and reproducible mass of the solder wire to give the same fume generation rate from test to test. A camera was placed inside the room which allowed the solder feed to be operated from outside without exposing the worker to the solder fume and allowing visual qualitative observation of the tests.

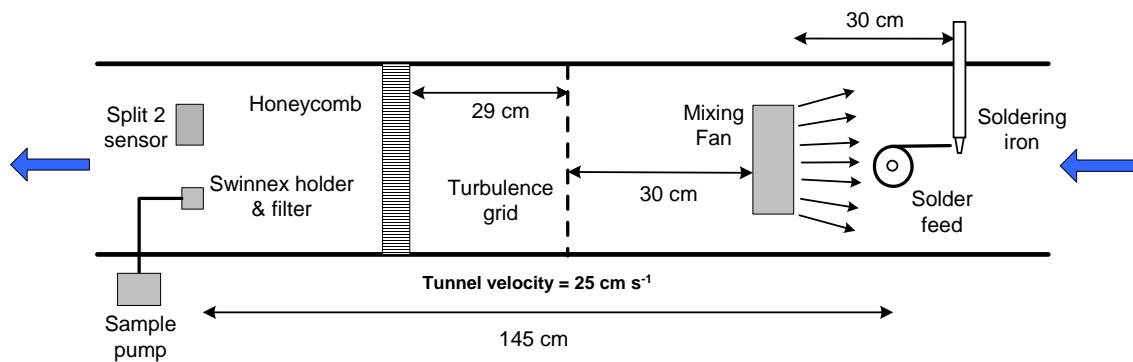
Two samplers were used, solder fume concentration in the breathing zone was measured using a Split 2 (SKC Instruments, S/N 03061851) dust monitor. This was mounted on a headpiece and held in front of the nose and mouth of the manikin 400 mm from the surface of the bench or table as shown in Figure 2.8 below. This sampling position was similar to one used during a study of an on-tip extraction system carried out at HSL in 2003[6]. Background fume concentration was measured using a Microdust Pro dust monitor (Casella Instruments S/N 1265553); the sampler was located at the position shown in Figure 2.7, 0.3 m from the back wall, 1.5 m from the sidewall and 1.46 m from the floor.



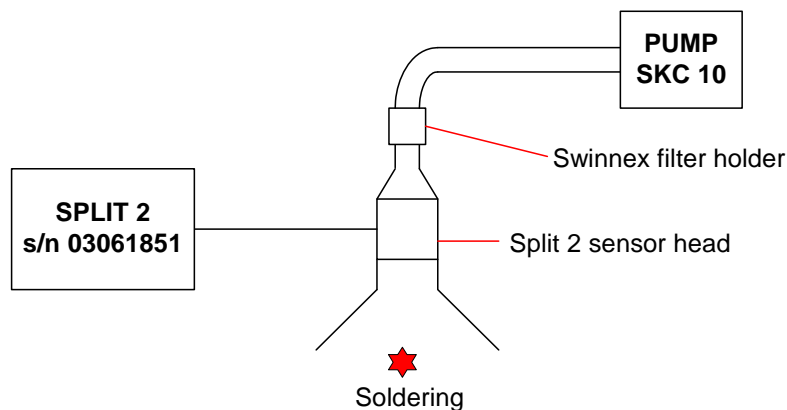
**Figure 2.8** Photograph and schematic diagram showing position of breathing zone sensor and soldering position for all tests

The instruments were calibrated against pumped samples collected on filters, as described in MDHS 83/2[7], to allow the calculation of a calibration factor to allow comparison between the personal and background measurements and comparison with previous exposure assessments in the literature. The Split 2 and Microdust Pro instruments were calibrated in a small wind tunnel using over a range of fume concentrations from 0 – 2  $\text{mgm}^{-3}$ , this was performed alongside a 13 mm 5  $\mu\text{m}$  pore size filter mounted in a standard Swinnex type sampling head, which was subsequently analysed using GC-FID, this is shown below in Figure 2.9. As during testing the breathing zone monitor would be exposed to concentrations exceeding 2  $\text{mgm}^{-3}$ , an additional hand calibration was carried out sampling the solder fume directly from the plume through the Split 2 sensor and collecting it onto a filter for analysis by GC-FID, this is shown in Figure 2.10. These two methods provided a calibration factor for each instrument which allowed us to calculate solder fume exposure that could be compared directly to results obtained using the standard analysis method.





**Figure 2.9** Wind tunnel calibration of real time dust monitors for concentration range 0 – 2 mgm<sup>-3</sup>



**Figure 2.10** Hand calibration of Split 2 real time dust monitor for concentration range 2 – 200 mgm<sup>-3</sup>

Previous work done at HSL[8] has shown that even at the higher ventilation rate of 5 ach the air inside the test room is not fully mixed. This means that the concentration measured at the background position is not representative of the average concentration in the test room as a whole, but at the measurement position and should be regarded only as an indication of the potential background exposure. In this report, when referred to, average background concentration means the average concentration at the background position over the period of a test.

### 2.3 TEST PROTOCOL & TESTING SCHEDULE

In general during Phase 2 tests were 16 minutes in duration, the exceptions to this were during testing of the tip extraction system to determine the time taken for the extract tube to become blocked and several tests studying the background fume concentration build up and decay. Average fume concentrations in the breathing zone and at the background position were calculated by discarding the first and last 30 seconds of each test, this gave an average concentration over 15 minutes making the result directly comparable with the short term exposure limit (S.T.E.L) of 0.15 mgm<sup>-3</sup> for colophony fume[4]. The diverging plume of fume created by soldering is narrow close to the breathing zone (typically 100 mm); it quickly rises vertically due to thermal effects but is highly susceptible to disturbing draughts. The narrow plume is highly concentrated and as such has a high concentration gradient; this means that only a small movement of the plume can drastically affect the exposure measured at the sampling position. When testing specific parameters, such as soldering scenario or LEV configuration, generally five replicates were performed and the mean exposure calculated to in an attempt to

account for the natural variation caused by the high concentration gradient of the plume. Three soldering scenarios were used. Moderate soldering was 1 s of soldering out of every 20 s, substantial soldering was 1 s out of every 10 s and extreme soldering was 2 s out of every 10 s.

For the majority of tests soldering was carried out on a standard size printed circuit board (PCB) measuring approximately 150 mm by 200 mm. Soldering was carried out using a pointed iron at a temperature of 360 °C. When testing the downdraught bench the PCB was positioned on the bench. By doing this the percentage open area of the extracted surface was reduced. To explore this effect further, tests were carried out using a large PCB, which measured approximately 380 mm by 360 mm.

Both the Split 2 and the Microdust Pro were checked against their own calibration filters before and after each set of five tests. The test room was purged with a general ventilation flow of 15 ach before each test until the average fume concentration at the background position was less than 0.010 mgm<sup>-3</sup>. The length of solder used for each test was weighed before and after to monitor the rate of use.

### **2.3.1 Uncontrolled Soldering**

The uncontrolled soldering set up was as shown above in Figure 2.8, with the background sampler in position B as shown in Figure 2.7. These tests were conducted on the table for comparison with the four LEV controls other than the downdraught bench. A summary of the tests carried out is as follows:

- Moderate soldering, general ventilation at 0.5 & 5 ach
- Substantial soldering, general ventilation at 0.5 & 5 ach
- Extreme soldering, general ventilation at 0.5 & 5 ach
- Extreme soldering, single long test to observe build up and decay of fume concentration, general ventilation at 0.5 ach
- Extreme soldering, long tests to observe build up and decay of fume concentration at two background positions, general ventilation at 5 ach to show effect of position of background fume concentration measurement

Two additional longer tests were performed to assess the build up and clearance of the background fume concentration. These tests comprised 45 minutes of extreme soldering with background fume concentrations being monitored for a further 45 minutes. In addition to the background sampler in the usual position, an extra Microdust Pro was placed at high level in the test room. This was positioned behind the right hand shoulder of the manikin, 0.3 m from the back wall, 1.6 m from the sidewall and 2.42 m from the ground.

### **2.3.2 Downdraught Bench**

It was necessary to perform a set of tests to measure exposure caused by uncontrolled extreme soldering on the downdraught bench because the table was higher than the bench making the geometry slightly different, although the position of the sensor relative to the soldering iron was identical. The PCB was always placed at the front edge of the bench, the soldering position was on the centreline 170 mm from the front edge and 25 mm from the bench surface as shown in Figure 2.8. A summary of the tests carried out is as follows:

**Table 2.1** Summary of testing carried out using the downdraught bench

Soldering scenario	Bench face velocity ms <sup>-1</sup>	PCB	PCB Position
Extreme	0.00	Small	On bench
Extreme	0.44	Small	On bench
Extreme	0.44	Large	On bench
Extreme	0.34	Small	On bench
Extreme	0.34	Large	On bench
Extreme	0.44	Small	175 mm above surface

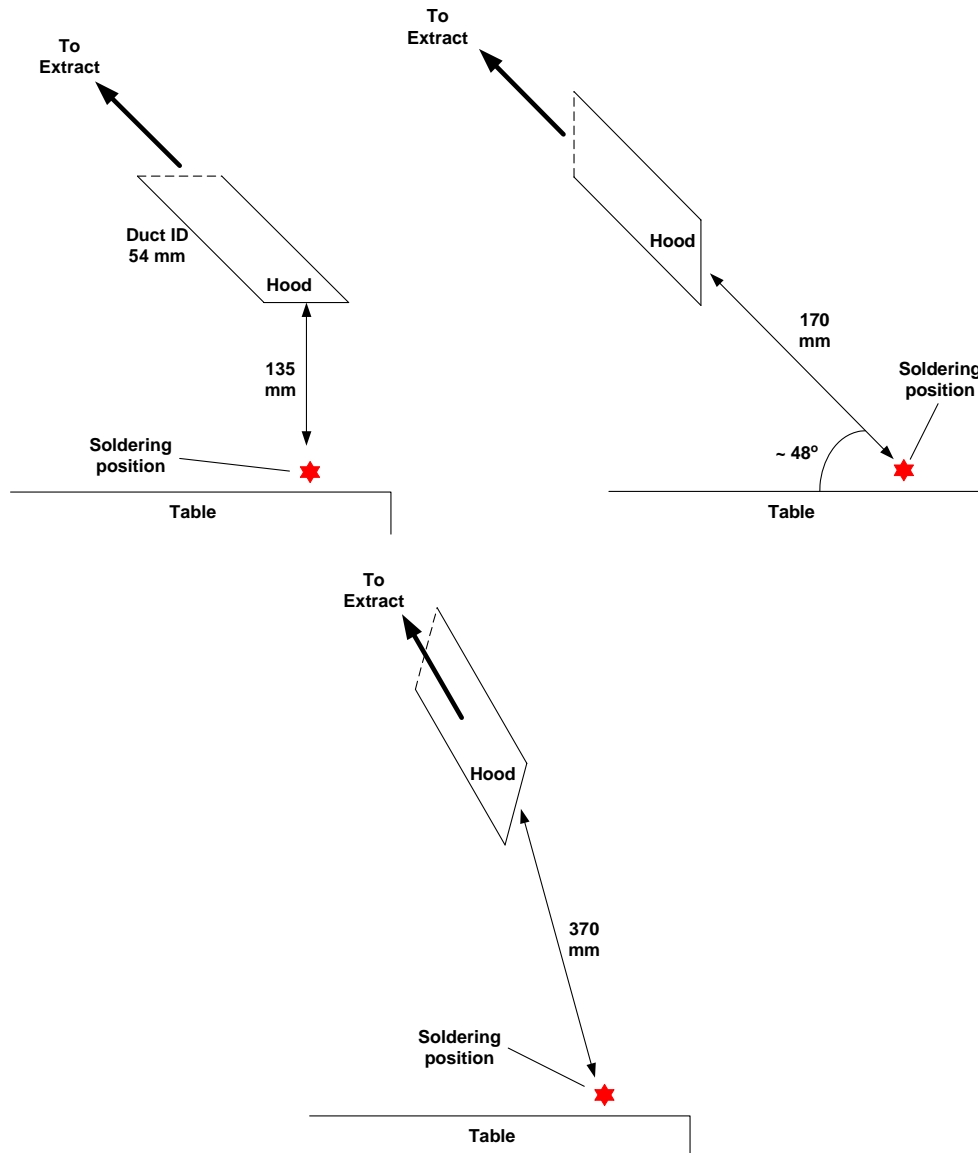
An additional one off test was carried out with the background sampler placed directly in the exhaust of the downdraught bench to assess filter efficiency.

### 2.3.3 Movable Capturing Hood

The mobile capturing hood was tested in three positions: good, realistic and poor as shown in Figure 2.11. The good position was directly above the soldering position at approximately 2.5 hood diameters. The second position was one more likely to be used by a real solderer as it did not obscure vision of the iron and work piece, this was behind the iron at an angle of 48° approximately three hood diameters from the soldering position. The final position was a poor one; above and behind the iron at approximately seven hood diameters, at the same height as the manikin's breathing zone. Each position was tested with the hood operating at two flow rates; the manufacturers recommended flow rate of 80 m<sup>3</sup>h<sup>-1</sup>, giving an average face velocity of 6.6 ms<sup>-1</sup>, and a reduced flow rate of 40 m<sup>3</sup>h<sup>-1</sup>, giving an average face velocity of 3.3 ms<sup>-1</sup>. General ventilation in the test room was set at 0.5 ach for all tests. A summary of the tests carried out is as follows:

**Table 2.2** Summary of testing carried out using the movable capturing hood

Soldering scenario	Hood position	Volume flow rate m <sup>3</sup> h <sup>-1</sup>
Extreme	Good	80
Extreme	Good	40
Extreme	Realistic	80
Extreme	Realistic	40
Extreme	Poor	80
Extreme	Poor	40



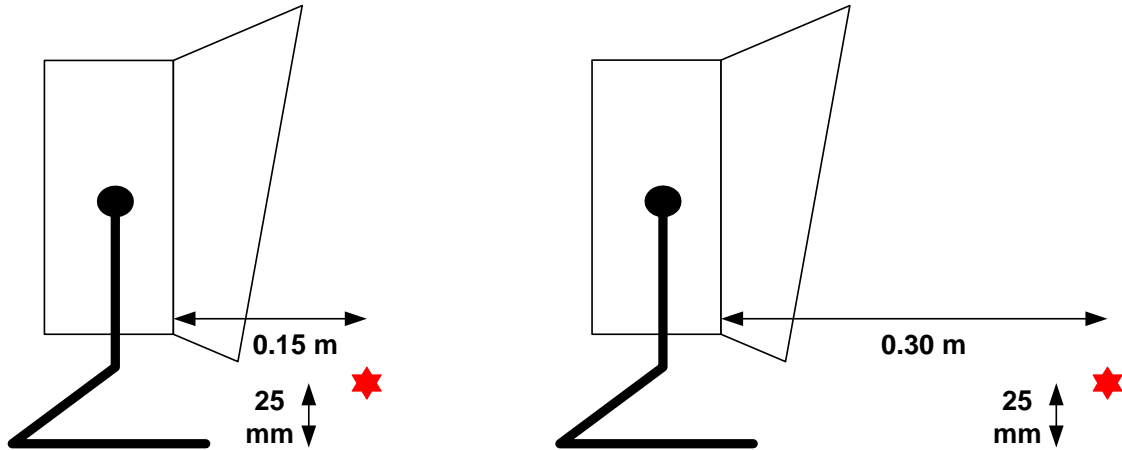
**Figure 2.11** Three positions of mobile capturing hood tested. Good position (top left), realistic position (top right) and poor position (bottom)

A series of tests were also performed to measure the capture efficiency of the mobile capturing hood. This was done by sampling soldering fume in the extract duct and calculating the ratio of fume concentration in the duct under specific test conditions to the fume concentration in the duct when all of the fume was captured, i.e. 100 %. Fume was sampled from within the duct at a position approximately 15 duct diameters downstream from the final bend, shown in the schematic portion of Figure 2.2, using a TSI Sidepak dust monitor. This sampling position was selected from experience gained during previous work[9] as a position at which the fume had fully mixed with the extracted air within the duct. A summary of the tests is given below:

- 100% capture measurements for both the high and low volume flow rates
- Capture efficiency measurements at the poor position at both high and low volume flow rates
- Capture efficiency measurement at the realistic position at the low volume flow rate

### 2.3.4 Air Displacement Box (ADB)

The air displacement box was tested in two positions, good and bad. The extent of the effective capturing zone was determined using a smoke tube, good and bad positions were defined as being inside and outside of the effective capturing zone, and these are shown in Figure 2.12. General ventilation in the test room for all tests was set at 0.5 ach.

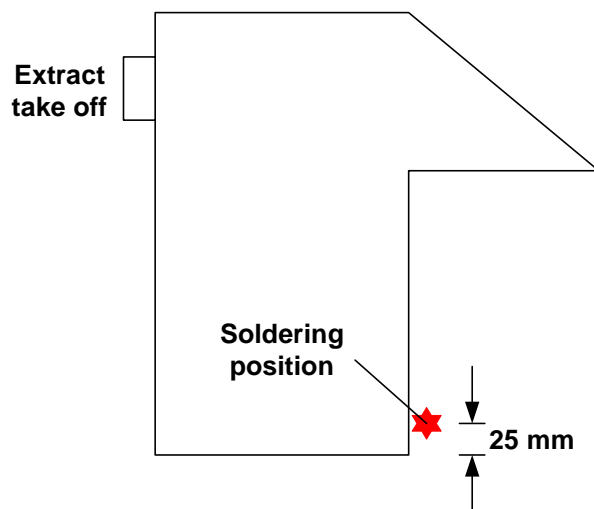


**Figure 2.12** Soldering positions for ADB tests, good position on left and poor position on right

Tests were carried out for extreme soldering in the good and bad positions.

### 2.3.5 Enclosing Hood

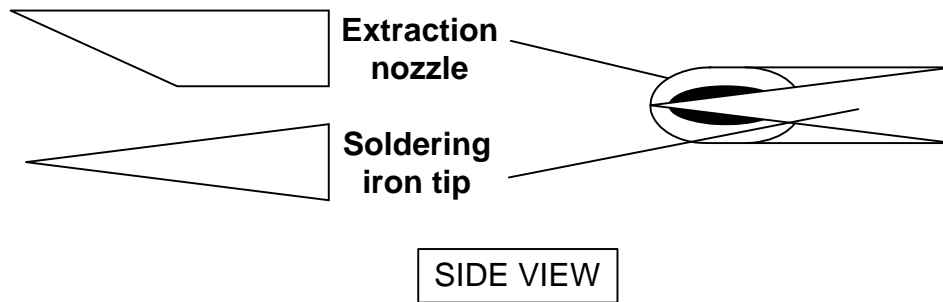
The enclosure was designed to operate with soldering taking place inside so it was only tested in this configuration, as shown below in Figure 2.13. Two operating volume flow rates were tested, these were  $80 \text{ m}^3\text{h}^{-1}$  and  $40 \text{ m}^3\text{h}^{-1}$  the same as for the mobile capturing hood. General ventilation for both sets of tests was set at 0.5 ach. Tests were carried out for extreme soldering inside the enclosure operating at both the high and low volume flow rate.



**Figure 2.13** Soldering position for tests using the enclosing hood

### 2.3.6 On-tip Extraction System (LVHV)

The system was tested with the extract nozzle in two orientations with respect to the soldering iron tip, vertically above and horizontally to the side, as shown below in Figure 2.14. The volume flow rate of the tip system had already been characterised during previous work, and was not altered for these tests; i.e. it was tested as found and allowed to block up naturally. Additional tests were performed afterwards to determine the time it took for the extract to become completely blocked.



**Figure 2.14** Two positions of extract nozzle tested, nozzle vertically above iron (left) and nozzle horizontally to the side of the iron (right)

A summary of the tests carried out is given below:

- Extreme soldering using the on-tip extraction system with the extract nozzle positioned vertically above the soldering iron tip
- Extreme soldering using the on-tip extraction system with the extract nozzle positioned horizontally to the side of the soldering iron tip
- Additional tests, extreme soldering using the on-tip extraction system with the extract nozzle positioned horizontally to the side of the soldering iron tip to determine time required for extract nozzle to block

## 3 EXPERIMENTAL RESULTS AND DISCUSSION

### 3.1 UNCONTROLLED SOLDERING

Table 3.1 below shows the measured fume concentrations in the breathing zone and at the background position. The results quoted in this table are the mean of five repeated determinants of the same test. As has been discussed in the previous section, average background concentration is the mean concentration at the background position over the course of the test and not the average concentration in the whole room.

*Table 3.1 Fume concentrations in the breathing zone and at the background position for uncontrolled soldering on the bench*

Soldering scenario	General ventilation rate ach	Mean mass of solder used mg	Average personal exposure $\text{mgm}^{-3}$ (St. Dev.)	Average background exposure $\text{mgm}^{-3}$ (St. Dev.)
Moderate	0.5	911	4.75 (1.39)	0.041 (0.009)
Moderate	5	956	3.74 (0.92)	0.010 (0.004)
Substantial	0.5	1752	14.02 (5.48)	0.208 (0.104)
Substantial	5	1727	9.27 (3.96)	0.015 (0.011)
Extreme	0.5	2652	17.79 (5.76)	0.170 (0.046)
Extreme	5	2498	13.34 (3.60)	0.068 (0.036)

As can be seen in Table 3.1, increasing the soldering frequency (from moderate to substantial to extreme) increases the average personal exposure. This is not a surprising result, as more solder was used, more fume was produced and therefore personal exposure increased. The average rate of solder use during moderate, substantial and extreme soldering was 1.0, 1.8 and 2.7  $\text{mgs}^{-1}$  respectively. Average fume concentration at the background position increased for substantial and extreme soldering when the general ventilation rate was 0.5 ach, both values exceeded the short-term 15-minute exposure limit of 0.15  $\text{mgm}^{-3}$  although the measured concentration was higher during the substantial test than the extreme test.

Personal exposure was significantly lower during tests performed at the higher general ventilation rate of 5 ach. There are two possible reasons for this: qualitative observations during the tests noted that the solder fume plume tended to move around more under the higher general ventilation conditions, this may be due to the greater degree of mixing within the room. Another possible reason could be the increased general ventilation diluting the background levels of fume, although this seems less likely as the differences in personal exposure between the two ventilation settings were an order of magnitude higher than the differences in background fume concentration.

Comparing background fume concentrations during the tests at 0.5 ach to those at 5 ach it can be seen that the greater dilution controlled the background concentration to a lower level. Background fume concentration did not exceed the short-term exposure limit during any of the tests at 5 ach; the concentration during the extreme test did exceed the long-term 8-hour TWA exposure limit of 0.05  $\text{mgm}^{-3}$ . Although it should be noted that 15 minutes is not long enough for the background fume concentration to reach equilibrium.

Table 3.2 below shows the measured fume concentrations in the breathing zone and at two background positions during the longer single tests at 0.5 and 5 ach. These tests lasted 90 minutes; 45 minutes of extreme soldering, during which both personal and background fume

concentrations were measured, followed by a further 45 minutes without soldering to observe the dilution of the background fume by the general ventilation. In these tests an additional background sampler was placed at approximately 2.4 m from the floor to observe the difference in fume concentration at different positions within the room. Full plots of the background fume concentration over the whole 90 minutes at both positions and general ventilation rates are shown in Figures 3.1 & 3.2. The results show that the personal exposure levels for extreme soldering at the two general ventilation rates appear to be reversed from the shorter tests. However, as was previously noted [10] the plume of solder fume has a high concentration gradient which means that the plume only has to drift a little to move into or out of the manikin's breathing zone. Taking this into account and considering that  $13.6 \text{ mgm}^{-3}$  and  $19.5 \text{ mgm}^{-3}$  are both approximately 100 times the S.T.E.L and both values were averaged over a 45-minute duration, they both represent gross exposure and there is in fact little difference between them.

The results below and the concentration plots shown in Figures 3.1 & 3.2 show that at the lower general ventilation rate of 0.5 ach there is a significant difference in fume concentration between the two background positions. Whereas at the higher general ventilation rate of 5 ach the average fume concentration at the two positions was similar and this is reflected in the plots shown in Figure 3.2, which are almost identical. The differences between fume concentrations at the two general ventilation rates are most likely caused by the higher degree of mixing at the higher air change rate, creating a more homogeneous atmosphere. Whereas at the lower ventilation rate the results suggested there is some stratification taking place.

At both air change rates and at all positions, the average fume concentration over the 45 minutes of soldering exceeded the S.T.E.L; i.e. just being in the room would result in exposure exceeding the S.T.E.L. It should also be noted from calculations based on perfect mixing that at 5 ach, the time taken for a contaminant to reach 95 % of the equilibrium concentration is 36 minutes and at 0.5 ach is 359 minutes. This means that at the lower general ventilation rate the background fume concentration had not reached equilibrium and would continue to rise.

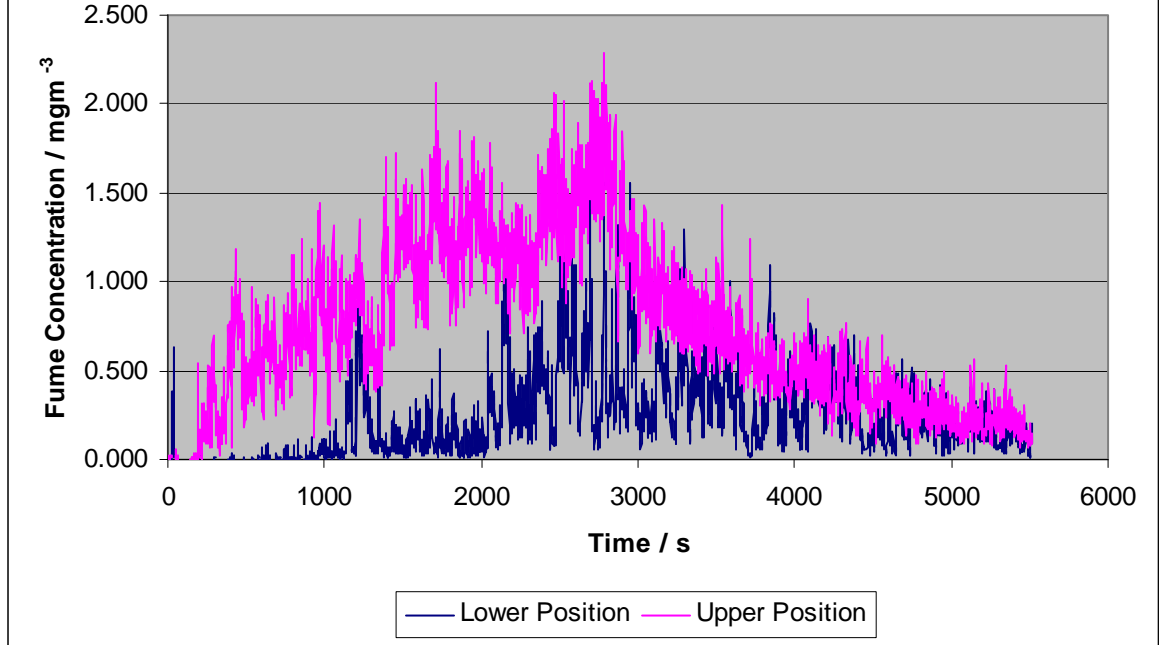
**Table 3.2** *Fume concentrations in the breathing zone and at two background positions for uncontrolled soldering on the bench during longer tests*

Soldering scenario	General ventilation rate ach	Average personal exposure $\text{mgm}^{-3}$	Average background exposure <sup>1</sup>	
			Lower Position $\text{mgm}^{-3}$	Upper Position $\text{mgm}^{-3}$
Extreme	0.5	13.64	0.182	0.938
Extreme	5	19.49	0.172	0.195

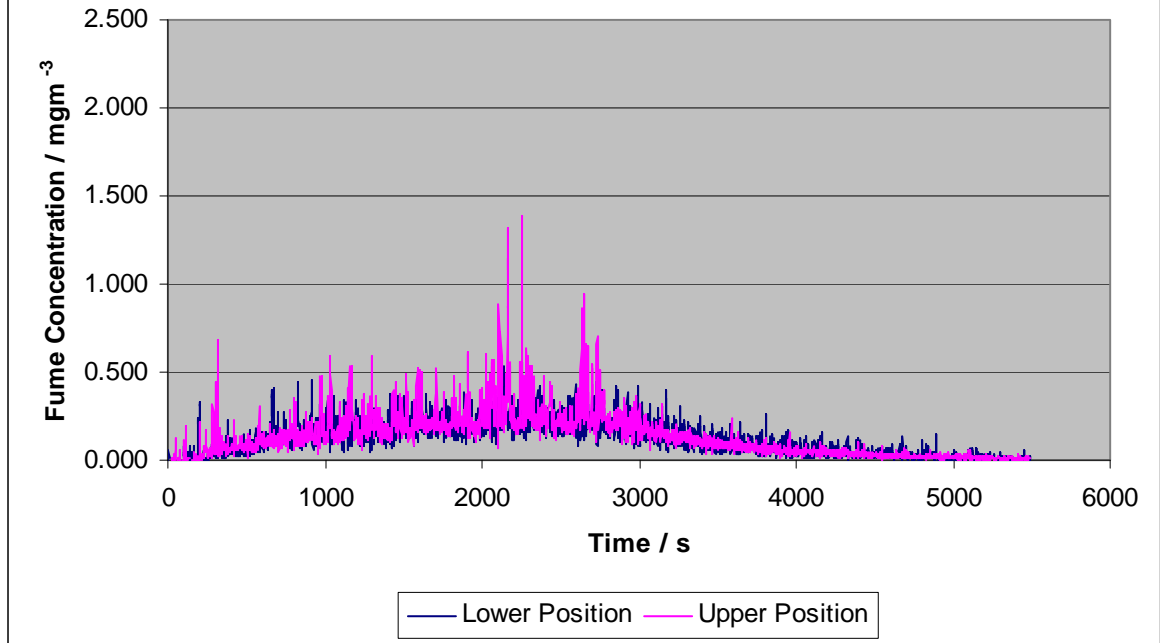
<sup>1</sup> This is the average fume concentration at each point over the first 45 minutes of the test whilst soldering was taking place and does not include the period when the fume concentration was being decreased by the room ventilation.



**Figure 3.1** Fume concentration at two background positions  
Extreme soldering 0.5 ach

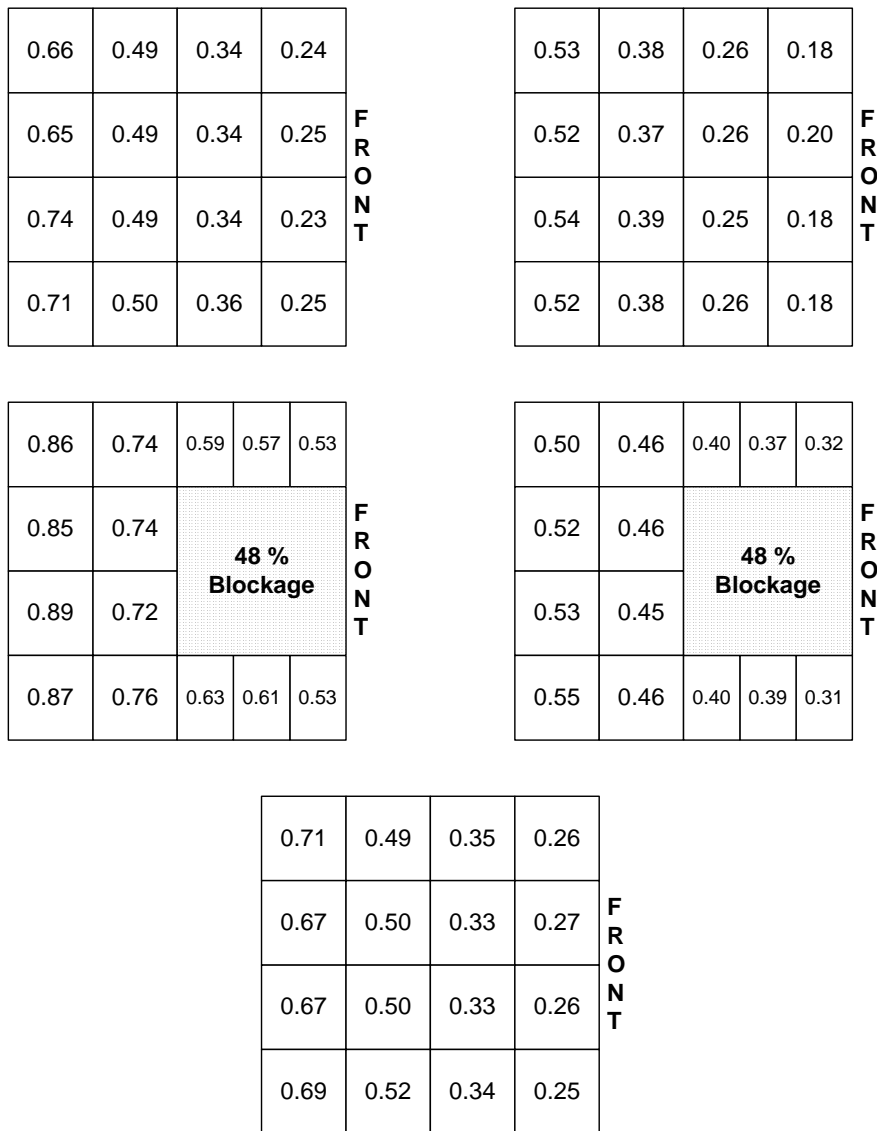


**Figure 3.2** Fume concentration at two background positions  
Extreme soldering 5 ach



### 3.2 DOWNDRAUGHT BENCH

The face velocity of the downdraught bench was measured in several configurations and at several volume flow rates. The manufacturers recommended flow rate for controlling solder fume with the fan speed controller set at approximately 75 %, an arbitrarily selected volume flow rate with the fan speed controller set at approximately 25 % and with the bench at maximum flow. The recommended and low volume flow rates were measured with and without the large printed circuit board, which blocked 48 % of the extracted surface. The maximum flow was only measured with no obstruction and is only given as a reference. The results of the face velocity measurements and the total volume flow are shown below in Figure 3.3 and Table 3.3, the quoted velocities are the mean of five measurements made at the centre of each square or rectangle.



**Figure 3.3** Schematic velocity profiles of the downdraught bench: manufacturers recommended flow (top left), reduced flow (top right), recommended flow with large blockage (middle left), reduced flow with large blockage (middle right) and maximum flow (bottom)

*Table 3.3 Downdraught bench average face velocities and volume flow rates*

Fan Speed Setting	Obstruction	Average Face velocity ms <sup>-1</sup>	Total Volume Flow m <sup>3</sup> h <sup>-1</sup>
Recommended	None	0.44	575
Recommended	Large PCB	0.71	522
Reduced	None	0.34	436
Reduced	Large PCB	0.44	321
Maximum	None	0.45	579

The face velocity was even from left to right but not quite symmetrical, this may be due to the inlet to the fan being on the left hand side as viewed from the front. There was a significant gradient from front to back; this was because the extracted surface was horizontally displaced from the main body of the bench with the front portion sticking out at the front as shown in Figure 2.5. The presence of the large obstruction reduced the volume flow rate by 9 % and 26 % for the recommended and reduced volume flow settings respectively. This had the effect of increasing the average face velocity at both operating flow rates due to the reduced extracted area. The average face velocity and volume flow with the bench set at the manufacturers recommended flow rate of 75 % on the fan control was essentially the same as when it was set at maximum.

Measured fume concentrations in the breathing zone and at the background position for tests on the downdraught bench are given below in Table 3.4. Personal and background exposures were measured again for uncontrolled extreme soldering on the downdraught bench. This measurement was made again because although the mannequin was set up so as that the breathing zone was in the same position relative to the soldering iron as for the other controls used on the ordinary table, the downdraught bench was a different height and shape. All tests with the downdraught bench were carried out with a general ventilation rate of 0.5 ach.

Average fume concentration in both the breathing zone and background positions were approximate 50 % greater than when measured on the ordinary table. As can be seen, control was very good when the bench was operating at the recommended flow, personal and background exposure were essentially zero during these tests. Observation of the tests showed that occasional small wisps of fume seemed to drift away from the bench, but not through the breathing zone of the manikin.

When the flow was reduced by approximately a quarter some control of the fume was lost. Although fume concentrations measured at the background position were negligible, personal exposure was 0.13 mgm<sup>-3</sup> with the small PCB and 0.72 mgm<sup>-3</sup> with the large PCB. Exposure when soldering on the small PCB with the bench at reduced flow was close to the S.T.E.L and it is likely that if this activity was undertaken throughout a work shift significant exposure would occur. The combination of reduced volume flow rate and the large obstruction further reduced the volume flow into the bench to approximately half of the recommended value, this caused significant exposure – almost five times the S.T.E.L. During these tests solder fume was observed rising upward from the iron into the breathing zone of the manikin before being overcome by the down flow of air into the bench and being extracted. This would explain the relatively high personal exposure with little fume seeming to escape into the background.

**Table 3.4** Fume concentrations in the breathing zone and at the background position using the downdraught bench to control extreme soldering

Test Conditions	Volume Flow Rate $\text{m}^3\text{h}^{-1}$	Mean mass of solder used mg	Average Personal Exposure $\text{mgm}^{-3}$ (St. Dev.)	Average Background Exposure $\text{mgm}^{-3}$ (St. Dev.)	Protection Factor
Uncontrolled extreme soldering on downdraught bench	0	2488	28.27 (4.63)	0.267 (0.080)	
Recommended flow small PCB	575	2888	0.00 (0.00)	0.001 (0.001)	$\infty$
Recommended flow large PCB	522	2770	0.01 (0.01)	0.002 (0.000)	2827
Low flow small PCB	436	2789	0.13 (0.06)	0.001 (0.000)	217
Low flow large PCB	321	2607	0.72 (0.26)	0.007 (0.003)	39
Recommended flow small PCB raised 175 mm	575	2597	0.08 (0.12)	0.001 (0.000)	353

A single test was performed with the background sampler placed in the exhaust of the downdraught bench. The average fume concentration measured in the exhaust over the course of a 15-minute test with extreme soldering was  $0.000 \text{ mgm}^{-3}$ , i.e. no particulate phase fume was detected indicating complete fume filtration.

### 3.3 MOBILE CAPTURING HOOD

The mobile capturing hood was tested in three positions at two operating flow rates; all tests were performed using extreme soldering with the general ventilation rate at 0.5 ach. The results are shown below in Table 3.5 along with fume concentration measurements for uncontrolled extreme soldering from Table 3.1.

As can be seen with the hood in a good or realistic position a high degree of control was achieved. The maximum fume concentration measured in the breathing zone was  $0.03 \text{ mgm}^{-3}$ , which is less than the 8-hour TWA W.E.L. Background fume levels were consistently low, typically approximately 20 % of the W.E.L. When the hood was placed in the poor position gross exposure occurred in the breathing zone of the manikin,  $3.37 \text{ mgm}^{-3}$  at the high flow rate and  $8.35 \text{ mgm}^{-3}$  at the low flow rate, this is 20 and 50 times the S.T.E.L respectively. Background fume concentrations were still low, although at the low flow rate the average concentration at the background position exceeded the 8-hour W.E.L. With the hood in the poor position, observation showed that much of the fume was captured and extracted, but as the hood was positioned near to the breathing zone some exposure occurred. Collectively these results show that the mobile capturing hood can be used to effectively control the solder fume if it is positioned correctly, repositioned when the soldering point moves and an adequate flow rate is maintained. Although it should be noted that background air movement was low. As background air movement increases it is likely that control will be less effective.

**Table 3.5** Fume concentrations in the breathing zone and at the background position using the mobile capturing hood to control extreme soldering

LEV Position	Volume Flow Rate $\text{m}^3\text{h}^{-1}$	Mean mass of solder used mg	Average Personal Exposure $\text{mgm}^{-3}$ (St. Dev.)	Average Background Exposure $\text{mgm}^{-3}$ (St. Dev.)	Protection Factor
Uncontrolled extreme	N/A	2652	17.79 (5.76)	0.170 (0.046)	N/A
Good	80	2815	0.01 (0.01)	0.008 (0.004)	1779
Good	40	2999	0.00 (0.00)	0.011 (0.011)	$\infty$
Realistic	80	2804	0.00 (0.01)	0.006 (0.002)	$\infty$
Realistic	40	2720	0.03 (0.04)	0.007 (0.002)	593
Poor	80	2831	3.37 (1.41)	0.012 (0.004)	5
Poor	40	2778	8.35 <sup>2</sup> (1.67)	0.077 (0.011)	2

A series of tests were performed to determine the capture efficiency of the mobile capturing hood for extreme soldering, the results are given below in Table 3.6. The 100 % test position was similar to the good position but the hood face was less than 1 hood diameter from the soldering iron.

**Table 3.6** Duct fume concentration and capture efficiency measurements of the mobile capturing hood in the poor and realistic positions

LEV Position	LEV Volume Flow Rate $\text{m}^3\text{h}^{-1}$	Average Fume Concentration $\text{mgm}^{-3}$	Capture Efficiency %
100 %	80	3.34	-
100 %	40	5.52	-
Poor	80	2.41	72
Poor	40	3.50	63
Realistic	40	5.27	95

The capture efficiency was then measured at the poor position for the high and low volume flow rate and at the realistic position for the low volume flow rate. The results are very interesting; at the poor position and at the high volume flow rate the measured capture efficiency was greater than 70 %. Considered in isolation this could be misleading, a capture efficiency of 70 % may seem satisfactory but when we consider that using the mobile capturing hood in this configuration leads to a personal exposure over 20 times the exposure limit it seems less so. The hood in the realistic position at the low volume flow rate had a capture efficiency of 95 %, this still equates to an average personal exposure of  $0.03 \text{ mgm}^{-3}$ . It was assumed that in the realistic position at the high volume flow rate and in the good position capture efficiency would be greater than 95 % and so was not measured.

### 3.4 AIR DISPLACEMENT BOX (ADB)

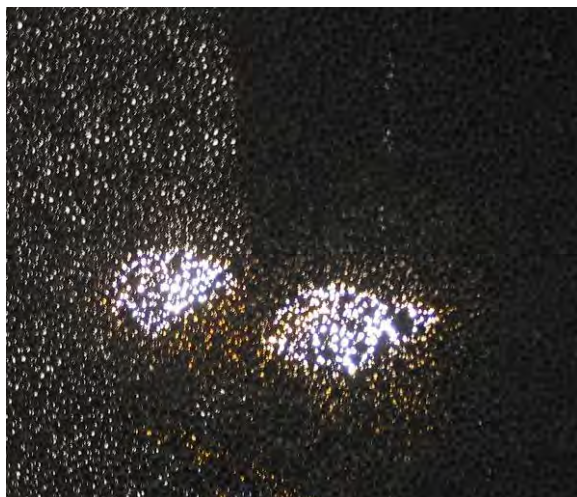
The ADB was tested in two positions relative to the soldering iron, good and bad. Before testing the effective capturing zone was defined using a smoke tube, the good position was inside this zone and the poor position just outside of it; the results are shown below in Table 3.7.

<sup>2</sup> This result is the mean concentration from 4 replicates, not the usual 5.

**Table 3.7** Fume concentrations in the breathing zone and at the background position using the air displacement box to control extreme soldering

LEV Position	Mean mass of solder used mg	Average Personal Exposure $\text{mgm}^{-3}$ (St. Dev.)	Average Background Exposure $\text{mgm}^{-3}$ (St. Dev.)	Protection Factor
Uncontrolled	2652	17.79 (5.76)	0.170 (0.046)	-
Good	2791	0.21 (0.04)	0.385 (0.030)	85
Poor	2809	0.43 (0.18)	0.372 (0.026)	41

The results show that average personal exposure is greater than the S.T.E.L regardless of the soldering position relative to the ADB. In tests where personal exposure occurred these were the only ones where background fume concentrations exceeded those in the breathing zone. It is interesting to note that the background levels were essentially the same for the two tests and both higher than that measured during uncontrolled extreme soldering.



**Figure 3.4** Photograph of activated carbon filter from the air displacement box held up to a light

Visual observation of the tests showed that in the good position almost the entire fume was drawn into the ADB, whereas in the poor position some was drawn into the ADB and some rose through the breathing zone of the manikin. This would explain the higher personal exposure in the poor position. In the good position almost no fume was seen to pass through the breathing zone, and therefore the personal exposure of  $0.21 \text{ mgm}^{-3}$  was likely caused by the build-up in the background concentration. Previous work has clearly demonstrated the unfiltered fume was present in the exhaust of the ADB[10]. Figure 3.4 above shows a photograph of one of the filters from the ADB. As can be seen the filter is porous and has holes several millimetres in diameter explaining why the filtration efficiency is considerably less than 100 %.

It would probably be more accurate to think of the ADB as a fume disperser than a fume extractor. Although the filter may absorb some of the fume, a significant proportion of it is exhausted back into the room and the mixing effect of the fan helps to create a homogeneous atmosphere within the room, shown by the similar background concentrations of the two sets of tests. When used and positioned correctly the ADB does protect the worker from direct exposure, but if used extensively simply replaces this with low-level secondary exposure that would also affect anybody else within the room.

### 3.5 ENCLOSING HOOD

The enclosure was tested at two operating volume flow rates, 80 m<sup>3</sup>h<sup>-1</sup> and 40 m<sup>3</sup>h<sup>-1</sup> the same as the mobile capturing hood. The results are shown below in Table 3.8.

*Table 3.8 Fume concentrations in the breathing zone and at the background position using the enclosing hood to control extreme soldering*

Volume Flow Rate m <sup>3</sup> h <sup>-1</sup>	Mean mass of solder used mg	Average Personal Exposure mgm <sup>-3</sup> (St. Dev.)	Average Background Exposure mgm <sup>-3</sup> (St. Dev.)	Protection Factor
Uncontrolled extreme soldering	2652	17.79 (5.76)	0.17 (0.046)	-
80	2849	0.00 (0.00)	0.005 (0.001)	∞
40	2771	0.00 (0.00)	0.010 (0.007)	∞

As can be seen the enclosure adequately controlled the emission of solder fume at both operating volume flow rates, it may even be possible to further reduce this flow rate. Background concentration levels were essentially zero. Without taking into account any ergonomic considerations or process requirements, the enclosure is a highly effective control measure. It provides physical separation of the worker's breathing zone from the process and removes the contaminant from the workplace, although some fume was detected at the background position this was at an extremely low level and is likely to be the residual background particle concentration in the room from previous tests. With suitable filtration the extracted air can also be returned to the workplace. However the enclosure is relatively small and would only work effectively if the process takes place inside of it. It would, for example be extremely difficult to solder on the large PCB used in the downdraught bench tests whilst maintaining effective control with the enclosure. For this a large design would be required.

### 3.6 ON-TIP EXTRACTION SYSTEM (LVHV)

The on-tip system was tested in two orientations; with the extract nozzle vertically above the iron tip and to the side; results are shown below in Table 3.9. There was no facility on the system to alter the volume flow rate so the extract tubing was cleaned before beginning and then tested as found. The volume flow was measured and found to be approximately 29 lmin<sup>-1</sup> or 1.7 m<sup>3</sup>h<sup>-1</sup> at maximum flow. Because of the way the extraction tube was mounted within the iron it was not possible to test the system with a larger diameter extraction tube.

*Table 3.9 Fume concentrations in the breathing zone and at the background position using the tip system to control extreme soldering*

LEV Orientation	Mean mass of solder used mg	Average Personal Exposure mgm <sup>-3</sup> (St. Dev.)	Average Background Exposure mgm <sup>-3</sup> (St. Dev.)	Protection Factor
Uncontrolled extreme soldering	2652	17.79 (5.76)	0.17 (0.046)	-
Vertically above	2724	0.00 (0.00)	0.008 (0.003)	∞
Horizontally beside	2559	0.00 (0.00)	0.007 (0.006)	∞

The results show that the tip extraction system is highly effective at controlling solder fume emissions; personal exposure levels were zero and background levels were negligible. The orientation of the extraction nozzle with respect to the soldering iron tip made no difference to

control effectiveness. The only parameter that affected control was the volume flow rate through the system and therefore the air velocity generated at the extraction tip. At maximum flow the system generated a calculated velocity of approximately  $24 \text{ ms}^{-1}$  at the tip, but as fume condensed in the tube, volume flow and hence face velocity decreased. In the tests shown above in Table 3.9 visual observation showed that very little fume escaped, some fume was seen to move up to approximately 100 mm from the extraction nozzle before being recaptured and extracted. Occasionally some fume was seen to escape entirely; initially this was rare but as testing progressed became more common.

After the LEV orientation testing was complete a further series of tests were carried out to determine the time taken for condensed fume to block the extraction system completely using the extreme soldering scenario; the results of these tests are shown below in Table 3.10.

**Table 3.10** Fume concentrations in the breathing zone and at the background position using the on-tip extraction system to control extreme soldering

Test Number	Average Personal Exposure <sup>3</sup> mgm <sup>-3</sup>	Average Background Exposure mgm <sup>-3</sup>
OT11	0.00	0.013
OT12	0.00	0.020
OT13	0.63	0.260

Before starting tests OT11 – OT13 a further twenty minutes of extreme soldering was performed whilst observing the performance of the LEV system. The system continued to have intermittent losses of control allowing small amounts of fume to escape capture. Most of these did not pass through the breathing zone of the manikin, but just rose straight into the background room air. Tests OT11 – OT13 were performed with the extract in the horizontal position using the extreme soldering scenario.

As can be seen in Tests OT11 and OT12 the personal exposure was zero, however approximately 1 minute into Test OT13 the extract completely failed. At this point the solder fume emission was completely uncontrolled and all of the generated fume was released into the room air, some passing through the breathing zone of the manikin. The loss of control was caused by a blockage in the extraction tubing created by condensed solder fume, in this case the blockage occurred at the point where the flexible tubing entered the base extraction unit. A significant amount of fume had also condensed in the extraction nozzle tip; a close up photograph of condensed fume in the extract tip after a series of tests is shown in Figure 3.3.

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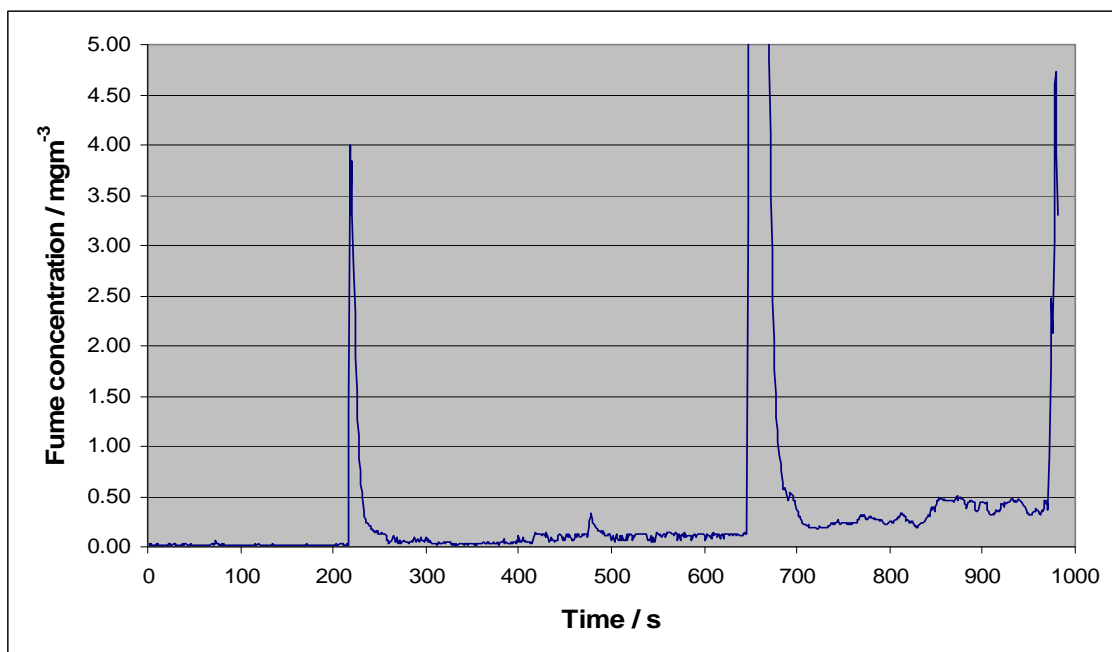
<sup>3</sup> These results show the average fume concentrations from single 15-minute tests conducted to determine the time taken for condensed solder fume to block the extraction system.





**Figure 3.3** Close up photograph showing condensed colophony fume in the extraction nozzle tip. Fume also tended to condense at the point where the tube enters the extraction base unit

The personal exposure data from Test OT13 is shown in Figure 3.4. The plot shows several large peaks at 3 - 5  $\text{mgm}^{-3}$  caused by fume passing directly through the breathing zone, it also shows a steady increase in exposure caused by the rising background levels.



**Figure 3.4** Fume concentration in the breathing zone of the manikin during extreme soldering controlled by on-tip extraction – TEST OT13

### 3.7 GENERAL DISCUSSION OF SOLDER FUME CONTROL

Fume concentrations measured during uncontrolled soldering in this study were of comparable magnitude to those measured during the study in 2003[6]. The standard method for measuring resin acids in solder flux fume is to use a 13 mm diameter 5 µm pore size filter mounted in a standard Swinnex type sampling head that in turn is mounted on the side arm of a pair of spectacles as detailed in HSE MDHS 83/2[7]. This method detects total resin acid concentration in an air sample collected onto a filter that is subsequently analysed in the laboratory. Several studies have been conducted using field-based trials collecting exposure data in workplaces using this method, these surveys generally reported total resin acid (TRA) concentrations in the range 0.00 - 2.29 mgm<sup>-3</sup>[11, 12].

An older method for measuring exposure to solder flux fume is to place the filter on the lapel, this method was used by Watson et al in field exposure assessments and measured concentrations of 0.02 - 0.19 mgm<sup>-3</sup> as an 8-hour TWA for uncontrolled and controlled soldering[13]. A further paper made exposure assessments in the field using an unspecified method sampling 'in the breathing zone'; they recorded concentrations of 0.02 - 0.65 mgm<sup>-3</sup> for controlled and uncontrolled soldering[14]. A paper by Pengelly et al[15] found that personal samples located near the breathing zone on a pair of spectacles collected 4 - 5 times as much fume as one located on the lapel. All of these methods involve the collection of a pumped air sample onto a filter for subsequent chemical analysis to determine the TRA concentration.

Solder fume concentration measurements of uncontrolled soldering showed that the plume of fume has a very high 'source strength'. This is to say that only a very short exposure to the plume will broach the short-term exposure limit and any prolonged exposure will very likely exceed the long-term limit very quickly. For instance, as shown in Table 3.1, 15 minutes of uncontrolled moderate soldering in a room with 0.5 ach general ventilation caused an average personal exposure of 4.75 mgm<sup>-3</sup>. This is over 30 times the S.T.E.L and equates to an 8-hour TWA exposure of 0.15 mgm<sup>-3</sup>, which is three times the W.E.L. This is only reduced to an average personal exposure of 3.74 mgm<sup>-3</sup> when performed in a room with a general ventilation rate of 5 ach, which still equates to an 8-hour TWA exposure twice the W.E.L after only 15 minutes of soldering. This being where moderate soldering is defined as 1 second of soldering in twenty. These results clearly demonstrate the need to use controls to effectively control solder fume exposure.

When comparing the controls, several factors need to be taken into account. These are effectiveness i.e. by how much does it reduce exposure, and usability - which includes suitability to process and ergonomic considerations and filtration.

When considering effectiveness alone, four of the controls are capable of reducing exposure to zero if maintained and used correctly. These are the downdraught bench, the mobile capturing hood, the enclosing hood and the on-tip extraction system. The air displacement box could possibly reduce exposure to zero but would have to be used in a sufficiently large space to dilute the unfiltered exhaust or be used only for very short duration tasks. As tested, in a small room (~47 m<sup>3</sup>) with a low ventilation rate, the build up of fume in the background causes significant exposure making the ADB unsuitable for long term use.

Having established that four of the five controls can adequately reduce exposure the usability of each system must be considered. The downdraught bench has several advantages; it is easy to work within the effective zone as the work piece can be placed on the extracted surface of the bench, which is effectively the face of a large low velocity hood. There are little or no ergonomic considerations as the bench simply replaces an ordinary bench, and it is simple to use, however the area of the extracted surface limits the size of the work piece. Obviously

anything with an area larger than the bench would require a larger bench. Also the bench would have little effect on fume generated from soldering inside large bulky pieces of equipment such as a television or tower pc that would shield the work area from the downward flow of air. A single test was performed on the downdraught bench with the soldering position raised 175 mm from the bench surface at the recommended volume flow rate. This resulted in exposure of  $0.08 \text{ mgm}^{-3}$ , which is greater than the W.E.L but less than the S.T.E.L. This implies that as the source moves away from the surface of the bench control is compromised. The combination of filters in the bench that was tested were highly effective. A measurement made in the exhaust using the Microdust Pro instrument had an average fume concentration of  $0.000 \text{ mgm}^{-3}$ , that is to say no particulate phase fume was detected in the downdraught bench exhaust. Although it should be noted that these tests only apply to the pre and particle filters as no sampling of the gaseous phase fume was performed. There is no visual indication on the bench of the volume flow rate or average face velocity, which could be a problem as testing showed that even a 25 - 35 % reduction can lead to a loss of control, this would cause an increased pressure drop as the filters become loaded.

The mobile capturing hood, as has been noted, is capable of reducing both personal and background exposure to zero if used correctly. With the capturing hood it is important that it be positioned correctly in order to capture the solder fume, i.e. the soldering position has to be within the effective capturing zone – or in a position where the entire fume rises into the capture zone. Traditionally capturing hoods operate by capturing contaminants and extracting them by inducing sufficient air velocity at the source. However, soldering is a hot process and the fume is emitted with an upward velocity. This means that if positioned above the iron it can operate in a mixed mode by intercepting the fume as it rises and capturing it.

When positioned in the good position the hood performed excellently, reducing exposure to zero at both the recommended and reduced flow rates. The good position was directly above the iron at approximately 2.5 hood diameters, this is further from the source than is generally recommended for capturing hoods, but with the thermal uplift provided by the hot iron it was able to capture the entire fume. The realistic position was further from the source – approximately 3.5 hood diameters – above and slightly behind the iron. This placed the soldering position outside of the effective capturing zone of the hood; the rising plume meant that the fume passed through this zone where it was captured. The poor position was approximately 7.5 hood diameters from the source above and behind the iron. This meant that although the rising plume passed through the capturing zone of the hood it also passed through the breathing zone of the worker causing high exposures at both flow rates.

The mobile hood was difficult to move once in position and because it only had two articulated joints was difficult to get into some positions. In the three positions tested the volume flow rate was not the primary factor in control. Rather it was position, as exposure was controlled in the good and realistic positions at both flow rates and not controlled in the poor position at both flow rates. Nevertheless, maintaining a sufficient volume flow rate is important and to this end the system should be used in conjunction with some form of airflow indicator. At 54 mm diameter the arm and duct is unlikely to become blocked by condensed fume but the filters will become loaded. A manometer measuring the pressure drop across the filter would provide a good indication and notification of a drop in volume flow rate.

The enclosing hood was extremely effective at containing the emission of solder fume. It is probably unnecessary to operate the enclosure at the higher flow rate of  $80 \text{ m}^3\text{h}^{-1}$  as it effectively contained the solder fume at the lower flow rate. This could possibly be reduced further as it needed only exhaust the fume as fast as it was produced. An advantage of the enclosure is the sloped viewing panel at the front which provides a physical barrier between the

rising solder fume and the worker's breathing zone, diverting the plume into the enclosure to be extracted.

However, it is probably the least adaptable of the tested controls. It was designed for use in the assembly of small electronics components on a production line and is ideally suited for this purpose. However, if the process were to change, especially to using larger pieces of equipment, the enclosure could become unusable, as they would not fit inside. Like the mobile capturing hood, the enclosure should be used with some form of flow monitoring device, either an airflow indicator or a device across the filter, as this will block with time. The airflow indicator could be a manometer monitoring hood static pressure.

The on-tip system is capable of reducing exposure to zero. The orientation of the extraction nozzle with respect to the iron tip, beside or above, did not affect control. It was not tested with the nozzle beneath the iron tip as it was considered unlikely to be used in this orientation. Qualitative visual observation of the tip extractor during phase 2 showed that fume could travel a significant distance, up to 100 mm from the nozzle, before being captured and drawn into the extract, however this would be dependant upon background air movements as with all capturing devices. It was easily the most adaptable of the controls tested being usable in almost any situation where the iron can go. It was possible to retract the extraction nozzle if space was particularly limited, however, this may well compromise the ability of the tip to capture the fume. The main advantage of the on-tip system is that it never needs to be repositioned as it is always in the optimum position for capture, removing one of the major user related problems with capturing hoods. This means that it would be suitable for use in a wide variety of processes and applications especially where the equipment or objects being soldered vary from task to task. It does have several disadvantages; the biggest of these is blockages caused by condensing solder fume in the extraction nozzle and tubing. This is shown above in Figure 3.4. Figure 3.5 below shows the extent of solder fume condensed onto the PCB and surrounding areas after only a few hours of soldering. This does not directly show solder fume condensed inside the extraction system, but gives an indication of the amount that can condense out. It should also be noted that, as with all capturing systems, control could be adversely affected by increased background air movements.



**Figure 3.5** Photograph showing condensed solder fume on the PCB and surroundings, also showing the mobile capturing hood in the realistic position. The slot in the soldering iron handle for the tip extraction nozzle can be seen just to the right of the mains cable.

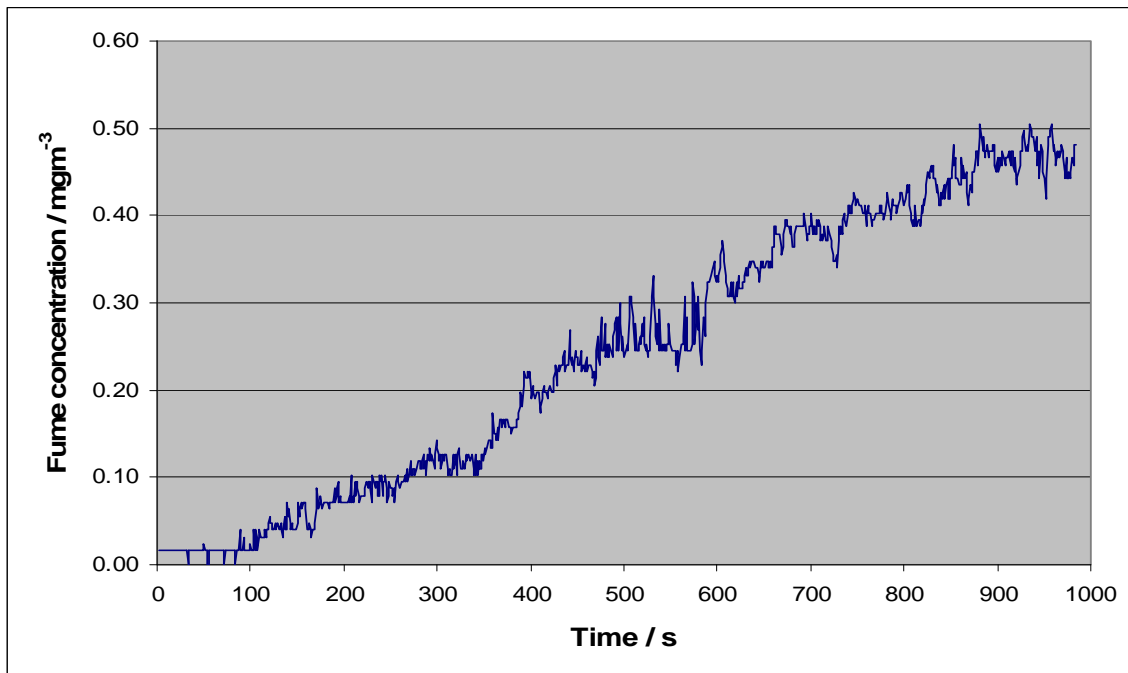
This image was taken with a flash as the condensed colophony is not easily visible under normal lighting with the naked eye. The most obvious blockage occurs at the tip of the extraction nozzle; regularly removing and cleaning the nozzle with a pipe cleaner can easily avoid this. When the tip system failed during testing the blockage actually occurred at the point where the flexible tube entered the extraction unit, this would have to be checked as part of a regular inspection. There is no flow indication on the system although this may not be necessary as a failure of the airflow is rapid and obvious. The system goes from being completely effective to entirely ineffective in the space of a few seconds, but as was noted above, regular inspection and cleaning will eliminate this problem. The filter in the extraction unit was highly effective; particle concentration measured in the exhaust was indistinguishable from the background. It should be noted though that a failure in the airflow could also be caused by filter loading and this should be included in a periodic maintenance inspection. A further possible drawback to the system is the increased dragging effect of the extraction tubing and its length, although the tubing is easily replaceable and can be made longer than the mains cable. During this study the on-tip extraction system became blocked with condensed colophony after approximately 1 – 2 hours of extreme soldering, this highlights the need for regular inspection and cleaning.

As has been previously noted the extraction nozzle used on the system in this study had an internal diameter of 5 mm, this was the case for most commercially available systems. Previous work at HSL tested a standard 5 mm system against a system using a 7 mm diameter extraction nozzle with a higher flow rate ( $\sim 80 \text{ lmin}^{-1}$ )[6]. The on-tip system in the previous study did not prove as effective as in this study but it was found that a higher degree of control was possible using the 7 mm system. The system itself was prone to the same problem of condensing colophony fume blocking the extraction nozzle and tubing compromising control. The system was designed specifically for use in an electronic manufacturer's production facility by retrofitting an existing proprietary on-tip extraction system. It was found that the system could become blocked after as little as an hours soldering - which is similar to that found in this study using a 5 mm system – and in fact required the operators to maintain an hourly cleaning regime.

The air displacement box was the only control not capable of reducing personal exposure to zero in these tests. This is due to the inadequate filter in the unit, meaning that the exhausted air contains a significant concentration on particulate phase fume. As these tests were performed in a relatively small room, total volume was  $46.7 \text{ m}^3$ , with a high frequency of soldering the background concentration built up quickly which caused exposures that exceeded the S.T.E.L in every test. When in a good position the air displacement box extracted the fume at source before it entered the breathing zone, but then subsequently returned it into the room air where the background fume concentration caused secondary exposure. Figure 3.6 below shows breathing zone concentration versus time of one of the tests with the air displacement box in a good position. As can be seen there are no peaks of high exposure characteristic of the solder fume plume passing through the breathing zone, but a steady increase of fume concentration as the background concentration increased. Having the air displacement box in a poor position, i.e. with the soldering position outside of the effective capturing zone increased the personal exposure by a factor of two but had little or no effect on the background fume concentration.

It should be noted that the reason for failure of the unit tested was the inadequate filtration. It would be possible to fit better filtration – for instance a HEPA filter – to improve performance. However, as the unit utilises an axial fan the addition of a high efficiency filter would cause a significant pressure drop, dramatically reducing the volume flow rate and impairing its ability to capture the fume. Similarly it would also be possible to direct the exhausted air away to a safe location, however the addition of significant lengths of ducting to the exhaust would again have a detrimental effect on the volume flow rate of air moved by the fan. Finally, it would be

possible to link the unit to an existing extraction system, however at this point it would simply be a mobile capturing hood.



**Figure 3.6** Fume concentration in the breathing zone of the manikin during extreme soldering controlled using the air displacement box in a good position – TEST ADB3

For example, when the air displacement box was positioned correctly to capture fume during extreme soldering in the test chamber (volume 46.7 m<sup>3</sup>) with a general ventilation rate of 0.5 ach, which is typical for a naturally ventilated room, the average personal exposure was 0.21 mgm<sup>-3</sup>. This result shows that were this amount of extreme soldering conducted in a significantly larger space (i.e. at least twice the size) the additional dilution of the unfiltered fume would likely reduce exposure to below the S.T.E.L. Likewise, reducing the emission rate by performing moderate or substantial soldering for a similarly short period would also likely have reduced the personal exposure to below the S.T.E.L. So although the air displacement box is unsuitable for an industrial production setting, if it were used in a large space with no other workers close to the solder fume laden air discharged from the rear of the device and only intermittent soldering i.e. a few minutes per day it could constitute an effective control if positioned correctly.

## 4 CONCLUSIONS

Exposure to solder fume in the form of fume concentrations were measured in the breathing zone of a manikin and at a background position within a test room for uncontrolled soldering. Personal and background exposure were again measured during soldering controlled using a variety of extraction systems which were designed to remove the fume. The tested controls were; a downdraught bench, a mobile capturing hood, an enclosing hood, an air displacement box and an on-tip extraction (LVHV) system. The capture efficiency of the mobile capturing hood was also measured in three positions.

Soldering was performed remotely from outside of the test room using an automatic feed system at three different rates, moderate, substantial and extreme. These were defined by the proportion of time spent feeding solder onto the iron tip and producing fume, these were; moderate 1 s in 20 s, substantial 1 s in 10 s, extreme 2 s in 10 s. From qualitative observations of the tests and comparing the quantitative exposure measurements to the 8-hour time weighted average workplace exposure limit (W.E.L) of  $0.05 \text{ mgm}^{-3}$  and 15-minute short-term exposure limit (S.T.E.L) of  $0.15 \text{ mgm}^{-3}$ [4] the following conclusions can be drawn:

- Uncontrolled soldering causes very high personal exposures, moderate 20 - 30 times the S.T.E.L, substantial and extreme 60 - 100 times the S.T.E.L.
- Even the best-case scenario, moderate soldering with a general ventilation rate of 5 air changes per hour (ach), caused an 8-hour TWA exposure of more than double the W.E.L.
- For uncontrolled soldering, fume concentration at the background position increased quickly and at the lower general ventilation rate of 0.5 ach exceeded the S.T.E.L.
- Increasing the general ventilation rate from 0.5 to 5 ach had little effect on personal exposure, but did reduce the background fume concentrations over the course of 15-minute tests. Therefore some form of control must be used to reduce exposure.
- If used correctly the downdraught bench, the mobile capturing hood, the enclosure and the on-tip extraction system are all capable of reducing exposure to zero.
- These four systems can fail if used incorrectly for instance;
  - If the soldering position moves the mobile capturing hood needs to be repositioned to keep it within the effective capturing zone
  - Obstructions of 50 % or more of the extracted surface of the downdraught bench can lead to a loss of control
  - The on-tip extraction system can become blocked with condensed colophony causing a loss of airflow and control
  - The enclosure is incapable of controlling fume emissions occurring outside of itself
- The air displacement box is capable of capturing the emitted fume at source, however it has inadequate filtration of the exhausted air, which is returned to the room causing secondary exposure by background fume. Nevertheless, it does offer some control by dispersing and diluting the fume emission.

- When comparing and contrasting controls a number of factors need to be considered;
  - Effectiveness – does it control exposure?
  - Usability – is it easy to use, reliable and maintain in good working order?
  - Adaptability – how does it cope with a variety of processes to be soldered?
- Each system has advantages and disadvantages, but in general terms;
  - For effective control the enclosure is the most suitable
  - For adaptability the on-tip system is the most suitable
  - For usability the downdraught bench is the most suitable

One of the aims of the project was to rank order the engineering controls tested. This was not as simple as comparing their quantitative performance at reducing exposure and required consideration of their usability and adaptability. In our opinion a more useful ranking would be to divide them into two groups, the first group of three being the better performing controls:

- Enclosing hood, downdraught bench and the on-tip extraction system

The second group the poorer performing controls:

- Mobile capturing hood and air displacement box

There is not much to choose between the top group and selection between the three would require careful consideration of the soldering process it will be applied to. The enclosure is easily the most robust and effective control but lacks adaptability; if the object to be soldered does not fit inside the enclosure it cannot control exposure. The downdraught bench is the easiest to use, one switch and then it provides a large surface on which to work. It is however limited by the size of object it can accommodate as blockages of 50 % or more can compromise control. The introduction of the downdraught system into a workplace would also require workbenches to be replaced.

The on-tip system is highly adaptable, the extract is always in the optimum position and control is highly effective. It could be hard to use in applications where space is very limited and does suffer from maintenance related issues. The extract becomes easily blocked which leads to a total loss of control, this is very black and white, it suddenly loses airflow and all control of the fume is lost. This drawback of the on-tip system needs to be considered carefully were constant soldering will be taking place. The mobile capturing hood has a relatively small effective capturing zone and so needs to be repositioned every time the soldering position moves. The articulated model tested was very difficult to reposition and had a limited range of motion, other completely flexible models are available, but with this form of LEV there is a high possibility of misuse leading to ineffective exposure control. It is also worth mentioning again that the on-tip extraction and movable capturing arm systems are both susceptible to disturbing draughts created by background air movements. The drawbacks of the air displacement box have been discussed at length and without effective filtration of the exhausted air it is unsuitable for industrial applications.



The relative advantages and disadvantages of the various LEV controls are shown below.

### **On-tip extraction**

- ✓ Is capable of reducing exposure to zero
- ✓ The extraction point is always close to the source eliminating the need to reposition the LEV when the soldering position moves
- ✓ The system is highly adaptable to changes of process and task
- ✓ Requires only a small volume air flow – approximately  $1.8 \text{ m}^3\text{h}^{-1}$
- ✗ The extra extraction tubing can cause a dragging effect making it slightly harder to use than a standard soldering iron. The presence of the extraction nozzle close to the tip can limit access in situations where space is restricted and may restrict visibility
- ✗ Solder fume tends to condense inside the narrow bore extraction nozzle and tubing causing blockages and restricted flow leading to a loss of control – this means that the system requires regular cleaning to function properly. During this study the system became blocked after approximately 1 – 2 hours of soldering

### **Downdraught bench**

- ✓ Is capable of reducing exposure to zero
- ✓ Because the surface of the bench is extracted the effective capturing zone encompasses the whole working area
- ✓ It is easy to use, does not require any repositioning of the extract when moving soldering position
- ✗ Requires a large volume air flow – approximately  $575 \text{ m}^3\text{h}^{-1}$  at maximum flow
- ✗ The size of objects that can be soldered is limited as blockages of more than 50 % of the extracted surface can compromise control
- ✗ It is unclear how the bench would perform when soldering objects that form cavities shielded from the downward flow of air such as the inside of televisions or tower PCs

### **Enclosing hood**

- ✓ Is capable of reducing exposure to zero
- ✓ It is highly resistant to disturbing draughts such as people moving around or the close presence of a cooling fan
- ✓ Provides a physical barrier between the source and the worker's breathing zone
- ✓ Requires a relatively small volume air flow – the enclosure maintained complete control of the fume emission operating at  $40 \text{ m}^3\text{h}^{-1}$
- ✓ Enclosures are ideally suited to production line work where identical or similar sized objects will be soldered

- × Enclosures are more difficult to use where objects of various sizes and shapes are encountered as they are only capable of controlling emissions that occur within the enclosed volume

### **Mobile capturing hood**

- ✓ Is capable of reducing exposure to zero if positioned correctly
- × Has a relatively small effective capturing zone which means that it needs to be repositioned when the soldering position moves to keep it within the working zone and maintain control
- × The model of mobile arm tested is difficult to move and reposition although other more flexible versions are available
- × If the hood is not positioned close enough to the source fume escapes capture and high exposures can occur

### **Air displacement box**

- ✓ It is simple and easy to use
- × Whilst it is capable of capturing fumes at source and preventing direct exposure, the filtration in the unit tested was ineffective. The exhausted air contained a high concentration of particulate phase fume, that, in the relatively small test room used (46.7 m<sup>3</sup>), caused the background concentration to increase rapidly, which in turn caused exposure that exceeded the S.T.E.L.
- × The integral filter in the unit is an activated carbon porous foam, which is very porous meaning that much of the fume passed straight through, unabsorbed
- × The air displacement box works on the same principle as the mobile capturing hood, which means it has a relatively small effective capturing zone. If the source is outside of this zone then control is ineffective and exposure occurs
- × The air displacement box tested would not be suitable for use where extensive and prolonged soldering will take place, such as a production line

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# Visualisation and control of solder fume exposure

## A quantitative assessment of LEV effectiveness

Colophony or Rosin Based Solder Flux Fume is a known cause of occupational asthma and as such exposure to it should be controlled. An effective method of engineering exposure control is to use local exhaust ventilation (LEV) to extract the fume at source. Personal exposure to solder fume was quantitatively measured in the breathing zone of a manikin, these exposures were then compared to those caused by uncontrolled soldering in order to assess five different LEV systems. The five LEV systems tested were a downdraught bench; an extracted bench top enclosure, a mobile capturing hood, an on-tip extraction system and a bench top fume absorber.

It was found that even a moderate amount of soldering when uncontrolled caused exposures over 50 times greater than the 8-hour Workplace Exposure Limit of  $0.05 \text{ mgm}^{-3}$  and over 30 times greater than the 15-minute Short Term Exposure Limit of  $0.15 \text{ mgm}^{-3}$ . It was found that all five LEV systems were capable of reducing exposure to zero if used correctly. Each system had distinct advantages and disadvantages that make their use more or less suitable in various situations.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the author alone and do not necessarily reflect HSE policy.