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Effective control of gas shielded arc welding fume

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Research Report

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Effective control of gas shielded arc welding fume

Mr Dom Pocock & Mr C John Saunders
Health and Safety Laboratory
Harpur Hill
Buxton
Derbyshire SK17 9JN

Mr Graham Carter
TWI
Granta Park
Great Abington
Cambridge CB1 6AL

HSE inspectors have noted that, although Local Exhaust Ventilation (LEV) was often available for controlling exposure to inert gas shielded welding fume, it frequently remained unused, due, partly to claims by welders that the LEV was responsible for removing shielding gas and thereby compromising the quality of the weld. However, there appeared to be few data to substantiate the welders' claims. HSE commissioned this research project to establish whether efficient welding fume capture could be achieved using LEV whilst, at the same time, maintaining weld metal integrity. The objectives of this research project were to be met in three phases:

- Phase 1 was to provide the information necessary to develop an experimental plan.
- Phase 2 was to determine the maximum cross flow velocity of air that could be tolerated before the onset of weld metal porosity during gas shielded arc welding using parameters defined in Phase 1.
- Phase 3 was to measure capture efficiencies for a range of different LEV hoods positioned at various distances and orientations to the welding arc, whilst monitoring weld metal integrity. An on-gun extraction system was also evaluated. This report gives a brief summary of the work carried out in phase 1 and 2, and details the work carried out in phase 3.

The report shows that when using standard welding parameters, satisfactory fume extraction is possible without compromising the weld integrity. The results are confirmed for a number of welding positions and with various extraction hoods in different positions. The results for the on-gun extraction equipment are evaluated against those observed for the stand-alone fume extraction equipment.

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FOREWORD

Several terms are used throughout this report to refer to the orientation of welding operations being tested, these are defined below.

In the flat - Welding on a test piece that is laying flat on the traverse i.e. parallel to the ground

In position - This refers to any welding where the test piece is on a vertical surface i.e. perpendicular to the ground

Vertical - Welding in position where the torch moves vertically i.e. top to bottom or vice versa

Horizontal - Welding in position where the torch moves from side to side i.e. left to right or vice versa

CONTENTS

EXECUTIVE SUMMARY

Objectives

HSE inspectors have noted that, although Local Exhaust Ventilation (LEV) was often available for controlling exposure to welding fume, it frequently remained unused, due, partly to claims by welders that the LEV was responsible for removing shielding gas and thereby compromising the quality of the weld. However, there appeared to be few data to substantiate the welders' claims. HSE commissioned this research project to establish whether efficient welding fume capture could be achieved using LEV whilst, at the same time, maintaining weld metal integrity.

The objectives of this research project were to be met in three phases;

- Phase 1 was to provide the information necessary to develop an experimental plan, examine data already available and define the methodology to be employed in other phases by means of a literature survey and review.

- Phase 2 was to determine the maximum cross flow velocity of air that could be tolerated before the onset of weld metal porosity during gas shielded arc welding using parameters defined in Phase 1. Experimental work for Phase 2 was carried out at The Welding Institute (TWI) facility at Granta Park in Cambridge. The output of this report was to be in the form of a TWI technical report.

- Phase 3 was to measure capture efficiencies for a range of different LEV hoods positioned at various distances and orientations to the welding arc, whilst monitoring weld metal integrity. In addition to this, and part funded by Nederman, an on-gun extraction system was to be evaluated. The output of this phase is the subject of this report.

Main Findings

Phase 1

The report concluded that very limited information relating to the use of LEV, its capture efficiency and its effect on weld metal integrity was available. It went on to make the following recommendations:

- Work should be performed to establish or confirm the air velocities that give rise to porosity, under a range of welding parameters, during MAG welding.

- Work should examine extraction efficiency whilst using generic types of extraction equipment.

- Testing should be carried out whilst using commonly used parameters and materials to provide wide applicability. In this respect, information has been gleaned to establish that the most commonly used material/ welding parameter combination is welding carbon or C-Mn steel, using the MAG process, with 1.0 or 2 mm diameter wire, a CO_2 or argon/CO_2/O_2 shielding gas at a flow rate of approximately 15 $lmin^{-1}$ and spray transfer.

- Further work should be carried out using optimised parameters, based on the baseline parameters. Literature showed that certain values of welding parameters can allow an increase in the critical air velocity before impairment of weld metal integrity, making it possible to employ higher extraction velocities.

Phase 2

The report concluded:

- The following parameters all decreased sensitivity to cross draughts: heavier shielding gases, higher shielding gas flow rates, shorter contact tip to work distances (CTWDs), slower traverse speeds, smaller diameter gas shrouds, spray as opposed to dip transfer and using a fluxed process.

- Using a combination of parameters that resulted in the least tolerance to cross draughts, only a cross draught velocity of up to 1 ms^{-1} could be tolerated before the onset of porosity. Using a combination of the best parameters, it was not possible to induce porosity with cross flows up to 6 ms^{-1}.

- The maximum cross flow velocities that can be tolerated under a variety of welding conditions were evaluated and will be used to define the nearest position at which the ventilation inlet should be placed in capture efficiency studies in Phase 3.

Phase 3

The hoods to be tested fell into three distinct groups; a) a large moveable hood operating at a High Volume (HV) flow rate, b) small tabletop mounted hoods operating at Low Volume (LV) flow rates and c) an on-gun extraction system, operating at a Low Volume flow rate but at a High extraction Velocity (LVHV). Capture efficiencies of the hoods were measured in a variety of orientations to a stationary arc and a constant cross draught. Measuring capture efficiency with a stationary arc and traversing test piece represents an idealised situation that would rarely be reproduced in a real life setting, with this in mind, some testing was carried out using a traversing welding torch and stationary test piece. In general, the following conclusions can be drawn for captor hood based LEV:

- High capture efficiencies are achievable using captor hood based LEV systems if positioned correctly without compromising weld metal integrity.

- For optimum control the hood should be repositioned frequently to keep the arc within one hood diameter.

- Changing consumables has little effect on capture efficiency.

- For moveable hoods, positioning the hood vertically above the arc or horizontally on the bench provides the best control.

- Positioning the hood above the arc at 45° is the least effective position.

- The HV system is more flexible than the LV system in that control can be maintained with the hood positioned further from the arc. This is because of the higher volume of air moved and larger face area. However, if positioned close enough the LV system can provide a high level of control in situations where limited space is available.

- Although in certain situations, a high level of capture efficiency can be maintained at greater distances, it is recommended that the hood be positioned one diameter from the weld and repositioned frequently to maintain control. In this position capture efficiency will be maximised and weld integrity will be maintained.

The on-gun (LVHV) system was evaluated when welding bead on plate and in horizontal/vertical fillets both in the flat and in position, and the following conclusions were drawn:

- The on-gun system has the advantage over traditional mobile LEV hoods, which have to be constantly repositioned, as the extract for on-gun systems is always close to the arc.
- Adjusting the extract nozzle to a position that would provide efficient fume extraction without compromising weld metal integrity was not a critical operation.
- For bead on plate welding, the on-gun extraction system tested provided a suitable alternative to hood based, local exhaust ventilation, as far as capture efficiency and weld metal integrity were concerned.
- The only situations where weld metal integrity was compromised was when the extract nozzle was positioned flush with the end of the gas shroud.

Recommendations

HSE/HSL should consider further methods for disseminating the key message, that it is possible to control arc welding fume using LEV without compromising weld integrity, to industry. It is recommended that further work be carried out to assess the effectiveness of on-gun extraction when welding fillets with varying fume emission rates.

1 INTRODUCTION

Welding generates fume, composed primarily of particles and agglomerates less than 1 μm in diameter [1, 2], and gases, all of which, if inhaled, can be harmful to health [3]. Consequently, fume control is often required to maintain exposures at acceptable levels. Control is best achieved using local exhaust ventilation (LEV). Ideally welding should take place in a ventilated booth or on a downdraft table in order to capture fume before it enters the welder's breathing zone [4, 5]. However, it is recognised that this is not always practical and so moveable hoods are frequently used to capture welding fume. For these to be effective they have to be positioned close to the fume generation point and need to be repositioned at frequent intervals to ensure that the fume generated is always within the capture zone [6]. This is sometimes difficult to achieve and does not always occur due to a variety of technical and human factors. When the fume and gases are not properly controlled at source they can enter the workers breathing zone before spreading throughout the workplace exposing others to hazardous substances.

HSE inspectors have noted that, although LEV was often available for controlling exposure to welding fume, it frequently remained unused. This situation applied particularly to gas-shielded arc welding processes, where the welders claimed that employing LEV could lead to weld metal defects. This is because arc welding requires a shielding gas to prevent the entrapment of air, specifically nitrogen, in the molten weld metal pool [7]. This can lead to defects and inclusions within the weld metal in the form of both surface (visible), and sub-surface porosity, which can compromise the integrity of the weld and make it brittle [8, 9]. However, there appeared to be few data to substantiate the welders' claims. To help resolve this unsatisfactory situation, HSE commissioned this research project to establish whether efficient welding fume capture could be achieved using LEV whilst, at the same time, maintaining weld metal integrity.

The research project was divided into three phases. Phase 1 of the work was to provide the information necessary to develop an experimental plan, examine data already available and define the methodology to be employed in other Phases. Phase 2 was to evaluate the maximum cross flow velocity of air that could be tolerated before the onset of weld metal porosity during gas shielded arc welding using parameters defined in Phase 1. Phase 3 was to measure capture efficiencies for a range of different LEV hoods positioned at various distances and orientations to the welding arc, whilst monitoring weld metal integrity.

Initially the project excluded on-gun extraction. These systems have the advantage that the extraction point is always close to the fume source but they have been reported to be ergonomically unsuitable because of the weight of the gun and the dragging effect of the extraction ducting, whilst the presence of the extract nozzle can obscure the welder's sight of the weld in tight situations. Further, it is generally recognised (it is stated in HSE guidance for inspectors [10]) that on-gun systems work efficiently whilst welding in butt joints, in the flat, and with the torch in a very upright orientation, but that they are less efficient when welding in position, or in horizontal/vertical fillets.

Manufacturers of on-gun extraction systems now claim that improvements in design have made them capable of efficient fume capture and ergonomically acceptable, whilst their reduced size allows improved vision of the work [10].

Nederman Ltd. was keen for the on-gun systems to be evaluated and were in a position to part fund this work, Therefore evaluation of on-gun extraction was included within the scope of this project.

Phase 1 and 2 of this project have been reported [11, 12]. Section 2 of this report briefly summarises the findings of both Phase 1 and 2 and details the work undertaken in Phase 3 including the findings of the on-gun extraction study.

2 SUMMARY OF WORK CARRIED OUT IN EARLIER PHASES

2.1 PHASE 1

The objective of Phase 1 of the project was to provide the information necessary to develop an experimental plan, examine data already available and define the methodology to be employed in other Phases. This was achieved by:

- Examining the range of commercial extraction equipment available and widely used in the welding industry.
- Establishing the minimum air velocity reported to be required to capture welding fume and the maximum air velocity that could be tolerated before the onset of weld metal porosity.
- Identifying suitable methodology for measuring capture efficiency during welding.
- Identifying widely used materials, processes and welding parameters.
- Identifying work performed previously in the area.

The report [11] concluded that very limited information relating to the use of LEV, its capture efficiency and its effect on weld metal integrity was available. It went on to make the following recommendations:

- Work should be performed to establish or confirm the air velocities that give rise to porosity, under a range of welding parameters, during MAG welding.
- Work should examine extraction efficiency whilst using generic types of extraction equipment.
- Testing should be carried out whilst using commonly used parameters and materials to provide wide applicability. In this respect, information has been gleaned to establish that the most commonly used material/ welding parameter combination is welding carbon or C-Mn steel, using the MAG process, with 1.0 or 2 mm diameter wire, a CO_2 or argon/CO_2/O_2 shielding gas at a flow rate of approximately 15 $lmin^{-1}$ and spray transfer.
- Further work should be carried out using optimised parameters, based on the baseline parameters. Literature showed that certain values of welding parameters can allow an increase in the critical air velocity before impairment of weld metal integrity, making it possible to employ higher extraction velocities.

2.2 PHASE 2

The objectives of Phase 2 of the project were:

1. To establish the cross flow velocities of air at which weld metal integrity will be impaired by porosity, under a variety of welding conditions during gas shielded arc welding.

2. To use the information generated to provide a starting point for experimentation in Phase 3, to evaluate the best capture efficiency that can be obtained, with various LEV systems, before weld metal integrity is destroyed by porosity.

The assessment criteria used to establish a reduction in metal weld integrity could be based on the presence of porosity in the weld or toughness of the weld. Changes in toughness are believed to provide a more stringent assessment of weld metal integrity stemming from entrainment of air, but toughness is only a requirement in a small proportion of MAG welding of unalloyed steel. As the results of this study should be applicable to the widest audience the decision was made to use porosity as the assessment criteria.

Welding was performed on test pieces in the presence of cross draughts of various strengths, to establish the velocity of cross draught (the critical velocity) at which weld metal integrity was destroyed, as shown by porosity. Initial judgement of the critical velocity was obtained through observation of visual porosity in the deposited metal but this was refined, subsequently, by examining welds, produced at velocities 0.25 and 0.5 ms^{-1} below the speed at which visual porosity had occurred, for sub surface porosity using X-ray techniques. The objective was to identify the velocity at which a sound weld was first obtained. Using this approach, the effect of different welding parameters on the critical velocity was examined.

The report [12] concluded:

1. Sensitivity to cross draughts was decreased by the following parameters: heavier shielding gases, higher shielding gas flow rates, shorter contact tip to work distances (CTWDs), slower traverse speeds, smaller diameter gas shrouds, spray as opposed to dip transfer and using a fluxed process.

2. Using a combination of parameters that resulted in the least tolerance to cross draughts, only a cross draught velocity of up to 1 ms^{-1} could be tolerated before the onset of porosity. Using a combination of the best parameters, it was not possible to induce porosity with cross flows up to 6 ms^{-1}.

3. The maximum cross flow velocities that can be tolerated under a of variety of welding conditions have been evaluated and will be used to define the nearest position at which the ventilation inlet may be placed in capture efficiency studies in Phase 3.

3 APPROACH AND METHODOLOGY

3.1 GENERAL

The hoods to be tested fell into three distinct groups; a large moveable hood operating at a High Volume (HV) flow rate; small tabletop mounted hoods operating at Low Volume (LV) flow rates and an on-gun extraction system, operating at a Low Volume flow rate but at a High extraction Velocity (LVHV).

The sampling strategy was determined from experience gained in the scoping study (see Appendix I) and was used to assess the capture efficiency of welding fume of the three different types of hoods. This comprised welding test pieces in the test cabin, extracting the fume using various LEV apparatus and sampling the fume isokinetically in the LEV duct. The ducting arrangement was slightly different when testing both the smaller hoods and the on-gun system. Fume that escaped capture was sampled in the sampling section as a means of monitoring the experiments and assessing alternative strategies for future use but was not considered for assessing LEV performance and fume capture. Unlike the scoping study (Appendix I), the welding was performed using an automated traverse and welding rig. This enabled variables to be fixed such as CTWD and arc travel speed in order to produce as constant as possible fume emission rate. It also removed the need to have a welder in the cabin during the experiments.

The capture efficiency is calculated from the equation;

$$E = \left(\frac{C_d}{C_{100\%}} \right) \times 100 \tag{1}$$

Where E is the capture efficiency (%), C_d is the fume concentration in the duct under specific test parameters (mgm^{-3}) and $C_{100\%}$ is the fume concentration (mgm^{-3}) in the duct under the same welding conditions with total fume capture (100% extract tests).

The fume concentration was calculated from measuring the mass of fume deposited on the filter during a test and knowledge of the volume flow rate in the duct, the sampling rate of the pump and the duration of the test.

$$C = \left(\frac{M_f - M_c}{Q_{sample} \times t_{test}} \right) \times 1000 \tag{2}$$

Where C (mgm^{-3}) is the concentration in the duct, M_f is mass of fume on the filter (mg), M_c is the correction applied from the control filters (mg), Q_{sample} is the sample pump flow rate ($Lmin^{-1}$) and t_{test} is the duration of the sampling (min). Weld metal integrity was assessed by examining the weld metal deposited in each test for porosity, this being the most significant defect to occur in carbon manganese weld metal. Initially, the assessment was made visually but any deposits where the weld bead appearance indicated that sub surface porosity might be present were subjected to radiographic examination.

3.2 CENTRELINE VELOCITIES OF THE HV AND LV HOODS

An important factor when considering the performance of LEV hoods is the air velocity they generate at certain points. To this end before commencing testing of the various hoods the air velocities generated along the centrelines were measured using a hot wire anemometer. The velocities were measured on a centreline perpendicular to the hood face and emanating from the geometric centre of the face, hood dimensions are given in sections 3.5 and 3.6. The centreline velocity profiles are shown in section 4.1.

3.3 ENVIRONMENTAL TEST CABIN

Figure 3.1 shows the experimental layout in the test cabin for welding in the flat, for tests welding in position the vice and welding tables were replaced by a vertical traverse (see Foreword for definitions of welding terms). Both pre-filters and High Efficiency Particulate Air (HEPA) filters were used to remove any background aerosols from the laboratory air. In addition, the pressure drop created by the filters improved the velocity profile in the cabin. The mixing fans and the baffle in the mouth of the sampling section, where the TEOM was located, were present to ensure complete mixing of the air entering the sampling section. These issues are discussed in more detail in the scoping trial in Appendix I.

Welding was carried out automatically on test pieces secured to a traversing system that was operated remotely, from outside the test cabin. Tests performed in the flat were carried out on a horizontal traverse with either the welding torch traversing a stationary test piece or the reverse. For both cases the test pieces were orientated with their length perpendicular to the airflow in the test cabin. Tables were positioned both upstream and downstream of the test piece with the table surfaces level with the upper surface of the test piece. This ensured the airflow was allowed to pass uninterrupted across the welding position and also provided a surface to site the tabletop hoods onto. Positional welding was carried out using a vertical traverse with the torch stationary and a traversing test piece. The traverse was positioned such that the airflow in the cabin was parallel to the surface of the test pieces.

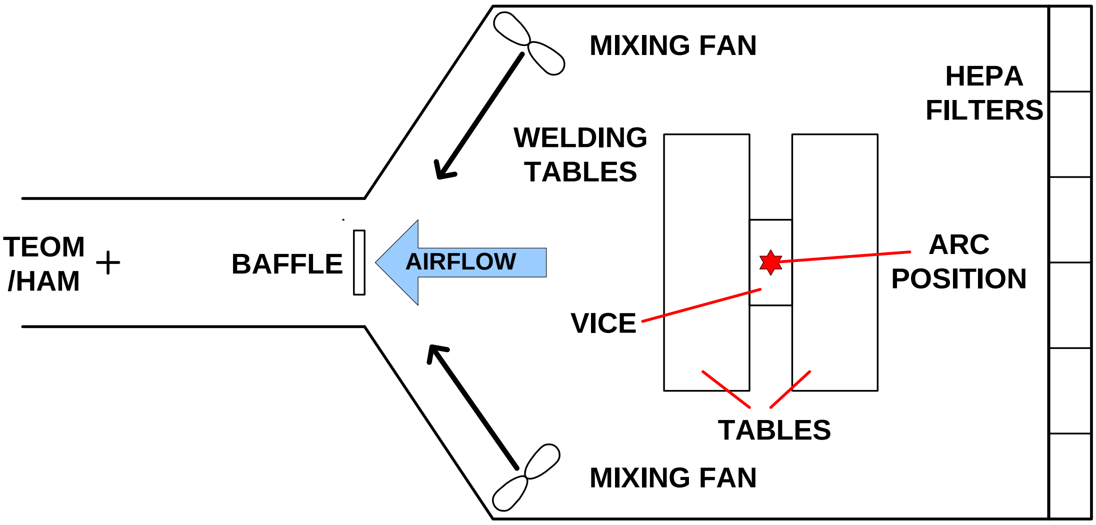


Figure 3.1 Schematic of test cabin layout during testing for welding in the flat

3.4 WELDING EQUIPMENT AND WELDING PARAMETERS

The power source was an ESAB AristoMiG 500 inverter, fitted with an ESAB AristoFeed 48 wire feed unit. Although connected to the welding torch inside the test cabin, the power source was positioned and operated from outside the cabin. Welding parameters were monitored using the AMV Weldcheck system. For tests conducted with bead on plate welding, the welding torch was at an angle of 70° to the test piece. A similar angle was used for fillet welding but the torch had a lead-in angle of approximately 30° to the horizontal leg of the test piece. A pushing technique was employed in all cases.

Two welding conditions were used throughout this project, the parameters for these are given in Table 3.1. Condition 1 was used exclusively with the LVHV on-gun system when welding in position using a double deoxidised mild steel wire. Condition 2 was used with all three LEV systems when welding in the flat using a double deoxidised mild steel wire and a PZ6113 flux cored wire for a series of tests with the Large HV hood. The test pieces were bright mild steel bar stock 50 mm x 12.5 mm and between 500 – 550 mm long.

Table 3.1: Welding parameters for conditions 1 & 2

Condition	*Wire diameter (mm)*	*CTWD (mm)*	*Current (A)*	*Voltage (V)*	*Shielding gas flow rate (L/min)*
1	1.0	12.5	130	19.5	15
2	1.2	20	260	33	18

3.5 LARGE HOOD, HIGH VOLUME (HV) SYSTEM

The HV system employed a Nederman elliptical hood that had a major axis of 300 mm with an aspect ratio 0.83, see Figure 3.2.

Figure 3.2 Nederman HV elliptical extract hood

The experimental set up was similar to the scoping study (see Appendix I) and is shown in Figure 3.3. The volume flow rate of the system as operated during the study was 800 m^3h^{-1}, to allow a constant volume flow rate should the filter become loaded and reduce flow. The volume flow rate was monitored using a 160 mm Wilson flowgrid, which allowed the calculation of the volume flow rate from the measured velocity pressure in the duct, much like an array of Pitot static tubes. The hood was connected to a series of 160 mm diameter flexible and rigid ducting. The extracted air was filtered before passing through the fan and discharged back into the laboratory. Sampling was conducted isokinetically at location 1, see Appendix I, with a single 7 mm diameter thin walled probe. This sampling position was selected as the optimum position after analysing the results of the scoping study described in Appendix I.

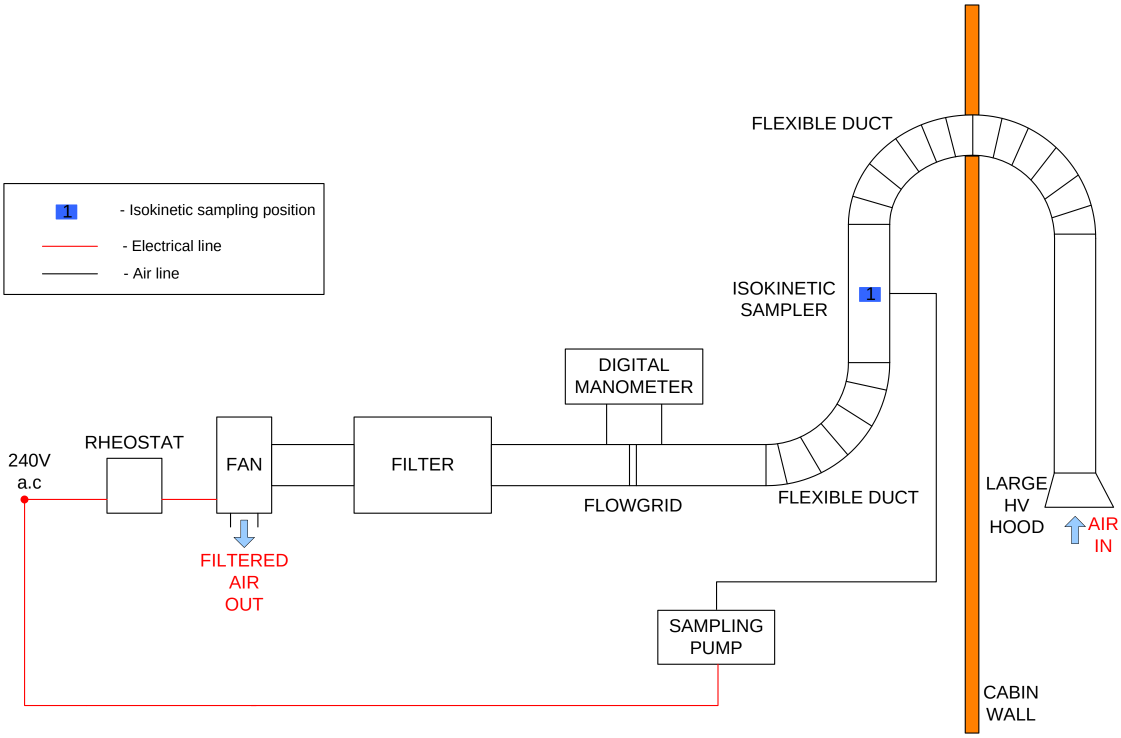


Figure 3.3 Experimental set up for trials of the large HV hood

Two types of welding wire were used; PZ6113 Flux cored wire and 1.2 mm diameter double deoxidised mild steel wire. A series of experiments were performed to assess the capture efficiency of the HV system and its effect, if any, on the quality of the weld produced. These experiments were divided into seven groups.

1. Positions vertically above the arc at; d=300, 600 and 900 mm with a stationary torch and traversing test piece; see Figure 3.4.

2. Positions at 45° above with the hood face perpendicular to the direction of the weld (perpendicular to the airflow in the cabin) at; d=300, 450 and 600 mm with a stationary torch and traversing test piece; see Figure 3.5.

3. Positions horizontally downstream with the face of the hood parallel to the direction of the weld (i.e. with the hood resting on the surface of the table) at; d=150, 300 and 600 mm with a stationary torch and traversing test piece; see Figure 3.6.

4. Positions horizontally upstream with the face of the hood parallel to the direction of the weld at; d=85, 150, 300, 450 and 600 mm with a stationary torch and traversing test piece; see Figure 3.6.

5. Positions vertically above a 300 mm and 450 mm weld at d=340 mm and 650 mm with a stationary test piece and traversing torch; see Figure 3.4.

6. d=650 mm vertically above a 300 mm and 450 mm weld with the cabin ventilation disabled, i.e. in still air; see Figure 3.4.

7. d=300 mm horizontally downstream perpendicular to the plane of the weld from a 300 mm and 450 mm weld with a traversing torch and stationary test piece; see Figure 3.6.

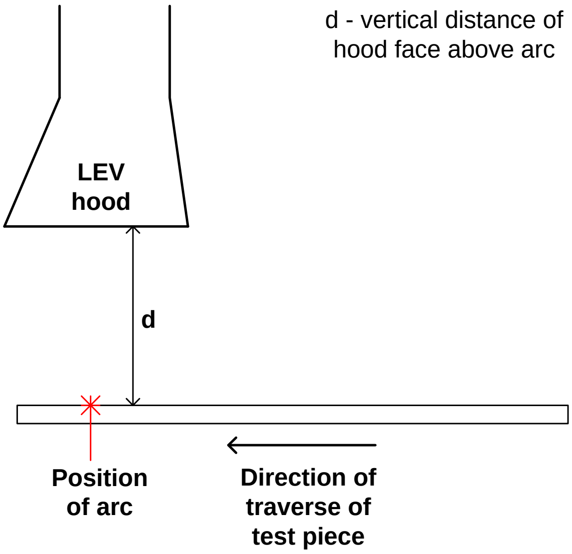


Figure 3.4 Test groups 1, 5 and 6. Side view of LEV hood positioned vertically above the arc. For groups 5 and 6 the test piece remained stationary and the welding torch traversed beneath the hood. Cabin airflow is into page.

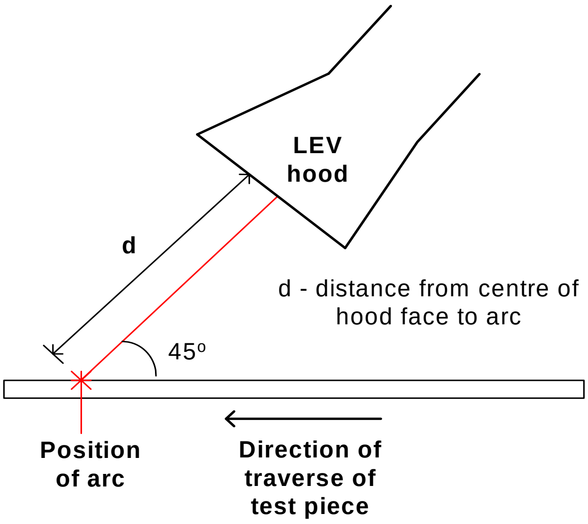


Figure 3.5 Test group 2. Side view of LEV hood positioned 45° above direction of weld; cabin airflow is into page.

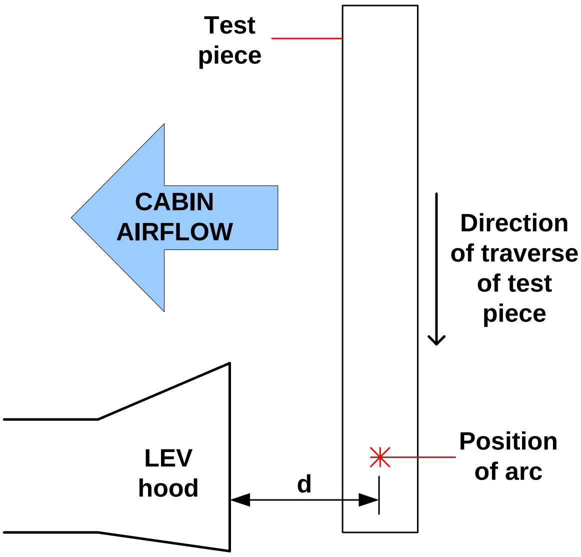


Figure 3.6 Test groups 3, 4 and 7. Plan view of LEV hood positioned horizontally downstream from weld with face parallel to direction of weld. For group 4 the hood was positioned upstream of the test piece and for group 7 the test piece remained stationary and the welding torch traversed across it.

In these descriptions upstream and downstream refer to the position of the LEV relative to the weld with respect to the direction of the airflow within the test cabin.

As was noted earlier, capture efficiency was evaluated as being the ratio of fume captured under specific test conditions to total fume capture under the same welding conditions. Total fume capture was taken to be the position at which the concentration of fume in the LEV duct was at a maximum. For all tests with the HV system this position was with the hood perpendicular to the plane of the weld, 150 mm (or ½ a hood diameter) horizontally downstream from the arc.

3.6 SMALL TABLETOP HOODS - LOW VOLUME (LV) SYSTEM

The LV system used a variety of hoods chosen for their common use in industry, for the purpose of this study they were referred to as; fishtail hood (a slot with an aspect ratio of approximately 0.15), circular hood and slot hood (aspect ratio of 0.013). All the hoods were factory fitted with a 45 mm diameter metal flexible duct and a magnetic mount. See Figure 3.7.

The hoods were of various sizes and shapes. The fishtail hood had an opening 205 mm wide and 30 mm high; the distance from the face of the hood to the duct was 100 mm. The circular hood had an opening of 45 mm diameter with a circular flange with a diameter of 80 mm. The slot opening was 4 mm by 300 mm with an 8 mm by 300 mm flange above and below the slot. The LV system, which connected to the 45mm diameter metal duct, was based on 75 mm diameter ducting using the hoods shown in Figure 3.7

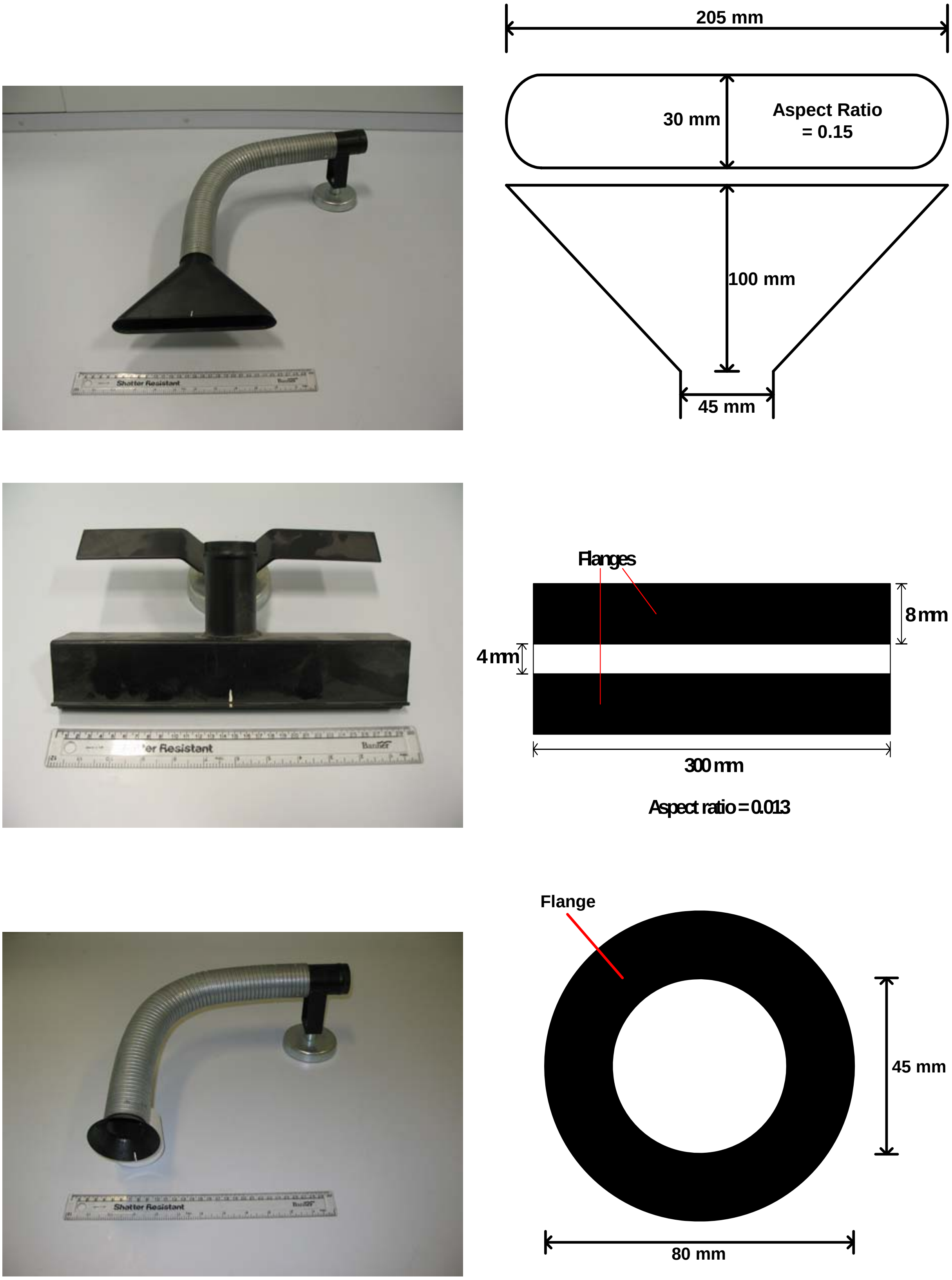


Figure 3.7 The three hoods used with the LV tabletop system. (Top Left) fishtail hood, (Top Right) fishtail hood front and plan view, (Middle Left) slot hood, (Middle Right) slot hood front view, (Bottom Left) circular hood and (Bottom Right) circular hood front view.

The fishtail hood was operated at a volume flow rate of 150 m^3h^{-1}, the circular hood at 136 m^3h^{-1} and the slot at 123.7 m^3h^{-1}. Ideally all the hoods would have been operated at 150 m^3h^{-1} but as the system pressures were different for each hood this was not possible. It was also necessary to set a flow rate slightly lower than the maximum achievable rate to provide some latitude to adjust the flow rate should the LEV filter become loaded. This would not have been possible had the fan been operating at maximum power. The flow rate was monitored using an orifice plate connected to a micromanometer to measure the pressure drop across the plate. In the LV system, volume flow rate is related to the pressure drop across the orifice plate by the equation;

$$Q = 6.808 \times \sqrt{P} \tag{3}$$

Where Q is the flow rate in m^3h^{-1}, P is the pressure drop across the orifice plate in Pa and 6.808 is a constant unique to the orifice plate. The experimental set up is shown in Figure 3.8.

Using experience gained during the scoping trials (Appendix I) the sampling point for the LV system was chosen to be in a straight section of 75 mm diameter duct 850 mm (~ 11 duct diameters) from a 90° bend and approximately 3 m of flexible 75 mm ducting after the hood. Applying the findings of the scoping study it was considered that the flow at this position would be fully developed and sampling isokinetically from the centre of the duct would provide a representative sample.

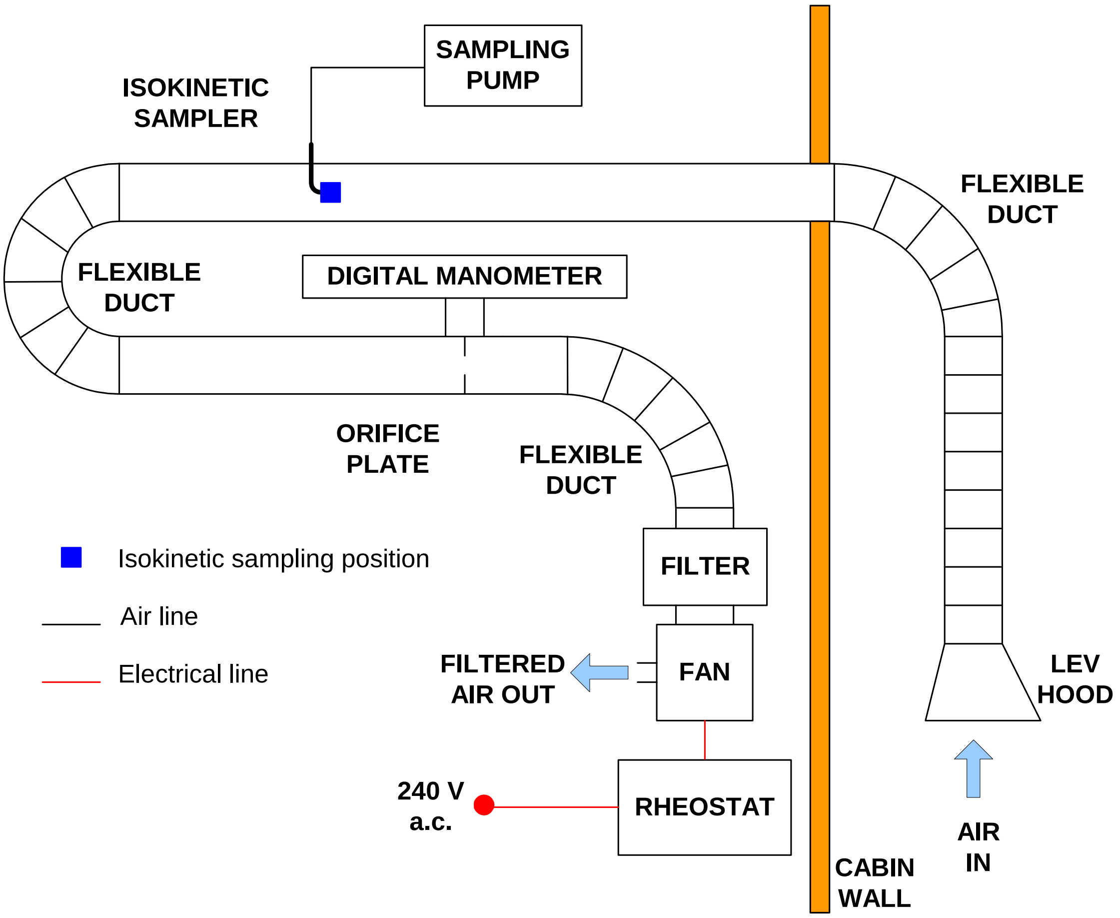


Figure 3.8 Schematic diagram of LEV and sampling set up for small LV hood system.

A series of experiments were performed to investigate the extraction efficiency of the LV system and its effect, if any, on the quality of the weld produced. These experiments were divided into six groups.

1. Using all three hoods at positions with the face parallel to the direction of the weld horizontally downstream d=75, 150, 225 and 300 mm from the arc with a stationary torch and traversing test piece; see Figure 3.9.
2. Using all three hoods at positions with the face parallel to the direction of the weld horizontally upstream d=75, 150 and 225 mm from the arc with a stationary torch and traversing test piece; see Figure 3.9.
3. Using the fishtail and circular hoods at d=75 mm horizontally downstream and laterally offset from the arc by L=75, 150 and 225 mm with a stationary torch and traversing test piece; see Figure 3.10.
4. Using the fishtail and circular hoods at d=75 mm horizontally upstream and laterally offset from the arc by L=75, 150 and 225 mm with a stationary torch and traversing test piece; see Figure 3.10.
5. Using all three hoods, d=75 mm horizontally downstream at the centre (position 1) and at right hand side (start) (position 2) of a 300 and 450 mm weld with stationary test piece and traversing torch; see Figure 3.10.
6. Using all three hoods, d=150 mm horizontally downstream at the centre (position 1) of a 300 mm weld with a stationary test piece and traversing torch; see Figure 3.10.

Both the fishtail and round hoods are designed to be mounted above a plane surface. For all the tests carried out the centre line of both hoods were positioned 60 mm from the surface of the table. The slot was designed to sit on the tabletop with the bottom flange flush with the surface of the table and was therefore positioned as such.

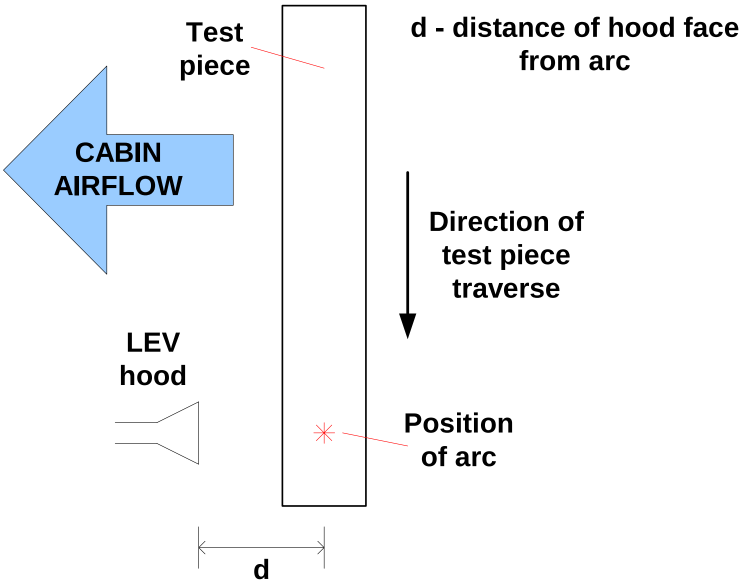


Figure 3.9 Test groups 1 and 2. Plan view of small LV hood positioned downstream for group 1. For group 2 the hood was positioned upstream.

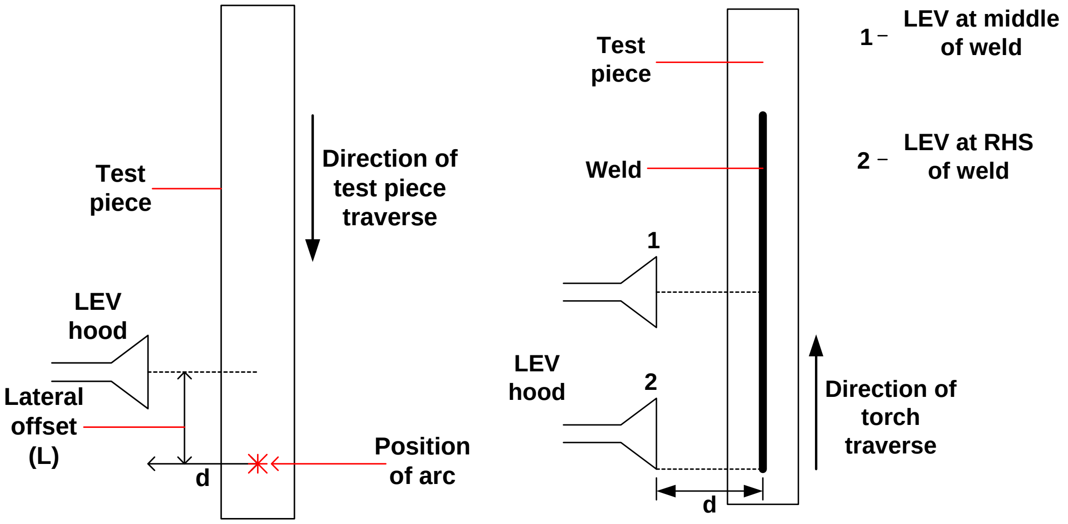


Figure 3.10 Test groups 3 and 4 (Left), groups 5 and 6 (Right). LEV hood positions for lateral offset and moving torch experiments

The 100 % test positions for the LV hoods were determined to be the points where the concentration of fume sampled in the duct was at a maximum. It was necessary to have a different 100 % position for each hood as they operated at different volume flow rates, which would directly affect the concentration of fume in the duct.

3.7 ON-GUN EXTRACTION SYSTEM

The on-gun (LVHV) extraction system consisted of an Abicor-Binzel RAB 25, air-cooled, fume extracting welding torch with an integral extraction system, connected to a Nederman P 30 extraction unit (Figures 3.11, 3.12 and 3.13). The nominal flow rate of the extracted air was 100 m^3h^{-1} and the static pressure at the nozzle was ~15 kPa.

Figure 3.11 Abicor-Binzel RAB 25 air cooled fume extracting welding torch

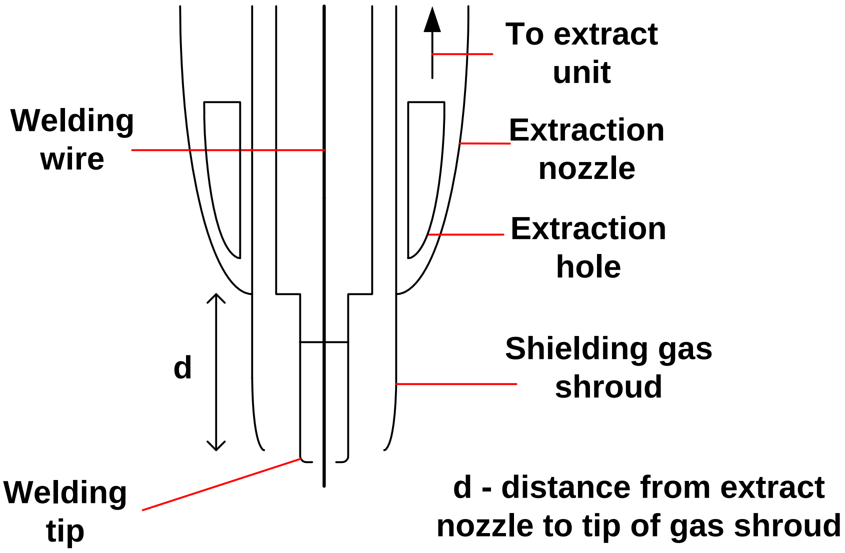


Figure 3.12 Schematic cross-section diagram of fume extracting welding torch

Figure 3.13 Nederman P 30 fume extraction unit

The sampling system is shown in Figure 3.14 and consisted of a 75 mm diameter duct, connected to the welding torch extract ducting at one end and to the extraction unit at the other. The system is not shown to scale. The extraction system is contained within the hose connecting the welding torch to the inverter. The outlet of this was connected to the 75 mm ducting by a short length of 32 mm diameter flexible hose and a bespoke expansion piece. The extracted air travels through the hose connecting the torch to the inverter, which is approximately 2 m in length and then into the sampling system. The sampling position is a further 2.8 m downstream; experience gained during the scoping trials (Appendix I) indicated that the flow would be fully developed at this point.

The flow rate of extracted air through the system was maintained at a constant level of 80 m^3h^{-1} using a diaphragm valve and was monitored using a micromanometer connected across an orifice plate. Although less than the maximum recommended airflow for the system, 80 m^3h^{-1}

allowed some latitude for adjusting airflow rate, should the filters on the extraction system become blocked. In addition to this, the sampling system (incorporating an orifice plate and a valve) added an extra resistance to the system, which would not be found in industry. An isokinetic sampling probe was positioned centrally within the duct diameter, the velocity of air entering the probe being matched to that in the extraction duct using an adjustable sampling pump and rotameter.

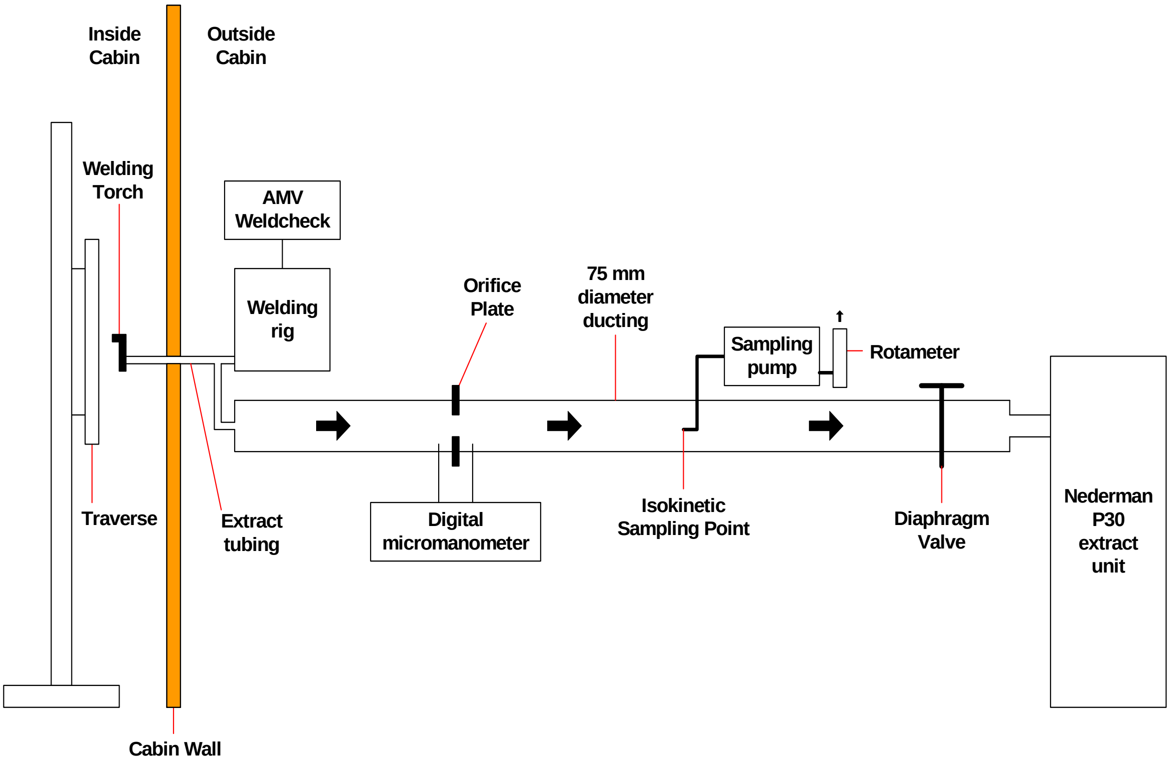


Figure 3.14 Schematic diagram of the on-gun extraction system and sampling set up

For the on-gun system, in general, three determinations were made under each specific set of conditions accompanied by three 100 % determinations made under identical conditions. Total capture for a given set of conditions was achieved by positioning, either, a funnel, or a box shaped enclosure of similar volume, around the torch, these are shown in Figures 3.15a and 3.15b. The funnel or enclosure ensured that any fume that initially escaped capture was trapped in the enclosure and ultimately captured. A series of experiments were carried out to investigate the capture efficiency of the on-gun system and its effect, if any, on the quality of the welds (bead on plate) produced.

- Welding bead on plate with Condition 1 (see Table 3.1) in the flat with the extraction nozzle flush with the bottom (d=0), d=7, 14 and 21 mm from the bottom of the gas shroud to ascertain the optimum position for the extraction nozzle.

- Welding bead on plate with Condition 1 in the flat with the extraction nozzle in the optimum position.

- Welding bead on plate with Condition 1 vertically upwards with the extraction nozzle in the optimum position.

- Welding bead on plate with Condition 1 vertically downwards with the extraction nozzle in the optimum position.

- Welding bead on plate with Condition 1 horizontally with the extraction nozzle in the optimum position.

- Welding a fillet with Condition 1 in the flat with the extraction nozzle in the optimum position. Note: this is the same ‘optimised position’ as for bead on plate and was used for the all the fillet welding.

- Welding a fillet with Condition 1 vertically upwards with the extraction nozzle in the optimum position.

- Welding a fillet with Condition 1 vertically downwards with the extraction nozzle in the optimum position.

- Welding bead on plate with Condition 2 (see Table 3.1) in the flat with the extract nozzle in the optimum position.

- Welding a fillet with Condition 2 in the flat with the extract nozzle in the optimum position.

Figure 3.15a The funnel enclosure in position and from the side

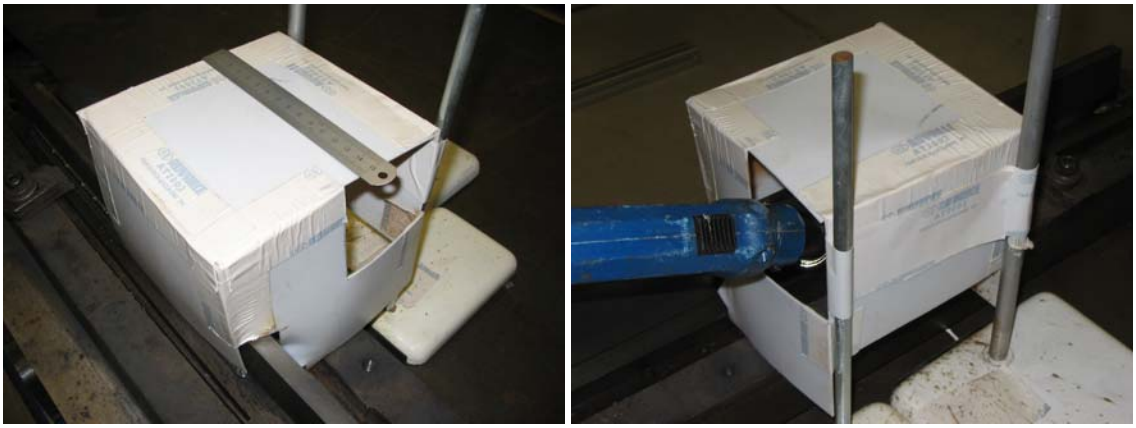


Figure 3.15b The box with scale and in position with torch

4 RESULTS

4.1 CENTRELINE VELOCITY PROFILES OF HV AND LV HOODS

The centreline velocity profiles of the large HV hood and the three tabletop LV hoods were measured using a TSI VelociCalc hot wire anemometer measuring a rolling 20 second average for 60 seconds. Velocities were measured along a line emanating perpendicular from the geometric centre of the face of the hood; the resulting profiles are shown below in Figures 4.1 – 4.4.

Figure 4.1 Centreline velocity profile of large HV hood

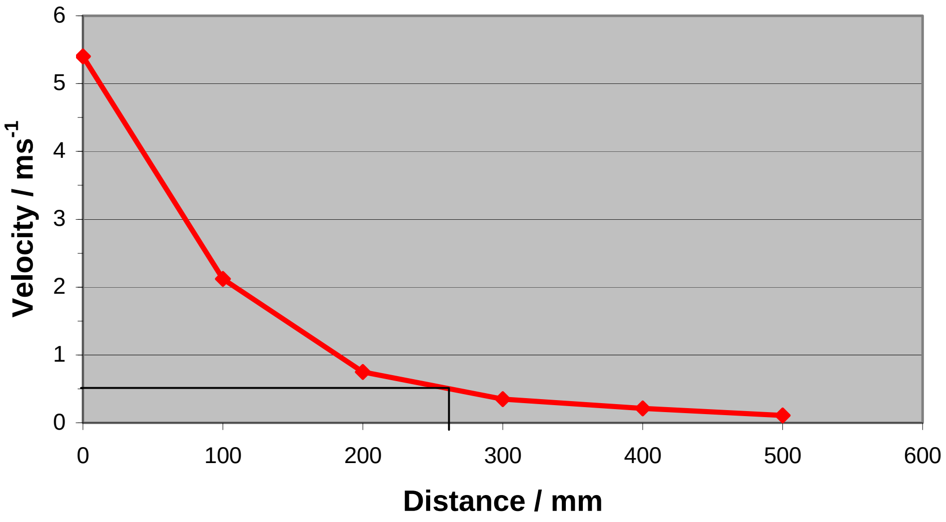


Figure 4.2 Centreline velocity profile of fishtail LV hood

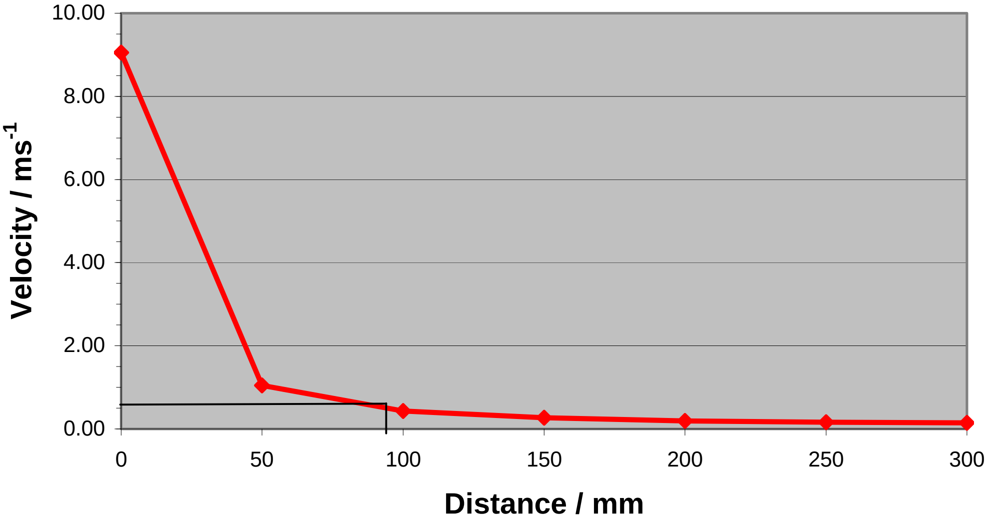


Figure 4.3 Centreline velocity profile of round LV hood

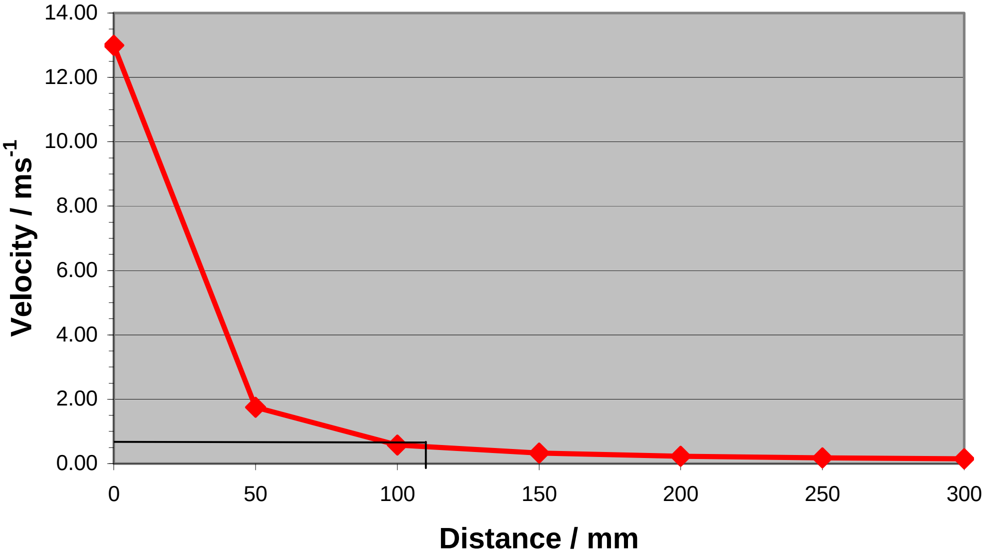
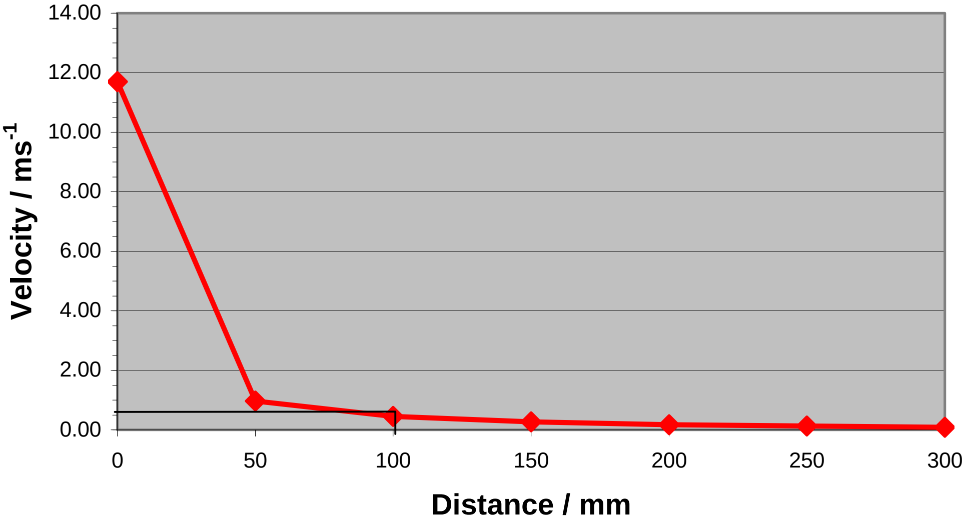


Figure 4.4 Centreline velocity profile of slot LV hood



These plots show how the air velocity induced by the various hoods decreases with distance from the face. The black line on each plot shows the approximate distance at which the velocity in front of the hood has fallen to 0.5 ms^{-1} which is the quoted minimum recommended capture velocity for welding fume [13].

Figure 4.1 shows the velocity profile along the centreline of the HV hood, the velocity at the face was approximately 5.5 ms^{-1}, the air velocity decreased to approximately 10 % of this value at one diameter (~300 mm) from the face.

The face velocities of the LV hoods were considerably higher but decreased more quickly with distance. This is because the decrease in velocity is related to the size and geometry of the hood. For the fishtail hood the velocity dropped to 10 % of the value at the face at approximately 60 mm from the face and to 0.5 ms^{-1} at approximately 90 mm. The circular hood has a diameter of 45 mm, its face velocity was 13 ms^{-1}, and the velocity fell to 10 % at approximately 70 mm and 0.5 ms^{-1} at 110 mm from the face. The slot hood had a face velocity of approximately 11.5 ms^{-1}, this decreased to 10 % at 40 mm and to 0.5 ms^{-1} at approximately 90 mm.

4.2 HV SYSTEM CAPTURE EFFICIENCY MEASUREMENTS

4.2.1 General

The full results tables for all the tests for the HV system are given in Appendix II section 9.1. All tests with the HV system were performed using welding Condition 2 (see Table 3.1 on p.7). Tests 1 – 28 were performed using a 1.2 mm flux cored wire, tests 15 – 17 were the 100 % extract tests, average fume concentration was 53 mgm^{-3}. Tests 29 – 42 were performed using a 1.2 mm mild steel wire, tests 31 & 32, average fume concentration was 53 mgm^{-3}. Tests 43 – 64 were also performed using the mild steel wire but used a traversing welding torch as opposed to a traversing test piece. For these moving torch tests 100 % extract tests were 61 – 64, average fume concentration was 27 mgm^{-3}.

Overall, when the hood was within one diameter of the fume generation point in any direction regardless of the 0.1 ms^{-1} cross draught, capture efficiency was greater that 80 %. With the hood positioned just a few centimetres closer capture efficiency was generally 90 % or higher. This essentially means that virtually the entire welding fume generated was being captured before entering the welders breathing zone. Depending on the positioning of the hood relative to the cross draught when placed perpendicular to the weld on the table, capture remains high out to two hood diameters on the downstream side or decreases precipitously on the upstream side. When the arc is moving in relation to the hood resting on the table, capture efficiency is also dependent on weld length as well as the position of the hood, 111 % for a 300 mm weld (this figure indicates that the magnitude of the errors in the measurements and this figure, essentially means all the welding fume was captured), and 79 – 88 % for a 450 mm weld.

One of the main objectives of the project was to assess the quality of the welds produced to check for any adverse effect of the LEV. Every weld was visually inspected for signs of surface porosity and a selection of welds were examined radiographically at TWI for evidence of sub-surface porosity. None of the welds produced during this project whilst using the large HV hood or the smaller tabletop hoods showed any evidence of porosity. One set of welds produced whilst using the on-gun system set up with the extract nozzle positioned flush with the bottom of the shielding gas shroud – i.e. with the extract in the closest possible position to the weld – produced weld with visible surface porosity. This, however, was an extreme test and the equipment is unlikely to be used in that configuration by a professional welder.

4.2.2 Capture efficiencies vertically above the arc

Table 4.1 Average capture efficiency

Test numbers	*Distance above arc (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
1 – 10	300	46	88
11 – 12	600	43	81
13 - 14	900	15	28

Results for tests 1 – 14 are given in Table 4.1 above. Average capture efficiency was 88 % at one hood diameter (~300 mm) where essentially all fume was captured, at two hood diameters 81 %, but at three diameters the large majority of fume was escaping capture where average capture efficiency was 28 %.

4.2.3 Capture efficiency with the hood at 45° in the plane of the weld

Table 4.2 Average capture efficiency at 45°

Test numbers	*Distance from arc (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
35 – 36	300	44	83
39 – 40	450	37	68
37 – 38	600	18	34

Results for tests 35 – 40 are given in Table 4.2 above. Average capture efficiency at one hood diameter was 83 % of fume generated but fell away rapidly and by two diameters average capture efficiency was 34 %. This does not compare favourably with positioning the hood directly above the arc.

4.2.4 Capture efficiency with the hood perpendicular to the plane of the weld resting on the table

4.2.4.1 Hood positioned downstream of the arc

Table 4.3 Average capture efficiency downstream from arc

Test numbers	*Distance from arc (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
15 - 17	150	53	100
18 – 19	300	51	95
21 – 21	600	44	82

Results for tests 15 – 21 are given above in Table 4.3. Capture efficiency downstream from the arc decreases slowly with increasing hood distance, capturing the entire fume at one diameter and falling to 82 % at two hood diameters.

4.2.4.2 Hood positioned upstream of the arc

Table 4.4 Average capture efficiency upstream from arc

Test numbers	*Distance from arc (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
33 – 34	85	55	103
31 – 32	150	53	100
25 – 26 & 29 - 30	300	50	93
27 – 28	450	32	59
22 – 23	600	1	3
24	600 in still air	15	27

Average capture efficiency upstream of the arc at one hood diameter was 93 %, but decreases rapidly with only a 0.1 ms^{-1} draught blowing from the hood face toward the fume generation point when efficiency falls to 3 % at two hood diameters. This compares to 82 % when the draught was towards the hood face.

4.2.5 Capture efficiency with a traversing torch and stationary test piece

4.2.5.1 Vertically above arc

In order to better simulate a real life situation where the generation point of the fume (the arc) is moving relative to the LEV hood, tests were performed with a traversing torch. Two weld lengths were investigated, 300 mm and 450 mm. These were deemed typical lengths that a welder would make before having to reposition himself, at which point the exhaust hood should be repositioned. Capture efficiencies were measured vertically above the arc, with the centre of the hood positioned above the centre point of each weld length, i.e. 150 mm from the start of the 300 mm weld and 225 mm from the start of the 450 mm weld.

Table 4.5 Capture efficiencies vertically above a moving torch

Test numbers	*Distance from arc (mm)*	*Weld length (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
43 - 44	340	300	23	86
45 – 46	340	450	28	101
49 – 50	650	300	25	93
47 – 48	650	450	19	70
51 – 52	650 in still air	300	20	72
53 – 54	650 in still air	450	25	93

As expected capture efficiency falls when the distance from hood to arc was increased. However, with the hood both 340 mm above the arc and with it 650 mm above the arc in still air the capture efficiency for a 450 mm weld is greater than for a 300 mm weld.

4.2.5.2 300 mm downstream from arc

Capture efficiencies were measured 300 mm downstream from the arc. The hood was positioned with the major axis (d=300 mm) parallel to the table. The centre of the hood was either positioned at the centre of each weld or at the start of the weld.

Table 4.6 Capture efficiencies downstream from a moving torch

Test numbers	*Position of hood relative to weld*	*Weld length (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
55 – 56	Centre	300	30	112
57 – 58	Centre	450	22	80
59 – 60	RHS	450	24	88

Table 4.6 above gives the results for tests 55 – 60. These results seem to indicate that the length of the weld is of higher importance than the positioning of the LEV hood. As the hood diameter is 300 mm placing the centre of the hood at the centre of a 300 mm weld also places both hood edges at the start and finish of the weld. Capture efficiency for this test was 112 %, why this is so high is not known, but could be attributed to welding spatter settling on the filter giving an artificially high gravimetric weight. However this is greater than the average fume concentration measured during the 100 % test and indicates that the entire fume was captured, whilst for a 450 mm weld some escapes but efficiency is higher when the LEV is placed at the centre of the weld. This finding highlights the limited capture field of a captor hood and therefore the importance of repositioning the hood at frequent intervals.

4.2.6 Effect of consumable on capture efficiency

Table 4.7 Effect of consumable on average capture efficiency

Test numbers	*LEV position*	*Consumable wire*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
11 – 12	Above	Flux-cored	43	81
41 – 42	Above	Mild steel	41	77
25 – 26	Upstream	Flux-cored	51	96
29 – 30	Upstream	Mild steel	48	90

These results indicate that the consumable does not affect capture efficiency; this is also confirmed in tests with the on-gun system in section 4.3.

4.2.7 Effect of draught on capture efficiency

Applying a draught towards or away from a hood positioned to the side of the weld has a large effect on the capture efficiency of a hood, as shown in Table 4.8. In still air the capture efficiency of the HV hood positioned 600 mm from the arc was measured to be 27%. With a draught towards the hood the capture efficiency increased to 83%. When the direction of the draft was reversed (away from the hood towards the arc) the capture efficiency fell to 3%.

It should be remembered that the airflow in the test cabin was unidirectional with relatively low turbulence. In a real welding situation the airflow is more likely to be random in direction and highly turbulent.

Table 4.8 Effect of draught on capture efficiency at 600 mm from the arc

Test numbers	*Cross draught (ms^{-1})*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
22 – 23	-0.1	1	3
24	0	15	27
20 – 21	0.1	44	83

4.3 LV SYSTEM CAPTURE EFFICIENCY MEASUREMENTS

4.3.1 General

It was necessary to perform a 100 % test for each hood due to the different operating flow rates of each hood creating differing dilutions of fume within the duct. It was initially intended to specify a single 100 % test position to be applied to all hoods but it was found that the maximum average fume concentration occurred at different positions depending on the hood geometry. This is discussed further in Sections 5.4 and 6.2.

Full results for all tests involving the low volume tabletop hoods can be found in Tables 9.4, 9.5 & 9.6 in Appendix II. Tests 65 – 130 were performed using MAG welding and Condition 2 testing the three tabletop LV hoods upstream and downstream. Tests 109 – 130 were also performed with the hoods off centre to provide information on capture efficiencies when the hoods were not in an ideal position. No tests were carried out with the slot hood off centre as it had a hood length of 300 mm and this was the approximate average length of the test welds.

The results of the 100 % extract tests for tests 65 – 130 are given below in Tables 4.9.

Table 4.9 Results for 100 % extract tests used for tests 65 - 130

Test numbers	*Hood*	*Hood position*	*Average fume concentration (mgm^{-3})*
67 – 68	Fishtail	150 mm downstream	112
90 – 91	Slot	75 mm upstream	97
103 – 104	Circular	75 mm upstream	103

Tests 131 – 162 were performed using MAG welding and Condition 2 with the LV hoods perpendicular to the plane of the weld with a stationary test piece and traversing torch to simulate a more realistic situation. These tests were performed several weeks after the first tests and the settings on the welding rig had been altered. This meant that although every care was taken to reproduce exactly the welding conditions, tip to work distance, arc travel speed etc. this could not be guaranteed and so the fume emission rate may have changed. It was therefore necessary to perform an additional 100 % test. This result is given in Table 4.10.

Table 4.10 Result of 100 % extract tests used for moving torch experiments

Test numbers	*Hood*	*Hood Position*	*Average fume concentration (mgm^{-3})*
139 - 140	Fishtail	75 mm downstream	142

No 100 % test was required for the circular hood as it was operated at the same volume flow rate as the fishtail for these experiments. There was no suitable 100 % for the slot hood as it was operated at a different flow rate to the other two hoods for these experiments, so fume concentrations only have been reported. Plots of the capture efficiency of the HV hood for all tests conducted can be found in Appendix III.

4.3.2 Capture efficiency with the hood perpendicular to the plane of the weld

4.3.2.1 Fishtail hood

Results for tests 65 – 78 are given below in Table 4.11.

Table 4.11 Capture efficiency of fishtail hood perpendicular to plane of weld

Test numbers	*Position*	*Distance from arc (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
77 - 78	Upstream	225	17	15
73 - 74	Upstream	150	57	51
75 - 76	Upstream	75	76	69
65 - 66	Downstream	75	89	80
67 – 68	Downstream	150	112	100
71 - 72	Downstream	225	55	50
69 - 70	Downstream	300	14	12

These results give the unusual feature of capture efficiency increasing with downstream distance from the arc, reaching a maximum at 150 mm and then falling again rapidly to 50 % at 225 mm downstream. This is likely to be related to the behaviour of the thermal welding plume combined with the cross flow and is discussed in more detail in section 5. Upstream from the arc efficiency was 69 % at 75 mm and then fell with increasing distance. The fishtail hood is essentially a slot having an aspect ratio of ~0.15 (major axis = 205 mm, minor axis = 30 mm). It is known that as the aspect ratio of a hood increases the velocity at a given point in front of the hood decreases for a fixed face area and flow rate[14]. These results and the centreline velocity measurements suggest that this is the case for the fishtail with an effective capture zone extending only 50 – 100 mm from the hood face.

4.3.2.2 Circular hood

Results for tests 95 – 108 using the circular hood upstream and downstream are given below in Table 4.12.

Table 4.12 Capture efficiency of circular hood perpendicular to plane of weld

Test numbers	*Position*	*Distance from arc (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
107 - 108	Upstream	225	19	18
105 – 106	Upstream	150	68	66
103 – 104	Upstream	75	103	100
95 – 96	Downstream	75	79	77
97 – 98	Downstream	150	70	68
99 – 100	Downstream	225	58	56
101 – 102	Downstream	300	36	35

Capture efficiency was greater 75 mm upstream than 75 mm downstream, 100 % compared to 77 % but decreased much more rapidly on the upstream side falling to 18 % 225 mm upstream compared to 56 % at the same distance from the arc downstream. The centreline velocity profile of the hood suggests that the effective capture zone of the hood extends to 110 mm from the hood face.

4.3.2.3 Slot hood

Results for tests 79 – 94 using the slot hood upstream and downstream are given below in Table 4.13.

Table 4.13 Capture efficiency of slot hood perpendicular to plane of weld

Test numbers	*Position*	*Distance from arc (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
92 – 94	Upstream	225	16	17
88 – 89	Upstream	150	61	63
90 – 91	Upstream	75	97	100
79 – 81	Downstream	75	84	87
82 – 83	Downstream	150	91	94
84 – 85	Downstream	225	48	49
86 – 87	Downstream	300	44	46

The slot hood also demonstrated greater efficiency at 150 mm downstream than 75 mm. Upstream, fume capture was at a maximum at 75 mm where the 100 % determination was made, although with average fume concentration at 97 mgm^{-3}, the difference between this position and at 75 mm and 150 mm downstream was minimal. The centreline profile of the slot hood suggests its effective capture zone extends to approximately 90 mm from the hood face.

4.3.3 Capture efficiency of LV hoods with a lateral offset

Results for tests 109 – 120 using the fishtail hood laterally offset from the arc are given below in Table 4.14.

Table 4.14 Capture efficiency of fishtail hood off centre

Test numbers	*Position*	*Offset distance (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
109 – 110	Downstream	150	83	74
111 – 112	Downstream	225	49	44
117 – 118	Upstream	75	101	91
115 – 116	Upstream	150	65	59
119 – 120	Upstream	225	120	20

The fishtail hood was tested at two positions 75 mm downstream and three positions 75 mm upstream. As was expected efficiency decreased with an increasing offset, when upstream the hood performed better with an offset of 75 mm (91 %) than when directly inline (69 %).

Results for tests 121 – 130 using the circular hood laterally offset from the arc are given below in Table 4.15.

Table 4.15 Capture efficiency of circular hood off centre

Test numbers	*Position*	*Offset distance (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
125 – 126	Downstream	75	95	92
127 – 128	Downstream	150	74	71
129 - 130	Downstream	225	33	32
121 – 122	Upstream	75	77	74
123 – 124	Upstream	150	50	48

The circular hood was tested at three positions 75 mm downstream, and two positions 75 mm upstream. Again, capture efficiency decreased with increasing offset distance.

4.3.4 Capture efficiency with a traversing torch and stationary test piece

4.3.4.1 Fishtail and circular hoods

Both the fishtail and circular hoods were tested in varying positions relative to 300 mm and 450 mm welds 75 mm downstream, and a single position 150 mm downstream with the centre of the hood positioned at the centre of a 300 mm weld. Results for tests 121 – 162 using the fishtail and circular hoods and a traversing welding torch are given below in Tables 4.16 and 4.17.

Under the test conditions these results show that the hoods are less efficient for longer welds. The measured capture efficiency of the fishtail hood is greater than 100 % at both 75 and 150 mm from the centre of a 300 mm weld, this is probably within the bounds of experimental uncertainty and indicates that all of the fume was being captured. The similar result of 93 % for the right hand edge of the 300 mm weld also suggests that the entire fume was being captured. The results suggest, as expected, that the positioning of the hood affects the capture efficiency, although this difference is less marked than that between the shorter and longer welds. The circular hood is less efficient than the fishtail as it always misses some of the fume, whilst for the shorter weld length, at least, the fishtail captures all of it.

Table 4.16 Capture efficiency of fishtail hood with moving torch

Test numbers	*Position relative to weld*	*Distance from arc (mm)*	*Weld length (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
148 - 149	Centre	75	300	159	112
146 – 147	RHS	75	300	132	93
141 – 143	Centre	75	450	105	74
144 – 145	RHS	75	450	88	62
150 – 151	Centre	150	300	150	106

Table 4.17 Capture efficiency of circular hood with moving torch

Test numbers	*Position relative to weld*	*Distance from arc (mm)*	*Weld length (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
152 – 153	Centre	75	300	113	79
154 – 155	RHS	75	300	93	66
158 – 160	Centre	75	450	90	63
161 – 162	RHS	75	450	62	43
156 - 157	Centre	150	300	119	84

4.3.4.2 Slot hood

A similar series of tests were performed with the slot hood as with the circular and fishtail hoods, except for the 300 mm welds where for the centre and right hand edge the hood was in the same position, as the hood was 300 mm wide. There was no suitable 100 % test for the slot hood so only average fume concentrations are reported here. Results for tests 131 – 138 using the slot hood and a traversing welding torch are given below in Table 4.18.

Table 4.18 Average fume concentrations for slot hood with moving torch

Test numbers	*Position relative to weld*	*Distance from arc (mm)*	*Weld length (mm)*	*Average fume concentration (mgm^{-3})*
131 – 132	Centre + RHS	75	300	137
135 – 136	Centre	75	450	140
137 - 138	RHS	75	450	159
133 – 135	Centre + RHS	150	300	150

The average fume concentrations, were all within 14 % of the highest value, measured at the right hand edge of the 450 mm weld, showing that there is little to choose between the weld lengths or relative positions of the hood. However, without a 100 % value there is no definitive way to determine what proportion of the generated fume the hood was capturing. Visually, however, during the moving torch tests, the slot hood was seen to capture virtually the entire fume being generated. Figure 4.5 supports this, which is a photograph taken during test 82 which had the same experimental setup as the above tests (i.e. slot hood positioned 150 mm downstream from a 300 mm weld). As can be seen very little fume can be seen escaping capture.

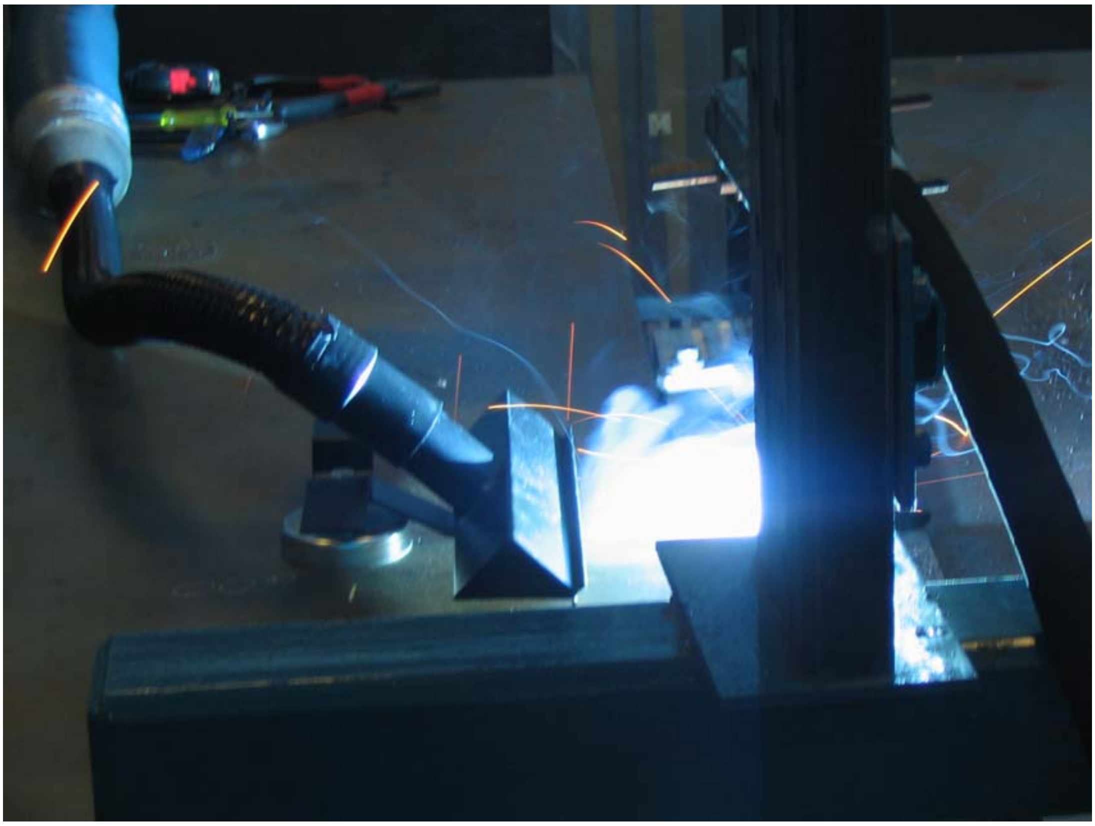


Figure 4.5 Still photograph of test 82; slot hood positioned 150 mm downstream from a 300 mm weld

4.4 ON-GUN EXTRACTION SYSTEM CAPTURE EFFICIENCY MEASUREMENTS

4.4.1 General

Full sets of results for capture efficiency measurements made using the on-gun system are given in Appendix II. The majority of capture efficiencies measured during bead on plate welding were greater than 90 %, with only one result obtained whilst welding horizontally being significantly lower. Results obtained with fillet welding proved to be difficult to interpret. Initial experiments to determine the capture efficiency when welding in a fillet in the flat were performed using a large enclosure, cuboid in shape measuring approximately 600 mm long, 300 mm wide by 400 mm high to provide 100 % capture measurements. These tests showed capture efficiency of ~90 % using a 1.0 mm wire and ~50 % when using a 1.2 mm wire. To determine the capture efficiency for fillets welding in position we initially used 100 % capture values from welding bead on plate in position. On analysis of these data, it became apparent that the fume emission rate from fillets was significantly different to that from welding bead on plate and so capture efficiency measurements were repeated using dedicated 100 % capture measurements. At the same time, capture efficiency measurements for welding fillets in the flat with both the 1.0 and 1.2 mm wires were repeated using the smaller cube shown in Figure 3.15b. Along with these four sets of repeated tests, capture efficiency measurements for bead on plate welding in the flat with the 1.0 mm wire were repeated for comparison.

In these repeated tests, the results for welding bead on plate in the flat were essentially identical changing from 89 % to 93 %. The results for welding fillets vertically upwards and downwards changed but this was to be expected as correct 100 % capture values were used in the repeated tests. For welding a fillet in the flat with the 1.2 mm wire capture efficiency changed from 46 % to 55 % but for the 1.0 mm wire from 95 % to 62 %, this is discussed later in section 4 and in section 5.

Maximum fume concentrations for the 100 % extract tests using the on-gun system are given in Table 4.19.

Table 4.19 Maximum fume concentrations from 100 % capture tests

Test numbers	*Description*	*Fume concentration (mgm^{-3})*
192 – 194	Bead on plate, horizontal.	301
163 – 164	Bead on plate, in the flat.	226
183 – 185	Bead on plate, vertically down.	193
180 – 182	Bead on plate, vertically up.	130
197a – 198a	Fillet, in the flat.	159
201 – 203	Fillet, vertically down.	141
207 - 209	Fillet, vertically up.	103

The fume concentrations in the extract duct, measured in the 100 % tests with a 1.0 mm diameter wire, were rather variable, depending upon the welding position, although the welding parameters had been maintained at as constant a level as possible. Highest concentrations were measured when welding bead on plate in the horizontal position. Other concentrations when welding bead on plate, were highest when welding in the flat, followed by vertically down and lowest when welding vertically up. Similarly, there were differences in concentration between the various positions when welding with the 1.0 mm wire in a horizontal/vertical fillet, although the differences were smaller. Testing was not carried out in the horizontal position, leaving the highest value for welding in the flat, then welding vertically down and lowest when welding vertically up. Thus, the results were lower than for bead on plate welding but the order had been retained.

4.4.2 Effect of extract nozzle position on capture efficiency

Results from this set of tests are given in Table 4.20.

Table 4.20 Capture efficiencies of varying extract nozzle positions

Test numbers	*Nozzle distance from gas shroud (mm)*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
165	0	268	120
166 - 167	7	205	93
168 - 169	14	238	107
170 - 171	21	172	78

The nozzle distance from gas shroud is shown as **d** in the schematic diagram of the on-gun torch, Figure 3.12. The concentration of fume in the extraction duct when the extract nozzle was positioned flush with the gas shroud of the gun was higher than the average concentration measured in the 100% checks. However, positioning the nozzle in this way caused a reduction in weld metal integrity, as shown by visual porosity, making this nozzle position unusable practically. Numerically this actually gave capture efficiency substantially higher than 100 % at

120 %, which may be due to an increased fume emission rate caused by the removal of shielding gas leading to compromised weld metal integrity. Highest capture efficiency was measured when the extract nozzle was 14 mm from the bottom of the gas shroud, making this the optimum position for welding bead on plate. The capture efficiency, at around 90 %, was somewhat lower when the extract nozzle was slightly nearer than the optimum position to the weld and lower still (78%) when it was further away. There were no visual indications of porosity in the welds deposited with the extraction nozzle 7, 14 and 21 mm from the bottom of the gas shroud. It should be noted that the position of the nozzle extract was not optimised for fillet welding.

4.4.3 Effect of welding position on capture efficiency

4.4.3.1 Bead on plate welding

A summary of results for bead on plate welding in a variety of positions is given in Table 4.21.

Table 4.21 Capture efficiency of bead on plate welding in the flat and in position

Test numbers	*Test description*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
172 – 176	In the flat, 1.0 mm wire	209	94
216 - 218	In the flat, 1.2 mm wire	400	93
177 - 179	Vertically up	140	107
186 - 188	Vertically down	166	90
189 - 191	Horizontally	214	74

The average capture efficiency when welding bead on plate in the flat with the 1.0 mm wire was 94 %. Thus, almost all the fume generated was captured. The results ranged from 84 to 101 % giving an indication of the reproducibility of the method. Extraction efficiency obtained with the 1.2 mm wire, at 93 %, was almost identical.

The average capture efficiency when welding bead on plate, vertically up was 107 %. Thus, slightly more fume was measured in the evaluation tests than in the 100 % check tests, although the difference was probably within the range of experimental error. Nevertheless, it is important to note that, for vertically up welding, all fume was captured. The average capture efficiency when welding bead on plate, vertically down, was 90 %. Whilst the efficiency was not quite as high as when welding vertically up, almost all the fume was captured and the result was again similar to that obtained when welding in the flat. The average capture efficiency when welding horizontally, at 74 %, was somewhat lower than for bead on plate welding in the flat, vertically up and down positions, reasons for this are discussed in section 5.

4.4.3.2 Fillet welding

A summary of results for measuring capture efficiency when welding in fillets is given in Table 4.22.

Table 4.22 Capture efficiency of fillet welding in the flat and in position

Test numbers	*Test description*	*Average fume concentration (mgm^{-3})*		*Average capture efficiency (%)*	
		Large[1]	*Small*	*Large*	*Small*
195a – 196a	In the flat, 1.0 mm wire	146	80	95	62
219a – 222a	In the flat, 1.2 mm wire	237	244	46	55
204 – 206	Vertically down	100		82	
210 - 212	Vertically up	82		81	

Initially, capture efficiency measurement for welding fillets in the flat were made using a 100 % capture value from tests using a large enclosure, measuring approximately (600 x 420 x 320) mm. Upon analysis of the results it was thought that the enclosure was too large in relation to the volume airflow of the extraction system and that fume was escaping. Capture efficiency measurements were repeated using a cube shaped enclosure (see Figure 3.15b) with a similar volume to the funnel enclosure used for the bead on plate determinations. Both sets of results are given in the full results tables in Appendix II. In all tests welding fillets in the flat with the exception of the first measurements made with the 1.0 mm wire in the large enclosure were lower than for welding bead on plate.

Average capture efficiency when welding fillets vertically up or down more closely approached that for welding bead on plate but was still somewhat lower. There was no difference in capture efficiency between welding vertically upwards or downwards.

4.4.4 Effect of welding in a fillet to welding bead on plate on capture efficiency

A summary of various results comparing bead on plate welding to fillet welding is given in Table 4.23

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[1] *Large and small refers to the enclosure used to determine 100 % capture values, the large box was deemed to be unsuitable so capture efficiency measurements were repeated using the small enclosure in Figure 3.15b.*

Table 4.23 Capture efficiency of bead on plate welding and fillet welding

Test numbers	*Test description*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
172 - 176	Bead on plate, in the flat, 1.0 mm wire	209	94
216 – 218	Bead on plate, in the flat, 1.2 mm wire	400	93
198b – 200b	Fillet, in the flat, 1.0 mm wire	80	62
222b – 224b	Fillet, in the flat, 1.2 mm wire	244	55
186 – 188	Bead on plate, vertically down	165	90
204 - 206	Fillet, vertically down	100	82
177 - 179	Bead on plate, vertically up	140	107
210 - 212	Fillet, vertically up	82	81

Overall, capture efficiency when welding fillets was lower than when welding bead on plate. This effect was most apparent when comparing the two welding types in the flat, where for bead on plate results indicate that all fume is captured and for fillets approximately half the fume escapes capture. The same can be said for positional welding, although the results for bead on plated are numerically different they both indicate that all fume is captured and for fillets some escapes. However, the extract nozzle position was only optimised for bead on plate and it was assumed that this position would apply to fillet welding. It may be that this assumption was incorrect and higher capture efficiencies for fillet welding could be achieved with a different nozzle position.

4.4.5 Effect of fume emission rate on capture efficiency

Table 4.23 summarises results from bead on plate welding in the flat with both diameters of wire.

Table 4.24 Capture efficiency of welding with 1.0 and 1.2 mm wires

Test numbers	*Test description*	*Average fume concentration (mgm^{-3})*	*Average capture efficiency (%)*
172 – 176	Bead on plate, 1.0 mm wire	209	94
216 - 218	Bead on plate, 1.2 mm wire	400	93

The fume concentrations measured in 100 % extract checks demonstrate that welding with the 1.2 mm diameter wire generated more fume than with the 1.0 mm wire, as much as four times in some cases. Comparative tests performed with both diameters of wire, bead on plate and in a fillet, provided similar capture efficiency data. This demonstrates that in most cases the on-gun extraction system tested works equally well with different fume emission rates under the conditions in which the tests were performed.

5 DISCUSSION

5.1 GENERAL

At the work planning stage of this project it was the intention to perform 100 % extract tests between every trial. However, the first few days of testing showed that highly repeatable tests were obtainable and the methodology was revised. It was then intended to perform a single set of 100 % tests for each welding condition and LEV set up, HV or LV. Subsequently, it was discovered that when the welding parameters had been altered and then reset to the specifications used for the 100 % tests the fume emission rate changed i.e. the repeatability was satisfactory, where repeatability is defined as ‘repeat tests with no alteration to the experimental set up’, but the reproducibility was not satisfactory, where reproducibility is defined as ‘significantly altering the experimental set up and welding parameters before returning them to the original configuration between tests’. This was true despite every care being taken to exactly reproduce the original parameters. Small changes in variables such as contact tip to work distance had a strong effect on emission rate. This meant that if the welding parameters were changed between a 100 % determination and a trial, the 100 % value was not applicable to the trial due to the changed fume emission rate. To this end, 100 % determinations were made for each set of trials using specific welding parameters. For instance tests 1 – 28 using flux cored arc welding and the HV LEV system used tests 15 – 17 as a 100 % value to determine capture efficiency. The other sets of trials were: tests 29 – 42 for MAG welding with a solid wire and HV LEV, 43 – 64 for MAG welding using a traversing torch for the HV LEV system. The LV was divided into two sections; the first had a stationary torch where the fume generation point was stationary relative to the LEV hood where a 100 % determination was made for each hood. The second section used a traversing torch to more realistically simulate actual welding operations and had its own 100 % determination.

Evaluating the on-gun system was slightly more complicated. Previous tests were only conducted in the flat, welding bead on plate to simulate butt welding. For the on-gun system, welding was performed in the flat and in position on vertical surfaces, welding in fillets was also investigated. It was apparent, from the average fume concentrations measured during testing to measure 100 % extract efficiency, that the emission rate of the fume varied depending on the welding position, even though the welding parameters were essentially the same. This confirmed the necessity to perform 100 % tests alongside each determination of capture efficiency.

The work in this project has shown that in most situations if used correctly local exhaust ventilation will, with some exceptions, provide high efficiency fume capture without compromising weld metal integrity. The purpose of this study was not to arbitrarily define a pass/fail criteria for various LEV configurations but to provide a quantitative measure of capture efficiency and ascertain whether the LEV would adversely affect the quality of the weld. It should be noted that a satisfactory level of control is dependent upon factors such as the work practices, the work situation, the welding duty cycle, the fume emission rate and composition in addition to the efficiency of fume capture. Therefore, capture efficiency should be used as one factor in a process of risk assessment and not a defining criterion of satisfactory control. The effect of this is that for any given process or task, the level of capture efficiency required is in large part defined by factors such as the welder’s duty cycle and the composition of the fume generated.

As expected from the results of Phase 2, none of the welds produced with the HV or LV systems showed any signs of visual porosity, and none of the welds submitted for radiographic analysis showed any indication of sub-surface porosity. Several welds produced with the on-gun system had visual surface porosity; these are discussed in section 7.2.

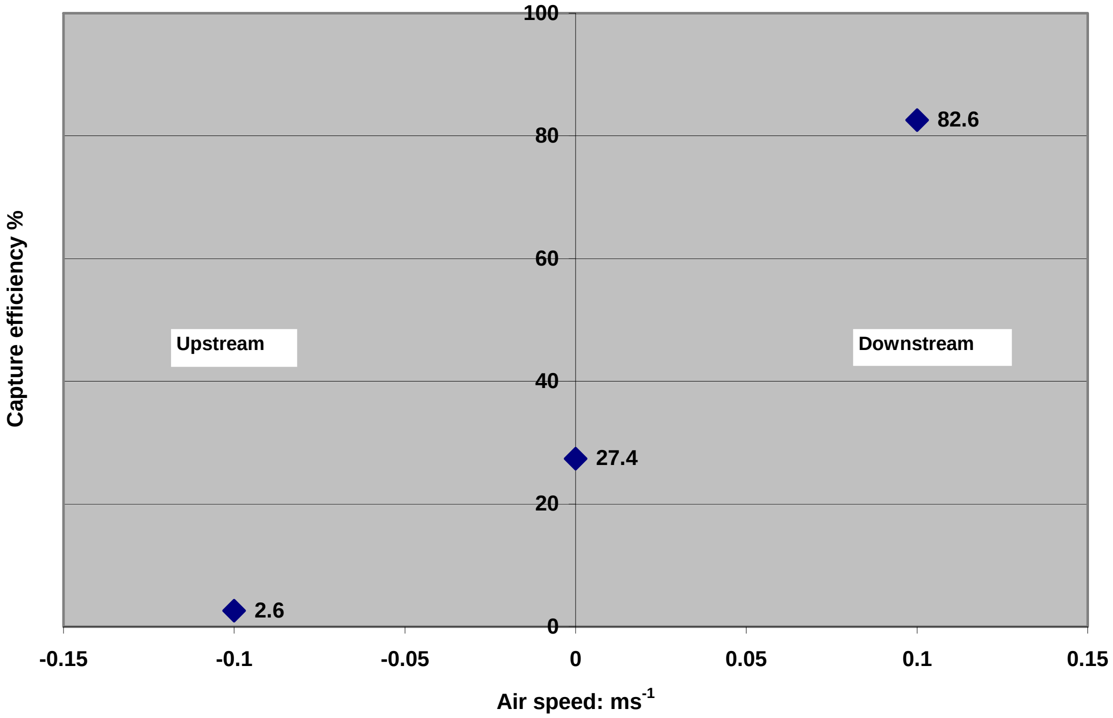
5.2 HV SYSTEM

The efficiency of the HV system was evaluated in several orientations, vertically above the arc, at 45° in the plane of the weld and at 90° (horizontal) perpendicular to the plane of the weld with the hood resting on the table both upstream and downstream. Overall, capture efficiency using the HV system provided a high level of control under the test conditions with the hood positioned within one diameter (300 mm) of the fume generation point in any direction. The exception to this was with the hood at 45° in the plane of the weld where at one hood diameter capture efficiency was 83 %. Vertically above the arc at one hood diameter capture efficiency was 88 % but still high at two hood diameters, 81 %. This is because the thermal uplift of the plume carries the fume into the hood making it act partly like a receptor hood, however at three diameters capture efficiency falls to less than 30 %. This is because as, the plume expanded with distance from the arc it was also diverted by the 0.1 ms^{-1} cross flow. With the hood at 45° the story is different, at one hood diameter capture efficiency is 83 % but quickly diminishes to 34 % at two hood diameters as the hood is no longer in the path of the thermal plume.

With the hood positioned 300 mm to the side (horizontal) for both the upstream and downstream position, the capture efficiencies were 93 % and 95% respectively. This is higher than when the hood was positioned 300 mm above the arc (88 %), albeit only slightly. This is at odds with the idea of a rising thermal plume. One would imagine that when the plume was rising towards the hood the highest capture efficiency would be with the hood directly above the arc. However, this can be explained, as when a hood is positioned on a large plane surface the induced velocity at any given distance in front of the hood is higher than for a suspended hood[15]. This is because the plane surface restricts where air can be drawn from, pushing the velocity contours further from the face of the hood.

When moving the hood out of the plane defined by the axis of the weld, any cross draughts must be carefully considered when positioning the hood. With the hood placed downstream from the emission point, capture efficiency as stated was high at one hood diameter and still high at two diameters, 82 %. This is partly due to the effect of the draught pushing the fume toward the hood. Placing the hood upstream changes this, capture efficiency is unaffected by the 0.1 ms^{-1} draught up to one hood diameter from the source as explained above. However, beyond this distance capture efficiency rapidly decreases until at two diameters only 3 % of fume mass is captured by the LEV system. These tests provided the starkest demonstration of the effect a draught can have on a captor hood. Three tests were performed with the hood positioned 600 mm (two hood diameters) from the source, with a draught blowing towards the hood, away from the hood and with no draught at all, the capture efficiencies are plotted below in Figure 5.1. It should be reiterated that these results were obtained under the conditions of the draught produced in the environmental test cabin, which operates under near plug (or piston) flow with a constant velocity and direction. Disturbing draughts encountered in the real workplace will have varying magnitudes and direction.

Figure 5.1 Plot of a disturbing draught against capture efficiency at 2 hood diameters. The figures next to the data points are average capture efficiencies



Whilst the HV system was being tested, two types of consumable were used; a flux cored wire and a solid wire. Several sets of tests were performed using both wires, the results showed good agreement; it is possible therefore to say that capture efficiency for the HV hood was independent of consumable.

All of these measured capture efficiencies represent an idealised view of the situation or a best-case scenario, as the fume emission point is stationary relative to the hood. A series of tests were performed using a traversing torch to assess the capture efficiency in a more realistic way. When the hood was placed vertically above the centre of a bead of length 300 mm fume capture was high at 340 and 650 mm above the arc. It was not possible to place the hood at 300 mm because the torch and its mounting had to traverse underneath it. For a 450 mm long weld bead all of the fume was captured at 340 mm but fell to 70 % at 650 mm. However, an unexpected result occurred when the cabin ventilation was disabled reducing the cross draught to near zero. In still air with the extract 650 mm above the arc, capture efficiency for a 450 mm weld rose to approximately 100 % but fell to 73 % for a 300 mm weld, no explanation for this can be offered. With the hood resting on the table one diameter downstream from the traversing torch for a 300 mm weld, the hood captured all of the fume, which is unsurprising as the hood diameter was 300 mm. For a 450 mm weld efficiency was slightly lower, the position of the hood relative to the weld did not make a large difference, 88 % at the end of the weld and 80 % at the middle.

5.3 LV SYSTEM

As the LV hoods were designed to be used close to a plane surface, they were only tested in this configuration. All testing took place with the hoods positioned upstream and downstream perpendicular to the weld. Two of the hoods had higher capture efficiencies when positioned 150 mm downstream than at 75 mm. These were the fishtail, where the 100 % value was at 150 mm downstream, and the slot hood. The slot and circular hoods achieved maximum capture when 75 mm upstream. It was originally intended to specify a single position for 100 % determinations for the three hoods but they had maximum fume capture at different positions. This was most likely due to the design of the individual hoods creating differently shaped capture zones and also the individual geometries affecting the flow of air past the hoods. The fishtail and slot hoods have wide capture zones that do not extend very far outwards from the face of the hood because of their low aspect ratios. The circular hood had a capture zone that extended further from the hood face but was not very wide.

The fishtail hood had maximum fume capture at 150 mm downstream (100%), capture efficiency was 80 % at 75 mm downstream. The tests were repeated later after the settings had been changed and reset, fume capture was again higher at 150 than 75 mm. It is difficult to explain this, but it may be that with the hood at 75mm, the thermal rise of the plume is, on occasion, sufficient to escape the capture zone with no hope of being recaptured. With the hood at 150 mm downstream of the arc, any escaping fume may be pushed towards the hood by the airflow through the cabin, offering an opportunity to be extracted. Beyond 150 mm downstream, capture efficiency of the fishtail hood decreases rapidly. Upstream, the fishtail consistently had the lowest capture efficiency of the three hoods the highest being 69 % 75 mm upstream. This efficiency rapidly decreased further with distance from the arc. It would appear that, in the presence of any air movement away from the face of the hood towards the source, the fishtail was unable to capture a large proportion of the fume generated. The hood performed better when set off centre to the arc or when a traversing torch was used, this is due to the shape of the capture zone but it is unclear as to why the capture efficiency was lower when directly in line with the arc. Overall, the fishtail hood performed best when downstream from the arc at a distance of 150 mm or closer. The same would probably be true in still air conditions although any disturbance to the source would adversely affect capture efficiency. Of the hoods tested with a traversing torch, the fishtail performed best, achieving high capture efficiencies for a 300 mm long weld at distances of both 75 and 150 mm from the arc. This indicates that the shape and size of the hood is important and must match the length of weld laid down. None of the hoods provided a high level of capture for a 450 mm weld. This indicates that LV hoods of the size tested should be repositioned after at least every 300 mm of weld laid down.

The circular hood had maximum fume capture at 75 mm upstream from the arc; like the fishtail this decreased rapidly with distance from the arc. Downstream capture was highest at a distance of 75 mm, but only 77 % of the fume was captured at this position. As would be expected, capture efficiency decreases with further distance from the arc. Unlike the fishtail hood, when close to the arc upstream, the circular hood has high capture efficiency, but beyond a distance of 75 mm capture efficiency decreases rapidly. The circular hood performed similarly when used off centre achieving capture efficiencies of less than 80 % at distances of 75 and 150 mm. The only way the circular hood can provide good control would be to use it at 75 mm or closer. However at these short distances, the velocity induced by the hood approaches that which induced porosity in welds during phase 2 testing, although none were found in the samples during this study.

The slot hood produced maximum fume capture when positioned 75 mm upstream from the arc, but, of the three LV hoods, it performed best over the largest range of distances. From 75 mm upstream through 75 mm and to 150 mm downstream, the capture efficiency of the hood was sufficient to provide control of the fume emission and prevent it from entering the breathing zone of a potential operator. This seems counter intuitive when considering the shape of the capture zone produced by the hood. Like the fishtail hood the slot has a low aspect ratio being 300 mm long and only 4 mm wide, but the slot had two flanges above and below. The bottom flange rests on the surface of the table, which greatly reduces the amount of air drawn from behind the hood. As stated earlier, resting a hood onto a surface pushes the velocity contours further from the hood when compared to the same hood freely suspended. The slot hood was tested with a traversing torch, but capture efficiencies could not be determined as there was no suitable 100 % value. Comparing the average fume concentrations from the various tests however, showed that the position of the hood relative to the weld made little difference. Average fume concentration did not change significantly when welding 300 or 450 mm welds. Visual inspection of these tests indicated that very little fume was escaping this hood, however this was a very subjective assessment. For the more realistic simulations of welding, using the traversing torch, the slot hood seemed to perform better than the other two hoods and, providing the hood was within 150 mm of the weld, against a plane surface and repositioned every 400 – 500 mm, it would provide a high level of control.

Overall, the LV hoods were able to provide high capture efficiencies in only a very limited range of positions, typically 75 – 150 mm from the arc. The relatively low volume of air moved by this system, typically 125 – 150 m^3h^{-1} meant that, although relatively high velocities were produced at the face, these very quickly decrease producing small effective capture zones. Additionally, the velocities produced very close to the face are high enough to produce porosity in the weld metal as shown in Phase 2 of this study making them unusable at very short distances from the arc. The LV hoods are difficult to move and reposition and, as in real situations the source generation point would very rarely remain stationary relative to the hood, it would have to be repositioned regularly to maintain high capture efficiencies.

Plots showing the capture efficiency of the three LV hoods for all tests can be found in Appendix III.

5.4 ON-GUN EXTRACTION SYSTEM

The work in this section of the project has shown that the on-gun fume extraction system evaluated will, with limited exceptions, provide a high level of fume capture, without compromising weld metal integrity. This is contrary to popular belief. However, the eventual consideration is whether on-gun extraction can approach the efficiency of conventional local exhaust ventilation systems, which when used properly should provide capture efficiencies approaching 100 %. Therefore, in order to compete, the on-gun system has to operate at capture efficiencies greater than 90 %. On this basis, on-gun extraction performed adequately for the majority of the configurations tested. Welding overhead may result in relatively low capture efficiency, but this configuration was outside the scope of the present study.

Not all of the differences in fume concentrations measured in 100 % checks were unexpected. For example, it is well known that welding in a fillet in the flat provides a lower fume emission rate than welding bead on plate. However, no data were available previously to suggest that welding in other positions generated different quantities of fume.

The results have shown that positioning the extract nozzle, in order to achieve efficient capture, whilst maintaining weld metal integrity, is not a difficult task. Weld metal integrity, as shown by porosity, was only compromised in an extreme position where the extraction nozzle was flush with the bottom of the gas shroud. None of the other positions examined resulted in any indication of weld metal porosity. Only a nozzle position at the other extreme, furthest from the weld, resulted in any reduction in capture efficiency. Thus, it should be very easy for a welder to adjust the nozzle position satisfactorily.

The fume generation rate is lower when welding in position when compared to welding in the flat. The capture efficiency when welding in position was similar to that of welding in the flat. Capture efficiency when welding vertically up is equal to that when welding vertically down.

However, slightly lower capture efficiency was obtained when welding horizontally. The reason for this lower value, measured during horizontal welding is unknown. A possible explanation concerns the characteristics of the weld, once the bead has been laid down it continues to emit fume, and when given off this fume rises. When welding vertically it is possible that this fume is subsequently recaptured as it passes the torch but when welding horizontally the torch has moved laterally and this fume is unlikely to be captured. Nevertheless, the results indicated that positional welding with the on-gun system evaluated, will, with the possible exception of horizontal welding, provide a high level of fume capture.

The results obtained for welding fillets in the flat are difficult to interpret and the true capture efficiency is still unknown. Following the completion of testing, we filmed welding a fillet in the flat using 1.0 mm wire with and without extraction and bead on plate in the flat and in position with and without extraction for comparison. Close inspection of these images shows that for bead on plate welding both in the flat and in position, whilst using extraction, almost no fume is seen to escape. The video of welding a fillet in the flat shows very little fume escaping capture suggesting that the capture efficiency is closer to the 95 % value than the 62 % value reported in Table 4.22. The images of fillet welding in position also seem to corroborate the capture efficiency measurements with the large majority of fume captured. These images should be treated with a degree of scepticism, due to the high degree of illumination cast by the arc. This illumination tends to exaggerate the amount of fume in the immediate vicinity of the arc whilst making any fume further away that has escaped capture harder to see. Consequently, it is difficult to recommend on-gun extraction for fillet welding without further work.

The video footage of fillet and bead on plate welding without extraction provides some valuable insight into the way in which fume is emitted from the two processes. Figure 5.2 below is a still image taken from the video of bead on plate welding in the flat without extraction. The welding was performed using a pushing technique and as can be seen the fume is emitted in front of the torch as the weld is laid down.

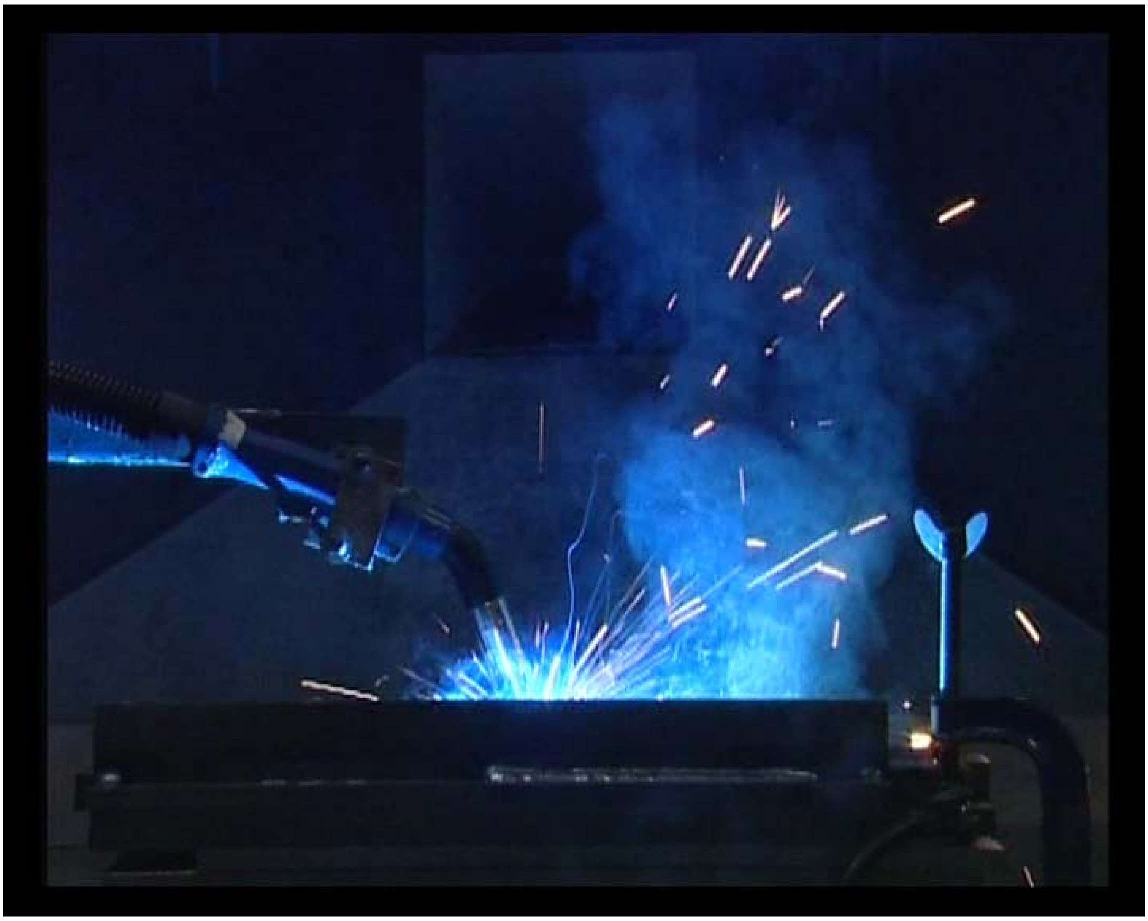


Figure 5.2 Bead on plate welding without extraction using a 1.0 mm wire

Figure 5.3 below shows a still from the video of fillet welding in the flat without extraction. As can be seen the fume appears to channel along the intersection of the plates formed by the fillet and is emitted at the ends of the fillet in both directions. It only then begins to rise.

Figure 5.3 Fillet welding without extraction using a 1.0 mm wire

Consider then the apparent discrepancy in capture efficiencies of fillet welding with the 1.0 and 1.2 mm wire, whilst remembering that the 1.2 mm wire produces two to three times the mass of fume. It may be that the combined factors of an increased mass of fume moving in two directions is too energetic a process for the on-gun system to adequately control when the 1.2 mm wire is used. This could be a possible explanation for the apparent lower capture efficiency with the 1.2 mm wire compared to the 1.0 mm. However, this is speculation only and further work would be required to prove it quantitatively. To complicate matters the nozzle extract position was only optimised for bead on plate and not fillet welding. This may be inconsequential, as there appeared to be a relatively large tolerance in extract position without dramatically affecting capture efficiency, as shown Table 4.20 where capture efficiency was close to 100% over a range of nozzle extract positions. Nevertheless, extract position for fillet welding should be optimised in any future work.

Capture efficiency was approximately the same for both emission rates (1.2 mm wire compared to 1.0 mm wire), for bead on plate welding. It is recognised that this statement can only be made for the consumables and welding parameters examined, but since the consumables were selected on the basis of common use, the statement should be applicable in a large number of cases.

6 CONCLUSIONS

6.1 HV AND LV HOODS

The capture efficiencies of two captor hood based LEV systems (a large mobile HV hood and a selection of small LV tabletop devices) were investigated using welding parameters and consumables that were considered to be in widespread use in industry. Capture efficiency was calculated by measuring the average fume concentration in the LEV extract duct by isokinetic sampling under specific test conditions and calculating this as a ratio to the average fume concentration measured under the same conditions with total fume capture. All tests were conducted while welding bead on plate to simulate butt welding, in the flat, in the presence of a 0.1 ms^{-1} cross draught inside an environmental test cabin. During testing, two different welding wires were used, making it possible to assess the effect of consumable on capture efficiency. The weld metal deposited in each test was examined for visual porosity to ensure that the LEV had not compromised the integrity of the weld by disturbing the shielding gas - none was found.

6.1.1 HV system

This system used an elliptical hood with a major axis of 300 mm connected to flexible ducting of diameter 160 mm, this was either mounted on a moveable arm or resting on the bench. The system was operated at a volume flow rate of 800 m^3h^{-1}, this was considered to be the lower value of its operating range and therefore the worst-case scenario. The hood was tested in a variety of positions relative to a stationary and traversing arc and from those tests the following conclusions were drawn:

1. The HV system is capable of capture efficiencies approaching 100 % without compromising the integrity of the weld metal if the hood is positioned within one hood diameter of the arc.

2. Changing consumable, solid welding wire or flux cored wire, and therefore fume emission rate has no effect on capture efficiency.

3. When the hood is mounted on an arm vertically above the weld, capture efficiency is high (greater than 80 %) up to two hood diameters from the arc. If the hood is placed at 45° from the vertical with the face of the hood perpendicular to the direction of the weld, capture efficiency is 82 % at a distance of one hood diameter but rapidly decreases beyond this distance. Maximum capture efficiency above the weld was achieved with the hood positioned vertically above the arc.

4. When the hood is placed on the bench with the face parallel to the direction of the weld, within one hood diameter of the arc, capture efficiency was very high regardless of the orientation to a cross draught of 0.1 ms^{-1}.

5. The orientation of the hood to a cross draught has a dramatic effect if the hood is positioned at a distance greater than one diameter from the arc. If the draught moves from the source toward the hood, capture efficiency is high up to a distance of two hood diameters. If the draught moves away from the hood toward the source, capture efficiency falls drastically at distances beyond one hood diameter from the arc. This highlights the ‘Achilles heel’ of all captor hoods; the induced velocity in front of the hood falls rapidly with increasing distance from the face.

6. When the hood was positioned vertically above a traversing torch the results were broadly similar to those for a stationary torch, showing higher capture at approximately

one hood diameter than two. Some results were unusual though, capture efficiency for a 300 mm weld were higher than for a 450 mm weld with the hood 340 mm from the arc but these efficiencies were reversed with the hood positioned 650 mm from the arc, no explanation can be offered for these results.

7. If the hood is positioned on the bench for side extraction one diameter from a traversing torch, capture efficiency was high for a 300 mm weld if the hood is positioned centrally. *For a longer weld of 450 mm, capture efficiency was too low to maintain control regardless of the positioning of the hood.*

8. Although in certain situations, a high level of capture efficiency can be maintained at greater distances, it is recommended that the hood be positioned one diameter from the weld and repositioned frequently to maintain control. In this position capture efficiency will be maximised and weld integrity will be maintained.

6.1.2 LV system

This system used a variety of hoods, connected to 75 mm diameter flexible ducting, that were positioned on the bench perpendicular to the plane of the weld. The system was operated at total volume flow rates of 123 – 150 m^3h^{-1} depending on the hood being used. The system was tested in a variety of positions relative to a stationary and traversing arc. From these tests the following conclusions have been drawn:

1. The LV system is capable of high capture efficiency only in a small range of positions. Control is maintained when the hoods were positioned 75 mm from the arc. Beyond these positions capture efficiency fell rapidly and control was lost.

2. In the presence of a 0.1 ms^{-1} cross draught, control can be maintained up to 150 mm from the weld using the fishtail and slot hoods, but only if the draught moves from the arc toward the hood. If the draught moves away from the hood all three hoods lose control beyond 75 mm from the arc. Even with the cross draught moving towards it, the circular hood cannot control the fume at 150 mm from the arc.

3. Tests with the circular and fishtail hood positioned 75 mm from the arc off centre from a stationary torch show that in order to maintain control they will need to be repositioned at a minimum for every 75 mm of weld.

4. Of the circular and fishtail hoods, only the fishtail achieved a high enough capture efficiency to control the fume from a traversing torch over the length of a 300 mm weld. This was entirely due to the design of the hood, which was effectively a 300 mm slot having an aspect ratio of 0.15. Capture efficiency was higher with the hood positioned at the centre of the weld than at the start.

5. None of the hoods were capable of achieving a high enough capture efficiency to control the fume for a weld of 450 mm in length.

6. No capture efficiency data was available for the slot hood used in conjunction with a traversing torch, however, average fume concentrations were the same for 300 and 450 mm welds.

6.2 ON-GUN EXTRACTION SYSTEM

The capture efficiency of an on-gun fume extraction system was assessed by comparing the concentration of fume captured whilst welding under a given set of parameters with the total fume concentration captured under the same conditions. Following capture efficiency measurements to optimise equipment parameters, capture efficiency was measured during bead on plate tests in the flat and in position with welding parameters and consumables chosen on the basis of common use, to make the results widely applicable. Tests were also conducted whilst welding horizontal/vertical fillets. In addition to evaluating capture efficiency in a number of welding configurations, the work programme made it possible to evaluate the effects of extract nozzle position and welding position. At the same time, weld metal was examined for porosity, to ensure that extracting the fume had not compromised its integrity, as shown by porosity. Other factors such as ergonomics and operability were not assessed. From the results, it was possible to draw the following conclusions:

1. Adjusting the extract nozzle to a position that would provide efficient fume extraction without compromising weld metal integrity was not a critical operation for bead on plate. However, the nozzle position was not optimised for fillet welding.

2. For butt welding, the on-gun extraction system tested provided a suitable alternative to the traditional extraction arm systems, as far as capture efficiency and weld metal integrity were concerned.

3. For fillet welding, the on-gun system tested can be recommended as a suitable alternative to captor hood based LEV for positional welding, but in the flat the results were less clear and further work is required to properly evaluate its effectiveness.

4. The only situations where weld metal integrity was compromised was when the extract nozzle was positioned flush with the end of the gas shroud.

5. Optimum capture efficiency was obtained with the extract nozzle approximately 14 mm from the end of the gas shroud. This, however, was an extreme test and the equipment is unlikely to be used in that configuration by a professional welder

6. The capture efficiency of the on-gun system tested was generally 90 % or above when welding bead on plate, whether welding was performed in the flat, vertically up or vertically down. The capture efficiency was 74 % when welding horizontally.

7. The capture efficiency when welding in horizontal/vertical fillets was generally lower than when welding bead on plate. The capture efficiency was 82 and 81 % respectively when welding vertically up and vertically down.

8. The on-gun system has the advantage over traditional extraction arm systmes, which have to be constantly repositioned, as the extract is always close to the arc.

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8 APPENDIX I: SCOPING STUDY TO DETERMINE WELDING FUME SAMPLING STRATEGY

8.1 INTRODUCTION

Initially the welding fume sampling strategy was to be based on the test methods described in draft EN 15012-3 - *Health and safety in welding and allied processes - Requirements, testing and marking of equipment for air filtration - Part 3: Determination of the capture efficiency of welding fume extraction devices*. The draft method described how to perform capture efficiency measurements in a ventilation test cabin conforming to BS EN 1093-4: 1996 *Safety of Machinery - Evaluation of the emission of airborne hazardous substances - Part 4: Capture efficiency of an exhaust system.* However, as the draft Standard was developed some members of the working group increasingly felt that there were deficiencies in the test method. Therefore the scoping study described here was carried out to develop a satisfactory welding fume sampling strategy for this research project.

8.2 ENVIRONMENTAL TEST CABIN

All the welding experiments in the scoping trials and capture efficiency trials were performed inside an environmental test cabin. The test cabin was a cuboid (4 m x 4 m x 3 m high) with a contraction leading to a 0.7 m square sampling section as shown in Figure 8.2. Experiments were carried out in the test cabin for several reasons; i) to contain any fume not captured by the LEV system and to safely discharge the contaminated air to atmosphere, ii) To drive fume not captured by the LEV system down the sampling section where the fume concentration could be measured, iii) to ensure the air velocity profiles in the vicinity of the welding process were reproducible for all tests and iv) to gain experience of using the environmental test cabin for measuring fume concentration and to therefore provide feed back to the CEN working group responsible for drafting EN Standard 15012-3. The test cabin can perform these functions because it can be used to set up and maintain a unidirectional flow of air with a uniform velocity across the cross section of the cabin, this is known as plug flow. To this end the velocity profile of the test cabin was measured using an ultrasonic anemometer. The wall opposite the sampling section of the test cabin was fitted with pre and HEPA filters to remove background particles from the ambient laboratory air. Once the air had passed through the cabin and the sampling section, it was exhausted outside of the building. The velocity profile was measured with the filters in place when the cabin had been sealed to prevent any air entering via advantageous openings. Figure 8.1 shows the velocity contour plot, which was plotted using the TECPLOT© program. The average velocity of air through the cabin was ~ 0.1 ms^{-1}, this was monitored by the use of a 0.7 m square flowgrid connected to a digital micromanometer mounted in the sampling section of the test cabin.

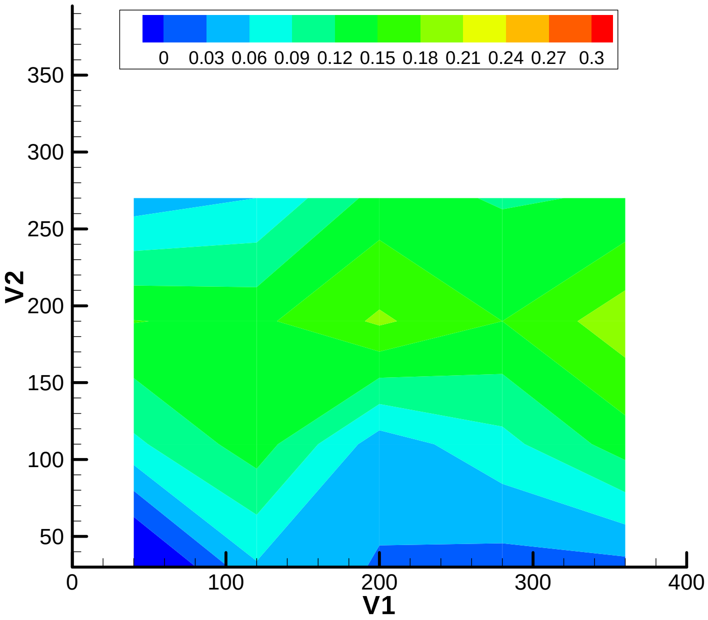

Figure 8.1 Velocity profile of test cabin, airflow is into page

8.3 SAMPLING STRATEGY

A two-fold sampling strategy was adopted; the first was to sample fume isokinetically in the LEV extract duct and perform gravimetric analysis, the second was to measure concentrations of fume in the sampling section of the environmental test cabin (see section 8.5) using a Tapered Element Oscillating Microbalance (TEOM). The first strategy is a direct measurement of the mass of fume captured; the second is a measurement of the mass of fume not captured by the extract system. Figure 8.2 shows a schematic diagram of the cabin and experimental set up used during the scoping trials. In order to calculate capture efficiency from either method precise knowledge of the fume generation rate is required. Initially it was thought that this could be measured using a fume box for each specific method of arc welding to be investigated, Metal Active Gas (MAG) welding with solid wire and Flux Cored Arc Welding (FCAW). It was later found to be necessary to make repeat measurements of total capture or 100 % tests; this is discussed in detail in further sections. For the scoping study, it was not relevant as the purpose was to investigate the sampling strategy to be used.

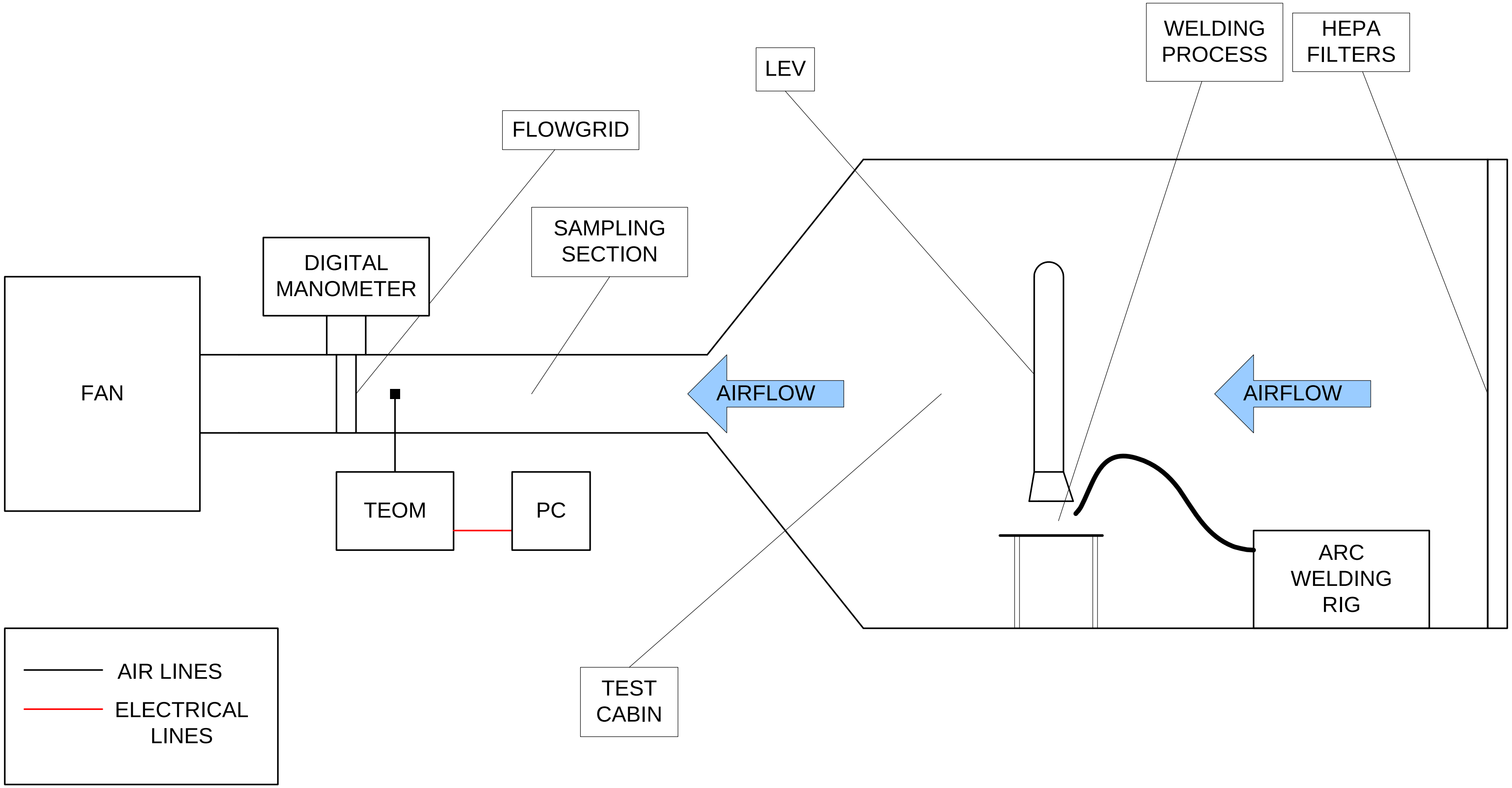

Figure 8.2 Schematic diagram of environmental test cabin and experimental set up

8.4 ISOKINETIC SAMPLING POSITIONS

8.4.1 Isokinetic sampling experimental set up

The mean diameter of particles generated during welding is in the range of 10 – 100 nm (i.e up to 0.1 μm) depending upon welding parameters and consumables. However, the particles will agglomerate to form larger particles or chains, which are of the order of 1 μm [2]. Nevertheless the resultant particulate matter is small enough to faithfully follow the airflow and therefore the need to sample isokinetically was not that great. However, to minimise errors a decision was made to undertake isokinetic sampling.

In a duct of diameter of 160 mm, a volume flow of 800 m^3h^{-1} gives an average air velocity of 11.05 ms^{-1}. In order to sample isokinetically the velocity at the sample entry point must be equal to this. The isokinetic sampling probes had a diameter of 7 mm; this means that for an entry speed of 11.05 ms^{-1}, 25.5 $lmin^{-1}$ of air must be sampled. The ideal sampling position is where the fume is uniformly distributed within the exhaust air and as close to the entry point of the duct so that losses to walls are minimised. This presents a dichotomy, as the greater the turbulence and further downstream the fume travels the greater the probability of uniform distribution of fume across the width of the duct, however, this increases the risk of losing particles to surfaces.

Two sampling locations were investigated; one approximately 11 diameters downstream of the hood in a straight section and the other a further 3.7 m downstream (2 m of which was flexible ducting) and included a 90^o bend.

The first position consisted of four isokinetic sampling probes located 11 diameters (1760 mm) from the extract hood in a straight section of duct of diameter 160 mm, see Figure 8.3. Points 1 – 3 were 40 mm from the edge of the duct spaced 120° apart, point 4 was located in the centre of the duct. These were selected in order to investigate the degree of uniformity of the fume concentration across the width of the duct.

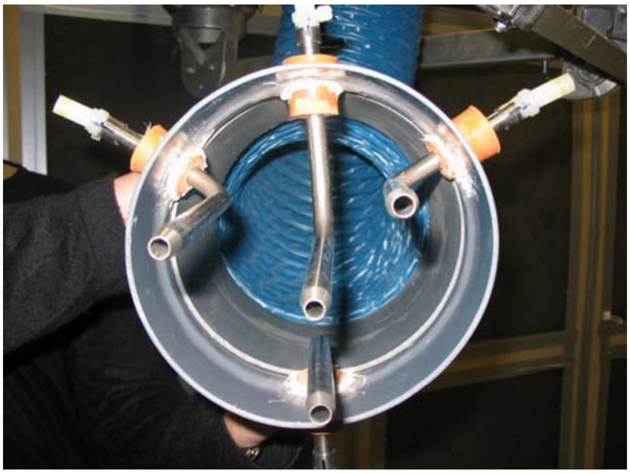

Figure 8.3 Isokinetic sampling positions 1 - 4 inside 160 mm diameter duct

The isokinetic probes were connected to sampling pumps fitted with rotameters to monitor flow. To capture welding fume for gravimetric analysis, filter cassettes were fitted inline holding 47 mm diameter GF/F glass microfibre filters (Figure 8.4).

Figure 8.4 Isokinetic sampling points and filter cassettes 1 – 4

Point 5 was located at the second sample location in a straight section of duct 1.7 m (10 diameters) as recommended by Hampl[16] from a 90° bend and approximately 2 m of 160 mm diameter flexible ducting after points 1 – 4. The isokinetic probe at point 5 was located in the centre of the duct and was connected to a sampling pump with an inline filter cassette similar to points 1 – 4. Figure 8.5 shows the 90° bend and straight section of duct fitted to the outside wall of the test cabin. The filter cassette at sampling point 5 and the five sampling pumps can be seen towards the bottom of the picture.

Figure 8.5 Sampling point 5 and sampling pumps

After sampling point 5 there was approximately 1 m length of 160 mm diameter flexible ducting connected by an expansion piece to a 250 mm diameter duct, approximately 2 m in length which was fitted with a flowgrid. The flow grid was used to monitor volume flow through the LEV system. The flowgrid was connected to a filter that removed any welding fume from the extracted air before it was discharged into the laboratory. A 2.2 kW, 50 Hz fan controlled by a rheostat, moved the air. The LEV and isokinetic sampling experimental set up is shown schematically in Figure 8.9.

The glass fibre filters were conditioned in an environmentally controlled balance room for 24 hours before pre weighing and conditioned for a further 24 hours after being exposed to welding fume before being re-weighed to determine the mass of fume sampled. Each numbered set of five filters for each test had 3 control filters that remained unexposed to fume to correct for environmentally caused change in mass.

Ten tests were performed, evaluating three LEV configurations; 100 % capture with the LEV hood close to the welding arc, intermediate or < 100 % capture with the LEV hood close to the arc but outside of the capture zone and ~ 0 % capture with the LEV hood more than 2 m upstream from the arc.

Figures 8.6 – 8.8 show the three different LEV hood positions investigated in the scoping trials. These tests were designed to demonstrate the ability of the sampling system to distinguish different capture efficiencies and to investigate particle losses in the duct between sampling positions 1 – 4 and 5 at different fume concentrations.

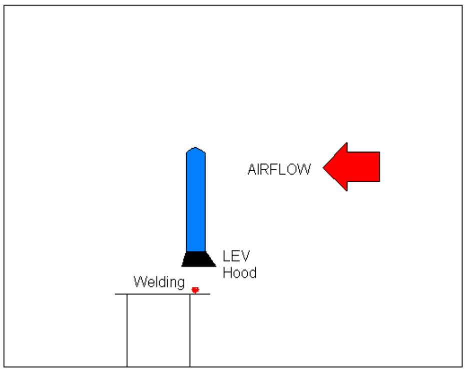

Figure 8.6 LEV configuration for tests 2 & 5, 100 % capture

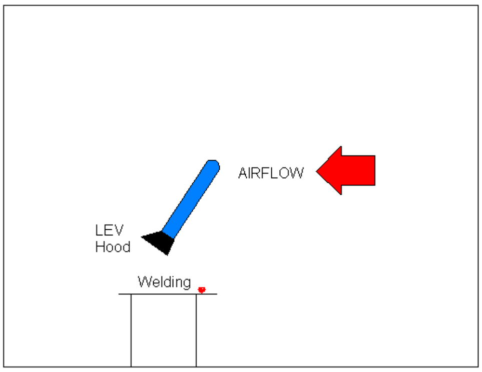

Figure 8.7 LEV configuration for tests 3,4,7, <100 % capture

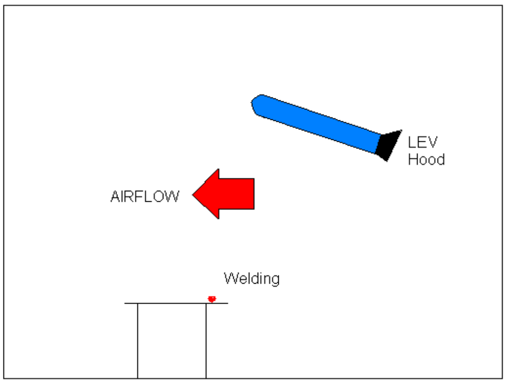

Figure 8.8 LEV configuration for tests 9 & 10, ~0% capture

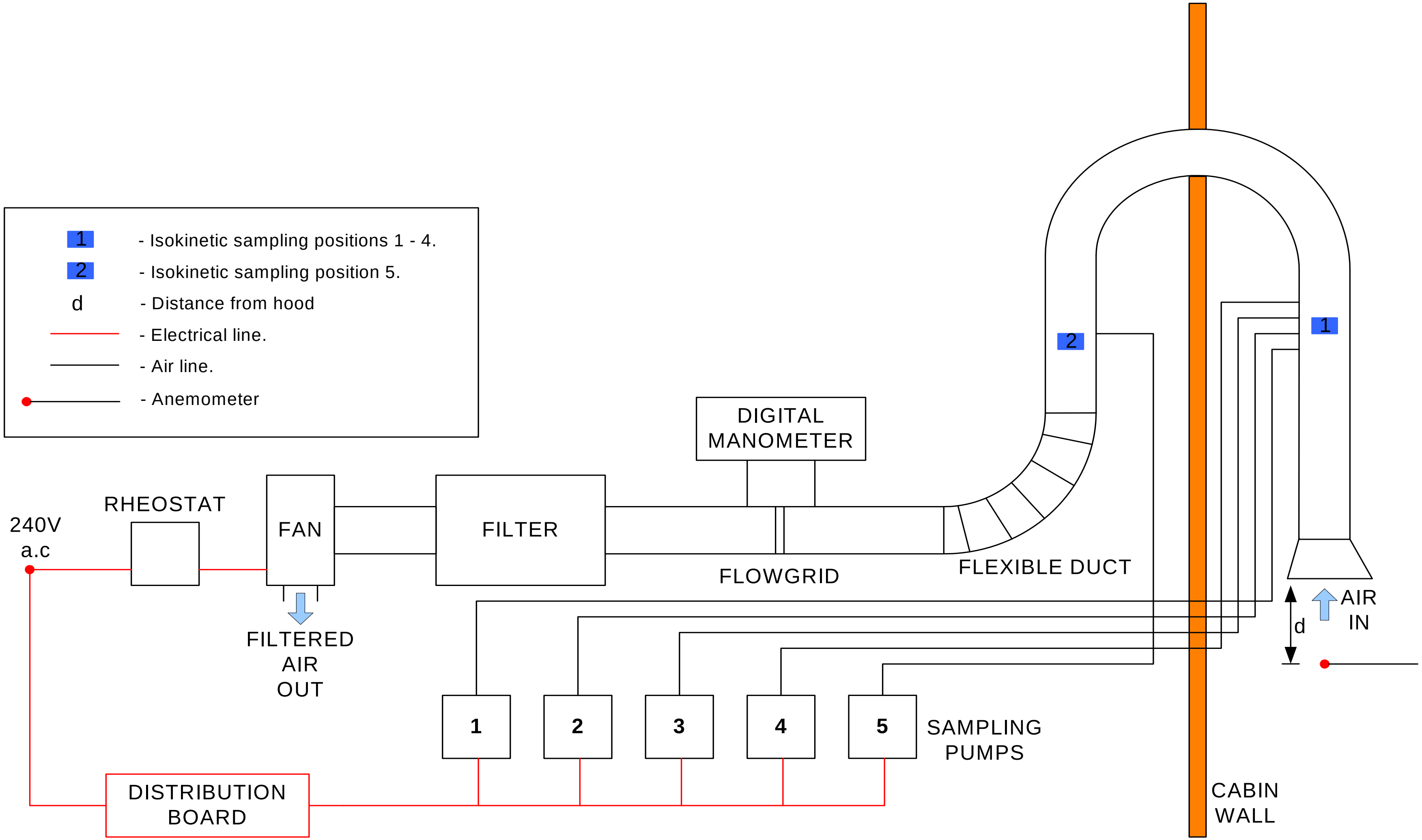

Figure 8.9 Schematic diagram of LEV and isokinetic sampling system

8.4.2 Experimental results

The scoping study used a large moveable Nederman elliptical hood connected to a 160mm diameter flexible duct. The LEV was designed to operate with a volume flow rate of approximately 1000 m^3h^{-1} and a minimum of 800 m^3h^{-1}. The latter flow rate was selected as the worst-case scenario found in the workplace. Welding was carried out be a welder from the HSL’s workshops section who welded bead on plate on 1 m lengths of bright mild steel using CO_2 as a shielding gas at a flow rate of 15 $lmin^{-1}$. This is not a typical welding condition and was different to that used in the extraction efficiency trials, but for the purposes of the scoping trials we were only interested in producing fume to sample.

Ten tests were carried out to determine the suitability of the two chosen sampling locations. The process used was MAG welding at 21 V; wire feed speed of 9 $m.min^{-1}$ and the consumable was 0.8 mm mild steel wire. For the first test, the shielding gas used was Argoshield Universal (12% CO_2: 2% O_2: 86% Ar) but this did not produce sufficient fume for analysis so tests 2 – 9 used 100% CO_2 as a shielding gas.

Table 8.1 Results from initial welding comparing positions 1 – 4 to position 5

Test ID	*Sample flow rate ($Lmin^{-1}$)*	*Test duration (mins:secs)*	*Average concentration at positions 1 – 4 (location 1) (mgm^{-3})*	*Standard deviation of positions 1 – 4 (location 1)*	*Concentration at position 5 (location 2) (mgm^{-3})*	*Comments*
1	25.5	1:00	0.10	0.67	-0.39	100% Extraction, discarded
2	25.5	1:50	23.40	8.56	23.53	100% Extraction
3	25.5	1:10	16.93	3.82	15.69	<100% Extraction
4	25.5	1:50	12.22	1.53	10.98	<100% Extraction
5	25.5	1:50	16.34	3.65	15.69	100% Extraction
6	25.5	1:50	13.86	33.06	12.55	100% Extraction, discarded
7	25.5	1:50	18.24	3.72	12.81	<100% Extraction
8	25.5	1:50	13.40	3.28	11.24	<100% Extraction
9	25.5	1:50	3.14	0.88	1.57	~0% Extraction
10	25.5	1:50	2.88	0.22	3.14	~0% Extraction

Table 8.1 shows fume concentrations measured at positions 1 – 5 for tests 1 – 10. Results for tests 1 and 6 can be discarded, test 1 used Argoshield Universal© as a shielding gas, combined with the consumables used this did not produce sufficient fume to give reliable measurements of the mass of fume collected on the filters in the isokinetic sampling lines. Each filter collected less than 0.1 mg of fume, the average change in mass of the three control filters was 0.05 mg,. In test 6, the filters were mixed up and placed in the wrong boxes after the test making before and after measurements of mass impossible. Considering tests 2, 3, 4, 5, 7, 8, 9 and 10 the standard deviation of the concentrations measured at positions 1-4 are a significant fraction of the average concentration. This is considered further in section 8.4 where particle concentrations are directly compared between the two sampling positions. These data cannot be used to assess the reproducibility of these tests, for instance tests 2 and 5 both had 100 % extraction yet the average concentration at positions 1-4 was 30 % lower in test 5. These discrepancies can be explained by the fact that the welding was manual and therefore variables such as arc travel

speed and the contact tip to work distance (CTWD) were constantly varying, this affects the arc current and crucially the fume generation rate.

Tests 2 and 5 were performed with the LEV hood in an optimum position collecting 100 % of the fume, the average fume concentration measured at positions 1 – 5 for these tests was 19.75 mgm^{-3}. Tests 3, 4, 7 and 8 were performed with the LEV in an intermediate position collecting most of the fume but not all, the average concentration in these tests was 13.94 mgm^{-3}. Tests 9 and 10 were performed with the LEV a long way from the arc collecting very little or no fume, the average concentration in these tests was 2.69 mgm^{-3}. There was still some doubt as to whether or not the flow was fully developed at positions 1 – 4 so if we consider just position 5. Tests 2 and 5 with 100 % capture average fume concentration was 19.61 mgm^{-3}. Tests 3, 4, 7 and 8 with < 100 % capture average concentration was 12.68 mgm^{-3}. Tests 9 and 10 with ~ 0 % capture average concentration was 2.36 mgm^{-3}.

Table 8.2 Results from initial welding tests assessing losses from positions 1 – 4 to position 5

Test ID	*Average upstream concentration at positions 1 – 4 (sample location 1) (mgm^{-3})*	*Downstream concentration at position 5 (sample location 2) (mgm^{-3})*	*Ratio of downstream to upstream*
1	0.10	-0.39	-3.90
2	23.40	23.53	1.01
3	16.93	15.69	0.93
4	12.22	10.98	0.90
5	16.34	15.69	0.96
6	13.86	12.55	0.91
7	18.24	12.81	0.70
8	13.40	11.24	0.84
9	3.14	1.57	0.50
10	2.88	3.14	1.09
[redacted]	[redacted]	Mean[2]	0.87

Table 8.2 shows concentrations measured at sample location 1 (positions 1 – 4) and sample location 2 (position 5) and the ratio between the two. This can be used as a measure of the losses in the duct between the two sampling positions. If tests 1 and 6 are omitted, the mean ratio of downstream concentration to upstream concentration is 0.87, this means that 13 % of the mass of fume is lost between sampling positions 1 – 4 and position 5.

8.4.3 Conclusions

The results shown in Table 8.1 show that it is possible to distinguish between 100 % capture, an intermediate level of capture and very little capture. As noted the standard deviations of the concentrations measured at sample location 1 (positions 1- 4) are a significant fraction of the average but not a constant fraction. The concentrations measured at the individual sampling positions are not shown but the spread of concentrations was not constant from test to test. If the flow in the duct at sample location 1 were fully developed the concentrations would be equal.

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[2] *This is the mean of Tests 2, 3, 4, 5, 7, 8, 9 and 10. Tests 1 and 6 have been omitted.*

This meant that we were not sure of obtaining a uniform representative sample of the fume in the duct, this issue is considered further in section 8.4.

The results shown in Table 8.2 show that on average 13 % of the mass of fume is lost between sample location 1 and location 2. In tests 9 and 10 where very little fume was collected, the maximum mass of fume was 0.18 mg at position 1 in test 9, whilst most were 0.10 mg or less and in test 10 the maximum fume collected was at position 5. The precision of the balance used to measure the masses of the filters is 0.01 mg, which is a 10 % difference in mass between an exposed and unexposed filter. If we omit tests 9 and 10, the average fume loss falls to 11 %. Therefore, we can say when significant masses of fume are collected, 11 % of the mass of fume is lost between sampling location 1 and 2. This would make direct comparisons between concentrations measured at sampling location 1 and 2 difficult.

8.5 ISOKINETIC SAMPLING POSITIONS II

8.5.1 Problem and approach

One of the criteria for selecting the most appropriate sampling strategy and location is that it must give a uniform and representative sample of the concentration of fume in the duct. Results from section 8.3 indicated that this is not the case at sampling location 1 and unknown at sampling location 2. We further investigated the isokinetic sampling positions to quantify the inhomogeneity of the flow at location 1 and 2 and assess the stability over time at location 2.

In order to assess losses and homogeneity at sampling location 1 and compare to location 2 we required a constant concentration of particles. This was not possible with manual welding and so we decided to use a sodium chloride (NaCl) aerosol generator (Figure 8.10). The NaCl generator was chosen because it can produce particles at a constant rate and the NaCl particles approximate welding fume sufficiently. Number concentrations of particles between 20 nm and 1 μm in the duct were monitored using a real time condensation particle counter called a P-TRAK.

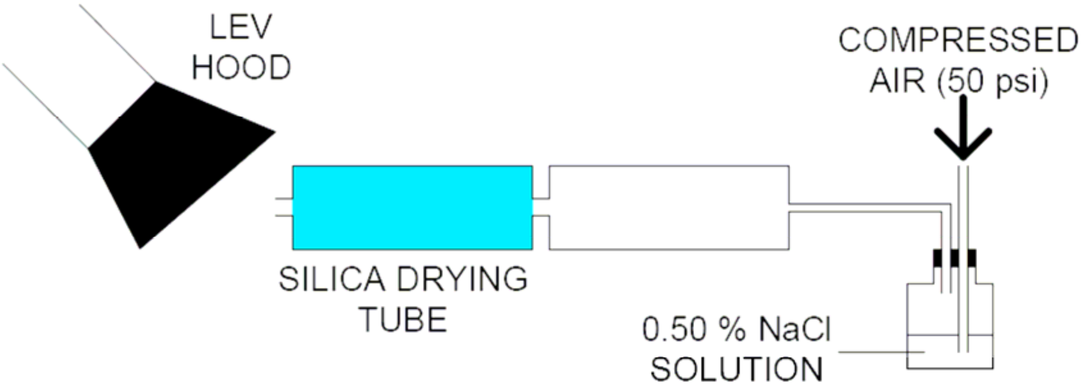


Figure 8.10 NaCl aerosol generator

8.5.2 Experimental set up

Several experiments were performed;

1. Using 2 P-TRAKs;

   i. Compare the number concentrations given by both P-TRAKs when monitoring the same aerosol and provide suitable correction factors, as each instrument will not report the same concentration.

   ii. Measure the background aerosol level in the cabin with and without the ventilation running.

   iii. Whilst generating a NaCl aerosol, place 1 P-TRAK at sampling location 2 and sequentially sample at sampling location 1 with the other P-TRAK.

2. Use a P-TRAK at sampling location 2 whilst generating a constant concentration of NaCl aerosol; this was monitored for 20 minutes to determine the stability of measurements at sampling location 2.

3. Perform a three-point traverse across the duct to determine the homogeneity of the flow at sampling location 2.

Figure 8.11 2 P-TRAKs measuring particle concentrations at sampling location 2

8.5.3 Experimental results

Experiment 1.i: The two P-TRAKs were found to have a 15.9 % variance in readings when measuring background particle concentrations in the cabin with the cabin ventilation off, subsequently a correction factor of 1.159 was applied to all readings measured by P-TRAK 2.

Experiment 1.ii: The mean background aerosol level in the cabin with the cabin ventilation of was found to be 4300 pt/cc (particles per cubic centimetre) from nineteen 10 second time averaged measurements. The mean background aerosol level in the cabin with the cabin ventilation running and the HEPA filters in position were found to be 10 pt/cc.

Experiment 1.iii: Table 8.3 shows the results from the comparison tests. The particle concentration is relatively constant from test to test; variations are due to slightly different pressures from the compressed air line. The particle concentrations at sample location 1 vary dramatically from 96900 pt/cc at position 2 to 6990 pt/cc at sample location 1/position 3, Figure 8.12 and Figure 8.13 show plots of the particle concentration against time for these two tests.

Table 8.3 P-TRAK results from homogeneity tests at sampling location 2and comparison to sampling location 1

Mean particle concentration Location 2/Pos 5 (pt/cc)	*Mean particle concentration Location 1/Pos 1 (pt/cc)*	*Mean particle concentration Location/1Pos 2 (pt/cc)*	*Mean particle concentration Location 1/Pos 3 (pt/cc)*	*Mean particle concentration Location 1/Pos 4 (pt/cc)*	*Difference between Location 1 and Location 2 (pt/cc)*
35900	27700				-8200
40000		96900			56900
35900			6990		-28910
37100				43700	6600

Figure 8.12 NaCl particle concentrations at sample location 1/position 2 and sample location 2

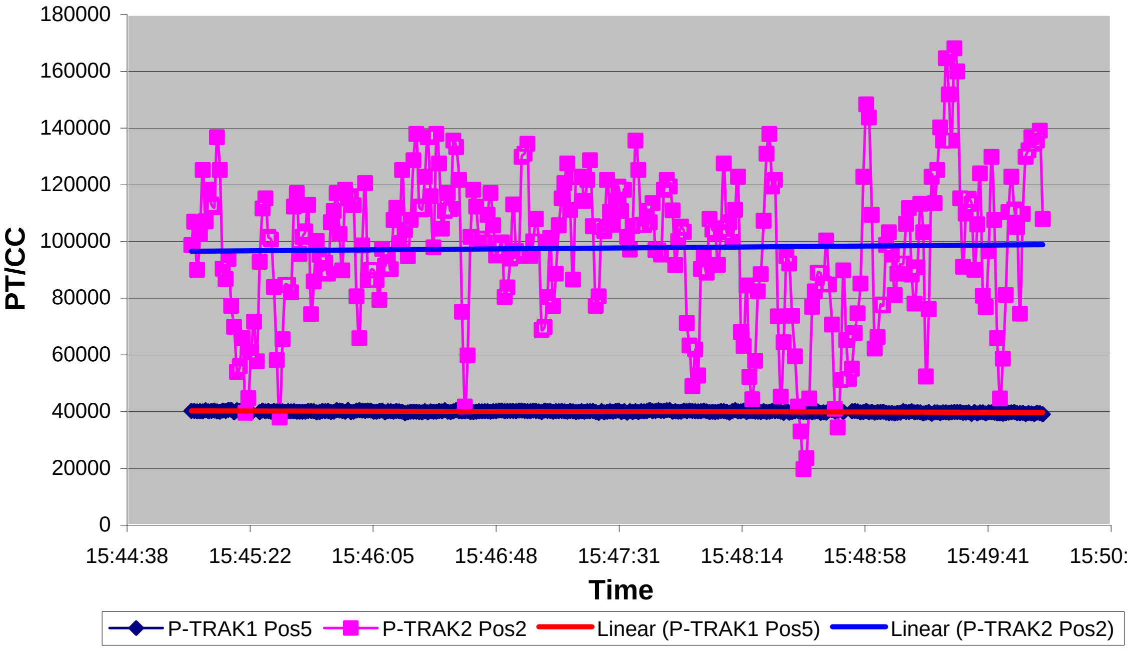
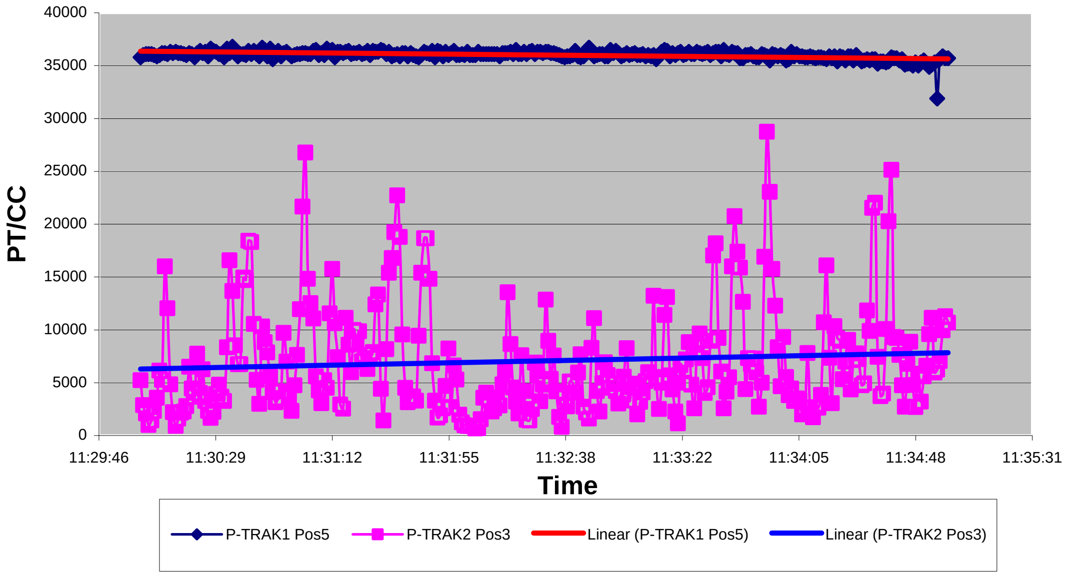


Figure 8.13 NaCl particle concentrations at sample location 1 /position 3 and sample location 2



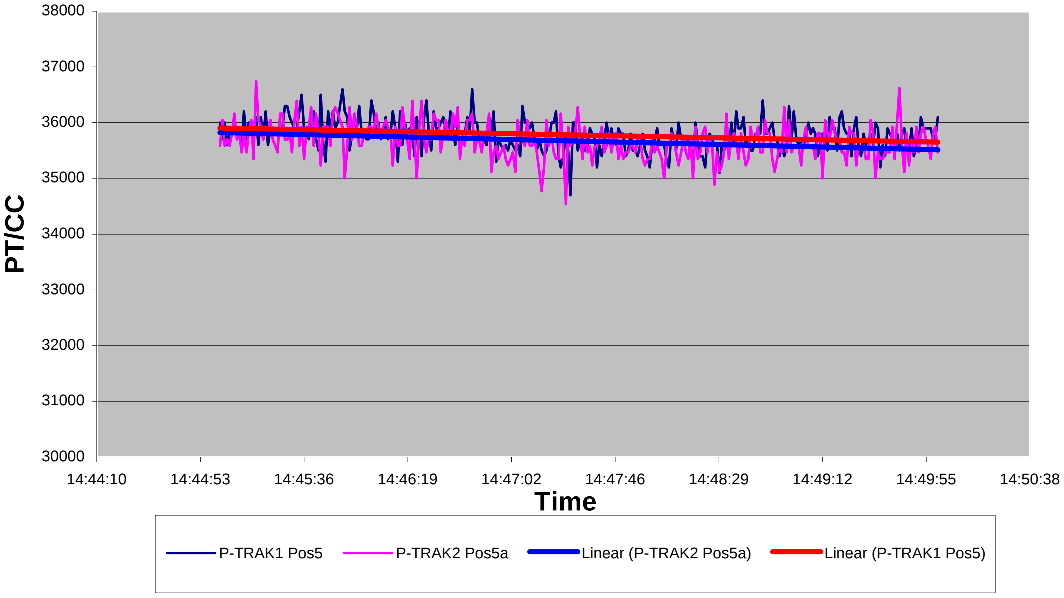
Experiment 2: The mean background particle concentration was 69 pt/cc measured over five minutes. A P-TRAK was used to measure the particle concentration at sample location 2 for twenty minutes; the mean was 25200 pt/cc and the standard deviation 533 pt/cc.

Experiment 3: Two P-TRAKs were used to sample at three points traversing the duct at location 2, one was at the centre of the duct (position 5), position 5a and 5b were 40 mm from the edge of the duct either side of position 5. Table 8.4 shows the results from the traverse, two positions were sampled in each test. Figure 8.14 shows the plots from one test, sampling at position 5 (centre of duct) and 5a (40 mm from edge of duct).

Table 8.4 P-TRAK results from traverse of duct at sampling location 2

Mean Particle Concentration position 5 (pt/cc)	***Mean Particle Concentration position 5a (pt/cc)***	***Mean Particle Concentration position 5b (pt/cc)***	***Difference (%)***
35777	35669		0.30
35076		35045	0.09
	35250	36503	3.43

Figure 8.14 NaCl particle concentrations at sample location 2, positions 5 and 5a



8.5.4 Discussion

The two P-TRAKs when measuring the same particle concentration gave values with a divergence of 15.9 %. To correct for this a factor of 1.159 was applied to all values read by P-TRAK 2. The mean background particle number concentration of particles between 20 nm and 1 µm in the test cabin without the cabin ventilation running was ~4000 pt/cc, whilst with the cabin ventilation running the background concentration was 10 pt/cc. A typical particle concentration measured in the duct was 25000 pt/cc; as all tests were performed with the cabin ventilation running the background can be ignored, as it is less than 0.05 % of the typical value.

The results from Experiment 1.iii shown in Table 8.3 show that the mean particle concentrations at sample location 1 (positions 1 - 4) vary considerably. The particle concentration at sample location 2 varied in each of these tests because of the method of producing the aerosol. The aerosol generator used compressed air, the gauge on the air line lacked the precision to control the flow sufficiently to produce the same particle concentration for every test. Even so the variation in concentration at positions at sample location 1 was an order of magnitude higher than the variation at sample location 2. The two plots shown in Figure 8.12 and Figure 8.13 show that the particle concentration at positions 2 and 3 (location 1) vary considerably with time. At position 2 at location 1 where the mean concentration was 96900 pt/cc, the maximum value was 168000 pt/cc and the minimum 19700 pt/cc, a range of 148000 pt/cc, which is 150 % of the mean value. Table 8.5 shows the mean concentrations and the standard deviation at positions 1 – 4 at location 1. As can be seen for all four positions the standard deviation is a significant fraction of the mean value. The conclusion of these tests is that the flow in the duct at sample location 1 is not fully developed and therefore it is not a suitable place to sample welding fume.

Table 8.5 Particle concentrations and standard deviations at sample location 1, positions 1 - 4

Position	*Mean particle concentration (pt/cc)*	*Standard Deviation (pt/cc)*	*% of mean*
1	27700	8175	30
2	96900	25664	26
3	6990	5209	75
4	43700	17057	39

The stability measurements at sample location 2 over a twenty-minute period had a mean value of 25200 pt/cc with a standard deviation of 533 pt/cc; this is 2 % of the mean, which shows that the particle concentration will remain stable over the course of a test. The traverse at position 5 shows that the concentration across the duct at position 5 is relatively constant at +/- 3 %. The conclusion of these tests is that the flow at sample location 2 is fully mixed and this position was suitable for sampling the welding fume and would give a representative sample of the concentration within the duct.

Measurements indicate that the concentration at sample location 2 was on average approximately 11% lower than at sample location 1. Therefore particles were being lost to the duct walls between the two sample positions. If the capture efficiency were calculated from the measured concentration in the duct divided by the calculated concentration based on the fume emission measurements there would be a systematic error due to the losses. This could be accounted for, but this assumes the emission rate remains constant between tests. Alternatively, the capture efficiency could be calculated from concentrations in the duct at location 2. i.e the ratio of the fume concentration in the duct when the hood is positioned at a specific position divided by the fume concentration in the duct when the hood captures the entire fume (100% capture). This would mitigate the errors due to losses, as they should apply equally to both measurements. The data in Table 8.2 demonstrates this for relatively high percentage capture.

8.6 SAMPLING WITH THE TEOM

In addition to sampling isokinetically in the extract duct of the LEV system (i.e a direct measurement of what was captured), sampling was carried out t in the sampling section of the test cabin. This was a measure of fume not captured by the LEV. Initially to do this a Tapered Element Oscillating Microbalance (TEOM) was used. The instrument comprises a glass element that is oscillated at its resonant frequency; sampled air is drawn across a filter through this element. As particles in the sampled air collect on the filter, the mass of the element increases altering the resonant frequency of the system. This allows a direct measurement of the mass of particles in the sampled air.

Thirteen tests were carried out, three five minute welds and ten one minute welds with varying degrees of capture by the LEV system whilst simultaneously sampling in the sampling section with the TEOM. Figure 8.15 shows the plot of mass concentration in the sampling section. The horizontal red lines show when welding was taking place and the test number. Tests 1 – 3 were five minute welds with no LEV extraction (i.e 0% capture, 100% of fume via the sampling section), tests 4 – 7 were one minute welds with 100 % extraction, tests 8 – 10 were one minute welds with partial extraction and tests 11 – 13 were one minute welds with no extraction.

Figure 8.15 shows the plot of mass concentration in the sampling section throughout the period of the testing. Following tests 1 – 3 there was no discernable increase in mass concentration despite fifteen minutes of welding with no LEV extraction. Overall, the plot from the TEOM oscillates a great deal, the negative values are a result of volatile compounds loading the filter and subsequently evaporating. These could be organic compounds, sulphates or nitrates from the ambient atmosphere, this effect is exacerbated because the temperature within the TEOM is approximately 50 °C. The instrument then returns a negative value because it is a rolling measurement of mass concentration. The largest measurements follow the completion of the last test (Test 13) and large peaks are measured for over ten minutes following the test. The airflow in the cabin is largely uniform across the cross-section (see Figure 8.1), this means that the time taken to clear the cabin of fume should be low, 1 – 2 minutes. Visualisation with smoke showed the test cabin cleared quickly with only a small area of recirculation caused by the wake of the LEV arm. The gradual dilution of this eddy would not account for a clearance time in excess of ten minutes. It does not explain why such large peaks were only observed once all welding had ceased, as there were intervals between tests when the mass concentration did not climb to such levels, especially after tests 1, 2 and 3 that had no LEV extraction and were separated by intervals of up to twenty minutes.

Figure 8.16 shows three expanded sections of Figure 8.15 during three tests. The top and middle plots show tests 4 and 9 respectively; test 9 was with partial extraction test 4 with 100 % extraction. There is little difference in each plot between the time when welding was taking place and afterward. There is also little difference between the two tests one with partial extraction and one with total extraction. The bottom plot is of the last test; this was a one minute weld with no extraction. The plot shows no appreciable activity during the weld and for the minute after it, for the following twelve minutes there were a series of large peaks. This was the only test where this happened.

It was therefore concluded that it was not possible to distinguish between 100 % extraction and partial extraction and the difference between these two and zero extraction was not always clear. It was not even possible to determine if a test was taking place with only the TEOM data. This did raise the question as to whether the flow at the measurement point in the sampling section was uniform; this is discussed in the next section. In addition, the instrument could only sample at ten second intervals and as the welding duration was likely to be the order of 60 s, its response time was deemed too slow to be suitable for use in this study For the remainder of the study, fume in the sampling section was measured using a Handheld Aerosol Monitor (HAM) a photometer that gave real time measurements.

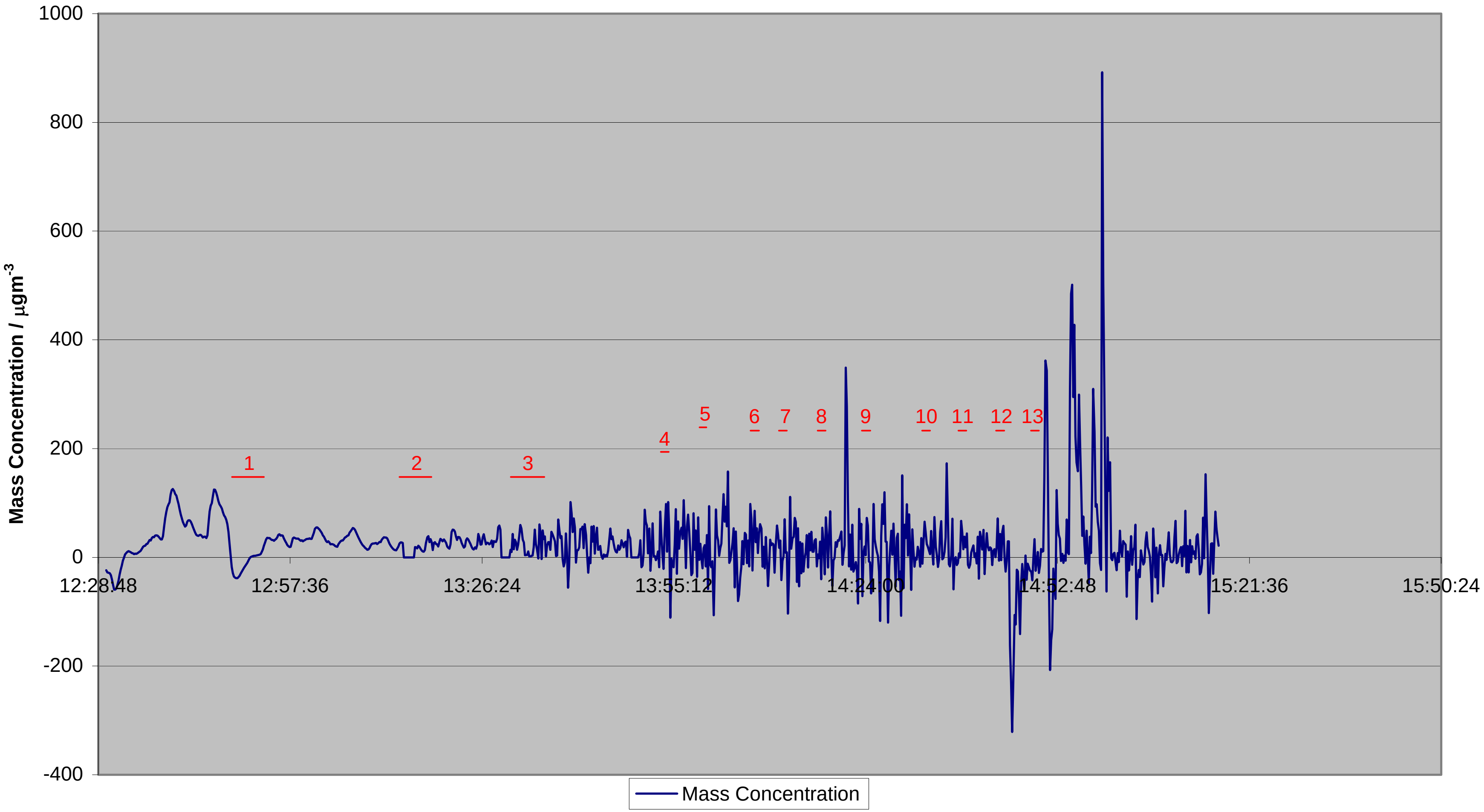


Figure 8.15 Mass concentration in sampling section measured with TEOM

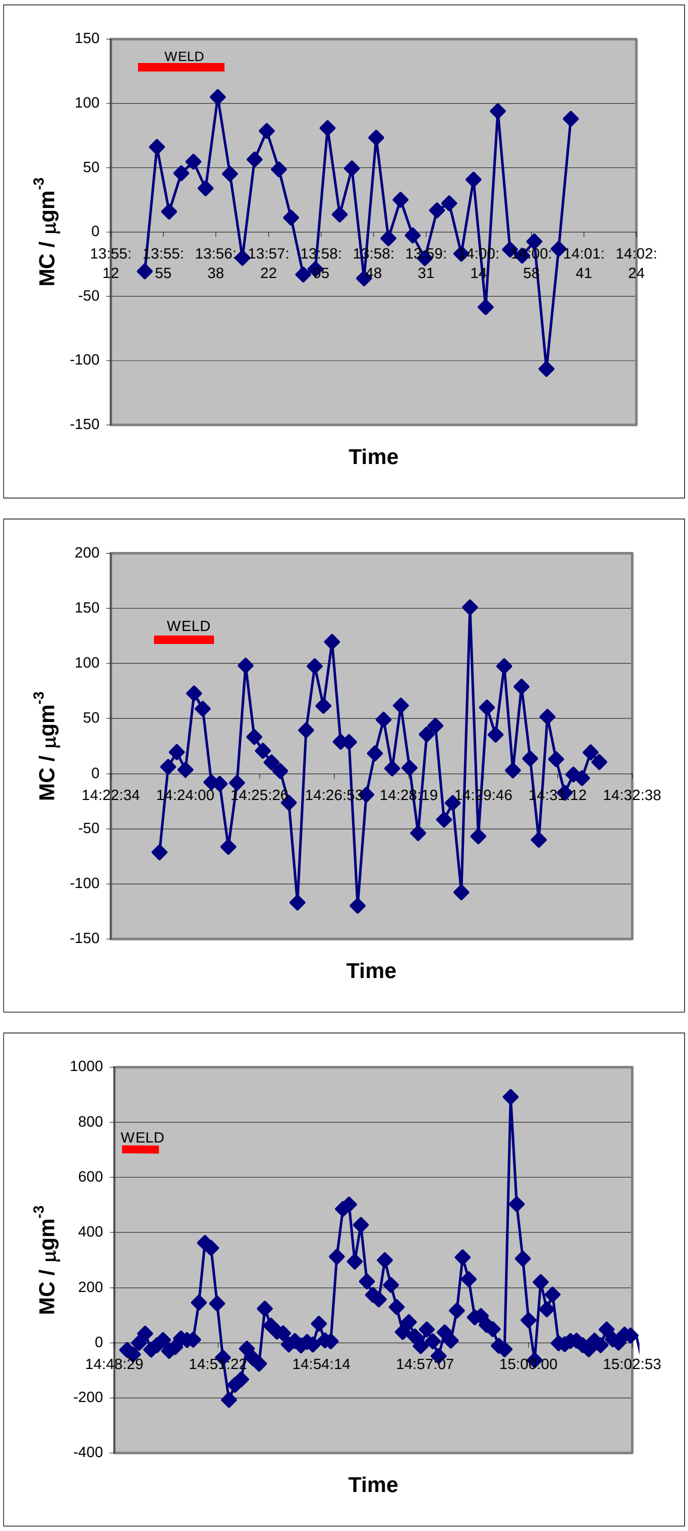


Figure 8.16 Expanded sections of mass concentration plot. Test 4 (top), Test 9 (middle) and Test 13 (bottom)

8.7 THE SAMPLING SECTION

Because fume was sampled in the sampling section at just one position we had to ensure that the fume in the sampling section was fully mixed with the airflow. In order to determine this the welding plume was visualised using smoke, which was emitted with an upward velocity to broadly mimic the thermal uplift of the welding arc.

The plume was observed to rise vertically for a short distance and then began to be deflected by the horizontal flow of air within the cabin. Once the plume reached the ceiling it followed along hugging the ceiling and upper surface of the contraction before travelling close to the roof of the sampling section with the majority of the smoke passing above the TEOM sampling head. In an attempt to remedy this, two mixing fans were positioned either side of the contraction and a square baffle in the mouth of the sampling section. The aim was to disturb and mix the air before it entered the sampling section see, Figure 8.17. A further experiment was undertaken to investigate the homogeneity of the flow at the HAM sampling position. Tracer gas was released at the welding point whilst a vertical and horizontal traverse was carried out in the sampling section at the TEOM sampling point. The tracer gas used was a neutrally buoyant mixture of 16 % sulphur hexafluoride (SF_6) in He. The SF_6 component of the gas mixture was detected using a Miran 1a infrared gas analyser. The tracer gas concentrations measured in both traverses are shown in Table 8.6. Distances were measured from the inside surface of the sampling section, which had a square cross section 700 mm x 700 mm.

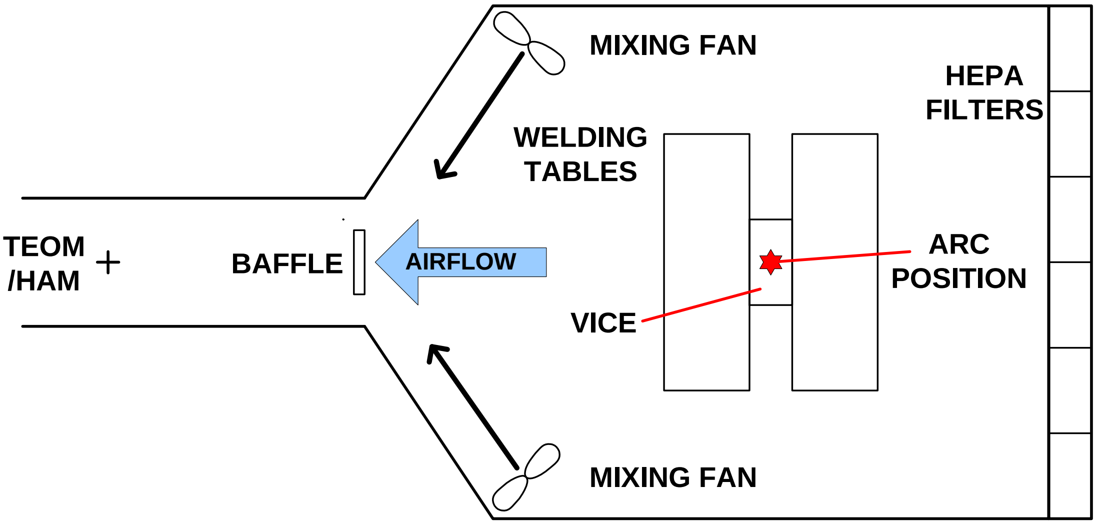


Figure 8.17 Schematic diagram showing a plan view of the test cabin as laid out during a test and the positions of the mixing fans and baffle

Next, the air velocities in the sampling section across the two traverses were measured using a hot wire anemometer; the results are shown in Table 8.7. These results show that even with the baffle in place and mixing fans disrupting and mixing flow entering the sampling section the flow at the measurement point is not fully mixed although reasonably close. To improve mixing the sample point would have to be moved further downstream. For these test this was not practical.

Table 8.6 Tracer gas concentrations in traverses of sampling section

Vertical Traverse		*Horizontal Traverse*	
Distance from edge (mm)	***[SF$_6$] (ppm)***	***Distance from edge (mm)***	***[SF$_6$] (ppm)***
100	0.26	100	0.35
200	0.30	200	0.33
300	0.33	300	0.30
350	0.30	350	0.27
400	0.26	400	0.23
500	0.22	500	0.22
600	0.16	600	0.21

Table 8.7 Air velocities in the sampling section

Vertical traverse		*Horizontal traverse*	
Distance from edge (mm)	***Velocity (ms^{-1})***	***Distance from edge (mm)***	***Velocity (ms^{-1})***
100	2.48	100	3.15
200	2.76	200	3.19
300	3.03	300	3.13
350	3.05	350	3.05
400	3.10	400	3.36
500	2.84	500	3.35
600	2.49	600	3.15

Measurements made with the HAM, with the mixing fans running and the baffle in place, gave much improved data. It was clearly visible from HAM data when welding was occurring in the cabin and when welding had ceased. However, the results were not reproducible enough to rely on them solely for calculating the capture efficiencies of the LEV. This may have been due to the fundamental method of particle detection. The HAM is a light scattering instrument and is therefore unable to detect unable particles less than 0.3 μm. As discussed earlier the size distribution of welding fume will vary over a large range with part of the size distribution falling below 0.3 μm. Therefore, for the remainder of the study, isokinetic sampling and gravimetric analysis in the LEV duct was used to evaluate capture of welding fume. However, measurement in the duct using the HAM continued as a further means of monitoring capture with the proviso that the flow was not fully mixed and that the samples may not have been representational. Whilst the data was not considered in the conclusions of the study, it served to provide further insights into alternative sampling strategies and also gave an indication of when the fume had cleared from the cabin and was safe to enter.

9 APPENDIX II: RESULTS TABLES

9.1 HV LEV SYSTEM

9.1.1 Flux Cored Arc Welding (FCAW)

Table 9.1: Results for flux cored arc welding using HV LEV system

Test Number	*Test Description and LEV Position*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
1	Extract 300 mm above arc.	800	2	46.99	88.39	
2	Extract 300 mm above arc.	800	2	46.27	87.03	
3	Extract 300 mm above arc.	800	2	44.75	84.19	
4	Extract 300 mm above arc.	800	2	47.47	89.30	
5	Extract 300 mm above arc.	800	2	48.51	91.25	
6	Extract 300 mm above arc.	800	2	46.27	87.05	
7	Extract 300 mm above arc.	800	2	46.65	87.75	
8	Extract 300 mm above arc.	800	2	47.86	90.02	
9	Extract 300 mm above arc.	800	2	47.94	90.19	
10	Extract 300 mm above arc.	800	2	42.82	80.55	87.57
11	Extract 600 mm above arc.	800	2	44.09	82.93	
12	Extract 600 mm above arc.	800	2	42.48	79.92	81.42
13	Extract 900 mm above arc.	800	2	15.03	28.28	
14	Extract 900 mm above arc.	800	2	14.25	26.80	27.54

Test Number	*Test Description and LEV Position*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
15	Extract horizontal 150 mm downstream from arc.	800	2	53.46	**100 % TEST**	
16	Extract horizontal 150 mm downstream from arc.	800	2	53.07	**100 % TEST**	
17	Extract horizontal 150 mm downstream from arc.	800	2	52.94	**100 % TEST**	100.00
18	Extract horizontal 300 mm downstream from arc.	800	2	52.26	98.31	
19	Extract horizontal 300 mm downstream from arc.	800	2	49.07	92.31	95.31
20	Extract horizontal 600 mm downstream from arc.	800	2	44.73	84.14	
21	Extract horizontal 600 mm downstream from arc.	800	2	42.70	80.33	82.24
22	Extract horizontal 600 mm upstream from arc.	800	2	1.20	2.25	
23	Extract horizontal 600 mm upstream from arc.	800	2	1.57	2.95	2.60
24	Still air. Extract horizontal 600 mm upstream from arc.	800	2	14.51	27.29	27.29
25	Extract horizontal 300 mm upstream from arc.	800	2	51.06	96.06	
26	Extract horizontal 300 mm upstream from arc.	800	2	51.37	96.64	96.35
27	Extract horizontal 450 mm upstream from arc.	800	2	32.55	61.23	
28	Extract horizontal 450 mm upstream from arc.	800	2	30.59	57.54	59.38

9.1.2 Metal Active Gas (MAG) Welding

Table 9.2: Results for metal active gas welding using HV LEV system

Test Number	*Test Description and LEV Position*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
29	Extract horizontal 300 mm upstream from arc.	800	2	48.01	90.03	
30	Extract horizontal 300 mm upstream from arc.	800	2	48.24	90.45	90.24
31	Extract horizontal 150 mm upstream from arc.	800	2	56.08	**100 % TEST**	
32	Extract horizontal 150 mm upstream from arc.	800	2	50.59	**100 % TEST**	100.00
33	Extract horizontal 85 mm upstream from arc.	800	2	52.55	98.54	
34	Extract horizontal 85 mm upstream from arc.	800	2	56.86	106.62	102.58
35	Extract 300 mm at 45° in plane of weld.	800	2	44.34	83.15	
36	Extract 300 mm at 45° in plane of weld.	800	2	43.92	82.36	82.75
37	Extract 600 mm at 45° in plane of weld.	800	2	16.86	31.62	
38	Extract 600 mm at 45° in plane of weld.	800	2	19.22	36.03	33.83
39	Extract 450 mm at 45° in plane of weld.	800	2	37.90	71.07	
40	Extract 450 mm at 45° in plane of weld.	800	2	35.11	65.83	68.45
41	Extract 600 mm above arc.	800	2	42.75	80.15	
42	Extract 600 mm above arc.	800	2	39.89	74.81	77.48

9.1.3 MAG Welding with a Traversing Torch

Table 9.3: Results for MAG welding with traversing torch using HV LEV system

Test Number	*Test Description and LEV Position*	*LEV Volume Flow (m^3h^{-1})*	*Welding Type*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
43	Extract 340 mm above centre of 300 mm weld.	800	2	24.44	90.00	86.39
44	Extract 340 mm above centre of 300 mm weld.	800	2	22.48	82.78	
45	Extract 340 mm above centre of 450 mm weld.	800	2	27.50	101.25	101.32
46	Extract 340 mm above centre of 450 mm weld.	800	2	27.54	101.39	
47	Extract 650 mm above centre of 450 mm weld.	800	2	20.22	74.44	70.11
48	Extract 650 mm above centre of 450 mm weld.	800	2	17.86	65.78	
49	Extract 650 mm above centre of 300 mm weld.	800	2	27.97	103.00	93.37
50	Extract 650 mm above centre of 300 mm weld.	800	2	22.75	83.74	
51	Extract 650 mm above centre of 300 mm weld in still air.	800	2	18.04	66.42	72.19
52	Extract 650 mm above centre of 300 mm weld in still air.	800	2	21.18	77.97	
53	Extract 650 mm above centre of 450 mm weld in still air.	800	2	25.88	95.30	93.37
54	Extract 650 mm above centre of 450 mm weld in still air.	800	2	24.84	91.45	
55	Extract 300 mm downstream at centre + RHS of 300 mm weld.	800	2	30.98	114.07	111.90
56	Extract 300 mm downstream at centre + RHS of 300 mm weld.	800	2	29.80	109.73	
57	Extract 300 mm downstream at centre of 450 mm weld.	800	2	21.96	80.86	79.89
58	Extract 300 mm downstream at centre of 450 mm weld.	800	2	21.44	78.93	
59	Extract 300 mm downstream at RHS of 450 mm weld.	800	2	23.79	87.60	88.08
60	Extract 300 mm downstream at RHS of 450 mm weld.	800	2	24.05	88.56	
61	100 % check, 150 mm downstream from 300 mm weld.	800	2	25.49	**100 % TEST**	100.00
62	100 % check, 150 mm downstream from 300 mm weld.	800	2	25.88	**100 % TEST**	
63	100 % check, 150 mm downstream from 300 mm weld.	800	2	26.27	**100 % TEST**	
64	100 % check, 150 mm downstream from 300 mm weld.	800	2	30.98	**100 % TEST**	

9.2 LV LEV SYSTEM

9.2.1 MAG Welding

Table 9.4: Results for MAG welding with LV LEV system

Test Number	*Test Description and LEV Position*	*LV Hood*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
65	Extract 75 mm downstream. 60 mm high.	Fishtail	150	2	85.87	76.99	80.10
66	Extract 75 mm downstream. 60 mm high.	Fishtail	150	2	86.42	77.49	
67	Extract 150 mm downstream. 60mm high.	Fishtail	150	2	117.74	**100 % TEST**	100.00
68	Extract 150 mm downstream. 60mm high.	Fishtail	150	2	105.31	**100 % TEST**	
69	Extract 300 mm downstream. 60 mm high.	Fishtail	150	2	13.27	11.90	12.23
70	Extract 300 mm downstream. 60 mm high.	Fishtail	150	2	14.00	12.55	
71	Extract 225 mm downstream. 60 mm high.	Fishtail	150	2	54.56	48.92	49.61
72	Extract 225 mm downstream. 60 mm high.	Fishtail	150	2	56.09	50.30	
73	Extract 150 mm upstream. 60 mm high.	Fishtail	150	2	60.06	53.85	51.13
74	Extract 150 mm upstream. 60 mm high.	Fishtail	150	2	53.99	48.40	
75	Extract 75 mm upstream. 60 mm high.	Fishtail	150	2	71.97	64.53	68.57
76	Extract 75 mm upstream. 60 mm high.	Fishtail	150	2	80.98	72.61	
77	Extract 225 mm upstream. 60 mm high.	Fishtail	150	2	18.91	16.95	15.39
78	Extract 225 mm upstream. 60 mm high.	Fishtail	150	2	15.42	13.83	
79	Extract 75 mm downstream.	Slot	123	2	95.02	97.95	86.96
80	Extract 75 mm downstream.	Slot	123	2	74.40	76.69	
81	Extract 75 mm downstream.	Slot	123	2	83.65	86.23	

Test Number	*Test Description and LEV Position*	*LV Hood*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
82	Extract 150 mm downstream.	Slot	123	2	95.02	97.95	
83	Extract 150 mm downstream.	Slot	123	2	86.57	89.24	93.59
84	Extract 225 mm downstream.	Slot	123	2	47.45	48.91	
85	Extract 225 mm downstream.	Slot	123	2	47.76	49.23	49.07
86	Extract 300 mm downstream.	Slot	123	2	22.89	23.59	
87	Extract 300 mm downstream.	Slot	123	2	65.67	67.70	45.65
88	Extract 150 mm upstream.	Slot	123	2	58.71	60.52	
89	Extract 150 mm upstream.	Slot	123	2	63.18	65.13	62.83
90	Extract 75 mm upstream.	Slot	123	2	98.19	**100 % TEST**	
91	Extract 75 mm upstream.	Slot	123	2	95.82	**100 % TEST**	100.00
92	Extract 225 mm upstream.	Slot	123	2	17.08	17.61	
93	Extract 225 mm upstream.	Slot	123	2	16.09	16.58	
94	Extract 225 mm upstream.	Slot	123	2	14.85	15.30	16.50
95	Extract 75 mm downstream. 60 mm high.	Circular	136	2	78.77	76.12	
96	Extract 75 mm downstream. 60 mm high.	Circular	136	2	79.60	76.93	76.52
97	Extract 150 mm downstream. 60 mm high.	Circular	136	2	76.12	73.56	
98	Extract 150 mm downstream. 60 mm high.	Circular	136	2	64.68	62.50	68.03
99	Extract 225 mm downstream. 60 mm high.	Circular	136	2	55.72	53.85	
100	Extract 225 mm downstream. 60 mm high.	Circular	136	2	60.70	58.66	56.25
101	Extract 300 mm downstream. 60 mm high.	Circular	136	2	42.79	41.35	
102	Extract 300 mm downstream. 60 mm high.	Circular	136	2	29.35	28.37	34.86

Test Number	***Test Description and LEV Position***	***LV Hood***	***LEV Volume Flow (m^3h^{-1})***	***Welding Condition***	***Fume Concentration (mgm^{-3})***	***LEV Efficiency (%)***	***Average (%)***
103	Extract 75 mm upstream. 60 mm high.	Circular	136	2	107.96	**100 % TEST**	
104	Extract 75 mm upstream. 60 mm high.	Circular	136	2	99.00	**100 % TEST**	100.00
105	Extract 150 mm upstream. 60 mm high.	Circular	136	2	67.82	65.54	
106	Extract 150 mm upstream. 60 mm high.	Circular	136	2	69.15	66.83	66.18
107	Extract 225 mm upstream. 60 mm high.	Circular	136	2	15.92	15.39	
108	Extract 225 mm upstream. 60 mm high.	Circular	136	2	21.26	20.54	17.96
109	Extract 75 mm downstream. 150 mm lateral offset.	Fishtail	150	2	77.11	69.14	
110	Extract 75 mm downstream. 150 mm lateral offset.	Fishtail	150	2	88.06	78.96	74.05
111	Extract 75 mm downstream. 225 mm lateral offset.	Fishtail	150	2	50.75	45.50	
112	Extract 75 mm downstream. 225 mm lateral offset.	Fishtail	150	2	46.77	41.93	43.72
113	Extract 75 mm downstream.	Fishtail	150	2	91.54	82.08	
114	Extract 75 mm downstream.	Fishtail	150	2	93.53	83.86	80.10
115	Extract 75 mm upstream. 150 mm lateral offset.	Fishtail	150	2	65.80	58.99	
116	Extract 75 mm upstream. 150 mm lateral offset.	Fishtail	150	2	65.17	58.44	58.71
117	Extract 75 mm upstream. 75 mm lateral offset.	Fishtail	150	2	94.53	84.76	
118	Extract 75 mm upstream. 75 mm lateral offset.	Fishtail	150	2	107.46	96.35	90.55
119	Extract 75 mm upstream. 225 mm lateral offset.	Fishtail	150	2	24.88	22.30	
120	Extract 75 mm upstream. 225 mm lateral offset.	Fishtail	150	2	18.91	16.95	19.63
121	Extract 75 mm upstream. 75 mm lateral offset.	Circular	136	2	79.46	76.79	
122	Extract 75 mm upstream. 75 mm lateral offset.	Circular	136	2	74.61	72.10	74.44

Test Number	*Test Description and LEV Position*	*LV Hood*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
123	Extract 75 mm upstream. 150 mm lateral offset.	Circular	136	2	49.75	48.08	48.25
124	Extract 75 mm upstream. 150 mm lateral offset.	Circular	136	2	50.11	48.42	
125	Extract 75 mm downstream. 75mm lateral offset.	Circular	136	2	100.50	97.12	91.84
126	Extract 75 mm downstream. 75mm lateral offset.	Circular	136	2	89.58	86.57	
127	Extract 75 mm downstream. 150 mm lateral offset.	Circular	136	2	68.49	66.18	71.49
128	Extract 75 mm downstream. 150 mm lateral offset.	Circular	136	2	79.46	76.79	
129	Extract 75 mm downstream. 225 mm lateral offset.	Circular	136	2	32.84	31.73	31.73
130	Extract 75 mm downstream. 225 mm lateral offset.	Circular	136	2	32.84	31.73	

9.2.2 MAG Welding with a Traversing Torch

Table 9.5: Results for MAG welding with traversing torch using slot hood

Test Number	*Test Description and LEV Position*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*Average (mgm^{-3})*
131	Extract 75 mm downstream at centre + RHS of 300 mm weld.	126	2	131.01	137.23
132	Extract 75 mm downstream at centre + RHS of 300 mm weld.	126	2	143.45	
133	Extract 150 mm downstream at centre + RHS of 300 mm weld.	126	2	153.40	150.17
134	Extract 150 mm downstream at centre + RHS of 300 mm weld.	126	2	146.93	
135	Extract 75 mm downstream at centre of 450 mm weld.	126	2	134.77	140.41
136	Extract 75 mm downstream at centre of 450 mm weld.	126	2	146.05	
137	Extract 75 mm downstream at RHS of 450 mm weld.	126	2	178.55	159.15
138	Extract 75 mm downstream at RHS of 450 mm weld.	126	2	139.75	

Table 9.6: Results for MAG welding with traversing torch using LV LEV system

Test Number	*Test Description and LEV Position*	*LV Hood*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
139	Extract 75 mm downstream. 60 mm high.	Fishtail	150	2	151.91	**100 % Test**	100.00
140	Extract 75 mm downstream. 60 mm high.	Fishtail	150	2	132.50	**100 % Test**	
141	Extract 75 mm downstream at centre of 450 mm weld.	Fishtail	150	2	96.96	68.18	74.17
142	Extract 75 mm downstream at centre of 450 mm weld.	Fishtail	148	2	108.57	76.34	
143	Extract 75 mm downstream at centre of 450 mm weld.	Fishtail	148	2	110.89	77.98	
144	Extract 75 mm downstream at RHS of 450 mm weld.	Fishtail	150	2	91.65	64.45	62.00
145	Extract 75 mm downstream at RHS of 450 mm weld.	Fishtail	150	2	84.69	59.55	
146	Extract 75 mm downstream at RHS of 300 mm weld.	Fishtail	150	2	128.52	90.38	93.00
147	Extract 75 mm downstream at RHS of 300 mm weld.	Fishtail	150	2	135.99	95.62	
148	Extract 75 mm downstream at centre of 300 mm weld.	Fishtail	150	2	152.90	107.51	111.53
149	Extract 75 mm downstream at centre of 300 mm weld.	Fishtail	150	2	164.34	115.56	
150	Extract 150 mm downstream at centre of 300 mm weld.	Fishtail	150	2	159.87	112.41	105.76
151	Extract 150 mm downstream at centre of 300 mm weld.	Fishtail	150	2	140.96	99.12	
152	Extract 75 mm downstream at centre of 300 mm weld.	Circular	148	2	117.08	82.32	79.18
153	Extract 75 mm downstream at centre of 300 mm weld.	Circular	148	2	108.13	76.03	
154	Extract 75 mm downstream at RHS of 300 mm weld.	Circular	148	2	94.20	66.23	65.71
155	Extract 75 mm downstream at RHS of 300 mm weld.	Circular	148	2	92.70	65.18	
156	Extract 150 mm downstream at centre of 300 mm weld.	Circular	148	2	115.59	81.27	83.55
157	Extract 150 mm downstream at centre of 300 mm weld.	Circular	148	2	122.06	85.82	
158	Extract 75 mm downstream at centre of 450 mm weld.	Circular	148	2	74.41	52.32	63.43
159	Extract 75 mm downstream at centre of 450 mm weld.	Circular	148	2	89.33	62.81	
160	Extract 75 mm downstream at centre of 450 mm weld.	Circular	148	2	106.91	75.17	
161	Extract 75 mm downstream at RHS of 450 mm weld.	Circular	148	2	67.44	47.42	43.34
162	Extract 75 mm downstream at RHS of 450 mm weld.	Circular	148	2	55.83	39.26	

9.3 ON-GUN RESULTS

Table9.7: Results for MAG welding using on-gun extraction system

Test Number	*Test Description and LEV Position*	*LEV Volume Flow (m^3h^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
163	100 % extract check bead on plate inside funnel	80	1	226.85	**100 % Test**	100
164	100 % extract check bead on plate inside funnel	80	1	219.63	**100 % Test**	
165	Bead on plate, in the flat, extract nozzle flush with bottom of gas shroud	80	1	267.81	120	120
166	Bead on plate, in the flat, extract nozzle 7mm from bottom of gas shroud	80	1	217.59	97	92
167	Bead on plate, in the flat, extract nozzle 7mm from bottom of gas shroud	80	1	192.04	86	
168	Bead on plate, in the flat, extract nozzle 14mm from bottom of gas shroud	80	1	240.37	108	107
169	Bead on plate, in the flat, extract nozzle 14mm from bottom of gas shroud	80	1	234.81	105	
170	Bead on plate, in the flat, extract nozzle 21mm from bottom of gas shroud	80	1	173.15	78	78
171	Bead on plate, in the flat, extract nozzle 21mm from bottom of gas shroud	80	1	171.48	77	
172	Bead on plate, in the flat	80	1	206.67	93	94
173	Bead on plate, in the flat	80	1	215	96	
174	Bead on plate, in the flat	80	1	225	101	
175	Bead on plate, in the flat	80	1	188.33	84	
176	Bead on plate, in the flat	80	1	211.9	95	
177	Bead on plate, vertically up	80	1	117.59	90	107
178	Bead on plate, vertically up	80	1	149.26	114	
179	Bead on plate, vertically up	80	1	153.15	117	
180	100% extract check, bead on plate, vertically up, inside funnel	80	1	130.74	**100 % Test**	100
181	100% extract check, bead on plate, vertically up, inside funnel	80	1	130.84	**100 % Test**	
182	100% extract check, bead on plate, vertically up, inside funnel	80	1	129.93	**100 % Test**	

Test Number	***Test Description and LEV Position***	***LEV Volume Flow (m^3h^{-1})***	***Welding Condition***	***Fume Concentration (mgm^{-3})***	***LEV Efficiency (%)***	***Average (%)***
183	100% extract check, bead on plate, vertically down, inside funnel	80	1	193.06	**100 % Test**	
184	100% extract check, bead on plate, vertically down, inside funnel	80	1	176.39	**100 % Test**	
185	100% extract check, bead on plate, vertically down, inside funnel	80	1	185.56	**100 % Test**	100
186	Bead on plate, vertically down	80	1	171.48	93	
187	Bead on plate, vertically down	80	1	153.15	83	
188	Bead on plate, vertically down	80	1	171.48	93	90
189	Bead on plate, horizontal	80	1	225.77	78	
190	Bead on plate, horizontal	80	1	219.51	76	
191	Bead on plate, horizontal	80	1	197.58	68	74
192	100% extract check, bead on plate, horizontal, inside funnel	80	1	289.26	**100 % Test**	
193	100% extract check, bead on plate, horizontal, inside funnel	80	1	277.04	**100 % Test**	
194	100% extract check, bead on plate, horizontal, inside funnel	80	1	301.48	**100 % Test**	100
195a	Fillet, in the flat	80	1	145.37	94	
196a	Fillet, in the flat	80	1	147.04	95	95
197a	100% extract check, fillet, in the flat inside large enclosure	80	1	149.72	**100 % Test**	
198a	100% extract check, fillet, in the flat inside large enclosure	80	1	159.89	**100 % Test**	100
195b	100% extract check, fillet, in the flat, inside box	80	1	121	**100 % Test**	
196b	100% extract check, fillet, in the flat, inside box	80	1	145	**100 % Test**	
197b	100% extract check, fillet, in the flat, inside box	80	1	119	**100 % Test**	100
198b	Fillet, in the flat	80	1	72	56	
199b	Fillet, in the flat	80	1	80	62	
200b	Fillet, in the flat	80	1	88	69	62
201	100% extract check, fillet, vertically down, inside funnel	80	1	141	**100 % Test**	
202	100% extract check, fillet, vertically down, inside funnel	80	1	112	**100 % Test**	
203	100% extract check, fillet, vertically down, inside funnel	80	1	113	**100 % Test**	100

Test Number	***Test Description and LEV Position***	***LEV Volume Flow (m^3h^{-1})***	***Welding Condition***	***Fume Concentration (mgm^{-3})***	***LEV Efficiency (%)***	***Average (%)***
204	Fillet, vertically down	80	1	103	84	
205	Fillet, vertically down	80	1	100	82	
206	Fillet, vertically down	80	1	96	79	82
207	100% extract check, fillet, vertically up, inside funnel	80	1	98	**100 % Test**	
208	100% extract check, fillet, vertically up, inside funnel	80	1	102	**100 % Test**	
209	100% extract check, fillet, vertically up, inside funnel	80	1	103	**100 % Test**	100
210	Fillet, vertically up	80	1	85	84	
211	Fillet, vertically up	80	1	81	80	
212	Fillet, vertically up	80	1	81	80	81
213	100% extract check, bead on plate, in the flat, inside box	80	2	436	**100 % Test**	
214	100% extract check, bead on plate, in the flat, inside box	80	2	412	**100 % Test**	
215	100% extract check, bead on plate, in the flat, inside box	80	2	439	**100 % Test**	100
216	Bead on plate, in the flat	80	2	386	90	
217	Bead on plate, in the flat	80	2	416	97	
218	Bead on plate, in the flat	80	2	398	93	93
219a	Fillet, in the flat	80	2	254.17	50	
220a	Fillet, in the flat	80	2	211.09	41	
221a	Fillet, in the flat	80	2	301.67	59	
222a	Fillet, in the flat	80	2	181.98	35	46
223a	100% extract check, fillet, in the flat, inside large enclosure	80	2	537.78	**100 % Test**	
224a	100% extract check, fillet, in the flat, inside large enclosure	80	2	487.78	**100 % Test**	100
219b	100% extract check, fillet, in the flat, inside box	80	2	494	**100 % Test**	
220b	100% extract check, fillet, in the flat, inside box	80	2	452	**100 % Test**	
221b	100% extract check, fillet, in the flat, inside box	80	2	375	**100 % Test**	100

Test Number	*Test Description and LEV Position*	*LEV Volume Flow (m^3hr^{-1})*	*Welding Condition*	*Fume Concentration (mgm^{-3})*	*LEV Efficiency (%)*	*Average (%)*
222b	Fillet, in the flat	80	2	275	62	
223b	Fillet, in the flat	80	2	208	47	
224b	Fillet, in the flat	80	2	249	57	55

10 APPENDIX III: PLOTS OF CAPTURE EFFICIENCY FOR HV AND LV HOODS

Figure 10.1 Capture efficiency above the arc: HV

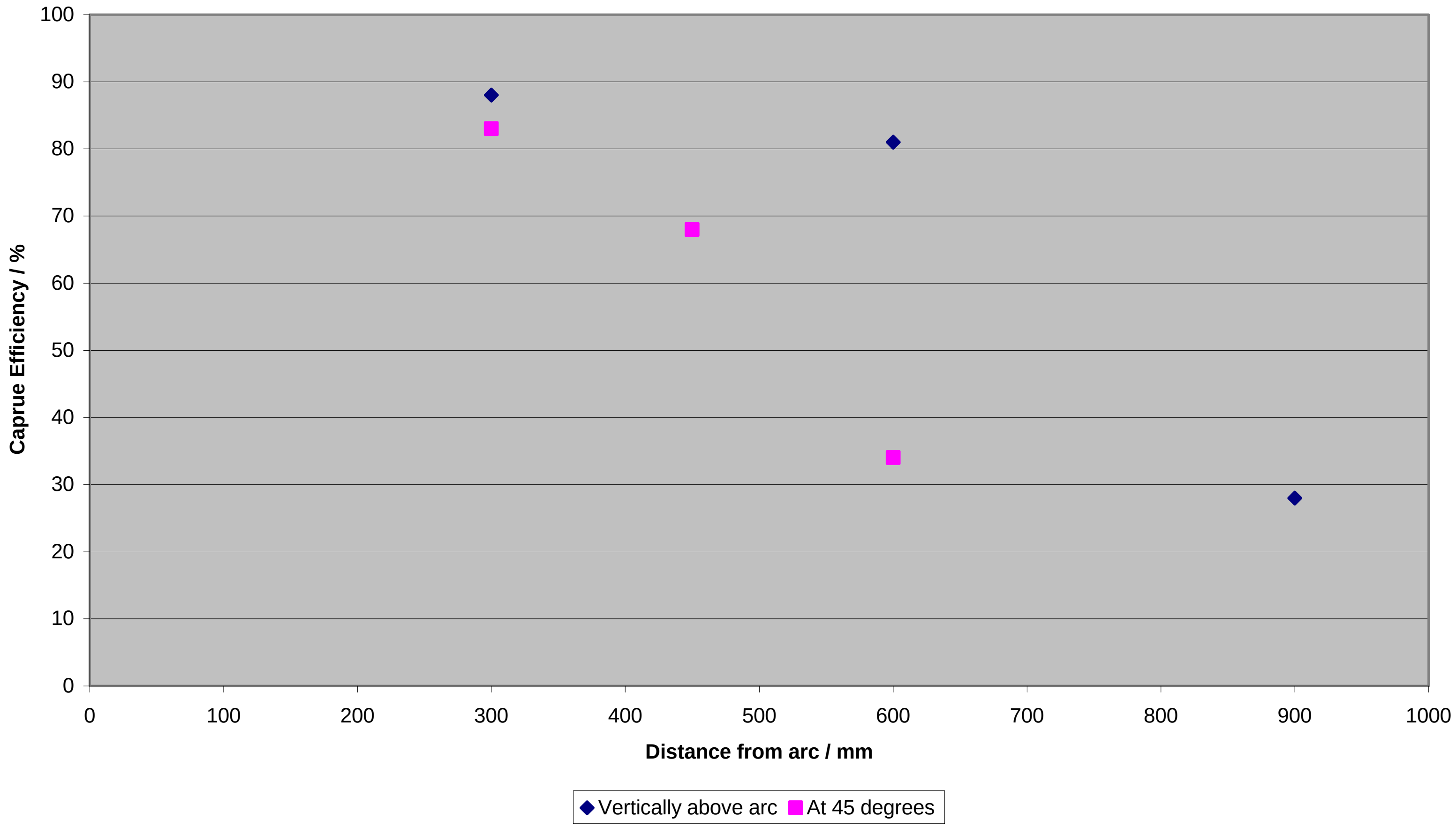


Figure 10.2 Capture efficiency horizontal from the arc: HV

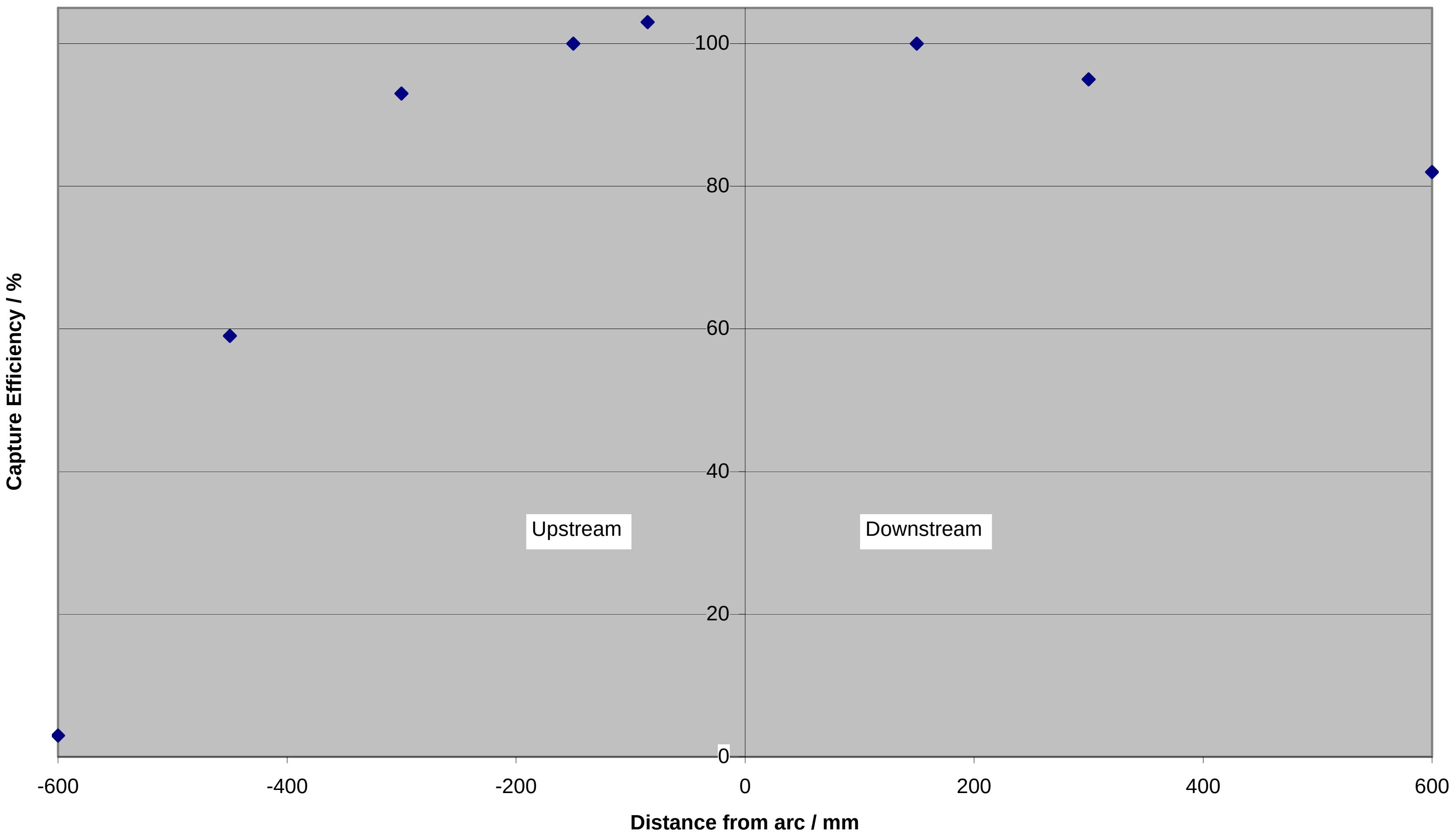


Figure 10.3 Capture efficiencies vertically above a moving torch: HV

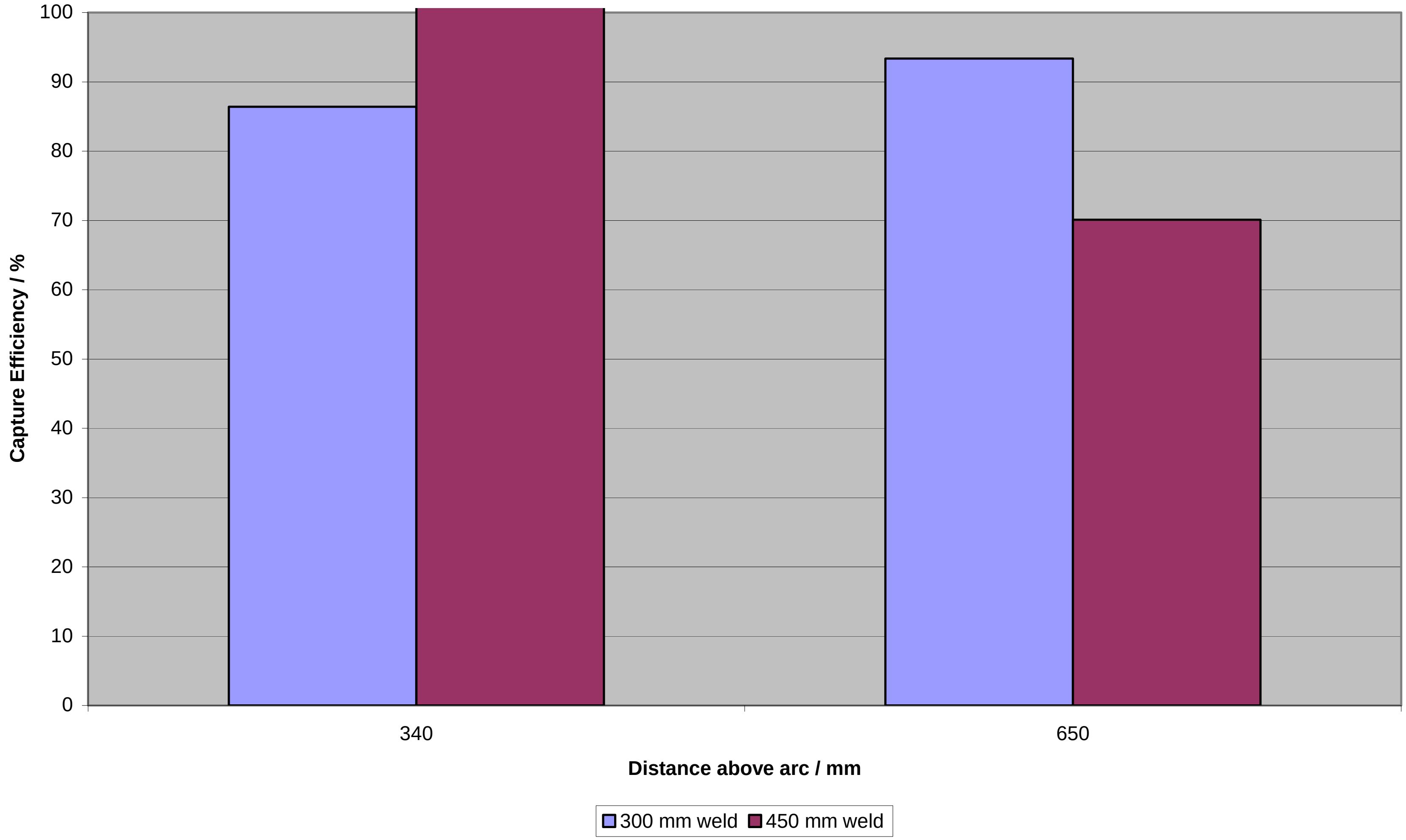


Figure 10.4 Capture efficiencies 300 mm downstream from moving torch: HV

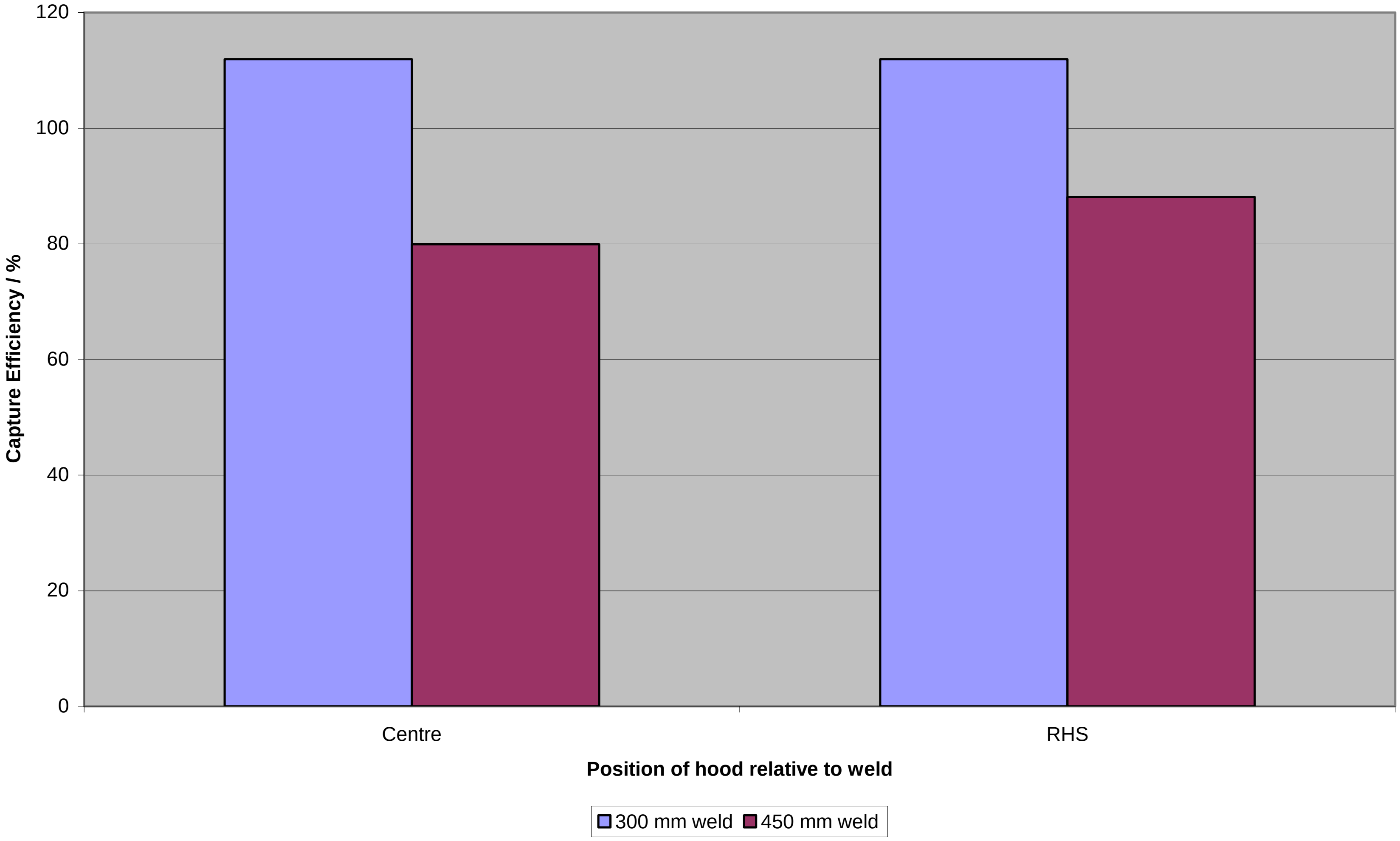


Figure 10.5 Capture efficiencies of LV hoods

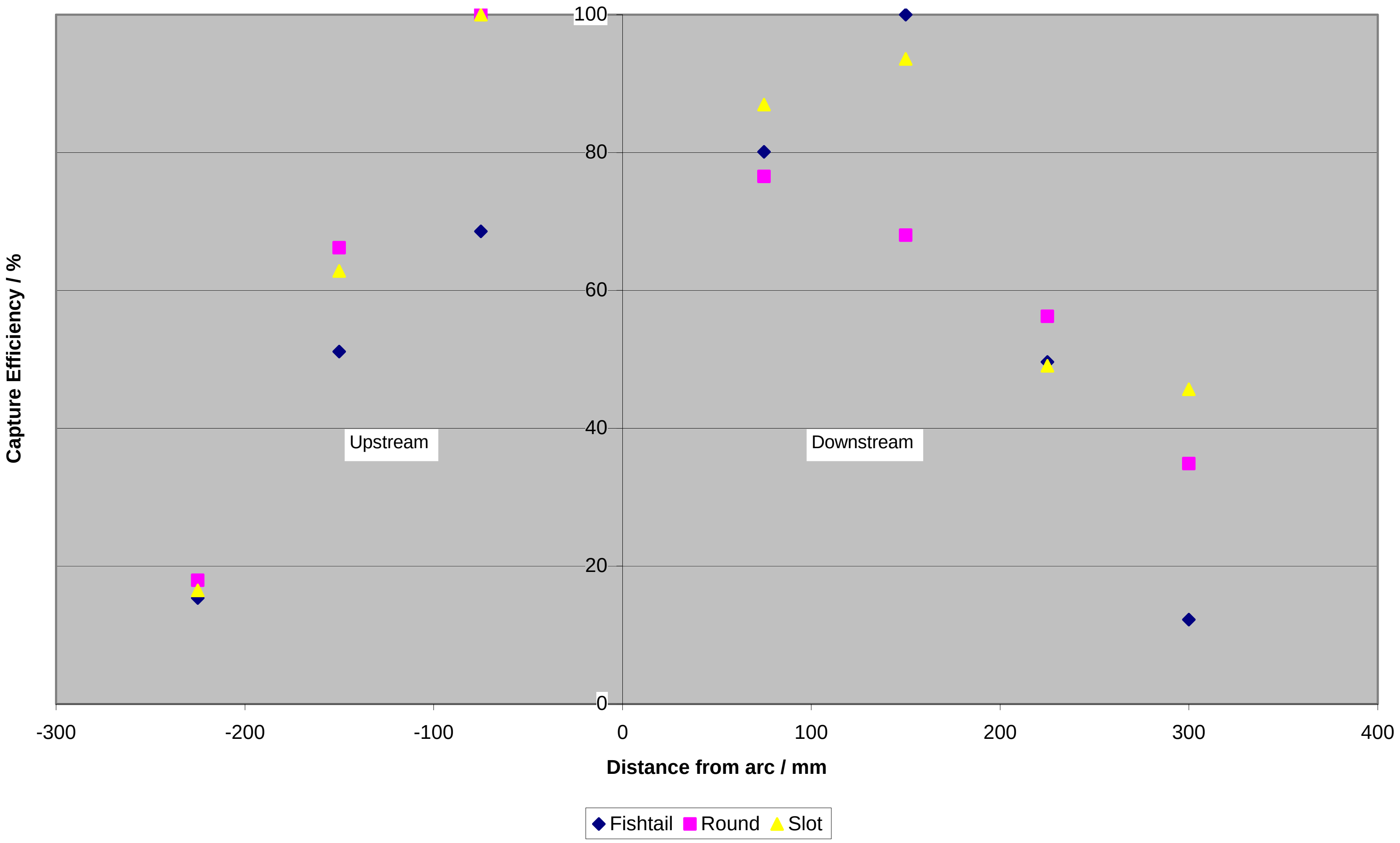


Figure 10.6 Capture efficiencies of LV hoods with lateral offsets

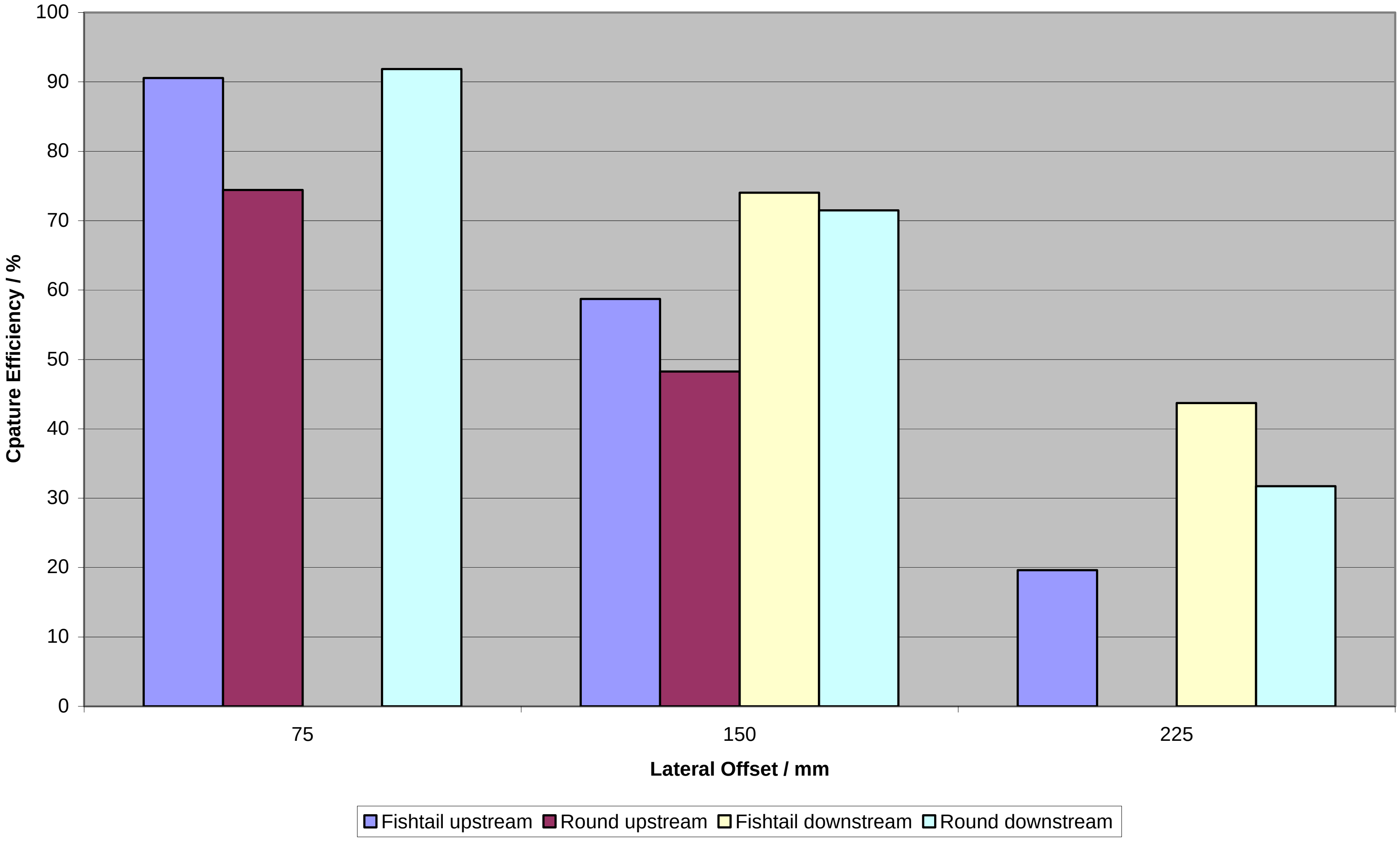
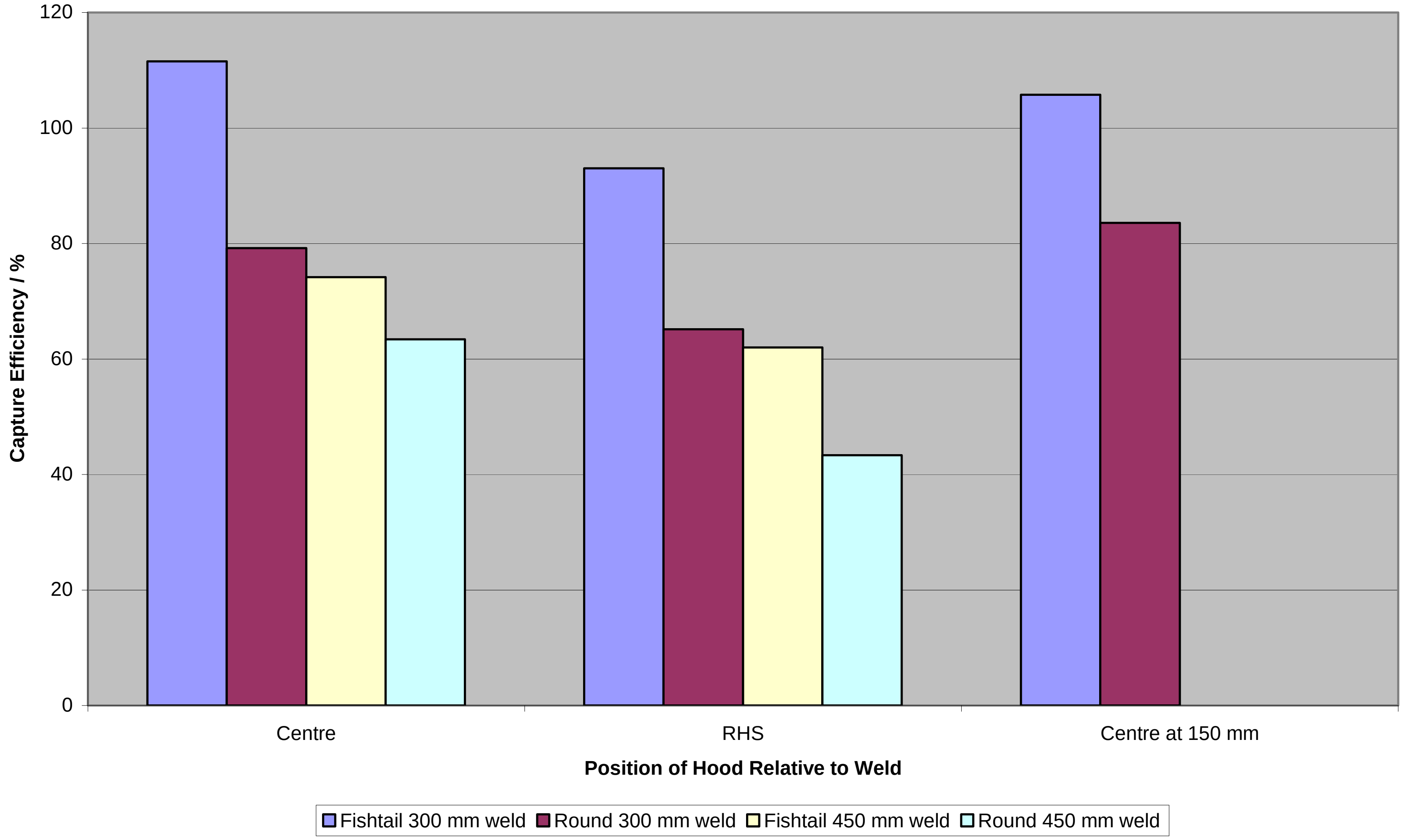


Figure 10.7 Capture efficiencies of LV hoods downstream from a moving torch



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Effective control of gas shielded arc welding fume

HSE inspectors have noted that, although Local Exhaust Ventilation (LEV) was often available for controlling exposure to inert gas shielded welding fume, it frequently remained unused, due, partly to claims by welders that the LEV was responsible for removing shielding gas and thereby compromising the quality of the weld. However, there appeared to be few data to substantiate the welders' claims. HSE commissioned this research project to establish whether efficient welding fume capture could be achieved using LEV whilst, at the same time, maintaining weld metal integrity. The objectives of this research project were to be met in three phases:

- Phase 1 was to provide the information necessary to develop an experimental plan.
- Phase 2 was to determine the maximum cross flow velocity of air that could be tolerated before the onset of weld metal porosity during gas shielded arc welding using parameters defined in Phase 1.
- Phase 3 was to measure capture efficiencies for a range of different LEV hoods positioned at various distances and orientations to the welding arc, whilst monitoring weld metal integrity. An on-gun extraction system was also evaluated. This report gives a brief summary of the work carried out in phase 1 and 2, and details the work carried out in phase 3.

The report shows that when using standard welding parameters, satisfactory fume extraction is possible without compromising the weld integrity. The results are confirmed for a number of welding positions and with various extraction hoods in different positions. The results for the on-gun extraction equipment are evaluated against those observed for the stand-alone fume extraction equipment.

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