DEVELOPMENT AND TESTING OF A NEW SAMPLER FOR WELDING FUME

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Abstract—The development of a new sampler having an inhalable entry and a porous foam plug, which can partition the respirable and non-respirable fractions of the sampled air, is described. The rationale for this partitioning is that welding fume is primarily respirable, where dust generated by other welding related processes is generally non-respirable. The sampler is designed to operate inside the welder’s face shield, and its attachment configuration fulfills the requirements stated in the proposed European Standard for welding fume sampling (CEN, 1996). The aspiration efficiency agrees well with that of a breathing mannequin wearing a face shield, although it undersamples compared to the inhalable convention (CEN, 1993) in wind tunnel tests. The penetration of welding fume through the porous foam is consistently around 72%, comparable to that through a conventional personal cyclone. Field trials have indicated that the sampler does not obstruct nodal work activity or vision. Finally, the new sampler has been included in the proposed European Standard. Crown copyright © 1997 Published by Elsevier Science Ltd

INTRODUCTION

Fume is produced during welding itself and is primarily an aerosol formed by condensation and oxidation of the vaporized metal. It may also contain other materials, such as flux components, which were originally part of the welding consumable or the metal being welded. This mixture of airborne gases and fine particles may be a risk to health, depending on the composition and concentration of the fume, and the duration of exposure.

In order to assess this risk, sampling of welding fume is carried out to determine its concentration and composition. In the U.K., the method recommended in British Standard BS6691: Part 1: 1986 (BSI, 1986) is commonly used. The BS6691 method (referred to as ‘BS method’ or ‘BS sampler’ in this paper) uses a 37-mm open-face filter holder, which is mounted 25 mm from the cheek of the welder, facing the face inside the face shield. A sampling flow rate of 1.8–2.2 l min⁻¹ is used, and the amount of welding fume is determined gravimetrically.

Similar sampling methods are used in Europe and elsewhere. For example, 37-mm ‘closed’ face samplers are used in Denmark with the sampler clipped to the inside of the face shield. The sampler position varies as the welder raises or lowers the face shield frequently. In France, a similar sampler is clipped to the headband of the face shield, pointing downward, such that the sampler remains at the same position when the face shield is raised. In Germany, a cone-shaped sampler is used. The sampler, with a flow rate of 3.5 l min⁻¹, is attached under the chin of the welder with the sampling orifice pointing forward.
There are a number of practical disadvantages associated with these methods. The BS method is criticized because (i) the large exposed filter surface is prone to damage and contamination; (ii) the sampling head tends to stick to the welder's face or facial hair; and (iii) in common with the French and Danish methods, it is difficult to position the sampler in the breathing zone as the welder frequently needs to put the face shield on and off. The breathing zone in the welding situation extends only to the space between the welder's face and the face shield when the shield is worn. As for the German method, it is difficult for the sampler to be located inside the face shield without interfering with the welder's movement.

In addition, it is not known whether the selection characteristics of these methods comply with the new CEN/ISO conventions for inhalable, thoracic and respirable aerosol (CEN, 1993; ISO, 1995) when mounted, as described in the welding fume sampling situation, instead of in the more conventional mounting on the upper torso.

The work described in this paper was carried out in consultation with a CEN working group (CEN/TC121/SC9/WG2), having the remit to standardize welding fume sampling methods in the EC, and aimed to provide an alternative sampling methodology and a better characterized sampler for more accurate determination of welding fume.

RATIONALE FOR THE DESIGN OF THE NEW SAMPLER

It is generally recognized that there are two major sources of the aerosol produced during welding processes. Fume is produced during welding itself and is primarily an aerosol formed by condensation and oxidation of the vaporized metal. It may also contain other materials, such as flux components, which were originally part of the welding consumable or the metal being welded. There are substantial data in the literature concerning the particle size distribution of welding fume, for example Jenkins et al. (1981), Hewett (1995) and Chung and Scott (1996). Most report that whereas welding fume is normally in the sub-micron range, typically below 0.2 μm, it forms chains and aggregates that are much larger geometrically but aerodynamically still within the respirable range. In a survey conducted in the workplace with a low-pressure impactor that had a resolution below 0.18 μm aerodynamic diameter, Hewett (1995) reported that there were no particles greater than 10 μm when welding alone.

As for grinding and similar finishing work activities alone, a recent study by Chung and Carter (1996), using a similar impactor to Hewett’s, shows that less than 30% of the aerosol that entered the impactor was below 10 μm. As the design of the impactor, which has a cut point of 18 μm at its entry, means that it severely undersamples larger particles, and because of the high velocity of dust generated by grinding, most of the larger particles actually miss the impactor as a result of inertia. Hence, the particle size distribution of this other source of aerosol in a welding shop must be wider and covers a much larger particle size than fume from arc welding. In common with other industries, the assumption that these particles are mostly outside the respirable range (by mass) must be valid.

This difference in size between the two aerosols gives the basis for the design of the new instrument. If the assumption is made that welding fume is respirable and
A new sampler for welding fume

the other aerosol is predominantly non-respirable, then a sampler having an inhalable entry that contains a respirable selector would enable more accurate estimation of the relative proportion of the two aerosols. The design of the new instrument was based on this rationale.

DESCRIPTION OF THE NEW SAMPLER

The design of the new instrument was derived from the three stage sampler (for inhalable, thoracic and respirable aerosol), first described by Lynch et al. (1985) and more recently by Aitken et al. (1993).

The components of the new sample are shown in Fig. 1. The sampling cassette has an orifice 15 mm in diameter with a protruding lip that extends through the outer casing. The design flow rate is 2 l. min⁻¹. This inlet is identical to the IOM personal sampler, which is intended to sample the inhalable fraction (Mark and Vincent, 1986). The cassette holds both the respirable selector and the collection filter. Air is drawn into the entry and through the respirable selector—a polyester foam plug—on to the filter. The cylindrical foam plug has a diameter of 30 mm and is 25 mm long. It has an open cell structure, graded according to its porosity, with 90 pores per inch (ppi). These foam plug specifications are identical to those in an earlier study (Aitken et al., 1993) in which it was shown that the penetration characteristics were a good match to the respirable curve, defined as a sub-fraction of the inhalable curve (CEN, 1993) (see Fig. 2). Hence, in this sampler, the respirable fraction is collected on the filter, and the non-respirable fraction trapped on the foam.

The sampling head is mounted horizontally behind the welding face shield with the entry facing forward. Mounting is achieved by using a spring 'C' clip on a bracket. The bracket is in turn fixed to an elasticated sportsman's headband worn under the face shield. A typical arrangement is shown in Fig. 3.

\[ 
\begin{array}{c}
\text{Fig. 2. Penetration through the respirable foam selector plug [from Aitken et al. (1993)].} \\
\text{——: respirable convention; • • •: fitted curve; O: penetration, P; O: means.}
\end{array}
\]
TESTING OF THE NEW SAMPLER

The testing of the new sampler was divided into three parts: (i) penetration of welding fume through the porous foam plugs; (ii) aspiration efficiency of the sampler; and (iii) field trials of the prototype instrument.

Penetration of welding fume through the porous foam plugs

As described earlier, the rationale for the new sampler was that welding fume was primarily respirable and thus would pass through any selector having a penetration characteristic corresponding to the respirable definition with (close to) 100% efficiency. It was necessary to determine whether this was the case for these foam plugs.

Vincent et al. (1993) considered that the primary deposition mechanisms operating in foam selectors of this type are impaction and sedimentation. However, given the nature of welding fume particles, which are known to have a very small individual size and a tendency to form chains and clumps, additional mechanisms, such as diffusion and interception, also may be important collection mechanisms in these foams.

A test rig able to generate welding fume by manual metal arc (MMA) welding on mild steel plates was set up to determine penetration of welding fume through foam plugs in three experimental arrangements: (i) calm air exposure, (ii) cyclic exposure and (iii) steady-state exposure. The choice of the different exposure regimes was to enable assessment of the plugs with fume having undergone a range of ageing processes.

In the calm air exposure measurements, a welding operation was carried out inside a steel ducting approximately 1.5 m long and with a cross-section of 0.4×0.4 m. After burning off one welding rod, which took about 1 min, the ducting was sealed, and sampling began. Eight samplers were arranged in pairs and located near to the top of the duct. Each pair comprised one sampler, containing a foam and filter in the cassette, and the other four containing only a filter. Penetration (P) of welding fume through each plug was calculated using:

\[
P = \frac{M_{f(\text{plug})}}{M_{f(\text{no plug})}},
\]

where \(M_f\) was the mass collected on the sampler filter. The sampling time of each pair was varied so that the penetration of fume with different age profiles was determined.

In the cyclic experiments, the penetration of relatively fresh welding fume was determined. In the same test rig, four samplers without foam plugs, two with the foams and two cyclones were used. Welding and sampling were carried out simultaneously for 10 s and then stopped. The air in the rig was cleaned out, and a second welding/sampling episode was repeated; a total of five repeats were carried out. Penetration was calculated using Equation (1), after correcting for flow rates.

In the final set of experiments, the test rig was rearranged with a fan to provide a steady-state fresh welding fume exposure facility. The mean velocity in the duct was controlled to 0.2 m s\(^{-1}\). The samplers used in the experiments were as follows:

three samplers containing foam plugs,
Fig. 1. Photograph of the disassembled new sampler.
Fig. 3. Typical arrangement of the sampler as worn by a welder.
Fig. 4. Experimental set-up for the testing of the samplers in a ventilated chamber with salt aerosol.
Fig. 7. SEM micrograph of chain aggregates of welding fume collected on a porous foam.
two samplers containing foam plugs that had been dipped in hyamine,
two samplers containing no plug, and
one cyclone.

The purpose of using the dipped plugs was to remove any possible electrostatic
effects. Penetration was again calculated using Equation (1).

Aspiration efficiency of the new sampler

It is now well established that for the sampling of aerosols in the workplace, it is
necessary to take account of the aspiration efficiency of the sampling instrument
being used. Although the design of the new welding fume sampler is based on the
IOM personal inhalable sampler, the nature of the aspiration efficiency curve for
personal samplers results from the combined effects of the sampler parameters, such
as orifice diameter and flow rate; the influence of the features of the body on which
the samplers are mounted and the precise way in which these factors interact are not
fully understood at this time. Since the new sampler is designed to be mounted on
the head, behind the face shield of a welder, whereas most personal samplers are
mounted on the torso of the wearer, it was necessary to measure the aspiration
efficiency of the sampler using methods akin to those used for the measurements of
inhalability and performance of personal inhalable samplers. In order to cover the
particle size of interest (approximately 0.2–90 μm), tests with this wide size range
were conducted.

Two sets of experiments were carried out to measure the aspiration efficiency of
the new sampler and the BS sampler. The first set of experiments was concerned
with measuring the aspiration efficiency of the new sampler over a range of sizes
appropriate to the inhalable convention. These experiments were consistent with the
work described to develop the IOM personal inhalable sampler (Mark and Vincent,
1986). In these, five grades of fused alumina, commercially available as Aloxite
(Al₂O₃), having mass median aerodynamic diameters of 6, 13, 26, 46 and 90 μm, and
a typical geometric standard deviation (σg) of 1.3, were used.

Test samplers were mounted on either side of the head of a breathing
mannequin, and the experiment was repeated with the samplers in reversed
positions. The mannequin, rotating slowly (with a reciprocal motion) inside a
3.2×1.8 m wind tunnel at a constant wind speed of 1 m s⁻¹, was set to aspirate
through the mouth at 20 l min⁻¹, with a sinusoidal breathing pattern of 20 breaths
per minute. Tests were carried out with the mannequin wearing a welding face shield
in both the visor up and visor down positions. The aspiration efficiency of the
sampler under test is given by the ratio of the concentration measured by the
sampler to the concentration present in the freestream air measured using isokinetic
reference probes.

The second set of experiments was conducted to measure the aspiration efficiency
of the test samplers in a simulated welding environment. A similar breathing
mannequin and method of attaching the samplers were used, but the experiment was
carried out in a 8-m³ ventilated chamber. The mannequin was inclined at an angle of
30° to vertical, above a fume generator, simulating a welding posture where the
welder would be pointing down to the work piece. Sodium chloride fume was
generated by burning off a salt stick, containing 0.14% sodium chloride, at a
temperature of approximately 1200°C, using an oxy-propane burner. Particle size
distribution of this aerosol was measured using a low-pressure impactor and was shown to have a mass median aerodynamic diameter of about 0.32 \( \mu \text{m} \) \((\sigma_g \approx 1.5)\). This compares well with ‘pure’ welding fume generated by metal–inert-gas welding (MIG) \((\sim 0.27 \ \mu \text{m})\) and MMA \((\sim 0.5 \ \mu \text{m})\) (Bradley and Chung, 1994). The plume of salt fume was visually similar to welding fume, the burner producing a highly concentrated, thermally driven plume of particles that travelled upwards towards the mannequin’s breathing zone. Figure 4 shows the experimental arrangement.

Typically, each experiment lasted about 5 min. The relative aspiration efficiencies of the samplers are derived from the ratios of concentrations measured:

\[
E_s = \frac{m_s}{m_m} \times \frac{F_m}{F_s}. \tag{2}
\]

where \(F_m\) is the mannequin flow rate, \(m_m\) is the mass collected on the mannequin filter, and \(F_s\) and \(m_s\) are the sampler flow rate and mass collected on the test sampler, respectively.

In addition, the penetration of the salt aerosol through the porous foam in the new sampler was measured:

\[
P = \frac{m_{\text{mass collected on filter}}}{m_{\text{total mass collected by sampler}}}. \tag{3}
\]

Field trials

Eight factories were visited in a series of field trials. These were major heavy industries using different types of welding processes; the range of activities in these site is summarized in Table 1. The sampling strategy was tested in trial runs in the laboratory before visits took place. Six or eight welders were chosen from each site to cover the range of welding situations. We also observed the work practice and recorded unexpected events. The factory management was asked for copies of their most recent monitoring results so that comparison with their established methods could be made. The other objectives of the field trial were to assess the acceptability of the new sampler to the welders and the ease of use of the new device.

RESULTS AND DISCUSSION

Penetration of welding fume through porous foam plugs

The results of the calm air exposure experiments of the penetration of ‘aged’ welding fume through the porous foam are shown in Fig. 5. It may be seen that penetration falls as fume ageing increases, falling to approximately 55% after 4 min and becoming stable at only about 30%. It is probable that this aged fume has been substantially aggregated and therefore not typical of the fresh fume to which welders (and thus the sampler) would normally be exposed.

The results of the cyclic exposure are shown in Table 2. In this experiment, the age of the welding fume is no longer than 15 s, and yet the fraction of fume penetrating is only about 63%, somewhat lower than expected, although this level of penetration closely matches that measured for the cyclone in the same experiment (59%).
### Table 1. Summary of activities of the factories visited in the field trial

<table>
<thead>
<tr>
<th>Site</th>
<th>Nature of business</th>
<th>Welding and allied processes*</th>
<th>Parent metals**</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Offshore platform manufacturers</td>
<td>MIG, MMA</td>
<td>HCS/CS, MS, SS</td>
<td>Open plan workshop, some close work</td>
</tr>
<tr>
<td>B</td>
<td>Ship building in general</td>
<td>MIG, MMA</td>
<td>CS, MS, SS</td>
<td>Open plan workshop</td>
</tr>
<tr>
<td>C</td>
<td>Metal casting for water and oil industries</td>
<td>MMA, MIG, flame cutting</td>
<td>HCS/CS, MS, SS</td>
<td>Open plan workshop, furnaces and mould shakers</td>
</tr>
<tr>
<td>D</td>
<td>Site engineering</td>
<td>TIG, MIG</td>
<td>CS, Al</td>
<td>Open plan workshop</td>
</tr>
<tr>
<td>E</td>
<td>Offshore platform manufacturers</td>
<td>MIG, MMA, arc gouging</td>
<td>HCS/CS, MS, SS</td>
<td>Open plan workshop, some close work</td>
</tr>
<tr>
<td>F</td>
<td>Defence systems manufacturer</td>
<td>MIG, MMA, TIG</td>
<td>HCS, SS, AS</td>
<td>Open plan workshop, some close work</td>
</tr>
<tr>
<td>G</td>
<td>Ship building</td>
<td>MIG, MMA</td>
<td>HCS, MS, SS, Al</td>
<td>Open plan workshop, some close work</td>
</tr>
<tr>
<td>H</td>
<td>Engineering work for offshore platforms</td>
<td>MIG, MMA</td>
<td>HCS/CS, MS, SS</td>
<td>unstable blank—results void</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Welding and allied processes*</th>
<th>Parent metals**</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIG</td>
<td>Metal inert gas welding</td>
</tr>
<tr>
<td>MMA</td>
<td>Manual metal arc welding</td>
</tr>
<tr>
<td>TIG</td>
<td>Tungsten inert gas welding</td>
</tr>
<tr>
<td></td>
<td>HCS/CS</td>
</tr>
<tr>
<td></td>
<td>High carbon or carbon steel</td>
</tr>
<tr>
<td></td>
<td>MS</td>
</tr>
<tr>
<td></td>
<td>Mild steel</td>
</tr>
<tr>
<td></td>
<td>SS</td>
</tr>
<tr>
<td></td>
<td>Stainless steel</td>
</tr>
<tr>
<td></td>
<td>AS</td>
</tr>
<tr>
<td></td>
<td>Armour steel</td>
</tr>
<tr>
<td></td>
<td>Al</td>
</tr>
<tr>
<td></td>
<td>Aluminium</td>
</tr>
</tbody>
</table>

The results of the steady exposures are shown in Fig. 6. In this experiment, a range of loadings between 0.2 and 5 mg has been achieved. Over this range, there is no evidence of penetration through the foam plugs reducing as the mass loading increases. The mean penetration is 0.80, higher than that measured in the cyclic exposure (~0.63) experiment. The agreement with the cyclone results is reasonable ($r^2 = 0.925$). The inference is that, since the penetration through the foam plug is very similar to that through the cyclone, it is unlikely that diffusion and interception play an important role in deposition in the foam plug.

From these results, it can be concluded that the penetration of welding fume through the size selecting foams is similar to the personal cyclones whose penetration curve is well characterized (Maynard and Kenny, 1995), and follows the respirable curve reasonably well. It also follows that, since a significant portion of the fume failed to pass through the respirable selectors, then by definition, this portion is non-respirable. It is probable that this non-respirable portion is composed mainly of welding fume chains and clumps, which have been described elsewhere. These aggregates account for approximately 20% of the mass collected using an inhalable sampler for 'freshly' generated fume, as would be expected during welding. If, however, the fume is allowed to age within a confined space, for example, welding in a closed workshop or inside a container, there is evidence that more aggregates are formed. In these circumstances, the penetration of welding fume drops down to only 30% for a fume that has aged for 30 min.

Long chain aggregates are found when welding fume samples are examined under a scanning electron microscope (SEM). Figure 7 shows an SEM micrograph.
of one of the test foam plugs in the cyclic exposure experiment, through which about 1 mg of fume had passed. It shows an extremely long filament (~400 \mu m) captured on the top of the foam. A number of these entities of various lengths were observed. For these structures to be intercepted intact, they must have been present in the airborne state before collection.

The aerodynamic diameter of these filaments is likely to be very small (the individual particles are as small as 0.2 \mu m) and would pass through any respirable selector (such as a cyclone) where inertial effects are dominant. The agreement of the foam and cyclone results, however, provided contradictory evidence. The consequences of these deposits for the size selection (of compact particles) by the foam will require further consideration.

Large numbers of measurements of aerosol penetration through the foam were obtained in the ventilated chamber experiment where a salt aerosol was used. An averaged penetration of 74% (standard deviation = ±12%) was measured, mid-range between the cyclic exposure (63%) and the freshly generated welding fume experiment (80%).

Table 2. Results of the cyclic exposure experiment

<table>
<thead>
<tr>
<th>Foam plug number</th>
<th>Penetration ($P_{foam}$)</th>
<th>Adjacent cyclone penetration ($P_{cyclone}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>0.54</td>
<td>0.56</td>
</tr>
<tr>
<td>7.2</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>8.1</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>8.2</td>
<td>0.63</td>
<td>0.57</td>
</tr>
<tr>
<td>Mean</td>
<td>0.63</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Fig. 5. Penetration of aged welding fume through the foam in calm air.
In a separate study, a mean penetration efficiency of 72% (±8%) was obtained for pure welding fume produced by both Metal Active Gas and Flux-Cored Arc Welding processes of stainless steel and mild steel over a range of exposure times in well-controlled laboratory conditions (Chung and Carter, 1996).

SEM observation of the salt fume samples also showed considerable agglomeration of the aerosol, collected on nucleopore® filters behind the face shield. The agreement between the two sets of experiments gives rise to the following conclusions:

1. welding fume is not entirely respirable as chains and agglomerates, with aerodynamic diameters outside the respirable range, can be formed;
2. the consistency of penetration provides a convenient factor for 'inhaled' welding fume to be calculated. Taking the arithmetic average of the three sets of data (0.72), the 'inhaled' welding fume only (that is excluding contributions from aerosols from other sources) is obtained by multiplying the measured concentration on the backing filter by 1.38.

Aspiration efficiency of the new sampler

Two sets of experiments were carried out to measure the aspiration efficiencies of the samplers. In the wind tunnel experiment, the samplers were mounted on a rotating mannequin and were exposed to a constant wind velocity of 1 m s⁻¹. The mannequin was rotated at 2 rev min⁻¹ and reciprocated in the opposite direction. The aspiration efficiencies of the samplers were measured with the welding face shield in either the up or down configuration. The visor down configuration is the
normal position of the face shield when the arc is struck. In the up configuration, the visor is lifted to a horizontal position, exposing the face. The results of these, averaged over two or three repeated experiments, are shown in Fig. 8.

The solid line represents the inhalable convention adopted by CEN (1993) and ISO (1995). The form of the inhalable convention is

$$E_i = 0.5 \times (1 + \exp(-0.06D)),\quad (4)$$

where $D$ is the particle aerodynamic diameter ($\mu m$).

The aspiration efficiency of the mannequin wearing a welding face shield, with the visor up and down, was also measured to compare with the inhalable convention. In both configurations, the mannequin undersamples with respect to the convention by some 30%. This was unexpected in the visor up configuration, although the mannequin head (wearing the face shield) is a very large bluff body, compared to the mannequin used in previous inhalability studies (Ogden and Birkett, 1977). In the visor down configuration, it covers the face (and mouth), which reduces immediate exposure to the dusty environment and results in substantial undersampling with respect to the inhalable convention.

The new sampler also undersamples compared with the inhalable convention in both visor up and down configurations, and more severely in the visor down situation. However, it follows the efficiency of the mannequin very well, except for the largest particle size studied. There are large variations in efficiency for the BS sampler which follows neither the inhalable convention nor the mannequin efficiency.

In the second set of experiments, a thermally generated sodium chloride fume was used to simulate a welding environment inside a ventilated chamber. The
relative aspiration efficiencies of the samplers were measured; the results are shown in Table 3. In these well-controlled experiments, both the BS and test samplers oversampled the mannequin similarly in both the visor up and down configurations. This is consistent with results obtained elsewhere with small particles (Ogden and Birkett, 1977).

Field trials

The result of one of the field trials is shown in Table 4 and provides a useful illustration of some of the consequences associated with the use of the new sampler. The site was a typical heavy engineering fabrication workshop where different welding processes and finishing tasks were taking place. Welders in this site were divided into gangs of three or four per set-up, so any one of the gang would be either welding, grinding, brushing or setting up work, a classical example of welding shop activity. In this example, welders B1–B4 were one of these gangs working round a 3-m-diameter mild steel structure.

The row labelled 'Weight Inhalable dust' is the total amount of aerosol collected by the sampler, and 'Weight Welding Fume' is the amount of material that penetrated the foam and was collected on the filter. This portion is assumed to be fume from the welds, that is 'pure welding fume'. The last row 'Corrected Welding

<table>
<thead>
<tr>
<th>Sample number</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>B6</th>
<th>B7</th>
<th>B8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling time (min)</td>
<td>150</td>
<td>169</td>
<td>164</td>
<td>162</td>
<td>23</td>
<td>125</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Total volume (l)</td>
<td>295</td>
<td>331</td>
<td>323</td>
<td>320</td>
<td>45</td>
<td>241</td>
<td>239</td>
<td>238</td>
</tr>
<tr>
<td>Weight inhalable dust* (mg)</td>
<td>1.62</td>
<td>1.52</td>
<td>1.83</td>
<td>2.04</td>
<td>0.10</td>
<td>0.97</td>
<td>2.98</td>
<td>4.75</td>
</tr>
<tr>
<td>Weight welding fume† (mg)</td>
<td>0.28</td>
<td>0.83</td>
<td>0.70</td>
<td>0.93</td>
<td>0.19</td>
<td>0.35</td>
<td>0.30</td>
<td>0.58</td>
</tr>
<tr>
<td>Welding fume concentration (mg m⁻³)</td>
<td>5.50</td>
<td>4.59</td>
<td>5.66</td>
<td>6.38</td>
<td>2.20</td>
<td>4.03</td>
<td>12.48</td>
<td>20.00</td>
</tr>
<tr>
<td>Corrected welding fume concentration‡ (mg m⁻³)</td>
<td>0.95</td>
<td>2.15</td>
<td>2.17</td>
<td>2.91</td>
<td>4.18</td>
<td>2.29</td>
<td>1.26</td>
<td>2.44</td>
</tr>
<tr>
<td>Corrected welding fume concentration (mg m⁻³)</td>
<td>1.31</td>
<td>3.46</td>
<td>2.99</td>
<td>4.02</td>
<td>5.77</td>
<td>3.16</td>
<td>1.74</td>
<td>3.37</td>
</tr>
</tbody>
</table>

*Total amount of dust particles entered the sampler.
†The amount of particles deposited on the backing filter of the sampler, considered to be mostly 'pure' welding fume.
‡'True' welding fume concentration, obtained by multiplying by 1.38, correcting for the penetration efficiency (72%) of the porous foam.
Fume concentration' is the corrected welding fume concentration obtained by multiplying row 'Welding Fume concentration' by 1.38, assuming (based on the laboratory studies) that the penetration efficiency of welding fume through the foam is 72%.

If the total concentrations 'Inhalable dust concentration' were taken for the exposure of 'welding fume' (as would be the case using the conventional BS method) then three of the four welders were exposed to concentrations above the Occupation Exposure Standard (OES) of 5 mg m\(^{-3}\). However, for all of these, the corrected welding fume concentration was lower and was below the OES. Examination of the activity log of the welders reveals that B1, B3 and B4 spent a large part of their time in finishing tasks, such as chipping and grinding; visual inspection found large debris on the front surface of the foams in these samples, which is consistent with these differences. Whereas B2 spent little time in finishing, although his total exposure was the lowest, his welding fume exposure was high.

B4 was also sampled in the afternoon under sample B6. The total amount of dust collected on B6 was lower than in the morning (B4), but the welding fume portion was similar, indicating that he did more welding and less finishing tasks in this period. This was confirmed by our observations.

Samples B7 and B8 are the most interesting. B8 included a period of about 15 min of arc gouging at the corner of a large flat structure. For the remainder of the sampling period, the welder was carrying out MMA welding. A huge cloud of dust was generated when arc gouging started. The concentration of total dust collected by the sampler, under the welder's large helmet with a hood attachment, was four times the OES. Yet the portion penetrating the foam, although high, was well within the OES.

A similar result was obtained for B7, who was welding some 4 m away downwind of B8. The welder actually stopped welding during arc gouging because the dust cloud was so dense that he could not set up his work. B7 had his face shield off (the sampler remained on the headband) while watching B8. On this sample, the amount of fume was relatively low, reflecting on the time that he actually spent on welding alone.

These results illustrate the usefulness of the size separator very well. The relative amount of dust sampled on to the foam and that which penetrates through matches the observation of the welders' activities—welders who work on processes that generate larger particles, such as grinding, have more dust collected on the foams.

The results were compared with the employer's previous monitoring data, measured using the current BS method (collected either behind the face shields or at the lapels). Fair agreement was obtained between these and the inhalable dust concentrations measured by the new sampler. A transition from the current BS method to the new method would therefore not cause any major problem. However, as the new sampler has the capability of separating welding fume from other sources of dust, more meaningful interpretation of the results can be obtained. The implications of the findings are:

1. The OES for total inhalable nuisance dust is 10 mg m\(^{-3}\), but there is a 5 mg m\(^{-3}\) 8-h TWA for welding fume. In situations encountered in our field trial, a number of samples are above the latter (using the BS method), but
well within the OES for nuisance dust. Under the Control of Substances Hazardous to Health Regulations (HSE, 1994), the employers will be required to control this exposure below 5 mg m\(^{-3}\), perhaps unnecessarily and expensively;

(2) In order to simplify measurement, EH54 (HSE, 1990) recommends the use of consumable manufacturers' fume analysis data for the calculation of concentrations of all constituents without detailed chemical analysis. From these data and using the published list of occupational exposure limits (HSE, 1995) it is possible to calculate the total concentration of welding fume, in mg m\(^{-3}\), at which any individual substance in the welding fume will reach its occupational exposure limit, using the formula:

\[
\frac{100A}{C} \text{mg m}^{-3},
\]

where \(A\) is the occupational exposure limit of the constituent substance, and \(C\) is the w/w concentration of \(A\) obtained from fume analysis information. For example, most MMA stainless steel consumables contain about 5% total chromium in the fume analysis from which hexavalent chromium (Cr VI) has a maximum exposure limit (MEL) of 0.05 mg m\(^{-3}\) (HSE, 1995). The total fume concentration must, therefore, not exceed 1 mg m\(^{-3}\) [assuming 100% conversion to Cr VI, although a figure of between 60 and 90% was suggested by Jenkins et al. (1981)] to ensure that the exposure of Cr VI is adequately controlled. It is evident from the results that the 'true' welding fume concentrations will give better pictures of the real welding fume exposures. Using a sampler that does not discriminate between total dust and welding fume will penalize industry by introducing unnecessary additional fume control measures.

As mentioned earlier, the welders perform a wide range of welding related activities, such as grinding, chipping and brushing. In doing so, they remove their welding face shields and put on grinding face shields frequently, making the attachment of conventional samplers impracticable. The new sampler is held by a C-clip on to a sportsman's elastic headband that fits comfortably under the cap, underneath the face shield. Because of this, the sampler can be used, even if a hand-held shield is used. We asked the welders' opinions of wearing the new sampler, and compared it to their experience of the BS method. The majority found the new sampler easy to put on and off, and it did not obstruct their vision or their normal work activity. The sampler would not be suitable for welders using the air-fed type face shield because of its size, however.

Managers at these sites showed particular interest in the sampler because it measures fume behind the face shield rather than at the lapel. BS6691 recommends that its sampler should be mounted in the former fashion, but the design is so awkward that most hygienists choose to attach the sampler at the lapel. The obvious disadvantage of such an arrangement is that the protection afforded by the face shield is ignored. Accordingly, the proposed European Standard (CEN, 1996) has made it clear that welding fume should be sampled 'in the breathing zone' and that 'breathing zone' in the industry extends '...only behind the welder's face shield'. The new sampler fulfils this requirement.
REFERENCES


HSE (1990) Guidance Note EH54—Assessment of Exposure to Fume from Welding and Allied Processes. Health and Safety Executive, HMSO.


