Occupational Exposure to Metalworking Fluid Mist and Sump Fluid Contaminants

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This paper summarizes the analytical and occupational hygiene findings from a recent survey of occupational exposure to metalworking fluids (MWFs) in the engineering industry. The aim of the survey was to link MWF mist exposure measurements with particular engineering processes and controls, and utilize the data obtained to develop exposure standards. At the same time the opportunity was taken to assess fluid management and control, including bacterial and fines contamination in the machine sumps. In general, occupational exposure to mineral oil MWF mist was controlled to <3 mg/m³ (8 h time-weighted average) and to <1 mg/m³ for water-mix MWF mist (in terms of the concentrate). These exposure values do not necessarily represent best practice, but are believed to be achievable and representative of industry as a whole. Gravimetric analysis of the total inhalable particulate was found to be a good predictor of mineral oil MWF mist but not for water-mix MWF mist. Grinding and drilling operations produced higher exposures than turning and milling for water-mix fluids. There were insufficient data to compare machining operations for mineral oil MWFs. On the whole, fluid management was found to be poor, with most sites failing to meet industry good practice or Health & Safety Executive (HSE) standards. Some of the operating procedures utilized were deficient or unsatisfactory. Poor standards of fluid management were found at all sizes of company. High levels of bacteria, endotoxin and fines were found in sumps, and control of other factors, such as water-mix fluid concentration, was often poor. Mineral oils had higher levels of fines than water-mix fluids (medians of 395 and 18 mg/l, respectively), and grinding produced high levels of fines in both types of MWF. Many water-mix sumps contained bacterial levels of >1 × 10⁶ CFU/ml, and endotoxin levels of >100000 EU/ml were not uncommon. The median values were 109000 CFU/ml and 8039 EU/ml, respectively. Mists could potentially contain extensive contamination from bacteria and endotoxin. Analysis of the data suggests that sumps operating under typical conditions for machining (a temperature of 20°C, a pH of 9 and a fluid strength below 10%), also appear to provide optimum conditions for the proliferation of bacteria. Low levels of benzo[*a*]pyrene (median 0.03 µg/g) were found in the mineral oils, and low levels of *N*-nitrosodiethanolamine (median 0.4 µg/ml) were found in the water-mix MWFs. The results of this work will contribute to guidance from the HSE, setting out accepted industry good practice, including guide values for MWF mist and sump fluid contaminants, with significant emphasis on sump fluid management (maintenance and monitoring), as well as control issues.

Keywords: oil mist; bacteria; cutting fluid; endotoxin; nitrosamines; polycyclic aromatic hydrocarbons

INTRODUCTION

Metalworking fluid (MWF) is a generic term covering a wide variety of fluids that are used as lubricants and coolants during the machining or treatment of metal components. They can be divided into neat mineral oils and water-mix fluids. The latter can be further subdivided into conventional oil in water emulsions (>60% mineral oil in the concentrate), semi-synthetic fluids (emulsions whose concentrate contains 5–60%

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oil) and synthetic fluids (true fluids or dispersions with <5% oil in the concentrate). Generally, they are all relatively complex mixtures, containing a package of additives to improve performance and stability. Each component may contribute to health effects, and hence the nature and severity of any health effects depends to some extent on the specific composition of the MWF. The main functions of MWFs are to cool the workpiece and tool and provide lubrication. MWFs also produce and preserve a good surface finish and remove swarf. Generally water-mix fluids are better coolants and neat oils are considered to be better lubricants. In recent times, due to economic, technical and health reasons, there has been a steady trend towards the use of water-mix fluids. The British Lubricants Federation estimate that current UK annual usage is ~20000 tonnes of neat oil and ~12000 tonnes of water-mix fluid concentrate (which on dilution equates to something like 240000 tonnes in the workplace). During their lifetime, MWF composition is likely to change, with increasing levels of bacteria (water mix fluids), metal fines and tramp oil (adulterant hydraulic and lubricating oil from the machine), and occasional additions of biocide. These changes may increase the risk of adverse health effects.

Exposure to MWFs can occur by contact with the skin (e.g. via contaminated surfaces) or by inhalation of an aerosol of MWF droplets. Such mists can form when a MWF has been subject to high shear forces or excess heat during use. The characteristics of the aerosol depend upon the MWF, the machining process taking place and any engineering controls, but mists can be relatively stable and long lasting. At typical concentrations, mist clouds can be difficult to see under normal diffuse lighting; however, back-lighting from a beamed intense light source, such as that from the sun or a dust lamp, can reveal the presence of the mist (Figs 1 and 2).

MWFs present a number of occupational health concerns. In terms of the number of people affected, dermatitis is by far the most important work-related health effect. In the period 1998–2000, EPIDERM (a surveillance scheme for occupational skin disease) and OPRA (the Occupational Physicians Reporting Activity) have reported an estimated annual average of 168 cases of contact dermatitis related to MWFs, and the true figure is almost certainly higher. Water-mix MWFs cause far more dermatitis than neat mineral oils. Irritant contact dermatitis is said to be the main type caused. However, there is evidence that primary or secondary allergic dermatitis may be under-diagnosed and far more common than is realized (Rycroft, 1991). MWF can weaken the skin's natural defences and a number of the fluid components can cause direct irritation to the skin. Contact with oil, emulsifiers and surfactants can degrease the skin, and water in aqueous fluids will also soften it. Contact with the workpiece, tool, swarf or fines can lead to

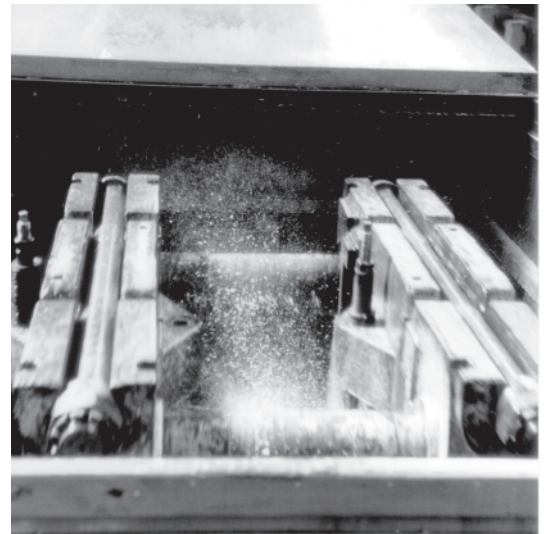**Fig. 1.** Emission of MWF mist.

Fig. 2. MWF mist made visible by direct sunlight.

micro-wounds of the skin. Alkaline pH (dependent on water-mix fluid strength) will destroy the skin's acid protective layer. The skin is then more vulnerable to infections from micro-organisms (bacteria, fungi and yeast), and attack by allergens and toxic substances such as endotoxin, metals (e.g. nickel, chromium and cobalt), and some fluid components or additives (e.g. biocide, corrosion inhibitors, coupling agents and emulsifiers). The low surface tensions found in water-mix fluids could intensify these effects. Inadequate washing and skincare facilities, lack of appropriate training and a lack of health surveillance will exacerbate the situation. Skin contact with the MWF should be minimized by good machine design and appropriate personal protective equipment (PPE). The relative magnitude of these

individual and combined effects and their exact mechanism is not fully understood and the Health & Safety Executive (HSE) plans to investigate them further in future work.

A range of respiratory effects have been associated with exposure to MWF mist such as irritation of the respiratory tract and impairment of lung function, but also including bronchitis and asthma (Kennedy et al., 1989; Greaves et al., 1997). In recent years (1998–2000) the Survey of Work-related and Occupational Respiratory Disease (SWORD) and OPRA have reported an estimated annual average of 11 new cases of occupational asthma related to exposure to cutting oils. In some cases it has been possible to identify the causative agents but in most studies this has not been possible. Possible causes of asthma include specific components found in some fluids, such as pine oil based re-odorants (Hendy et al., 1985; Robertson and Weir, 1988), ethanolamine (Vallieres et al., 1977) and methyl esters of fatty acids (Spallek, 1989). There is also evidence of immunological response to gram-negative bacteria, particularly *Pseudomonas* (Mattsby-Baltzer et al., 1989; Travers-Glass and Crook, 1994), and also of toxicological response to the endotoxin derived from them (Thorne and DeKosker, 1996). Inhalation of endotoxin can result in short-term 'flu-like' symptoms and exposure may exacerbate symptoms in those with pre-existing asthma. There are other possible causative agents, including other bacteria such as *Mycobacterium* spp. Occasionally mineral oil mists, especially low-viscosity oils in the presence of high concentrations of mineral oil or hydrocarbon vapour, have been associated with a range of potential respiratory effects including pneumonitis (Proudfit et al., 1950), lipoid pneumonia (Cullen et al., 1981), fibrosis (Skyberg et al., 1986, 1992) and 'increased linear striations' with no discernible symptoms (Jones, 1961). The effects appear to require prolonged exposure and are fairly rare.

In Great Britain, the occupational exposure standards (OESs) for mineral oil mists were 5 mg/m^3 for an 8 h time-weighted average (TWA) and 10 mg/m^3 for short-term exposure (15 min reference period). These standards were derived from American Conference of Governmental Industrial Hygienists Threshold Limit Values and were applicable mainly to relatively simple straight-chain oils used as cool-ants and lubricants in metalworking processes. The values were set primarily to minimize complaints of irritation from workers and the limit strictly applies only to neat, highly refined oils, i.e. those that do not present a carcinogenic hazard. However, modern MWFs are more complex mixtures containing various additives and there is now much greater use of aqueous systems, some of which contain no mineral oil. The Health and Safety Commission's Advisory Committee on Toxic Substances (ACTS) concluded

that the OESs should no longer apply to mineral oil MWFs, given the potential for substantial variability in their composition and for contamination during industrial use. The Committee also felt that it was not possible to derive revised OES values for mineral oil MWFs due to the absence of evidence for a level of inhalation exposure that would not cause any health effects, and that would be applicable to all possible compositions of such fluids. (ACTS considered the scope of the existing OESs and recommended that they should remain in place for other—non-metal-working—applications of mineral oil.) The Committee further concluded that no occupational exposure limit could be derived for water-mix MWF, for the same reasons. The HSE proposed to the Health and Safety Commission (HSC) that it consult on a revision to the scope of the mineral oil mist OESs, in particular to remove MWFs. Subject to final approval by ACTS and the HSC, MWFs will, from 2003, be removed from the scope of the mineral oil mist OES. This change will be publicized by the HSE in 2003.

The Chemicals (Hazard Information and Packaging for Supply) Regulations (CHIP2) 1994 (as amended) Approved Supply List contains European Union-agreed classifications for a number of petroleum substances. In many cases, classification for carcino-genicity is based on the presence of marker substances, e.g. polycyclic aromatic hydrocarbons (PAHs). The mineral oils used in the engineering industry for MWFs are highly refined and thus not classified for carcinogenicity. Classification for other effects (e.g. flammability and irritancy) may be required from the supplier.

When exposure to MWFs was considered in the early 1990s by the Working Group on the Assessment of Toxic Chemicals (WATCH), it became apparent that there was a lack of good-quality mineral oil mist exposure data and no water-mix mist exposure data. A survey was consequently commissioned by the HSE to gather exposure data and control information. This report contains both a summary of the sampling and analytical results from the survey and details on other issues such as mist control and fluid manage-ment. The aim of the survey was to link exposure measurements with particular engineering processes and controls, and utilize the data obtained to develop exposure standards for mists from both mineral oil and water-mix MWF. Although the main objective of the survey was concerned with MWF mist, the oppor-tunity was taken to assess fluid management and control, including bacterial and fines contamination in the machine sumps (Table 1).

SAMPLING AND ANALYSIS

Twenty-four sites were initially selected for inclu-sion in the survey to provide a cross-section of indus-tries and processes. The sites were selected to include

Table 1. Source and health concerns of metalworking fluid contaminants

Contaminant	Source	Health concern
Airborne mist (neat oils and water mix fluids)	Produced by atomization or evaporation–condensation of the fluid when in use	Eye, nose and throat complaints, irritation of the respiratory tract, impairment of lung function, bronchitis and asthma, and also in certain infrequent circumstances pneumonitis, lipoid pneumonia and fibrosis
Fines (neat oils and water mix fluids)	Formed from the work piece during the machining process	Skin contact is considered to be a contributory factor to dermatitis. High levels may lead to unacceptable damage to the skin
Total viable aerobic bacteria (usually *Pseudomonas*); sulphate-reducing bacteria; and fungi (water mix fluids)	Bacteria can heavily colonize poorly managed MWF sumps following initial contamination via dust and debris, or from the water used to make up the fluid. Exacerbated by lengthy use of recirculated fluid and inadequate cleaning of sumps before refilling	The allergenic challenge from inhalation of MWF mists contaminated with microbes is of concern, and there may be a contribution to MWF dermatitic potential
Endotoxin (water mix fluids)	Lipopolysaccharide material released from the cell walls of Gram-negative bacteria (see above)	Inhalation can result in short term 'flu-like' symptoms, and skin contact may have an impact on the MWF dermatitic potential
Nitrosamines (principally *N*-nitrosodiethanolamine) (water-mix fluids)	Reaction product of nitrite and secondary amines (e.g. diethanolamine) within the fluid	Carcinogenic. Once a major problem in water mix fluids, but latterly, with the reduction in use of the nitrite precursor in formulations, their prevalence has decreased
Polycyclic aromatic hydrocarbons (EPA 16 with 4–6 rings, including benzo[*a*]pyrene) (neat oils)	Present in mildly refined base oils and as a product of thermal degradation at very high temperatures.	Many PAHs are carcinogens. Once a major concern in neat oils, since a change to highly refined base oils in reputable products the risk of exposure has decreased. The rate of formation during machining is considered to be low (Evans *et al.*, 1989)

engineering companies that would be representative of the UK engineering industry as a whole. No attempt was made to identify good or bad sites or to concentrate on either small to medium sized enterprises or larger companies. The sites selected avoided concentration on particular fluids, processes or level of automation, but consideration was given to ensuring sufficient data for both mineral oil and water-mix MWFs. There was a greater difficulty in identifying mineral oil users because of the lower level of use and sampling method restrictions; the processes chosen were restricted to those using oils with viscosities greater than 18 cSt at 40°C. Lighter mineral oils have been found to be susceptible to evaporative loss from the filter during sampling (Simpson *et al.*, 2000). The results from five surveys carried out as part of HSE's routine inspection activities and two surveys from a previous pilot study were also included in the data set, making 31 sites in total.

MWF mist samples

The personal exposure of workers to MWF mist was measured by collection of filter samples with multi-orifice samplers and gravimetric analysis for total inhalable particulates (TIP) as described in HSE method MDHS 14 (HSE, 2000a). Unpumped control samples were exposed in parallel with the personal samples to try and determine any contribution from

splashing of the filters. The filters were further analysed for MWFs: mineral oil mist samples were reweighed after cyclohexane solvent extraction as given in HSE method MDHS 84 (HSE, 1997), and water-mix MWF samples were analysed by the elemental marker method described in MDHS 95 (HSE, 1999). The elemental marker method involves measurement of an element (usually boron or potassium) in both the sample and the machine sump fluid, using either inductively coupled plasma–atomic emission spectrometry (ICP-AES) or flame atomic absorption spectrometry (FAAS). If the strength of the MWF concentrate in the sump fluid (% m/v) is known, then the airborne MWF concentrate can be calculated. Sump fluid strength was measured by refractometry or, when the condition of the emulsion made this difficult, by the acid split method (both described in MDHS 95). The aqueous water-mix mist concentration was further used to calculate a theoretical airborne endotoxin concentration using data from measurements on the sump fluid.

Machine sump samples

Bulk samples of MWFs were taken from each oil sump, sampled at the point of application at the work piece or cutting tool. Some sites used central sumps servicing several machines, in which case a single sample was taken. The temperature and pH of the

water-mix MWFs were measured on site. Both mineral oil and water-mix MWFs were analysed for fines and the mineral oils were also analysed for PAHs. The water-mix MWFs were analysed for bacteriological content and endotoxins, and those containing diethanol-amine were analysed for nitrosamines. The bulk water-mix MWF samples were also used to calibrate analysis of the mist samples.

The fines suspended in the fluids were determined gravimetrically. Aliquots (50 ml) of the thoroughly mixed water-mix MWF were centrifuged at 1500 r.p.m. for 20 min. The supernatant was carefully removed and the sediment dispersed with water and filtered through a pre-weighed cellulose nitrate filter under suction. After alternately washing with three portions each of propan-2-ol and water, the dried filter was reweighed to determine the fines content. Mineral oils were analysed by a similar method, but 25 ml aliquots were first dispersed in 25 ml petroleum spirit and petroleum spirit was also used to transfer and wash the sample.

Bacteriological contamination of the water-mix sump fluids was measured by plate counts and dip slide analyses. Dip slides comprise a plastic paddle coated on each side with agar media and housed in a sterile plastic bottle. The paddle is briefly dipped into a liquid sample and incubated in the bottle to yield growth from bacteria adhering to the agar. Dip slides provide a simple, low-cost, commercially available test to estimate the microbiological content of aqueous samples without the need for laboratory facilities. However, dip slides have been found in the past to underestimate the bacterial content of MWFs, often by over a factor of 10 compared to plate counts (HSE, 1994). It was assumed that the mineral oils would not support bacterial growth because of a lack of water, but a limited number of samples were analysed to verify this. Likewise, it was not anticipated that conditions in MWF sumps would favour fungal growth, but a limited number of samples were analysed to verify this. Where possible, the tests were done on the day following receipt, otherwise the samples were stored in a refrigerator prior to analysis.

Plate count analyses were performed following a procedure previously used for MWFs (Travers-Glass and Crook, 1994). A range of agar media and incubation temperatures were used to maximize the yield of the culturable micro-organisms present. Bacteria were grown at 37 and 25°C on nutrient agar plates and at 30°C on Fastidious Anaerobe Agar (FAA). Fungi were grown at 25°C on malt agar. Bacterial concentrations from the highest yielding agar media (expressed as colony-forming units per millilitre of original liquid, CFU/ml) were quoted.

The dip slides used were a combination of two agar media, Plate Count Agar and Violet Red Bile Glucose Agar, one on each side of the plastic paddle (Oxoid, Basingstoke, UK). They were dipped in undiluted

sump samples, removed and left to incubate at 25°C in a sterile bottle with the cap loosened. The number of colonies were estimated by visual comparison with a series of charts and expressed as CFU/ml, with an upper limit on the charts of 10^6/ml. Results from the highest yielding agar media are quoted.

Sump fluids were also analysed for sulphate-reducing bacteria (SRB) which can thrive in conditions of oxygen depletion such as those that can occur in MWF sumps, and are responsible for releasing hydrogen sulphide gas. Their presence was tested for by using undiluted samples to inoculate agar media based, commercially available test kits (SigTest; ECHA, Cardiff, UK) which were incubated for 6 days at 30°C.

Measurement of the endotoxins involved centrifugation of the MWFs at 1000 g for 10 min, serial dilution with water and analysis using a commercially available test system based on the *Limulus* amoebocyte lysate assay (Kinetic-QCL automated system; Bio-Whittaker Inc., Walkersville, MD), as used in previous studies on the endotoxin content of MWFs by the authors and by others (Thorne and DeKosker, 1996).

The PAH content of the mineral oils was measured using a method based on one previously used for PAHs in mineral quench oils (Simpson and Ellwood, 1995) involving solvent extraction using hexane and dimethyl sulphoxide followed by analysis using gas chromatography–mass spectrometry (GC-MS). Analysis was restricted to the following compounds (four to six ring compounds in the US EPA list of 16 priority pollutant PAHs) due to low recovery of lighter PAHs: fluoranthene, pyrene, benzo[*a*]anthracene, chrysene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, benzo[*a*]pyrene, indeno[1,2,3-*cd*]pyrene, dibenzo[*a,h*]anthracene and benzo[*g,h,i*]perylene. These values were summed to produce a 'total PAH' result.

Water-mix MWFs which contained diethanolamine were analysed for the presence of the carcinogen *N*-nitrosodiethanolamine (NDELA), and some other fluids which were not stated as containing diethanol-amine were also included as controls. The samples were extracted into ethyl acetate and derivatized using bis-(trimethylsilyl)-trifluoroacetamide to form the trimethylsilyl ester. This was then quantified by gas chromatography using a thermal energy analyser.

Survey on processes, controls and management

A considerable amount of occupational hygiene information was collected during each visit. This included not only the details of the individuals' work (MWF in use, machining process, metal worked, etc.), but also the companies' policy on management of the MWFs, control measures present (engineering controls, personal protective equipment, welfare,

Table 2. Summary statistics for 8 h time-weighted average air sample results

Analyte	Number	Minimum	Maximum	Median	Mean	Geometric mean	Geometric standard deviation
Mineral oil TIP (mg/m^3)	45	0.06	4.38	0.55	1.11	0.61	3.26
Mineral oil mist (mg/m^3)	40	0.03	3.74	0.78	1.23	0.67	3.76
Water-mix TIP (mg/m^3)	296	<0.04	23.06	0.32	0.67	0.33	3.05
Water-mix MWF concentrate (mg/m^3)	298	<0.01	13.2	0.12	0.35	0.13	3.9
Airborne endotoxin (EU/m^3)	141	0.02	28 794	97.52	683.1	50.41	15.99

etc.), observations on the day of the survey and any reported health problems.

RESULTS

Summary statistical results for the air sample analyses are presented in Table 2, sump sample analyses in Table 3 and percentiles in Table 4. Values less than the limit of detection (LOD) for an analysis (three times the standard deviation of the blanks) were assigned a value equal to half the LOD for calculating the summary statistics. When calculating the theoretical airborne endotoxin concentration, if the sump endotoxin concentration was less than the LOD, then the airborne concentration was deemed to be less than the LOD, and a value of half the LOD was used for the summary statistics. If the MWF concentration was less than the LOD, then the value was not used. Sump endotoxin concentrations could reach very large values and consequently any airborne value calculated using a mist concentration less than the LOD could still be quite high, possibly dwarfing figures calculated from values where both sump endotoxin and MWF mist concentrations were accurately measured and introducing an unacceptable bias into the results.

Any filter sample which was accompanied by a control filter that showed signs of significant splashing (values greater than the LOD and greater than 10% of the sample filter) was excluded as was any dependent, associated result (i.e. airborne endotoxin).

DISCUSSION

MWF mist

Mineral oil mist was measured at 11 of the 31 sites, producing 40 personal exposure results (Table 2), with a geometric mean of 0.67 mg/m^3, none of which exceeded a 5 mg/m^3 8 h TWA. The TIP and mist concentrations correlated well (Fig. 3). The equation of the regression line is given by: oil mist = 0.0889 + 0.892 TIP, and has a correlation coefficient of 0.957, indicating that TIP could provide a good estimator of exposure to oil mist for these samples. Although this is a relatively small data set, the results indicate that exposure to oil mist can be controlled to significantly

<5 mg/m^3. However, it should be noted that this data applies only to oils with viscosities >18 cSt at 40°C; lower-viscosity oils may behave differently. It seems reasonable to assume that most companies using mineral oil MWFs are controlling exposure to below this limit. A value of 3 mg/m^3, for instance, would fall between the 90th and 95th percentiles (Table 4). An in-house oil mist limit of 2 mg/m^3 used by some companies is approximately equivalent to the 75th percentile.

Water-mix MWF mist was measured at 27 of the 31 sites, producing 298 personal exposure results with a geometric mean of 0.13 mg/m^3 (Table 2). One sample (TIP 23.1 mg/m^3, mist 13.2 mg/m^3) exceeded the TIP 8 h TWA dust limit of 10 mg/m^3, but was a distinct outlier. The results suggest that most exposures are below the in-house limit of 2 mg/m^3 used by some companies, and that the majority (>90%) were controlling exposure to <1 mg/m^3 8 h TWA. A plot of mist (MWF concentrate) versus TIP (Fig. 4) shows a high degree of scatter which, with the exclusion of the outlier mentioned, had a correlation coefficient of 0.598. A number of points appear to correlate on a line with a slope equal to ~1, but other points deviate significantly, most notably those having much higher TIPs than mist concentrations, presumably due to either the inclusion of material other than MWFs in the aerosol (e.g. trampoil), or the loss of volatile components present in the original concentrate (e.g. water or glycol ethers). Further investigation reveals that of 22 wayward points, >1 mg/m^3 and with TIP greater than twice the mist concentration, 16 were from grinding (11 from the same site), five were from turning and the other was from drilling. Based on these findings, it would appear that TIP cannot be used as a predictor of water-mix concentrate mist concentration.

Differences in exposure levels by machining operation were investigated by classifying activities as turning, milling, drilling, sawing and grinding (or multi-operation in some cases). There were insufficient mineral oil mist data to compare operations, but by comparing geometric mean values the water-mix mist data suggest that grinding, drilling and 'multiple operations' produce higher exposures to water-mix mist than turning and milling (Table 5).

Table 3. Summary statistics for sump fluid analyses

Analyte	MWF matrix	No.	Minimum	Maximum	Median	Mean	Standard deviation	Geometric mean	Geometric standard deviation
Sump pH	Water	299	5.4	10.5	8.8	8.7	0.7	8.7	1.08
Sump temperature (°C)	Water	297	10.7	44.1	21.6	21.9	3.8	21.6	1.18
Strength (%)	Water	269	0.3	37.5	4.9	6.07	5.2	4.6	2.1
Fines (mg/l)	Water	294	<4	2200	18	56	165	20	3.49
Fines (mg/l)	Mineral oil	24	80	1230	395	464	291	385	1.9
Total bacteria, plate counts (CFU/ml)	Water	157	<10	195000000	109000	11992300	30926000	17749	565
Total bacteria, dip slides (CFU/ml)	Water	142	<100	1000000	10000	348320	461290	9611	68.2
Endotoxins (EU/ml)	Water	154	<0.05	1870000	8039	87874	245255	3419	60
NDELA (µg/ml)	Water	13	<0.05	1.16	0.4	0.41	0.35	0.23	3.97
PAH (4–6 ring EPA 16) (µg/g)	Mineral oil	19	0.23	4.82	2.62	2.38	1.43	1.74	2.64
BAP (µg/g)	Mineral oil	19	<0.01	0.23	0.03	0.04	0.06	0.02	3.75

Results from 20% of the mineral oil mist samples were rejected due to the detection of splashes on the control filters, while 7% of the water-mix samples were rejected. Grinding produced the highest rate of rejection (14%) and turning the lowest (1%) for water-mix fluids. The sub-sets of the mineral oil mist samples were too small to produce reliable interpretations. It is recommended that control filters are considered when measuring mist from grinding operations to get a full appreciation of the results.

The use of enclosures, local exhaust ventilation (LEV), splash guards and computer control might be expected to have some effect on airborne exposure. However, little can be concluded from the data since the size of the data sets were small, and more importantly, it was not possible to compare different sites and machining processes because no account could be taken of differences in machine design, work process, work load, etc. The true effect of these controls can only be established by comparing exposures on a given machine with the controls both 'on' and 'off'. Table 6 shows the extent of the use of the different control strategies. Most sites utilized several different control techniques; newer machines tended

to be fully enclosed computer numerical controlled (CNC) devices, whereas older machines relied on splash guards.

Once the MWF has been in use for some time it may present new hazards from, for example, bacteria, endotoxins and nitrosamines. Workers exposed to mists arising from such MWFs will also be exposed to these additional hazards. The calculated airborne endotoxin results of up to 28 794 EU/m^3 (Table 2) suggest that workers may be exposed to high levels of endotoxins. At present there are no occupational exposure limits for endotoxin in any country; however, the Dutch Expert Committee on Occupational Standards (DECOS), a committee of the health council of The Netherlands, proposed a health-based occupational exposure limit for airborne endotoxin of 50 EU/m^3 (DECOS, 1998), but this was considered to be not feasible economically, and a limit of 200 EU/m^3 was applied (Douwes *et al.*, 2003). In this survey 35% of calculated airborne endotoxin concentrations were >200 EU/m^3.

These data represent typical exposures from typical machining processes, where control ranged from poor to good; they do not represent exposure to MWFs that could be regarded as best practice. Based on the survey results, mineral oil MWF mist concentrations of 3 mg/m^3, and water-mix MWF mist concentrations of 1 mg/m^3 are likely to be achievable levels; most exposures were well below these values. There were insufficient data to identify benchmark levels (i.e. best practice) for each machining process,

Table 4. Metalworking fluid analyte concentration percentiles

Analyte	90th percentile	95th percentile
Mist measurements		
Mineral oil TIP	2.8 mg/m^3	3.3 mg/m^3
Mineral oil mist	2.8 mg/m^3	3.4 mg/m^3
Water-mix TIP	1.4 mg/m^3	1.9 mg/m^3
Water-mix mist	0.8 mg/m^3	1.6 mg/m^3
Airborne endotoxin	968 EU/m^3	1825 EU/m^3
Sump measurements		
Mineral oil fines	900 mg/l	970 mg/l
Water-mix fines	90 mg/l	270 mg/l
Total bacteria	4.3×10^7 CFU/ml	8.3×10^7 CFU/ml
Sump endotoxin	2.0×10^5 EU/ml	5.1×10^8 EU/ml
NDELA	0.96 µg/ml	1.16 µg/ml
PAH	4.21 µg/g	4.82 µg/g
BAP	0.10 µg/g	0.23 µg/g

Fig. 3. Mineral oil mist versus mineral oil mist TIP (mg/m^3).

Table 5. Water-mix metalworking fluid mist results (mg/m^3) by process

Process	Number	Minimum	Maximum	Median	Mean	Geometric mean	Geometric standard deviation
Turning	75	<0.01	1.82	0.06	0.15	0.07	3.32
Milling	80	<0.01	0.92	0.07	0.13	0.08	2.84
Drilling	28	0.04	0.9	0.14	0.22	0.16	2.29
Grinding	61	<0.02	13.22	0.35	0.73	0.29	3.87
Sawing	5	<0.05	0.61	0.23	0.27	0.18	3.23
Multiple operations	42	<0.01	3.22	0.2	0.71	0.28	4.81

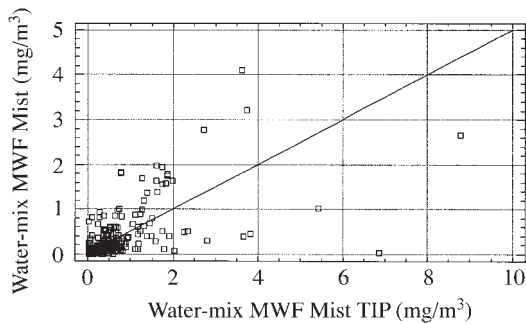**Fig. 4.** Water-mix MWF mist versus water-mix MWF mist TIP (mg/m^3).

Table 6. Mist control methods

Control method	Frequency (no. of companies)
Automation/computer control (CNC)	20
Ventilation	
LEV	12[a]
General: roof fans, remote mist filters, etc.	4
Natural: vents, open shutters, etc.	12
Splash guard (excluding enclosures)	18
No controls	1

[a]Seven reported to be filter mist units.

since the data sets were not large enough for each process and, within each data set, there were many differences in production rates, control techniques and so on. The data represent snapshots of the exposures at each of the sites surveyed. However, since a relatively large number of exposure data were collected from workers using a variety of engineering processes, MWFs and control techniques, it seems reasonable to assume that, in general, exposures to MWFs in engineering workshops across the UK would not differ significantly from the data reported here.

MWF sump contaminants

Despite the small number of mineral oil results, there seems to be a clear tendency for levels of fines found suspended in the fluid to be higher in mineral oils than water-mix fluids as shown by the medians in Table 3 (395 mg/l for mineral oil, 18 mg/l for water-mix fluids). The main cause of this effect is believed to be the differences in the fluid viscosities, with fines remaining suspended longer in more viscous fluids. Fines levels may be a significant contributory factor leading to dermatitis and they can also interfere with the performance of some machining operations (e.g. surface grinding). The degree of contamination will be dependent upon machining operation, the type of metal being machined and the type of fines generated. There is no health-based guidance on acceptable levels of fines, but a 100 p.p.m. level (based on a MWF supplier's standard for machining performance of the fluid) may be regarded as an indicator that a sump fluid is grossly contaminated; 91% of water mix fluids had fines levels below 100 p.p.m. compared to only one of 24 mineral oil samples. Further examination of the data revealed that of six significantly high mineral oils samples, three had been used for grinding and three for turning. Consideration of the water-mix fluids with the ten highest fines levels revealed that eight were used for grinding and the other two were used for milling and sawing. Grinding appears to produce the highest levels of fines in MWFs.

Measures can be taken to remove swarf and fines from the sump fluid. Six companies used only automated systems for the removal of swarf (e.g. conveyors and auger screws), five used only manual removal methods (buckets and shovels) and a further 12 used both. Four companies did not report a method and the remaining company did not generate swarf. Sixteen companies used filters (including magnetic, paper, mesh and drum filters) for the removal of fines, one used active sedimentation and eight did not remove fines other than during sump fluid changes.

The criteria and bandings to define well and poorly managed MWF sumps in terms of bacterial and endotoxin contamination were based on earlier work (Travers-Glass and Crook, 1994) and previous observations by HSE occupational hygienists (HSE, 1994).

The extent of total bacterial contamination in the water-mix MWF sump samples (plate count analysis) is illustrated in Fig. 5, and ranged from not detected to 1.95×10^8 CFU/ml. The most contaminated sumps ($\geq 10^6$ CFU/ml) were not confined to any particular location and included samples from 22 of the 31 sites. Dipslide results, which are semi-quantitative and less scientifically rigorous, broadly showed reasonable agreement with the plate counts but did tend to underestimate concentrations as expected. The upper limit of 10^6 CFU/ml on the dip slide analysis will have impacted upon the values in Table 3 to some extent. Dip slides provide a good simple method of screening MWF sumps for bacteria but people managing MWFs should bear in mind that the results may be lower than the true values. Total bacteria was determined on ten mineral oil samples from five sites to demonstrate the low level of contamination expected; eight samples had levels less than the LOD and the remaining two had 20 and 137 CFU/ml, respectively. Additional tests for fungal contamination and SRB performed on most water-mix MWFs revealed little contamination; two sumps had fungal growth at levels above the 10 CFU/ml LOD (65 and 640 CFU/ml), and four sumps had measurable but insignificant SRB concentrations (10^2–10^3 CFU/ml).
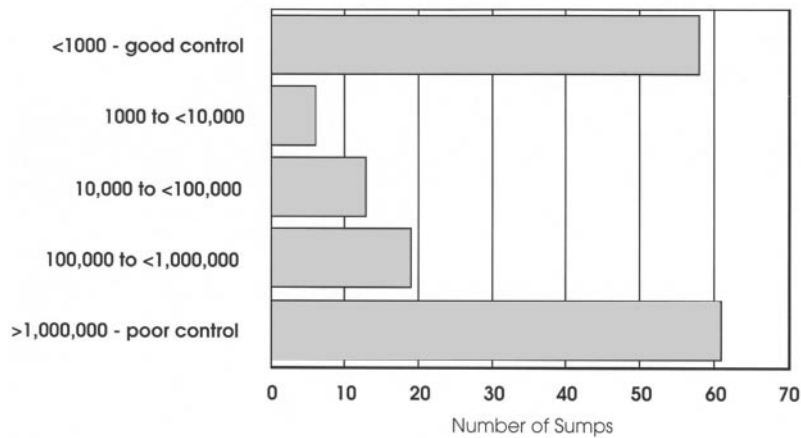
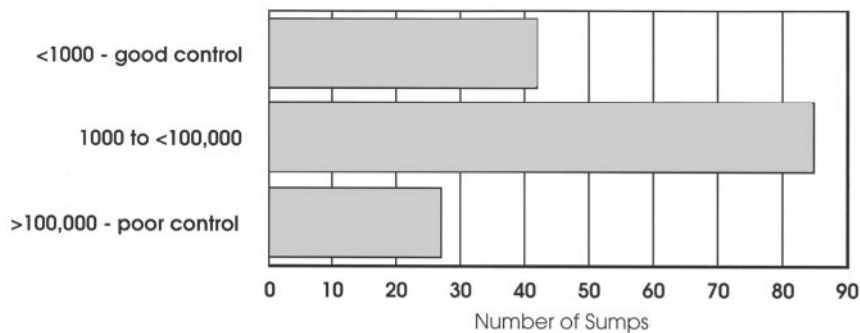**Fig. 5.** Sump bacteria levels (CFU/ml).

Fig. 6. Sump endotoxin levels (EU/ml).

The extent of endotoxin contamination in the water-mix MWFs is illustrated in Fig. 6, and ranged from not detected to 1.87×10^6 EU/ml. By comparison, in a Canadian study of 140 machine sumps in 19 factories, endotoxin levels ranged from 1.10 to 3.46×10^5 EU/ml (Park *et al.*, 2001). The most contaminated samples ($\geq 10^5$ EU/ml) were not confined to any particular location and included samples from 15 of the 31 sites. Endotoxin analyses were performed on three mineral oils from different sites, producing contamination levels of 25, 37 and 50 EU/ml. No direct relationship between sump endotoxin and bacteria levels could be discerned. Although in most cases heavy bacterial growth was associated with high endotoxin levels, as has been observed in previous studies (Thorne *et al.*, 1996), in some samples there was a high count of one parameter and a low count of the other. This is because endotoxin measurements also record non-culturable cell debris. Fresh colonization of a sump may give rise to high bacteria and low endotoxin levels, whereas low bacteria and high endotoxin levels may indicate more dead bacteria, possibly as a result of recent biocide addition. Without a history of the maintenance and age of the sump fluids it is not possible to interpret any relationship.

Further analysis of the data suggests that bacterial growth in water-mix fluid sumps depends on pH, temperature and fluid strength (Figs 7, 8 and 9), among other factors. Similarly, in attempting to develop a model for predicting endotoxin concentrations in sump fluids, Park *et al.* (2001) found that MWF pH and temperature were significant predictors, as were contamination with tramp oil and the type of MWF used (mineral oil based, water mixed fluids being associated with high endotoxin concentration more than synthetic oils). However, fluid strength was not considered by them to be a significant predictor. It is already known that bacteria growth generates organic acids which lower pH. Optimum conditions for the proliferation of bacteria appear to be temperatures between approximately 18 and 26°C, pH in the range 7.3–9.3 and fluid strength of <10%. Sump conditions outside these ranges may be an indication of a failure to control these aspects. They cannot therefore be regarded as a means to controlling bacteria. It is understood that fluid strength should typically be <10%, temperature ~20°C and pH ~9 (i.e. within the ranges identified above). These coincident sets of conditions may be the reason why high bacteriological levels are found at sites of both good and bad levels of fluid management. Companies that maintain
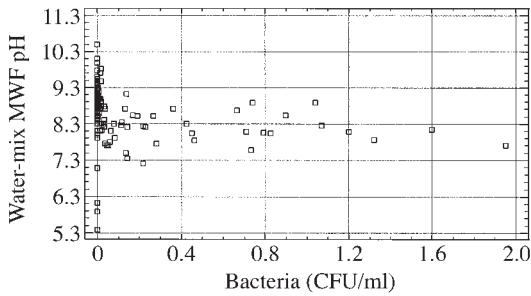
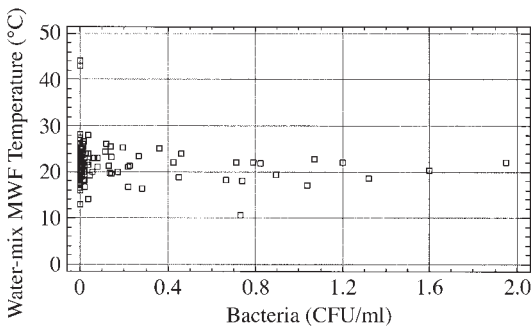**Fig. 7.** Water-mix MWF pH versus bacteria (CFU/ml). *x*-axis values × 10[8].

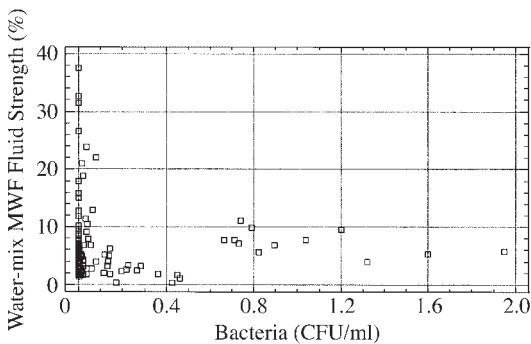**Fig. 8.** Water-mix MWF temperature (°C) versus bacteria (CFU/ml). *x*-axis values × 10[8].

Fig. 9. Water-mix MWF fluid strength (%) versus bacteria (CFU/ml). *x*-axis values × 10[8].

sumps at optimum strength, temperature and pH may also be providing conditions for increased proliferation of bacteria and thus increasing the importance of other aspects of sump management (sump cleaning, replenishment methods, removal of tramp oil, etc.). The assumptions that the temperature and pH ranges identified here favour bacterial growth, and that growth is inhibited at fluid strengths of >10% are considered to be reasonable ones but they have not been rigorously tested. The relationship between fluid management and bacterial levels is discussed later.

PAH and nitrosamine results are reproduced in Table 3. The 'total PAH' concentrations found in the

mineral oils ranged from 0.23 to 4.82 µg/g. Pyrene was the predominant PAH with chrysene also a significant component in some samples. In studies of used cutting oils, Eyres (1981) found 'total PAH' levels (comparable compounds) of 4.36–12.71 µg/g in nine oils, and Evans *et al.* (1989) found 2.58–7.26 µg/g in an oil sampled periodically over 5 yr. Comparison of the data using benzo[*a*]pyrene (BAP) as an example finds levels of <0.01–0.23 µg/g in this study (nine samples being less than the LOD), whereas Eyres found 0.02–0.42 µg/g, and Evans *et al.* found 0.11–0.40 µg/g. Although the levels are of a similar low order of magnitude, the values from this survey are generally smaller than those from the other two data sets. Measurements of NDELA ranged from <LOD (0.05 µg/ml) to 1.16 µg/ml. For comparison, Javholm *et al.* (1991) found NDELA at concentrations between <0.02 and 0.51 p.p.m. (µg/ml can be taken to be p.p.m.). The results from this survey are marginally higher than those of Jarvholm *et al.*, but could still be considered to be low. Neither sets of MWF samples were said to contain nitrite. Limited nitrosation may have been caused by the presence of oxides of nitrogen solvated from the surrounding air.

MWF management

Consideration was given to determining relationships between sump fluid measurements and sump fluid management. Management of MWFs involves monitoring and maintaining the fluid. The level of contaminants affecting health are monitored in addition to those characteristics of the fluid that affect machining performance. The MWF is periodically topped up, modified with further additive (e.g. biocide), or the whole fluid can be replaced. The method of replenishment or replacement can have a large effect on both the strength and the bacteriological content of water-mix MWF. At many sites sumps were topped up manually by the individual operators at their discretion. This could explain why sump fluid strengths reported by the companies were sometimes significantly different from the measured fluid strengths, although sites with automated mixing systems were also found to have discrepancies. One site with measured strengths of 0.3–7.3% reported values of 4–5%. At another site where strengths of 15–37.5% were measured, sump fluid concentrations of ~3% were reported. Incorrect fluid strength (outside of the supplier's specification) can lead to poor machine performance and increased inhalation and dermal exposure to the MWF concentrate. The degree of sump fluid monitoring found is illustrated in Fig. 10. Five companies did no fluid monitoring, three sites monitored just fluid strength and three sites just monitored visual appearance. Although only six sites monitored bacteriological levels, checks on pH, odour and biocide levels indirectly monitor bacteria levels.
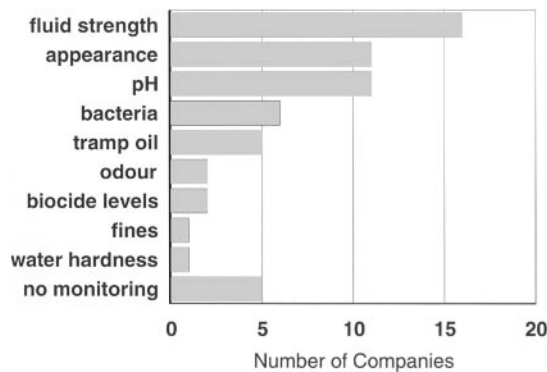
Fig. 10. Criteria used to monitor MWF.

Assessment of the factors that result in poor sump fluid condition can be difficult. The number of complicating factors means that, for any given contaminant, it was not possible to establish how each management aspect affected that contaminant. For example, a company that appeared to have a good sump-cleaning protocol and monitored the sump condition may still have had sumps with very high bacteriological levels, possibly resulting from other factors not reported during this study (e.g. poor personal hygiene practices or general orderliness). As the information on control/management was collected by site and not by individual sump, comparisons were made by a generic site approach. One important factor that it was not practical to obtain for this study was the age of each sump fluid.

The reason for the above difficulties in making comparisons between approaches seems to be due to the complexity of fluid management. As mentioned earlier, where a company ensures that a sump operates at the optimum temperature, pH and fluid strength, it may be providing an environment for the proliferation of bacteria. Maintaining bacteria at low levels then becomes a greater challenge. Companies that did not manage their sump fluid were found on some occasions to have low bacteria, possibly due to a failure to control temperature, pH or fluid strength, any one of which could inhibit the growth of bacteria. Although these are assumptions, further weight is given by the fact that of all the sumps measured, where pH, temperature and fluid strength were known and fell within the identified optimum ranges, only 13 sumps had bacteria counts of <1000 CFU/ml. These 13 sumps were from six sites, five of which had high bacteria levels in other sumps.

Two sites showed very good performance for fluid management; the pH, temperature and fluid strength were well managed and bacteria levels were low. At one site there were no identified poor fluid management issues during the site survey. Controls were in place for swarf, fines and tramp oil removal and suppression, and fluid replenishment methods appeared to be good. Sump cleaners and biocides were also used. Four sumps measured were found to have bacteria levels of <10 CFU/ml, although another sump at this site had 3 150 000 CFU/ml. The other well-managed site was found to have a similarly good approach to fluid management with all three sumps measured having bacteria levels of <10 CFU/ml. It seems that these two sites demonstrate that good fluid management is achievable. The other four sites with one or more well-managed sumps also had a number of other sumps with high bacteriological levels. There may be other reasons for these low bacteria counts, for instance sumps may have recently been cleaned and refilled. It should be noted that 11 of these 13 sumps had bacteriological levels of less than the LOD (10 CFU/ml).

It was difficult to categorize the 31 sites as poor, reasonable or good for fluid management or MWF mist control. Although some sites appeared to be good as described above, most sites were failing in some respect. In an attempt to gain an overall impression of the sites' approach to the management of health risks from MWFs, each site was rated based on the information gained at the site (i.e. not the analytical results) on three different criteria, namely:

(a) MWF management;
(b) control of occupational exposure—inhalation; and
(c) control of occupational exposure—skin.

Out of the 29 sites considered (the two pilot study sites were not rated), seven were rated good, 15 were rated intermediate and seven were rated poor. The seven rated good were regarded as having a good approach to managing the health risks from MWFs. Of these seven sites rated as good, only two had sumps with fines levels >100 p.p.m. and only two had poorly managed fluid strengths. Five of the seven sites had one or more sumps with very high bacteria levels (by the criteria used in this report). It is also interesting that four sites had sumps with very low bacteria levels where the other factors (temperature, pH and fluid strength) were also maintained, as was discussed earlier.

Those judged as poor included one site that had the highest fines level measured (2200 p.p.m.) and another site where a fluid strength of 37.5% was measured. Two other sites had high fines levels and five other sites had poorly controlled fluid strengths. Six out of the seven lowly rated sites had sump bacteria levels regarded by the criteria used in this report as being in the highest category.

The ratings are subjective, but the survey's findings show some differences between those sites regarded as being poor and those regarded as being good at managing the risks from MWFs.

Three of the sites judged to be good reported cases of skin irritation and dermatitis. Four of those judged to be poor also reported cases of skin irritation and dermatitis. There were a total of 13 reports of skin irritation and dermatitis and three reports of respiratory health problems. These reports were anecdotal and relied on workers/supervisors being willing to report health issues. There was therefore likely to have been under-reporting of such cases. It should be noted that four sites that had sumps with low bacteria counts and where other factors appeared to be well maintained, reported cases of skin irritation and dermatitis.

There were many reports of poor fluid management. At least four sites mixed their MWF concentrate and water directly into the sump. Three companies reported that sumps were only completely replenished when workers complained or difficulties were being experienced and most had no defined monitoring criteria for changing the fluid. Only 16 sites reported the use of system cleaners. At many sites, fluid 'top up' was at the operator's discretion. Poor correlation between measured fluid strength and the supplier's specification were found at many sites.

The use of additives was limited, with only nine sites using biocide. Fluid monitoring for most sites only involved visual appearance or the measurement of fluid strength. Eight sites had no method for fines removal and at some sites removal of swarf/fines was reported to be 'by hand'. This method of removal 'by hand' generally involved a shovel and bucket but also appears to involve the workers actually placing their hands into the fluid to drag out the sediment.

Control issues

This work has raised issues related to control. It has already been mentioned that it was not possible to compare the personal mist exposures with respect to the various control methods because no account could be taken of the unique circumstances of each situation (differences in machine design, work process, workload, etc.). Both the nature of the process and the presence of any engineering controls will influence the generation of and exposure to oil mist. Process parameters include machine speed, delivery of the MWF (volume, rate and direction), and the composition and strength of the MWF. Engineering controls include splash guards, enclosures, ventilation (both general and LEV) and automation. The process settings and the engineering controls should complement each other rather than compete. The LEV or enclosure should not simply be there to overcome the failings of the process design, competing with the high levels of mist produced. There was evidence of some bad practice in the control of oil mist emissions. Splash guards ranged in design and effectiveness and an operator's unwillingness to replace the guard every time the machine is started

could compromise any potential benefit. Remotely positioned filter mist units and mist precipitators at some sites may have had an effect on reducing background levels of mist but would not have reduced exposure at source. In some instances the control of MWF mist was reliant on natural ventilation and thus there were reports that visible mist levels were greater during winter, when doors and windows tended to be shut.

With the changes to the UK exposure limits made, there was a need for a new source of standards for control. HSE's major new package of guidance, *Working Safely with Metal Working Fluids Pack* (HSE, 2002), provides that standard. This good practice guidance sets out the standards of control that constitute good management of health risks in the engineering industry. It includes guidance standards for mists arising from neat oil and water-mix MWFs, and for sump contaminants such as fines and bacteria.

This user-friendly package of guidance includes poster, monitoring chart and laminated task sheets for operators that detail established good practice for common jobs, such as sump cleaning. It was developed with the help of industry trade bodies who represent the fluid and machine suppliers, the relevant trade union, employers' representatives, as well as Envirowise, a government programme that provides practical environmental advice for business.

CONCLUSIONS

Occupational exposure to mineral oil MWF mist can be controlled to well below 3 mg/m^3, and exposure to water-mix MWF mist can be controlled to well below 1 mg/m^3. Total inhalable particulate can be used to estimate mineral oil mist exposure but cannot be used for water-mix MWF concentrate mist exposure. Mists can potentially contain extensive contamination such as bacteria and endotoxin.

On the whole, fluid management was found to be poor, with most sites failing to meet industry good practice or HSE standards. High levels of bacteria, endotoxin and fines were found in sumps, and control of other factors such as water-mix fluid concentration was often poor. Some of the operating procedures utilized were deficient or unsatisfactory. Poor standards of fluid management were found at all sizes of company.

Following this work, the HSE has developed new guidance material setting out standards for the reduction of health risks to workers exposed to MWFs. These guidelines address all routes of exposure, including skin contact, with significant emphasis on sump fluid management. The new guidance presents accepted industry good practice, describing methods for controlling exposure to mist and managing sump fluids. It will enable companies to compare their results and working practices to established good

practice and includes guide values for mineral oil and water-mix MWF mist, and for sump fluid contaminant levels.

Full details of this survey can be found in HSE's Exposure Assessment Document EH74/4 'Metal Working Fluids (MWFs)' (HSE, 2000b).

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