Comparison of Measured Dermal Dust Exposures with Predicted Exposures Given by the EASE Expert System

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Received 5 March 2004; in final form 22 September 2004; published online 13 January 2005

Estimation and Assessment of Substance Exposure (EASE) is a rule-based computer expert system used by regulatory authorities within the European Union to assist in assessing exposure for both new and existing substances. It can provide estimates of both inhalation exposure levels and dermal exposure levels to the hands and forearms. This article describes the results of a study in which measurements of workplace dermal zinc exposures were collected for an industry-wide risk assessment and also compared with the levels predicted by EASE. Measurements were obtained from subjects in seven different workplaces that were producing or working with zinc metal or zinc compounds. The work activities were grouped a priori into one of three categories used by EASE for dermal exposure assessment: 'non-dispersive use with intermittent direct handling', 'wide dispersive use with intermittent direct handling' and 'wide dispersive use with extensive direct handling'. The predicted exposure ranges for these categories are 0.1–1, 1–5 and 5–15 mg cm\(^{-2}\) day\(^{-1}\). Although the average measured exposure levels for each of the categories increased in line with the predictions from EASE, the model overestimated dermal exposure to the hands by a factor of ~50 when the mid-point of the EASE range was compared with the measured mean exposure. Furthermore, a significant additional exposure was found on other parts of the workers' bodies for which EASE does not provide any estimates. Interpretation of the dermal exposure data was complicated by the use of protective gloves, which might have limited the amount of zinc dust adhering to the workers' skin. However, observation of the work activities suggested that the pattern of glove use was such that they would not provide a consistent level of protection. This study provided an opportunity to collect a large amount of dermal zinc exposure data for risk assessment purposes and also enabled a dermal sampling method to be developed and assessed. There is no standard method for dermal dust exposure measurement, and the choice of method was a key factor in the exposure estimation process. With regard to comparison with the EASE predictions, it is possible that EASE could appear to perform more accurately if its predictions were compared with measurements obtained using surrogate skin sampling methods. However, we believe that such sampling can provide a gross overestimate of the dust on the skin surface. We suggest that further development of the EASE system is necessary to ensure that it better reflects whole-body dermal exposures to dusts.

Keywords: dermal exposure; dermal sampling; EASE; exposure assessment; risk assessment; zinc

INTRODUCTION

The Estimation and Assessment of Substance Exposure (EASE) model was developed by the UK Health & Safety Executive (HSE) to assist with exposure assessment for both new and existing substances (HSE, 1996a). The model is based on a series of logical criteria contained within a computer-based expert system and can be used to predict exposures using task- and situation-specific information about the substance and the methods of control. A comprehensive review of the EASE model is being prepared as a companion paper (Creely et al., 2005).

For inhalation exposures, the model predicts a range of expected exposure levels for a given set of circumstances. The dermal exposure model predicts the potential exposure to the hands and forearms expressed as a mass per unit area of exposed skin per day (mg cm\(^{-2}\) day\(^{-1}\)). This evaluation is based on
information about the method and frequency of handling of contaminated objects and assumes an exposed anatomical area of approximately 2000 cm², based on the guidelines of the Organisation for Economic Co-operation and Development (OECD, 1997).

The two principal criteria used in the EASE model to predict dermal exposure are the dermal contact level (possible values—‘none’, ‘incidental’, ‘intermittent’ and ‘extensive’) and the pattern of use (‘closed system’, ‘limited use’—termed ‘inclusion into matrix or non-dispersive use’ in the model—and ‘uncontrolled release’—termed ‘wide dispersive use’). The predictions or ‘endpoints’ are expressed as exposure ranges, which can take five different values, from ‘very low’ to 5–15 mg cm⁻² day⁻¹.

The EASE model has been used to estimate exposures to a range of different chemicals, including zinc compounds (ECB, 2004), and the overall objectives of this study were to gather actual dermal exposure data for the regulatory risk assessment and also to establish whether EASE produces reliable estimates of dermal exposure to dusts. This objective was achieved by collecting measurements of dermal zinc exposure from a range of workplace situations and comparing these with the predicted exposures. Zinc is ubiquitous in the environment, and human exposure is primarily by ingestion. Zinc is widespread in foods and water, and is an essential trace element necessary for human health. Occupational exposure is limited mainly to galvanizing, smelting, welding, brass foundry work and production of zinc chemical powders including zinc metal dust and zinc oxide, which is used in rubber tyre manufacturing, animal feedstuff, toothpaste and cosmetics. Since working with zinc is not generally considered to be a high-risk activity, particularly in terms of skin contact, this research provided an opportunity to study the mechanisms and levels of dermal exposure where there are no specific dermal exposure controls in place.

The study was carried out in two phases. In the first phase, a sampling method was developed and tested in the laboratory. As part of the first phase a set of preliminary dermal exposure measurements was obtained from a galvanizing plant and a chemical plant producing zinc oxide. In the second phase, further work was carried out to validate the sampling method and additional dermal zinc exposure measurements were obtained from a range of workplace situations, including a second galvanizing plant, three other zinc chemical factories and a zinc refinery.

The survey work carried out as part of this assessment thus provided an opportunity to develop and test a dermal sampling method and to study some of the factors that affect the collection of dermal exposure measurements in the field. The results from the method validation tests are elaborated in detail and some areas for further research are indicated.

METHODS

The various tasks observed in each of the workplaces were categorized in terms of the EASE model so that the exposure measurements could be compared with the EASE predictions. Information about the working practices and control measures was used as an input to the EASE model, and this provided predicted exposure levels for each category of task. The categorization was done after consideration of the dermal contact level and pattern of use and is a matter of professional judgement, assisted by online help embedded in the EASE computer program. The categorization was done by an experienced user (G.W.H.) of the EASE model, before the results of the dermal sampling surveys were known.

Dermal exposure was measured using moist wipes to remove particulate matter from the skin contaminant layer (Schneider et al., 1999). Before the site surveys, recovery trials were carried out to determine the sampling efficiency of the wipe method. In addition, control samples were collected from non-occupationally exposed individuals to establish a biological baseline or background level of zinc on the skin surface.

Method validation

Samples of zinc oxide, zinc dust and zinc powder were obtained directly from one of the workplaces included in this study and these were used to establish the recovery efficiency of the sampling and analytical procedures. The compounds used for the validation of the method are identified as follows:

- Zinc oxide: Delox 20 Zinc Oxide
- Zinc dust: Delaville Superfine dust
- Zinc powder: P150 Powder

Zinc oxide is produced by the combustion of zinc ingots in a furnace ensuring a good supply of atmospheric oxygen. Zinc dust and zinc powder are produced in a similar manner but in an inert atmosphere. Zinc oxide is a fine white powder with average particle size in the region of 0.2 µm. Zinc dust takes the form of a fine grey powder with typical particle size in the range 3–7 µm, depending on specification. The industry term ‘zinc powder’ actually refers to a relatively coarse form of zinc dust, with a particle size in the range 50–150 µm. All of these zinc compounds are insoluble in water, and the particle shape is generally spherical.

Five types of moist wipes were tested to establish their suitability for sampling and their compatibility with the analytical techniques. Of these, only Jeyes ‘Wet Ones’ were compatible with the analytical reagents, so these were adopted for use. The solution used for these wipes contains a wide range of ingredients, including water and propylene glycol. Sample
were analysed to determine the background level of zinc in each wipe.

Since zinc is a trace element essential for human survival, it was taken into account that there could be naturally occurring zinc deposits on human skin. In order to establish a background level, a number of volunteers were recruited from the Institute of Occupational Medicine (IOM) staff. This control group included only people who were not occupationally exposed to zinc and who had not recently used hand creams or lotions that might have contained zinc compounds. Wipe samples were collected from the palms, the backs of the hands and the forearms using an acetate template with a sampling aperture measuring 25 cm². Each individual sample of the relevant anatomical area comprised three separate wipes, applied one after the other.

After the control samples had been collected from each volunteer, a known weight of zinc oxide, zinc metal dust or zinc metal powder was applied to the back of one hand. This was rubbed into the skin using a finger from the volunteer’s opposite hand. Five individual wipes were then used to clean the finger and the back of the hand. Each wipe sample was placed into a separate container and analysed individually. This was done in order to determine the number of wipe samples necessary for complete recovery of the zinc from the skin.

The samples were digested in 10% nitric acid in 250 ml glass bottles, using enough acid to cover the wipe completely. The bottles were placed on a hot-plate and heated for about 3 h, making sure that the wipe was immersed and that the solution did not boil. The solution was then allowed to cool, filtered, and made up to a known volume with 10% nitric acid. A commercial defoamer solution (Rug Doctor Defoamer) was added to the preparation (1% by volume) to suppress bubbles during vacuum filtration of the solutions. The samples were then analysed for elemental zinc using inductively coupled plasma atomic emission spectroscopy (ICP/AES) following a documented in-house method based on method ID121 of the Occupational Safety and Health Administration (OSHA, 1991). Calibration standards were prepared using known weights of Analar grade reagents and the sample masses were determined with reference to these standards.

**Sampling methodology**

With the exception of the zinc refinery, all of the factories had relatively small numbers of workers involved in the production activities. The general strategy was therefore to sample all of the process workers who were directly involved in handling zinc products. In the zinc refinery the tasks involving the greatest potential for exposure were selected. This included workers who were involved with the transfer of raw materials, workers in the smelting and molten metal refining areas, and those involved with packing of the final product.

Samples were collected using wet wipes applied to the hands, the inside of the forearms, the forehead, the neck and the chest. The sample from the chest was obtained to assess the degree of contamination under the work clothes. Each sample was obtained using an acetate template with an aperture of 25 cm², and three consecutive wipes were collected from the same area of skin each time.

The hand and forearm samples were collected on three occasions over the working shift (before meals and other rest breaks) to ensure that no contamination was lost when the subjects washed their hands. The forehead, neck and chest samples were collected once at the end of the working shift. The samples relating to each particular area of the body, for each individual, were bulked together to limit the number of separate samples to be analysed. In the case of the hand and forearm samples, the measured exposure is calculated as the average of the three separate samples collected from each of these areas.

Field blank samples were collected after each batch of wipe samples was obtained in order to check for adventitious contamination.

**Repeat contact and maximum load tests**

After the workplace investigations had been completed, controlled tests were carried out to investigate the rate of dermal loading and the practical maximum level of skin contamination for zinc oxide and zinc dust. This was done in order to aid the interpretation of the workplace exposure data.

These tests were conducted using healthy human volunteers drawn from a pool of external contacts previously identified for other volunteer studies. The project protocol, volunteer selection and informative procedures were reviewed by an internal IOM committee, which considered the ethical issues relating to these experiments. All the subjects gave their informed consent before participating.

A maximum loading level for immersion was assessed by inserting the subject’s hands into freshly opened 25 kg sacks of zinc oxide or zinc dust, so that the hands were fully immersed into the bulk material. Dermal exposure samples were then obtained by applying moist wipes as previously described, collecting the surface contamination from the backs and palms of each hand.

A second test was carried out to determine loading levels likely to be obtained by repeated contact with contaminated surfaces. In this case, the subject pressed down on a smooth aluminium plate covered with a layer of zinc oxide. Wipe samples were collected from each palm after one surface contact, and
this sampling was repeated for two, four and then eight consecutive surface contacts. The whole procedure was repeated with a total of six volunteers. These data provided an indication of the rate at which maximum loading would occur. This experiment was not repeated for zinc dust because of time constraints.

Dermal exposure measurements were collected for a common industrial task simulated in a controlled laboratory environment. This involved manual opening and tipping of varying numbers of 25 kg sacks of zinc oxide into an open bin. Tests were carried out for each of four volunteers after a single bag dump, then two, four and eight sequential bag dumps. Immediately after each simulated task was completed, the subject’s hands and forearms were sampled by collecting wipe samples from the palms, backs of the hands and forearms. This particular manual task was selected because it was a task performed during the workplace surveys and because it is generally considered to be a ‘reasonable worst case scenario’ under EU regulatory risk assessment guidelines. It could be categorized in terms of EASE as ‘wide dispersive use with extensive direct handling’ and has a predicted exposure range of 5–15 mg cm⁻² day⁻¹. It was not feasible to repeat this test for zinc dust, which in any case is normally packed in drums or smaller sized polythene sacks.

**Evaluation of the dustiness of zinc oxide and zinc metal dust**

Samples of zinc oxide and zinc metal dust were obtained from industry and tested to determine their relative dustiness. This was done using a rotating-drum dustiness tester by the UK Health & Safety Laboratory, Sheffield. A pre-weighed quantity of each sample was agitated in the rotating drum and samples of airborne dust were collected onto a three-stage collector containing size-selective foam elements as described in MDHS 81 (HSE, 1996b). This enabled the quantity of airborne dust to be evaluated for a given mass of dust, and in each case the inhalable, thoracic and respirable dust size fractions were established. Three measurements were obtained for each sample and the mean level and standard deviation for each sample were calculated and expressed in terms of milligrams per kilogram of dust.

**Statistical methods**

The workplace exposure data for each exposure category were summarized in terms of maximum, minimum and geometric mean levels using Microsoft Excel 2002. The results from the hand immersion, repeat contact and bag dumping tests were analysed using SPSS version 11.5. Differences between different categories of data were investigated using two-sample t-tests. For example, a two-sample t-test was carried out to compare each of the exposure scenarios for Phases 1 and 2, respectively. Since the data were log-normally distributed, they were log transformed prior to analysis.

The results of the immersion tasks were analysed using the Wilcoxon rank test in order to determine whether there were significant differences in the potential loading levels for zinc dust and zinc oxide. The results of the different skin loadings from the repeat contact tests were analysed using the Friedman test to determine whether there were any differences between different numbers of contacts. This procedure was repeated for the skin loading data for the repeat bag dumping trials. The latter data were analysed for the hands and forearms combined, whereas the repeat contact tests were for the palms of the hands only. Any significant results were investigated further by carrying out the Wilcoxon rank test on paired data, for example, one contact with two contacts, one with four, one with eight, and so on. Since there were six possible pairings, the significance level must be adjusted accordingly, and so the Bonferroni correction was applied. In other words, a P-value < 0.05/6 = 0.008 was considered to be significant.

**DESCRIPTION OF EXPOSURE SCENARIOS**

**Galvanizing**

Two galvanizing companies were included in the study. In this industrial process, metal items were cleaned, pickled in acid, prefluxed with zinc ammonium chloride and then dipped into a tank of molten zinc. Extract ventilation was commonly fitted to the dip tanks, but in the case of one factory, the extraction equipment did not prevent emissions into the workplace.

The majority of the workers wore cotton coveralls and heat-protective gloves or gauntlets, although this practice was not strictly observed. Gloves were worn by all workers whenever there was potential for contact with hot metal surfaces, molten metal or sharp metal edges. However, dermal zinc exposures occurred as a result of direct handling of finished products and also direct contact with machinery, work surfaces and clothing (including the gloves) which had been contaminated with dust and other debris.

**Zinc chemical product manufacturing**

The second group of factories produced technical grades of zinc oxide, zinc metal dust and zinc metal powder. Four such companies were included in the study. In these workplaces exposure generally occurred in three different ways: direct handling of
zinc ingots while loading furnaces, packaging of powder products and cleaning/maintenance tasks. Typically, the zinc products were packed in 25 kg sacks using semiautomatic bagging equipment. This work was carried out continuously or in rotation with other jobs, depending on how individual companies organized their work. The workers were also involved in loading and unloading flexible intermediate bulk containers (FIBCs) or ‘big bags’, which involved some direct contact with dusty surfaces. Maintenance work involved tasks such as breaking transfer lines to clear blockages, causing significant contamination of the workplace.

At the zinc chemical production sites the furnace workers wore gloves to protect themselves from contact with hot surfaces, but these gloves were not kept in clean areas and so provided little protection against general surface contamination. For packaging and maintenance work the pattern of glove use was variable; some workers wore gloves occasionally, others never wore gloves.

Zinc refinery

The zinc refinery processed and refined ore rich in zinc, lead and cadmium to produce metal ingots. The ore, which was principally zinc sulphide, was transferred into the plant by conveyor and melted in the blast furnace. The molten zinc was tapped off from holding tanks and then transferred to the refinery, where it was purified by distillation in an enclosed system.

There were three to four operators in the raw materials handling area, and all had set routines to inspect and clean blockages from specific conveyor transfer points. Material that built up on the conveyors was cleaned using shovels or other hand tools. However, blockages within machines were more difficult to clear and required the use of compressed-air lances. Dust liberated by the use of the compressed air produced gross contamination of work clothing and exposed areas of skin.

There were six workers in the furnace areas involved in slugging and drossing operations. These involved raking off waste material from the molten metal held in separation baths or at transfer points. Material that built up on the conveyors was cleaned using shovels or other hand tools. However, blockages within machines were more difficult to clear and required the use of compressed-air lances. Dust liberated by the use of the compressed air produced gross contamination of work clothing and exposed areas of skin.

There were six workers in the furnace areas involved in tapping furnaces, transferring ladles of molten metal and preparation of moulds. These workers were involved in tapping furnaces, transferring ladles of molten metal and preparation of moulds. The workers involved with molten metal work all wore heat-protective clothing, which included gloves, during these tasks.

RESULTS

Method validation

Blank samples containing three individual wipes contained an average of 24 μg zinc (standard deviation, SD = 7.6). Translating this into a swab surface area of 25 cm², the limit of detection was calculated as 0.0009 mg cm⁻², using a value of three times the SD.

Analysis of 46 wipe samples taken from the control subjects showed that the average, blank-corrected, background level of zinc was 0.0008 mg cm⁻² (SD = 0.0008). Therefore, the practical limit of detection for the method, based on 3 × SD for these data, was 0.0024 mg cm⁻².

The sampling recovery tests were intended to evaluate the required number of sequential wipes necessary to remove known levels of surface contamination. The geometric mean (GM) recovery efficiency was 102% using five sequential wipes, with individual recoveries varying from 70 to 126%. Considering only the first three wipes, the corresponding GM was 98%. The individual recoveries in this case varied from 67 to 118%. The three-wipe method was considered to be a more practical option and so the field samples were collected using three sequential wipes at each body location.

Dermal exposure measurements

The exposure data organized according to the EASE categories are summarized in Table 1. These data are blank corrected, but are not subsequently corrected for background levels of zinc as found in the control group, since these were very low. The data from the two phases of the study are presented separately because the measurement methods for sampling the hands were slightly different: in Phase 1 only the backs of the hands were sampled, whereas both the palms and the backs of the hands were sampled in Phase 2. In general, approximately three times as much dust was deposited on the palms as on the backs, so the Phase 1 summary data were corrected to account for this. Also, the data are presented separately since this allows a comparison to be made with the airborne dust sampling that was carried out during the Phase 1 surveys. No corresponding airborne dust measurements were collected during Phase 2.

The galvanizing activities and zinc refinery work were categorized according to the EASE model as non-dispersive use with intermittent direct handling. The GM hand/arm exposure from the Phase 1 survey was 0.010 mg cm⁻² compared with 0.009 mg cm⁻² obtained from the Phase 2 surveys. Both these exposure levels were much lower than the predicted exposure range of 0.1–1 mg cm⁻² for this EASE category.
The routine production tasks from the zinc oxide and zinc dust production processes were categorized in terms of EASE as wide dispersive use with intermittent direct handling. For the Phase 1 survey, the GM hand/arm exposure was 0.048 mg cm\(^{-2}\) compared with 0.055 mg cm\(^{-2}\) in Phase 2. Again, these exposures were less than the predicted range of 1–5 mg cm\(^{-2}\) for this EASE category.

The dustiest tasks overall were associated with intensive direct handling of zinc oxide and zinc dust. For these tasks the exposures were categorized as wide dispersive use with extensive direct handling. In this case the GM hand/arm exposure for the Phase 1 survey was 0.186 mg cm\(^{-2}\) compared with 0.215 mg cm\(^{-2}\) in Phase 2. Again, these were less than the predicted exposure range of 5–15 mg cm\(^{-2}\) for the EASE category.

In the case of the first exposure scenario (galvanizing and molten metal work in the refinery), the \(t\)-test indicated that there was no significant difference between the hand/arm exposures in the two phases of the project \((P = 0.53)\). This was consistent with the observation that the working conditions and the patterns of glove use were very similar in each case. For the remaining two scenarios the \(t\)-tests also indicated that the data were not significantly different \((P = 0.59\) for routine tasks and \(P = 0.558\) for the dustiest work).

The dermal zinc exposures for the different industries included in the surveys are summarized in Figs 1 and 2. For simplicity, only the hand/arm, neck and forehead data are included. The figures illustrate the potential for wide variation in exposure levels within each industry sector.

**Dermal exposures and airborne dust levels**

The combined hand/arm, neck and forehead exposure data for the Phase 1 factories are summarized and compared with the airborne dust exposure data from these plants reported by Groat et al. (1999). The airborne dust concentrations were collected by personal sampling at the time of the dermal exposure assessments. The results are also illustrated in Fig. 1. No air samples were collected during the Phase 2 surveys.

The inhalable dust exposures for the galvanizing plant were in the range 0.2–1.1 mg m\(^{-3}\) and the corresponding figure for the zinc oxide factory was 1.3–3.8 mg m\(^{-3}\). The fact that the dermal exposure data increased in line with the airborne dust exposures would appear to support the suggestion of Schneider et al. (1999) that dermal exposure is related to inhalation exposures, probably because a proportion of the airborne dust settles out and contaminates the surfaces that the workers come into contact with.

**Repeat contact and maximum loading tests**

The controlled laboratory tests carried out to determine the rates and maximum levels of skin surface loading for zinc oxide and zinc dust were intended to be used for comparison with the field survey measurements and to help interpret these data.

The skin surface loading for immersion of the hands into zinc oxide was in the range 0.39–0.94 mg cm\(^{-2}\), with an average of 0.73 mg cm\(^{-2}\). The corresponding results for zinc metal dust were in the range 3.75–6.41 mg cm\(^{-2}\), with an average of 4.84 mg cm\(^{-2}\) (see Table 2). The \(P\)-value for the Wilcoxon rank test was 0.028, which indicates that there was a significant increase in the level of surface loading when immersing the hands into zinc metal dust compared with immersion into zinc oxide. These data are summarized in Fig. 3.

For the repeat contact tests, the average dermal loading for one contact was 0.198 mg cm\(^{-2}\), two contacts produced 0.163 mg cm\(^{-2}\), four contacts gave 0.230 mg cm\(^{-2}\), and eight gave 0.237 mg cm\(^{-2}\) (see Table 3). The \(P\)-value for the Friedman test was 0.102, which indicates that there was no significant increase in skin surface loading for zinc oxide associated with an increasing number of contacts, at least for up to eight repeat contact tests. These data are summarized in Fig. 4.

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Table 1. Comparison of predicted hand/arm dermal zinc exposures with measured levels

<table>
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<tr>
<th>Exposure scenario</th>
<th>Predicted range (mg cm(^{-2}))</th>
<th>Measured range (mg cm(^{-2}))</th>
<th>Geometric mean exposure (mg cm(^{-2}))</th>
<th>No. of measurements</th>
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<td>Phase 2 survey</td>
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*EASE category for exposure scenario: 1, non-dispersive use with intermittent direct handling (galvanizing factory and zinc refinery); 2, wide dispersive use with intermittent direct handling (zinc oxide/zinc dust production—furnace/warehousing); 3, wide dispersive use with extensive direct handling (zinc oxide/zinc dust production—bagging/other dusty jobs).
The results of the test procedure for repeated bag dumps (of zinc oxide) were analysed for the hands and forearms combined, by the number of bags emptied. In this case, the average skin surface loadings for one, two, four and eight sequential bag dumps were 0.046, 0.027, 0.041 and 0.089 mg cm$^{-2}$, respectively (see Table 4). For these data, the Friedman test gave $P = 0.038$, which means that there was a significant difference between the various levels, indicating that there was an increase in skin contamination with increasing numbers of bag dumps. The combined hand/arm data for the bag dumping exercise are summarized in Fig. 5.

In order to investigate these data further, the Wilcoxon rank test was carried out on pairs of average skin loading data. The $P$-value for this test was 0.038, indicating that there was no significant difference in the results, given the adjusted significance level of 0.008 obtained by applying the Bonferroni correction. None of the individual Wilcoxon tests was significant. This is likely to be due to the small number of data points, so a degree of caution is required when interpreting these results. While the data do not support a gradual increase in skin surface loading with increasing numbers of bag dumps, there is a

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Skin surface loading for test material (mg cm$^{-2}$)</th>
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Table 2. Results of maximum skin surface loadings for immersion into zinc oxide and zinc dust, sampling backs and palms of left and right hands.

Fig. 1. Comparison of dermal zinc exposures by industry (Phase 1 surveys, including corresponding airborne dust measurements).

Fig. 2. Comparison of dermal zinc exposures by industry (Phase 2 surveys).
strong indication that there was a greater skin surface loading from eight sequential bag dumps than from one or two.

Since there was a strong indication from the immersion data that the skin is capable of retaining higher levels of zinc metal dust than of zinc oxide, samples of these materials were analysed for relative dustiness. The results of the test procedure showed that the dustiness levels for inhalable, thoracic and respirable dust for zinc metal dust were 664, 430 and 131 mg kg\(^{-1}\), respectively. The corresponding results for zinc oxide were 290, 45 and 10 mg kg\(^{-1}\). The results of this procedure are summarized in Table 5.

In terms of the quantity of inhalable, thoracic and respirable dust produced by each substance, it is clear that zinc metal dust is much dustier than zinc oxide. This was unexpected from the workplace data and is supported by the immersion tests, but it is interesting to note that the average particle size for zinc oxide is quoted as being much smaller than that for zinc dust, that is, 0.2 \(\mu\)m compared with 3–7 \(\mu\)m. It is therefore clear that particle size is not the single most important factor in governing the dustiness of a particular material.

Following this observation, the data from the Phase 2 surveys were reviewed and the exposures for zinc dust workers were separated out from those for zinc oxide workers. The average skin loadings for zinc metal dust workers were slightly higher than those for zinc oxide workers, but not significantly. This comparison is illustrated in Fig. 6, and it can be seen that there was generally little difference in the combined hand/arm, neck and forehead exposure levels, although there are relatively fewer data points for zinc dust workers (\(N = 8\)) than for zinc oxide workers (\(N = 21\)).

**DISCUSSION**

From Table 1 it is apparent that EASE consistently overestimated dermal exposure. Based on a comparison of the single-point GM exposures with the mid-point of the EASE predictions, the EASE predictions were \(\sim 50\) times greater than the measured exposures. It is noted that the EASE predictions increased in line with the average measured exposures, and this is consistent with previous validation trials of EASE in relation to the inhalation part of the model.
This at least gives some reassurance for users of the model that EASE tends to err on the side of safety, although it may be argued that EASE is overly conservative for risk estimation purposes.

Although there were slight differences in the sampling protocols used in Phases 1 and 2, the exposure measurements obtained from the different companies were very similar in magnitude when similar tasks were being compared. However, as is typical of dermal exposure assessment, there was considerable variability within tasks and industry sectors. Many factors, including the sampling method, could account for these differences. However, it is likely that the differences are mainly due to variations in the behaviour of the individual subjects and the particular conditions in the different workplaces. For example, there appeared to be more intensive working practices at the zinc chemical factories included in the Phase 2 surveys than at the zinc oxide plant included for Phase 1, and these may partly explain the spread in the results, particularly in the case of the head and neck sample results. A key factor to consider is that the workers did not perceive there to be a risk to health associated with dermal exposure to zinc compounds. Consequently, very high exposures could occur during common tasks, and thus a high level of variability between subjects can be expected.

The results of the laboratory trials show that the skin will support much higher levels of zinc metal dust than of zinc oxide and that zinc dust generates more airborne dust than zinc oxide. This would not be immediately apparent by considering the particle sizes of the two materials since zinc oxide has a much smaller mean particle size. However, zinc oxide has a tendency to agglomerate, and the reduced skin loadings in the tests are best explained by this property making it more likely to fall off the skin. Neither of the workplaces included in Phase 1 produced zinc dust, but some of the factory personnel in the Phase 2 surveys were involved with the manufacture and packaging of zinc dust. Splitting the exposure data for zinc dust workers and zinc oxide workers did not reveal any significant differences in dermal exposures between these two groups, although average skin loadings for the zinc dust workers were slightly higher than those for the zinc oxide workers. It is possible that the dermal exposures reached an equilibrium level, possibly determined in part by shedding of dust from the skin owing to contact with tools, clothing and other surfaces.

Also, the laboratory tests revealed variability in skin contamination levels between different volunteers taking part in the repeat contact tests, which

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>No. of bag dumps</th>
<th>Skin surface loading (mg cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Backs and palms of both hands</td>
<td>Both forearms</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>0.050 0.030 0.003 0.022</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0.056 0.038 0.045</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>0.045 0.044 0.044</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>0.052 0.087 0.073 0.046</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>0.026 0.005 0.013</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>0.054 0.020 0.034</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>0.038 0.019 0.027</td>
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<tr>
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<td>2</td>
<td>0.044 0.027 0.034 0.027</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
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<tr>
<td>8</td>
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<td>8</td>
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<td>0.101 0.026 0.056</td>
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<td>0.076 0.051 0.061</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>0.230 0.138 0.175 0.089</td>
</tr>
</tbody>
</table>
may be due to the skin condition or skin moisture content of the subjects concerned. This is also likely to be a factor in explaining the between-worker variability in the industry measurements.

Validity of the dermal sampling method

Much of the published work on dermal exposures has been concerned with liquid pesticides. In these cases, a variety of sampling techniques have been used, for example, surrogate skin methods, which include patch samplers and cotton gloves, and removal methods, including hand-washing or wiping techniques (Brouwer et al., 2000). Fenske et al. (1999) reported comparative sampling trials on dermal hand exposure to pesticide using glove samplers, wipes, and hand-wash techniques. This work illustrated how the choice of sampling method influenced the magnitude of the exposure measurements. Glove sampling tended to produce the highest measure of exposure, with hand-washing next, and the wipe method the lowest measurements. However, a common criticism of the glove or patch sample method is that the sample media may act as a reservoir, tending to soak up the contaminant and retain it in much higher quantities than would normally be expected for human skin (Cherrie and Robertson, 1995). Hand-washing using sealable polythene bags is usually carried out only for substances that are water soluble or otherwise easily removed from the skin, and hence it has been widely adopted for pesticide exposure assessment.

The sampling technique used for this study was selected because of concerns about the overloading of patches or gloves and the expectation that zinc oxide would not be efficiently removed from the skin by hand-washing since it is insoluble in water. The wipe sampling technique was therefore considered to be the most practical option in the circumstances. However, none of the alternative techniques was tested for this particular application, and there is a lack of data in the literature for comparison. Further work would be necessary to determine whether patches or gloves could be used in the zinc industry to measure potential dermal exposures.

In this study, it was apparent that there were higher dermal zinc levels on the palms of the hands than the backs of the hands. The ratio of zinc deposits on the palms to backs was \( \frac{C_24}{C_3} \), using all the available data obtained from the Phase 2 investigations. To account for this, the exposure data from Phase 1 were adjusted to estimate whole-hand exposures. This illustrates one of the main drawbacks with patch sampling in general: the sample surface may not be representative of the anatomical area under consideration.

Limitations of the EASE model

The dermal exposure component of EASE is based on a simple model, using limited information about the workplace, substance and task to derive an estimate of cumulative exposure over a working shift. This is in contrast with the inhalation model, which appears to provide exposure predictions for particular tasks—or at least does not make the distinction between task and task duration. The two different approaches within the same system are liable to result in confusion among users, and a more consistent approach would be desirable. Furthermore, it is not possible to use EASE to predict an average dermal exposure for a simple combination of different tasks. It is, therefore, difficult to compare actual exposure measurements with predictions based on this approach.
The EASE model also does not take into account the physical properties of the substance under consideration, and this may be an important factor. In our laboratory hand-immersion tests, we demonstrated that there is an approximate 3-fold difference in potential exposure between zinc dust and zinc oxide, although there seems to be less of a difference between the measured exposures of zinc oxide workers and zinc dust workers.

The level of contamination on unprotected skin will build up as a consequence of transport through various exposure routes, for example, direct contact with the source, from contaminated surfaces, and from deposition of airborne dust onto the skin as described by Schneider et al. (1999). Particulate contamination may be removed from the skin contaminant layer owing to contact with other surfaces, or it may simply fall off owing to overloading. The reported exposures in this study, for the hands and arms, are average measurements; the sampling method involved collecting samples of the skin contaminant layer three times during the working shift. These were bulked together and the average value was calculated based on the number of samples collected. This approach assumes that the zinc deposits do not continue to build up indefinitely. The repeat contact laboratory tests demonstrated that for zinc oxide, the dermal zinc loading quickly reaches a level that does not change with further contacts. The measured levels for these tests also compare favourably with the measurements obtained in the industrial situation. Thus it seems to us to be appropriate to use the mean value from the three sets of wipes collected in the field.

It is clear from the maximum loading tests (by immersion of the hands into sacks of zinc oxide and zinc metal dust) that all of the workplace measurements were well under the maximum loading levels for both these substances. This provides reassurance that the sampling method did not overestimate exposures. This comparison is illustrated in Fig. 7, which uses all the hand/arm exposure data for the workplace sectors against all the data for each of the laboratory simulations.

As noted above, the comparison of the measured exposures with the EASE predictions is complicated by the use of protective gloves in the workplace. EASE is intended to predict the potential exposure, that is, the level of contamination likely to occur to unprotected skin or outer clothing. It may, therefore, be argued that the measures of dermal exposure obtained by wipe sampling the skin of a gloved hand are not directly comparable with the predicted values. In the galvanizing industry and the molten metal handling areas of the zinc refinery, gloves were worn frequently, but no attempt was made to keep the gloves clean and they were reused until they no longer provided physical protection for the hands. In the galvanizing factories, workers frequently removed their gloves, for example, when writing or when resting. At such times, the hands could become contaminated owing to contact with dusty surfaces. The gloves were replaced on the contaminated hands, thereby increasing the potential for exposure. In the case of the galvanizing factory in Phase 2, it was noted that the workers’ hands were visibly contaminated with metal particles. Clearly, these zinc particles had made their way inside the gloves from frequent removal and replacement of the gloves in the workplace.

Similar observations were made in the zinc chemical factories. In these cases, the contaminating effects were much greater owing to the intrinsic dustiness of the processes. Again, gloves were not intended to control dermal exposures, but to protect the skin from abrasion or cuts. Many workers did not use gloves at all, and others wore them at various
times. It was observed that many workers who wore gloves had heavily contaminated skin when the gloves were removed at the time of sampling. Again, it was obvious that the insides of the gloves had become contaminated owing to repeated removal and replacement while working in dusty areas.

The data from the bag dumping exercise, where the subjects did not wear gloves, compare favourably with the workplace exposures, and this provides some reassurance that the intermittent use of gloves did not affect the exposure measurements to a great degree. In fact, the measured workplace exposures are generally higher than the laboratory simulations. This indicates that dermal exposure in the workplace cannot be explained solely by the tasks or substances concerned, or by whether or not gloves are worn. Factors such as the levels of surface contamination and human behaviour are likely to be important determinants of exposure.

The measures of zinc exposure produced by this study and by the EASE predictions are expressed in terms of the mass of contaminant per unit area of skin, that is, the surface loading. The value of surface loading as a measure of exposure is debatable, particularly for relatively insoluble substances such as zinc. This is because once the skin is completely covered with dust, additional loading may not have a corresponding increase in the potential to cause irritation or increase the rate of absorption. Rather than using measures of skin surface loading, it may be more appropriate to consider the solubility and concentration of compounds in the skin contaminant layer as discussed by Cherrie and Robertson (1995).

CONCLUSION

The EASE model provides dermal exposure estimates for generalized categories of work with hazardous substances. The model for dermal exposure is simplistic and tends to overestimate exposures when compared with workplace dermal exposure measurements made using wipe sampling. Nevertheless, the model is simple to use and is capable of providing exposure predictions where there are no existing data. This study illustrates that patterns of dermal exposure may be highly variable, both within individual workplaces and within categories of tasks. Furthermore, exposure occurs across the whole body, not just on the hands and forearms, which is not taken into account by EASE.

The EASE model has been used for estimating dermal exposures in regulatory risk assessments, but in general EASE is conservative and overestimates dermal exposure by a factor of ~50. It is clear that further work is necessary to refine the EASE model to improve its reliability in these circumstances. Practical exposure assessment methods must incorporate all the elements relevant to exposure if they are to be useful in assessing human health risks.

Acknowledgements—This work was funded by the International Lead Zinc Research Organisation (ILZRO program ZEH-4) and the authors express their gratitude to all those from within the zinc industry who participated in the study. The authors are grateful to Paul Roberts, who conducted the dustiness tests at the UK Health & Safety Laboratory, Sheffield. Thanks are also due to other IOM scientists: Karen Creely for her assistance with the field assessments, Carolyn McGonagle for carrying out the sample analyses and Dr Anne Soutar for carrying out the statistical analyses.

REFERENCES