Critical Evaluation of Historical Occupational Aerosol Exposure Records: Applications to Nickel and Lead

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Published or unpublished data sets on individual occupational exposure situations are frequently combined and used for some wider purpose, either hazard evaluation or standards setting. This paper describes a model by which such individual data sets for occupational aerosol exposures might be evaluated in terms of their usefulness in this regard. For workplace aerosols, the model is centered around the particle size-selective framework for aerosol exposure assessment that has emerged in recent years as a rational basis for standards setting. In this paper, reported occupational exposures to airborne nickel and lead are used as examples. In a comprehensive review, 106 published peer-reviewed sources of potentially useful exposure data were found for nickel and 111 similar reports for lead. In addition, for lead 116 unpublished reports in the form of hazard evaluation reports from the US National Institute for Occupational Safety and Health were also examined. For both nickel and lead, a wide range of industry sectors was represented, and the data sets cover the period from 1930 to the present day. It was found that such published data sets are highly inconsistent in terms of the criteria by which the data were obtained, notably for the paucity of essential details of the methods that were used. In contrast, for the lead exposures, the unpublished government reports are more consistent, since they usually followed recognized exposure assessment standards. However, the latter may be misleading because they may have tended to represent high exposure situations. The evaluation model described in this paper provides not only a basis for the evaluation of historical exposure data but also guidelines for new exposure assessment to be carried out in the future. Meanwhile, although many of the historical exposure data sets were found to be generally quite weak in terms of their immediate usefulness, attention is drawn to some of their statistical properties that might allow their enhancement for the purposes of hazard evaluation and retrospective exposure assessment exercises.

Keywords: aerosol exposure; critical evaluation; historical records; lead; nickel

INTRODUCTION

Hazard surveillance in the occupational setting may be defined as the ongoing and systematic collection, analysis, interpretation and dissemination of current and historical data on occupational hazards, hazard controls and new processes and technologies for the purpose of the prevention of disease or injury in the workplace (Greife et al., 1995). Occupational exposure data reported in the open literature represent an important pool of information in the evaluation and control of workplace hazards. For a given workplace, such data are useful in identifying specific workers exposed to potentially harmful levels of airborne contaminants and in identifying control measures to reduce exposures. However, the value of each such individual data set for a given type of exposure should not be limited just to the workplace in question, but should also be capable of being added to a larger pool in order to achieve hazard surveillance in the wider sense. In turn, such pools of data become important tools in the standards setting process. For example, in the UK, the Health & Safety Executive (HSE) routinely brings such data pools to its Working Group on the Assessment of Toxic Chemicals (the ‘WATCH’ Committee), its primary
forum for the scientific discussion of occupational exposure limits. In the USA, the National Occupational Research Agenda (NORA) of the National Institute for Occupational Safety and Health (NIOSH) has included surveillance research methods as one of its 21 top research priorities (NIOSH, 1996).

Many efforts to employ occupational exposure data from diverse groups of sources in making wider inferences about the exposures of working populations have appeared in the peer-reviewed literature. However, closer inspection of these reports reveals that the manner of collection and detail of the reporting of the individual data sets is highly variable. This is of course inevitable, since each data set will have been collected with a specific intention and that intention will have been different in each case. However, this in itself presents a problem for the application of the cumulative data set unless there is some way in which the data can be combined to take into account that inhomogeneity.

In addition to the peer-reviewed literature, exposure data collected by governmental agencies in the course of workplace inspections (e.g. by NIOSH in the USA and HSE in the UK) are other potentially valuable resources. These unpublished data sets can be more readily interpreted because they are usually collected according to standardized protocols set out by the agencies in question. But they themselves are often limited by the fact that sampling may have been selectively carried out by compliance officers in areas of intense exposure, as well as by the exclusion from the pool of inspected workplaces of small operations that may be exempt from the scope of regulatory activities.

For data sets to be combined in the way suggested implies the requirement that they all be consistent in some fundamental way. So it is a major concern that such consistency might not always exist. To discuss this, we return to a fundamental principle of exposure assessment: namely that it should be carried out within a framework that requires adherence to health-related criteria that clearly identify exactly what it is that is to be measured, followed by the application of measurement techniques and sampling strategies that demonstrably match those criteria. Such a framework is especially relevant to aerosols, where health effects are strongly related to where particles are deposited inside the respiratory tract after inhalation, which in turn is largely dependent on particle size. The past two decades have seen the emergence of a set of quantitative guidelines that define a number of particle size fractions, specifically the inhalable, thoracic and respirable fractions, as reviewed in the book recently published by the American Conference of Governmental Industrial Hygienists (ACGIH) (Vincent, 1999). In turn, aerosol sampling instrumentation options have emerged matching one or more of these criteria and are commercially available. Such a framework for aerosol standards is now being widely applied around the world, by many governments in various regulatory frameworks and by private industries within their own internal hazard surveillance programs.

Recent papers in the Annals of Occupational Hygiene have addressed the question of how to improve the use of measured workplace exposure data for the purpose of regulatory risk assessment. Money and Margary (2002) argued that all available data sets should not be regarded as equally useful in this regard, noting that the exposure information should be relevant to the need and that such information should be weighted with regard to an agreed hierarchy that expresses that relevance. Tielemans et al. (2002) argued that current applications of occupational exposure data sets in hazard assessment and standards setting are largely subjective and proposed a decision tree by which such data sets could be rated in terms of their ability to progress through a succession of levels, the first concerned with completeness of relevant occupational hygiene information, the second with questions of variability and precision, the third with internal validity and the fourth with external validity. This then comes close to providing a workable practical evaluation tool.

The work described in this paper began in the early 1990s when such questions were being posed, in particular as they related to the application of historical data for occupational nickel exposures in a specific standards setting exercise. It also seeks to provide a way to rate, and perhaps weight, individual data sets in an overall pool of data. Although initially driven by interest in the case of nickel, it is generic for the consideration of all occupational aerosol exposures. With this in mind, the paper proposes a general model by which to classify individual data sets for occupational aerosol exposures from both published and unpublished sources in relation to their utility in hazard surveillance. It then proceeds to examine historical occupational nickel and lead exposure records as specific examples.

**MATERIALS AND METHODS**

Understanding the nature of aerosol exposure by inhalation and how particle deposition in various parts of the respiratory tract can contribute differently to exposure-related health risks provides an important foundation for aerosol exposure assessment. An ideal set of aerosol exposure data should be obtained by a sampling method that matches one or more particle size-selective criteria that are clearly linked with relevant health effects, used within a sampling strategy that is representative of the workforces of interest and backed up by analytical proced-
ures that provide results for the appropriate chemical species.

Such characteristics in individual data sets in a given pool were sought in the present enquiry. However, it was not surprising to discover that finding occupational exposure data collected and reported in such an ideal manner is rare. There are several reasons. Firstly, historical data sets are likely to be characterized by large differences in how the reported exposure data were collected, involving great variations in the types of sampling instruments used, as well as the sampling strategies, analytical methods and statistical procedures employed. Secondly, the amount of detail provided by the individual authors about industrial processes, sampling methodology and statistical characteristics of the data varies considerably, depending on where the data were presented. Furthermore, the primary purposes for which the data were originally collected may differ, ranging from the assessment of the compliance status of a particular workplace to the correlation of airborne contaminant levels with a biological index of exposure, to the evaluation of a particular exposure control methodology. Another important consideration is the degree to which supporting information is reported; for example, the inclusion of details on the use of personal or area sampling strategies, sample duration or the identification of the analytical method employed.

To draw together such differences, we have developed a qualitative tool for rating the reports of exposure data. Such a tool should produce a sufficiently steep gradient so that two or more distinct classes can be identified and these classes should differ in a manner that relates to the utility of each report in relation to the broad question of hazard surveillance. It must recognize that a written report presenting occupational exposure data should contain references to two distinct stages, data collection and data reduction and presentation. It is possible in principle to develop the tool in such a way as to reflect the modern principles of exposure assessment in considerable detail, including reference to desired specific technical properties and statistical properties. However, it is the present intention to generate a tool that adheres to the central principles and refers to the primary areas that need to be addressed and yet remains simple and flexible in its use.

Figure 1 shows the tool that resulted from all these considerations. In this tiered structure a data set that does not proceed beyond Level 0 would contain only minimal information. For example, it might contain rough estimates of exposure but no actual measured data. Or it may refer only to a general industry sector, but fail to identify or distinguish between individual worksites. Such a data set is considered to be without value for the desired practical purpose. In contrast, a data set that in both its execution and reporting meets all the desired characteristics such that it truly reflects the health-related exposures of the workers in question would achieve the ideal Level 4. Here, not only are the sampling methods and strategy well defined, but they also conform to appropriate health-related particle size-selective sampling criteria. In addition, they contain references to measurement of the distributions of particle size and chemical species, statistical properties of workers’ exposures, whether or not respiratory protection was being used and possible contributions to dose arising from exposure by routes other than inhalation. In other words, a Level 4 data set would contain all the information that would be required to make the fullest possible evaluation of the hazard. In between the two extremes it is valuable to identify intermediate levels in order to reflect the ‘gradient’ between the characteristics of the data sets. It is noted that the tool is based on essentially scientific considerations. As it is presented, although the tool does not explicitly address the question of the intent underlying each data set, this is covered at Level 2 by evaluation of the data in terms of its statistical properties, where sampling for compliance purposes may be acknowledged as being fundamentally biased.

Again, as stated, the aim has been to develop a tool that is useful and includes a reference to the primary important qualities required of exposure data sets, but is also simple enough that it can provide the desired gradient between less and more useful data sets and not be overly exclusive. So in Fig. 1 the technical requirements are quite broad; for example, sampling duration should be reported for a data set to progress to Level 2, but no specifications are given with regard to what is and what is not acceptable. The statistical requirements are also quite broad; for example, some consideration of statistical properties should be given in order that a data set can progress to Level 3, but no actual specifications are given about the level of detail that is needed (e.g. specific statistical requirements for defining working groups, information about numbers of actual workers sampled, repeat samples on individual workers, etc.).

Finally, it is important to note that, as an overarching rationale for application of the proposed evaluation tool, it should be applied by experts well versed in the principles of occupational hygiene and exposure assessment, either professional occupational hygienists or occupational hygiene scholars.

RESULTS

Nickel

Airborne nickel is considered to be a hazard in many workplaces, including both the nickel primary producing and using sectors. Doll et al. (1990) reported a major epidemiological study in the primary nickel industry and although the link
Fig. 1. Schematic illustration of the process for evaluating reports containing occupational exposure data for lead.
between lung and nasal cancer and exposure to various nickel species was clearly established, it was freely acknowledged that the available historical exposure data were insufficiently well characterized to enable that link to be quantified. This prompted new research during the 1990s to better characterize nickel exposures in the primary nickel production, nickel alloy production and nickel electroplating industries, both by our group as well as others. Such research was further stimulated by the lowering by ACGIH of its threshold limit values (TLVs) for nickel and their expression in terms of more than one chemical species (ACGIH, 2002).

In our study, reports detailing occupational exposure data for nickel were identified by conducting a search on MEDLINE, Cancerlit, Excerpta Medica and Toxline. There were 258 such reports. Data sets not proceeding beyond Level 0 in the application of the evaluation tool (see above) were rejected. For these, information was very sparse; for example, no actual exposure values were reported or worksites were not identified beyond a very general allusion to industry sectors. After eliminating these sources, the search yielded 106 acceptable published reports representing 11 specific industry sectors. After eliminating these sources, the search yielded 106 acceptable published reports representing 11 specific industry sectors, including a variety of quite well-defined primary production and user industries plus a twelfth group embodying a variety of miscellaneous other occupational exposure situations. The latter group was quite diverse, including for example glass manufacture, magnet manufacture, foundries, polishing and de-burring, flame spraying of nickel-containing powders, etc. The numbers of reports found for all 12 groups are listed in Table 1. They cover the periods pre-1960, 1961–80 and 1981–present.

These data reports reflect a wide range of sampling methods. Although all the exposure data are reported in terms of total nickel (i.e. all species), most of the earlier ones (pre-1960) were derived from measurements that were originally obtained (and recorded in industry files) by gravimetric analysis of material collected on filter media during area sampling or by the counting of particles collected by konimeter in workers’ breathing zones. So in the published reports these metrics had been converted into total nickel using conversion factors available from the best information available at the time. More recent reports contained data from personal sampling campaigns, where total nickel was determined directly from filter deposits by appropriate analytical methods. For these, the most favored analytical method was inductively coupled plasma absorption emission spectrometry (ICP-AES).

Figure 2a and b shows the distribution of scores obtained using the evaluation tool for the occupational nickel exposures. The evaluations were carried out directly with respect to the data as reported, without any refinement (see below). Figure 2a shows that a high proportion of the data sets fall into the lowest category, although there is a significant proportion that advances to Level 3, especially for the more recent data sets. A small proportion of very recent data sets reaches Level 4, including some from our own group carried out in the light of an awareness of the significance of the new particle size-selective sampling criteria. When the results are plotted in

<table>
<thead>
<tr>
<th>Industry sector</th>
<th>No. of data sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mining</td>
<td>3</td>
</tr>
<tr>
<td>2. Smelting</td>
<td>7</td>
</tr>
<tr>
<td>3. Refining</td>
<td>15</td>
</tr>
<tr>
<td>4. Steel production</td>
<td>9</td>
</tr>
<tr>
<td>5. Nickel alloy production</td>
<td>6</td>
</tr>
<tr>
<td>6. Welding and hot cutting</td>
<td>26</td>
</tr>
<tr>
<td>7. Forging, grinding and hot cutting</td>
<td>6</td>
</tr>
<tr>
<td>8. Nickel plating</td>
<td>11</td>
</tr>
<tr>
<td>9. Nickel chemical production</td>
<td>2</td>
</tr>
<tr>
<td>10. Nickel catalyst production</td>
<td>3</td>
</tr>
<tr>
<td>11. Nickel-cadmium battery production</td>
<td>4</td>
</tr>
<tr>
<td>12. Miscellaneous</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>106</td>
</tr>
</tbody>
</table>

Fig. 2. (a) Distribution of evaluation scores for occupational nickel exposure, in terms of number of sources (i.e. data sets).
(b) Distribution of evaluation scores for occupational nickel exposure, in terms of number of data records.
terms of the number of actual data records (see Fig. 2b), the tendency of the data to fall within the lowest category is even more marked. Here, a very large proportion does not advance beyond Level 1.

For the data sets analyzed here for nickel, all the reports were taken from the peer-reviewed literature, and most of these were for the purposes of epidemiological enquiry. So any significant bias towards ‘worst case’ situations was not expected.

Lead

A similar exercise was carried out for occupational lead exposures. Here, firstly, there were a larger number of industry sectors relevant to such exposures. Secondly, the search for historical records also included unpublished reports from government agencies. As a result, the discussion that follows differs somewhat from that for nickel.

Airborne lead in workplaces represents a major category of occupational aerosol exposure and has been extensively studied. Froines et al. (1990) conducted an analysis of a large set of occupational lead exposure data obtained in compliance inspections by the US Occupational Safety and Health Administration (OSHA) conducted between 1979 and 1985. The objectives of their study included the examination of the distribution of airborne lead levels across relevant industries and the identification of job titles associated with excessive lead exposure. Data were categorized according to standard industrial classifications (SICs) and the year in which sampling took place. More than one-third of the observed exposures were found to exceed the permissible exposure limit (PEL) of 50 µg/m³ in 52 SICs and a number of job titles associated with particularly high lead exposures were identified. An analysis of data from six SICs with the highest exposures revealed no apparent trends in observed exposures over the time period examined. In our study, reports detailing occupational exposure data for lead were again identified by conducting a search on MEDLINE, Cancerlit, Excerpta Medica and Toxline. In addition, unlike for nickel, a search was conducted for reports detailing occupational exposure data for airborne lead available through the US National Technical Information Service (NTIS). These searches yielded a large number of abstracts for reports that were considered likely to contain occupational exposure data for lead; only those which were considered likely to contain such data were retrieved for more in-depth examination. Most notable were the Health Hazard Evaluation Reports (HHERs) from NIOSH, describing field surveys of occupational exposures carried out in response to specific requests by plant managers or employees or their representatives. Because of their predominance among unpublished reports, HHERs were the only type of unpublished report retained in the pool. The numbers of reports found for 26 industry sectors are included in Table 2.

Again, as for nickel, data sets for lead falling at Level 0 were rejected, and once more a significant proportion of the citations emerging from the search fell into this category. All the reports that progressed to Level 1 and beyond were classified on the basis of the industrial sector or process represented by the data. The search yielded 111 acceptable published and 116 acceptable unpublished reports. The total number of acceptable sources was therefore 227, representing 25 specific industry sectors, including a variety of primary production and user industries and a large group of miscellaneous industries.

Most of the published reports represented sampling campaigns carried out during 1968–1994. The unpublished HHERs represented campaigns conducted during 1975–1993. In order to detect overall trends in exposure levels in particular industries, the reports were assigned into just three categories based on the year in which the reported exposure data were collected, pre-1960, 1961–1980 and 1981–present.

<table>
<thead>
<tr>
<th>Industry sector</th>
<th>No. of data sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Accumulator production</td>
<td>4</td>
</tr>
<tr>
<td>2. Battery production</td>
<td>23</td>
</tr>
<tr>
<td>3. Bearing manufacture</td>
<td>2</td>
</tr>
<tr>
<td>4. Capacitor and resistance manufacture</td>
<td>3</td>
</tr>
<tr>
<td>5. Copper smelting</td>
<td>2</td>
</tr>
<tr>
<td>6. Electronics manufacture</td>
<td>6</td>
</tr>
<tr>
<td>7. Fire assaying / precious metals refining</td>
<td>7</td>
</tr>
<tr>
<td>8. Firing ranges</td>
<td>30</td>
</tr>
<tr>
<td>9. Foundries</td>
<td>10</td>
</tr>
<tr>
<td>10. Glass manufacture</td>
<td>6</td>
</tr>
<tr>
<td>11. Highway maintenance and regulation</td>
<td>6</td>
</tr>
<tr>
<td>12. Lead smelting (primary)</td>
<td>8</td>
</tr>
<tr>
<td>13. Lead smelting (secondary)</td>
<td>6</td>
</tr>
<tr>
<td>14. Municipal waste incineration</td>
<td>3</td>
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<tr>
<td>15. Paint removal</td>
<td>6</td>
</tr>
<tr>
<td>16. Power plants</td>
<td>2</td>
</tr>
<tr>
<td>17. Printing</td>
<td>2</td>
</tr>
<tr>
<td>18. PVC plastics manufacture</td>
<td>5</td>
</tr>
<tr>
<td>19. Radiator repair</td>
<td>15</td>
</tr>
<tr>
<td>20. Radiotherapy shielding fabrication</td>
<td>3</td>
</tr>
<tr>
<td>21. Silk screening operations</td>
<td>2</td>
</tr>
<tr>
<td>22. Steel production</td>
<td>5</td>
</tr>
<tr>
<td>23. Tank lining</td>
<td>3</td>
</tr>
<tr>
<td>24. Tractor manufacture</td>
<td>2</td>
</tr>
<tr>
<td>25. Valve manufacture</td>
<td>5</td>
</tr>
<tr>
<td>26. Miscellaneous</td>
<td>61</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>227</strong></td>
</tr>
</tbody>
</table>
Where this information could not be gleaned from the report, the year of publication was used as a surrogate. The data reports reflect a wide range of sampling methods. Many, especially the more recent ones, contained results from personal sampling campaigns. A large proportion (about 50%) of HHERs reported lead exposure data from both personal and area sampling. All reported results are reported in terms of total lead (i.e. all species), for which atomic absorption spectroscopy was the analytical method most commonly used. Inductively coupled plasma emission methods were also employed in some instances, especially in those studies for which exposure measurements were simultaneously made for a variety of metallic elements in addition to lead.

Figure 3 shows the distribution of scores obtained using the evaluation tool shown in Fig. 1 for the occupational lead exposures. The figure shows the results for both the published and the unpublished data sets. Here only the numbers of data sets are shown. It is seen that the majority of published reports fall into Level 1, suffering from weak application and/or reporting of sampling and analytical methods. The better described ones reach Level 2 and those where personal sampling was used reach Level 3. Only a very small proportion reach Level 4 (one study only, in fact, and that was a relatively recent study from our group that set out specifically to obtain such data).

For the unpublished reports the majority reach Level 2, mainly because the data are very consistent and well described in terms of methodology. However, none of these move on into Level 3 because the collection of data in many of the published reports are likely to have been statistically biased due to compliance and hazard control objectives. According to NIOSH (1992), health hazard evaluations are generally carried out ‘… in response to concerns expressed by employees, employee representatives, or employers to find whether there is a health hazard to employees caused by exposure to hazardous materials in the workplace’. The workplaces described in the HHERs may, therefore, represent a select group of workplaces where there has already been the suggestion that potentially unhealthy work conditions might exist. This in turn suggests that the exposure levels described in these reports may be higher than in other workplaces in the same industry. As noted by Rappaport (1991), this scenario is commonly encountered in occupational exposure assessment and may result in exposure estimates that are artificially inflated.

**DISCUSSION**

Not surprisingly, the reported exposure levels for the industry sectors examined are highly variable. The historical data sets themselves are seen to vary quite widely in terms of the way in which the information is presented. There were, however, certain features common to most of the data sets with regard to data reporting. The majority included: (i) the lowest and highest exposure concentrations; (ii) the number of data records (n); (iii) the average exposure level. For the purposes of the following discussion, such data sets may be regarded in a rudimentary sense as ‘complete’ for the purpose of basic exposure estimation. For the rest, there was one subgroup of data sets where there were gaps in one or more of even these important pieces of basic information. However, there was also a small subgroup where data were communicated much more fully in the form of tables or graphs, thus providing the opportunity for a full retrospective analysis. For the central body of ‘complete’ data sets it is interesting to examine whether they exhibit properties that can be generalized, which in turn might potentially be useful in the overall evaluation of the data pool.

We first examined the 106 published data sets for occupational nickel exposure and found that 78 were ‘complete’ according to our rudimentary definition. A relationship was sought between the average, low and high exposure values and the number of samples. Here, it is intuitive that, for the well-known log normal properties of distributions of occupational exposures to airborne contaminants, the larger the number of data records the more likely it is that higher values of exposure will be found. So it was postulated that the ratio

\[ r_1 = \frac{\text{arithmetic mean}}{(\text{high} - \text{low})} \]  

is a useful metric for embodying some of the statistical properties of the pool of data sets. This quantity is dimensionless and so the actual level of exposure is normalized across all the data sets in the pool.

The nickel exposure data sets are represented in Fig. 4 in the form of \( r_1 \) versus \( n \) for the ‘complete’ 78
data sets. Since the individual data records were not always explicit about how the average was defined, in the calculation of \( r_1 \) it was assumed that the reported value was in fact the arithmetic mean. Figure 4 shows that \( r_1 \) clearly falls steadily as \( n \) increases, and, as already mentioned, this result is intuitive. However, determination of the exact form of \( r_1 \) versus \( n \) involves considerations of the asymptotic distributions of the maxima and minima for the exposure distributions of interest. This mathematical problem has been discussed in detail in a book by Galambos (1987) and it is clear that the development of an explicit functional relationship is far from trivial, so this was not attempted in the present work. Instead, we embarked on a series of numerical simulations that would provide a good picture of what might be expected theoretically.

Multiple Monte Carlo simulations were performed in which numbers of samples (\( n \)) were randomly taken from log normal exposure distributions with geometric standard deviations (GSD) of 1.5, 2.5, 3.5 and 5.0. In this study \( n \) ranged from 2 (the smallest integer for which \( r_1 \) may be calculated) to 3000 (close to the upper end of the range for which actual data for occupational nickel exposures were reported). Here, for occupational exposures it is considered that GSD = 1.5 corresponds to low variability, GSD = 2.5 corresponds to moderate variability and GSD = 3.5 corresponds to high variability [British Occupational Hygiene Society (BOHS, 1993); Mulhausen and Damiano, 1998]. It follows that GSD = 5.0 corresponds to very high variability. The calculations were performed using the software package Crystal Ball® (2000 version; Decisioneering Inc., Denver, CO), linked up with EXCEL® (Microsoft, Seattle, WA). Of the order of 500 such synthetic sampling runs were thus carried out. The simulated results are shown alongside the actual data in Fig. 4. Here it is seen that there is a trend in which \( r_1 \) falls more steeply with increasing \( n \) for the larger values of GSD. However, within the overall scatter exhibited by both the actual and simulated data there is quite good agreement between the two.

Looking at the graph in Fig. 4, there are just two obvious outliers and, in view of the overall agreement elsewhere, these merited closer attention. It was found that both come from the diverse ‘Miscellaneous’ group. One, for \( n = 87 \), related to workplaces where nickel oxide was being used to manufacture electrical resistors (Roels et al., 1993). The other data set, for \( n = 3044 \) to the far bottom right of the graph in Fig. 4, was concerned with workers’ exposures to metallic nickel during the manufacture of porous media for application in-plant for uranium enrichment by gaseous diffusion (Godbold and Tompkins, 1979). For both data sets the average exposure was, in fact, reported in terms of the geometric mean and not the arithmetic mean. Since, for a log normal distribution the geometric mean is less than the arithmetic mean, this would at least partially account for the fact that the \( r_1 \) values for these two data sets both fell well below the trend line for all the other data sets. Even so, we also note the acknowledgement by Godbold and Tompkins that the geometric mean of
0.13 mg/m³ might be ‘… on the low side’. Overall, it is reasonable that these two data sets (at least) may be regarded as outliers.

Inspection of the results of the Monte Carlo simulations for each of the four GSD values shows that the trend of \( r_1 \) versus \( n \) follows a simple power function (again see Fig. 4). These simulated data are well represented by the power function

\[
r_1 = n^{k \cdot \text{GSD}}
\]

where \( k = 0.12 \pm 0.01 \). For the actual historical data, after removal of the two obvious outliers, the best fit power function yields

\[
r_1 = n^{-0.55} \quad \text{with} \quad R^2 = 0.54
\]

from which it is possible to make rough, but workable, estimates of the mean exposure levels for data sets where only the low and high values are given along with the number of data records (i.e. only the mean is missing). There are some of these among the incomplete data sets for occupational nickel exposures.

That does not quite complete the picture, however. In addition, there are some data sets where only the low and high values are given, with no mean and not even the number of data records. For these, equation (2) is not very helpful, but a rough estimate may be made from inspection of the ‘complete’ data sets in terms of the simpler relation

\[
r_2 = (\text{mean low})/(\text{high} – \text{low})
\]

for which

\[
r_2 = 0.190 \pm 0.017 \quad \text{(SE)}
\]

From the preceding it becomes possible, if desired, to obtain a more complete usable summary of the data sets for occupational nickel exposures. In fact, 16 additional data sets were ‘recovered’ in this way.

The same approach may be applied to the occupational lead exposure data. Here, only the 111 published data sets were included. For these, 66 met our rudimentary definition for ‘completeness’, a smaller proportion than for nickel. The complete data sets for lead are represented in the form of \( r_1 \) versus \( n \) in Fig. 5 and empirical relations similar to those given for nickel in equations (2) and (3) are easily available. This graph also shows the Monte Carlo-derived curves corresponding to equation (2), and once again we see good broad agreement between the actual data and theory.

**CONCLUDING REMARKS**

The exercise described here draws attention to a number of features of historical aerosol exposure data records that have important implications for hazard evaluation. Data sets like those identified in this study (i.e. for nickel and lead) are widely used for the purpose of standards setting, in the first instance to provide exposure histories for workers in epidemiological studies where health effects may have long latency periods. In the case of nickel, for example, occupational cancers may be associated with expos-
ures that began decades prior to onset of the disease. For this purpose, it is important that data records throughout the whole period relevant to the exposure histories of worker cohorts of interest are related to consistent health-related measurement criteria and are described in sufficient detail. They cannot simply be taken at face value. Data sets that reach the highest level in the evaluation tool demonstrably follow the broad principles embodied in modern occupational aerosol standards, i.e. the exposure measurements must have been carried out with regard to the health effects relevant to the substance in question and with respect to the fractional deposition of particles in the respiratory tract upon inhalation. The measurements should also adequately reflect the actual exposures of workers by the adoption of rigorous occupational hygiene practices for exposure assessment, including obtaining sufficient numbers of personal samples using sampling instrumentation matching appropriate criteria and following rigorous documented procedures. It is not surprising that the earliest data sets are the ones most likely to fall short, since many of the principles referred to have crystallized only in relatively recent years. In the meantime, it is hoped that the evaluation tool outlined in Fig. 1 will provide a guideline for future field exposure assessment activities.

However, notwithstanding the inherent weaknesses of most of the individual data sets as they stand, the inspections reported in this paper lend support to the growing field of retrospective exposure assessment. This is a field where new methods are emerging that will permit enhancement of those earlier data sets beyond that described in this paper and so further elevate their usefulness. In this way, data sets not originally meeting the highest requirements can still be useful. Indeed, since these data are all that are available to describe previous workers’ exposure histories, thoughtful retrospective exposure assessment is desirable, rather than simply discarding these records. One good example is the study reported by Ramachandran (2001). Although this work embodied methodologies generic to occupational retrospective exposure assessment in the widest sense, it dealt specifically with the example of exposures to nickel-containing aerosols in the nickel primary production industry. An important feature of that work was the examination of the relationships between exposure measures using different sampling devices and strategies, and the uncertainties and biases between them, and the development of conversion factors. In this way, data sets originally falling within Level 1 might be elevated to higher levels. It is encouraging that NIOSH in the USA has recognized this need and is currently funding two projects in this area (see http://www.2.cdc.gov/nioshprojects).

In the meantime, analysis of the data sets described in this paper shows some interesting trends that may be useful in a wider context. The empirical observation of relatively simple associations between the measured low and high exposure levels, means and numbers of data records points to some properties that may be generalized. Although the equations relating the ratio \( r_1 = \text{mean/(high–low)} \) to the number of samples \( (n) \) are entirely empirical, they do relate plausibly to the statistical nature of occupational exposures like those described in this paper and are in excellent agreement with the results of Monte Carlo simulations for exposures with moderate to high variability.

In conclusion, from what has been described here it is apparent that the available reported data for occupational nickel and lead exposures are generally not sufficiently well described to enable them to be combined to form a truly useful pool of data for broad hazard surveillance purposes. The same is likely to be true for other substances. This underlines the importance in the conduct of all occupational exposure assessment and epidemiology, and its subsequent reporting, of paying appropriate attention to the basic principles of exposure assessment. This means ensuring that: (i) exposure measurements are made using sampling techniques and strategies that properly relate to the health effects underlying the need for exposure assessment; (ii) the data and qualifying information are reported in sufficient detail that readers may subsequently make a judgment as to the value of the data set in question. For the latter an evaluation tool like that described in this paper for occupational exposure to airborne nickel and lead can be useful. The same philosophy may be applied more widely for the assessment of other occupational chemical hazards and in environmental health more generally.

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