Pergamon

PII: S0003-4878(01)00022-9

*Ann. occup. Hyg.*, Vol. 45, No. 4, pp. 275–282, 2001

Printed in Great Britain.
0003-4878/01/$20.00

# Estimating Mean Exposures from Censored Data: Exposure to Benzene in the Australian Petroleum Industry

**D. C. GLASS†* and C. N. GRAY‡**

*†Department of Epidemiology and Preventive Medicine, Monash University, Victoria, Australia, formerly Health Watch, Department of Public Health and Community Medicine, The University of Melbourne* 200 *Berkeley Street, Carlton, Victoria* 3053, *Australia; ‡Occupational Hygiene Unit, Faculty of Science and Technology, Deakin University, Victoria, Australia*

**A retrospective assessment of exposure to benzene was carried out for a nested case control study of lympho-haematopoietic cancers, including leukaemia, in the Australian petroleum industry. Each job or task in the industry was assigned a Base Estimate (BE) of exposure derived from task-based personal exposure assessments carried out by the company occupational hygienists. The BEs corresponded to the estimated arithmetic mean exposure to benzene for each job or task and were used in a deterministic algorithm to estimate the exposure of subjects in the study.**

**Nearly all of the data sets underlying the BEs were found to contain some values below the limit of detection (LOD) of the sampling and analytical methods and some were very heavily censored; up to 95% of the data were below the LOD in some data sets. It was necessary, therefore, to use a method of calculating the arithmetic mean exposures that took into account the censored data.**

**Three different methods were employed in an attempt to select the most appropriate method for the particular data in the study. A common method is to replace the missing (censored) values with half the detection limit. This method has been recommended for data sets where much of the data are below the limit of detection or where the data are highly skewed; with a geometric standard deviation of 3 or more. Another method, involving replacing the censored data with the limit of detection divided by the square root of 2, has been recommended when relatively few data are below the detection limit or where data are not highly skewed. A third method that was examined is Cohen's method. This involves mathematical extrapolation of the left-hand tail of the distribution, based on the distribution of the uncensored data, and calculation of the maximum likelihood estimate of the arithmetic mean.**

**When these three methods were applied to the data in this study it was found that the first two simple methods give similar results in most cases. Cohen's method on the other hand, gave results that were generally, but not always, higher than simpler methods and in some cases gave extremely high and even implausible estimates of the mean. It appears that if the data deviate substantially from a simple log-normal distribution, particularly if high outliers are present, then Cohen's method produces erratic and unreliable estimates. After examining these results, and both the distributions and proportions of censored data, it was decided that the half limit of detection method was most suitable in this particular study.** 

*Keywords:* benzene; retrospective exposure assessment; epidemiology; limit of detection; censored data

## INTRODUCTION

Detailed assessments of exposure to benzene in the Australian petroleum industry have been carried out as part of a case-control study of lympho-haematopoietic (LH) cancer (leukaemia, multiple myeloma and

Received 17 August 2000; in final form 19 January 2001.
*Author to whom correspondence should be addressed. Tel.: 61-3-990-30554

non-Hodgkin's lymphoma). The case control study was nested within a large cohort study known as Health Watch which is an epidemiological health surveillance program that has been operating since 1980. Health Watch was run until 1998 by the University of Melbourne and is now based at the University of Adelaide. It consists of a prospective cohort study of all causes of mortality and cancer incidence among almost 17 000 mainly blue-collar employees. In 1987 an excess of LH cancers was identified in this cohort and a case control study was later initiated to investigate the possible association between the LH cancers and exposure to benzene. The case control study is being undertaken jointly by Monash and Deakin Universities.

Seventy-nine confirmed cases of LH cancer were identified within the cohort and each case was matched with five controls giving a total of 474 subjects (some controls were used for more than one case). The benzene exposure of the cases and controls was retrospectively assessed. Detailed occupational histories were obtained for all subjects by structured interview and these were individually assessed in order to allocate jobs and tasks to each time period. Each of these jobs and tasks was given a Base Estimate (BE) of exposure in ppm to benzene corresponding to the arithmetic mean of the measured exposures. Most of the BEs were derived from the results of task-based personal exposure measurements supplied by company occupational hygienists. A few BEs were augmented with data from the literature. The task and job exposure histories for individuals were used along with the BEs and modifier factors to account for changes in technology and product composition, in a deterministic algorithm, in order to calculate various quantitative exposure metrics for each individual. The exposure assessment process is described in more detail elsewhere (Glass *et al*., 2000). The exposure metrics that were examined in the epidemiological analysis included long term average exposure (ppm) and cumulative exposure (ppm-years). These metrics were generated from the various BEs and hence relied upon estimation of the arithmetic mean of the task-based exposure data. However, it was found that many of these data sets were censored, i.e. they contained some results below the limit of detection (LOD). In order to take account of the censored data, three different methods were used and the results were compared.

## METHODS

There were 36 different BEs based wholly on industry data. Some of the 36 underlying data sets were very robust with several hundred data points mostly associated with refinery unit operations, while others were smaller and seven sets had less than 10 data points (Fig. 1). Tests of log-normality on the larger data sets showed that most of them had approximately log-normal distributions; examples are shown in Figs. 2 and 3. The data set for 'Instrument fitters' was the most anomalous. Most of their exposures were low, but Instrument Fitters carry out occasional high exposure tasks and these were included in the data set. This lack of log-normality, particularly the presence of high exposure outliers makes the statistical analysis problematic in such cases. If sufficient information was available, it would be more appropriate to separate these data according to the tasks and analyse the subsets independently.

Exposure to benzene is generally low in the industry, so exposure measurements are frequently below the LOD. Of the 36 data sets, 35 had at least one data point below the limit of detection and some were highly censored (Fig. 4). For the most heavily censored data set only 5% of the results were above the limit of detection.

A further complication arose because there were multiple limits of detection for most of the data sets in this study. There were three main reasons for this multiplicity of detection limits: the data came from different companies who may have used slightly different sampling and analytical techniques; analytical detection limits have changed over time; and chiefly because detection limits expressed as air concentrations are heavily dependent on the flow rate and duration of the sample (the sample volume). For example, the data for the general job category 'Refinery Operator Not Directly Exposed to Benzene' came from several refineries and showed several clusters of data when censored points were plotted, at half the detection limits of 0.01, 0.02, 0.03, 0.05, 0.07, 0.09, 0.1 and 0.2 ppm for the various samples (Fig. 5).

In order to calculate the mean of a censored data set, account must be taken of the data below the limit of detection; they cannot be excluded from the calculation nor assumed to be zero without introducing unnecessary and sometimes large errors. Several methods are available to account for the censored values. The simplest method is to set all values below the LOD to a half the LOD (Method 1). This method has been recommended for data sets where much of the data are below the limit of detection or where the data are highly skewed; with a GSD of 3 or more. Another recommended approach is to replace the values below the LOD with the LOD divided by the square root of 2 (Method 2). This has been recommended when relatively few data are below the detection limit or where data are not highly skewed (Hornung and Reed, 1990).

A third approach is Cohen's method (Method 3) as described by Perkins *et al*. (1990). This allows extrapolation of the left-hand tail of a censored normal (Gaussian) distribution, based on the distribution of the uncensored data. This is possible, even with heavily censored data sets, provided that the underlying distribution of the data is known. A similar method

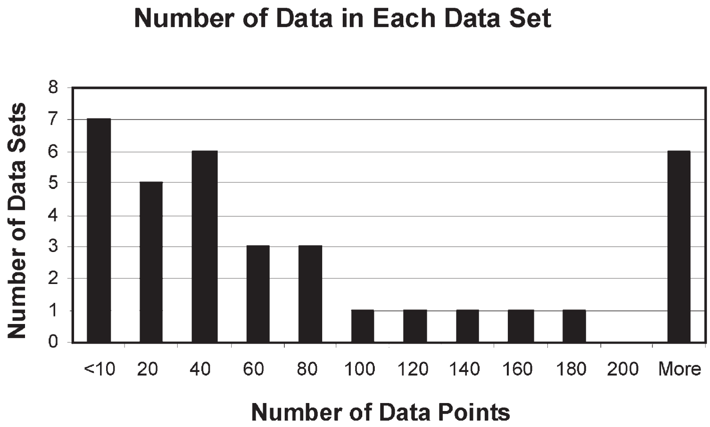


Fig. 1. Distribution of sizes of data sets.

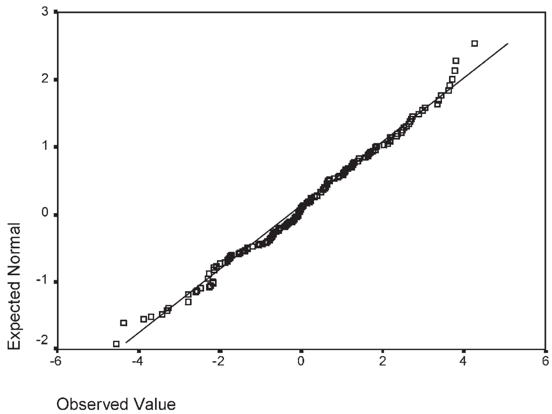


Fig. 2. Typical plot showing near log-normality of benzene exposure data (ppm) for a large data set (rail car filling).

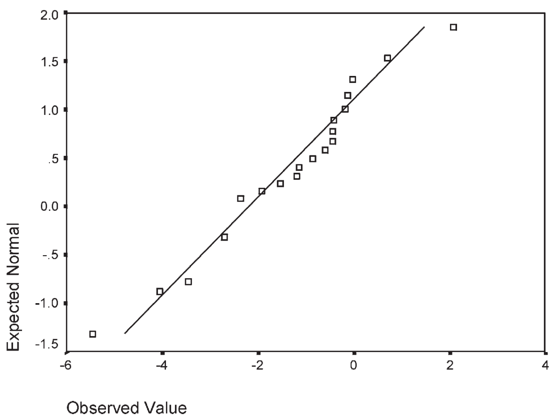


Fig. 3. Typical plot showing approximate log-normality of benzene exposure data (ppm) for a small data set (bottom loading of road tankers).

suggested by Hald (1952), based on extrapolation of the missing data from information contained in the uncensored data has previously been shown to be a reliable method for large simulated data sets with a strictly defined distribution (Hornung and Reed, 1990). It has been reported that Hald's method is not applicable when more than 50% of the data are below the limit of detection, whereas Cohen's method can be applied even if the censoring point is greater than the median of the distribution (Perkins *et al*., 1990). If it can be assumed that the exposures have a log-normal distribution, then the data can be easily transformed into a normal distribution suitable for Cohen's method by taking the logarithm of each value.

After testing the data for log-normality the method involves taking the logarithms of the uncensored data and determining their mean ($\bar{X}_{\log}$) and variance ($s^2_{\log}$). The proportion of uncensored measurements ($h$) and the logarithm of the limit of detection ($X_0$) are also calculated. These are then used to calculate a parameter ($\gamma$):

$$\gamma = \frac{s^2_{\log}}{\bar{X}_{\log} - X_0} \tag{1}$$

The parameters $\gamma$ and $h$ can in turn be used to obtain an 'auxiliary estimator function' ($\lambda$). Normally this is obtained from tables (Cohen, 1961) but for convenience in this study polynomial functions were fitted to the tabulated data so that they could be used in spreadsheet calculations.

When $\gamma = 0$ (no censoring), $\lambda$ can be approximated by the quartic function:

$$\lambda = 9.87224 \times h^4 - 10.64875 \times h^3 + 4.92012 \times h^2 + 0.61938 \times h^2 \tag{2}$$

and when $\gamma = 1$ (100% censoring), $\lambda$ can be approximated by the quartic function:

$$\lambda = 10.21793 \times h^4 - 10.90729 \times h^3 + 4.97864 \times h^2 + 1.12723 \times h \tag{3}$$

For values of $h$ between 0 and 1, $\lambda$ can be obtained by linear interpolation between the values obtained by these two equations (1 and 2). The mean ($\hat{M}_{\log}$) of the total distribution of logarithms including the missing (censored) data is then estimated by:

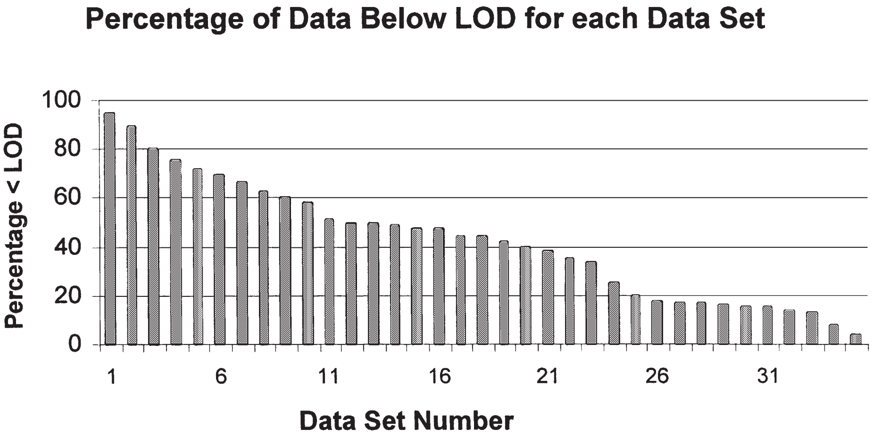


Fig. 4. Percentage of censored data in each data set.

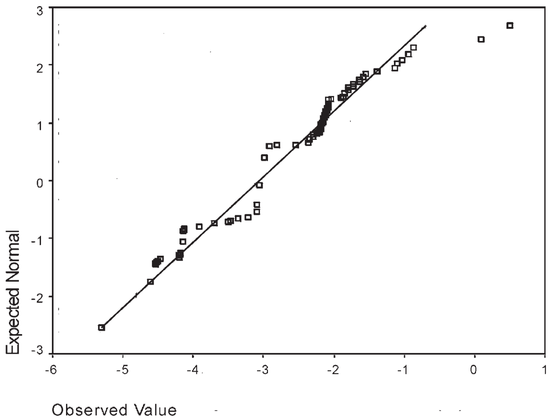


Fig. 5. Cumulative plot of log benzene exposure concentration (ppm) for 'Refinery Operators Not Exposed'.

$$\hat{M}_{\log} = \bar{X}_{\log} - \lambda(\bar{X}_{\log} - X_0) \tag{4}$$

and the variance ($\hat{s}^2_{\log}$) of the total distribution of logarithms is estimated by:

$$\hat{s}^2_{\log} = s^2_{\log} + \lambda(\bar{X}_{\log} - X_0)^2 \tag{5}$$

The maximum likelihood estimate of the arithmetic mean ($M_a$) of the untransformed log-normal distribution is then given by:

$$M_a = \exp\{\hat{M}_{\log} + 0.5\hat{s}^2_{\log}\} \tag{6}$$

The confidence limits of the arithmetic mean can also be calculated although this will not be described here (see Hald, 1952).

Cohen's method has, however, a serious drawback, it can only be used on data that have a single limit of detection. In this study only six of 35 data sets had a single censoring point. The mean was calculated using Cohen's method for these six data sets. For the remaining data sets, with multiple limits of detection, it was necessary to modify the data in order to fit the requirement of a single censoring point. A valid approach is to select the highest limit of detection in the data set and censor all data below this value. This results in some data being discarded, but is an unbiased technique. An approach that is not valid is to use the lowest limit of detection. This would involve assigning all censored data (and any measured data points below the lowest limit of detection) to the range less than the minimum detection limit when in fact some of them were of higher values. The result of this would be to artificially skew the distribution, possibly severely.

## RESULTS

The means of the data sets were very similar when calculated using LOD/2 (Method 1) and LOD/√2 (Method 2) for censored data (Table 1). For almost two thirds (22) of the 35 data sets these two methods resulted in means that were within 5% of each other; three quarters (27) were within 10% and all but two were within 20%. These two data sets were for 'Sour Water' work and 'Airport Background' for which the proportions of censored data were 98.3% and 95% respectively. In general, as the proportion of censored data in the data set, increased, the difference between the calculated means decreased, as expressed by their ratio (Method 1÷Method 2) (see Fig. 6).

Table 1 also gives the mean values calculated by Cohen's method (Method 3) where the data sets had a single limit of detection. All but one of the means calculated by Cohen's method are greater than those calculated by the simpler methods (Table 2).

Because all censored data must lie between zero and the limit of detection, it would be expected that Cohen's method would give a mean lying somewhere between the arithmetic means calculated with the censored data given a value of either zero or the LOD, provided that the data sets had log-normal distributions. These calculations were performed for all the data sets with a single censoring point, and the results are shown in Table 2. In most cases the mean esti-

Table 1. Effect of limit of detection assumptions on estimated mean exposures for various tasks in the Australian petroleum industry

| Base estimate | # Data points | Proportion <LOD (%) | Estimated arithmetic mean Method 1 (LOD/2) | Method 2 (LOD/√2) | Method 3 (Cohen's) | GSD | Ratio 1/2 | Ratio 1/3 |
|---|---|---|---|---|---|---|---|---|
| Airport background | 20 | 95.0 | 0.08 | 0.11 | | 2.48 | 0.71 | |
| Barge loading | 20 | 15.0 | 2.21 | 2.21 | 4.32 | 6.09 | 1.00 | 1.96 |
| CCU operator | 295 | 69.5 | 0.16 | 0.17 | | 2.68 | 0.93 | |
| CDU operator | 404 | 47.0 | 0.11 | 0.11 | | 3.93 | 0.95 | |
| DAP op. pre '89 | 152 | 15.8 | 1.85 | 1.86 | | 3.35 | 0.99 | |
| DAP head op. pre '89 | 46 | 34.8 | 0.74 | 0.76 | | 2.91 | 0.97 | |
| DAP maintenance | 27 | 7.4 | 1.02 | 1.02 | 1.12 | 3.68 | 1.00 | 1.1 |
| Drum fill stub, enclosed | 22 | 0.0 | 3.90 | 3.90 | | 3.27 | 1.00 | |
| Drum fill stub, open | 106 | 19.8 | 3.52 | 3.53 | | 4.62 | 0.97 | |
| Drum fill stub, LEV | 24 | 4.2 | 1.55 | 1.55 | | 6.33 | 1.00 | |
| Drum laundry | 4 | 25.0 | 0.39 | 0.39 | 0.48 | 3.59 | 0.99 | 1.24 |
| Drum preparation | 8 | 62.5 | 0.14 | 0.16 | | 2.29 | 0.89 | |
| Instrument fitter | 42 | 71.4 | 0.48 | 0.49 | | 7.74 | 0.98 | |
| Interceptor cleaning | 14 | 50.0 | 0.12 | 0.13 | | 1.93 | 0.89 | |
| Lab bench high | 534 | 12.9 | 0.74 | 0.74 | | 6.14 | 1.00 | |
| Lab bench low | 65 | 47.7 | 0.15 | 0.15 | | 5.27 | 0.97 | |
| Lab other | 127 | 48.8 | 0.09 | 0.09 | | 4.17 | 0.90 | |
| Offshore operators | 6 | 50.0 | 0.02 | 0.02 | 0.06 | 5.61 | 0.98 | 2.95 |
| Onshore operators | 37 | 75.7 | 0.06 | 0.06 | | 5.16 | 0.89 | |
| Rail car loading | 179 | 16.8 | 3.77 | 3.78 | | 7.94 | 1.00 | |
| Refinery fitter | 330 | 39.7 | 0.35 | 0.35 | | 6.93 | 0.99 | |
| Refinery operator NE | 275 | 66.6 | 0.07 | 0.09 | | 2.43 | 0.86 | |
| Refinery op. plantwide | 25 | 44.0 | 0.08 | 0.08 | | 3.31 | 0.93 | |
| Reformer operator | 261 | 33.3 | 0.39 | 0.39 | | 4.87 | 0.98 | |
| Refuelling Avgas | 9 | 44.4 | 1.65 | 1.67 | | 5.49 | 0.99 | |
| Road tank bottom load | 31 | 41.9 | 0.55 | 0.60 | | 7.19 | 0.92 | |
| Road tank top load | 68 | 17.6 | 1.76 | 1.78 | | 6.23 | 0.99 | |
| Ship load/unload | 77 | 15.6 | 0.11 | 0.11 | | 7.96 | 1.00 | |
| Sour water | 28 | 89.3 | 0.06 | 0.08 | 0.04 | 1.55 | 0.78 | 0.72 |
| Tank test crude | 12 | 16.7 | 0.30 | 0.30 | 0.79 | 10.53 | 1.00 | 2.6 |
| Tank cleaning crude | 59 | 13.6 | 2.01 | 2.01 | | 11.92 | 1.00 | |
| Tank Fm — refinery | 94 | 51.1 | 0.14 | 0.14 | | 5.79 | 0.98 | |
| Tank Fm — terminal | 10 | 80.0 | 0.36 | 0.39 | | 2.85 | 0.91 | |
| Terminal fitter | 13 | 38.5 | 0.67 | 0.70 | | 6.95 | 0.97 | |
| Terminal operator NE | 10 | 60.0 | 0.14 | 0.15 | | 2.25 | 0.90 | |
| Upstream fitter | 12 | 58.3 | 0.04 | 0.05 | | 4.96 | 0.85 | |

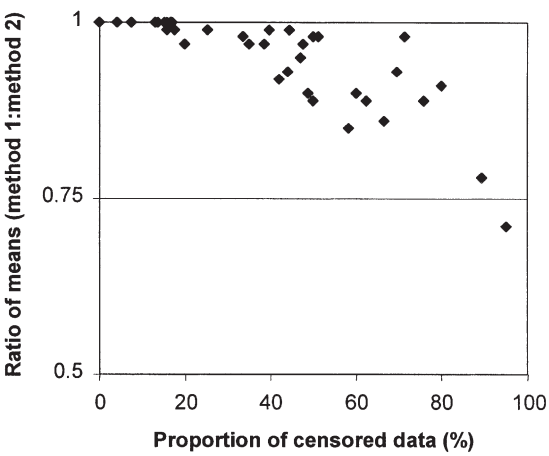


Fig. 6. Ratio of means calculated by Method 1 (LOD/2) and Method 2 (LOD/√2) versus proportion of censored data.

mated by Cohen's method was substantially greater than that calculated when the censored data was assigned a value equal to the LOD.

For the data sets that had multiple limits of detection, the data were artificially censored at the maximum LOD and Cohen's method was then applied. The results are presented in Table 3. In the majority of cases the mean predicted by Cohen's method with the data artificially censored at the maximum LOD was greater than that from the simpler LOD/2 method (Table 4). It is evident from Tables 3 and 4 that Cohen's method produces much more erratic results with these data sets than those produced by either of the simpler methods.

The mean for 'Instrument Fitters' obtained using Cohen's method was extremely high, confirming that this method is not applicable to such non-log-normal data sets.

Table 2. Comparison of means for data sets with single censoring points calculated using different values below the censoring point and by Cohen's method

| | Value assigned to censored data | | | | Cohen's estimate |
|---|---|---|---|---|---|
| | Zero | LOD | LOD/2 | LOD/√2 | |
| Barge load | 2.206 | 2.215 | 2.21 | 2.21 | 4.32 |
| DAP maintenance | 1.014 | 1.021 | 1.02 | 1.02 | 1.12 |
| Drum laundry | 0.375 | 0.398 | 0.39 | 0.39 | 0.48 |
| Offshore ops | 0.019 | 0.021 | 0.02 | 0.02 | 0.06 |
| Sour water | 0.020 | 0.104 | 0.06 | 0.08 | 0.04 |
| Tank test crude | 0.302 | 0.303 | 0.3 | 0.3 | 0.79 |

Table 3. Comparison of means for data sets with multiple limits of detection calculated using Cohen's method and taking the highest limit of detection

| | | | Method of calculating mean | |
|---|---|---|---|---|
| Base estimate | # Data points | Proportion <LOD (%) | LOD/2 | Cohen's (max LOD) |
| Airport background | 20 | 95.0 | 0.08 | 0.26 |
| CCU operator | 295 | 69.5 | 0.16 | 0.13 |
| CDU operator | 404 | 47.0 | 0.11 | 0.15 |
| DAP op. pre '89 | 152 | 15.8 | 1.85 | 1.90 |
| DAP head op. pre '89 | 46 | 34.8 | 0.74 | 0.78 |
| Drum fill stub, open | 106 | 19.81 | 3.52 | 3.87 |
| Drum fill stub, LEV | 24 | 4.2 | 1.55 | 2.93 |
| Drum preparation | 8 | 62.5 | 0.14 | 0.17 |
| Instrument fitter | 42 | 71.4 | 0.48 | 96.33[a] |
| Interceptor cleaning | 14 | 50.0 | 0.12 | 0.21 |
| Lab bench high | 534 | 12.9 | 0.74 | 0.91 |
| Lab bench low | 65 | 47.7 | 0.15 | 0.16 |
| Lab other | 127 | 48.8 | 0.09 | 0.37 |
| Onshore operators | 37 | 75.7 | 0.06 | 0.06 |
| Rail car loading | 179 | 16.8 | 3.77 | 4.69 |
| Refinery fitter | 330 | 39.7 | 0.35 | 0.42 |
| Refinery operator NE | 275 | 66.6 | 0.07 | 0.01 |
| Ref. op. plantwide | 25 | 44.0 | 0.08 | 0.08 |
| Reformer operator | 261 | 33.3 | 0.39 | 0.50 |
| Refuelling Avgas | 9 | 44.4 | 1.65 | 4.50 |
| Road tank bottom load | 31 | 41.9 | 0.55 | 0.71 |
| Road tank top load | 68 | 17.6 | 1.76 | 2.02 |
| Ship load/unload | 77 | 15.6 | 0.11 | 0.12 |
| Tank cleaning crude | 59 | 13.6 | 2.01 | 4.99 |
| Tank Fm — refinery | 94 | 51.1 | 0.14 | 0.15 |
| Tank Fm — terminal | 10 | 80.0 | 0.36 | 0.45 |
| Terminal fitter | 13 | 38.5 | 0.67 | 1.79 |
| Terminal op. NE | 10 | 60.0 | 0.14 | 0.17 |
| Upstream fitter | 12 | 58.3 | 0.04 | 5.15 |

[a]Analysis showed this data set to contain a number of high exposures that were outside the log-normal distribution for the remainder of the data.

Table 4. Summary of the comparison of the results of Cohen's method and Method 1 (LOD/2). The data for the 'Instrument fitter' have been excluded

| Ratio of means: Cohen's÷Method 1 | Approximate proportion of data sets (%) |
|---|---|
| <1 | 10 |
| 1–1.1 | 28 |
| 1.1–1.5 | 34 |
| 1.5–3 | 17 |
| 3–5 | 7 |
| 5–10 | 4 |
| Total | 100 |

## DISCUSSION

For the purposes of an epidemiological investigation, it was necessary to estimate the mean exposure for a wide range of tasks in the Australian petroleum industry from sometimes heavily censored data. Most of the data sets were approximately log-normal, although that for 'Instrument Fitters' contained high exposure outliers. Many of the data sets suffered from multiple limits of detection because of differences in sample air volumes and sampling and analytical techniques. Two simple methods of dealing with censored data, involving replacing results below the limit of detection either by LOD/2 or LOD/√2, gave broadly similar results. In most cases the differences in the mean exposures calculated by these two methods was very small (less than 5%) and only when censoring was particularly heavy (more than 90% of the results below the limit of detection) did the difference exceed about 25%. An alternative method (Cohen's method) was used to calculate the maximum likelihood estimate of the arithmetic mean by extrapolation of the uncensored data into the censored region below the limit of detection. This approach is possible only where there is a single censoring point hence it could only be applied without modification to the small number of data sets that had a single limit of detection. In most of these cases Cohen's method produced an estimate of the arithmetic mean considerably greater than the mean derived from the two simpler methods. The fact that this estimate was higher in some cases than that obtained by setting the censored results equal to the limit of detection indicates that Cohen's method overestimated the means for these particular data sets. For those data sets with multiple limits of detection, the maximum limit of detection was taken as the censoring point; all data below this were assumed to be below the limit of detection even when actual measured values were available. For most of the multiple censored data sets, Cohen's method with the data modified in this way resulted in similar or somewhat larger estimates of the mean than the simple methods based on either LOD/2 or LOD/$\sqrt{2}$.

In some cases the mean estimated using Cohen's method was very much larger and appeared to be implausible e.g. Drum Fill Stub LEV and Tank Cleaning Crude, see Table 1. If in a data set with multiple limits of detection, a few data are censored with an unacceptably high limit of detection it may be better to discard these data entirely, rather than artificially censoring an unnecessarily large proportion of the uncensored data. However, this might introduce some bias.

The reason for the wide fluctuation in the results obtained by Cohen's method might be found in the way it extrapolates the missing left tail of the distribution on the basis of the distribution of uncensored data. The method relies critically upon the assumption that the transformed data have a normal (Gaussian) symmetrical distribution. The parameters of this distribution are calculated from the mean and variance of the log-transformed data. If the distribution of this transformed data deviates substantially from that of a censored normal distribution, particularly if it is skewed by some high values, then the estimated arithmetic mean of the total untransformed distribution including the missing (censored) data is strongly affected. It is critical that the assumption made about the log-normality of the distribution is valid, because Cohen's method can produce highly erroneous results if there is a large deviation from normality in the transformed data.

For the simple purpose of estimating the mean, the LOD/2 method is adequate. Its use however reduces the standard deviation of the distribution. This means that confidence limits of the mean exposure which are calculated on this basis are underestimated. In theory, Cohen's method allows the calculation of more accurate confidence limits.

## CONCLUSIONS

Cohen's method is not widely used for censored data in occupational hygiene investigations and this may be due in part to its cumbersome nature and the need to look up the values of certain parameters in tables. It is relatively easy to program a spreadsheet with the statistical functions needed for these parameters, or as in this work, to use polynomial functions to approximate the parameters. This can make this somewhat complex method much more accessible for routine use.

Methods similar to Cohen's, based on extrapolation of the missing data from information contained in the uncensored data, have previously been shown to be reliable for large simulated data sets with a strictly defined distribution (Hornung and Reed, 1990). The results of the present work suggest that they may not be reliable for practical data sets that do not have a strictly log-normal distribution.

More rigorous analysis using simulated data sets is necessary to investigate the effect of deviations from log-normality, but this is beyond the scope of the present investigation that aimed only to estimate the mean of particular data sets for epidemiological purposes. The simple methods based on either LOD/2 or LOD/$\sqrt{2}$ are independent of the distribution of the uncensored data and although slightly biased, are reliable. The LOD/2 method was eventually used in the epidemiological analysis because some of the data sets were heavily censored and some were highly skewed and had geometric standard deviations greater than 3 (Hornung and Reed, 1990).

*Acknowledgements*—The authors would like to thank The Commonwealth Government, MSA, The Energy Research and Development Corporation, the Australian Institute of Petroleum (AIP), The Universities of Melbourne, Monash and Deakin who financed and supported this study. The authors gladly acknowledge the valuable help from the AIP, several petroleum companies and in particular from Sharann Johnson (BP Oil), Graham Ward (Caltex Australia Ltd), Noel Tresider (consultant Petroch Services Pty Ltd), David Hamilton (Esso Australia Ltd), Doug Rhodes and Heather Jackson (Shell Company of Australia Ltd). We would also like to thank Dick Manuell, Geoff Adams and the other members of the Health Watch team from Melbourne University.

## REFERENCES

Cohen AC. Table for maximum likelihood estimates: singly truncated and singly censored samples. Technometrics 1961;3:535–41.

Glass DC, Adams GG, Manuell RW, Bisby JA. Retrospective exposure assessment for benzene in the Australian petroleum industry. Ann. Occup. Hyg. 2000;44(4):301–20.

Hald A. Statistical theory with engineering applications. New York: John Wiley and Sons Inc, 1952.

Hornung RW, Reed LD. Estimation of average concentration in the presence of non-detectable values. Appl. Occup. Envir. Hyg. 1990;5(1):46–51.

Perkins JL, Cutter GN, Cleveland MS. Estimating the mean, variance and confidence limit from censored (<limit of detection), lognormally-distributed exposure data. Am. Ind. Hyg. Assoc. J. 1990;51(8):416–9.