



Development of a Job-Exposure Matrix (AsbJEM) to Estimate Occupational Exposure to Asbestos in Australia

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ABSTRACT

Introduction: Occupational exposure data on asbestos are limited and poorly integrated in Australia so that estimates of disease risk and attribution of disease causation are usually calculated from data that are not specific for local conditions.

Objective: To develop a job-exposure matrix (AsbJEM) to estimate occupational asbestos exposure levels in Australia, making optimal use of the available exposure data.

Methods: A dossier of all available exposure data in Australia and information on industry practices and controls was provided to an expert panel consisting of three local industrial hygienists with thorough knowledge of local and international work practices. The expert panel estimated asbestos exposures for combinations of occupation, industry, and time period. Intensity and frequency grades were estimated to enable the calculation of annual exposure levels for each occupation–industry combination for each time period. Two indicators of asbestos exposure intensity (mode and peak) were used to account for different patterns of exposure between occupations. Additionally, the probable type of asbestos fibre was determined for each situation.

Results: Asbestos exposures were estimated for 537 combinations of 224 occupations and 60 industries for four time periods (1943–1966; 1967–1986; 1987–2003; ≥ 2004). Workers in the asbestos manufacturing, shipyard, and insulation industries were estimated to have had the highest average exposures. Up until 1986, 46 occupation–industry combinations were estimated to have had exposures exceeding the current Australian exposure standard of 0.1 f ml^{-1} . Over 90% of exposed occupations were considered to have had exposure to a mixture of asbestos varieties including crocidolite.

Conclusion: The AsbJEM provides empirically based quantified estimates of asbestos exposure levels for Australian jobs since 1943. This exposure assessment application will contribute to improved understanding and prediction of asbestos-related diseases and attribution of disease causation.

KEYWORDS: amosite; asbestosis; asbestos-related diseases; chrysotile; crocidolite; exposure assessment; fibres; JEM; mesothelioma

INTRODUCTION

Australia consumed large quantities of asbestos following World War II (Xu *et al.*, 1985) and was for a time one of the world's largest producers of crocidolite, which is the most carcinogenic asbestos fibre type for mesothelioma (Hodgson and Darnton, 2000). By 1954, Australia had the highest per capita asbestos consumption worldwide (Lin *et al.*, 2007). Consumption peaked at 70 000 tonnes per year in 1975 (Musk and de Klerk, 2004). Asbestos was banned from all building materials in Australia in 1989, although production and sale of all other asbestos products were not prohibited completely until 2003 (NOHSC, 2005).

As a result of the extensive use of asbestos in the past, Australians have one of the highest rates of mesothelioma in the world. The male age-standardized incidence rate was 4.3 cases per 100 000 person-years in 2012 (Australian Mesothelioma Registry, 2012). The rate is particularly high in Western Australia, namely 7.2 per 100 000 person-years in 2012 (Australian Mesothelioma Registry, 2012), mainly due to the crocidolite that was mined at Wittenoom between 1943 and 1966 (Musk *et al.*, 1992).

Although recent observations suggest that an increasing proportion of mesothelioma cases are caused by non-occupational exposures, by far the majority of mesothelioma cases are attributable to previous occupational exposure (Olsen *et al.*, 2011; Rushton *et al.*, 2012). In order to predict future cases of mesothelioma and other asbestos-related diseases, to estimate exposure–response relationships, to model risks taking into account dynamic patterns in exposure histories, and to attribute disease causation to asbestos exposure, detailed exposure assessment is essential (Lenters *et al.*, 2011; Vermeulen and Chadeau-Hyam, 2012). Lifetime exposure to asbestos therefore needs to be assessed on an individual basis to enable the estimation of cumulative exposure levels and time since first exposure. In order to quantify risks, quantitative exposure estimates based on measurement data are required. Obtaining such data is challenging due to

their retrospective character and the wide range of workplaces in the general population.

Despite considerable production and use of asbestos, occupational exposure data have been limited and poorly integrated in Australia. Levels of exposure to crocidolite among Wittenoom miners have been assessed in detail (de Klerk *et al.*, 1989), but due to the lack of asbestos exposure data in other industries, studies often had to rely on exposure surrogates such as job titles obtained from occupational histories or extrapolated estimates from international studies which may not be appropriate for Australian working conditions. A systematic approach to estimate occupational exposure to asbestos in Australian workplaces is required to make optimal use of these sparse data.

The aim of this study was to create a job-exposure matrix (JEM) for asbestos exposure under Australian working conditions, other than in the Wittenoom mine, since 1943 using all relevant and available data.

METHODS

Occupational exposure information

Local reports with results from area monitoring within workplace environments and personal occupational measurements were collected. Additionally, results from international studies were reviewed to provide additional guidance on industries where Australian exposure data were limited.

Airborne asbestos measurements were reported in 3497 records in government documents, laboratory simulation records from occupational hygiene consultancies in Victoria, airborne fibre monitoring records from an occupational hygiene consultancy in Western Australia, and national and international publications (Table 1). The data included exposure measurements from 57 industries and 89 occupations from 1937 to 2007 in Australia, as well as records from Canada, France, Germany, Finland, Puerto Rico, Slovenia, Sweden, the UK, and the USA. Task-specific information was documented in 818 records. Nearly 70%

Table 1. Sources of exposure data.

| Source of exposure measurements | Country | Time period | Industries | Occupations | Measurements ^a |
|--|-------------|-------------|--------------------------|-------------|---------------------------|
| Australian Occupational Hygiene Consultancy Records (unpublished) | Australia | 1989–2007 | 45 | | 14 605 |
| Western Australia Department of Consumer & Employee Protection (unpublished) | Australia | 1986–2007 | 1 | 23 | 10 163 |
| New South Wales Dust and Diseases Board (unpublished) | Australia | 1970–1989 | (19 task-product groups) | | 872 |
| Kilpatrick & Kottick Laboratory simulations (unpublished) | Australia | 1999 | (29 tasks/simulations) | | 40 |
| WA Advisory Committee on Hazardous Substances, 1990 | Australia | 1990 | 1 | | 13 |
| Cumpston, 1978 | Australia | 1975–1978 | 4 | | 28 |
| Brown, 1981 (review) | Australia | 1976–1981 | 4 | 8 | 33 |
| | UK | 1971–1979 | 2 | 1 | 35 |
| | USA | 1968–1978 | 4 | 1 | 96 |
| | Puerto Rico | 1978 | 1 | | 3 |
| Woitowitz <i>et al.</i> , 1983 (review) | Canada | <1972–1978 | 3 | 13 | 814 |
| | Sweden | 1972–1978 | 2 | 2 | 273 |
| | UK | 1952–1966 | 1 | 14 | 56 |
| | USA | <1945–1973 | 7 | | 2680 |
| Kauppinen <i>et al.</i> , 1998 | Finland | 1960–1997 | | 20 | 60 |
| Dodic-Fikfak <i>et al.</i> , 2001 | Slovenia | 1961–1989 | 1 | | ≥1000 |
| Health & Safety Executive (HSE, 1984) | UK | 1984 | 1 | | 23 |

Table 1. Continued

| Source of exposure measurements | Country | Time period | Industries | Occupations | Measurements ^a |
|--|---------|-------------|-----------------------------|-------------|---------------------------|
| Williams <i>et al.</i> , 2007 (review) | UK | 1968–1971 | 1 | 1 | 1 |
| | USA | 1937–2006 | 5 | 9 | 4478 |
| Dewes, 1986 | USA | 1982–1983 | 1 | 5 | 336 |
| Lange <i>et al.</i> , 1996 | USA | 1996 | 1 | | 265 |
| Lees, 1989 | France | 1980–1983 | (6 task-specific exposures) | | 315 |
| | USA | 1970–1989 | | | 665 |
| Nolan and Langer, 1989 | USA | 1975–1988 | 1 | | 767 |
| Price, 1989 | USA | 1988 | 1 | | 251 |

^aWhere information on the number of measurements was unavailable, the number of measurements was an approximation based on the number of measurement records.

of the reported measurements related to Australian exposure conditions.

Exposure assessment process

A panel of three experienced occupational hygienists, who were familiar with the Australian conditions with regards to asbestos use, was established. Under guidance of one of the authors (S.C.v.O.), the expert panel was asked to examine the collected exposure information in order to assess the asbestos exposure for each combination of occupation, industry, and time period.

Four time periods of interest were identified based on changes in Australian asbestos consumption and legislation: 1943–1966 when the Wittenoom crocidolite mine was in operation and crocidolite became increasingly available as a cheap construction material; 1967–1986 when asbestos health hazards were recognized and occupational exposure limits were introduced; 1987–2003 when the use of raw crocidolite was prohibited and further limitations and controls were placed on other types of asbestos; and ≥ 2004 when all new asbestos use was prohibited.

The asbestos type was defined as the type of asbestos fibres to which workers within a particular occupation–industry–time period combination were most likely to have been exposed. The categories used were ‘amosite’, ‘chrysotile’, ‘mixture including crocidolite’, ‘mixture not including crocidolite’.

Exposure measures consisted of the intensity and frequency of asbestos exposure, estimated for both the ‘mode exposure’ and ‘peak exposure’. Mode exposure was defined as the most common exposure in a particular job, when exposed above background level. Peak exposure was defined as a short-term intense exposure, arbitrarily set at 15 min. This peak exposure was considered to have occurred on the same day as the mode exposure.

Collected monitoring data results were not statistically modelled but were used to assist the experts in the assignment of exposure intensity levels. The experts also took into account when, where, and how measurements were taken, e.g. whether it were personal or area monitoring results. The majority of the airborne asbestos measurements were expressed as fibres per millilitre ($f\ ml^{-1}$) or an equivalent measure according to the membrane filter method for evaluating airborne asbestos fibres (NIOSH, 1994). Some earlier estimates utilized airborne asbestos measurements in

millions of particles per cubic foot (mppcf), but these were few and were therefore only used to provide an indication of the presence of exposure.

Intensity of exposure was assigned in five categories, based on the mid-point of five exposure ranges according to the Australian Standard for asbestos exposure [0.1 f ml⁻¹ (Safe Work Australia, 2011)] and expressed as a time-weighted average (TWA) for an 8-h working day. The estimated exposure levels were classified in the following categories: 0.0001 f ml⁻¹ as background (Brown, 2001); 0.05 f ml⁻¹ (0.01–0.1 f ml⁻¹) as low; 0.5 f ml⁻¹ (0.1–1 f ml⁻¹) as medium; 12 f ml⁻¹ (1–25 f ml⁻¹) as high; and 37.5 f ml⁻¹ (25–50 f ml⁻¹) as very high.

Frequency of exposure reflected the experts' assessment of the occurrence of exposure in a particular job or industry within a working year (240 days, assuming 4 weeks of holidays): annually (1 day per year); biannually (2 days per year); monthly (11 days per year); weekly (48 days per year); or daily (240 days per year). Days represented a standard 8-h working shift.

The expert panel assessment process started with the selection of an industry. All available literature for that industry was then reviewed. Next, possible exposures were discussed by occupation within the industry, taking into consideration factors influencing exposure over time, such as changes in work practices, legislation, the introduction of controls, and changes in the asbestos types which were used. Thus each industry–occupation–time period combination present in the AsbJEM was individually considered by the expert panel, until consensus was reached. The experts assigned categorical values of exposures. For example, the mode asbestos exposure of a carpenter in construction (1967–1986) was assessed as 'low' and 'weekly', with a peak exposure occurring once a month at a high level.

The annual average exposures were calculated for each industry–occupation combination by summing the peak, mode, and background exposures, divided by the number of working days in a year (240):

- Peak exposure was calculated by multiplying peak intensity by peak frequency. The peak frequency variable was multiplied by a constant (15/480) allowing peak exposures to be expressed as 15 min of high exposure within a standard 8-h working day (=480 min);

- Mode exposure was calculated by multiplying mode intensity by the number of mode days exposed in a year, subtracting the total time exposed to peak levels (since peak and mode exposures were considered to have occurred on the same days);
- Background exposure was calculated by subtracting the mode exposed days from the total number of days in the working year (240) and multiplied by the background level of 0.0001 f ml⁻¹.

For example, in the case of a carpenter working in the construction industry, the annual average exposure was 0.027 f ml⁻¹ for each year from 1967 to 1986. This was derived from a mode intensity of 0.05 f ml⁻¹, a mode frequency of 48 days per year, a peak intensity of 12 f ml⁻¹, and a peak frequency of 11 days per year. The remaining time, their exposure level was set at background.

| | |
|----------------------------|---|
| Peak frequency | 11 days per year * (15/480) =0.34 days per year |
| Peak exposure | 12 f ml ⁻¹ * 0.34 =4.125 |
| Mode exposure | 0.05 f ml ⁻¹ * [48 days per year – Peak frequency (0.34 days per year)] =2.38 |
| Background exposure | 0.0001 f ml ⁻¹ * [240 days per year – Mode frequency (48 days per year)] =0.019 |
| Annual average exposure | (4.125 + 2.38 + 0.019)/240 days per year =0.027 f ml ⁻¹ |

RESULTS

A total of 537 combinations of 224 occupations and 60 industries with potential exposure to asbestos were identified. Of these combinations, 486 were assessed to involve asbestos exposure levels above background level at any time period. The type of asbestos was

most often (>90%) considered to be a 'mixture of fibres including crocidolite' in the occupations where asbestos exposure levels were above background. The expert panel assigned the same categorical values to each job–industry combination for time periods 1 and 2. Therefore, the results for these two periods are presented together (1943–1986).

Selected examples of annual average exposure levels estimated for each of these combinations, for each time period, are shown in Tables 2 and 3. Table 2 shows different occupations that are set on a shipping wharf. The occupation of 'fitter' was assessed as having an average exposure level of 0.0531 f ml^{-1} each year between 1943 and 1986, when working on a wharf. The annual average for the periods 1987–2003 and from 2004 onwards was the background exposure level of 0.0001 f ml^{-1} . The occupation of 'fitter' exists in many more industries and Table 3 shows the assessments for fitters in the different industries/locations.

The AsbJEM estimates of asbestos exposure levels for each of the industry–occupation combinations, for each time period, can be found in Supplementary Tables S1 and S2, available at *Annals of Occupational Hygiene* online. Particularly, high annual average asbestos exposure levels for the years before 1987 were estimated for occupations in the asbestos manufacturing industry (up to 12 f ml^{-1}), as well as among asbestos removalists and insulators (2.44 f ml^{-1}). Up until 1986, 46 occupation–industry combinations were estimated to have had exposures exceeding the current Australian exposure standard of 0.1 f ml^{-1} . These jobs included artificers, insulators, asbestos removalists, and workers in the manufacturing and transport of asbestos.

Asbestos exposure levels decreased markedly during the period 1987–2003, when higher exposures (i.e. $>0.1 \text{ f ml}^{-1}$ as a TWA for an 8-h working day) were not considered to have occurred any longer. In the latest period (from 2004 onwards), all mode exposure levels were considered to be down to background levels. However, peak exposures still occurred, resulting in slightly increased annual average exposure levels for some occupations such as asbestos removalists and boilermakers/welders.

DISCUSSION

The AsbJEM was developed based on expert assessments incorporating all available historical exposure

data relevant to Australian conditions and provides asbestos exposure estimates for all relevant occupations in Australia since 1943. Exposure levels were estimated for 224 occupations in 60 industries. The asbestos manufacturing, shipyard, and insulation industries were estimated to have had the highest exposures which declined with time. Over 90% of exposed occupations included in the AsbJEM were considered to have had exposure to a mixture of asbestos fibres including crocidolite. The AsbJEM can be used to estimate exposure–response relationships for asbestos-related diseases among Australian workers exposed to asbestos in a range of occupations, industries, and time periods.

Occupational exposure assessment studies often make use of experts, such as occupational hygienists, chemists, engineers, and other professionals, to infer exposures from job histories or to estimate exposures based on a review of subject-reported information. Experts are expected to have a better vantage point than subjects themselves: (i) by training, they understand the mechanisms of occupational exposures and know where to find data about them; (ii) within the context of a study, they know the types of exposure considered relevant; and (iii) based on study data, they have an overview of the range of relevant jobs. Experts are generally considered to provide reliable exposure estimates (Siemiatycki *et al.*, 1997; Teschke *et al.*, 2002).

Quantitative exposure measurements have been described as the best estimates of actual dose (Teschke *et al.*, 2002). However, retrospective exposure data is often incomplete and does not represent all occupations at risk. Although government measurement databases do exist in Australia, they are limited and few have data prior to 1986. Establishment of regular occupational exposure monitoring programs in the Western Australian industry did not commence until after the introduction of legislation in 1984 (DOCEP, 1996). Monitoring prior to this date was *ad hoc* and site-specific and therefore limited. Furthermore, the majority of data was not collected for research purposes and information on monitoring strategies was often not recorded. Most data were collected for surveillance purposes in industrial settings. Inconsistencies in measurement strategies and sampling techniques complicate distinguishing trends in exposure, which has been reported for other

Table 2. Annual average asbestos exposure for the different time periods for occupations that are set on a 'Wharf' (all fibre types on the wharf were 'mixtures including crocidolite').

| Occupation | Time periods 1 and 2 (1943–1986) | | | | Time period 3 (1987–2003) | | | | Time period 4 (≥ 2004) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---------------------|----------------------------------|-----|------|----|--|------|------|------|-------------------------------|--------|--|-----|------|---|--------|---|--|------|---|--------|---|-----|------|---|--------|---|-----|------|---|--------|---|-----|------|---|--------|---|-----|------|---|--------|
| | Mode | | Peak | | Annual Average Exposure (f ml^{-1}) | | Mode | | Peak | | Annual Average Exposure (f ml^{-1}) | | Mode | | Peak | | Annual Average Exposure (f ml^{-1}) | | | | | | | | | | | | | | | | | | | | | | | |
| | I | F | I | F | I | F | I | F | I | F | I | F | I | F | I | F | I | F | | | | | | | | | | | | | | | | | | | | | | |
| Clerk | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 |
| Coordinator | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 |
| Crane driver | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 |
| Dock master | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 |
| Driver | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 |
| Labourer/worker | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 |
| Purchasing officer | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 |
| Tally clerk | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 | B | 240 | 0.05 | 1 | 0.0001 |
| Forklift operator | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 |
| Downhold cleaner | 0.05 | 240 | 12 | 2 | 0.0531 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 |
| Downholder | 0.05 | 240 | 12 | 2 | 0.0531 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 |
| Fitter | 0.05 | 240 | 12 | 2 | 0.0531 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 |
| Shed supervisor | 0.05 | 240 | 12 | 2 | 0.0531 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 |
| Stevadore | 0.05 | 240 | 12 | 2 | 0.0531 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 |
| Storeman | 0.05 | 240 | 12 | 2 | 0.0531 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 |
| Wharfhand | 0.05 | 240 | 12 | 2 | 0.0531 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 | B | 240 | 0.05 | 2 | 0.0001 |
| Lumper asbestos | 0.5 | 240 | 37.5 | 11 | 0.5530 | B | 240 | — | — | 0.0001 | B | 240 | — | — | 0.0001 | B | 240 | — | — | 0.0001 | B | 240 | — | — | 0.0001 | B | 240 | — | — | 0.0001 | B | 240 | — | — | 0.0001 | B | 240 | — | — | 0.0001 |
| Asbestos removalist | 12 | 48 | 37.5 | 11 | 2.4366 | 0.05 | 48 | 12 | 2 | 0.0132 | 0.05 | 48 | 12 | 2 | 0.0132 | B | 240 | 0.5 | 1 | 0.0002 | B | 240 | 0.5 | 1 | 0.0002 | B | 240 | 0.5 | 1 | 0.0002 | B | 240 | 0.5 | 1 | 0.0002 | B | 240 | 0.5 | 1 | 0.0002 |

B = background level of 0.0001 f ml^{-1} ; F = frequency of exposure (in days per year); I = intensity of exposure (in f ml^{-1})

Table 3. Annual average asbestos exposure for the different time periods for the occupation 'Fitter'.

| Industry/location | Time periods 1 and 2 (1943–1986) | | | | Time period 3 (1987–2003) | | | | Time period 4 (≥2004) | | | | | | | | |
|------------------------|----------------------------------|------|------|--------|---|-----|------------|------|-----------------------|--------|--------|-----|---|-----|--------|--------|-----|
| | Mode | | Peak | | Annual average exposure (f ml ⁻¹) | | Fibre type | | Mode | | Peak | | Annual average exposure (f ml ⁻¹) | | | | |
| | I | F | I | F | I | F | I | F | I | F | I | F | I | F | | | |
| Transport | B | 0.05 | 11 | 0.0002 | MiC | B | 240 | 0.05 | 2 | 0.0001 | MiC | B | 240 | — | 0.0001 | MiC | |
| Water authority | 0.05 | 48 | 0.5 | 48 | 0.0129 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Wharf | 0.05 | 240 | 12 | 2 | 0.0531 | MiC | B | 240 | 0.05 | 2 | 0.0001 | MiC | B | 240 | — | 0.0001 | MiC |
| Abattoir | 0.05 | 48 | 12 | 48 | 0.0848 | Am | B | 240 | 0.5 | 11 | 0.0008 | Am | B | 240 | — | 0.0001 | Am |
| Air conditioning | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | 0.05 | 11 | 0.5 | 11 | 0.0030 | MiC | B | 240 | — | 0.0001 | MiC |
| Armed forces | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Brewery | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Brickworks | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Building (housing) | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | 0.05 | 11 | 0.5 | 11 | 0.0030 | MiC | B | 240 | — | 0.0001 | MiC |
| Cement | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Chemical manufacturing | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Cold store | 0.05 | 48 | 12 | 48 | 0.0848 | Am | B | 240 | 0.5 | 11 | 0.0008 | Am | B | 240 | — | 0.0001 | Am |
| Construction | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | 0.05 | 11 | 0.5 | 11 | 0.0030 | MiC | B | 240 | — | 0.0001 | MiC |
| Engineering | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Foundry | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Hospital | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Manufacturing | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Marine | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Mining | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Power supply | 0.05 | 48 | 12 | 48 | 0.0848 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |

Table 3. Continued

| Industry/location | Time periods 1 and 2 (1943–1986) | | | | Time period 3 (1987–2003) | | | | Time period 4 (≥2004) | | | | | | | |
|------------------------|----------------------------------|-----|---|------------|---------------------------|------|------|---|-----------------------|--------|-----|------|---|---|--------|-----|
| | Mode | | Annual average exposure (f ml ⁻¹) | Fibre type | Mode | | Peak | Annual average exposure (f ml ⁻¹) | Fibre type | Mode | | Peak | Annual average exposure (f ml ⁻¹) | | | |
| | I | F | I | F | I | F | I | F | I | F | I | F | | | | |
| Railway | 0.05 | 48 | 12 | 48 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Refrigeration | 0.05 | 48 | 12 | 48 | MiC | 0.05 | 11 | 0.5 | 11 | 0.0030 | MiC | B | 240 | — | 0.0001 | MiC |
| Shipyards | 0.05 | 48 | 12 | 48 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Steel | 0.05 | 48 | 12 | 48 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Ventilation | 0.05 | 48 | 12 | 48 | MiC | B | 240 | 0.5 | 11 | 0.0008 | MiC | B | 240 | — | 0.0001 | MiC |
| Asbestos manufacturing | 0.05 | 240 | 12 | 48 | MiC | 0.05 | 240 | 12 | 2 | 0.0531 | Chr | N/A | — | — | — | — |

Am, amosite; B, background level of 0.0001 f ml⁻¹; Chr, chrysotile; F, frequency of exposure (in days per year); I, intensity of exposure (in f ml⁻¹); MiC, mixture including crocidolite; N/A, not applicable, since no asbestos was manufactured after 2003.

collections of retrospective data on asbestos exposure (Swuste *et al.*, 2008; Hyland *et al.*, 2010).

Measurement data, where available, were used in the development of the AsbJEM to assist the expert panel of local industrial hygienists to assign exposure levels. Therefore, the strengths of available monitoring measurements and expert assessments were combined. We used similar methods as have been used for the development of the Finnish JEM (Kauppinen *et al.*, 1998). The latter has recently shown to be able to detect the well-known association between asbestos exposure and the risk of mesothelioma (Offermans *et al.*, 2014).

Expert assessments have previously been considered as a 'pseudo gold standard' when used in conjunction with measurements of airborne fibre levels (Swuste *et al.*, 2008). The information from measurement data has enabled the quantification of the categorical exposure levels. However, the experts' opinion was essential to assess data quality and to make the final decision on each cell in the matrix. When assigning exposure estimates for similar occupations for the AsbJEM, the expert panel reviewed the occupations by industry, and then cross-referenced their estimates by job title. This ensured that variation between similar titles would be reflected in the estimates. Due to the absence of adequate exposure measurements for the first time period, estimates were based solely on expert opinion and the literature on consumption and industry practice. From the comments made by the expert panel, it appeared that they were most confident of estimates made for the years between 1967 and 2003.

Asbestos workers, insulators, waterside workers (including shipyard, wharf, navy, and marine), carpenters/joiners, boilermakers/welders, power supply, and railway workers were estimated to have experienced the highest levels of asbestos exposure. These jobs are consistent with those shown to have a high risk of mesothelioma in Australia (Yeung and Rogers, 2001; Leigh and Driscoll, 2003).

Overall, estimated annual average exposure levels in AsbJEM may appear relatively low. However, they are similar to full-shift asbestos exposures reported elsewhere. For example, simulation studies on fabricating gaskets yielded average 8-h TWAs between 0.02 and 0.14 f ml⁻¹; exposures between 0.006 and 0.01 f ml⁻¹ as 8-h TWA were reported for electricians; exposures for welders were all <0.01 f ml⁻¹; and concentrations during boiler repair and boiler insulation

work ranged from 0.02 to 0.3 f ml⁻¹ (Williams *et al.*, 2007). In AsbJEM, annual average exposure levels for gasket manufacturing were 0.0671 f ml⁻¹ prior to 1986 and 0.0025 from 1987 to 2003; electricians were assigned 0.0107 f ml⁻¹ and 0.0102 f ml⁻¹ in those time periods; and welders and boilermakers were assigned 0.0531 f ml⁻¹ prior to 1986 and either 0.0531 or 0.0506 f ml⁻¹ from 1987 to 2003, depending on the industry. Similarities are not unexpected as some of the asbestos exposure levels reported in the international literature helped inform the expert panel during the exposure assessment process, in addition to data available in Australia.

Many asbestos measurements reported in literature result from short-term samples (Williams *et al.*, 2007). Short-term measurements taken during specific (asbestos exposed) tasks will reveal much higher levels than the actual average exposure of a full work shift over a working year, which was estimated for AsbJEM. Therefore, direct comparison of exposure concentrations from those short-term measurements with annual average exposure levels is not appropriate. Moreover, when developing a JEM, estimations are aimed to represent the most likely exposure for each cell, here each job–industry–time period combination. A JEM will therefore not capture the whole range of potential exposure levels within each combination, i.e. a JEM does not account for variability between individuals within the same job (Kauppinen *et al.*, 1998; Kromhout *et al.*, 1993).

Exposure intensities are likely to fluctuate depending on specific tasks and other workplace circumstances. Therefore, two indicators of asbestos exposure intensity (mode and peak) were combined to allow greater specificity between occupational groups. Accounting for different patterns of exposure is considered particularly important where workers with similar job titles may have experienced dissimilar exposures in different industries as a result of their daily tasks. As can be seen in the ‘fitter’ example in Table 3, the estimated annual average exposure levels (1943–1986) ranged from 0.0002 f ml⁻¹ for a fitter in transport to 0.5719 f ml⁻¹ for fitters in the asbestos manufacturing. The changes in exposure levels in the next time period (1987–2003) differed by industry as well. Also the type of asbestos fibre was dependent on the industry: fitters in abattoirs and cold stores were predominantly exposed to amosite and chrysotile,

whereas other fitters were exposed to a mixture including crocidolite. Fitters in asbestos manufacturing were exposed to a mixture including crocidolite before 1987 and to chrysotile between 1987 and 2003.

The division of the assessments into specific time periods, reflecting changes in asbestos consumption, production, and legislation in Australia, allowed for variation in exposure estimates over time. Exposure limits were first recommended in Australia in 1964 at 5 mppcf for all types of asbestos, almost 30 years after exposure controls had been implemented in the USA and the UK (Musk *et al.*, 1992). These recommendations were not enforced in Australian legislation until 1978, with the Factories and Shops Act imposing an exposure limit of 2 f ml⁻¹ for amosite and chrysotile, and 0.1 f ml⁻¹ for crocidolite (Musk *et al.*, 1992). The introduction of exposure limits was accompanied by a marked drop in asbestos consumption after 1980 (Xu *et al.*, 1985), and it is likely that workers’ exposures also declined. The further use of all asbestos was prohibited in 2003 (crocidolite in 1986) and the national exposure standard for all asbestos types has been 0.1 f ml⁻¹ since (NOHSC, 2005). The time-specific estimations in the AsbJEM were similar to those estimated in JEMs from the Netherlands, the USA, and Finland (Kauppinen *et al.*, 1998; Dement *et al.*, 2008; Swuste *et al.*, 2008).

Initially, we had identified four time periods of interest based on changes in Australian asbestos consumption and legislation. However, jobs were assigned the same exposure levels by the expert panel in the first two periods (1943–1966 and 1967–1986). Firstly, the expert panel classified occupations on a semi-quantitative scale. A high-exposure job would have been high in both periods. Secondly, asbestos exposure levels generally went up from 1943 onwards because of increased production and availability. Levels started to decrease again in the mid-1960s due to the recognition of health hazards, resulting in improvements in awareness, engineering controls, and use of personal protective equipment. As a result, those two periods were considered to have been comparable in terms of exposure overall. Moreover, as indicated above, the experts were less confident about the assignments for the earlier periods, resulting in the same assignments for the first two time periods.

The asbestos type was documented to help identify occupations where exposure was likely to have been to amphiboles (including crocidolite and amosite),

which are associated with a greater risk for mesothelioma than serpentine (chrysotile) asbestos (Hodgson and Darnton, 2000). The potency differences for lung cancer are still disputed. In a recent meta-analysis for lung cancer and asbestos, the slope of the exposure–response relationship was roughly eight times higher for exposure to amphiboles versus chrysotile fibres (Lenters *et al.*, 2011); however, the potency of the more typical Australian exposure to mixed fibres has not been assessed. The vast majority (>90%) of occupations having exposure to asbestos above background level were assessed as having been exposed to a mixture of amphiboles and serpentine.

The experts assigned a mixture of fibre types, including crocidolite, to a large part of the occupation–industry combinations, because of the widespread use of blue asbestos in Australia. The decision by the expert panel for a fibre type classification other than the mixture including crocidolite was only made for industries that clearly involved other types of asbestos. These industries were abattoirs (amosite), asbestos manufacturing 1987–2003 (chrysotile), coal/diamond mining (chrysotile), cold stores (amosite), gasket manufacturing (chrysotile), insulation factory worker (mixture not including crocidolite), insulation/lagging 1987–2003 (chrysotile), and material handlers 1987–2003 (chrysotile).

AsbJEM can provide a quantified estimate of asbestos exposure for any individual with a history of having worked in Australia, based on knowledge of the person's occupation, the industry or location, year started working, and time spent (in months or years) or year finished. Summing the exposure estimates for each year will provide an estimate of the cumulative asbestos exposure that an individual has experienced over his or her working life in this country. This way, the AsbJEM enables characterizing the distribution of occupational exposure to asbestos in the Australian population. The AsbJEM will improve the interpretation and prediction of trends in asbestos-related diseases, identification of occupational risks, examination of exposure–response relationships, and estimation of the degree of likelihood that any particular disease was due to a particular episode of past occupational exposure.

SUPPLEMENTARY DATA

Supplementary data can be found at <http://annhyg.oxfordjournals.org/>.

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