An Australian stocks and flows model for asbestos

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Abstract

All available data on asbestos consumption in Australia were collated in order to determine the most common asbestos containing materials remaining in the built environment. The proportion of asbestos contained within each material and the types of products these materials are most commonly found in was also determined. The lifetime of these asbestos containing products was estimated in order to develop a model that projects stocks and flows of asbestos products in Australia through to the year 2100. The model is based on a Weibull distribution and was built in an excel spreadsheet to make it user-friendly and accessible. The nature of the products under consideration means both their asbestos content and lifetime parameters are highly variable, and so for each of these a high and low estimate is presented along with the estimate used in the model. The user is able to vary the parameters in the model as better data become available.

Keywords

Asbestos cement; asbestos containing materials; asbestos consumption in Australia; environmental contamination; stocks and flows modelling; hazardous waste projection.

1 Introduction

Global records from the British Geological Survey (2015) provide a detailed record of the mass of asbestos consumed in Australia annually from 1920 through to 2003, when it was banned. However, information about the subsequent dispersion of asbestos into the built environment and product stocks is not documented. Therefore, although we know how much asbestos was consumed within Australia, we know much less about where it went, how much remains in the built environment, and how much is going to waste each year.

Currently in Australia almost all asbestos containing waste is disposed of to landfills. Landfills generally document and report to government the quantities of asbestos containing material received, but the actual quantity of asbestos is not obvious because this type of waste is often received mixed with building demolition materials or soil. Pickin and Randell (2015) collated data on landfilled asbestos containing material from each jurisdiction in Australia. The reported quantities are shown in Figure 1. The report goes on discuss issues with the data collection process, such inconsistencies between reporting requirements for each state.

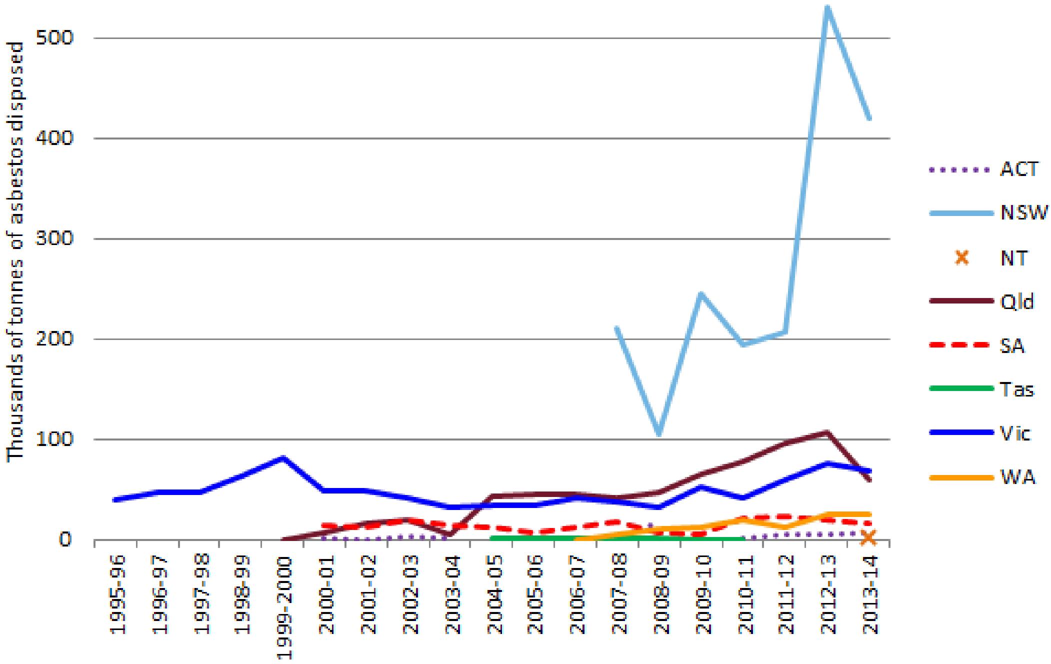

Figure 1: Asbestos quantities disposed by jurisdiction and year (Pickin and Randell 2015)

Notes: Qld and Vic tracking system data were corrected to remove 'storage', which was assumed to be double-counted. SA data may include some limited double-counting. In NSW, waste with even the smallest proportion of asbestos contamination must all be classified as asbestos waste, so asbestos waste may include significant proportions of other demolition materials.

On commission to the Australian Government Asbestos Safety and Eradication Agency, we developed a model that estimates the remaining stock of asbestos in the built environment and projects when this will be discarded as waste. The conceptually simple model enables best estimate responses to questions such as 'what proportion of consumed asbestos remains in use in stocks?' and 'when can we expect the asbestos waste stream to decline?'

In section 2 of this report we provide an overview of the model. In section 3 we specify the product groups used in the model and explain how we estimated their lifetime parameters. In section 4 we present data relating to the years in which asbestos was consumed for each product group. In section 5 we describe our estimates for the content of asbestos found in each product group. In section 6 we present the results of the model and discuss its sensitivity to varying the inputs. In section 7 we present the main conclusions.

2 Model overview

The model inputs comprise: annual asbestos consumption; estimates of the proportions of the consumed asbestos that went into certain product groups; estimates of the average proportion of the mass of each product group made up of asbestos; and estimates of the lifetime distributions of each product group. The manipulation of this information enables an estimate to be generated of the stocks and flows to waste of asbestos in any given year.

As well as providing a best estimate, high and low range estimates were made throughout, reflecting uncertainty in the various estimates. The user can readily vary model parameters as a method to assess the model sensitivity to reasonable values and to provide for updating when better information becomes available. The model is unable to differentiate between different types of asbestos, and does not account for the impact of government interventions. Because we wanted the model to be user friendly and widely accessible, it was built in Microsoft Office Excel 2010.

3 Model inputs

3.1 Asbestos consumption

The Minerals UK data sets available from the British Geological Survey (BGS 2015) provided detail of asbestos production, imports and exports for the years 1920 to 2003. From this we were able to determine apparent asbestos consumption in Australia as:

Apparent consumption = Production – Exports + Imports

Although other data sources were available, the BGS data was the only one that provided annual data for all years. Figure 2 shows the annual apparent consumption of asbestos in Australia from 1920 to 2003. Total consumption over this period was 12.8 million tonnes (Mt).

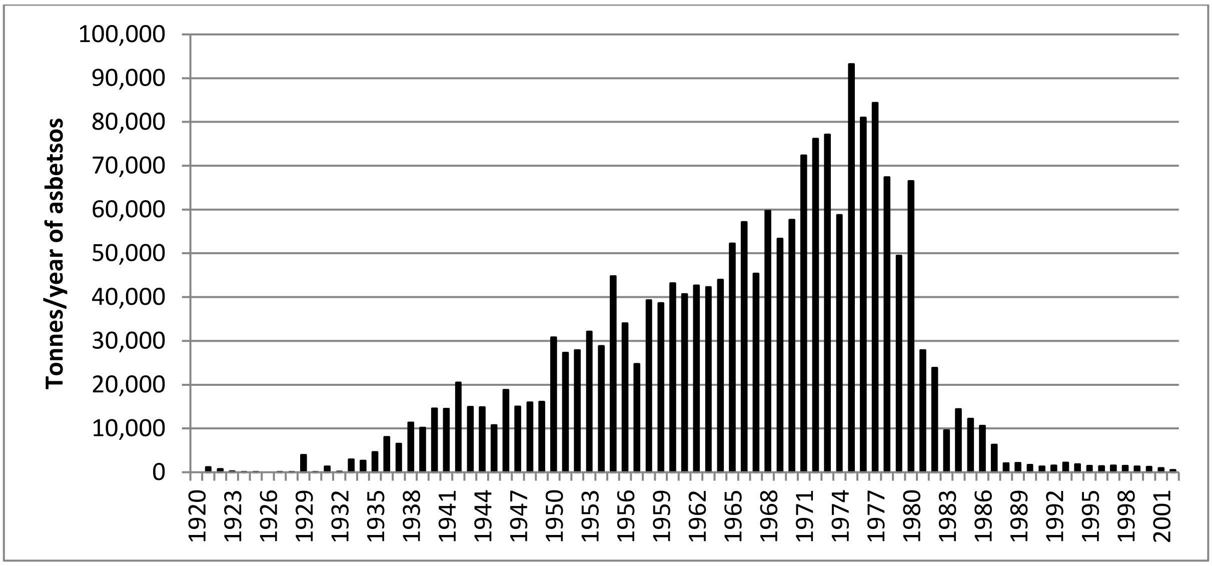

Figure 2: Apparent consumption of asbestos in Australia 1920-2003

3.2 Asbestos product groups found in Australia

It is estimated that 90% of the asbestos consumed in Australia went into cement (ASCC 2008). This can be divided into two broad categories, cement water pipes and cement building materials. In our analysis we further divide cement in buildings into domestic and commercial, due to the different average lifespans of these two building types. Cement water pipes are reported to have consumed up to 40% of asbestos cement, or 36% of total asbestos consumed (The Allen Consulting Group 2013).

To apportion asbestos cement between commercial and domestic buildings we used the "value of building work" dataset available from the Australian Bureau of Statistics (2015). This provides total spend on buildings separated into the two categories. The proportion of domestic building ranged between 50 and 70%, so we selected the mean of 60% domestic.

Details on the remaining 10% of asbestos were not available from an Australian based data source, therefore we used data from the U. S. Geological Survey (Virta 2006) to determine the proportions. Table 1 shows the total asbestos consumed in each product group.

Table 1: Cumulative amount of asbestos consumed in each product group from 1920 - 2003

Product	Total Consumption (kt)	Percentage of Total
Total asbestos consumed in Australia	12,837	100
Cement sheeting residential	4,168	32
Cement sheeting commercial	2,778	22
Cement water pipes	4,631	36
Flooring products	279	3
Friction products	52	1
Roofing	154	2
Other*	771	4

* The group ‘other’ contains a mixture of products that each account for less than 1% of total asbestos consumption.

3.3 Lifespan of asbestos product groups

In order to predict the quantity of these products that remain the built environment, we estimated the mean lifetime (L_{av}) and the years until 10% (L_{10}) remained in stock. From these two parameters we developed a Weibull function to predict the annual removal of asbestos products from the environment overtime from 1920 through 2100. Our assumption that a Weibull function would provide an appropriate approximation of product removal rate comes from its use in other similar policy analysis research. For example it is used by U.S. Department of Energy to estimate the removal rate of household appliances in analyses that respond to energy efficiency legislation (for example, see Chapter 9 of DOE 2011).

The Weibull function predicts the probability that a product is removed from use in the years following its initial purchase. Similar to a normal distribution, a Weibull function allows for a failure rate that changes over time. The outline of the function is determined by two parameters: the scale parameter (A) affects the peak of the distribution. The peak occurs at the number of years after initial consumption that half of the asbestos has been removed from the built environment. A low value for A indicates a lot of asbestos is removed every year, and the peak year is reached quickly, while a higher A value means the converse. The second parameter, called the shape parameter (B), determines how the failure rate changes over time. A shape parameter value greater than 1 indicates a removal rate that increases over time. This is generally the form we would expect for these scenarios, i.e. as a product gets older, the probability of it being discarded increase. Where B=1 the rate of the removal is the same every year and the function becomes exponential. B less than 1 indicates that the rate of removal decreases over time. In some instances, where the number of years until 90% of the product group is removed, was more than three times the mean lifetime of the product, the best fit Weibull function had a B of less than 1. As we know this is not an accurate representation of reality, in these instances we assumed B had a value of 1. In other words, we modified the Weibull distribution so that rates of removal do not decrease over time.

The model has the appropriate Weibull parameters for every combination of L_{av} and L_{10} built in. Therefore it is not necessary for the user to understand the Weibull function, as the parameters will be selected automatically when the lifetime parameters are changed.

3.4 Commercial Buildings

The L_{av} and L_{10} parameters found for commercial buildings were applied to both cement sheeting - commercial and roofing. Lifetimes of commercial buildings vary widely. Vetter and Ashford

(2011), for example, found the useful life of buildings typically ranges from 25 to 70 years. A study of the lives of buildings in North America (O'Connor 2004) found that the actual lifetime of buildings was a lot shorter than the rated lifetime of their structural components. This is because the motivation for building demolition is influenced by factors such as changing land values and lack of building suitability, rather than structural failure. The report further indicates the mean age of buildings being demolished by structural material. For concrete buildings over half were in the age range 26-50 years. A similar study conducted in Japan (Komatsu et al. 1994) found the mean lifetime of non-residential buildings to be 34.8 years. The Allen Consulting Group (2013) report also acknowledged a wide range of building lifetimes exist, and estimated a mean of 40 years. Based on the correlation of these studies we assume the mean lifetime (L_{av}) to be 40 years, with a sensitivity range of 25 to 50 years.

The O'Connor (2004) study reported two other pieces of data that helped us estimate the years after consumption at which 10% of asbestos remains (L_{10}). Firstly they state that only one third of concrete based buildings are more than 50 years old. Secondly they present the lifetime these buildings should be able to reach based on the quality of their structural components. This value, based on surveys of architects, structural engineers, builders, and developers, was found to be 87.2 years. From these data we assume L_{10} of commercial buildings is 75 years, with a sensitivity range of 70 to 85.

3.5 Residential buildings

The lifetime of residential buildings is also highly variable. In Japan, Komatsu et al. (1994) found the average lifetime of concrete residential buildings to be 50.6 years. O'Connor (2004) reported on a U.K. study that found the average age of demolished residential buildings ranged from 11-32 years. The findings of the O'Connor study indicated that the lifetime of residential buildings tends to be longer than non-residential. They found mean residential buildings to be in the 75-100 year age range; however, these were mostly wood based rather than concrete. The distribution of household ages in Australia available from the Australian Bureau of Statistics (2013) indicates that around half of the current stock is more than 30 years old. An Australian based study by Kapambwe et al. (2009), based on a survey of architects, suggested the average lifespan for an Australian dwelling is 61 years. L_{av} of 60 years was therefore chosen as a sensible value, consistent with Kapambwe et al. (2009). We present a sensitivity range of 50 to 75 with this estimate. The L_{10} is estimated at 100 years, with a sensitivity range of 75-100 years.

3.6 Asbestos cement pipes

The lifetime of cement water pipes was investigated by Wang et al. (2012). This study collated 14 years' worth of pipe failure events data, providing an assessment of the age of pipes when they need to be replaced. The study was based in Western Australia, and there may be environmental factors that affected the lifetime of pipes. For example pipes deteriorate due to both their surrounding environment and the quality of water flowing through them (Davis et al. 2008) so applicability to the rest of Australia is an assumption. L_{av} was estimated to be 50 years, with a sensitivity range of 40-75 years. The rated lifetimes of asbestos cement water pipes are 80-100 years (Davis et al. 2008, Wang et al. 2012). Thus for L_{10} we assume 80 years, with a sensitivity range of 80-100 years.

3.7 Flooring

Flooring is considered separately from other asbestos products contained in buildings because it can be replaced without disturbing the key structural components of the building. Asbestos flooring is most commonly in the form of vinyl tiles. These come with a warranty of 10 to 25 years, indicating their potential mean lifetime lies within this range (Hosking Hardwood 2014; Realtor.com 2015). However, it is also possible to cover asbestos vinyl tiles with other flooring when its appearance is no longer desirable (The Flooring Lady 2015). This option may be preferred, in many cases, to employing specialty asbestos removalists. We assume the L_{av} of vinyl flooring to be 15 years with a sensitivity range of 15-25 years, based on the typical warranty. L_{10} is taken to be 50 years, to coincide with the mean lifetime of a building to account for people choosing to cover their asbestos vinyl flooring when it becomes dated, rather than having it removed. The sensitivity range of this value is 25-50 years.

3.8 Friction products

As explained earlier friction products are found in motor vehicles. We determined the lifetime variables by collating data on the age distribution of vehicles in Australia from the Australian Bureau of Statistics (2014). The data are shown in Table 2. Various sources indicated that friction products in vehicles such as brake shoes, pads and clutch plates are generally expected to be replaced after three years. However, we were unable to find any data sources to confirm this. Therefore we took the conservative approach of assuming these products were retired at the same time as the vehicle. The mean vehicle age across the three survey years was calculated to be 10 years. We adopt this as the L_{av} for the whole period of asbestos consumption. As all the data were consistent we do not present a sensitivity range for this estimate.

Table 2: Total number of motor vehicles in Australia 2010-2012 (ABS 2014)

Survey Year	**2010**		**2011**		**2012**	
Age (years)	Total	Cumulative Percentage	Total	Cumulative Percentage	Total	Cumulative Percentage
0	153,402	1%	16,861	0%	22,182	0%
1	941,354	7%	987,642	6%	933,486	6%
2	1,080,794	14%	970,701	12%	1,105,519	12%
3	1,096,254	20%	1,078,492	19%	970,016	18%
4	1,017,980	27%	1,088,635	25%	1,070,672	25%
5	1,036,337	33%	1,011,134	32%	1,082,912	31%
6	966,210	39%	1,027,929	38%	1,003,084	37%
7	921,136	45%	957,593	44%	1,017,547	43%
8	819,330	50%	912,243	49%	946,372	49%
9	770,302	55%	809,147	54%	899,991	54%
10	772,459	60%	757,867	59%	795,276	59%
11	734,623	64%	756,933	64%	740,790	63%
12	747,625	69%	715,334	68%	735,191	68%
13	634,530	73%	721,771	72%	688,026	72%

Survey Year	2010		2011		2012	
Age (years)	Total	Cumulative Percentage	Total	Cumulative Percentage	Total	Cumulative Percentage
14	532,248	76%	604,310	76%	685,699	76%
15	511,560	79%	501,115	79%	563,773	79%
16	469,465	82%	476,589	82%	459,877	82%
17	386,719	85%	433,112	85%	431,196	85%
18	342,575	87%	351,625	87%	386,799	87%
19	291,444	89%	308,037	89%	309,059	89%
20 and older	1,813,650	100%	1,859,843	100%	1,871,880	100%

To determine L_{10} we looked at the cumulative percentage of vehicles in each age category. For all three years of survey data, the oldest 10% of vehicles was 20 years and over. Therefore we assume an L_{10} of 20 years with a sensitivity range of 17-30 years, to account for the three year variation in the datasets.

3.9 Other

As explained in the section on asbestos consumption, this category contains a mixture of materials that each account for less than 1% of total asbestos consumption. It includes some products that are assumed to have a relatively short lifespan, such as asbestos textiles, as well as products that are found in buildings which would have a similar lifetime to those estimated for buildings above. We assume L_{av} of 10 years as more of the products within this category have shorter lifetimes, with a sensitivity range of 5-50 years. The L_{10} is estimated to be 80 years, with a sensitivity range of 50-100 years.

Table 3 summarizes the lifetime parameters for each product group.

Table 3: Lifetime parameter estimates for each asbestos product group

Product Group	Mean lifetime (years)			Time to 10% remains (years)		
	Best	Low	High	Best	Low	High

Cement sheeting- Domestic	60	50	75	100	75	100
Cement sheeting – Commercial	40	25	50	75	70	85
Cement water pipes	50	40	75	80	80	100
Flooring products	15	10	25	50	25	50
Friction products	10	10	10	20	15	30
Roofing products	40	25	50	75	70	85
Other	10	5	50	80	50	100

4 Year of manufacture

The UK data set shows asbestos consumption as starting in 1921, and accelerating from the 1930s to peak at 93,000 tonnes in 1975, then decelerating rapidly to 2,000 tonnes by 1999 and to zero in 2003. We were only able to find a small amount of information on the allocations of asbestos to the different product groups in specific years. The only two pieces of information available were that asbestos cement water pipes were constructed from 1930s to the late 1970s (Davies et al 2008) and that asbestos use in buildings ceased in the late 80s. Various sources give a specific year ranges, but these are not always consistent. We considered consumption patterns by the decade rather than per year, with variability in roofing, flooring and cement sheeting. Table 4 shows the assumed proportions of asbestos consumed in each product group per decade.

Table 4: Estimated percentage of asbestos consumed in each product group per decade

Product Group	**1920s**	**1930s**	**1940s**	**1950s**	**1960s**	**1970s**	**1980s**	**1990s**	**2000s**
Cement sheeting- Domestic	51%	31%	31%	31%	31%	31%	51%	0%	0%
Cement sheeting – Commercial	34%	21%	21%	21%	21%	21%	34%	0%	0%
Cement water pipes	0%	40%	40%	40%	40%	40%	0%	0%	0%

Flooring products	5%	3%	3%	3%	3%	3%	5%	%	%
Friction products	2%	1%	1%	1%	1%	1%	2%	40%	40%
Roofing products	3%	2%	2%	2%	2%	2%	3%	0%	0%
Other	6%	3%	3%	3%	3%	3%	6%	60%	60%

5 Asbestos content of product groups

The model aims to estimate stocks and flows of asbestos containing products, requiring an estimate of the proportion of asbestos found in each product group. This was done through a review of the literature to estimate the average asbestos content of the different product groups. Multiple estimates were found in all cases. Different manufacturers used slightly different mixes, and sometimes the same manufacturer altered their product over time. Therefore all values are presented with a sensitivity range. The model allows the user to vary the asbestos content.

For asbestos cement used in water pipes, two sources provided an estimate of the asbestos content. Pure Technologies (2015) reported 15-20% while Allen Consulting Group (2013) reported 10-15%. We took the overlap of these two ranges, 15%, for our analysis with a suggested sensitivity range of 10-20%.

For asbestos cement sheeting used in buildings (both domestic and commercial) various estimates of the asbestos content are available. The U.S. Environmental Protection Agency (1990) reports the range to be 12-50% for various cement products. The U.K. Department of Environment, Transport and Regions (1999) reports the proportion to be mainly 10-15%, but can be up to 40%. The Asbestos Information Centre (2015) also reports the proportion to be 10-15%. We took the proportion to be 15% as this seems to correspond to the most common asbestos containing cement products. This value is consistent with other studies (Bilbija 2011; Kazan-Allen 2012).

The proportion of asbestos in flooring varies widely depending on the particular product. For example vinyl tiles are reported to contain between 8 and 30% asbestos, while floor backing (an insulating layer under the tiles) can be up to 100% asbestos (U.S. EPA 1990; Workplace Health and Safety Queensland 2011). Vinyl flooring appears to be the most common use of asbestos flooring in Australia. Therefore we assumed 20% to be a reasonable estimate.

There are a variety of asbestos roofing products, which were grouped together in the U.S. Geological Survey. table of consumption by end use (Virta, 2006). The proportion of asbestos in these products ranges from 10-30% (U.S.EPA 1990). We assumed a percentage of 20% for our analysis.

The asbestos content of friction products also varies widely with a reported range of 30-80% (The Mesothelioma Center, 2015). We applied the middle of this range at 55%.

The asbestos content for the other category has a very broad range of 1-85% (U.S. EPA 1990). We used an estimate of 10% as more products fall in the lower end of this range.

Note that there is another aspect of 'dilution' of asbestos flows – the mixing of asbestos containing material with other materials (demolition waste, soil etc.). This 'dilution' does not form part of the primary model but is considered using secondary waste data. Table 5 shows the proportions used in the model, along with the sensitivity ranges considered.

Table 5: Asbestos content of the considered product groups

Product Group	**Estimated proportion of asbestos in product (%)**	**Sensitivity range (%)**	
		Low	**High**
Cement sheeting- Domestic	15	10	50
Cement sheeting – Commercial	15	10	50

Cement water pipes	15	10	20
Flooring products	20	8	30
Friction products	55	30	80
Roofing products	20	10	30
Other	10	1	85

6 Results and Discussion

6.1 Stocks

We used the model to generate asbestos stocks in Australia for 1920 through to 2100 for the best, low and high asbestos lifetime estimates found in Table 3. Both L_{av} and L_{10} were adjusted, for example the short lifetime estimate uses the shortest L_{av} and shortest L_{10}. This was done in order to determine the broadest variation in results across the selection of estimated values. The results are shown in Figure 3.

In the best estimate: in 1981, stocks peaked at 10.5 Mt; by 2011, 50% of the total asbestos consumed remains in use; in 2016, 44% (5.6 Mt) remains in stock; and by 2055, 10% will remain.

As can be seen in the early years the stocks for all three estimates are very similar – the year of peak asbestos stocks is very similar ranging between 1980 and 1986. Thereafter, the estimates diverge as the shorter lifetime stocks start to decline more rapidly, the difference increasing until the 2050s and converging towards that end of the analysis period. The largest L_{10} estimate is 100 years, and as consumption of asbestos ceased in 2003, by 2100 all products would have reached there L_{10} estimate, for both the long and short estimates.

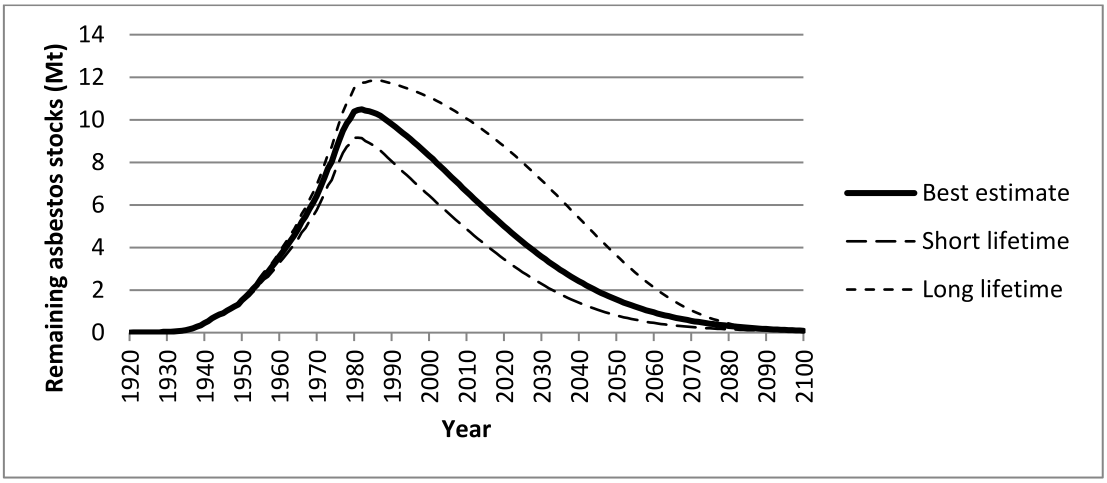

Figure 3: Australian asbestos product group stocks at various lifetime estimates with mid-range estimate of asbestos content

6.2 Waste Flows

Similarly we used the model to generate waste flows of asbestos containing material. Figure 4 shows the modelled results at the three estimates of products lifetimes found in Table 3. The variation in peak year varies strongly from 1983 for the short lifetime estimate to 2041 for the long lifetime estimate. In the best estimate, asbestos waste quantities peaked in 2004 at 170 kt and decline thereafter. This is not consistent with recorded data from landfills, which show that uneven annual quantities of asbestos containing but, in recent years, an apparent upward trend. However, as discussed, many consignments of asbestos containing waste comprise mainly soil and demolition rubble, and variation in these volumes could mask the trend in waste asbestos containing products.

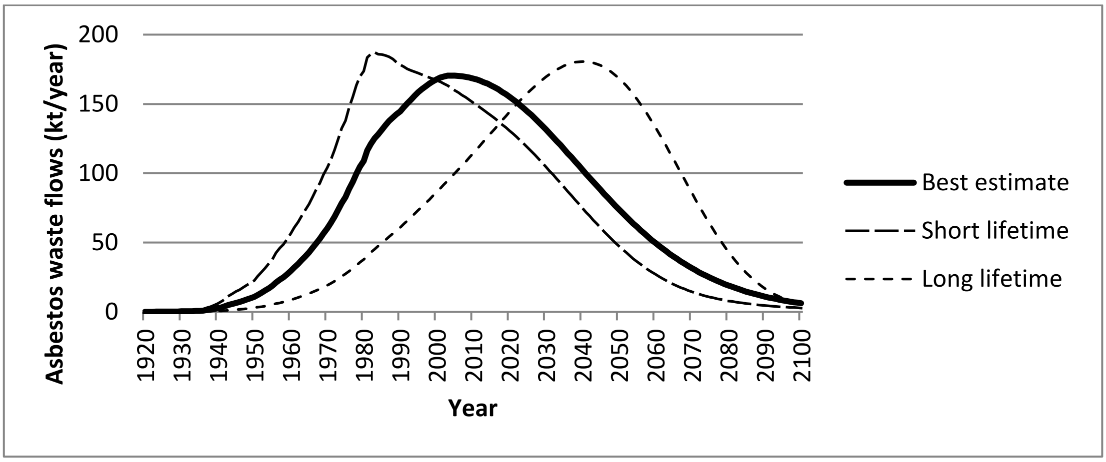

Figure 4: Asbestos product waste flows with varied lifetime estimates and mid-range asbestos content estimate

7 Conclusion

The model described in this paper provides a first-order estimate of stocks and flows for asbestos in Australia. Under the best estimate, asbestos stocks peaked in 1981 at waste quantities in 2014, and in 2016, 44% of consumed asbestos remains in use.

Sensitivity analysis shows significant variation in the results, reflecting uncertainty in some input parameters – particularly the lifespan parameters of the product groups. The model allows users to readily alter these key input parameters should better input data become available.

It is difficult to project future asbestos waste management requirements based on trends of asbestos containing materials received at Australian landfill sites. This is because reporting requirements vary in different states. Therefore this model provides an alternative method for projecting future waste management requirements by approaching the problem from a stocks model. This will provide a first order indication of the annual quantities of asbestos containing waste expected to be generated per year into the future. This will in turn contribute to understanding capacity needs to ensure the safe disposal of this waste.

8 Acknowledgements

The work was funded by the Australian Government. The Asbestos Safety and Eradication Agency, which commissioned the project on which this paper is based, provided feedback at various stages of the model development.

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