INTERNATIONAL ENVIRONMENTAL IERF RESEARCH FOUNDATION

Submission to the EPA's Request for

Additional Information to Protect Americans from Legacy Uses and Associated Disposal of Asbestos

By

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In questions of science, the authority of a thousand is not worthy the humble reasoning of a single individual.
Galileo Galilei

August 21, 2026

Necessary Considerations for a Science-Based Risk Evaluation of Asbestos Fiber Types in the EPA's Planned Rulemaking

Introduction

There is no mineral fiber known as asbestos; rather asbestos is a commercial term that encompasses six different minerals that occur naturally in a fibrous form. Five of the asbestos minerals are in the amphibole family: crocidolite, amosite, tremolite, actinolite, and anthophyllite. One of the asbestos minerals is in an entirely different mineral family of serpentine minerals: chrysotile. The different asbestos minerals have dramatically different risk profiles, with some differing by orders of magnitude for comparable exposures. The history of asbestos regulation in the United States reveals regulatory processes that have studiously ignored scientific assessments of the risks of different asbestos minerals. As the EPA approaches its rulemaking with respect to "legacy" asbestos, the agency's risk evaluation, if it is to be true to the scientific evidence, must follow the exhaustive data on the differential in fiber type pathogenic potency.

History of the Asbestos Ban in the United States

The history of the federal government's efforts to regulate the entire family of asbestos minerals reveals a studied ignorance of the varied health effects of different asbestos minerals by "lumping" them all into one category of material. The federal government's effort to ban asbestos started with an advanced notice of proposed rulemaking by the US Environmental Protection Agency on October 17, 1979. That year the total US consumption of asbestos was about 560,000 tons and about 6.6% was the more carcinogenic amosite asbestos and crocidolite asbestos[the two most commonly used minerals in the class of commercial amphibole asbestos, the balance being the dramatically less potent chrysotile asbestos (see Hodgson & Darnton 2000)].

In the 2026, none of the commercial amphibole asbestos types is in production worldwide, and the US use of chrysotile asbestos decreased by 99.95% to about 300 tons per year.US consumption in the U.S., in 1980, was 4.9 pounds per person; by 2026, it had decreased to about 0.002 pounds per person. Markedly fewer people are currently exposed to asbestos and the commercial amphibole asbestos types were no longer being mined worldwide. As populations exposed to airborne asbestos at the current permissible exposure limit (PEL) the risk of developing asbestos-related cancer in the U.S. has been vastly reduced and crocidolite the most potent cause of human mesothelioma is no longer in commercial use.

A year prior to the asbestos ban being proposed, the U.S. National Cancer Institute (NCI) and the National Institute of Environmental Health Sciences (NIEHS) fallaciously predicted that 2 million premature *cancer deaths* would occur over the next thirty years (≈67,000 per year) from past asbestos exposure or "roughly 17% of the total cancer incidence experienced in that period" (Efron, 1984). Making a 30-year projection of asbestos-related cancer deaths was a bold, largely unprecedented claim. The prediction would soon thereafter be shown to be wildly inaccurate and irresponsible, although the popular media continued to perpetuate the hyperbolic predictions.

The draft NIEHS report was the basis for a notorious speech by Secretary Califano (HEW). The report was not peer reviewed, and it was released to the press without input from the medical or scientific community. The report addressed nine occupational carcinogens, but the estimate of 2,000,000 asbestos-related cancers brought the focus of attention to asbestos.

The asbestos prediction was based on the assumption that *any worker exposed to any type or concentration of asbestos* would have an asbestos-related cancer risk similar to an asbestos insulation worker (Wilson et al., 2001). This assumption has several flaws including the obvious failures to account for the reduction in the permissible exposure levels (PEL) for asbestos and for the insulation worker's heavy exposures to the most pathogenic commercial amphibole asbestos types. The insulation workers' asbestos exposures were distinctly different from the average asbestos worker, and certainly from trades that had only incidental asbestos exposures or only chrysotile exposures.

The assumptions of the NIEHS report were incorrect and the predicted numbers of asbestos-related cancer deaths have not occurred. The *extremely high cancer risk predicted* in 1978-79 did drive the regulatory climate at the time, leading to a call for an asbestos ban the following year. What was critically needed then as well as now is accurate information for designing effective public policy.

Mr. Califano's use of the NIEHS prediction of asbestos-related cancer mortality in the millions created in the public's mind a deep seated, unfounded fear of asbestos, which exists to this day. Epidemiologic data show that the actual incidence of asbestos-related cancer can be greatly reduced by controlling exposure and by eliminating the use of the commercial amphibole asbestos fiber types.

More than a decade after Mr. Califano's exercise in fear mongering, the EPA attempted a ban on asbestos, without regard to mineral fiber type. On October 18, 1991 the 5th Circuit Court of Appeal vacated EPA's ban because the agency had "failed to muster substantial evidence" to support its rulemaking. (*Corrosion Proof Fittings v. EPA*, 947 F.2d 1201 (5th Cir. 1991)). The overturning has been described by some as a "technical ruling" and blamed the asbestos industry; the fact of the matter was that the *EPA had simply failed* to meet their burden to justify the ban.

In 1986, the EPA estimated that a ban on asbestos shingles would "cost $23-34 million to save 0.32 statistic lives ($72-106 million per life)." The 5th Circuit went on to query why EPA would consider asbestos so dangerous if for example "...over the next 13 years, we can expect more than a dozen deaths from ingested *toothpicks* - a death toll more than twice what the EPA predicts will flow from the quarter billion-dollar bans on asbestos pipe, shingles and roof coatings." It is instructive to compare the EPA's rather modest claims of excess asbestos-related cancer death in the 1980s, with the vastly higher predictions in 1978 by the NCI-NIEHS.

The Court of Appeal's decision in *Corrosion Proof Fittings* remanded the matter back to EPA to muster further evidence in support of the agency's claim that controlled use asbestos constitutes an "unreasonable risk". EPA never provided such additional evidence, and for the controlled use of chrysotile asbestos, the evidence does not exist. The EPA has historically relied, and it currently relies on the health experience of individuals exposed to the commercial amphiboles asbestos-types and cohorts exposed to both chrysotile and commercial amphiboles to support the health hazard evaluation of chrysotile asbestos. The U.S. federal regulatory agencies have never properly considered the importance of asbestos fiber type in their rulemaking. The approach of viewing asbestos as a single substance for regulatory purposes is not remotely supported by the current medical and scientific knowledge. The U.S. federal regulatory agencies have consistently and zealously followed this sophistry with any basis in the scientific record.

The past efforts to pass legislation banning asbestos and the current rulemaking have not addressed any of the 5th Circuit's concerns about mustering substantial evidence. Controlled use of chrysotile asbestos is feasible and it has been happening for a long time in many parts of the world (Nolan *et al.,* 2001). From time to time, there are calls for a ban on asbestos, but there is a complete lack of the "substantial evidence" asked for by the 5th Circuit to show that controlled chrysotile asbestos exposure presents an "unreasonable risk." The evidence that would substantially support such a conclusion with respect to chrysotile simply does not exist (Wilson *et al.*, 2001, Camus 2001a,b).

The zealous quest for a total ban on asbestos, without regard to fiber type, (mostly in the U.S. although more recently globally) has regularly been advanced in *opinion* pieces in various medical journals (See Chen *et al*., 2019, LaDou *et al*., 20121 & Burki 2024). Reports have also appeared in scholarly journals to show that the risk of asbestos-related diseases could be effectively managed by limiting airborne exposure to chrysotile given that there is a dramatic range in health hazards among the six asbestos types (Wilson *et al*., 2001, Camus 2001a, b). On the other hand, the expectation that the six asbestos mineral could be effectively controlled as a single substance has been conclusively shown to be false (Hodgson & Darnton, 2000). All of the opinion pieces suggesting a total ban is necessary to eliminate the risk have in common the following beliefs:

1. An immediate and total ban on all uses of asbestos without any exception is needed,
2. All form of asbestos are proven human carcinogens,
3. All asbestos illness and deaths are preventable only by a ban,
4. All asbestos substitutes are safer than asbestos even though there is limited or no evidence to support the claim,
5. There is no evidence of a threshold below which there is no risk of asbestos-related disease particularly mesothelioma,
6. Asbestos has very limited use in many developed countries such as the US and banned in many including the European Union, they argue against the controlled use of asbestos in the underdeveloped world.

None of these six claims is sustainable, especially when we understand that they ignore relevant considerations of dose and duration, and most importantly, of mineral fiber type.

Asbestos Exposures in the U.S. have changed since an Asbestos Ban was first proposed in 1978

In the early 1970s, all the commercial asbestos fiber types (crocidolite, amosite & chrysotile) were being used in the United States. Asbestos consumption was above 500,000 tons per year, and the permissible asbestos exposure level (PEL) was initially set at 12 fibers/ml (equal to or great than 5 microns in length). Under those conditions, an asbestos ban might have perhaps been justifiable at that time, given that our knowledge was much more limited. Beginning in 1971, asbestos was the first substance regulated by the newly formed U.S. Occupational Safety and Health Administration (OSHA). Since that first OSHA regulation, the scientific evidence and understanding has grown exponentially with respect to understanding the relevance of mineral fiber type, as well as dose and durations of exposure. Today, the scientific evidence overwhelmingly supports the safe use of chrysotile, and that evidence eliminates the scientific justification for a ban of all asbestos fiber types in the United States.

Currently, the permissible exposure limit (PEL) for workplace exposure to any kind of asbestos fiber has been reduced to 0.1fibers/ml or 120-fold lower than the 1971 asbestos standard and many hundreds of times lower than the historical high asbestos exposure levels associated with asbestos-related disease before the advent of OSHA (Figure 1).

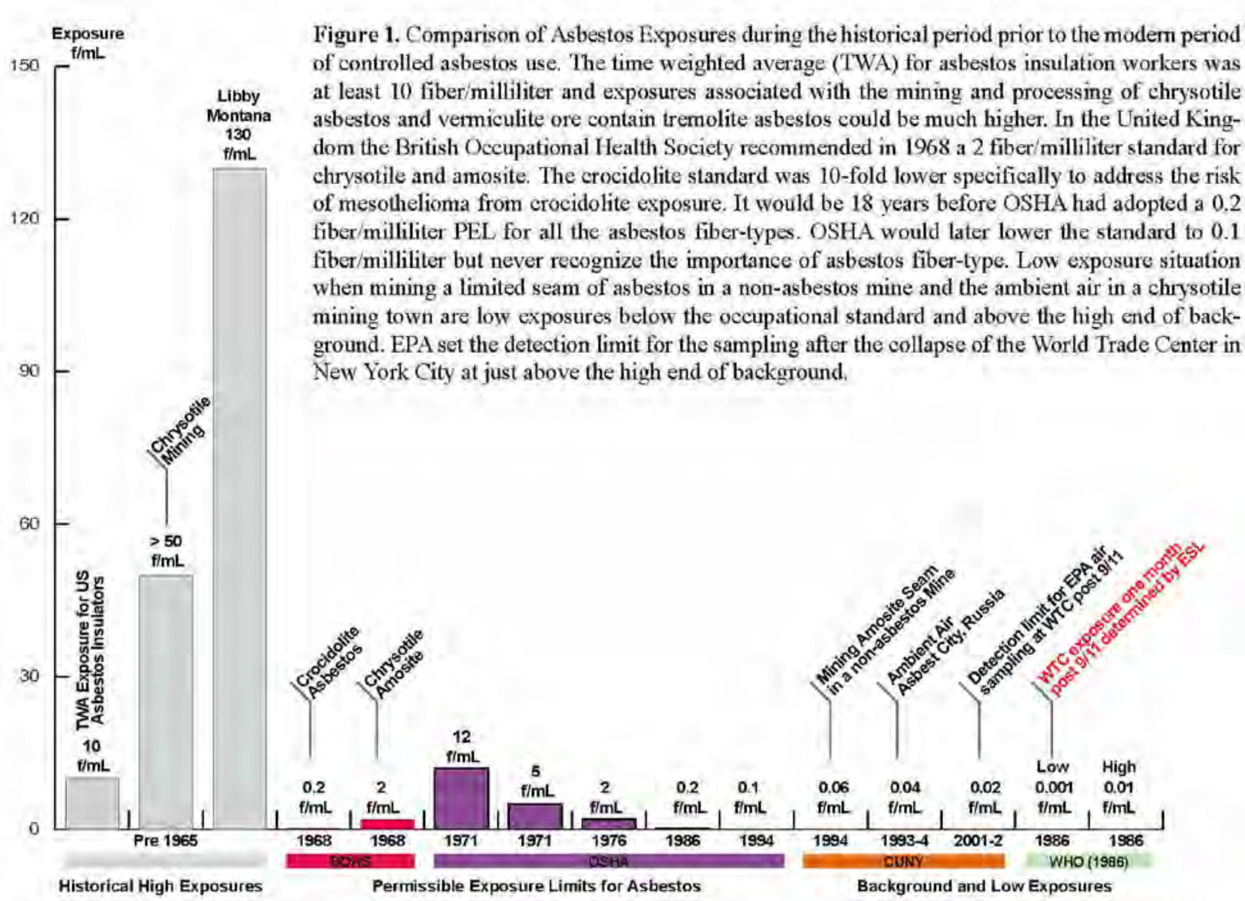

Figure 1. Comparison of Asbestos Exposures during the historical period prior to the modern period of controlled asbestos use. The time weighted average (TWA) for asbestos insulation workers was at least 10 fiber/milliliter and exposures associated with the mining and processing of chrysotile asbestos and vermiculite ore contain tremolite asbestos could be much higher. In the United Kingdom the British Occupational Health Society recommended in 1968 a 2 fiber/milliliter standard for chrysotile and amosite. The crocidolite standard was 10-fold lower specifically to address the risk of mesothelioma from crocidolite exposure. It would be 18 years before OSHA had adopted a 0.2 fiber/milliliter PEL for all the asbestos fiber-types. OSHA would later lower the standard to 0.1 fiber/milliliter but never recognize the importance of asbestos fiber-type. Low exposure situation when mining a limited seam of asbestos in a non-asbestos mine and the ambient air in a chrysotile mining town are low exposures below the occupational standard and above the high end of background. EPA set the detection limit for the sampling after the collapse of the World Trade Center in New York City at just above the high end of background.

The current U.S. permissible exposure level for asbestos is among the lowest in the world. The EPA risk assessment for the current ban proposal argues that the current US permissible exposure level is not "safe," but the agency does not clearly define "safe" and why chrysotile, as opposed to the much more dangerous amphiboles, does not meet that criterion. The EPA has not adequately considered that the elimination of the commercial amphibole asbestos-types and the 99.95% reduction in levels of exposure to chrysotile asbestos have completely changed any risk calculus with respect to future chrysotile exposure. Similarly, the EPA has not considered the vastly reduced workforce that has potential occupational exposure, and the extensive training required for manufacturing or abatement workers.

The EPA's proposed rulemaking must consider the potential and actual dangers of exposure to chrysotile substitutes. For years people were told of the negative health effects of butter and advised to use substitutes, but today we recognize that some varieties of margarine are more dangerous than butter. The health effects of asbestos-substitutes must be evaluated in any meaningful asbestos risk evaluation.

Periods of Asbestos-Related Disease

The natural history of asbestos-related disease in the United States can be divided into three different time periods: a historically high exposure period that resulted from poorly controlled use of all kinds of asbestos from which our knowledge of the asbestos-related diseases is derived. This historical period ended with the OSHA promulgating an asbestos permissible exposure limiting (PEL) in 1971, next followed a transition period when occupational asbestos exposures were lowered. The transition period ended in 1994 when the current 0.1f/mL PEL for asbestos was adopted (and the removal of commercial amphibole from production at about the same time) beginning the modern period of controlled asbestos use (Figure 1). The EPA has not addressed this transition period nor the reduced risk from the halt in the use of commercial amphibole asbestos. With the PEL reduction to 0.1f/mL, use of asbestos was greatly reduced meaning fewer worker were occupationally exposed. The impact of these changes has yet to be adequately addressed in the rulemaking.

The latency period (from first asbestos exposure during the historical period to the development of asbestos-related cancer) *is at least* 15 years and in epidemiology studies it is generally 20 to 25 years before significant increases in asbestos-related cancers occur. Most, if not all, of the asbestos epidemiology studies analyzed the health outcomes of workers first exposed in the historical period to asbestos before 1971. Future U.S. regulatory policy should not be based on historical information with little semblance to the current situation.

In testimony before the Senate, NIOSH indicated a continuing interest in asbestos-related disease among a cohort of South Carolina textile workers (Hein *et al*., 2007). The plant opened in 1909 and closed its doors in 1977. The type of asbestos products manufactured in South Carolina are no longer produced or used in the U.S., and the worker cumulative exposures to asbestos have only been crudely estimated. Among the 1,841 deaths in the cohort (about 65% of the total workforce), there were three mesothelioma, an overall mortality of 0.16%, about the same as the general male U.S. population (0.17% see Table 1). Contrary to the claims of advocacy groups, the heavy historical exposure to chrysotile in this well-studied group of textile workers did not produce dramatic increases in mesothelioma rates. Heavy historical exposures to chrysotile simply have not produced the dramatic increase in mesothelioma (17% of all deaths) found for example among those workers fabricating cigarette filters with crocidolite (Hodgson & Darnton, 2000)

Table 1. The percentage of deaths due to mesothelioma in the United States in 2003 is given for the general population and the specifically males and females. About 2,560 mesotheliomas occurred in the United States in 2003 where the disease was about 4-fold more common in males than females. 2,448,288 deaths occurred in the US that year with 1,201,964 in males. U.S. males in 2003 are expected to have 1 mesothelioma in 600 deaths. Recently in the U.S. general population mesothelioma accounts for 1 death in 1, 000 deaths in the general population and 1 in 600 and 2,000 for males and females respectively.

Asbestos Fiber-Type	Mesothelioma Deaths Per 1,000 in General Population	Total № of Mesotheliomas/ Deaths (%) §	Average Cumulative Exposure f/ml x Years
United States	**1**	**2,560(0.1%)**	***Bkgd*†**
Males	**1.7**	**2,000(0.17%)**	***Bkgd***
Females	**0.45**	**560(0.045%)**	***Bkgd***

†World Health Organization (1986) estimated the global background for asbestos in the ambient air to be between 0.001 and 0.01 fibers/milliliter and chrysotile is the predominant fiber-type.

§Mesothelioma as a percentage of all deaths.

As a group, the three major U.S. chrysotile exposed cohorts have reported 2,002 deaths with three mesotheliomas (Table 2). The risk of mesothelioma among the males in these three chrysotile-exposed cohorts is less than that experienced by the general male population (Table 1 & 2). In the U.S., one male in 600 dies of a mesothelioma or 0.17% while in the chrysotile exposed cohorts three mesotheliomas occurred in 2,002 deaths or 0.15%. The Relative Risk (RR) is 0.88 (Table 2). Only slightly higher RRs for mesothelioma are associated with chrysotile mining and milling, where exposures were significantly higher (Table 2).

Table 2. Data for the five chrysotile-exposed cohorts all the mesotheliomas are pleural. General causation for chrysotile asbestos exposure doubling the background risk of pleural mesothelioma is marginal among the Quebec miners and millers. It critically depends upon the estimate of background mesotheliomas. Adding in manufacturing workers makes the evidence weaker.

Fiber type	Name and Location	Mesotheliomas /all deaths (%)	Exposure f/ml x yrs	Risk Ratio Obs fraction /background
	Miners & Millers			
	Canadian Mines	33/7,456 (0.44%)	600	**2.0 (0.44/0.22)**
	Manufacturers			
Chrysotile	**Charleston South Carolina** *Males only in Charleston SC*	3/1,186 (0.25%) §	28	**1.5** (0.25/0.17)
Chrysotile	**New Orleans, LA**	0/259 (0%)	22	**0**
Chrysotile	**Connecticut**	0/557 (0%)	46	**0**
	All Males Manufacturers	***3/2,002 (0.15%)***		**0.88 (0.15/0.17)**
	TOTAL all studies	***39/10,540 (0.37%)***	***170***	**1.5**

§ Hein *et al.* 2007 the other data are from Hodgson and Darnton, 2001.

What has changed to justify the U.S. regulation to ban asbestos now?

Now as we re-visit the ban issue almost 35 years later much has happened to make a complete ban of asbestos in the U.S. an even less attractive public health policy than it was originally. In 1992, the dangerous, highly pathogenic amosite asbestos left commerce worldwide to be followed by the even more pathogenic crocidolite asbestos in 1997 (Figure 2). Crocidolite is the fiber type first and most robustly associated with mesothelioma in the Republic of South Africa (RSA) (Wagner *et al.*, 1960).

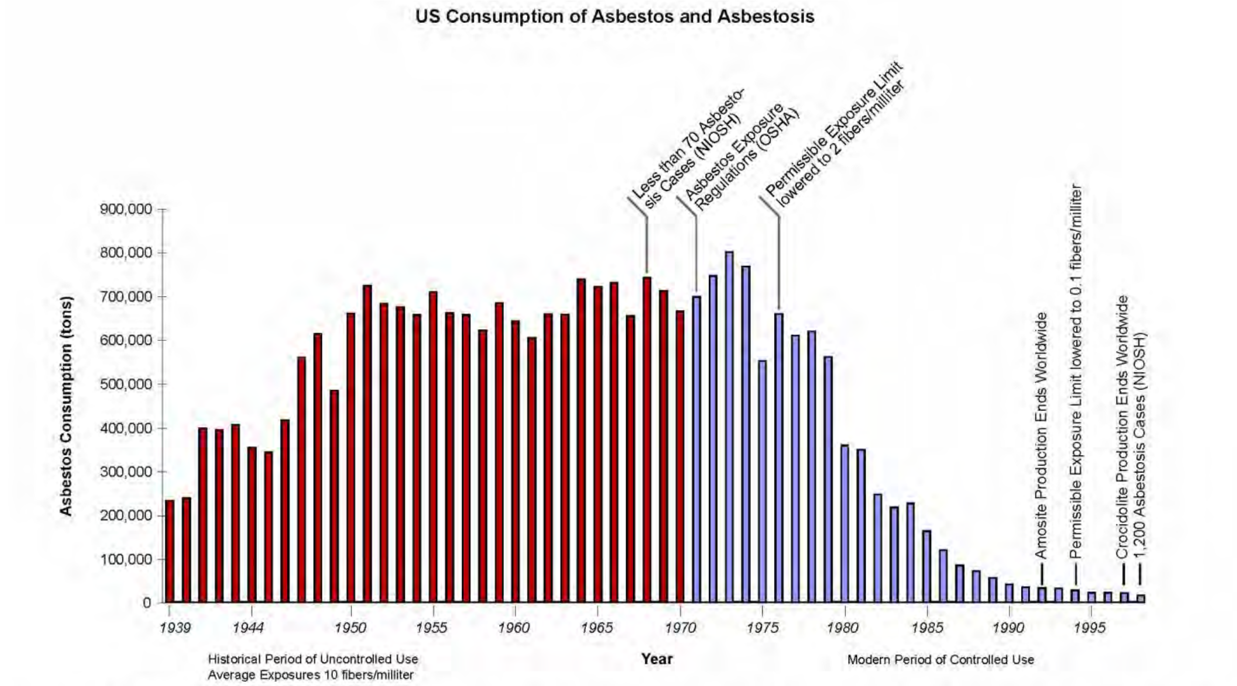

Figure 2. United States consumption of asbestos from 1939 to 1968 was 17,310,187 tons and airborne asbestos exposures were approximately 10 fibers/milliliter for Time Weighted Averages (certain task involved significantly higher exposures). From 1969 to 1998 US consumption of asbestos decreased to 9,523,469 ton and a permissible exposure limit for asbestos was adopted that was reduced to 0.1fiber/milliliter by 1994. Why did the number of asbestosis cases increase from less than 70 in 1968 to around 1,200 in 1998?

The crocidolite fiber type is particularly potent and can cause mesothelioma even after low level exposure; this observation began the public health concern about non-occupational exposure to asbestos causing cancer (Table 3).

Table 3. Mesothelioma mortality in 10 epidemiologic cohort studies of individuals exposed to crocidolite, amosite, actinolite asbestos and tremolite asbestos where general causation is well established. The average cumulative exposures are from Hodgson and Darnton, 2000 while the Risk Ratios (RR) have been added. Only the cohorts with occupational exposure to amphibole asbestos were useful for establishing causation. The non-occupational cohort studies were either negative or suggestive.

Asbestos Fiber-Type	Cohort Name	Total № of Mesotheliomas/ Deaths (%)	Mean Cumulative Exposure f/ml x Years§	Risk Ratio (>2)
Crocidolite	Miners			
	South Africa(SA)	20/423 (4.7%)	16.4	28(4.7/0.17)
	Wittenoom, Australia	72/719(9.1%)	23	54(9.1/0.17)
	Factory Workers			
	Massachusetts	5/28 (17.8%)	120	104(17.8/0.17)
Summary		***97/1,170(8.3%)***	***53***	**48 (8.3/0.17)**
Amosite	Paterson, NJ			
	Workers	17/740(2.3%)	65	13.5(2.3/0.17)
	Household	4/115 (3.5%)	Unknown	20.5(3.5/0.17)
	Neighborhood	1/780(0.12%)	Unknown	0.7(0.12/0.17)
	Tyler, TX	6/222(2.7%)		16(2.7/0.17)
	Uxbridge, UK	5/333(1.5%)		6(1.5/0.17)
	South African Miners	4/648(0.6%)	23.6	3.5(0.6/0.17)
Summary		***37/2,838(1.3%)***	***47.2***	7.7(1.3/0.17)
Tremolite-Actinolite Asbestos	Miners, Libby, MT†	**12/286 (4.2%)**		**25**(4.2/0.17)
Mean for four amphibole asbestos minerals		**146/4,294 (3.4%)**	***50***	**20(3.4/0.17)**

§Hodgson and Darnton, 2001. † McDonald *et al.* 2004.

Nolan *et al.*, 2006 analyzed the lung content of 43 mesothelioma cases from the RSA which mined and produced three mineral fiber types, crocidolite, amosite and chrysotile. This is the only lung content analysis series of South African mesothelioma cases. Crocidolite was the predominate asbestos-type found and often the only asbestos-type found. Of the four environmental mesothelioma cases in the series, three were crocidolite only and the fourth was 96% crocidolite, which is between 4- and 59-fold below the concentration of chrysotile in the U.S. general population where asbestos is found without asbestos-related disease. The results are consistent with epidemiology reports indicating mesothelioma can develop in individuals with exposure to crocidolite described as brief and/or slight (Wagner *et al.*, 1960, Hodgson & Darnton, 2000). RSA produced all the commercial asbestos fiber type, but mesothelioma was rarely, if ever, found in the chrysotile workers (Nolan *et al.*, 2006). The mesothelioma potency of crocidolite is demonstrable different from, and greater than, amosite. (Hodgson & Darnton 2000, Nolan *et al.*, 2006).

Crocidolite asbestos and high exposure to amosite asbestos are the major etiological agents in this disease. (Hodgson & Darnton 2000, Nolan *et al.*, 2007). However, high aspect ratio tremolite asbestos has been shown to be associated with both occupational and environmental mesothelioma. Consumption of these two commercial amphibole asbestos fiber types started to decline in the 1960s and the US incidence of mesothelioma has been declining since the 1990s (Weill *et al.*, 2004, Price 2022). These favorable trends are not commonly known or appreciated as lives saved with controlled use.

A further consideration is that earlier investigators assumed all mesothelioma were asbestos-related. Now there are multiple lines of emerging evidence for a background of mesothelioma without asbestos exposure (Price 2022). Of the 43 mesothelioma case in the series by Nolan *et al.*, 2007, seven did not contain asbestos with a detection limits from 0.013 to 0.037 millions of fibers per gram of dried lung tissue. All the cases with no detectable asbestos were in males, while three of the four environmental mesothelioma cases were in females.

Fewer than 38% of the countries around the world have chosen to ban asbestos (most after the EPA ban was vacated in 1991) but worldwide consumption has remained in excess of 1,000,000 metric tons per annum. Not all of the World Health Organization (WHO) member countries have banned asbestos. The countries not banning chrysotile are largely developing countries and those producing asbestos. None of the nine most populous nations (India, China, Indonesia, USA, Pakistan, Nigeria, Bangladesh, Russia & Ethiopia) has banned the use of asbestos. These nine countries represent slightly more the 50% of the world's population. The U.S. has tried to ban asbestos for the last 47-years with very limited policy success, but it has enjoyed practical success with the reduction in asbestos consumptions to a trivial level. The U.S. has eliminated the commercial use of amphibole asbestos, which helps understand the epidemiologic trends that show a reduction in U.S. cases of mesothelioma. (Price 2022).

Although it is easy to find editorials calling for total bans on asbestos, few, if any, provide cogent risk arguments for enacting such a policy. In many places, effectuated bans limited amphibole asbestos, and allowed certain uses of asbestos, especially chrysotile, in critical applications such as gaskets to contain corrosive gases, in rocket engines and diaphragms for production of chlorine.

The Court of Appeal's review in *Corrosion Proof Fittings* (1991) is unique in requiring judicial review of regulatory processes, such as an asbestos ban. Such open and transparent judicial review of government policy simply does not happen in many other countries. To our knowledge the issues raised by the 5th Circuit have never been addressed in any country where asbestos has been banned; nor have they been adequately addressed by the EPA

The significantly higher carcinogenic potency of the commercial amphibole asbestos minerals (amosite and crocidolite) compared to chrysotile has been well understood for many years with an important quantitative risk assessment by Hodgson & Darnton, appearing in 2000, leading to a consensus in the medical and scientific community (Table 3). The estimate in the range of potency between crocidolite asbestos and chrysotile asbestos for mesothelioma is 500 to 1. These are huge differences in pathogenic potency and offer an explanation why a single occupational exposure standard based on averaging would not yield an effective standard or policy. A similar pattern exists for lung cancer risk but less clear cut. Hodgson & Darnton 2000 found the commercial amphibole asbestos types to 10 to 50 more potent at producing lung cancer. The difficulty in obtaining accurate smoking histories in epidemiologic analyses may be partly responsible for producing the wide range. Smoking is not a co-factor for mesothelioma.

After reviewing the epidemiology available for assessment of chrysotile asbestos as a cause of mesothelioma, Yarborough (2006) concluded that the "risk of chrysotile for mesothelioma in most regulatory context reflects public policies, not the application of the scientific method as applied to epidemiology studies." Yarborough refutes the claim, argued in S.742 and elsewhere, that the current asbestos PEL, applied to chrysotile exposures, does not protect workers. Consideration of fiber type is necessary to formulate an effective PELs for the various asbestos-types.

Historical Legacy from High Exposure and Amphibole Asbestos

The first asbestos exposures in all the other major asbestos cohort studies began decades prior to the beginning of the transition period in 1971. Due to the long latency for asbestos-related cancers, cases continue to develop from these exposures. Projections by Price (2022) "Based on my analysis for SEER data for 1973 through 2005 published in 2009 projected that around 2040 virtually all the mesothelioma cases in the U.S. will background cases". These cases are the historic legacy from poorly controlled use of asbestos and the use of commercial amphibole asbestos which some have referred to as the "iron grip of latency". Those exposures occurred many years ago and their consequences *cannot be undone* by any legislation or public health action. The projection for the future indicates that the end is in sight for asbestos-related mesotheliomas.

Currently, the U.S. is using around 300 tons of chrysotile asbestos a year mainly in the chlorine gas processing and insulation for the space shuttle. Others have tried to justify an asbestos ban by claiming the U.S. is using unlabeled asbestos products; the evidence for this claim is weak and limited. OSHA and Consumer Product Safety Commission (CPSC) requires most asbestos-containing products to be labeled as such, and since 1994 OSHA requires exposures to be controlled at the PEL of 0.1f/mL.

About 32-years have passed since the current asbestos standard was adopted. Therefore, the latency period is sufficient to observe the mortality experience of modern asbestos workers. We know of no epidemiology studies of workers exposed only after 1994. A problem is that very few workers continue to be exposed currently compared to past populations. Past risk assessments on asbestos suffer from fatal invalidity by using data on the past high (and mixed fiber type) asbestos exposures experienced by asbestos workers. To understand the trend of asbestos-related disease currently and in the future requires a risk assessment based upon exposure to only chrysotile at the current PEL.

What are the Risks of Asbestos-Related Cancer with the Controlled Use of Chrysotile Asbestos?

This question can be answered by doing a risk assessment for asbestos-related cancer.

This risk assessment, which is simple, straightforward and follows principles well established in the last 20 years, must be addressed first. Then, if these risks are unacceptable by pre-specified criteria, the proposed Agency rulemaking might have a substantial basis. If, on the other hand, the risks are null or negligible, the time of the people and the Congress, and the courts, should not be wasted. There are already too many unnecessary laws. The cohorts of asbestos exposed workers used to develop the risk assessment were exposed primarily, if not exclusively, prior to 1971 and therefore represent the historic period of asbestos exposure that cannot scientifically be used to predict the future.

This is an excellent example of how to learn from past mistakes. Perhaps we have already taken all the actions necessary to avoid a repetition or continuation of hazard from asbestos-related cancer.

Exposure to 0.1f/mL, the PEL since 1994, for 45 years leads to a cumulative exposure of 4.5f/mL x years. In their Senate testimony on June 12, 2007, NIOSH claimed asbestos exposure at the current PEL would cause 3.4 asbestos-related cancers per 1,000 workers over their lifetimes. This claim has been quoted in the current EPA record. The NIOSH projection is based on a risk model developed in 1986 that projects average risk for exposure to all three commercial asbestos fiber types – crocidolite, amosite, and chrysotile used in commerce in the U.S prior to that time.

Currently only chrysotile asbestos continues to be used in commerce in the U.S. and worldwide. Therefore, to project future asbestos-related cancers we used the asbestos-type risk assessments developed by Hodgson & Darnton in 2000, which projects cancer risks for the three asbestos fiber types. These epidemiologists work at the Heath Safety Executive, an agency of the United Kingdom government and work independently of both labor and management influence. As noted, the overwhelming majority of the public erroneously believe asbestos to be a single substance not, six different minerals, but the EPA knows better.

There are, to be sure, many additional chrysotile studies published after Hodgson & Darnton (2000), up to the present day. The entire body of scientific data greatly supports the huge differential in pathogenic potency between chrysotile and the amphibole asbestos fiber types. The authors of this report recently have come by a summary of 26 chrysotile exposure studies, up to the present, along with a synthesis of the data in those studies for no observable effect levels for chrysotile exposure. The summaries and synthesis, which we believe will be important for the Agency's rulemaking, are attached as Appendix A, and the data synthesis is attached as Appendix B, to this report.

These predictions differ from those provided by NIOSH in three important ways:

First, NIOSH's estimates are higher than those for chrysotile asbestos and lower than for the two commercial amphibole asbestos fiber types. A similar asbestos exposure leads to a significantly lower health hazard for a chrysotile-exposed population than, for a population otherwise identical, exposed to commercial amphibole asbestos. We argue that NIOSH's choice to average the potency of the fiber types is a significant contributing factor to any asbestos-related disease found in workers starting during the transition period (Figure 1, Table 4). The NIOSH procedures over-protect the chrysotile exposed worker while under-protect those exposed to commercial amphiboles.

Table 4. The lifetime risk from both asbestos-related cancers (lung and mesothelioma) are totaled and shown as the lifetime risk at the current PEL. At the Senate Hearing, NIOSH claimed 3.5 asbestos-related cancers per 1,000 for their asbestos fiber with average potency and opined the target was to get below 1 per 1,000. Note that for chrysotile the lifetime cumulative exposure at the current permissible exposure is about 15-fold below this while the commercial amphibole asbestos fiber-types are between 4.7 and 23.6-fold above the target. NIOSH needs to include the cancer risks associated with the amphibole asbestos fiber-types otherwise their regulatory policy falls to the ground.

Source	Asbestos Fiber-Type	Cumulative Asbestos Exposure	Lifetime Risk of Asbestos-Related Cancer (per 1,000 deaths)
NIOSH	Average for Mixed	4.5 f/mL x years	3.5†
NIOSH-Target			<1
Hodgson & Darnton	Chrysotile	4.5 f/mL x years	0.067(67%)§
Hodgson & Darnton	Amosite	4.5 f/mL x years	4.7-5.6(96%)
Hodgson & Darnton	Crocidolite	4.5 f/mL x years	22.7-23.6(99%)

§Percentage of risk associated with mesothelioma.

† NIOSH estimates are for asbestos-related lung cancer, mesothelioma, and gastrointestinal cancer. We limit this analysis to lung cancer and mesothelioma. Recently the Institute of Medicine concluded that among other cancers historically associated with asbestos a casual relationship is likely only for laryngeal cancer (IOM, 2006). There is no asbestos risk assessment for laryngeal cancer. However, 80-90% of laryngeal cancers are related to alcohol and smoking (Higginson *et al.* 1992), therefore asbestos-related laryngeal cancers are not included in our projections. It is rare disease in women and about 10-fold less common in males than smoking-related lung cancer (Higginson *et al.* 1992).

Secondly, our asbestos-related cancer risk due to commercial amphiboles exposure is reported as a range while NIOSH has a single value. This is to account for the different rates of the lung cancer from amphibole asbestos exposures occurring in the different cohorts of workers. Each cohort is exposed to "only one of these two fiber types". Lung cancer as a function of exposure is similar for the two amphibole asbestos fiber types, between 10 to 50-fold greater than for chrysotile, NIOSH's prediction lacks this refinement (Hodgson & Darnton, 2000).

Third, we assume the workers do not smoke while NIOSH did not say if they smoke or not. The lung cancer risk is at least 10-fold higher for smokers than those who do not smoke, and probably much higher. Exposure to all types of asbestos increases your lung cancer risk as a proportion of your underlying lung cancer risk (Figure 3).

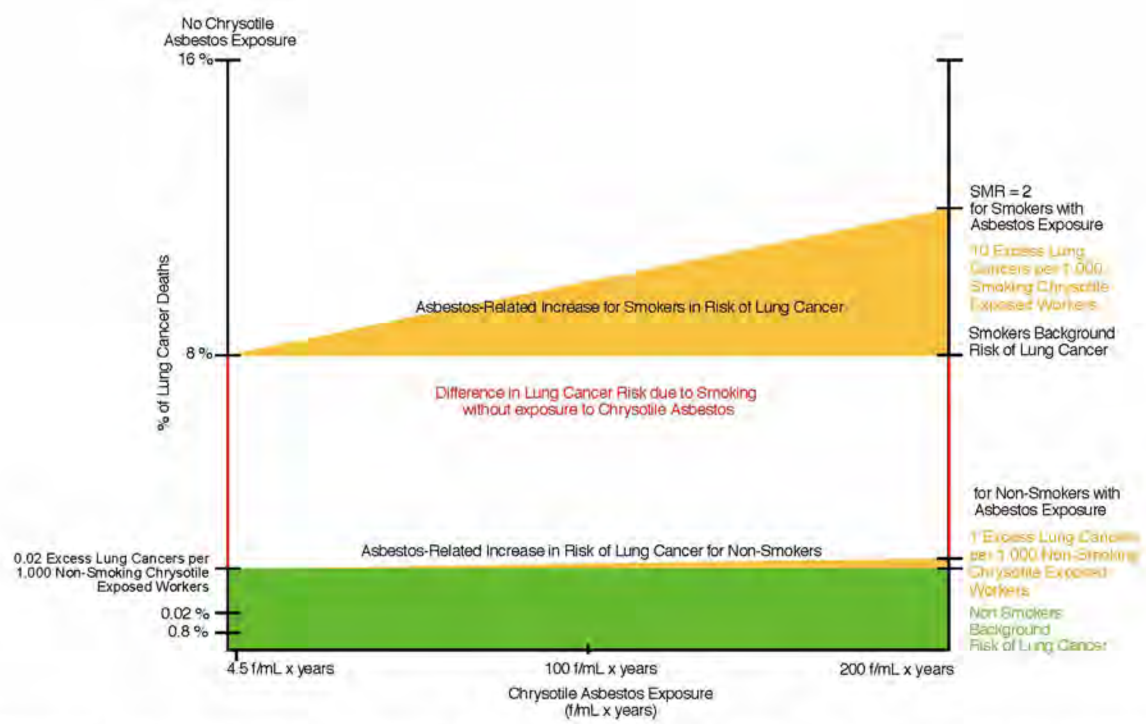

Figure 3. Exposure to asbestos increases lung cancer risk by 0.02 per 1,000 chrysotile asbestos workers with 45 years of exposure at the 0.1 fiber/milliliter asbestos permissible exposure limit. Smokers experience an excess lung cancer risk which is 10-fold greater. In their testimony NIOSH indicated 1 excess death over a working lifetime or less was the target. Approximately 200 fiber/milliliter x years of chrysotile exposure approach 1 excess asbestos-related lung cancer in 1,000 worker.

Therefore, the lung cancer risk among smokers for a given asbestos exposure would be greater than in a non-smoker. High cumulative exposures to asbestos can cause a dramatic increase in lung cancer while at low cumulative exposure the dominant risk factor is your smoking habit (Figure 3). With the modern PEL since 1994, the major risk factor for lung cancer is whether you smoke or not. NIOSH opined that asbestos is the leading cause of lung cancer among non-smokers. It is not clear how they came to this conclusion. Lung cancer risk among non-smokers is about 8 lung cancer cases per 1,000 non-smokers deaths. The increase in the lung cancer risk due to asbestos is calculated as a proportion to the underling lung cancer risk with modern controlled exposures will always be very small about 0.022 lung cancer deaths for 1,000 asbestos workers from a lifetime of asbestos exposure at the modern PEL. Other causes of lung cancer besides tobacco are arsenic, mustard gas [chloromethyl (pyriline) ethers], polycyclic aromatic hydrocarbons, hexavalent forms of chromium, air pollution including fine particles, ionizing radiation and radon (Higginson *et al.*, 1992).

The fiber type specific lifetime risk for chrysotile asbestos is more than 50-fold below the NIOSH prediction for exposure to fiber of average potency. NIOSH averages in the higher effects for the amphibole asbestos fiber types and our calculation provides more texture as to the contribution of the different fiber types. Considering chrysotile is the only type of asbestos left in commerce the risk should be to this type.

At the Senate Hearing, NIOSH stated that its goal is to have an upper limit of 1 occupationally related death per 1,000 worker lifetimes and NIOSH went on to claim that asbestos at the current PEL does not meet that goal (it is 3.4 per 1,000). With the departure of commercial amphibole asbestos from commerce, chrysotile asbestos at the current PEL is about 15-fold below NIOSH's target goal (Table 4). If the asbestos-related cancers associated with the more potent commercial amphibole asbestos fiber types are excluded NIOSH's rationale for asbestos regulation falls to the ground.

The more significant risk associated with the amphibole asbestos has been removed from the U.S. by market forces rather than the government regulatory action. The proposed ban would not affect amphibole asbestos *currently in place or exposures that have already occurred.* Extensive regulations currently exist, at the federal and state level, to address asbestos in place. If passed, the ban on asbestos would be prospective or forward looking not re-visiting the asbestos in place issues.

Predictions for the number of asbestos-related deaths presented at the Senate Hearings are all from exposures that occurred prior to the modern period. The asbestos-related diseases are currently occurring among individuals whose cumulative asbestos exposures are higher than allowed in the modern period and in many cases were to asbestos fiber types, i.e. amphibole asbestos, no longer used.

Risk assessment is also useful for predicting the total number of asbestos-related deaths associated with a public health policy of controlled use of chrysotile asbestos

In 2025, the total number of deaths in the United States was 2,448,017. If all of these people worked with chrysotile for 45 years at the current permissible exposure level of 0.1f/mL there would have been 164 asbestos-related cancer deaths based on our risk estimate for chrysotile of 0.067 asbestos-related cancers per 1,000 deaths. We know of no one who would argue that the general U.S. population had such a significant asbestos exposure. So this number of asbestos-related deaths would not be realized. Also, the tens of thousands of asbestos-related death described in the LaDou editorial suggesting a ban on asbestos are wildly inconsistent with the risk assessment models. To our knowledge the EPA Rulemaking did consider this conflicting information.

We estimate at most 1% (24,483) of deaths would have such a high cumulative exposure based on the current US asbestos consumption and uses. It seems very unlikely that 24,483 people would be exposed to asbestos considering its current limit usage. Therefore, continuing with our policy of controlled use of chrysotile asbestos, once time eliminates the legacy of asbestos-related disease from past exposures, less than two asbestos-related deaths would be expected to occur each year in the United States. The 10,000 deaths in the S.742 are not going to occur from the current US asbestos permissible exposure limit. (*See* Price (2022) for further discussion of background.)

As the 5th Circuit Court noted in its 1991 opinion striking down EPA's attempt to ban asbestos-containing products, some risks of asbestos-related cancer are similar in magnitude to choking to death on a toothpick (United States, 1991). The risks EPA claimed in its first effort to ban asbestos and its recent claims have not be adequately explained by the agency. We seem not to have made much progress from the hysterical 1978 NCI-NIEHS annual projection of ≈67,000 asbestos-related cancers.

We conclude based on totality of the evidence in the United States, all the steps required for mitigating the health effects associated with asbestos exposure have already been taken and a ban on chrysotile asbestos will be no more than a symbolic gestureand not have any practical effect.

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APPENDIX A

Full summaries of 26 chrysotile exposure studies

Full summaries of 26 chrysotile exposure studies

For each publication the summary includes:

- **Purpose of the study**
- **Key conclusions**
- **The specific asbestos types studied; chrysotile, amoiste, crocidolite and possibly tremolite.**
- **The range and mean exposure concentrations measured for each type of asbestos**
- **Any comparison presented of these concentrations with no effect levels for either mesothelioma or lung cancer.**

The following publications have been reviewed_

1. Perry et al. 2026 — Asbestos-cement pipe cutting with powered saw
2. Paustenbach et al. 2006 — Automobile exhaust system removal (mechanics)
3. Ierardi et al. 2021 — Airborne asbestos exposures in dentistry
4. Green et al. 1997 — Pulmonary fibrosis in chrysotile textile workers (Charleston, SC)
5. Murphy et al. 2020 — Baie Verte chrysotile miners/millers exposure assessment
6. Mutetwa et al. 2022 — Zimbabwe asbestos-cement manufacturing JEM
7. Perry, Kissell & Paustenbach 2026 — Asbestos exposure from cutting cement pipe with a powered saw (reformatted)
8. Louie et al. 2025 — Airborne chrysotile from valve packing replacement
9. Case, Korchevskiy & Korchevskiy 2025 — Updated exposure estimation, Québec chrysotile miners/millers cohort
10. Goodman, Korchevskiy & Wylie 2025 — Comparison of methodological approaches to model asbestos thresholds for mesothelioma
11. Goodman et al. 2025 (Frontiers in Epidemiology) — Challenges in defining thresholds: asbestos and silica
12. Kurzhunbaeva et al. 2024 — Occupational exposure to chrysotile, Kyrgyzstan cement factory
13. Anderson et al. 2024 — Drilling mud additives
14. Goodman et al. 1999 — Cancer in asbestos-exposed occupational cohorts (meta-analysis)
15. Mutetwa et al. 2023 — Prediction of ARDs and chrysotile exposure concentrations, Zimbabwe AC factories
16. Bernstein 2022 — Health effects of short fiber chrysotile and amphibole asbestos
17. Finley et al. 2012 — Tremolite asbestos exposures from commercial products (+ 2018 corrigendum)
18. Mutetwa, Moyo & Brouwer 2021 — Trends in airborne chrysotile fibre concentrations, Zimbabwe A/C factories 1996–2016
19. Silvestri et al. 2020 — Asbestos exposure of chrysotile miners/millers, Balangero, Italy
20. Sahmel et al. 2014 — Take-home exposure from chrysotile-contaminated clothing
21. Goodman et al. 2013 — Electricians' chrysotile asbestos exposure from electrical products, mesothelioma/lung cancer risk

22. Jiang et al. 2008 — Airborne chrysotile from handling/unpacking/repacking automobile clutch disc boxes
23. Madl et al. 2008 — Airborne chrysotile from unpacking/repacking automobile brake pad and shoe boxes
24. Cattaneo et al. 2012 — Airborne chrysotile in serpentine quarries and stone processing, Valmalenco, Italy
25. McDonald et al. 1980 — Dust exposure and mortality in chrysotile mining, 1910-75 *(just completed)*
26. Williams, Phelka & Paustenbach 2007 — A review of historical exposures to asbestos among skilled craftsmen (1940–2006) *(just completed)*

1. Perry, Kissell & Paustenbach (2026) — "Evaluation of exposure to asbestos from the cutting of cement pipe with a powered saw"

Inhalation Toxicology, DOI: 10.1080/08958378.2026.2697434

Purpose of the Study

The study aimed to characterize occupational airborne asbestos exposures generated when asbestos-containing cement (A/C) pipe is cut using a gas-powered abrasive (chopsaw) saw — considered a worst-case, high-emission cutting method historically used before the 1980s. Seven sections of four-inch A/C pipe (25–30% chrysotile, 10–15% crocidolite by weight) were cut under two simulated field conditions — above ground and within a shored trench — to generate personal air-sampling data. These data were used to reconstruct historical 8-hour time-weighted average (TWA) exposures and 45-year cumulative lifetime exposures for pipe-cutting workers, which were then compared against published no-observed-adverse-effect levels (NOAELs) and occupational exposure limits (OELs) for lung cancer and mesothelioma.

A secondary purpose was methodological: samples originally analyzed in 2016 using NIOSH Method 7400 Issue #2 were reanalyzed in 2026 using the updated Issue #3 method (which uses stricter, more accurate fiber-width criteria), allowing the authors to compare results across analytical generations.

Key Conclusions

- All calculated 8-hour TWAs were well below the contemporaneous OSHA permissible exposure limits (PELs) in effect during the era A/C pipe was commonly used (2 f/cc and higher, pre-1980s).
- Cumulative lifetime exposure estimates (0.061–0.98 f/cc-years for chrysotile; 0.023–0.13 f/cc-years for crocidolite, depending on scenario and analysis year) were below published NOAELs for both fiber types.

- Chrysotile cumulative exposures were 60- to 390-fold below NOAEL/OEL thresholds from multiple modern reviews.
- Crocidolite cumulative exposures were closer to — but did not exceed — proposed acceptable exposure levels, falling roughly 2- to 8-fold below thresholds identified as protective against excess mesothelioma risk.
- The updated (2026) NIOSH 7400 Issue #3 reanalysis produced lower fiber counts than the original 2016 Issue #2 analysis (~31% lower in-trench; ~7% lower above-ground), reflecting stricter fiber-counting criteria.
- Overall, the authors concluded that historical occupational asbestos risks from A/C pipe cutting were likely **overestimated** for the majority of workers, particularly since abrasive power-saw cutting was a discouraged/non-recommended practice historically (manual snap-cutting was preferred and produces far lower exposures).
- Compared to the *current* OSHA PEL of 0.1 f/cc, combined TWA exposures would exceed the limit under the study's conservative assumptions, but would fall under the limit using less conservative (more realistic) assumptions about cutting frequency.

Asbestos Types Studied

- **Chrysotile** (serpentine) — 25–30% by weight of test pipe
- **Crocidolite** (amphibole) — 10–15% by weight of test pipe
- Amosite and tremolite were **not** directly tested in the pipe material, though they are discussed in the introduction/background for context on relative fiber potency.

Exposure Concentrations Measured (PCM-Equivalent, PCME)

Scenario	Fiber Type	30-min Mean PCME (Original 2016 analysis)	30-min Mean PCME (Updated 2026 analysis)	Range (updated)
Above-ground	Chrysotile	0.63 f/cc (±0.44)	0.59 f/cc (±0.37)	0.05–1.01 f/cc
Above-ground	Crocidolite	0.25 f/cc (±0.13)	0.23 f/cc (±0.14)	0–0.44 f/cc
Above-ground	Total	0.87 f/cc	0.81 f/cc	0.14–1.19 f/cc
In-trench	Chrysotile	13.56 f/cc (±0.87)	9.33 f/cc (±0.72)	8.29–10.56 f/cc
In-trench	Crocidolite	1.78 f/cc (±0.59)	1.23 f/cc (±0.44)	0.92–2.10 f/cc
In-trench	Total	15.34 f/cc	10.55 f/cc	9.41–12.16 f/cc

Resulting 8-hour TWAs (assuming 8 minutes of cutting/day): 0.010 f/cc (chrysotile) and 0.004 f/cc (crocidolite) above ground; 0.16 f/cc and 0.021 f/cc in-trench.

Cumulative lifetime exposures (45-year career, once weekly): 0.061–0.98 f/cc-years (chrysotile) and 0.023–0.13 f/cc-years (crocidolite), depending on scenario.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

The study compared its cumulative exposure estimates against several published thresholds:

- **Pierce et al. (2016):** NOAELs of 89–168 f/cc-years (chrysotile lung cancer), 208–415 f/cc-years (chrysotile mesothelioma), 2–17 f/cc-years (crocidolite/amosite lung cancer), 0.4–0.8 f/cc-years (crocidolite mesothelioma)
- **Beckett et al. (2023):** 0.6–1 f/cc-years (crocidolite), 2–5 f/cc-years (amosite), 250–379 f/cc-years (chrysotile) — protective against 1-in-1000 mesothelioma risk
- **Goodman et al. (2025):** 0.25 f/cc-years (crocidolite), 1 f/cc-years (amosite), 90 f/cc-years (non-textile chrysotile)
- **Stevens et al. (2025):** 0.3, 2, 10, and 100 f/cc-years for crocidolite, amosite, textile chrysotile, and non-textile chrysotile respectively, with corresponding OELs of 0.01, 0.05, 0.2, and 2 f/cc

The study's calculated chrysotile cumulative exposures were **60- to 390-fold below** these NOAEL/OEL thresholds. Crocidolite cumulative exposures were closer to the thresholds — approximately **2- to 8-fold below** the levels found not to cause mesothelioma — representing the more borderline finding of the paper, though still within the "safe" range under all cited studies.

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2. Paustenbach et al. (2006) — "Chrysotile asbestos exposure associated with removal of automobile exhaust systems (ca. 1945–1975) by mechanics: Results of a simulation study"

Journal of Exposure Science and Environmental Epidemiology, 16, 156–171

Purpose of the Study

This study characterized personal and bystander airborne asbestos exposures during the removal of automobile exhaust systems (mufflers, exhaust pipes, and manifolds) containing asbestos gaskets and asbestos-lined mufflers, replicating conditions typical of automotive repair work from approximately 1945–1975. The goal was to estimate an 8-hour time-weighted average (TWA) exposure for mechanics performing this type of repair work, using 16 pre-1974 vehicles with old or original exhaust systems at an active muffler shop, with work performed by experienced mechanics using their normal, decades-unchanged work practices.

Key Conclusions

- Airborne chrysotile concentrations were low: average adjusted PCM concentrations of 0.018 f/cc for mechanics and 0.008 f/cc for bystanders during gasket/muffler removal activities.
- Of 82 PCM samples and 88 TEM samples collected, only a handful (4 PCM samples confirmed by TEM) showed detectable asbestos above the analytical sensitivity limit; the large majority of samples were non-detectable.

- Estimated 8-hour TWAs for mechanics were 0.01 f/cc (single exhaust systems, 4 cars/day) and 0.006 f/cc (dual exhaust systems, 2 cars/day) — roughly 10-fold below the current OSHA PEL of 0.1 f/cc for chrysotile.
- Bystander 8-hour TWAs were even lower: 0.005 f/cc and 0.003 f/cc for single and dual exhaust system work, respectively.
- The authors concluded these estimates likely represent worst-case exposures (due to poor shop ventilation simulated, high proportion of non-detect samples, and conservative task assumptions), and that historical exposures to mechanics performing exhaust system repair were substantially below all current and historical occupational exposure limits for asbestos, often not even detectable.

Asbestos Type Studied

- **Chrysotile** only — bulk analysis (XRD/PLM) of gaskets and muffler linings found chrysotile ranging from 9.5% to 80.1% by weight; **no amphibole asbestos** (e.g., crocidolite) was detected in any gasket or muffler sample tested.

Exposure Concentrations Measured (Chrysotile only)

Sample type	PCM Mean (f/cc)	PCM Range	TEM Mean (f/cc)	PCM-adjusted Mean (f/cc)	PCM-adjusted Range
Personal (mechanic)	0.022	0.006–0.066	0.013	0.018	0.002–0.04
Bystander	0.012	0.004–0.030	0.004	0.008	0.0008–0.015
Remote (indoor)	0.005	0.002–0.015	0.002	0.003	0.0014–0.004
Background (indoor, pre-work)	0.008	0.0008–0.022	0.0004	0.022*	—
Ambient (outdoor)	0.003	0.0009–0.005	0.001	—	—

*Based on only one sample confirmed by TEM; not considered representative.

Calculated 8-hour TWAs:

- Mechanic, single exhaust system: 0.01 f/cc
- Mechanic, dual exhaust system: 0.006 f/cc
- Bystander, single exhaust system: 0.005 f/cc
- Bystander, dual exhaust system: 0.003 f/cc

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

This paper does **not** present a formal cumulative exposure (f/cc-years) calculation or direct comparison to published chrysotile NOAELs for lung cancer or mesothelioma (unlike some of the other papers in this set). Instead, the comparison made is against **occupational exposure limits (OELs)**:

- The calculated 8-hour TWAs (0.006–0.01 f/cc for mechanics; 0.003–0.005 f/cc for bystanders) were compared to the **current OSHA PEL of 0.1 f/cc** for chrysotile asbestos, and found to be approximately **10-fold lower**.
- The authors also note these exposures were below **all historical OSHA PELs** for asbestos (which ranged from 2 f/cc to 12 f/cc during the 1945–1975 study period), and were comparable to 8-hour TWAs reported in other studies of industrial/maritime gasket removal work (which did not exceed 0.031 f/cc using similar hand-tool methods).

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3. Ierardi et al. (2021) — "Potential airborne asbestos exposures in dentistry: a comprehensive review and risk assessment"

Critical Reviews in Toxicology, 51:4, 301–327

Purpose of the Study

This comprehensive literature review and risk assessment aimed to characterize potential historical airborne asbestos exposures among dental professionals (dentists, dental laboratory technicians, dental hygienists, and dental assistants) from the use of three chrysotile-containing dental products: casting ring liner (CRL, used ~1930–1987 in the "lost-wax" casting process), investment material (possibly asbestos-containing before 1930), and periodontal dressing powder (PDP, used ~1923–1976). The authors calculated 8-hour TWA exposures and cumulative lifetime asbestos exposures for each product-specific task and compared these to regulatory standards and published health-based no-effect levels for asbestos-related disease (ARD).

Key Conclusions

- For CRL tearing and placement, the upper-bound calculated personal 8-hour TWA was 0.022 f/cc — below the current OSHA PEL/ACGIH TLV of 0.1 f/cc.
- All samples collected during PDP mixing resulted in non-measurable (non-detectable) fiber concentrations, suggesting exposures from this task were very low or zero.
- The greatest estimated cumulative asbestos exposure for dental professionals (dentists, using CRL tearing/placement, over a 15.1-year average career) was 0.33 f/cc-years — far below published chrysotile NOAELs for lung cancer (89–168 f/cc-years) and mesothelioma (208–415 f/cc-years).
- The authors concluded that use of asbestos-containing CRL and/or PDP is not expected to pose an increased risk of ARD among dental professionals, consistent with the lack of increased ARD risk reported in epidemiological studies of these occupations (though 12 mesothelioma case reports exist in the literature, these are considered low-quality evidence for causation).

Asbestos Types Studied

- **Chrysotile** — the predominant and essentially only intentionally used fiber type in CRL (40–95% by volume) and PDP (3–14.29% by weight).

- **Tremolite/actinolite** (amphiboles) — found only as trace contaminants (≤0.1%) in some CRL bulk samples via TEM after acid/base digestion; asbestiform habit not confirmed.
- **Crocidolite** — not intentionally used in U.S. dental products; found in only one historical case report (a British dentist), of uncertain/unexplained origin.

Exposure Concentrations Measured

CRL (tearing, placement) — Personal:

- Range: 0.008 f/cc (240 min duration) to 3.5 f/cc (3 min duration) by PCM
- Upper-bound calculated 8-hour TWA: **0.022 f/cc**

CRL (tearing, placement) — Area/bystander:

- Range: <0.07–0.7 f/cc (short duration) to 0.005 f/cc (90 min)
- Upper-bound calculated 8-hour TWA: **0.0044 f/cc**

CRL — placement only (no tearing): <0.01 f/cc (non-detectable) — no TWA calculated due to entirely censored data.

CRL — dismantling: 0.0046–27 f/cc reported across studies, but not used for exposure estimates because chrysotile is largely converted to forsterite/other magnesium silicates at the high heat-treatment temperatures (250–900°C) used before dismantling.

PDP (mixing):

- Personal: <0.0044 to <0.297 f/cc (all non-detectable, censored)
- Area: <0.0054 to <0.396 f/cc (all non-detectable)
- No TWA calculated due to entirely non-detectable dataset.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

- Benchmarked against Pierce et al. (2016) chrysotile NOAELs: **89–168 f/cc-years** (lung cancer) and **208–415 f/cc-years** (pleural mesothelioma).
- Cumulative exposure estimates by profession (CRL tearing/placement, personal):
    - Dental assistants: 0.12 f/cc-years
    - Dental hygienists: 0.23 f/cc-years
    - Dental laboratory technicians: 0.28 f/cc-years
    - **Dentists (highest): 0.33 f/cc-years**
- Even assuming an extended 45-year working lifetime, the dentist cumulative exposure estimate would only reach ~0.99 f/cc-years — still orders of magnitude below the NOAELs.
- Bystander cumulative exposure (dentists): 0.066 f/cc-years — also far below NOAELs.
- The 8-h TWA for personal CRL exposure fell into AIHA Category 2 ("well controlled exposure"); bystander exposure fell into Category 1 ("highly controlled exposure").

4. Green et al. (1997) — "Exposure and mineralogical correlates of pulmonary fibrosis in chrysotile asbestos workers"

Occupational and Environmental Medicine, 54, 549–559

Purpose of the Study

This necropsy-based study examined the relationship between lifetime cumulative asbestos exposure, pathological grade of pulmonary fibrosis (asbestosis), and lung burden of asbestos fibers in 54 former workers of a chrysotile asbestos textile plant in Charleston, South Carolina (in operation 1896–1975+). The study also aimed to determine the minimal cumulative exposure level necessary to produce a histological lesion consistent with asbestosis, and secondarily documented pleural plaques and lung cancer prevalence in this population compared to a matched control group.

Key Conclusions

- A significant positive correlation (r = 0.67, P<0.0001) was found between lifetime cumulative asbestos exposure and total lung fiber burden.
- Pulmonary fibrosis correlated significantly with both cumulative exposure (r=0.60) and lung fiber concentration (r=0.62); tremolite lung concentration was a *better* predictor of fibrosis severity than chrysotile concentration, despite chrysotile being the overwhelmingly dominant exposure.
- Asbestosis (grade 2+ severity) was consistently found in workers with lifetime cumulative exposures exceeding 20 fibre-years.
- Chrysotile and tremolite fibers in textile workers' lungs were significantly longer and had greater aspect ratios than in controls (median chrysotile length 1.5 µm vs. 0.5 µm in controls) — the authors propose this exposure to unusually long chrysotile fibers in the textile industry as the most plausible explanation for the very high mortality from lung cancer and asbestosis observed in this cohort (historically ~50-fold greater lung cancer risk than chrysotile miners/millers at equivalent exposure).
- Textile workers with lung cancer (18.2% of cohort vs. 5.8% in controls) had significantly greater cumulative exposures and fibrosis scores than those without lung cancer.

Asbestos Types Studied

- **Chrysotile** — the predominant raw material processed (~3–4 million kg/year), sourced from Quebec, British Columbia, and Zimbabwe.
- **Tremolite** — present as a contaminant (~1%) in the raw chrysotile ore; found in substantial concentrations in workers' lungs.
- **Crocidolite** — a small amount was woven into tape/braided packing from the 1950s to ~1975 (total <1000 kg processed); found in low levels in some workers' lungs.
- **Amosite** — also detected in lung tissue at low geometric mean concentrations, though not a raw material processed at the plant (likely a minor contaminant or cross-contamination source).

Exposure Concentrations (Occupational Exposure & Lung Fiber Burden)

Cumulative occupational exposure (expressed as fibre-years, i.e., fibres >5 µm/ml × years):

- Median (range) for all workers: 30.2 (0.1–370.0) fibre-years
- By years employed: ranged from median 2.4 fibre-years (0.1–1.3 yrs employed) to 120.3 fibre-years (>27.3 yrs employed)
- Male workers had higher median cumulative exposure (34.6 fibre-years) than female workers (25.6 fibre-years)

Lung fiber burden (fibres × 10^6/g dry lung, geometric means):

Fiber type	Controls	Asbestos workers	P value
All fibres	16.02	52.46	<0.0001
Chrysotile	6.71	33.45	<0.0001
Tremolite	0.26	3.56	<0.0001
Amosite/crocidolite	0.21	0.47	=0.031
Anthophyllite	0.13	0.16	=0.43

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

This paper does **not** directly compute or cite modern published NOAEL/OEL benchmarks (e.g., Pierce et al. or Stevens et al., which postdate this 1997 publication). Instead, it establishes its own threshold observation: **asbestosis of grade 2 or greater severity was consistently observed above ~20 fibre-years of cumulative exposure**, with three cases occurring even in the 10–20 fibre-year range. The paper notes that exposures in the 6.8–27.4 fibre-year range were associated with a standardized mortality ratio (SMR) of 1.56 for non-malignant respiratory disease in a related follow-up mortality study of the same plant (Dement et al. 1994). The paper's primary contribution is establishing an **exposure-response relationship for fibrosis** (not a formal comparison to independently published no-effect levels), and highlighting that this cohort's fibrosis and cancer risk substantially exceeded what would be predicted from chrysotile exposure alone in other cohorts (e.g., miners/millers), implicating fiber length as a key modifying factor.

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5. Murphy, Bornstein, Oudyk & Demers (2021) — "A Quantitative Retrospective Exposure Assessment for Former Chrysotile Asbestos Miners and Millers from Baie Verte, NL, Canada"

Annals of Work Exposures and Health, 65(1), 113–126

Purpose of the Study

This study describes the development of a job exposure matrix (JEM) for reconstructing historical chrysotile asbestos exposures among former employees of the Baie Verte chrysotile asbestos mine/mill (Newfoundland, Canada; operational 1963–1994), as part of the Baie Verte Miners' Registry (established 2008) to assist with employee registration and compensation claims. The study analyzed industrial hygiene data collected between 1963 and 1994 to assess the validity and quality of this data for use in retrospective exposure assessment and epidemiologic study, dividing workers into 52 exposure groups (EGs) based on job title and department.

Key Conclusions

- Most EGs (82.6%, or 43 of 52) fit a log-normal exposure distribution; a few (6 EGs) fit normal distributions, and three were bimodal.
- Geometric standard deviations (GSDs) ranged from 1.74 to 5.61, with 55% of EGs exceeding a GSD of 2.5, indicating considerable within-group exposure variability.
- 89.8% of JEM cells had "good" or "very good" sample size quality (>10 samples); only 1% were "poor" quality (≤6 samples).
- Exposures were very high in early operational years (averaging 6–42 f/ml across departments in 1963–1975) and declined substantially over time due to control measures (dust collectors, ventilation, wet processing) implemented especially after the 1976 Selikoff report and a 14-week strike (1978–1980).
- Overall, the data were deemed adequate for estimating cumulative asbestos exposures, though between-worker variability (exceeding 20% in many EGs) is an important caveat for using these estimates to adjudicate individual compensation claims.
- Exposure levels at Baie Verte were generally intermediate between other chrysotile mining/milling cohorts — higher than the Italian Balangero cohort for drilling/crushing, but generally lower than Québec chrysotile mining cohorts.

Asbestos Type Studied

- **Chrysotile** exclusively — this was a chrysotile mine/mill; the paper does not report amphibole content or contamination analysis (unlike some of the other papers in this set, e.g., the Zimbabwe JEM paper, which explicitly tested for amphibole contamination). No breakdown by amosite, crocidolite, or tremolite is presented; all exposure and lung-burden style data in this paper pertain to chrysotile fiber concentrations only.

Exposure Concentrations Measured (Chrysotile, by Department, f/ml — Time-Weighted Averages)

Department	1963–66	1967–68	1969–71	1972–74	1975	1976–79	1980–84	1985–90	1991–94
Mill	18.13	28.17	12.94	7.83	1.76	2.24	1.55	1.11	0.89
Pit	41.90	37.74	18.29	9.40	1.93	0.43	0.28	0.23	—
E&R	16.81	21.80	9.12	4.55	0.94	0.85	0.59	0.46	0.37
QC	12.99	22.19	8.87	6.12	1.56	1.17	0.91	1.03	1.32
EmpRel	6.12	8.81	3.69	2.15	0.44	—	0.16	0.06	0.09
OS	8.45	13.81	4.78	2.60	0.50	0.46	0.14	0.04	—

- Highest single-job exposure (1976–1994 period): "Dry Rock Storage Attendant" — overall average 3.19 f/ml, peak of 18.8 f/ml (1980).

- Lowest single-job exposure: "Backhoe Operator" (Pit) — average 0.08 f/ml, peak 0.26 f/ml (1982).
- Peak historical exposures (1963–1975 period): "Shuttle Operator," "Primary Crusher Operator," "Dryer Operator," "Secondary Crusher Operator," "Dry Rock Storage Attendant" — average 66.55 f/ml at 1968 peak.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

This paper is purely an **exposure reconstruction/JEM validation study** — it does **not** calculate cumulative lifetime exposure estimates in f/cc-years for individual workers within the paper itself (that calculation is performed downstream using the JEM for compensation/epidemiologic purposes, but not reported here), and it does **not** present any comparison to published NOAELs or OELs for lung cancer or mesothelioma. The only comparative benchmarking presented is **against other chrysotile mining/milling cohorts' exposure levels** (Italian Balangero cohort and Québec cohort), not against health-based no-effect levels.

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6. Mutetwa, Moyo & Brouwer (2022) — "Job Exposure Matrix for Chrysotile Asbestos Fibre in the Asbestos Cement Manufacturing (ACM) Industry in Zimbabwe"

International Journal of Environmental Research and Public Health, 19, 2680

Purpose of the Study

This study aimed to construct a job exposure matrix (JEM) specific to the chrysotile asbestos-cement manufacturing (ACM) industry in Zimbabwe, using personal exposure chrysotile fiber concentration data collected by two ACM factories (Harare and Bulawayo) between 1996 and 2020. The JEM was intended to support future epidemiological studies of asbestos-related disease (ARD) in this understudied national industry, and the study additionally analyzed raw chrysotile material for amphibole contamination.

Key Conclusions

- All jobs/occupations in both factories had annual mean personal exposure concentrations exceeding the occupational exposure limit (OEL) of 0.1 f/mL, **except** for the period 2009–2016 at the Harare factory and 2009–2020 at the Bulawayo factory (during which most exposures fell below or near the OEL).
- Despite the Harare factory ceasing AC manufacturing activity in 2017, personal exposure concentrations remained elevated (0.10–0.12 f/mL) for 2018–2020, likely due to resuspension of historically accumulated chrysotile fiber from floors with no clean-up and discontinued wet-suppression work practices.
- Amphibole minerals (tremolite, anthophyllite, crocidolite, actinolite) were detected in almost all bulk chrysotile samples analyzed — 4 of 6 local (Zimbabwean-mined) samples and 5 of 6 imported (Russian) samples contained amphiboles, including crocidolite and actinolite in some imported samples.

- Exposure concentrations declined substantially over time at both factories, attributed to improved occupational hygiene practices, though the industry's own internally-adopted 0.2 f/mL standard (used 1996–2000, prior to any national statutory limit) likely explains elevated early exposures.
- Statistically significant differences in exposure existed between time periods for nearly all job categories ($p<0.001$).

Asbestos Types Studied

- **Chrysotile** — primary and intentionally used raw material; PCM-based measurement could not distinguish chrysotile from amphibole fibers, so all reported air concentrations are total fiber counts assumed to be predominantly chrysotile.
- **Tremolite** — detected as a contaminant in bulk samples (both local and imported).
- **Anthophyllite** — detected in local samples.
- **Crocidolite** — detected in imported (Russian) chrysotile samples only.
- **Actinolite** — detected in some imported samples.

Exposure Concentrations Measured (Chrysotile Fiber, by Job/Factory, f/mL — Annual Means)

Selected examples from the JEM (full table covers 9 job categories):

Job	Factory	1996–2000	2001–2008	2009–2016	2017/18–2020
Saw cutting operator	Harare	0.19	0.13	0.07	0.10
Saw cutting operator	Bulawayo	0.17	0.12	0.06	0.05
Kollergang operator	Harare	0.13	0.12	0.07	0.12
Kollergang operator	Bulawayo	0.14	0.12	0.07	0.06
Ground hard waste	Harare	0.16	0.13	0.07	0.12
Ground hard waste	Bulawayo	0.13	0.11	0.07	0.06
Fettling table	Harare	0.12	0.12	—	0.11
Laundry room	Harare	0.13	0.13	0.05	0.11

The OEL of 0.1 f/mL was exceeded in nearly all job/period combinations except the 2009–2016 Harare and 2009–2020 Bulawayo periods.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

This study **does not** calculate cumulative lifetime exposures (f/cc-years) for individual workers, nor does it compare exposure data to published chrysotile NOAELs for lung cancer or mesothelioma (e.g., Pierce et al., Stevens et al.). Instead, the paper's comparative benchmark is exclusively the **regulatory OEL of 0.1 f/mL** (used in Zimbabwe, South Africa, and per ACGIH guidelines). The authors' risk discussion is qualitative, noting that the detection of amphiboles (particularly crocidolite, one of the most potent asbestos fiber types for mesothelioma) in the chrysotile raw material used by both factories "further heighten[s] the possible risk of ARD occurrence," but no quantitative dose-response or no-effect-level comparison is presented — this JEM is intended as a foundational tool for *future* epidemiological/exposure-response studies rather than a risk characterization in itself.

7. Perry, Kissell & Paustenbach 2026 — Asbestos exposure from cutting cement pipe with a powered saw

Purpose: To characterize occupational airborne asbestos exposures generated when asbestos-containing cement (A/C) pipe is cut using a gas-powered abrasive (chopsaw) saw — a worst-case, high-emission cutting method historically used before the 1980s. Seven sections of four-inch A/C pipe (25–30% chrysotile, 10–15% crocidolite by weight) were cut under two simulated field conditions (above ground and within a shored trench) to generate personal air-sampling data, which were used to reconstruct historical 8-hour TWA and 45-year cumulative lifetime exposures for pipe-cutting workers and compare these against published NOAELs and OELs for lung cancer and mesothelioma. A secondary, methodological purpose was to compare fiber counts from samples originally analyzed in 2016 (NIOSH Method 7400 Issue #2) against a 2026 reanalysis using the updated, stricter Issue #3 fiber-width criteria.

Key conclusions: All calculated 8-hour TWAs were well below the contemporaneous OSHA PELs in effect during the era A/C pipe was commonly used (2 f/cc and higher, pre-1980s). Cumulative lifetime exposure estimates (0.061–0.98 f/cc-years for chrysotile; 0.023–0.13 f/cc-years for crocidolite) were below published NOAELs for both fiber types, with chrysotile 60- to 390-fold below thresholds from multiple modern reviews; crocidolite exposures were closer to — but did not exceed — proposed acceptable levels, falling roughly 2- to 8-fold below thresholds identified as protective against excess mesothelioma risk. The updated 2026 NIOSH 7400 Issue #3 reanalysis produced lower fiber counts than the original 2016 Issue #2 analysis (~31% lower in-trench; ~7% lower above-ground), reflecting stricter fiber-counting criteria. The authors concluded that historical occupational asbestos risks from A/C pipe cutting were likely overestimated for most workers, particularly since abrasive power-saw cutting was a discouraged/non-recommended practice historically (manual snap-cutting was preferred and produces far lower exposures). Compared to the current OSHA PEL of 0.1 f/cc, combined TWA exposures would exceed the limit under the study's conservative assumptions, but would fall under the limit using less conservative (more realistic) assumptions about cutting frequency.

Asbestos types studied: Chrysotile (25–30% by weight of test pipe) and crocidolite (10–15% by weight). Amosite and tremolite were not directly tested in the pipe material but were discussed in the introduction/background for context on relative fiber potency.

Exposure concentrations (PCM-equivalent, PCME):

Scenario	Fiber Type	30-min Mean PCME (2016 analysis)	30-min Mean PCME (2026 analysis)	Range (updated)
Aboveground	Chrysotile	0.63 f/cc (±0.44)	0.59 f/cc (±0.37)	0.05–1.01 f/cc
Aboveground	Crocidolite	0.25 f/cc (±0.13)	0.23 f/cc (±0.14)	0–0.44 f/cc
Aboveground	Total	0.87 f/cc	0.81 f/cc	0.14–1.19 f/cc
In-trench	Chrysotile	13.56 f/cc (±0.87)	9.33 f/cc (±0.72)	8.29–10.56 f/cc
In-trench	Crocidolite	1.78 f/cc (±0.59)	1.23 f/cc (±0.44)	0.92–2.10 f/cc
In-trench	Total	15.34 f/cc	10.55 f/cc	9.41–12.16 f/cc

Resulting 8-hour TWAs (assuming 8 minutes of cutting/day): 0.010 f/cc (chrysotile) and 0.004 f/cc (crocidolite) above ground; 0.16 f/cc and 0.021 f/cc in-trench. Cumulative lifetime exposures (45-year career, once weekly): 0.061–0.98 f/cc-years (chrysotile) and 0.023–0.13 f/cc-years (crocidolite), depending on scenario.

Comparison to no-effect/threshold levels: The study compared its cumulative exposure estimates against several published thresholds:

- **Pierce et al. (2016):** NOAELs of 89–168 f/cc-years (chrysotile lung cancer), 208–415 f/cc-years (chrysotile mesothelioma), 2–17 f/cc-years (crocidolite/amosite lung cancer), 0.4–0.8 f/cc-years (crocidolite mesothelioma)
- **Beckett et al. (2023):** 0.6–1 f/cc-years (crocidolite), 2–5 f/cc-years (amosite), 250–379 f/cc-years (chrysotile) — protective against 1-in-1000 mesothelioma risk
- **Goodman et al. (2025):** 0.25 f/cc-years (crocidolite), 1 f/cc-years (amosite), 90 f/cc-years (non-textile chrysotile)
- **Stevens et al. (2025):** 0.3, 2, 10, and 100 f/cc-years for crocidolite, amosite, textile chrysotile, and non-textile chrysotile respectively, with corresponding OELs of 0.01, 0.05, 0.2, and 2 f/cc

The study's calculated chrysotile cumulative exposures were 60- to 390-fold below these NOAEL/OEL thresholds. Crocidolite cumulative exposures were closer to the thresholds — approximately 2- to 8-fold below the levels found not to cause mesothelioma — representing the more borderline finding of the paper, though still within the "safe" range under all cited studies.

8. Louie et al. 2025 — Airborne chrysotile concentrations from valve packing replacement during repair/overhaul

Purpose: To characterize airborne fiber and chrysotile exposure associated with removing and replacing chrysotile-containing packing material during valve repair/overhaul, including novel scenarios not previously studied in the literature: high-frequency/back-to-back packing replacement (16 valves in succession), use of compressed air and sanding, cleanup activities, and take-home (clothes-handling) exposure potential. Work was performed by a career engineer on 21 in-service/out-of-service valves in a warehouse with no mechanical ventilation, using both standard and nonstandard work practices.

Key conclusions: All partial-shift and task-based personal and area airborne fiber/chrysotile concentrations were well below the OSHA 8-hr TWA PEL (0.1 f/cc) and 30-min Excursion Limit (1 f/cc) for asbestos, including under an upper-bound scenario of continuous packing replacement on 16 valves in ~1.5 hr. Nonstandard practices (sanding, compressed air) did not increase exposure above the baseline "16 valves in succession" scenario — in fact, that upper-bound continuous-replacement scenario produced somewhat higher exposures than any single-valve event using compressed air or sanding. No chrysotile was detected in bystander area samples at 9.1 m in most events, nor in clothes-handling/take-home samples. No correlation was found between PCM fiber counts and general particulate matter (PM) concentrations, meaning visible dustiness is not a reliable proxy for asbestos exposure. Results were consistent with prior peer-reviewed valve-packing literature showing full-shift exposures below the current OSHA PEL.

Asbestos types studied: Chrysotile only. Bulk packing samples analyzed at 20.91–62.77% chrysotile by PLM (existing valve packing) and 25.65–38.82% chrysotile (replacement packing sourced from eBay). No amosite, crocidolite, or tremolite detected; no asbestiform amphibole fibers detected in any air sample.

Exposure concentrations (PCM and PCM-equivalent chrysotile, PCME):

Sample Type	PCM (fiber)	PCME (chrysotile)
Partial-shift personal, Day 1 avg	0.0333 f/cc	0.0018 f/cc
Partial-shift personal, Day 2 avg	0.0144 f/cc	0.0022 f/cc
Partial-shift personal, overall avg	0.0239 f/cc	0.0020 f/cc
Partial-shift area, 9.1 m, overall avg	0.0038 f/cc	0.0011 f/cc
Task-based personal, Event 1 (16 valves succession)	0.0487 f/cc	0.0378 f/cc (range 0.0042–0.0790)
Task-based personal, single-valve events (Events 4–7)	0.0046–0.0415 f/cc	0–0.0074 f/cc
Cleanup (task-based personal)	0.0272–0.0415 f/cc	0.0047–0.0162 f/cc
Clothes handling/shakeout (personal & area)	0–0.0114 f/cc	Not detected
Background/ambient/clearance	≤0.0156 f/cc (non-asbestos fibers)	Not detected

Comparison to no-effect/threshold levels: The paper's comparisons are limited to the OSHA regulatory PEL (0.1 f/cc 8-hr TWA) and EL (1 f/cc 30-min), not epidemiological no-effect/threshold levels for mesothelioma or lung cancer. All measured concentrations were one to two orders of magnitude below the OSHA PEL and EL. The authors note this is consistent with prior valve-packing literature (Boelter et al., Mangold et al., Madl et al.), which similarly found full-shift TWA concentrations below 0.1 f/cc for packing-only work, and they explicitly frame their upper-bound scenario (16 valves in succession) as representative of the highest-exposure conditions plausible under realistic maintenance/repair practices.

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9. Case, Korchevskiy & Korchevskiy 2025 — Updates on exposure estimation for the Québec chrysotile miners/millers cohort

Purpose: To re-derive cumulative chrysotile exposure estimates for the McGill Québec miners/millers cohort using newly available paired midget-impinger (MPCF) and PCM fiber-count data (the Dagbert 1976 dataset), in order to (1) test whether updated exposure conversion affects the meta-analytic mesothelioma potency factor for chrysotile as calculated by Darnton (2023), and (2) estimate a practical/statistical threshold of cumulative chrysotile exposure below which mesothelioma risk is not elevated.

Key conclusions: Using two regression approaches to convert midget-impinger dust measurements to PCM fiber concentrations, average cumulative cohort exposure was estimated at 528.5 f/cc-years (Equation 4) or 979 f/cc-years (Equation 5), consistent with

Darnton's prior estimate of ~600 f/cc-years. Meta-analytic mesothelioma potency (R_M) for all chrysotile types was estimated at 0.0014% (95% CI 0.0010–0.0018), and for non-textile chrysotile at 0.0011% (95% CI 0.0008–0.0015) — closely matching Darnton's published values, supporting retention of the Québec cohort in meta-analyses rather than exclusion (as in EPA's 2020 TSCA risk evaluation). Statistical simulations found average cumulative-exposure thresholds for a nonzero mesothelioma dose-response of 35.9–65.9 f/cc-years (depending on conversion equation used), and random-subsample analysis found no mesothelioma cases at average cumulative exposures as high as 309–577 f/cc-years, with consistent non-zero risk only above 480–1,058 f/cc-years. Chrysotile lung burden was not expected to be elevated below ~178–307 f/cc-years cumulative exposure; a tremolite threshold of ~5 f/cc-years was also estimated.

Asbestos types studied: Chrysotile (primary focus, Québec cohort); tremolite (secondary, addressed as a natural contaminant/co-exposure in Québec ore, via lung-burden regression).

Exposure concentrations (cumulative, cohort-level; not task-based air sampling):

Metric	Value
Average cumulative cohort exposure (Equation 4)	528.5 f/cc-years (95% CI 510.3–546.7)
Average cumulative cohort exposure (Equation 5)	979.3 f/cc-years (95% CI 945–1,013)
Lowest exposure in a confirmed mesothelioma case	18 f/cc-years (all 30 cases) to 28–50 f/cc-years (high-confidence cases only)
No-mesothelioma-observed subsample averages	up to 309 f/cc-years (Eq. 4) or 577 f/cc-years (Eq. 5)

Comparison to no-effect levels: This is the central purpose of the paper. Multiple threshold estimates were derived: 18–50 f/cc-years (LOAEL, based on lowest-exposure confirmed cases); 35.9 f/cc-years (SD 15.4) via linear-log dose-response modeling (Equation 4 conversion); 65.9 f/cc-years (SD 29.6) via Equation 5 conversion; 8.9 MPCF-years (equivalent midget-impinger threshold); and no-mesothelioma-observed levels up to 309–577 f/cc-years in subsample simulations. These are explicitly framed as candidate "practical thresholds" for non-elevated mesothelioma risk from chrysotile, not formal regulatory NOAELs.

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10. Goodman, Korchevskiy & Wylie 2025 Comparison of methodological approaches to model asbestos thresholds for mesothelioma

Purpose: To review and compare multiple statistical/theoretical modeling approaches (Monte Carlo threshold simulation, intensity-duration threshold modeling based on the Peto age-mortality model, the "filter model" from Schaeffer et al., fiber-characteristic thresholds, and SEER-registry-based multistage clonal expansion modeling) for estimating threshold cumulative exposure levels below which mesothelioma risk is not elevated, across chrysotile and amphibole asbestos types.

Key conclusions: Multiple independent modeling approaches converge on the existence of a threshold for non-textile chrysotile-induced mesothelioma, with a central-tendency estimate of ~90 f/cc-years (range across methods: 25.6 f/cc-years [Monte Carlo simulation] to 90 f/cc-years [intensity-duration/Peto model] to 162 f/cc-years [filter model]). A Monte Carlo analysis found 72% of dose-response models fit to non-textile chrysotile cohort data supported a threshold relationship rather than a linear no-threshold model. Extrapolating via relative-potency ratios, thresholds for other fiber types were estimated: amosite 1.04 f/cc-years, crocidolite 0.25 f/cc-years, Libby amphibole asbestos (LAA)/tremolite surrogate 4.3–10.9 f/cc-years. Fiber-characteristic-based thresholds (width, length, rigidity, solubility) were reviewed qualitatively as supporting a biological basis for thresholds. Lung-burden studies (Gilham et al. 2016; Rödelsperger et al. 1999) support ~0.1 million amphibole fibers >5 μm/dry gram lung tissue as a possible threshold.

Asbestos types studied: Chrysotile (non-textile, primary quantitative focus), plus amosite, crocidolite, and Libby amphibole asbestos/tremolite (thresholds extrapolated via potency ratios rather than directly modeled from cohort data).

Exposure concentrations (cohort-level cumulative exposures used as model inputs, from Table 1):

Cohort	Type	Cumulative Exposure (f/cc-years)
Québec miners/millers	Chrysotile (NT)	600
Balangero miners/millers	Chrysotile (NT)	700–721
Qinghai miners	Chrysotile (NT)	120
New Orleans (plant 2)	Chrysotile (NT)	22
Connecticut friction products	Chrysotile (NT)	46
Russian miners/millers	Chrysotile (NT)	33.6

Comparison to no-effect levels: This is the paper's central purpose. Threshold estimates derived: ~90 f/cc-years (central tendency, non-textile chrysotile), with component estimates of 25.6 f/cc-years (Monte Carlo, 95% CI 3.3–52.9), 90 f/cc-years (intensity-duration/Peto model), and 162 f/cc-years (filter model). These were compared to Beckett et al.'s (2023) NOAEL range of 100–1,599 f/cc-years and Pierce et al.'s (2016) NOAEL of 208–415 f/cc-years, and found to be generally consistent with, or somewhat lower than, those ranges. Derived amphibole/other-mineral thresholds: amosite 1.04 f/cc-years, crocidolite 0.25 f/cc-years, LAA 4.3–10.9 f/cc-years, fluoro-edenite 1.08 f/cc-years.

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11. Goodman et al. 2025 (Frontiers in Epidemiology) — Challenges in defining thresholds for health effects: asbestos and silica

Purpose: A conference-summary/conceptual paper (Monticello III) synthesizing multiple presentations on the biological, statistical, and epidemiological evidence for thresholds in asbestos (mesothelioma) and silica (silicosis) dose-response relationships, including a specific re-analysis of Québec cohort data by Korchevskiy for a "practical threshold" and discussion of biobank-based future approaches.

Key conclusions: Biological mechanisms (cytotoxicity/regenerative proliferation, chronic inflammation, HMGB-1-mediated cell survival) support threshold-based rather than linear-no-threshold dose-response for mesothelioma. A focused re-analysis of 23 higher-confidence Québec mesothelioma cases (using Dagbert paired midget-impinger/PCM data) found average cumulative cohort exposure of ~500 f/cc-years (close to Darnton's 600 f/cc-years), with the 23 mesothelioma cases averaging >1,000 f/cc-years cumulative exposure and the single lowest case at 135.7 f/cc-years; a chrysotile-lung-burden-based subset (17 cases) yielded a central-tendency threshold of ~148.8 f/cc-years. A separate case-control study of 10 female mesothelioma cases (occupational + para-occupational/domestic exposure) in the same mining region found average reconstructed exposure of 226.1 f/cc-years. Overall, minimal mesothelioma risk was found well above ~100 f/cc-years equivalent EMP exposure. Statistical/theoretical models summarized from companion work (Goodman et al. 2025, Front Public Health) suggested thresholds of 25.6–162 f/cc-years for chrysotile, 4.3 f/cc-years for Libby amphiboles, 1.04 f/cc-years for amosite, and 0.25 f/cc-years for crocidolite.

Asbestos types studied: Chrysotile (primary, Québec cohort) and tremolite (co-contaminant in Québec ore, particularly in the "Area A"/original mine complex); amosite and crocidolite discussed via the Johns-Manville Asbestos-town factory comparison and via extrapolated thresholds from companion work; Libby amphibole asbestos referenced.

Exposure concentrations (cumulative):

Group	Cumulative Exposure
Québec cohort overall	~500–600 f/cc-years average
23 confirmed mesothelioma cases	mean >1,000 f/cc-years; lowest individual case 135.7 f/cc-years
Chrysotile-lung-burden subset (n=17)	central tendency threshold 148.8 f/cc-years
Female para-occupational/domestic cases (n=10)	mean 226.1 f/cc-years (range 84.5–525.6)
Johns-Manville crocidolite/amosite factory workers	5 mesotheliomas/553 deaths, despite cumulative exposure "an order of magnitude lower" than chrysotile miners/millers

Comparison to no-effect levels: Central theme of the paper. The Québec-specific reanalysis suggests minimal mesothelioma risk below roughly 100 f/cc-years cumulative chrysotile-equivalent EMP exposure, consistent with Beckett et al. and Pierce et al. NOAEL estimates cited elsewhere in the companion literature. The paper explicitly frames this as a "practical" rather than formally proven statistical threshold, given Hodgson & Darnton's caveat that "direct statistical confirmation of a threshold from human data is virtually impossible."

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12. Kurzhunbaeva et al. 2024 — Occupational exposure to chrysotile in an asbestos-cement factory in Kyrgyzstan

Purpose: To assess current occupational exposure to chrysotile fibers among workers at an active asbestos-cement manufacturing facility in Kyrgyzstan (a country that continues to mine/process chrysotile), across three job tasks (Similar Exposure Groups, SEGs): asbestos loading, asbestos-cement mixing, and cutting of asbestos-cement sheets. Personal 8-hour samples were analyzed by SEM-EDX for fiber-specific compositional identification.

Key conclusions: Workers across all three SEGs were exposed to chrysotile fibers at levels far exceeding modern Western regulatory limits, documenting that high occupational asbestos exposures — comparable to those seen in Italy and other Western countries in the 1970s, before major exposure-control efforts — persist today in some low/middle-income countries still mining and processing chrysotile. Exposure was highest for sawmill/cutting work (SEG-3) and asbestos loading (SEG-1), with sheet-mixing (SEG-2) somewhat lower but still exceeding EU OELVs. All samples exceeded the current EU OELV (0.1 ff/ml) and would greatly exceed the EU's forthcoming stricter limits (0.01 ff/ml by 2029; 0.002 ff/ml thereafter).

Asbestos types studied: Chrysotile only (confirmed via SEM-EDX compositional fiber analysis; the factory uses "only pure chrysotile" in production).

Exposure concentrations (chrysotile, personal 8-hr samples, geometric mean ± GSD):

SEG	Task	GM (ff/ml)	GSD	Individual Sample Range (ff/ml)
SEG-1	Asbestos loading	2.2	2.1	~1.0–7.5
SEG-2	Asbestos-cement mixing	0.91	2.6	~0.26–3.3
SEG-3	Cutting of A/C sheets (sawmills)	4.7	1.6	~3.0–12.5

Comparison to no-effect levels: No mesothelioma/lung-cancer no-effect-level comparison is presented. The paper instead compares measured concentrations to regulatory occupational exposure limits: the current EU OELV of 0.1 ff/ml (Directive 2009/148/EC, PCM-based) — all SEGs' GMs exceeded this by roughly 9- to 47-fold — and the EU's future stricter limits (0.01 ff/ml by 2029, 0.002 ff/ml from 2029 onward, electron-microscopy based), which would be exceeded even more dramatically. Historical comparison is made to 1970s-era Italian asbestos-cement plants (e.g., Casale Monferrato Eternit plant), where similar or higher concentrations (up to 303.8 ff/ml in mixing areas in 1971) were measured before major exposure controls were implemented in the late 1970s–1980s (declining to 0.15–1.1 ff/ml by the late 1970s); the Kyrgyzstan results are described as comparable to that pre-regulation era.

13. Anderson et al. (2024) — "Asbestos exposures associated with the use and handling of drilling mud additives"

Toxicology and Industrial Health

Purpose of the Study

This paper summarizes a historical industrial hygiene (IH) dataset (1972–1985) characterizing airborne asbestos exposures during the use and handling of short-fiber chrysotile asbestos as a drilling mud additive (DMA) on more than 20 U.S. land-based and offshore oil/gas rigs (plus one Norwegian North Sea rig). Chrysotile was used as a viscosifier/loss-circulation agent, added manually in small quantities (rarely >500 lb at a time) roughly once per shift. The goal was to fill a literature gap, since no prior published studies characterized actual measured exposures for drilling rig workers handling asbestos-containing DMAs (prior work relied on simulation/surrogate data).

Key Conclusions

- The dataset (1,171 personal/area air samples) showed that asbestos-handling tasks were short in duration (average ~33 min; >80% <30 min) and infrequent (roughly once per 8-hr shift).
- Calculated 8-hour TWA exposures, based on short-term plus long-term sampling, did not exceed contemporaneous OSHA PELs at any point in the 1972–1985 period.
- No relationship was found between sample duration, number of bags handled, or bags handled per minute and airborne concentration (all R^2 <0.03).
- PCM analysis cannot reliably differentiate chrysotile from other fibers (including non-asbestos background dust from a dusty rig environment), so reported chrysotile concentrations likely overestimate true chrysotile exposure.
- Authors concluded that chrysotile DMA exposures on rigs, given short duration/frequency/quantities, would not be expected to confer significant asbestos-related disease risk based on established risk models.

Asbestos Types Studied

- **Chrysotile only** (short-fiber, granular/pelletized forms). No amosite, crocidolite, or tremolite exposures were characterized (though tremolite/amphibole contamination is not discussed as relevant here).

Exposure Concentrations Measured

Metric	Sample Type	n	AM (f/cc)	GM (f/cc)
Short-term (<240 min), during handling	Personal, total fibers	132	1.49	0.549
Short-term, during handling	Area, total fibers	132	0.40	0.156
Short-term, during handling	Personal, chrysotile fibers	67	0.772	0.314
Short-term, during handling	Area, chrysotile fibers	92	0.22	0.11
Long-term (>240 min)	Total fibers (n=5, 4 bystander)	5	0.06	—

Metric	Sample Type	n	AM (f/cc)	GM (f/cc)
Long-term	Chrysotile (1 direct-exposure sample)	1	0.3	—
Calculated 8-h TWA	Total fibers	66	**0.17**	0.094
Calculated 8-h TWA	Chrysotile	28	**0.1**	0.049

By task (personal, short-term, total fibers): AM ranged from 0.62 f/cc (dumping+disposal) to 3.39 f/cc (dumping+handling). By task (chrysotile only): AM ranged from 0.32 f/cc (disposal) to 1.35 f/cc (handling).

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

The paper compares calculated 8-h TWAs directly to the *contemporaneous* OSHA PELs in effect during the study period rather than to modern NOAEL/exposure-response benchmarks: 12 f/cc (1971), 5 f/cc (Dec. 1971), 2 f/cc (1975), 0.2 f/cc (1986). All 8-h TWA values (mean 0.17 f/cc total fiber, 0.1 f/cc chrysotile) were below every one of these historical PELs, including the more stringent 1986 standard. No formal comparison to published mesothelioma/lung cancer NOAELs (e.g., Pierce et al., Hodgson & Darnton) is presented in this paper.

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14. Goodman, Morgan, Ray, Malloy & Zhao (1999) — "Cancer in asbestos-exposed occupational cohorts: a meta-analysis"

Cancer Causes & Control, 10(5): 453–465

Purpose of the Study

This is a meta-analysis (not an exposure-measurement study) that pooled data from 69 published asbestos-exposed occupational cohorts (68 articles, 1967–1997) reporting standardized mortality/incidence rates (SMRs/SIRs) for lung, laryngeal, gastrointestinal, urinary, and lymphohematopoietic cancers. The objective was to quantify overall cancer risk associated with occupational asbestos exposure across the literature and to examine dose-response relationships using proportionate mesothelioma mortality as a proxy for asbestos exposure intensity (since direct exposure measurements were unavailable for most included cohorts).

Key Conclusions

- Pooled lung cancer meta-SMR = 163 (with ≥10-yr latency; 95% CI 158–169) and 148 (without latency), but with extreme statistical heterogeneity ($p<10^{-9}$) across studies.
- A clear dose-response relationship was found between the percentage of cohort deaths due to mesothelioma (proxy for exposure) and lung cancer risk: meta-SMR rose from 127 (lowest mesothelioma tertile) to 138 (mid) to 285 (highest tertile); Pearson r=0.591 (p<0.001).

- Laryngeal cancer meta-SMR = 157, homogeneous across studies, but with **no** dose-response relationship to mesothelioma proportion (r=−0.070, ns).
- No significant excess was found for gastrointestinal (meta-SMR 103–108), urinary (kidney 111–120, bladder 98–100), or lymphohematopoietic cancers (89–95), and none of these showed a dose-response relationship with mesothelioma proportion.
- The authors conclude that, apart from mesothelioma, lung cancer is the only malignancy with unequivocal association with asbestos exposure, and that the magnitude of that association is frequently overestimated when a single summary risk estimate is used without accounting for heterogeneity.
- Occupational category strongest associations: asbestos product manufacturers (meta-SMR 192), cement workers (170), asbestos miners/millers (135).

Asbestos Types Studied

This is a cross-cohort meta-analysis rather than a fiber-specific exposure study; cohorts included mixed exposures (chrysotile, amosite, crocidolite, and mixed/unspecified fiber types) across mining/milling, textile, cement, shipyard, insulation, and friction-product manufacturing settings. Fiber type is **not** systematically disaggregated in the analysis — exposure intensity is instead proxied by proportionate mesothelioma mortality (tertiles: ≤0.6%, 0.7–2.4%, >2.4% of all cohort deaths).

Exposure Concentrations Measured

No direct airborne fiber concentration data (f/cc) are reported or measured in this paper; exposure is characterized indirectly via cohort-level SMRs and proportionate mesothelioma mortality as a surrogate dose metric. No range/mean f/cc values are given for chrysotile, amosite, crocidolite, or tremolite.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

The paper does not derive or compare against modern quantitative NOAELs/OELs (in f/cc or f/cc-years). Instead, it demonstrates a statistically significant positive correlation between proportionate mesothelioma mortality (used as an exposure proxy) and lung cancer meta-SMR, supporting the general principle that cancer risk scales with cumulative asbestos dose, but without deriving specific threshold exposure levels.

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15. Mutetwa, Moyo & Brouwer (2023) — "Prediction of Asbestos-Related Diseases (ARDs) and Chrysotile Asbestos Exposure Concentrations in Asbestos-Cement (AC) Manufacturing Factories in Zimbabwe"

International Journal of Environmental Research and Public Health, 20(1): 58

Purpose of the Study

Using a previously developed job-exposure matrix (JEM; Mutetwa et al. 2022) built from 3,066 personal airborne chrysotile measurements (1996–2020) at two Zimbabwean asbestos-cement (AC) factories (Harare and Bulawayo), this study applied OSHA's linear dose-response cancer risk assessment model to predict asbestos-related disease (ARD) burden — lung cancer, mesothelioma, gastrointestinal cancer, and asbestosis — after 1, 10, 20, and 25 years of exposure at concentrations experienced during specific time periods and job titles (e.g., saw cutting, kollergang, fettling table, ground hard waste, pipe operations).

Key Conclusions

- Predicted cumulative cancer cases after 25 years ranged from 116–555 per 100,000 workers (Harare) and 116–497 per 100,000 (Bulawayo), depending on job/time-period, with saw cutting, kollergang, and ground hard waste operators at highest risk, particularly for exposures predating 2008.
- Overall factory-wide predicted total cancer cases after 25 years: 324/100,000 (Harare) and 347/100,000 (Bulawayo).
- Predicted asbestosis incidence after 25 years ranged from 50–260 cases/100,000 (0.05–0.26%) by job; overall factory averages were 150 (Harare) and 170 (Bulawayo) cases/100,000 (0.15–0.17% incidence).
- Predicted cases were substantially lower than reported in other OSHA-model studies (e.g., Jafari et al., which found ~499 cases/100,000 after 1 year and ~6,965/100,000 after 20 years), reflecting the comparatively low cumulative exposures (max 4.3–4.8 f/mL-years) versus historical exposures elsewhere (200–300 f/mL-years in the 1970s).
- Exposure trends declined over time at both factories (particularly Bulawayo, reaching 0.04–0.07 f/mL by 2018–2020), though Harare showed a modest uptick 2018–2020.
- Using OSHA's "significant risk" criterion (>1 case/1,000 workers), overall cancer mortality risk (2.89–4.63 cases/1,000) could be considered significant, though this is below the 4-cases/1,000 benchmark used by some countries (Netherlands, Germany) as an acceptable risk level.

Asbestos Types Studied

- **Chrysotile only.** No amosite, crocidolite, or tremolite exposure data are presented (Zimbabwean AC manufacturing has used only chrysotile).

Exposure Concentrations Measured (Mean personal airborne chrysotile, by job/time period)

Time Period	Harare Mean (f/mL)	Bulawayo Mean (f/mL)
1996–2000	0.11–0.19	0.13–0.17
2001–2008	0.11–0.13	0.11–0.12
2009–2016	0.05–0.07	0.05–0.07
2018–2020	0.10–0.12	0.04–0.06

Cumulative exposures (25-year duration) ranged from **1.0 to 4.8 f/mL-years** across jobs/time periods (highest for saw cutting operators, 1996–2000, both factories).

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

The study relies on OSHA's linear dose-response model (derived from Table 1: cancer mortality per 100,000 exposed workers at fixed f/mL levels for 1-, 20-, and 45-year exposures) rather than externally-derived NOAEL/OEL benchmarks. It notes its cumulative exposures (max 4.3–4.8 f/mL-years) are far below historical exposures reported in other cohorts (200–300 f/mL-years in the 1970s) and below levels used in other OSHA-model-based predictions (e.g., Jafari et al. 2010). The paper references the OSHA "1 excess cancer death per 1,000 workers" significant-risk threshold and alternative national benchmarks (4/1,000, Netherlands/Germany) as points of comparison for interpreting the predicted 2.89–4.63/1,000 risk range, rather than citing specific f/cc-year NOAELs for chrysotile mesothelioma/lung cancer.

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16. Bernstein (2022) — "The health effects of short fiber chrysotile and amphibole asbestos"

Critical Reviews in Toxicology (review article)

Purpose of the Study

This is a comprehensive literature review (not a new exposure-measurement study) examining the toxicological, epidemiological, and in-vitro evidence regarding whether short asbestos fibers (chrysotile and amphibole, generally defined as <5–10 µm in length) contribute to asbestos-related disease. The review addresses fiber distribution, biopersistence, inhalation toxicology, in-vitro studies, and lung/pleural clearance mechanisms to determine whether short fibers pose meaningful carcinogenic/fibrogenic risk, in contrast to long fibers (>10–20 µm).

Key Conclusions

- Across epidemiology, toxicology, and in-vitro literature, short chrysotile and amphibole fibers (<5–10 µm) show no significant contribution to lung cancer or mesothelioma risk.
- QSAR models show fiber aspect ratio and Mg content are strong predictors of carcinogenic potency; short amphibole fibers/particles predict to have essentially no potency.
- Motor vehicle mechanics (including brake repair workers, predominantly exposed to short chrysotile fibers from brake wear) show no increased mesothelioma risk in meta-analyses (overall SRRE 0.64, 95% CI 0.38–1.09).
- Multiple chronic inhalation toxicology studies (Ilgren & Chatfield; Platek/Stettler; Wagner et al.) using short chrysotile (largely <5 µm) at high exposure concentrations (0.79–7.78 mg/m³) found no tumors above control levels.
- Bernstein et al.'s own 90-day brake-dust inhalation study found chrysotile-containing brake dust (largely <5 µm fibers) produced no significant pathological/tumorigenic response, while long-fiber amosite/crocidolite produced dose-related tumors.
- Short fibers are efficiently cleared via macrophage phagocytosis and, importantly, via lymphatic transport (shown to have the highest clearance rate in confocal-imaging

studies), whereas long, biopersistent fibers (particularly amphiboles) frustrate macrophage clearance and drive chronic inflammation linked to carcinogenesis.
- Chrysotile is comparatively less biopersistent than amphiboles: long chrysotile fibers break down/dissolve (half-times of 28–42 days even for long fibers in 90-day studies), while amphiboles (encased in an insoluble crystalline silica shell) persist indefinitely at neutral/acidic pH.

Asbestos Types Studied

This review covers **chrysotile, amosite, and crocidolite** (and briefly erionite, tremolite/actinolite, anthophyllite in the context of comparative potency modeling), synthesizing data across dozens of underlying epidemiological, toxicological, and in-vitro studies rather than presenting new field-measured exposure data.

Exposure Concentrations Measured

No new field/occupational air sampling data are generated. The review reports exposure concentrations used in cited *toxicology* studies (not human occupational settings), e.g.:

- Bernstein et al. (2020a): short chrysotile inhalation at 665 and 753 f/cm³ (90-day study)
- Ilgren & Chatfield (1997/98): Coalinga chrysotile at 7.78 ± 1.46 mg/m³
- Platek/Stettler: chrysotile at 1 ± 0.28 mg/m³ (rats/monkeys)
- Davis et al. (1986): amosite at 1.9–11.6 mg/m³ (long vs. short fiber)
- Bernstein et al. (2021) brake dust study: chrysotile brake dust at 0.20–0.67 mg/m³ (36–78 fibers/cm³ total)
  These are experimental animal/simulation exposure concentrations, not measured human occupational exposures, and are not presented as ranges/means for a specific workplace.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

The review does not derive quantitative f/cc or f/cc-year NOAELs itself, but it supports (via ATSDR 2004 expert panel consensus, cited directly) the conclusion that "asbestos and SVFs shorter than 5 µm are unlikely to cause cancer in humans." It references Berman & Crump's meta-analysis finding that the best-estimate potency of short fibers (5–10 µm) for both lung cancer and mesothelioma is zero, and that shortening the fiber-length cutoff to <5 µm found no consistent evidence of potency at any length. The overall thrust of the paper functionally establishes that fiber length — not just cumulative fiber count/mass — is a critical determinant relevant to interpreting NOAEL/exposure-response data for short-fiber-dominated exposure scenarios (e.g., brake repair, drilling mud additive handling).

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17. Finley, Pierce, Phelka, Adams, Paustenbach, Thuett & Barlow (2012) — "Evaluation of tremolite asbestos exposures associated with the use of commercial products"

Critical Reviews in Toxicology, 42(2): 119–146

Purpose of the Study

This review/analysis addresses tremolite asbestos specifically — a non-commercial amphibole contaminant sometimes present in chrysotile, talc, and vermiculite deposits/products. Because essentially nothing was published on tremolite exposure-response relationships prior to this paper, the authors: (1) derived exposure-response benchmarks (LOAEL/NOAEL) for tremolite and mesothelioma using two high-exposure mining cohorts (Thetford Mines chrysotile miners, Canada; Libby, Montana vermiculite miners), and (2) estimated cumulative tremolite exposures associated with various consumer/occupational product-use scenarios (auto brake/clutch repair, joint compound use, vermiculite gardening products, Zonolite attic insulation removal) for comparison against those benchmarks.

Key Conclusions

- Derived tremolite-asbestos-equivalent LOAEL for mesothelioma (lowest bounded exposure with statistically significant increased risk): **35–73 f/cc-years**, based on the Thetford Mines cohort (12 "high probability" mesothelioma cases).
- Derived tremolite NOAEL range: **0.05–2.6 f/cc-years**, based on the Libby vermiculite cohort (Larson et al. 2010 rate-ratio analysis; assuming tremolite = 6% of "Libby amphibole").
- All estimated cumulative tremolite exposures from consumer/occupational product-use scenarios were far below these NOAEL/LOAEL benchmarks (by several orders of magnitude): auto mechanics 0.028 f/cc-year; joint compound (consumer) 0.0006 f/cc-year; vermiculite gardening products 0.034 f/cc-year; Zonolite attic insulation removal (one-time) 0.0002 f/cc-year.
- No published study has confirmed the presence of asbestiform tremolite fibers in any tested automotive brake, clutch, or gasket sample; airborne sampling during friction-product handling likewise found no detectable tremolite (detection limits 0.001–0.009 f/cc).
- Epidemiology of auto mechanics/brake workers shows no elevated mesothelioma risk, consistent with negligible tremolite (and chrysotile) exposure from these products.
- Authors conclude tremolite asbestos is almost certainly less potent than amosite/crocidolite (based on iron content and in-vitro reactive-oxygen-species generation ranking: crocidolite > amosite > tremolite > chrysotile) but likely more potent than chrysotile.

Asbestos Types Studied

- **Tremolite** (primary focus, asbestiform vs. non-asbestiform distinguished throughout)
- **Chrysotile** (as the host material in mining/consumer-product scenarios)
- **Amosite and crocidolite** discussed comparatively (potency ranking context, e.g., Hodgson & Darnton mesothelioma risk ratio 1:100:500 for chrysotile:amosite:crocidolite) but not directly measured in this paper's exposure estimates.

Exposure Concentrations Measured (Tremolite-specific)

Setting	Measured/Estimated Concentration	Notes
Thetford Mines, ambient town air (1980s)	0.0015 f/cc (mean)	vs. 0.074 f/cc chrysotile (~2% ratio)
Thetford Mines, estimated airborne tremolite (1949–1966)	0.06–2.6 f/cc (declining over time)	Derived from historical dust counts
Libby, Montana dry mill (pre-1964)	13–182 f/cc ("asbestiform tremolite-actinolite")	Job-category dependent
Libby mine (pre-1971)	<2–23 f/cc	Non-drillers vs. drillers
Libby, 1977–1982 (all jobs)	<1 f/cc (8-h TWA)	
Auto mechanics, brake/clutch handling (TWA)	≤0.0004 f/cc (worst-case estimate)	Below LOD in most direct sampling (LOD 0.001–0.009 f/cc)
Joint compound, consumer use (8-h TWA)	≤0.008 f/cc	Worst-case assumption
Vermiculite garden products (personal, task-based)	Up to 0.0935 s/cc	USEPA (2000) data
Zonolite attic insulation removal (task-based TWA)	0.53–14.4 f/cc (PCM); <0.33–10.3 s/cc (TEM)	Ewing et al. 2010; total "Libby amphibole," not tremolite-specific

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer

This paper is unique among the batch in that it **derives** the NOAEL/LOAEL benchmarks itself (35–73 f/cc-year LOAEL from Thetford; 0.05–2.6 f/cc-year NOAEL from Libby) rather than citing external ones, then explicitly compares estimated consumer/occupational cumulative tremolite exposures against them. All product-use cumulative exposure estimates (0.0002–0.034 f/cc-year) were several orders of magnitude below even the NOAEL end of the range, leading the authors to conclude that tremolite exposure from chrysotile-, talc-, and vermiculite-containing consumer products is very unlikely to pose a measurable mesothelioma risk. The authors note substantial uncertainty in these derived benchmarks (incomplete cohort follow-up, assumed fiber:dust conversion ratios, assumed tremolite content of "Libby amphibole" and Thetford chrysotile) and flag them as reasonable approximations rather than precise thresholds.

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18. Mutetwa, Moyo & Brouwer (2021) "Trends in Airborne Chrysotile Asbestos Fibre Concentrations in Asbestos Cement Manufacturing Factories in Zimbabwe from 1996 to 2016" *Int. J. Environ. Res. Public Health, DOI: 10.3390/ijerph182010755*

Purpose of the Study
This secondary data analysis examined roughly 3,000 personal exposure measurements (1,663 monthly averages) collected between 1996 and 2016 at two Zimbabwean chrysotile asbestos-cement (A/C) manufacturing factories (Harare and Bulawayo), to characterize temporal trends in airborne chrysotile fibre concentrations across various operational areas (cutting saws, fettling tables, kollergang, moulded goods, ground hard waste, laundry rooms, pipe/lathe operations, multi-cutter). The study also sought to compare exposure levels against Zimbabwe's non-statutory 0.1 f/mL occupational exposure limit (OEL) and to contextualize findings against international trends.

Key Conclusions

- Personal exposure concentrations declined substantially over the 21-year period: overall factory means fell from 0.11–0.18 f/mL (1996–2000) to 0.03–0.12 f/mL (2009–2016), a 60–67% reduction.
- Despite the downward trend, 60.3% (Harare) and 58.6% (Bulawayo) of all measurements exceeded the 0.1 f/mL OEL, with overexposure concentrated before 2008.
- Fettling table operations had the highest proportion of overexposure in both factories (76.2% Harare, 84.3% Bulawayo); multi-cutter operations in Bulawayo were also high (81.3%).
- The decline was attributed to a mix of factors: pursuit of ISO 9001/14001 and OHSAS 18001 certification (achieved 2001), economic contraction/hyperinflation (2001–2008) suppressing production, and post-2009 retooling with imported fibre following economic stabilization.
- Trends were broadly consistent with declines reported in other countries (Germany, Sweden, Japan, Thailand, Korea), though Zimbabwean levels in the 1990s were comparable to or somewhat lower than those in some other studies.

Asbestos Types Studied

- Chrysotile (serpentine) only — this was a dedicated chrysotile cement manufacturing operation; no amphiboles (amosite, crocidolite, tremolite) were assessed or reported.

Exposure Concentrations Measured (Personal, f/mL)

Factory	Period	Mean (f/mL)	Range
Harare	1996–2000	0.14	0.11–0.18
Harare	2001–2008	0.12	0.07–0.18
Harare	2009–2016	0.06	0.04–0.12
Bulawayo	1996–2000	0.14	0.09–0.22

Factory	Period	Mean (f/mL)	Range
Bulawayo	2001–2008	0.11	0.09–0.15
Bulawayo	2009–2016	~0.05	0.03–0.10

By task, the highest overall means were at cutting saw and fettling table operations (up to 0.16–0.19 f/mL in early years), declining to 0.05–0.07 f/mL by 2009–2016.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer
The paper does not compare cumulative or task-specific exposures against published chrysotile NOAELs/LOAELs for mesothelioma or lung cancer (e.g., Pierce, Goodman, Stevens-type thresholds). Its comparison is limited to the local/regional OEL of 0.1 f/mL (aligned with OSHA/ACGIH) and the earlier industry action level of 0.2 f/mL used in the 1990s. No lifetime cumulative exposure (f/mL-year) estimates or disease-risk-threshold comparisons are presented.

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19. Finley et al. (2012, corrected 2018) — "Evaluation of tremolite asbestos exposures associated with the use of commercial products"

Critical Reviews in Toxicology, 42(2):119–146; Corrigendum DOI: 10.1080/10408444.2018.1429535

Purpose of the Study
This review sought to (1) characterize the exposure–response relationship between tremolite asbestos and mesothelioma using two high-exposure mining cohorts (Thetford Mines, Quebec chrysotile mines; Libby, Montana vermiculite mine), deriving LOAEL/NOAEL benchmarks, and (2) estimate cumulative tremolite asbestos exposures associated with various consumer/occupational product-use scenarios (automotive friction products, joint compound, vermiculite garden products, attic insulation), to assess whether such exposures pose a meaningful mesothelioma risk.

Key Conclusions

- Tremolite LOAEL for mesothelioma (derived from Thetford Mines high-probability cases): **35–73 f/cc-years**.
- Tremolite NOAEL (as corrected in the 2018 corrigendum, derived from Libby cohort data): **0.5–2.6 f/cc-years** (originally misreported as 0.05–2.6).
- All estimated consumer/product-use cumulative tremolite exposures were several orders of magnitude below these thresholds: career auto mechanic ≈0.028 f/cc-yr; non-occupational joint compound use ≈0.0006 f/cc-yr; vermiculite gardening products ≈0.034 f/cc-yr; one-time homeowner Zonolite attic insulation removal ≈0.0002 f/cc-yr.
- No published studies have confirmed tremolite fibers in automotive friction products (brakes, clutches, gaskets) at detectable levels via TEM; when detected in bulk chrysotile/talc products, tremolite is usually non-asbestiform (and thus of low/no carcinogenic potency).

- Authors conclude tremolite asbestos is likely more potent than chrysotile for mesothelioma but far less potent than amosite/crocidolite, and that consumer exposures to tremolite via chrysotile-, talc-, or vermiculite-containing products present minimal to negligible health risk.

Asbestos Types Studied

- **Tremolite** (primary focus, asbestiform vs. non-asbestiform distinction emphasized)
- Chrysotile (as the tremolite-contaminated source material in mining/friction/joint-compound scenarios)
- Libby "amphibole" (mixture of winchite [~84%], richterite [~11%], tremolite [~6%]) — tremolite-equivalent exposures calculated by applying the 6% factor
- Amosite and crocidolite discussed comparatively (potency ranking) but not directly measured

Exposure Concentrations Measured (Cumulative, tremolite asbestos-equivalent, f/cc-years)

Scenario	Cumulative Exposure
Occupational: friction products (brake mechanic)	0.028
Consumer: joint compound (chrysotile & talc)	0.0006
Consumer: vermiculite gardening products	0.034
Consumer: Zonolite attic insulation removal (one-time)	0.0002
Libby vermiculite workers (mesothelioma cases, median)	~50 (Libby amphibole); tremolite-equivalent ~3
Thetford Mines miners/millers (12 high-probability mesothelioma cases)	35–73

Airborne tremolite estimates at Thetford ranged from ~2.6 f/cc (1949) declining to ~0.2–0.35 f/cc by the mid-1960s (derived from dust-count conversion).

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer
This is the central purpose of the paper. All consumer/occupational product-use tremolite exposures (0.0002–0.034 f/cc-yr) fall far below both the derived NOAEL (0.5–2.6 f/cc-yr) and LOAEL (35–73 f/cc-yr) for mesothelioma. The authors note substantial uncertainty in these benchmarks (incomplete cohort follow-up, assumed tremolite content of chrysotile ore, single fiber:dust conversion ratios) but conclude the margin of safety is large enough that the qualitative conclusion — minimal risk from consumer product use — is robust to these uncertainties.

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20. Silvestri et al. (2020) — "Asbestos Exposure of Chrysotile Miners and Millers in Balangero, Italy" Annals of Work Exposures and Health, DOI: 10.1093/annweh/wxaa045

Purpose of the Study
To quantitatively reconstruct historical airborne asbestos exposure levels for workers at the Balangero chrysotile mine (Western Europe's largest, active 1917–1990), in support of a cohort mortality/mesothelioma-incidence study prompted by identification of 14 mesothelioma cases among former Amiantifera employees and subcontractors. Exposure was reconstructed by work-area and year using industrial hygiene surveys (from 1968), internal monitoring (1975–1989), and experimental/simulated reconstructions of pre-1968 conditions, then linked to individual job-histories to calculate cumulative exposures (f/mL-years).

Key Conclusions

- Exposure levels varied enormously by era and work-area, spanning roughly two orders of magnitude over the mine's operating history.
- Mining area concentrations were ~20 f/mL until the mid-1950s, dropping to ~5 f/mL after a shift from "glory hole" to open-bench mining, and to <1 f/mL by the late 1970s.
- Milling/beneficiation areas had substantially higher initial concentrations (up to ~250 f/mL in beneficiation before mid-1950s enclosures/filters reduced it to ~50 f/mL); concentrations across milling areas did not fall below 1 f/mL until the mid-1980s.
- Cumulative worker exposures were highly skewed: 13.3% of workers exceeded 1000 f/mL-years cumulative exposure; 50.4% exceeded 100 f/mL-years; median cumulative exposure was 106.7 f/mL-years.
- Only two pleural cancer deaths had been identified in earlier (1990) mortality follow-up, historically used to support a low chrysotile potency estimate relative to amphiboles — but a subsequent Registry review identified 14 mesothelioma cases among Balangero-associated workers, prompting this reassessment.
- Balangero exposure levels were higher than comparable Russian (Asbest) chrysotile mine estimates during the 1950s–60s, though lower than some Chinese and Brazilian mine estimates in more recent decades.

Asbestos Types Studied

- **Chrysotile** only, as the mined/milled commercial product.
- Balangeroite (a non-amphibole fibrous silicate related to gageite, distinct from tremolite/amphiboles) was present at 0.2–1% of ore by weight and is discussed as a secondary fibrous mineral, but is explicitly noted to have lower durability than tremolite and is not classified as amphibole asbestos.
- No tremolite contamination was reported in the ore (per Piolatto et al. 1990), though the detection limit for that determination was not specified. A single documented instance of pilot-scale crocidolite processing (one week, 1978/79, for testing purposes only) is noted but was not part of routine production.

Exposure Concentrations Measured (Chrysotile, f/mL, by work-area and era)

Work-area	Early period (pre-1950s)	Later period
Mining	~20 f/mL	<1 f/mL (late 1970s onward)
Beneficiation	~250 f/mL, then ~175 f/mL	~50 f/mL (mid-1950s); <1 f/mL not until mid-1980s
Crushing/drying/mixing/packaging/dumping-site	~40–70 f/mL	Gradual decline, <1 f/mL only by mid-1980s

Cumulative exposure distribution across the cohort (974 workers, 15,760 person-years): 18% <10 f/mL-yr; 32% 10–100 f/mL-yr; 37% 100–1000 f/mL-yr; 13% >1000 f/mL-yr.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer
The paper does not present a direct quantitative comparison of exposure estimates to published NOAEL/LOAEL thresholds for chrysotile mesothelioma or lung cancer risk (e.g., Pierce et al., Goodman et al.). Its focus is exposure reconstruction methodology to support a companion epidemiological mortality/incidence study (Ferrante et al. 2020), referenced but not detailed here. The paper notes contemporaneous ACGIH TLV context (5 mppcf) was frequently exceeded historically, but does not map cumulative exposures against modern disease-risk benchmarks.

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21. **Sahmel** et al. (2014) — "Evaluation of Take-Home Exposure and Risk Associated with the Handling of Clothing Contaminated with Chrysotile Asbestos" *Risk Analysis, 34(8), DOI: 10.1111/risa.12174*

Purpose of the Study
To experimentally characterize the relationship between simulated workplace airborne chrysotile concentrations, contamination of work clothing, and resulting "take-home" (para-occupational) airborne exposures during handling/shake-out of contaminated clothing — and to estimate cumulative lifetime take-home doses and associated risk, addressing a data gap since most prior take-home epidemiology involved amphibole/mixed-fiber exposures rather than chrysotile alone.

Key Conclusions

- Clothing was loaded at three target airborne chrysotile levels (low: ~0.01 f/cc; medium: 0.88–2.42 f/cc; high: 2.38–3.30 f/cc, TEM) via mannequins in a controlled chamber, then handled/shaken out by study participants.
- Personal breathing-zone chrysotile concentrations during active 15-minute clothes handling ranged 0.014–0.097 f/cc (TEM); concentrations dropped 86–87% during a subsequent 15-minute period of inactivity.
- Bystander (6–12 ft away) concentrations were consistently lower (62–88% below personal handler concentrations).

- Eight-hour TWA take-home concentrations were only 0.2–1.4% of the corresponding eight-hour TWA workplace loading concentrations; on a 40-hour work-week basis, take-home ratios were 0.03–0.27%.
- PCM (non-specific fiber) results were 2- to 50-fold higher than TEM (chrysotile-specific) results during clothes handling, indicating most PCM-countable fibers were clothing fibers, not asbestos — underscoring that historical PCM-only take-home studies likely overestimated chrysotile exposure.
- Estimated lifetime cumulative chrysotile doses for clothes handlers (0.00044–0.0047 f/cc-year) and bystanders (0.00011–0.00059 f/cc-year) were below or consistent with estimated lifetime cumulative doses from ambient background chrysotile exposure alone (0.0035–0.105 f/cc-year).
- Authors conclude chrysotile-specific take-home exposures at the levels tested would not measurably increase asbestos-related disease risk above background, contrasting with epidemiological findings of increased risk associated with amosite/mixed-fiber take-home exposures in other industries.

Asbestos Types Studied

- **Chrysotile** only (Grade 7T chrysotile used experimentally). Amosite is discussed comparatively (regarding differing take-home epidemiology and particle characteristics) but not tested. No crocidolite or tremolite testing.

Exposure Concentrations Measured (f/cc, TEM unless noted)

Measurement context	Range/Mean
Loading (simulated workplace), 6 events	0.01–3.30 f/cc
Clothes handling, active 15-min (personal)	0.014–0.097 f/cc
Clothes handling, subsequent 15-min inactivity	0.009–0.014 f/cc
30-min personal (handling + inactivity)	0.006–0.063 f/cc
30-min bystander (6–12 ft)	62–88% lower than personal
8-hr TWA take-home (personal)	0.0004–0.0040 f/cc
8-hr TWA take-home (bystander)	0.0002–0.0007 f/cc

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer
Rather than comparing to published NOAEL/LOAEL fiber-year thresholds directly, the paper benchmarks estimated **cumulative lifetime doses** (clothes handler: 0.00044–0.0047 f/cc-yr; bystander: 0.00011–0.00059 f/cc-yr) against estimated lifetime cumulative ambient/background chrysotile doses (0.0035–0.105 f/cc-yr) and against published upper-bound cumulative lifetime chrysotile doses for vehicle mechanics (1.96–2.79 f/cc-yr, citing Finley et al. 2007) — noting that epidemiology shows no significantly increased mesothelioma/lung cancer risk in either ambient-exposed populations or brake mechanics at these dose ranges, supporting a conclusion of negligible risk for chrysotile take-home exposure at the levels studied.

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22. Goodman **et** al. (2013) — "Electricians' Chrysotile Asbestos Exposure from Electrical Products and Risks of Mesothelioma and Lung Cancer" Regulatory Toxicology and Pharmacology, In Press

Purpose of the Study
This critical review examined whether electricians face an increased risk of mesothelioma and lung cancer, and if so, whether exposure to chrysotile asbestos in electrical products (wire insulation, circuit boards, motor controllers) could be responsible. The authors reviewed epidemiology literature on electricians, industrial hygiene data on electrician asbestos exposures (including grinding/drilling of encapsulated chrysotile products), and compared these exposures to those of automobile brake workers (a group not shown to have elevated mesothelioma/lung cancer risk).

Key Conclusions

- Most (not all) epidemiology studies show electricians at some increased risk for mesothelioma and lung cancer, but none allowed assessment of risk attributable specifically to chrysotile versus amphibole exposure.
- Electrician exposure studies consistently reported 8-hour TWA concentrations below the current OSHA PEL (0.1 f/cc), including during grinding/drilling of encapsulated chrysotile electrical products.
- Other craftsmen working near electricians (e.g., insulators) had much higher, largely amphibole exposures (up to 3,021 f/cc in some studies).
- Chrysotile fibers released from encapsulated electrical products are short and resin-coated, limiting respiratory deposition/retention.
- Mechanistic and biopersistence data support a threshold mode of action for chrysotile carcinogenesis, unlike amphiboles.
- The authors concluded the most likely cause of lung cancer in electricians is smoking, and the most likely cause of mesothelioma is bystander/renovation exposure to amphibole asbestos — not chrysotile in electrical products.

Asbestos Types Studied

- **Chrysotile** — primary component of electrical wire insulation (24–40%) and circuit board/motor controller resins (1–31%)
- **Amphibole** (crocidolite, amosite) — present in thermal/acoustic insulation (up to 85% amphibole pre-1970) encountered by electricians as bystanders
- Tremolite discussed only as a potential contaminant in a threshold-mechanism discussion, not directly measured

Exposure Concentrations Measured (PCM unless noted)

Source/Activity	Concentration	Exposure Duration
Cutting/stripping wire (personal)	0.006 f/cc	2-hr sample
Cutting/stripping cable (6 samples)	<0.007–0.01 f/cc	8-hr TWA

Source/Activity	Concentration	Exposure Duration
Cable pulling (personal)	0.033–0.104 f/cc	30-min
Cable splicing (personal)	<0.011–0.073 f/cc	20–30 min
Building renovation w/ sprayed fireproofing (Paik et al.)	Geo. mean 0.13 f/cc	Not reported
Simulated cable installation above ceiling (Keyes 1991)	0.13–0.34 f/cc (personal, PCM)	~2.5 hr
Simulated maintenance tasks (Keyes 1994)	0.01–0.25 f/cc	1–3 hr
Office building O&M (Kinney 1994)	Mean 0.0095 f/cc	Area samples
Maintenance (Corn 1994)	Up to 0.0619 f/cc	8-hr TWA
Cable pulling/repair (Mlynarek 1996)	0.0059–0.013 f/cc	8-hr TWA
Grinding resin plaques, 0.8–18% chrysotile (Faulring 1975)	Up to 1.2 f/cc	4–5 min
Sawing/sanding/drilling phenolic material, 31% chrysotile (Mowat 2005)	0.006–0.08 f/cc	8-hr TWA
Power generation electricians, steam turbine work (Felten 2010)	33 f/cc-yr (cumulative)	Career
Power distribution electricians (Felten 2010)	2.8 f/cc-yr (cumulative)	Career
Insulators removing amphibole (comparison)	6.74–3,021 f/cc	Various

OSHA PEL = 0.1 f/cc (current, 8-hr TWA)

Comparison to NOAELs/OELs
The paper cites Pierce et al. (2008), which found "no-effect" cumulative chrysotile exposure levels of approximately **15–500 f/cc-years** for mesothelioma and **25–1,000 f/cc-years** for lung cancer in predominantly chrysotile-exposed cohorts. All reported electrician 8-hr TWA exposures (essentially all <0.1 f/cc, most far lower) and estimated cumulative exposures (e.g., 2.8–33 f/cc-yr for power industry electricians) fall well below these thresholds. The paper also references automobile brake worker cumulative exposures (e.g., 0.16–2.6 f/cc-yr from various studies) as a conservative comparator, noting brake workers have chrysotile exposures higher than most electricians yet are not at increased mesothelioma/lung cancer risk — reinforcing that electricians' chrysotile exposures from electrical products are below any threshold for carcinogenesis.

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23. Jiang et al. (**2008**) — "A study of airborne chrysotile concentrations associated with handling, unpacking, and repacking boxes of automobile clutch discs" Regulatory Toxicology and Pharmacology 51: 87–97

Purpose of the Study
This simulation study characterized worker and bystander airborne asbestos exposures during the handling, unpacking, and repacking of boxes of asbestos-containing (chrysotile) automobile clutch discs (manufactured pre-mid-1980s), a scenario not previously studied

(unlike brake repair/handling, which had been characterized in prior work by the same group). The study also assessed cleanup and clothes-handling exposures, and fiber size/morphology.

Key Conclusions

- Airborne asbestos concentrations increased with the number of boxes unpacked/repacked.
- Repetitive stacking of unopened boxes produced *higher* concentrations than unpacking/repacking, likely due to more frequent box-to-box friction/agitation.
- Cleanup and clothes-handling tasks generated very low, often non-detectable concentrations.
- No amphibole fibers were detected in any of the 24 clutch linings tested (mean chrysotile content 33.7% ± 2.0%, range 20–52%).
- Only ~29% of free asbestos fibers >5 µm were of respirable width (<0.7 µm); very few (3%) of fibers >20 µm were respirable-width, and a substantial fraction of respirable-width fibers were bound in clusters/matrix material (reducing likely biological availability).
- All short-term (15-min, 30-min) and 8-hour TWA exposures were far below historical and current OSHA short-term and 8-hour occupational exposure limits.
- Estimated cumulative lifetime exposures for various worker scenarios (mechanic, counterman, parts picker) were similar to or lower than previously estimated cumulative exposures for brake mechanics — a population not shown to have increased asbestos-related disease risk.

Asbestos Types Studied

- **Chrysotile only** — mean 33.7% ± 2.0% (range 20–52%) by weight in clutch linings (XRD)
- **Amphibole** — none detected in any clutch (PLM, LOD 1%)

Exposure Concentrations Measured (PCM-adjusted, f/cc)

Activity	1st 15-min (worker)	30-min TWA (worker)	8-hr TWA (worker)
Unpack/repack 1 box	0.051	0.026	0.002
Unpack/repack 1 box + dry wipe	0.050	0.027	0.002
Unpack/repack 1 box + spray clean	0.046	0.023	0.001
Unpack/repack 2 boxes	0.196	0.099	0.0062
Continuous box stacking (27 boxes)	0.231	0.212	0.0133
Counter cleanup	0.002	0.002	0.0001
Clothes handling	0.003	0.002	0.0001

Bystander concentrations (5 ft away) were consistently lower (≤0.02 f/cc) and often indistinguishable from background; remote-area and ambient samples were essentially all non-detectable. Current OSHA PEL = 0.1 f/cc (8-hr); OSHA 30-min excursion limit = 1 f/cc; historical 15-min ceiling = 10 f/cc — none were approached in any scenario.

Comparison to NOAELs/OELs

The paper compares its estimated cumulative lifetime exposures to published "no-effect" cumulative chrysotile levels: **25–1,000 f/cc-years for lung cancer** and **15–500 f/cc-years for mesothelioma** (citing Pierce et al., 2008, among others). Example cumulative estimates derived in this paper: a 40-year mechanic performing one clutch change/week = 0.065 f/cc-years; a counterman unpacking/repacking 10 boxes/week for 20 years = 0.62 f/cc-years; a parts picker stacking 200 boxes/week for 5 years = 0.066 f/cc-years. All of these are far below the cited no-effect thresholds and are also comparable to or lower than previously estimated cumulative exposures for brake mechanics (0.41–2.79 f/cc-years), a population with no demonstrated excess asbestos-disease risk — supporting the conclusion that clutch box handling does not pose a meaningful health risk.

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24. Madl et al. (**2008**) — "Exposure to Chrysotile Asbestos Associated with Unpacking and Repacking Boxes of Automobile Brake Pads and Shoes" Annals of Occupational Hygiene 52(6): 463–479

Purpose of the Study

This two-phase simulation study characterized short-term and 8-hour TWA airborne chrysotile exposures for workers (and bystanders) unpacking and repacking boxes of asbestos-containing automobile brake pads (62 boxes) and brake shoes (43 boxes), manufactured before the mid-1970s. The study addressed a scenario — handling *new*, boxed brake components — not covered by prior brake-repair exposure literature, relevant to mechanics, parts-counter staff, and warehouse parts pickers.

Key Conclusions

- Airborne asbestos concentrations increased with the number of boxes handled (strong positive correlation, r = 0.91–0.99 for pads).
- Handling brake **pad** boxes produced 2- to 7-fold higher worker concentrations than handling brake **shoe** boxes (likely due to shoe curvature/packing reducing part-to-part friction).
- Worker breathing-zone concentrations were consistently higher than bystander (1.5 m) concentrations, which were higher than remote-area concentrations.
- Cleanup and clothes-handling tasks produced lower airborne concentrations than active box-handling.
- Fiber size/morphology analysis found only ~30% of fibers were of respirable width (<0.7 µm), and very few (0–7%) were both respirable-width and >20 µm long (the size range considered most disease-relevant); PLM found no amphibole in any brake pad or shoe.
- All calculated 8-hour TWAs remained below the current OSHA PEL of 0.1 f/cc, even for upper-bound scenarios (e.g., 40 boxes/day = 0.063 f/cc).

Asbestos Types Studied

- **Chrysotile only** — average content 27–45% by weight depending on testing phase/event (individual samples 3–60%)
- **Amphibole** — none detected (PLM)

Exposure Concentrations Measured (PCME, f/cc)

Scenario	Worker, 30-min avg	Bystander, 30-min avg
4–20 boxes of brake pads	0.086–0.368	0.004–0.035
4–20 boxes of brake shoes	0.021–0.126	0.002–0.011
Cleanup	0.004	0.002
Clothes handling	0.011	0.010

8-hour TWA estimates: 0.002–0.021 f/cc for handling 4–16 boxes; 0.063 f/cc for an upper-bound 40-boxes/day scenario — all below the OSHA PEL of 0.1 f/cc. OSHA 30-min excursion limit (1 f/cc) and historical 15-min ceiling (10 f/cc) were also not approached in any scenario.

Comparison to NOAELs/OELs
This paper does not present its own cumulative (f/cc-year) exposure estimates or directly compare to published NOAELs/OELs for mesothelioma or lung cancer; its comparisons are limited to historical and current **short-term and 8-hour occupational exposure limits** (OSHA PEL 0.1 f/cc 8-hr; 1 f/cc 30-min excursion; 10 f/cc historical 15-min ceiling), all of which were met. (Note: the companion 2008 clutch-disc paper by Jiang et al., using the same research group/protocol, does extend this type of data to cumulative f/cc-year comparisons against published no-effect thresholds.)

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25. Cattaneo et al. (2012) — "Airborne Concentrations of Chrysotile Asbestos in Serpentine Quarries **and** Stone Processing Facilities in Valmalenco, Italy" Annals of Occupational Hygiene, pp. 1–13

Purpose of the Study
This study quantified airborne chrysotile concentrations arising from the extraction and processing of serpentinite rock (used for building materials — wall coverings, tiles, stove components) at five quarry sites in Valmalenco, Italy, an area with naturally occurring but geologically variable chrysotile contamination. The study also measured ambient/environmental concentrations near quarries, processing facilities, and nearby towns, and developed a TEM-based diameter criterion (0.25 µm cutoff) to distinguish chrysotile fibers from morphologically similar but non-asbestos antigorite fibers (the dominant serpentine mineral in the host rock), to avoid overestimating chrysotile exposure via conventional EDS analysis alone.

Key Conclusions

- The only asbestos type found in Valmalenco was chrysotile; amphibole fibers were never detected.

- Airborne chrysotile contamination was highly **site-dependent**, reflecting variable natural chrysotile vein density across quarries.
- Block cutting with multi-blade/multi-disc cutters and drilling at the most contaminated quarry sites generated the highest exposures, in some cases exceeding the occupational exposure limit (OEL) of 0.1 f/mL.
- Working foliated serpentinites (vs. massive serpentinites) produced airborne concentrations comparable to ambient background levels.
- Only ~8% (7 of 83) of occupational samples exceeded the 0.1 f/mL OEL; most exceedances involved fixed-site (not personal) sampling during indoor multi-blade/multi-disc cutting where workers were not typically present.
- Dry drilling and dry activities generally produced higher concentrations than wet activities.
- Environmental (ambient) concentrations were almost always below the Italian environmental limit (0.002 f/mL), with one exception near a quarry property boundary (attributed to dust from truck traffic, not processing).

Asbestos Types Studied

- **Chrysotile only** — the sole asbestos type identified; distinguished from non-asbestos antigorite fibers via TEM/SAED (chrysotile fibrils mean diameter 0.07 μm; chrysotile bundles mean diameter 0.85 μm; vs. antigorite mean diameter 1.42 μm)
- No amphibole or tremolite detected

Exposure Concentrations Measured (f/mL)

Setting	Mean (SD)	Median	Range
All occupational samples	0.0500 (0.2275)	0.0021	0.00005–1.85
Extraction (quarrying)	0.0265 (0.1184)	0.0023	0.0004–0.753
Processing	0.0971 (0.3333)	0.0047	0.0004–1.85
Ambient (all)	0.0005 (0.0011)	0.0003	0.00005–0.0053
Extraction Site E (most contaminated)	0.4488 (0.677)	0.0375	0.0006–1.85
Multi-blade cutting (highest activity)	0.311 (0.592)	0.0509	0.0004–1.85
Quarry proximity ambient	0.00109 (0.0019)	0.0003	0.00005–0.0053

Occupational exposure limit (ACGIH TLV / OSHA PEL / NIOSH REL) = 0.1 f/mL (8-hr TWA); Italian environmental limit = 0.002 f/mL.

Comparison to NOAELs/OELs

This paper compares measured concentrations only against regulatory **occupational exposure limits** (0.1 f/mL, 8-hr TWA) and the Italian **environmental** limit (0.002 f/mL) — it does not present cumulative (f/cc-year) lifetime exposure estimates or compare directly to published mesothelioma/lung cancer NOAELs (unlike the Goodman, Jiang, or Perry papers). It notes that most measured occupational exposures were below the OEL except for sporadic, localized peak activities (multi-blade/multi-disc cutting, wet/dry drilling at the most heavily mineralized quarry), and recommends site-specific risk management (automation of high-exposure cutting activities, ventilation, wet methods) rather than presenting a cancer-risk

26. McDonald et al. (1980) — "Dust exposure and mortality in chrysotile mining, 1910-75"

British Journal of Industrial Medicine 37: 11-24

Purpose of the Study
This paper reports a further mortality follow-up (to the end of 1975) of a birth cohort of 11,379 workers (10,939 men, 440 women, born 1891–1920) employed for one month or more in the chrysotile mines and mills of Asbestos and Thetford Mines, Quebec. The primary aim, consistent across earlier reports from this long-running research program (begun 1966), was to define as accurately as possible the quantitative relationship between cumulative chrysotile dust exposure and mortality — particularly lung cancer, but also pneumoconiosis, mesothelioma, and other causes of death — using both external-comparison ("man-years") and matched case-control ("Miettinen") methods of cohort analysis.

Key Conclusions

- By the end of 1975, 4,463 men and 84 women had died; overall mortality was modestly elevated (SMR 1.06 for men, 1926–75), with the excess concentrated at the dustier Thetford Mines site (SMR 1.10) versus Asbestos (SMR 1.02).
- Clear, essentially **linear** dose-response relationships were found between accumulated dust exposure (mpcf·y) and total mortality, lung cancer, and pneumoconiosis. The fitted linear model for lung cancer relative risk was: **RR = 1 + 0.0014 (mpcf·y)**.
- Ten men and one woman died of pleural mesothelioma (11 cases total among 11,379 workers); mesothelioma deaths followed a clear exposure-dependent trend, though the paper notes interpretation of this is complex and was reserved for a separate report.
- Lung cancer risk increased with both dust exposure and smoking; the two factors appeared compatible with either an additive or multiplicative interaction model, but were incompatible with a model in which asbestos increases lung cancer risk only in the presence of smoking. Lung cancer occurred in non-smokers as well.
- Analysis of the 1,904 men with ≥20 years' service in the low/medium dust groups (averaging 6.6 mpcf, ~20 fibres/cc — far above modern permissible levels) still showed a statistically significant pneumoconiosis excess, but lung cancer and other cause-specific excesses did not reach conventional significance, illustrating the limits of statistical power even in a very large cohort at exposure levels now considered unacceptable.
- No excess of laryngeal cancer was found, and no relation to dust exposure was found for laryngeal or other abdominal cancers — associations here were with smoking, not dust.
- Findings were interpreted as supporting a linear, no-threshold exposure-response relationship for lung cancer and pneumoconiosis, though the authors caution this does not constitute proof and that extrapolation to low exposures carries inherent uncertainty.

Asbestos Types Studied

- **Chrysotile only** (serpentine). This is a pure chrysotile mining/milling cohort; no amphibole (amosite, crocidolite, tremolite) co-exposure is reported or discussed as present in this workforce.

Exposure Concentrations / Metrics Used
Unlike fiber-concentration air-sampling studies, this paper characterizes lifetime exposure using **accumulated dust exposure**, expressed in millions of particles per cubic foot multiplied by years (**mpcf·y**), derived from over 4,000 midget-impinger dust counts (1949–66) plus historical reconstruction for earlier years.

Exposure category (accumulated to age 45)	% of cohort	Lung cancer SMR	Pneumoconiosis SMR
< 30 mpcf·y	50.2%	0.93	2.98
30 – < 300 mpcf·y	33.9%	1.18	10.81
≥ 300 mpcf·y	15.9%	2.25	54.00

- Mean dust "concentrations" by service/exposure subgroup ranged from **~2.5 mpcf (low)** to **~46.8–82.6 mpcf (very high)** depending on length of service.
- A widely cited conversion at the time (noted in the companion Williams et al. 2007 review) was **~1 mpcf ≈ 6 fibres/cc**, though the authors themselves note the true conversion factor for this cohort may be closer to **1–5 fibres/ml per mpcf** (Gibbs & Lachance).
- For the very heavily exposed long-service subgroup, mean concentrations reached the equivalent of roughly **20 fibres/cc** for men with ≥20 years' service in the "low/medium" exposure bands.

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer
This paper predates the modern NOAEL/OEL framework used in later risk-assessment literature (e.g., Pierce, Beckett, Goodman, Stevens thresholds cited in the Perry et al. 2026 paper) and does not present such comparisons. Instead, it establishes the underlying linear exposure-response slope for lung cancer (RR = 1 + 0.0014 mpcf·y) that later analyses have drawn upon. The authors speculate that dust concentrations in the Quebec mills in the early 1950s (before dust suppression) may have carried a lung cancer risk "equivalent to heavy smoking," whereas at more recent (late-1970s) concentrations of ~1 mpcf, the added risk might approximate less than one cigarette per day — but they emphasize this is speculative given uncertainty in the exposure-response interaction model.

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27. Williams, Phelka & Paustenbach (2007) — "A Review of Historical Exposures to Asbestos Among Skilled Craftsmen (1940–2006)"

Journal of Toxicology and Environmental Health, Part B, 10:319–377

Purpose of the Study
This is a comprehensive literature review and synthesis (not a new exposure measurement study) compiling over 50 published and selected unpublished sources reporting historical airborne asbestos concentrations for 13 skilled craft categories — **insulators, pipefitters, boilermakers, masons, welders, sheet-metal workers, millwrights, electricians, carpenters, painters, laborers, maintenance workers, and abatement workers** — across both shipyard and nonshipyard settings from the 1940s to 2006. The goal was to characterize

typical task-specific airborne fiber (or dust) concentrations for each craft, compare these to occupational exposure limits (OELs) in effect at the time, and provide a resource for reconstructing historical exposures where site-specific data are lacking.

Key Conclusions

- **Insulators** experienced by far the highest exposures among the trades studied — generally 2–10 fibres/cc for task-duration or shift-long samples from the late 1960s/early 1970s in nonshipyard settings, with substantially higher levels (often 10–100+ fibres/cc) during **spraying, cutting/prefabrication with power saws, and removal** activities, particularly in confined shipyard spaces. British naval dockyards showed the most extreme values (up to several hundred fibres/cc) due to routine spray-applied amosite/crocidolite insulation.
- For **most other crafts** (pipefitters, welders, sheet-metal workers, electricians, carpenters, painters, laborers, maintenance/abatement workers), average fiber concentrations typically ranged from **<0.01 to ~1 fibres/cc**, with higher values associated with powered tool use, drywall/joint-compound sanding, and cleanup of insulation debris.
- Improved industrial hygiene practices from the early 1970s onward (respirators, ventilation, better housekeeping) reduced average insulator fiber concentrations roughly **2- to 5-fold**.
- Although many historical measurements exceeded the *current* OSHA PEL of 0.1 fibres/cc, most **did not exceed the OELs in place at the time** they were collected (except during ripout/demolition or spray-application activities in enclosed/onboard-ship spaces).
- Reported fiber concentrations likely **understate actual personal exposure** in some cases, since many samples reflect short-term tasks only and workers sometimes wore respiratory protection.
- Available data could not reliably determine whether measured fibers were serpentine (chrysotile) or amphibole in composition — a major limitation given the markedly different potency of these fiber types for mesothelioma.
- After insulators, **boilermakers** were estimated to be the next most heavily exposed craft in shipyard settings (frequent proximity to insulation removal during boiler repair); **sheet-metal workers, maintenance workers, and electricians** followed at lower but still measurable exposure levels; **welders, masons, and millwrights** generally had minimal direct exposure except via secondary/bystander exposure near insulators.
- "Bystander" (secondary) exposures to nearby trades were generally estimated at no more than **~1/10th** of the primary worker's breathing-zone concentration, though confined shipboard spaces were an exception.

Asbestos Types Studied

- **Chrysotile —** the dominant fiber type in most insulation, gasket, cement, and building products from the early 1920s to mid-1930s, and again from ~1960 onward.
- **Amosite —** extensively used (especially by the U.S. Navy) from the mid-1930s through the Vietnam War era (1940s–mid-1970s), particularly in pipe/block insulation and shipboard products.
- **Crocidolite —** used to a lesser extent, notably in some cement, roofing, gasket, and (in British shipyards) sprayed insulation products from the 1940s–1960s.

- **Tremolite —** mentioned only as a contaminant (e.g., in vermiculite used on some U.S. naval ship hulls, at 1–3%) rather than as a deliberately used product fiber.
- The review's product-composition table (Table 1) documents that many products blended fiber types (e.g., chrysotile/amosite mixes in Kaylo, Unibestos, Maranite, Thermobestos), and that "chrysotile-only" branding sometimes did not reflect actual composition due to cross-contamination during manufacturing.

Exposure Concentrations Measured (by craft, illustrative ranges from the review's tables)

Craft	Typical airborne fiber concentration (fibres/cc)	Notes
Insulators (nonshipyard)	~2–10 (task/shift samples, late 1960s–70s)	Higher (10s–100s) during spraying, cutting, removal
Insulators (shipyard, US)	~2-fold higher than nonshipyard	—
Insulators (British naval dockyard)	7.3–256 (avg.); up to 579 (max)	Sprayed amosite/crocidolite common
Pipefitters	<0.05–0.9 (gasket/packing work)	Markedly lower than insulators
Welders	<0.01–5	Occasional high bystander values
Sheet-metal workers	0.1–0.3 (typical); up to 1.6 (bystander)	—
Electricians	0.001–0.25	—
Carpenters	~0.01–0.35 (nonshipyard); >20 (British construction, board work)	—
Painters	0.08 (typical); 5–10 (drywall sanding)	—
Laborers	0.005–3.4 (cleanup-dependent)	—
Maintenance workers	~0.1–1 (could exceed 10 without controls, per HEI review)	—
Abatement workers	~0.02–1.4 (controlled removal); up to 10–100 without controls	Respirator use reduces personal exposure ~90%

Comparison to NOAELs/OELs for Mesothelioma and Lung Cancer
The review does not evaluate modern NOAEL thresholds (as in the Perry et al. framework) but instead tracks compliance with the **historical OEL trajectory**: ACGIH's first limit of 5 mppcf (1946, ≈30 fibres/cc), OSHA's 12 fibres/cc (1971), 5 fibres/cc (1972), 2 fibres/cc (1976), 0.2 fibres/cc (1986), and the current 0.1 fibres/cc (1994) — roughly a 100-fold tightening from the 1970s to 1990s. The authors show (Figure 2) that the large majority of average insulator task concentrations from the 1960s–70s fell **below the contemporaneous OEL in effect at the time**, even though most would exceed today's 0.1 fibres/cc PEL. Only a minority of studied data sets (about 12 of 60+) exceeded the 8-hour TWA OEL applicable when the measurements were collected.

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APPENDIX B

Synthesis of 26 chrysotile exposure studies

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26 chrysotile exposure studies

Chrysotile Asbestos Exposure by Product / Use Category — Synthesis of 26 Published Studies

This synthesis groups the 26 reviewed publications by product type or exposure scenario, reports the chrysotile concentrations measured in each, and — where the source paper made one — states how those concentrations compare to published no-observed-adverse-effect levels (NOAELs) or occupational exposure limits (OELs) for lung cancer and mesothelioma. Every figure below is drawn directly from, and attributed to, the individual article summary of record.

Overall Pattern

Across nearly all product- and task-based studies in this set (as opposed to the historical mining/milling and manufacturing cohorts, discussed separately below), measured chrysotile concentrations and — where calculable — cumulative lifetime (f/cc-year) exposures fell well below every published no-effect benchmark for chrysotile-related lung cancer or mesothelioma, typically by one to three orders of magnitude. The main exceptions are (a) historical mining, milling, and asbestos-cement manufacturing operations, particularly pre-1980s, where measured concentrations and cumulative exposures directly approached or exceeded modern thresholds; and (b) currently operating chrysotile-processing facilities in lower/middle-income countries (Kyrgyzstan), where present-day exposures still exceed regulatory OELs.

Published No-Effect / Threshold Benchmarks Cited Across the Literature

Several of the reviewed articles function primarily as sources of the comparison benchmarks used elsewhere in this set. These are consolidated here for reference.

Source	Chrysotile Threshold (cumulative, f/cc-years)	Notes
Pierce et al. 2016 / 2008	Lung cancer NOAEL 89–168 (2016) / 25–1,000 (2008); mesothelioma NOAEL 208–415 (2016) / 15–500 (2008)	Cited repeatedly as the primary regulatory-style benchmark (Perry 2026, Ierardi 2021, Jiang 2008, Goodman 2013)
Beckett et al. 2023	250–379 (chrysotile), protective against 1-in-1000 mesothelioma risk	Cited in Perry 2026 and Goodman/Korchevskiy/Wylie 2025
Goodman, Korchevskiy & Wylie 2025	~90 (central tendency; range 25.6–162, non-textile chrysotile)	Derived via Monte Carlo, intensity-duration/Peto, and filter models
Stevens et al. 2025	10 (textile) / 100 (non-textile chrysotile); OELs 0.2 / 2 f/cc	Cited in Perry 2026
Case, Korchevskiy & Korchevskiy 2025	35.9–65.9 (statistical threshold); 18–50 (lowest confirmed meso case, Québec cohort)	Re-derivation from Québec miners/millers cohort (Dagbert dataset)
Goodman et al. 2025 (Frontiers)	~100–148.8 (Québec cohort re-analysis, chrysotile-lung-burden subset)	Conference synthesis (Monticello III)
Finley et al. 2012 / 2018 corrigendum	Tremolite (not chrysotile): NOAEL 0.5–2.6; LOAEL 35–73	Relevant where tremolite is a chrysotile-ore contaminant

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1. Mining, Milling & Quarrying

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Comparison to No-Effect Level / Benchmark
Murphy et al. 2020 — Baie Verte, Canada	Chrysotile mine/mill, job-exposure matrix (1963–1994)	6–42 f/mL by department (1963–75 era); declined to <1 f/mL by 1990s; peak dept. avg. 66.55 f/mL (1968)	No cumulative f/cc-yr or NOAEL comparison presented (JEM validation study only)
Silvestri et al. 2020 — Balangero, Italy	Chrysotile mine/mill (1917–1990)	~1–250 f/mL by work area/era (beneficiation highest); median cumulative 106.7 f/mL-yr; 13.3% of cohort >1,000 f/mL-yr	No NOAEL comparison presented (exposure-reconstruction methodology paper)
McDonald et al. 1980 — Québec mining cohort	Chrysotile mine/mill (1910–75 birth cohort, n=11,379)	Dust metric (mpcf·y); mean subgroup concentrations ~2.5–82.6 mpcf; long-service subgroup ≈20 f/cc-equivalent	Predates modern NOAEL framework; established linear dose-response RR = 1 + 0.0014(mpcf·y) used by later papers
Case, Korchevskiy & Korchevskiy 2025 — Québec cohort re-derivation	Re-analysis of same Québec miners/millers cohort	Average cumulative cohort exposure 528.5–979.3 f/cc-years (two conversion methods)	Derived a statistical threshold of 35.9–65.9 f/cc-yr; lowest confirmed mesothelioma case at 18–50 f/cc-yr
Cattaneo et al. 2012 — Valmalenco serpentine quarries, Italy	Serpentinite (building stone) extraction/processing; naturally occurring chrysotile	0.00005–1.85 f/mL (occupational); mean 0.05 f/mL; only 8% of samples exceeded OEL	Compared only to OEL (0.1 f/mL, 8% exceeded) and Italian environmental limit (0.002 f/mL); no cumulative/NOAEL comparison

Murphy et al. 2020 illustrates the marked reduction in exposure concentrations in mining that cured in the mid-1970s – see Appendix 1 for the implication for asbestos cohort studies.

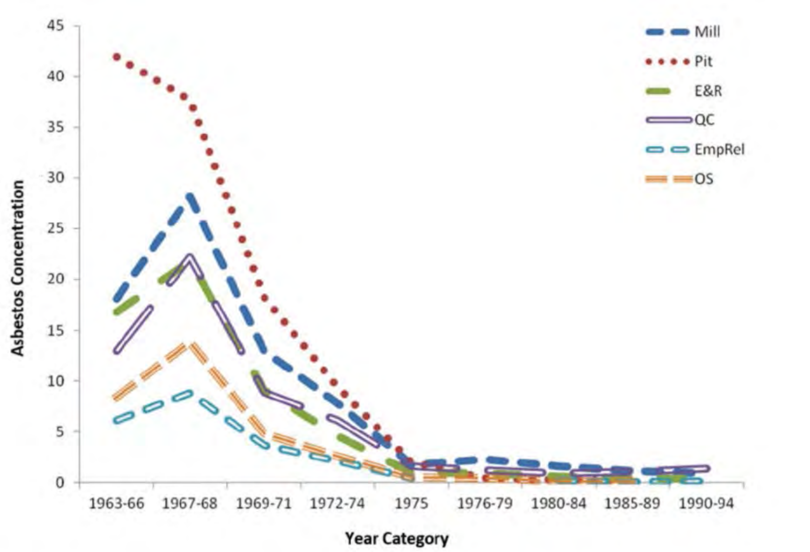

Figure 3. Yearly average concentrations of asbestos fibres, 1963–1994, in the various departments of the Baie Verte mine/mill complex.

2. Asbestos-Cement Manufacturing

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
Mutetwa et al. 2022 — Zimbabwe A/C factories JEM	Asbestos-cement manufacturing (Harare & Bulawayo, 1996–2020)	0.10–0.19 f/mL annual means by job/period; amphiboles (tremolite, crocidolite, actinolite) detected as raw-material contaminants	Compared only to OEL of 0.1 f/mL (exceeded in nearly all job/period combinations except 2009–2016/2020); no NOAEL comparison	This paper presents only annual mean concentrations, not a cumulative (f/cc-yr) estimate, so it cannot be compared directly. Using the companion Mutetwa et al. (2023) cumulative estimate from the same JEM (1.0–4.8 f/cc-yr, 25-yr career): 19- to 415-fold below Pierce (2016); 52- to 379-fold below Beckett (2023); 19- to 90-fold below Goodman (2025); 21- to 100-fold below Stevens (2025, non-textile).
Mutetwa, Moyo & Brouwer 2021 — Zimbabwe A/C factories, trends	Same two factories, 1996–2016 trend analysis	0.03–0.18 f/mL by period; ~60% decline 1996→2016	Compared only to OEL of 0.1 f/mL (58–60% of all measurements exceeded it); no cumulative/NOAEL comparison	No cumulative estimate is presented in this paper. Applying the same companion Mutetwa et al. (2023) cumulative range (1.0–4.8 f/cc-yr) for these factories, exposure would fall far below all four thresholds by the margins above; since these concentrations run generally lower than the 2022 JEM figures, the true margin is likely larger still.
Mutetwa et al. 2023 — Zimbabwe A/C factories, ARD prediction	Same factories; OSHA linear risk model applied to JEM	0.04–0.19 f/mL mean by job/period; cumulative 1.0–4.8 f/mL-years (25-yr exposure)	Predicted 2.89–4.63 excess cancer deaths/1,000 workers vs. OSHA "significant risk" benchmark of 1/1,000 (and Netherlands/Germany's 4/1,000); no external NOAEL cited	Far below all four thresholds: 19- to 415-fold below Pierce (2016, 89–415 f/cc-yr); 52- to 379-fold below Beckett (2023, 250–379 f/cc-yr); 19- to 90-fold below Goodman (2025, 90 f/cc-yr); 21- to 100-fold below Stevens (2025, 100 f/cc-yr non-textile).
Kurzhunbaeva et al. 2024 — Kyrgyzstan A/C factory (current operation)	Active asbestos-cement manufacturing (loading, mixing, cutting)	Geometric means 0.91–4.7 ff/mL by task; individual samples up to 12.5 ff/mL	All tasks exceeded the current EU OELV of 0.1 ff/mL by 9- to 47-fold; would far exceed EU's forthcoming 0.01/0.002 ff/mL limits; no NOAEL/cumulative comparison — described as comparable to 1970s pre-regulation Italy	No cumulative estimate is presented. For illustration only, a 25-year career at these GM task concentrations would give ~23–118 f/cc-yr: the low end sits below all four thresholds, but the high end (cutting/sawmill, GM 4.7 ff/mL) would meet or exceed Goodman (2025, 90 f/cc-yr) and Stevens (2025, 100 f/cc-yr), and fall within

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
				Pierce's (2016) 89–168 f/cc-yr lung-cancer NOAEL range, though still below Pierce's mesothelioma NOAEL and Beckett (2023).

3. Cement Pipe Cutting

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
Perry, Kissell & Paustenbach 2026	Cutting asbestos-cement pipe with a powered (chopsaw) saw; 25–30% chrysotile, 10–15% crocidolite pipe	0.59–9.33 f/cc (30-min chrysotile, above-ground vs. in-trench); cumulative 0.061–0.98 f/cc-yr chrysotile	Chrysotile cumulative exposure 60- to 390-fold below Pierce (2016), Beckett (2023), Goodman (2025) and Stevens (2025) NOAELs; crocidolite closer to (but below) thresholds, 2- to 8-fold margin	Far below all four thresholds: 91- to 6,803-fold below Pierce (2016, 89–415 f/cc-yr); 255- to 6,213-fold below Beckett (2023, 250–379 f/cc-yr); 92- to 1,475-fold below Goodman (2025, 90 f/cc-yr); 102- to 1,639-fold below Stevens (2025, 100 f/cc-yr non-textile). (Crocidolite exposure, 0.023–0.13 f/cc-yr, is not evaluated against these four chrysotile-specific benchmarks.)

4. Automotive Friction Products (Brakes, Clutches, Exhaust)

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
Paustenbach et al. 2006 — Exhaust system removal	Muffler/exhaust gasket removal by mechanics (ca. 1945–1975 vehicles)	8-hr TWA 0.006–0.01 f/cc (mechanics); 0.003–0.005 f/cc (bystanders)	~10-fold below OSHA PEL (0.1 f/cc); no cumulative f/cc-yr or NOAEL comparison presented	No cumulative estimate is presented in this paper. For illustration only, a 30-year mechanic career at these TWAs would give ~0.18–0.3 f/cc-yr — roughly 300- to over 2,300-fold below all four thresholds (Pierce 2016, Beckett 2023, Goodman 2025, Stevens 2025).
Jiang et al. 2008 — Clutch disc box handling	Unpacking/repacking/handling boxed chrysotile clutch discs (20–52% chrysotile)	8-hr TWA 0.0001–0.0133 f/cc; cumulative estimates 0.065–0.62 f/cc-yr depending on worker scenario	Far below Pierce (2008) no-effect levels (15–500 mesothelioma / 25–1,000 lung cancer f/cc-yr); comparable to or below brake-mechanic cumulative exposures	Far below all four thresholds: 144- to 6,385-fold below Pierce (2016); 403- to 5,831-fold below Beckett (2023); 145- to 1,385-fold below Goodman (2025); 161-

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
			(0.41–2.79 f/cc-yr), a group with no demonstrated excess risk	to 1,538-fold below Stevens (2025, non-textile).
Madl et al. 2008 — Brake pad/shoe box handling	Unpacking/repacking boxed brake pads (27–45% chrysotile) and shoes	30-min worker 0.021–0.368 f/cc; 8-hr TWA 0.002–0.063 f/cc (up to 40 boxes/day upper bound)	Compared only to OSHA PEL (0.1 f/cc, not exceeded) and excursion/ceiling limits; no cumulative or NOAEL comparison presented in this paper	No cumulative estimate is presented in this paper. For illustration only, a 35-year mechanic career at these TWAs would give ~0.07–2.2 f/cc-yr — roughly 40-fold below Goodman (2025, 90 f/cc-yr) at the upper-bound TWA, to well over 1,000-fold below all four thresholds at the lower-bound TWA.
Goodman et al. 2013 — Electricians (brake-worker comparator)	Cites brake-mechanic literature as a conservative comparator for electricians' chrysotile exposure	Brake-worker cumulative exposures cited: 0.16–2.6 f/cc-yr across various studies	Brake workers (higher chrysotile exposure than most electricians) show no increased mesothelioma/lung cancer risk — used as supporting evidence, not a formal NOAEL	Below all four thresholds across the full cited range: 34- to 2,594-fold below Pierce (2016); 96- to 2,369-fold below Beckett (2023); 35- to 563-fold below Goodman (2025); 38- to 625-fold below Stevens (2025, non-textile).
Bernstein 2022 — Short-fiber chrysotile/amphibole review	Literature review incl. brake-dust inhalation toxicology and brake-mechanic epidemiology	No new field data; cites experimental chrysotile brake-dust concentrations of 0.20–0.67 mg/m³ (36–78 fibers/cm³) in toxicology studies	Meta-analysis of brake mechanics found no increased mesothelioma risk (summary relative risk estimate 0.64, 95% CI 0.38–1.09); supports a threshold/no-effect interpretation for short chrysotile fibers generally	This review reports experimental (mg/m³) and relative-risk data, not cumulative f/cc-year exposures, so a numeric comparison to these four thresholds isn't possible. Its no-elevated-risk finding for brake mechanics (SRRE 0.64) is qualitatively consistent with the wide margins found for brake-related work elsewhere in this table (Jiang 2008, Goodman 2013).
Sahmel et al. 2014 — Take-home from contaminated clothing	Handling/shake-out of chrysotile-contaminated work clothing (para-occupational)	8-hr TWA take-home 0.0004–0.0040 f/cc (personal), 0.0002–0.0007 f/cc (bystander); cumulative lifetime	Below or consistent with estimated lifetime ambient/background chrysotile dose (0.0035–0.105 f/cc-yr) and far below brake-mechanic	Far below all four thresholds by several orders of magnitude: ~18,900- to 943,000-fold below Pierce (2016); ~53,000- to 861,000-fold below

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
		dose 0.00044–0.0047 f/cc-yr (handler)	cumulative dose (1.96–2.79 f/cc-yr, no excess risk)	Beckett (2023); ~19,000- to 205,000-fold below Goodman (2025); ~21,000- to 227,000-fold below Stevens (2025, non-textile).

5. Industrial Maintenance & Trades (Valve Packing, Drilling Fluids, Electrical, Skilled Crafts)

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
Louie et al. 2025 — Valve packing replacement	Removal/replacement of chrysotile valve packing (20.9–62.8% chrysotile) during repair/overhaul	PCM-equivalent chrysotile 0.0011–0.0378 f/cc across tasks; upper-bound continuous-replacement scenario highest	Below OSHA 8-hr PEL (0.1 f/cc) and 30-min excursion limit (1 f/cc) in all scenarios; no cumulative/NOAEL comparison presented	No cumulative (f/cc-yr) estimate is presented — the paper's data are discrete task/event measurements with no assumed annual work frequency from which a cumulative dose could be derived, so a direct comparison to these four thresholds is not possible from the source data.
Anderson et al. 2024 — Drilling mud additives	Handling chrysotile drilling-mud additive (DMA) on oil/gas rigs (1972–1985)	8-hr TWA chrysotile: AM 0.1 f/cc, GM 0.049 f/cc	Compared only to historical OSHA PELs in effect at the time (12 → 0.2 f/cc); below all of them, including the strictest (1986) standard; no modern NOAEL comparison	No cumulative estimate is presented in this paper. For illustration only, a 20-year rig-worker career at these TWAs would give ~1.0–2.0 f/cc-yr — far below all four thresholds, from ~45-fold below Goodman (2025, 90 f/cc-yr) to over 400-fold below Beckett (2023, 250–379 f/cc-yr) at the lower exposure estimate.
Goodman et al. 2013 — Electricians and electrical products	Grinding/drilling/handling chrysotile-containing wire insulation, circuit boards, motor controllers (24–40% and 1–31% chrysotile)	8-hr TWA essentially all <0.1 f/cc (most far lower); cumulative 2.8–33 f/cc-yr for power-industry electricians	Far below Pierce (2008) no-effect levels (15–500 mesothelioma / 25–1,000 lung cancer f/cc-yr)	Below all four thresholds, but with the narrowest margin found anywhere in this synthesis at the top of the cited range (steam-turbine electricians, 33 f/cc-yr): only ~2.7-fold below Pierce (2016, 89 f/cc-yr) and Goodman (2025, 90 f/cc-yr). At the lower end (power-distribution electricians, 2.8 f/cc-yr), the margin widens to ~135- to 148-fold below Beckett (2023) and Pierce's

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
				mesothelioma NOAEL (415 f/cc-yr).
Williams, Phelka & Paustenbach 2007 — Skilled craftsmen review (1940–2006)	Literature synthesis across 13 trades (insulators, pipefitters, boilermakers, electricians, carpenters, etc.); mixed chrysotile/amosite/crocidolite products	Chrysotile-predominant trades typically <0.01–1 f/cc; insulators (often amosite/crocidolite-heavy) far higher, 2–10 f/cc typical, 10s–100s f/cc during spraying/removal	Compared to the historical OEL trajectory (5 mppcf in 1946 → 0.1 f/cc in 1994) rather than modern NOAELs; most historical task averages were below the OEL in effect at the time, though many would exceed today's 0.1 f/cc PEL	This review reports task-level, not cumulative, concentrations across mixed fiber types and does not itself calculate cumulative exposure, so a direct comparison isn't possible from the source data. For illustration only, chrysotile-predominant trades (<0.01–1 f/cc) over a 30–40-year career would give ~0.3–40 f/cc-yr — likely below Goodman (2025, 90 f/cc-yr) and Stevens (2025, 100 f/cc-yr) for most trades, though sustained high-task exposures could approach them. These four chrysotile-specific benchmarks do not directly apply to insulators, whose exposure here is predominantly amosite/crocidolite, not chrysotile.

6. Dental Products

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
Ierardi et al. 2021	Chrysotile-containing casting ring liner (CRL, 40–95% chrysotile) and periodontal dressing powder (3–14.29% chrysotile)	CRL personal 8-hr TWA up to 0.022 f/cc; PDP mixing entirely non-detectable	Highest cumulative exposure (dentists, CRL, 15.1-yr career): 0.33 f/cc-yr — far below Pierce (2016) NOAELs of 89–168 (lung cancer) and 208–415 (mesothelioma) f/cc-yr	Far below all four thresholds across the reported cumulative-exposure range (0.12–0.33 f/cc-yr by profession): 270- to 3,458-fold below Pierce (2016); 758- to 3,158-fold below Beckett (2023); 273- to 750-fold below Goodman (2025); 303- to 833-fold below Stevens (2025, non-textile).

7. Textile Manufacturing

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
Green et al. 1997 — Charleston, SC chrysotile textile plant	Chrysotile textile manufacturing (1896–1975+); tremolite present as ore contaminant	Cumulative exposure expressed in fibre-years: median 30.2 (range 0.1–370)	No modern NOAEL cited (predates that literature); paper's own finding: asbestosis (grade 2+) consistently appeared above ~20 fibre-years cumulative exposure	Note: exposure here is expressed in fibre-years (fibres >5 µm/ml × years), a related but not strictly identical metric to the f/cc-years used below, so this comparison is approximate. As a textile cohort, Stevens' (2025) applicable value is its textile-specific threshold (10 f/cc-yr), not the 100 f/cc-yr non-textile figure used elsewhere in this table. Median cohort exposure (30.2) is below Pierce (2016, 89–415), Beckett (2023, 250–379), and Goodman (2025, 90), but exceeds Stevens' textile threshold (10) by ~3-fold — meaning roughly half the cohort exceeded it. At the upper end of the range (370), exposure exceeds all four: ~2–4-fold above Pierce's lung-cancer NOAEL and Goodman (2025), at or above Beckett (2023) and Pierce's mesothelioma NOAEL, and ~37-fold above Stevens' textile threshold — consistent with the elevated fibrosis and lung cancer this paper documents in the cohort.

8. Meta-Analyses & Threshold-Modeling Studies (Not Product-Specific)

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
Goodman, Korchevskiy & Wylie 2025	Statistical/theoretical threshold modeling across chrysotile and amphibole cohorts	Model inputs drawn from existing cohorts (e.g., Québec 600 f/cc-yr, Balangero 700–721 f/cc-yr, Qinghai 120 f/cc-yr)	Derived non-textile chrysotile threshold ≈90 f/cc-yr (range 25.6–162), generally consistent with or below Beckett (2023) and Pierce (2016) ranges	This paper is itself the source of the "Goodman (2025)" benchmark (≈90 f/cc-yr) used throughout this table, so it cannot be compared against itself. Its own derived range (25.6–162 f/cc-yr) brackets Pierce's (2016) lung-cancer NOAEL (89–168) and sits below Pierce's mesothelioma NOAEL (208–415) and Beckett (2023, 250–379) — broadly consistent with, and

Source (Article)	Product / Exposure Scenario	Chrysotile Concentration Measured	Results as presented in the publication	Comparison to No-Effect Level / Benchmark
				somewhat more conservative than, both.
Goodman et al. 2025 (Frontiers in Epidemiology)	Conference synthesis (Monticello III) on threshold biology and Québec cohort re-analysis	Québec cohort ~500–600 f/cc-yr average; 23 confirmed mesothelioma cases averaged >1,000 f/cc-yr (lowest case 135.7)	Minimal mesothelioma risk suggested below ~100 f/cc-yr chrysotile-equivalent cumulative exposure	The cohort's own findings exceed all four thresholds: average cumulative exposure (~500–600 f/cc-yr) is ~1.3- to 6.7-fold above Pierce (2016, 89–415) and Beckett (2023, 250–379), and ~5.6- to 6.7-fold above Goodman (2025, 90) and Stevens (2025, 100 non-textile). The lowest individual confirmed mesothelioma case (135.7 f/cc-yr) already exceeds Goodman (2025) and Stevens (2025). This is expected, since these are the exposures associated with confirmed disease in the source cohort; the paper's own derived practical threshold (~100–148.8 f/cc-yr) sits close to Goodman (2025)/Stevens (2025) but below Pierce's mesothelioma NOAEL and Beckett (2023).
Goodman et al. 1999 — Meta-analysis of 69 cohorts	Cross-cohort meta-analysis (mixed fiber types, not chrysotile-specific)	No direct f/cc data; exposure proxied by proportionate mesothelioma mortality (tertiles)	No NOAEL derived; established that lung-cancer risk (pooled meta-SMR 163) scales with a mesothelioma-mortality dose proxy (r=0.591, p<0.001)	This meta-analysis does not report chrysotile concentrations or cumulative exposures in f/cc or f/cc-year terms — exposure is proxied by proportionate mesothelioma mortality — so a numerical comparison to these four thresholds is not possible from the source data.
Finley et al. 2012 / 2018 corrigendum	Tremolite exposure via chrysotile-, talc-, and vermiculite-containing consumer products	Product-use tremolite-equivalent cumulative exposures: 0.0002–0.034 f/cc-yr (auto mechanics, joint compound, garden products, attic insulation)	All estimates several orders of magnitude below the paper's own derived tremolite NOAEL (0.5–2.6 f/cc-yr) and LOAEL (35–73 f/cc-yr)	These four benchmarks are chrysotile-specific and don't directly apply to this paper's tremolite findings. Against the paper's own tremolite-specific benchmarks (NOAEL 0.5–2.6 f/cc-yr; LOAEL 35–73 f/cc-yr), all product-use estimates (0.0002–0.034 f/cc-yr) remained several orders of magnitude below.

Summary Observations

- Modern task- and product-based chrysotile exposures (pipe cutting, automotive friction products, valve packing, drilling fluids, dental products, electrical products) are consistently reported at cumulative exposures 1–3 orders of magnitude below every published NOAEL/threshold benchmark, regardless of which benchmark set (Pierce, Beckett, Goodman/Korchevskiy/Wylie, Stevens) is applied.
- Historical mining, milling, and asbestos-cement manufacturing operations — particularly pre-1980s — are the clear exception: measured concentrations (tens to hundreds of f/mL) and cumulative exposures (Balangero median 106.7 f/mL-yr; Québec cohort average 528–979 f/cc-yr) fall within or above the range associated with elevated disease risk in the same literature.
- Crocidolite exposure during pipe cutting (Perry et al. 2026) was the one product-specific scenario in this set where measured exposures approached (though did not exceed) proposed no-effect thresholds — a narrower margin than any of the chrysotile-only findings.
- A currently operating chrysotile-cement facility in Kyrgyzstan (Kurzhunbaeva et al. 2024) reports exposures comparable to 1970s-era Western manufacturing, though that paper did not calculate cumulative lifetime exposure or compare against mesothelioma/lung-cancer NOAELs directly.
- Several papers (Bernstein 2022; Goodman et al. 2013; Sahmel et al. 2014; Jiang et al. 2008) draw on brake-mechanic epidemiology — a well-studied population with measurable but modest chrysotile exposure and no demonstrated excess mesothelioma/lung cancer risk — as a real-world benchmark supporting the plausibility of a threshold, complementing the purely statistical/modeled thresholds derived elsewhere in the set.
- As presented in Appendix 1, the 17 cohort studies included by Hodgson & Darton, 2000 are all based on a time period where exposure concentrations were relatively uncontrolled. This is in comparison to current use today as presented above where potential exposure concentrations are orders of magnitude lower.

No-Effect Level / Benchmark

The No-Effect Level / Benchmark is based on four NOAEL/OEL benchmarks described by Perry et al. (2026) using as the basis the potency factors derived from:

- Hodgson & Darnton (2000) estimated lung cancer risk differentials of 1:10 to 1:50 between chrysotile and amphiboles.
- Berman & Crump (2008) calculated the mesothelioma potency of chrysotile to be ~1/200th that of amphiboles.
- Darnton (2023) updated the Hodgson & Darnton (2000) cohort data and confirmed similarly large fiber-type differences.

The four NOAEL/OEL sources

1. Pierce et al. (2016) — the primary/original NOAEL source

Conducted a comprehensive review of exposure–response data from cohorts predominantly exposed to chrysotile. Derived:

- Chrysotile lung cancer NOAEL: 89–168 f/cc-years
- Chrysotile mesothelioma NOAEL: 208–415 f/cc-years
- Using the Hodgson & Darnton (2000) and Berman & Crump (2008) potency factors, they additionally back-calculated:

combined crocidolite/amosite lung cancer NOAEL of 2–17 f/cc-years, and a crocidolite-specific mesothelioma NOAEL of 0.4–0.8 f/cc-years.

Reference: Pierce JS, Ruestow PS, Finley BL. 2016. An updated evaluation of reported no-observed adverse effect levels for chrysotile asbestos for lung cancer and mesothelioma. Crit Rev Toxicol. 46(7):561–586.

2. Beckett et al. (2023) — updated/revised NOAELs

Concluded the following cumulative exposures are sufficient to protect against a 1-in-1000 excess mesothelioma risk:

- Crocidolite: 0.6–1 f/cc-years
- Amosite: 2–5 f/cc-years
- Chrysotile: 250–379 f/cc-years

Reference: Beckett EM et al. 2023. An updated evaluation of reported no-observed adverse effect levels for chrysotile, amosite, and crocidolite asbestos for lung cancer and mesothelioma. Crit Rev Toxicol. 53(10):611–657.

3. Goodman, Korchevskiy & Wylie (2025) — more conservative modeled thresholds

Suggested tighter cumulative exposures:
- Crocidolite: 0.25 f/cc-years
- Amosite: 1 f/cc-years
- Non-textile chrysotile: 90 f/cc-years

Perry et al. note these values are "quite similar" to Stevens et al. (2025), below.
Reference: Goodman JE, Korchevskiy A, Wylie AG. 2025. Comparison of various methodological approaches to model asbestos thresholds for mesothelioma. Front Public Health. 13:1569343.
4. Stevens et al. (2025) — the most recent, and the only one distinguishing textile vs. non-textile chrysotile
Applied a benchmark dose approach to 14 epidemiological studies to propose cumulative lifetime exposures satisfying a theoretical 1-in-1000 mesothelioma risk (pleural + peritoneal combined):
- Crocidolite: 0.3 f/cc-years → OEL 0.01 f/cc
- Amosite: 2 f/cc-years → OEL 0.05 f/cc
- Textile chrysotile: 10 f/cc-years → OEL 0.2 f/cc
- Non-textile chrysotile: 100 f/cc-years → OEL 2 f/cc

Reference: Stevens ME, Paustenbach DJ, Korchevskiy A. 2025. Exposure-response analysis of recent epidemiological data: proposed risk based occupational exposure limits for various mineral types of asbestos. Chem Biol Interact. 419:111645.
These were pooled to obtain NOAEL ranges as a single comparison band for cohorts exposed to:
- predominantly chrysotile and estimated no-observed- adverse-effect levels (NOAELs) of 89–168 f/cc-years for chrysotile-related lung cancer and 208–415 f/cc- years for mesothelioma.
- NOAELs of 2–17 f/cc-years were estimated for lung cancer associated with combined crocidolite and amosite exposures, and 0.4–0.8 f/cc-years for mesothelioma associated specifically with crocidolite.

Reference List — Chrysotile Asbestos Exposure by Product/Use Category

Full citations for the studies referenced in the “Chrysotile Asbestos Exposure by Product/Use Category” synthesis document (which states it draws on 26 reviewed publications). This list totals 29 citations because a few of those publications have companion or corrigendum entries cited alongside them (Pierce et al. 2008 and 2016, two related benchmark papers; the Finley et al. 2012 tremolite paper and its 2018 corrigendum; and three separate Mutetwa et al. papers on the Zimbabwe cohort).

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Appendix 1

Calendar-Year Ranges of Worker Exposure from the 17 cohort studies included by Hodgson & Darton, 2000

The following table summarizes for the 17 cohort studies included by Hodgson & Darton, 2000 the study reference, the type of cohort, the asbestos fiber types and most importantly the exposure / employment years of the cohort population. All studies are based on a time period where exposure concentrations were relatively uncontrolled.   This is in comparison to current use today as presented above where potential exposure concentrations are orders of magnitude lower.

Exposure/employment years for cohorts in the reviewed asbestos epidemiology publications.

Publication	Cohort	Fiber type(s)	Exposure / employment years
Albin et al. 1990a	Swedish asbestos-cement plant (Lomma)	>95% chrysotile; crocidolite (≤3–4% of use, mainly pre-1966, sheets only); amosite (≤18%, briefly in 1950s)	1907–1977
de Klerk et al. 1994	Wittenoom crocidolite miners/millers, W. Australia	Crocidolite only	1943–1966
Dement et al. 1994	Charleston, SC chrysotile textile plant	Chrysotile (predominant, from Quebec/British Columbia/Rhodesia); crocidolite yarn in small quantities, 1950s–1975 (~2,000 lb/yr vs. 6–8 million lb/yr chrysotile), never carded, spun, or twisted	1940–1965 (hire window); follow-up extended to 1990
Enterline et al. 1987	US asbestos manufacturing retirees (multi-plant)	*Amosite, chrysotile, and crocidolite (multi-plant cohort; not broken down by plant in the paper's own text — drawn from a secondary source)*	Retired 1941–1967 (not a hire window); avg. career 25 yrs (range 3–51 yrs), so exposure likely began as early as the 1890s–1900s for some
Finkelstein 1984	Ontario asbestos-cement factory (Scarborough)	Board operation (1955–1970): chrysotile only. Pipe operation: chrysotile and crocidolite	1948–1960 (plant began production 1948; primary cohort restricted to workers hired before 1960 with ≥1 yr employment; follow-up to 1977/1981)
Hughes et al. 1987	New Orleans asbestos-cement plants (2)	Plant 1: chrysotile (primary) + small amosite (corrugated siding) + crocidolite occasionally from 1962. Plant 2: chrysotile + crocidolite	Plant 1: 1942–1969; Plant 2: 1937–1969 (both plants opened in the 1920s; small “early worker” survivor subgroups employed before 1942/1937 respectively;

Publication	Cohort	Fiber type(s)	Exposure / employment years
		(steady, pipe production from 1946); amosite never used	pipe production/crocidolite use at Plant 2 began 1946; follow-up to 1982)
Liddell et al. 1997	Quebec chrysotile miners/millers	Chrysotile only	Cohort defined by birth years 1891–1920; followed from first employment (earliest 1904) to 1992
McDonald et al. 1983 (BJIM 40:361–367)	South Carolina chrysotile textile plant	Chrysotile (sole type for main products); crocidolite yarn briefly (early 1950s–1972, one location only); amosite used experimentally in carding in the late 1950s but soon abandoned	1938–1958
McDonald et al. 1983 (BJIM 39:368–374)	Pennsylvania chrysotile/amosite/crocidolite textile plant	Chrysotile (main); crocidolite and amosite also used from 1924 (insulation blankets, packings, filter materials); amosite peaked at 600 tons in 1943	1938–1959
McDonald et al. 1984 (BJIM 41:151–157)	Connecticut chrysotile friction-products plant	Chrysotile only; some anthophyllite added from 1957 (paper discs/bands); ~400 lb crocidolite handled experimentally 1964–1972 only	1938–1958
Neuberger & Kundi 1990	Austrian asbestos-cement industry (Vöcklabruck)	*Not stated in the available abstract/extract; asbestos-cement plants of this era were typically predominantly chrysotile, but this is not independently confirmed for this specific paper*	1950–1981
Newhouse & Sullivan 1989	Ferodo (UK) friction-materials factory	Chrysotile throughout; crocidolite used only on one particular contract, in two short periods before 1944	1941–1979
Peto et al. 1985	Rochdale (England) asbestos textile factory	Chrysotile throughout; crocidolite (~15% of use) between 1932 and 1968	Principal cohort: 1933–1974 (3,211 men); plus 145 men first employed before 1933 with 20+ yrs service (exact start year not stated); followed to 30 June 1983
Piolatto et al. 1990	Balangero chrysotile mine, Italy	Chrysotile (mine ore also contains balangeroite, a related non-asbestiform fibrous mineral)	1946–1987
Seidman & Selikoff 1990	US/Canada asbestos insulation workers (union)	*Not fiber-specific in this paper — insulation trades of this era typically involved amosite, chrysotile, and crocidolite in varying combinations*	Cohort = union members enrolled 1/1/1967; individual work start varies (some already 20+ yrs by 1967, i.e., began before ≈1947); mortality tracked 1967–1976 and 1977–1986

Publication	Cohort	Fiber type(s)	Exposure / employment years
Seidman et al. 1986	Paterson, NJ amosite insulation factory (wartime)	Amosite only	Hired 1941–1945; factory operated until 1954, so some workers' employment extended to 1954
Sluis-Cremer et al. 1992	South African amphibole miners	Three subcohorts: amosite only (3,212 men); crocidolite only (3,430 men); both amosite and crocidolite ("mixed," 675 men)	First asbestos exposure ranged from as early as 1925 through 1980 (personnel records initiated 1945–1955 at major mines; cohort established 1981); follow-up to 31 Dec 1980
Talcott et al. 1989	Massachusetts cigarette-filter (crocidolite) workers	Crocidolite only	1951–1957

Reference List for Appendix 1

Full citations for all 18 publications, verified against each paper's own title page/header where the full text was available in this review.

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