Presence of asbestos fibres in indoor and outdoor air in the city of Thetford Mines: Estimation of lung cancer and mesothelioma risks

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ABSTRACT

In the autumn of 2007, the *Association des victimes de l'amiante du Québec* (AVAQ – a Québec association for asbestos victims) and the *Ministère du Développement durable, de l'Environnement et des Parcs du Québec* (MDDEP – Québec ministry of sustainable development, the environment and parks) published studies on the asbestos concentrations measured in indoor and outdoor air in Thetford Mines. The findings motivated the public health authorities in Chaudière-Appalaches and Estrie to request the assistance of the *Institut national de santé publique du Québec* (INSPQ – Québec institute of public health) to conduct an assessment of the risk of lung cancer and mesothelioma of the pleura in this population.

Asbestos is divided into two families: amphiboles (crocidolite, amosite, tremolite, actinolite and anthophyllite) and serpentines (chrysotile). The three main diseases associated asbestos exposure are asbestosis, lung cancer and mesothelioma of the pleura and peritoneum. The risk of mesothelioma of the pleura attributable to exposure to amphiboles is higher than the risk attributable to chrysotile. In addition, mesothelioma could be caused by low and sporadic exposures to asbestos, and asbestosis is unlikely to occur among individuals exposed non-occupationally to asbestos concentrations generally present in the environment. That is why only the risk associated with the two cancers was considered.

Two approaches were used to conduct the carcinogenic risk assessment in Thetford Mines. The first approach is derived from the methodology proposed in the *Lignes directrices pour la réalisation des évaluations du risque toxicologique pour la santé humaine* (guidelines for conducting assessments of toxicological risk to human health) of the *Ministère de la Santé et des Services sociaux du Québec* (MSSS). This method is based on the assumption that the risk is the same for exposure to amphiboles or to chrysotile. The second approach is derived from the recent model by Berman and Crump. In this model, the risk associated with amphiboles differs from that associated with chrysotile. The two procedures take into account the average lifetime exposure dose (sum of the average exposure dose by inhalation of indoor air and the average exposure dose by inhalation of outdoor air) and a cancer potency factor specific to asbestos.

The exposure dose for indoor air was calculated using concentrations reported in the AVAQ study. In 2003 and 2004, the authors of that study evaluated asbestos concentrations in indoor air in 26 residences in the city of Thetford Mines. Most of the asbestos fibres detected were chrysotile fibres, but actinolite and tremolite were also detected. As prescribed by the MSSS, the upper limit (UL) of the 95% confidence interval (95% CI) of the arithmetic mean of the concentrations measured was utilized to assess exposure. It is 0.0031 fibre/ml (f/ml). For outdoor air, the results of the 2004 MDDEP study of ambient air in the city of Thetford Mines were used. Chrysotile and amosite fibres were detected in the samples. The UL of the 95% CI is 0.0035 f/ml. Based on these two series of data, the average lifetime exposure dose is 0.0031 f/ml.

With this dose, according to the methodology of the guidelines, the lifetime excess mortality from lung cancer and from mesothelioma is between 72 and 125 per 100,000 persons in Thetford Mines continuously exposed to asbestos during their lifetime. The lifetime excess mortality from these same cancers, estimated using the Berman and Crump model, is 8.2 per 100,000 persons with a continuous lifetime exposure to chrysotile fibres.

For comparative purposes, the risks associated with asbestos fibre concentrations generally found in the environment were calculated. They vary from 0.46 to 7.1 per 100,000 persons depending on the approach utilized (Berman and Crump model or MSSS guidelines).

The average asbestos fibres concentration measured in the indoor air of residences in the city of Thetford Mines is 1.7 times lower than that found in 17 schools in Québec, and 1.4 times lower than that measured in two residences affected by dust created by the collapse of the World Trade Center (WTC) towers a few days after the events of September 11, 2001. However, the average asbestos structures concentration in Thetford Mines is 232 times higher than the background level measured in apartments in New York City. Lastly, the average asbestos concentration (structures or fibres) in the houses in Thetford Mines is 4 to 46 times higher than the average concentrations found in the United States in residences and public buildings having asbestos containing materials (ACM).

The average concentration of asbestos fibres measured by the MDDEP in outdoor air in the city of Thetford Mines has remained stable since 1997. However, it is 215 times higher than that measured in samples taken across the United States and 7 times higher than the detection limit of the analytical method utilized to measure asbestos concentrations in urban areas in Québec and areas close to an inactive tailings site in Tring-Jonction in 2004.

Finally, of the four indoor air quality criteria listed, only the WTC criterion was retained (0.0009 PCMe asbestos fibre /ml), because it is the only one that took health effects into account. Nineteen percent of the indoor air samples in the AVAQ study exceeded this criterion. When more than 10% of samples exceed the selected criterion, it is considered that a health impact could have occurred or could occur. None of the outdoor air quality criteria were retained.

The results of the risk assessments must be interpreted with caution since they include uncertainties related to, for example, 1) the determination of the lifetime unit risks, which are developed from dose-response relationship models derived from epidemiological studies conducted among workers; 2) the statistical models utilized to extrapolate the results obtained from cohorts of workers to a population exposed to low doses in the environment; and 3) the concentrations employed to determine the average lifetime exposure dose based on the AVAQ and MDDEP studies. These uncertainties could have led to an overestimation or underestimation of the risks calculated, which it is difficult to quantify.

Notwithstanding the uncertainties and the limitations cited above, the results of the risk assessment and the comparative analysis of the asbestos concentrations measured in Thetford Mines suggest a health risk attributable to the presence of airborne asbestos in this region. The risk levels estimated in this study can only be extrapolated to the entire population of Thetford Mines insofar as the concentrations from these two data sources are representative of the concentrations to which the entire population of the city is exposed. It would be appropriate to test the risk estimated by the two approaches against recent epidemiological data on lung cancer and mesothelioma of the pleura in Thetford Mines in order to identify whether there is an overestimation or underestimation of the risk, even though the epidemiological data from the 2000s derives from exposure that took place between the 1960s and the 1980s approximately.

In conclusion, it is important to emphasize that, according to the WHO, there is no evidence of a safe threshold for the carcinogenic effects of asbestos, and an increased cancer risk has been observed in populations exposed to very low concentrations of asbestos. In light of this, it is desirable to reduce exposure as much as possible. Consequently, certain control measures must be contemplated such as prohibiting access to mine tailings sites or halting the use of mine tailings for backfill and for abrasive or other purposes. As well, it would be appropriate to take new measurements of asbestos in the air in Thetford Mines in order to monitor exposure over time, to ensure that it does not increase.

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INTRODUCTION

Asbestos is a group of natural fibrous minerals, composed of silicates, that are or have been commercially exploited. These minerals are divided into two mineralogical categories: amphiboles, which include crocidolite, amosite, tremolite, actinolite and anthophyllite; and serpentines, which include only chrysotile (World Health Organization [WHO], 2006a).

Asbestos fibres are flexible and resistant notably to traction, heat and chemical products. Because of their physicochemical properties, they are incorporated into numerous products such as cement, asphalt, plastics, textiles, construction materials, brake pads and insulating and fire-retardant materials for buildings (Lajoie et al*.,* 2003; Agency for Toxic Substances and Disease Registry [ATSDR], 2001).

In 2006, Canada was the world's fifth largest producer of chrysotile asbestos (Natural Resources Canada, 2006). The country does not exploit amphibole asbestos. The Canadian production is concentrated in Québec in the cities of Thetford Mines, in the Chaudière-Appalaches region, and Asbestos, in Estrie. In Thetford Mines, only the open-pit mine Lac d'Amiante du Canada in the Black Lake area is still in operation. The underground Bell mine, active for 130 years, closed for good on March 28, 2008 (Bussières, 2008). The open-pit mine Jeffrey d'Asbestos temporarily laid off its employees on June 30, 2008 (Radio-Canada, 2008).

The population that lives in these mining cities is potentially exposed to asbestos fibres, which are dispersed in the environment. Sources of exposure include mining activities and mine tailings accumulated in mine tailings sites (Couture and Bisson, 2006; Lajoie et al., 2003). In the region of Thetford Mines, some mine tailings sites are said to be active, which is to say that mine tailings are still being dumped there or that they are regularly used as a source of materials, such as backfill. The asbestos contained in these backfill sites can also be dispersed in the ambient air. Other mine tailings sites are said to be inactive, but vehicle traffic in them is sometimes tolerated (Couture and Bisson, 2006). The loading of mine tailings from tailings sites into trucks and their transportation to cities could also contribute to propagating asbestos fibres in ambient air (Marier, Charney, Rousseau, Lanthier and Van Raalte, 2007).

The principal exposure pathway for asbestos is inhalation, and the associated effects are first seen in the respiratory system (Lajoie et al., 2003). These effects have been demonstrated mainly among workers and laboratory animals (*Sous-comité sur l'épidémiologie des maladies reliées à l'exposition à l'amiante*, 2003). Hence, the assessment of airborne asbestos concentrations enables public health workers to determine the extent of exposure and, consequently, the risk to the population. Indeed, public health officials in Chaudière-Appalaches and Estrie were recently questioned by the media about the publication of studies conducted in Thetford Mines and surrounding areas.

In studies carried out in 2000 and 2005, the *Ministère du Développement durable, de l'Environnement et des Parcs du Québec* (MDDEP – Québec ministry of sustainable development, the environment and parks) measured asbestos fibres in the air above lands backfilled with mine tailings (Couture and Bisson, 2006; MENVQ, 2001). Based on the results obtained, the MDDEP and the *Institut national de santé publique du Québec* (INSPQ) recommended that these landfill sites be covered by a non-contaminated material (R. Gauthier and A. J. Nantel, personal communication, December 8, 2005). In 2004, the same ministry also took ambient air samples on the roofs of buildings in the city of Thetford Mines (Bisson and Couture, 2007). Despite the presence of asbestos fibres, the authors of the report concluded that the total fibre concentrations found were approximately 10 times below the air quality criterion for asbestos in effect in Ontario (the MDDEP has no official air quality criterion for asbestos).

In another study, in 2003 and in 2004, the *Association des victimes de l'amiante du Québec* (AVAQ – Québec asbestos victims association) measured the asbestos concentrations in the air of some residences in the city of Thetford Mines (Marier et al., 2007). According to the authors, the results obtained constitute a public health threat.

A detailed description of the AVAQ and MDDEP studies is presented in Appendix 1 (including methodology, raw and combined results, conclusions, recommendations and strengths and weaknesses of these studies).

In light of these data, the INSPQ received the mandate to assess the human health risks arising from the presence of asbestos fibres in the ambient air and in the indoor air of residences in the city of Thetford Mines. The goal of this assessment is to provide scientific information in order to guide decisions regarding the management of the environmental risks associated with asbestos exposure in Québec's mining towns. The steps employed are presented in Chapter 2.

To this main objective are added the following secondary objectives: 1) to survey the asbestos levels measured over time in the city of Thetford Mines and 2) to compare them to the levels obtained in studies conducted in other settings and to asbestos criteria established by some organizations. These aspects are dealt with in Chapter 3.

Finally, it should be stated that the determination of asbestos fibre concentrations is complex and several methods of analysis are possible. These are explained in Chapter 1.

1 METHODS FOR THE ANALYSIS OF ASBESTOS FIBRES

Unlike most chemical substances, asbestos is not measured according to the mass per volume sampled but rather according to the number of structures per volume of air sampled (Perry, 2004). A structure can be defined as being a simple fibre, a bundle of fibres or a cluster or matrix of fibre containing particles[a]. The structure concentration is determined by microscopy.

The two types of microscopy most utilized in Québec to analyze asbestos concentrations are phase contrast microscopy (PCM) and transmission electron microscopy (TEM).

PCM analysis does not specifically differentiate asbestos fibres. All the other types of fibres (e.g.: cellulose, artificial fibres, etc.) are therefore counted, which can lead to an overestimation of the actual concentration of asbestos fibres. Additionally, since the magnification obtained by PCM is low (400 X), a certain number of fibres of small diameter are not visible (HEI-AR, 1991). This analysis is nevertheless recommended to measure asbestos concentration in the workplace because the nature of the predominant fibres is generally known beforehand.

TEM analysis is preferred when measuring asbestos concentrations in the environment since the nature of the fibres is not always known. This type of analysis makes it possible not only to specifically distinguish asbestos fibres from other fibres, but also to differentiate the type of asbestos fibres (serpentines versus amphiboles) (Perry, 2004). Moreover, since the magnification is better than with PCM (10,000 X), it is possible to see asbestos fibres, which are very thin, sometimes even fibres as small as 0.2 nanometre (nm) in diameter (HEI-AR, 1991).

There are two methods to prepare TEM samples: the direct and the indirect methods. With the direct method, the sample is used practically as is, while with the indirect method, the sample is treated notably with ultrasounds that can result in the fragmentation of fibres and thereby increase their number in the sample (Dion and Perrault, 2000).

The NIOSH 7400 protocol describes the analysis of fibres by PCM (The National Institute for Occupational Health and Safety [NIOSH], 1994a). In Québec, the *Institut de recherche Robert-Sauvé en santé et en sécurité du travail* (IRSST - Robert Sauvé health and safety research institute) has developed its own protocol: IRSST 243-1 (IRSST, 1991). According to the latter, fibres with a diameter ≥ 3 µm are not counted, contrary to the NIOSH 7400 protocol. It should be stated that the magnification obtained by these two protocols is not sufficient to distinguish fibres with a diameter < 0.25 µm.

The fibre counting criteria utilized in the two methods are presented in Table 1.

The NIOSH 7402 protocol (direct method) describes the analysis of fibres by TEM (NIOSH, 1994b). The counting criteria are almost equivalent to those in the NIOSH 7400 protocol, even though TEM makes it possible to observe thinner fibres (NIOSH, 1994b; Perry, 2004).

[a] According to the *Petit Larousse illustré 2008*, a bundle is a collection of long, thin objects linked together. A cluster is a substance, a mass formed of primitively disparate elements, closely and securely joined together. [translation]

The asbestos fibre concentration is expressed as a phase contrast microscopy equivalent (or PCMe), meaning the fibre concentrations according to the PCM counting criteria.

The AHERA (Asbestos Hazard Emergency Response Act) protocol is defined in the U.S. act of the same name (U. S. Environmental Protection Agency [U.S. EPA], 1987). According to this protocol, each single asbestos fibre that conforms to the counting criteria is counted as being a structure, as is any bundle, cluster or matrix possessing at least one asbestos fibre that meets the criteria. This rule differs from the other protocols under which each fibre or bundle is counted as a fibre, and each fibre within a complex structure is also counted as a fibre (Perry, 2004).

Table 1: Criteria for counting asbestos fibres by PCM and by TEM

	Length (L) micrometre (µm)	Diameter (D) micrometre (µm)	L/D	Concentration unit
PCM				
NIOSH 7400	> 5	≥ 0.25[a]	≥ 3:1	Total fibres/ml of air (f/ml)
IRSST-243-1	> 5	≥ 0.25[a] and < 3	> 3:1	Total fibres/ml of air (f/ml)
TEM				
NIOSH 7402	> 5	> 0.25	≥ 3:1	PCMe asbestos fibres/ml of air (PCMe fibres/ml)
AHERA	≥ 0.5	No restriction	≥ 5:1	Structures/mm^2 of filter or structures/ml of air (s/mm^2 or s/ml)

[a] No minimum diameter is specified by these two protocols, but their magnification is not sufficient to distinguish fibres of a diameter < 0.25 µm.

L/D: Length to diameter ratio; PCMe: phase contrast microscopy equivalent.

Another protocol is sometimes utilized for TEM analyses, the ISO 10312 (Perry, 2004). It is more costly and takes longer, but the concentration of a single sample can be expressed by one or several series of counting criteria (e.g.: PCMe fibres or structures of a length > 10 µm and of a length/diameter ratio (L/D) ≥ 5:1).

Some authors employ TEM using variants of these protocols or protocols they have designed (Lee and Van Orden, 2008; Marier et al., 2007). The counting criteria can therefore differ from those presented in Table 1. For example, in 1986, Sébastien et al., (cited in Lajoie et al., 2003), measured fibre concentrations > 5 µm and with a L/D ratio of ≥ 3:1, with no restriction for the diameter.

Lastly, according to the International System of Units (IS), the unit of measure of the concentration should be expressed in f/cm^3 (Table 1). However, many authors choose to express concentration in f/ml, which is equivalent to 1 f/cm^3.

2 EXPOSURE TO ASBESTOS FIBRES IN THE CITY OF THETFORD MINES: RISK ASSESSMENT

This chapter is devoted to the assessment of the environmental risks to human health arising from the presence of asbestos fibres in the ambient air and indoor air of residences in the city of Thetford Mines. Since the context is environmental exposure, the effects retained for the risk assessment are lung cancer and mesothelioma, the two diseases most likely to develop in a population exposed to asbestos in its environment (Berman and Crump, 2003). Two approaches are used to perform the assessment.

The first approach is derived from the methodology set out in the *Lignes directrices pour la réalisation des évaluations du risque toxicologique pour la santé humaine* (guidelines to assess toxicological risk to human health), proposed by the *Ministère de la Santé et des Services sociaux du Québec* (MSSS, 2002). In this method, lifetime mortality risk for (or lifetime excess mortality[b] from) cancer is calculated by multiplying an average lifetime exposure dose by a series of lifetime unit risks specific to asbestos. The determination of these unit risks is based on the assumption that the risk is the same for exposure to amphiboles or to chrysotile. The second approach is derived from the recent model by Berman and Crump (2003). In this model, the risk associated with amphiboles differs from that associated with chrysotile.

But first, the health effects of asbestos fibres, their toxicokinetics and their principle mechanisms of action are reviewed.

2.1 HEALTH EFFECTS, TOXICOKINETICS AND MECHANISMS OF ACTION

The three main types of effects associated with a chronic exposure to asbestos are asbestosis, lung cancer and mesothelioma of the pleura and peritoneum. All types of asbestos have been associated with the three diseases (*Institut national de la santé et de la recherche médicale* [Inserm, 1997]).

Asbestosis is characterized by a progressive fibrous thickening of the alveolar walls of the lungs. The development of this disease usually results from a significant exposure to asbestos, as has been observed in certain workplaces (Berman and Crump, 2003). According to the Agency for Toxic Substances and Disease Registry (ATSDR), cases of asbestosis are unlikely among individuals exposed non-occupationally to concentrations generally present in the environment (ATSDR, 2001).

Lung cancer affects the epithelial cells, and its minimum latency period is 10 years with an average of approximately 20 years. Asbestos is not the only etiological factor for this disease. However, it is not possible to histologically distinguish cancers caused by asbestos from those caused by other factors such as smoking or exposure to radon. Cigarette smoke and asbestos interact in synergy in the development of lung cancer. Lastly, the toxic potential of amphiboles is higher than that of chrysotile (Berman and Crump, 2003; Hodgson and Darnton, 2000). Nevertheless, uncertainties persist concerning this issue. For example, the

[b] Meaning projected over a lifetime.

highest relative risks for cancer were observed among a cohort of textile workers in South Carolina, exposed exclusively to chrysotile fibres. These results constitute a departure from the results reported among mine and mill workers in Québec (Berman and Crump, 2008).

Unlike lung cancer, mesothelioma of the pleura or the peritoneum is associated with a direct or indirect exposure to asbestos (*Sous-comité sur l'épidémiologie des maladies reliées à l'exposition à l'amiante*, 2003). But this association has only been demonstrated since the 1960s (Gibbs and Berry, 2007). The latency period of this cancer varies between 20 and 40 years and even beyond. These are rare tumours, and the pleura is affected much more often than the peritoneum. Many authors agree that the risk attributable to exposure to amphibole fibres is higher than the risk attributable to chrysotile fibres, but discrepancies exist regarding the extent of this difference (Berman and Crump, 2003; Gibbs and Berry, 2007; HEI-AR, 1991; Hodgson and Darnton, 2000; *Sous-comité sur l'épidémiologie des maladies reliées à l'exposition à l'amiante*, 2003). Mesothelioma could also be caused by low and sporadic exposures to asbestos (Dodson, Atkinson and Levin, 2003; *Sous-comité sur l'épidémiologie des maladies reliées à l'exposition à l'amiante*, 2003).

The transportation and deposit of the inhaled fibres in the respiratory tree are strongly influenced by the aerodynamic diameter (AD) of these fibres. The AD corresponds to the diameter of a spherical particle of 1 g/cm^3, which has the same settling velocity as the particle studied (Canadian Centre for Occupational Health and Safety [CCOHS], 1997; *Commission de la santé et de la sécurité du travail* [CSST], 2000). This parameter depends mainly on fibre length and diameter, but it appears that diameter plays a greater role (Bernstein et al., 2005). For example, fibres with a diameter > 3 µm are deposited in the upper airways, while long, thin fibres, such as those with an AD < 1 µm, are carried deeper into the distal airways and alveolar regions (CCOHS, 1997; ATSDR, 2001).

Inhaled asbestos fibres are cleared from the lungs by means of several processes: dissolution in biological fluids, mucociliary transport, phagocytosis by alveolar macrophages, encapsulation by proteins and transfer into the pulmonary interstitium toward the lymph ducts or toward the pleura or peritoneum (ATSDR, 2001, 2007; Bernstein et al., 2005). It should be remembered that the pleura and the peritoneum are the development sites of asbestos-related mesotheliomas.

The efficiency of these mechanisms is modulated by a number of factors such as the length of the fibres, their pulmonary load, their physicochemical properties or the presence of other agents (NIOSH, 2008). For example, cigarette smoke affects the activity of mucociliary cells. As well, fibres of a length at least equivalent to the diameter of the macrophages are not completely phagocytized. Phagocytosis is also less efficient for shorter fibres during high exposures, probably due to a saturation phenomenon (Bernstein et al., 2005).

The deposit rate and deposit site of fibres in the respiratory tree and the efficiency of their clearance influences the time of residence in the lungs – their biopersistance (NIOSH, 2008). Biopersistance is an important indicator of toxic potential but is not the only one.

The mechanisms of asbestos toxicity are even less well understood and probably involve several overlapping processes. Essentially, they are divided into three categories: interaction with macromolecules; formation of reactive oxygen species; and release of cell mediators (ATSDR, 2001, 2007).

First, the adsorption of asbestos to cellular macromolecules such as proteins, membrane lipids, DNA and RNA produces notably the deletion of chromosome segments, a decrease in cytochrome P-450 activity, an increase in cell membrane rigidity and an increase in the permeability of pulmonary epithelium.

Next, the action of macrophages on asbestos fibres generates hydrogen peroxide and superoxide radical anion (H_2O_2, O_2^-). These latter, via the Haber-Weiss reaction, form the hydroxyl radical ($OH^\cdot$), a powerful oxidant. Iron ions present on fibre surfaces catalyze this reaction. Diverse oxidative stresses can ensue: lipid peroxidation of cell membranes and an increase in their permeability, cytotoxicity, cellular proliferation, genotoxicity and apoptosis.

Lastly, the presence of asbestos in the respiratory system induces the release of cell mediators by macrophages and by pulmonary and pleural cells. These mediators are likely to cause a series of reactions such as cell proliferation, macrophage recruitment and inflammation. Although still poorly understood, the inflammatory response plays an important role in the formation of asbestos-related lung diseases.

To conclude, all types of asbestos fibres are classified in Group A (human carcinogen) by the U.S. EPA (1993) and in Group 1 (carcinogenic to humans) by the International Agency for Research on Cancer (IARC, 2008).

2.2 RISK ASSESSMENT USING THE MSSS GUIDELINES

Lifetime mortality risk for (or lifetime excess mortality from) lung cancer and for mesothelioma (R) is calculated using the procedure described in the MSSS guidelines (2002) for performing assessments of toxicological risk to human health.

Lifetime mortality risk[c] is obtained by multiplying the average lifetime exposure dose (D_{avg}) by the lifetime unit risk (UR) specific to the contaminant (Equation 1). For asbestos, the UR represents the lifetime mortality risk for lung cancer and for mesothelioma attributable to a continuous lifetime exposure of 1 asbestos fibre/ml ($(f/ml)^{-1}$). The D_{avg} reflects the cumulative exposure to asbestos during a lifetime (f/ml).

$$R = D_{avg} \times UR \qquad \textbf{Equation 1}$$

[c] To lighten the text, the expression *lifetime mortality risk* is employed. It corresponds to lifetime mortality risk for lung cancer and for mesothelioma of the pleura and peritoneum, following a continuous exposure over a lifetime.

2.2.1 Lifetime unit risks selected

A review of the literature led to the identification and selection of some lifetime unit risks. These are derived from dose-response relationships observed during epidemiological studies conducted in the workplace.

In fact, the dose-response relationship is used to predict the risk of developing an effect, which will have a health impact, following an exposure to a given concentration of a substance. The dose-response relationships established for asbestos come from studies in which workers are generally exposed to concentrations > 1 f/ml. However, in the non-occupational environment, the concentrations found are below 1 f/ml, and the effects are difficult to observe. This constitutes a limitation in the determination of the dose-response curve.

To resolve this limitation, several authors have extrapolated, from epidemiological studies conducted among workers, the lung cancer and mesothelioma mortality risks attributable to environmental exposures. Between the years 1980 and 2000, a first series of studies was published, including studies by Nicholson (1986), the U. S. Environmental Protection Agency (U.S. EPA, 1993), the United States National Research Council (NRC, 1984), the Ontario Royal Commission (ORC) (Mustard, Uffen, Dewees, Laskin and Kahn, 1984), the United Kingdom Health and Safety Commission (HSC) (Doll and Peto, 1985), the U.S. Consumer Product Safety Commission (CPSC) (1983), the California Environmental Protection Agency (California Air Resources Board, 1986; California Environmental Protection Agency [Cal/EPA] and the Office of Environmental Hazard Health Assessment [OEHHA], 2002), Hugues and Weill (1986), the Health Effects Institute-Asbestos Research (HEI-AR, 1991), the *Institut national de la santé et de la recherche médicale de France* (Inserm, 1997) and the World Health Organization (WHO-Europe, 2000). The fundamental assumptions are the same for all these authors and are listed below.

- The relationships derived from workplace exposure data apply also to low concentrations found in the environment.
- The relationships apply to asbestos fibres of a length > 5 µm.
- The relationships are linear relative to cumulative exposure, and they have no threshold relative to exposure.
- The risk does not diminish after the end of exposure.
- The risk gradient is identical for amphiboles and chrysotile, with the exception of the Inserm for mesothelioma.
- Although it is the incidence of lung cancer and mesothelioma that is described, in practice, it is actually the mortality relative to these two effects that is retained.
- In the case of lung cancer, the combined effects of asbestos exposure and smoking are multiplicative.

As well, the dose-response relationships, for each of the cancers, are expressed with the same algorithms (Equations 2 and 3). However, there are variants in the value of certain parameters.

Lung cancer

The dose-response relationship for lung cancer is a relative risk model represented by Equation 2:

$$I_{PE}(t) = I_{PnE}(t) \times (1 + K_L \times f \times d - t_0) \quad \textbf{Equation 2}$$

Where:

$I_{PE}(t)$: Incidence (or mortality rate), at age *t,* of lung cancer in a population exposed to asbestos.

$I_{PnE}(t)$: Incidence (or mortality rate) of lung cancer at age *t* in a population not exposed to asbestos (control population) and whose smoking habits are the same as those of the exposed population.

K_L: Potency factor, the increase in lung cancer per average cumulative exposure unit $(\text{f/ml*year})^{-1}$. This is an indicator of the carcinogenic potential of asbestos. This variable is independent of age, sex and smoking habits.

f : Average exposure concentration (f/ml).

d : Duration of exposure (years).

t_0: Minimum period required to induce the effect, or lag (years).

Mesothelioma

The dose-response relationship in the case of mesothelioma is an absolute risk model that is not contingent on the incidence of mesothelioma in an unexposed population. As well, the increase in the risk of developing a mesothelioma is proportional to a power of time elapsed since onset of exposure (Equation 3).

$$I_M(t) = K_M \times f \times \left[(T - t_0)^n - (T - t_0 - d)^n\right] \quad \textbf{Equation 3}$$

Where:

$I_M(t)$: Incidence (or mortality rate), at age *t,* of mesothelioma in a population exposed to asbestos.

K_M: Potency factor, the increase of mesothelioma per average cumulative exposure unit $(\text{f/ml*year})^{-1}$.

f : Average exposure concentration (f/ml).

T : Period elapsed since onset of exposure (years). Also, T = t - t_1 where t_1 is the age at onset of exposure.

t_0: Minimum period required to induce the effect, or lag (years).

d : Duration of exposure (years).

The K_L and K_M values represent the set of cancer potency factors obtained for each cohort of workers. For example, the K_M of Nicholson (1986) derives from the weighted geometric mean of four weighted geometric means calculated according to the type of procedure. As well, to take into account the fact that an environmental exposure occurs continuously, some authors have adjusted the values of K_L and K_M by an F factor. For example, 168 hours/week for a continuous exposure divided by 40 hours/week, relative to an occupational exposure, yields an F factor of 4.2 according to Nicholson.

The lifetime unit risk (UR) is therefore determined from Equations 2 and 3. For lung cancer, the risk attributable to a continuous asbestos exposure is the result of the difference between the lifetime lung cancer mortality risk in the exposed population (Equation 2) and the expected lifetime lung cancer mortality risk in the control population (Inserm, 1997). It varies by age relative to the lung cancer mortality rate and the all-cause mortality rate. For mesothelioma, the lifetime unit risk is obtained from Equation 3, but the all-cause mortality rates among the control population are also taken into account (Inserm, 1997). The determination of the UR is explained in more detail in Appendix 2.

On this subject, Nicholson's study, published in 1986, appears to be the most well respected in the scientific community, since it has been reused and adapted by other authors. In addition, it is referenced in the population risk analysis, contained in the U.S. EPA database *Integrated Risk Information System* (IRIS). That is why the UR retained for the risk assessment are taken from Nicholson and from the organizations that relied on his procedure: the U.S. EPA and the HEI-AR (Table 2) (HEI-AR, 1991; Nicholson, 1986; U.S. EPA, 1993).

The unit risks from the NRC, the ORC, the HSC, Hugues and Weill, the Inserm and the WHO were not selected, either because they are anterior to those of Nicholson or because they do not apply to a lifetime exposure duration (NRC, 1984; Doll and Peto, 1985; Hughes and Weill, 1986; Inserm, 1997; Mustard et al., 1984; WHO-Europe, 2000).

The Cal/EPA procedure is based on Nicholson (1986), but also on the NRC, the ORC and the U.S. CPSC. The UR retained by the Cal/EPA is the highest among those estimated for different sub-groups, that is, the lifetime unit risk for mesothelioma among non-smoking women. It was obtained from the largest K_M found in the four epidemiological studies selected. The choice of such a cautious unit risk is justified notably by the organization's assumption that carcinogenic effects are exerted by short fibres (< 5 µm) as well as long fibres (> 5 µm) (California Air Resources Board, 1986). However, this unit risk reflects the dose-response relationship observed for a single cohort of workers. Since it is not representative of the available data set on workers exposed to asbestos, it is not retained in this analysis.

Table 2: Comparison of estimated lifetime unit risks (UR) per 100 persons with a continuous lifetime exposure to 1 f/ml of asbestos in the environment

UR (f/ml)$^{-1}$	Nicholson (1986)	U.S. EPA, 1988 (U.S. EPA, 1993)	HEI-AR, 1990 (HEI-AR, 1991)
Lung cancer	17 M 5 W	nc	nc
Mesothelioma	19 M 28 W	nc	nc
Lung cancer and mesothelioma	35 MW[a] (0.35)	23 MW (0.23)	40 MW (0.40)

[a] Value estimated from unit risks determined by Nicholson, see the text below.
nc: Not calculated.
M: Men.
W: Women.
MW: Men and women combined.

Unlike the two organizations, Nicholson did not determine an average UR for the two cancers and for men and women combined (Table 2). However, by combining the unit risks for lung cancer, a value of 11/100 for men and women, [(17+5)/2]/100, is obtained. In the same way, the combined unit risk for mesothelioma is 23.5/100. The lifetime unit risk (UR) utilized for the two cancers is 35/100 (11 + 23.5).

The parameter values utilized to derive the lifetime unit risks in Table 2 are shown in Table 3. The U.S. EPA employed the same parameters as did Nicholson with the exception of the F factor. The U.S. EPA factor is based on the ratio of the air volume potentially inhaled continuously per week to the air volume potentially inhaled per work week (140 m^3/50 m^3), while Nicholson's factor corresponds to the number of hours of continuous exposure per week divided by the number of hours of exposure per work week (168h/40h). Lastly, the parameters considered by the HEI-AR are also practically the same as those established by Nicholson, but the lifetime duration and the control population are different.

Table 3: Parameter values utilized in the determination of lifetime unit risks

Parameters	Units	Variables	Nicholson (1986)	U.S. EPA, 1988 (1993)	HEI-AR, 1990 (1991)
Concentration of exposure	f/ml	f	0.0001	0.0001	0.00001
Duration of exposure (lifetime)	years	d	70[a]	70[a]	80
Adjustment factor for a continuous exposure	-	F	4.2	2.8	NA
Dose-response relationship – Lung cancer (Equation 2)					
Potency factor	(f/ml*year)$^{-1}$	K_L X100	1	1	1
Control population selected	-	-	United States, 1977	United States, 1977	United States, 1986
Lag	years	t_0	NA	NA	NA
Dose-response relationship – Mesothelioma (Equation 3)					
Potency factor	(f/ml*year)$^{-1}$	K_m X 10^8	1.0	1.0	1.0
Duration from onset of exposure	years	T	70	70	80
Power n	-	n	3.0	3.0	3.0
Lag	years	t_0	10	10	10

[a] Lifetime duration is not specified, but usually the U.S. EPA considers lifetime risks to age 70.
NA: Information not available.

2.2.2 Determination of average lifetime exposure dose

The calculation of the average lifetime exposure dose (D_{avg}) considers only inhalation since it is the main exposure pathway for asbestos and the effects are mainly observed in the respiratory system.

A lifetime is divided into five age groups, < 6 months, 6 months to 4 years, 4 to 11 years, 11 to 19 years and > 19 years to end of life (MSSS, 2002). The D_{avg} is obtained by weighting the average exposure dose of each age group relative to its duration (Equation 4):

$$D_{avg} = \frac{\sum_{i=1}^{5} D_{avg_i} \times G_i}{\sum_{i=1}^{5} G_i}$$ **Equation 4**

Where:

D_{avg} = Average lifetime exposure dose (f/ml).

D_{avg_i} = Average exposure dose of age group *i* (f/ml).

G_i = Duration of age group *i* (years).

For each age group, the D_{avg_i} is the sum of the average exposure dose by inhalation of indoor air and the average exposure dose by inhalation of outdoor air (Equation 5).

$$D_{avg\,i} = D_{ind\,i} + D_{out\,i}$$ **Equation 5**

Where:

$D_{avg\,i}$ = Average exposure dose of age group *i* (f/ml).

$D_{ind\,i}$ = Average exposure dose of age group *i*, indoor air (f/ml).

$D_{out\,i}$ = Average exposure dose of age group *i*, outdoor air (f/ml).

$D_{ind\,i}$ and $D_{out\,i}$ are based on the asbestos concentration in indoor air and outdoor air as well as the proportion of time spent indoors and outdoors in a day (Equation 6). The proportions of time spent indoors and outdoors are respectively 0.94 and 0.06 for the group over age 19, and 0.88 and 0.12 for the group age 19 and under (MSSS, 2002).

$$D_{ind\,i} = C_{ind} \times P_{ind_i} \text{ and } D_{out\,i} = C_{out} \times P_{out\,i}$$ **Equation 6**

Where:

C_{ind} = Asbestos fibre concentration in indoor air (f/ml).

C_{out} = Asbestos fibre concentration in outdoor air (f/ml).

P_{ind_i} = Proportion of time that age group *i* spends indoors.

P_{out_i} = Proportion of time that age group *i* spends outdoors.

Indoor air

The indoor air concentrations employed in this report come from the AVAQ study (Marier et al., 2007). In 2003 and 2004, the authors of that study evaluated the asbestos concentrations in indoor air in 26 residences in the city of Thetford Mines. Asbestos fibres were detected in 15 of the 26 houses sampled. The majority of the homes (24/26) were located within a radius of 2 kilometres or less of the mine tailings sites, 20 of these were in the direction of the prevailing winds and 4 were in the direction against the prevailing winds. In addition, 58% of the residences were located within a radius of 1 kilometre or less of the mine tailings sites.

The samplers were placed in the middle of the most frequented room in the house, 1 to 1.2 metres from the floor. Each sampling lasted 80 minutes and the modified aggressive method was employed. According to the U.S. EPA, this method consists in placing a fan on the floor in the middle of the room in order to simulate normal air movement (U.S. EPA, 2005, 2007). Again according to the U.S. EPA, this technique is used to recreate over the long term the routine activities practiced by the residents (U.S. EPA, 2003a). EPA employed this method during the campaign to sample residences as part of the cleanup program implemented after the events of September 11, 2001.

The data collected by the authors of the study show that asbestos containing materials (ACM) were present in 3 of the 26 residences. The other residences contained no ACM or had never contained ACM. As well, earthwork materials (covered or not) were spread over the grounds of 17 residences. At the time of the study, only one resident was exposed sporadically to asbestos in the workplace. Lastly, one of the residents of one home had already been occupationally exposed to asbestos a few years prior to the study, when living in his current residence (Marier et al., 2007).

The samples were analyzed by TEM according to the modified NIOSH 7402 protocol (fibres > 5 µm long, between 0.25 and 3 µm in diameter and with a L/D ratio > 3:1). However, the total air volume collected in each residence, which was 1,220 L, is below the minimum required by the protocol. The authors calculated the 95% confidence interval (95% CI) of each concentration measured to show the variability.

Most of the asbestos fibres detected were chrysotile fibres, but one actinolite fibre was identified in two residences and a tremolite fibre was detected in three residences. The concentrations measured range from < 0.000553 to 0.010 PCMe fibre/ml (n = 26). The arithmetic mean calculated from the AVAQ's set of values is 0.0020 PCMe fibre /ml, with an upper limit (UL) of the 95% CI of 0.0031 (Table 4). The UL of the 95% CI of the average concentration in PCMe fibres/ml is utilized as exposure datum, as prescribed by the MSSS (2002). A value equal to the detection limit was attributed to the concentrations below this limit, because more than 15% of the results are below the detection limit (*Groupe scientifique sur l'évaluation du risque toxicologique - Institut national de santé publique du Québec*, 2008).

An analysis using the AHERA protocol was also performed. The concentrations measured with this protocol (n = 28) range from < 0.004 to 0.311 structure/ml (s/ml).

Outdoor air

The study carried out in 2004 in the ambient air of the city of Thetford Mines by the MDDEP (Bisson and Couture, 2007) is preferred to the study performed by the same ministry in 2000 and 2005 on lands backfilled with mine tailings (Couture and Bisson, 2006; MENVQ, 2001), owing to the greater number of samples taken (see Appendix 1). As well, during the sampling done in 2004, asbestos concentrations from all sources of contamination in the ambient air, including from landfills, should have been measured.

To carry out this study, between January and August 2004, two samplers were placed on the roofs of public buildings, approximately 9 metres above the ground. One of the samplers was located near the mine and mill, while the other was located a bit further downwind. Both samplers were influenced by the prevailing winds. The samples obtained (n = 125) were analyzed by PCM using the IRSST-243-1 protocol, and the concentrations varied between < 0.0015 and 0.056 f/ml (fibres > 5 μm long, ≥ 0.25 μm and < 3 μm in diameter and with a L/D ratio of > 3:1). Seven of these samples were also analyzed by TEM according to the modified NIOSH 7402 protocol (fibres > 5 μm long, < 3 μm in diameter and with a L/D ratio of > 3:1). These were samples for which the PCM values were among the highest. Given that fibres thinner than 0.25 μm were measured during this study, the concentrations cannot be expressed in PCMe fibres/ml, but must be expressed in f/ml (Y. Couture, personal communication, June 19, 2008).

The TEM concentrations ranged from < 0.0006 to 0.0082 fibre/ml. Chrysotile fibres were detected in 2 samples, and 4 other samples contained between 4 and 14 amosite fibres. No fibre was found in the last sample. The TEM analysis also made it possible to report the results in total fibres/ml.

Since only seven samples were analyzed by TEM, the maximum concentration measured should therefore be employed as exposure datum according to the MSSS, because the quantity of data available does not permit obtaining a representative distribution of the values. In fact, the Monte-Carlo simulation software, *Crystal Ball*™, requires a minimum of 15 values to define a continuous value distribution.

On the other hand, the 125 samples analyzed by PCM better reflect the variation of total fibre concentrations. As well, using the results obtained by PCM, asbestos fibre concentrations were estimated with the approach of Madl et al*.* (2008) based on a guideline in the NIOSH 7402 protocol (NIOSH, 1994b). First, a ratio is established between the asbestos fibre concentration determined by TEM and the total fibre concentration also determined by TEM. One of the seven samples had an asbestos fibre concentration below the detection limit and was excluded. In the six other samples, the average asbestos fibre concentration is 0.00495 f/ml. For these same samples, the average total fibre concentration is 0.00988 f/ml. According to these data, approximately 50% (0.00495/0.00988) of the total fibres measured are asbestos fibres. The assumption by which the established ratio can be applied to the set of results in PCM is retained.

The ratio was then applied to the total fibre concentrations obtained by PCM. Note that a value equal to half the detection limit was attributed to the results below this limit. The asbestos fibre concentrations estimated in this way range from 0.00038 to 0.028 f/ml. The average is 0.0029 f/ml, with an upper limit of the 95% CI of 0.0035 (Table 4). In compliance with MSSS guidelines, this latter value is retained as an outdoor air exposure datum in the determination of the average lifetime exposure dose.

Table 4: Asbestos fibre concentrations measured in indoor air and outdoor air in the city of Thetford Mines

	Outdoor air MDDEP (Bisson and Couture, 2007) (f/ml)	Indoor air AVAQ (Marier et al., 2007) (PCMe fibres/ml)
Counting criteria	L > 5 μm, D < 3 μm and ratio L/D > 3:1	L > 5 μm, D ≥ 0.25 μm and < 3 μm and ratio L/D > 3:1
Average	0.0029	0.0020
Minimum	0.00038	0.000553
Maximum	0.028	0.010
Upper limit of 95% CI	0.0035	0.0031

The average lifetime exposure dose (D_{avg}), obtained from concentrations measured in indoor and outdoor air as well as from equations 4 to 6, is 0.0031 f/ml, whether the lifetime is set at age 70 as with Nicholson and the U.S. EPA, or at age 80 as with the HEI-AR (see Table 3). Note that the exposure attributable to indoor air inhalation contributes to 91.7% of this dose, while outdoor air inhalation contributes to 8.3%.

2.2.3 Determination of lifetime risk

The estimation of lifetime mortality risk for lung cancer and for mesothelioma (R) varies between 72 and 125 per 100,000 persons in the city of Thetford Mines continuously exposed to asbestos throughout their lifetime (Table 5).

Table 5: Estimated lifetime mortality risk based on unit risks per 100,000 persons in the city of Thetford Mines with a continuous lifetime exposure to asbestos fibres

	Nicholson (1986)	U.S. EPA, 1988 (1993)	HEI-AR, 1990 (1991)
LIfetime unit risk[a] UR (f/ml)$^{-1}$	0.35	0.23	0.40
Average lifetime exposure dose D_{avg} (f/ml)	0.0031	0.0031	0.0031
Lifetime mortality risk R	110	72	125

[a] The unit risks are presented in Table 2.

2.3 Risk assessment using the Berman and Crump model

Since the 2000s, risk assessment studies relating to asbestos exposure have changed. In addition to considering updated epidemiological data, they tend toward a differentiation of the risks attributable to amphiboles and those attributable to chrysotile. Two of these studies are of particular interest: the model of Hodgson and Darnton (2000) and that of Berman and Crump (2003).

Hodgson and Darnton (2000) calculated the exposure-specific lung cancer mortality (R_L) by finding the ratio of the number of excess lung cancer cases (the number of measured lung cancers minus the number of expected lung cancers) multiplied by 100, divided by the product of the cumulative exposure and the number of expected cancers. The authors conclude that the carcinogenic potential associated with lung cancer is 10 to 50 times higher for amphiboles than for chrysotile.

The exposure-specific mesothelioma mortality (R_M) was obtained by calculating the ratio of the number of mesothelioma deaths multiplied by 100, divided by the product of the cumulative exposure and the total expected deaths from all causes, adjusted for age first exposed at 30 years. The conclusions of the analysis showed that the carcinogenic potential associated with mesothelioma is 100 to 500 times higher for amphiboles than for chrysotile.

The authors then assessed separately, based on fibre type, the lung cancer and mesothelioma risks for a 5-year exposure, starting at age 30.

Berman and Crump (2003) integrated more recent epidemiological data, collected among different groups of workers, with the U.S. EPA dose-response relationships defined by Nicholson. As a result of their analysis of these data, the authors propose that the dose-response relationships established by Nicholson adequately predict the dependence on exposure duration long after the end of exposure, but predict less well the linear dependence on the exposure concentration. In fact, instead of a linear relationship between dose and effect, the epidemiological data suggest a supra-linear relationship for lung cancer and mesothelioma. However, the authors believe that the statistical analyses are convincing enough to justify the use of linear models.

Furthermore, a variable α was added to the dose-response relationship for lung cancer (Equation 7). It represents the ratio between the rate of lung cancer in the exposed population and the rate in the control population. The dose-response relationship for mesothelioma is identical to that presented in Equation 3.

$$I_{PE}(t) = \alpha * I_{PnE}(t) * (1 + K_L * f * d - t_0)$$ **Equation 7**

$$I_M(t) = K_M * f * \left[(T - t_0)^n - (T - t_0 - d)^n\right]$$ **Equation 3**

Lastly, according to Berman and Crump's statistical analyses on lung cancer, the hypothesis that chrysotile does not possess a carcinogenic potential can be rejected and the hypothesis suggesting that chrysotile is as carcinogenic as amphiboles cannot be rejected. With regard to mesothelioma, the hypothesis suggesting that chrysotile is as carcinogenic as amphiboles can be rejected, while the hypothesis proposing that chrysotile does not possess a carcinogenic potential cannot be rejected.

For this second part of the analysis, the lifetime mortality risk for the population of the city of Thetford Mines is estimated using the Berman and Crump model. It is preferred to that of Hodgson and Darnton, because the latter does not consider a lifelong exposure. In addition, with the approach of Berman and Crump, it is possible to select the control population most representative of the exposed population. Lastly, the authors determined cancer potency factors for PCMe fibre/ml concentrations rather than for concentrations determined by PCM.

Lifetime mortality risk was obtained using the methodology described in Appendix E of their report. Table 6 presents the parameter values utilized.

Table 6: Parameter values utilized in the determination of lifetime mortality risk for the population of the city of Thetford Mines using the methodology of Berman and Crump

Parameter	Unit	Value
Duration of exposure d	years	80
Lag t_0	years	10[a]
Average lifetime exposure dose D_{avg}	f/ml	0.0031
Potency factors[b]	(PCMe chrysotile fibres /mlX year)$^{-1}$	
K_L X 100		0.23
K_M X 10^8		0.025
Adjustment factor for a continuous exposure F	-	3.04
Control population	-	Chaudière-Appalaches, 2000 to 2003
Variable α	-	1

[a] Lag period in 10-year increments for the dose-response relationship of lung cancer and mesothelioma.

[b] Taken from Table 7-17 in the Berman and Crump report (2003): chrysotile fibres > 5 µm long, ≥ 0.2 µm in diameter and with a L/D ratio of ≥ 3.

The upper limits of the 95% CI of the average concentrations in indoor air and outdoor air are retained as exposure datum (Table 4). According to the model, the end of life risk corresponds to the sum of the risks for each age group. In theory, the exposure doses should not all be exactly the same among the age 19 and under group and among the group over age 19, due to the proportion of time spent indoors and outdoors by each of the groups (see Equations 5 and 6). However, according to the calculations performed, the exposure dose of each age group is equal to the average lifetime exposure dose, which is 0.0031 f/ml. Moreover, the K_L and K_M values of Berman and Crump for “pure” PCMe chrysotile fibres are retained. These same potency factors were also utilized recently by a scientific committee at the HSC in the United Kingdom in a comparative risk assessment with the Hodgson and Darnton model (WATCH, 2007). The postulate by which this population is exposed only to chrysotile is therefore established.

Berman and Crump recommend using the mortality rates of the control population for the following sub-groups: male smokers, male non-smokers, female smokers and female non-smokers. They suggest then combining the estimated risks for these sub-groups in order to apply them to the general population. However, such data were not found either in Québec or in Canada. The rates (uncorrected for smoking) among men and among women in the

Chaudière-Appalaches health and social service region were therefore retained. The average all-cause mortality rates (2000 to 2003) were provided by the INSPQ team *Études et analyses de l'état de santé de la population* (L. Paquette, personal communication, April 25, 2008). The average lung cancer mortality rates for the same period were taken from a parameter search conducted on the *Infocentre de santé publique* site administered by the INSPQ (http://www.infocentre.inspq.rtss.qc.ca/portail/sante/public/infocentre/accueil/?lang=fr). All these rates were calculated using data taken from the MSSS death registry (October 2005 version) and from the MSSS *Service du développement de l'information* (February 2005 version).

Last, the factor α for lung cancer is set at 1, which means that the lung cancer rate in the control population is not different from that in the exposed population. Thus, the smoking habits of the Thetford Mines sector are considered similar to those of the Chaudière-Appalaches region.

Calculated using Equations 7 and 3 and using the parameters indicated in Table 6, the lifetime mortality risk for lung cancer and for mesothelioma is 11.5 per 100,000 men and 4.88 per 100,000 women in the city of Thetford Mines, continuously exposed during their lifetime to chrysotile fibres. Lifetime mortality risk for both sexes equals 8.2 per 100,000 persons exposed. This value is between 9 and 15 times higher than the values calculated from lifetime unit risks (see Table 5).

3 COMPARATIVE ANALYSIS OF THE ASBESTOS CONCENTRATIONS MEASURED IN THE CITY OF THETFORD MINES

The aim of this chapter is 1) to survey the asbestos levels measured over time in the city of Thetford Mines and 2) to compare them with levels obtained in studies conducted in other settings and with asbestos criteria established by different organizations. The conditions for the comparisons are the similarity of the sampling protocols and the analytical methods employed by the studies.

3.1 INDOOR AIR

The only study that characterized asbestos in indoor air in the city of Thetford Mines is the AVAQ study. The sampling protocol, the analytical methods and the results have already been presented at point 2.2.2 and in Appendix 1.

3.1.1 Comparison with other settings

The AVAQ results are compared with those of Dion and Perrault (2000), Chatfield and Kominsky (2001), the U.S. EPA (2003b) and Lee and Van Orden (2008). In all these studies, the concentrations inside buildings were determined by TEM. The AVAQ, Chatfield and Kominsky and the U.S. EPA used the direct method. Dion and Perrault used the direct method for 80.5% of the samples. Lee and Van Orden do not specify the method used.

At the end of the 1990s, Dion and Perrault sampled asbestos in 17 schools having ACM (n = 77). These schools were selected based on the following criteria: high concentration of asbestos in ACM, high level of degradation of sprayed asbestos[d] and moderate to high friability of ACM. Additionally, the sampling of the rooms (e.g.: gymnasium, classrooms, corridors) took place under the normal conditions of occupation.

On September 18, 2001, Chatfield and Kominsky sampled the indoor air of two apartments (n = 6) affected by the collapse of the World Trade Center (WTC) towers in order to characterize their degree of asbestos contamination. These apartments were located four streets north of Ground Zero, and their rooms had not been ventilated at the time of the sampling.

In 2002, the U.S. EPA sampled the airborne asbestos in 62 apartments and common rooms of residential buildings in Upper Manhattan, New York City (n = 14) in order to characterize the urban background level of asbestos in Manhattan; these buildings had not been affected by the dust cloud from the destruction of the WTC towers (U.S. EPA, 2003b). When possible, an oscillating fan was placed at the sampling station just as in the AVAQ study. If this was not possible, the air conditioning system was turned on.

[d] Procedure that consisted in pulverizing a basic mixture of asbestos fibres onto walls and ceilings in order to protect them against fire and improve the acoustic insulation. Asbestos spraying has been prohibited in Québec since the end of the 1970s.

Starting in the 1980s and for a period of at least 20 years, Lee and Van Orden measured the asbestos present inside buildings all across the United States that were the subject of litigation relating to the removal of ACM alleged to represent a health hazard. During their study, the researchers took air samples in 317 schools (n = 1,615), 234 public and commercial buildings (n = 1,336) and 5 residences (n = 39). The presence, type and condition of the ACM were examined in these buildings. The authors do not state whether the rooms sampled were ventilated or not.

Table 7 compares the AVAQ results obtained using the AHERA protocol with those of the U.S. EPA and of Lee and Van Orden. The U.S. EPA average concentration was calculated by attributing to the results below the detection limit (DL) a value equal to half the DL. Lee and Van Orden, however, attributed a value of zero to results below the detection limit. For AVAQ, only one result was below the DL, and the average remained unchanged irrespective of the value given to the values below the DL.

Table 8 compares the AVAQ PCMe fibre concentrations with those of Dion and Perrault, Chatfield and Kominsky and Lee and Van Orden. The averages of Dion and Perrault, and of Lee and Van Orden were estimated by attributing a value of zero to the results below the DL. This same rule was applied to the AVAQ results and to two of the six samples of Chatfield and Kominsky in which no asbestos fibre was found. In addition, it should be noted that the counting criteria for asbestos fibres are not exactly the same for each pair of authors.

The average concentration in asbestos structures, measured in the residences of the city of Thetford Mines, is between 28 and 46 times higher than the concentrations found in the residences and public and commercial buildings in the United States (Table 7). When the concentration is expressed in PCMe asbestos fibres, the average concentration obtained by the AVAQ is between 36 and 45 times higher (Table 8). However, the difference with U.S. schools is slightly less significant; the results of the AVAQ study are between 4 (s/ml) and 16 times (PCMe/ml) fibres higher than those obtained in the study by Lee and Van Orden (Tables 7 and 8).

Also, the average asbestos structure concentration, measured in the indoor air of the houses sampled in Thetford Mines, is 232 times higher than that found inside Upper Manhattan residences in New York City (Table 7).

Moreover, the average PCMe fibre concentration in Thetford Mines is 1.4 times lower than that found a few days after the events of September 11 in two residences affected by dust from the collapse of the WTC towers (Table 8).

The comparison with schools in Québec, where degraded ACM were present, shows that the average concentration in asbestos fibres obtained by Dion and Perrault is 1.7 times higher than that reported by the AVAQ (Table 8).

Table 7: Comparison of s/ml concentrations in the AVAQ study with those found during two other studies

	AVAQ (Marier et al., 2007)	U.S. EPA (2003b)	Lee and Van Orden (2008)[a]
Place	Residences in the city of Thetford Mines	Residences in Upper Manhattan (New York City)	Buildings across the United States
Counting criteria	L > 0.5 µm L/D > 5:1	NA	L ≥ 0.5 µm L/D ≥ 5:1
Detection limit	0.004	0.0004	0.0030
n	28	48	S: 1.615 R: 39 PB: 590 B: 746
Arithmetic mean	0.051	0.00022	S: 0.013 R: 0.0018 PB: 0.0014 B: 0.0011

[a] For certain samples in this study (percentage unknown), the total air volume collected is below what is required by the AHERA protocol.

S: schools.

R: residences.

PB: public buildings.

B: businesses.

n: number of samplings.

NA: information not available.

Table 8: Comparison of PCMe fibre/ml concentrations in the AVAQ study with those found during three other studies

	AVAQ (Marier et al., 2007)	Dion and Perrault (2000)	Chatfield and Kominsky (2001)	Lee and Van Orden (2008)
Place	Residences in the city of Thetford Mines	Schools in Québec with presence of degraded ACM	Residences four blocks north of Ground Zero (New York City)	Buildings across the United States
Counting criteria	L > 5 µm D: 0.25-3 µm L/D > 3:1	L ≥ 5 µm D: < 3 µm L/D > 3:1	L > 5 µm D: > 0.25 µm L/D ≥ 3:	L ≥ 5 µm D: ≥ 0.25 µm L/D ≥ 3:1
Detection limit	0.000553	0.0001 to 0.0037	0.0015 to 0.00022	NA
n	26	77	6	S: 1,615 R: 39 PB: 590 B: 746
Arithmetic mean	0.0018	0.0031	0.0026	S: 0.00011 R: 0.00005 PB: 0.00004 B: 0.00005

S: schools.
R: residences.
PB: public buildings.
B: businesses.
n: number of samplings.
NA: information not available.

3.1.2 Comparison with air quality criteria

The AVAQ results are compared to the air quality criteria described below. Some of the criteria have the force of law such as the AHERA criterion in the United States and the criterion in France.

Québec criterion

The only criterion established in Québec is the MSSS management criterion, defined in connection with the management of asbestos containing materials (ACM) in public buildings.

This criterion was set at 0.01 f/ml[e], and it is interpreted in the following manner: “[…] a value greater than or equal to 0.01 f/ml calls for immediate preventive measures. In a first phase, these can be temporary (e.g.: cleaning), but the rooms should not be used until it is proven by a second sampling that the levels are below 0.01 f/ml. Then, permanent corrective measures must be implemented to ensure, over a period of one year, that the asbestos levels in the ambient air are maintained at the lowest possible level.” (*Comité aviseur sur l’exposition à l’amiante au Québec*, 2000) [translation].

As this is a management criterion utilized in special cases and not a criterion based on health effects, it does not seem relevant to compare the AVAQ results with this criterion.

AHERA criterion

The U.S. AHERA (40 CFR Part 763) is a law requiring schools to implement an inspection program to determine if in-place ACM could release asbestos fibres. The aim of this program is to avoid situations that could represent a risk to human health or the environment (U.S. EPA, 1987).

When corrective measures such as encapsulation or removal of materials are undertaken, designated persons must verify the effectiveness of the measures. These measures are considered satisfactory when the average asbestos concentration in five air samples collected in the affected functional space is not statistically significantly different from the average concentration of five air samples collected outside the affected functional space and, in addition, the average of three control samples does not exceed 70 S/mm^2 of filter or 0.022 structure/ml of air. This value is defined as the filter background asbestos level, meaning the concentration that is considered indistinguishable from the concentration measured on a blank (filter for which no air has been drawn).

A provision in the act also stipulates that, if the average of the samples collected in the affected functional space is < 70 S/mm^2 and the minimum air volumes are collected, the corrective measures are considered complete.

The average of the concentrations measured by the AVAQ using the AHERA protocol is 0.051 structure/ml (Table 7). This concentration simply indicates that on average the samples contained asbestos concentrations greater than those of the blank filters. Again, this is not a criterion based on long-term health effects.

French criterion

In France, since 2003, the *Code de la santé publique* states that owners of buildings in which ACM are found must undertake confinement or removal work, if the asbestos concentrations measured by TEM are > 0.005 f/ml (France, 2008). This criterion replaced that of 0.025 f/ml, which was in effect from 1996 to 2003.

[e] Fibres of a length > 5 μm, a diameter between 0.25 and 3 μm and with an L/D ratio of ≥ 3.

In the legal sense, the notion of building applies to any constructed building, the sole exception being residential buildings having only one lodging (individual homes). The data on which the French criterion is based were not found.

Since the counting rules of the French criterion are not specified and it was not possible to obtain the information on which this criterion was based, it is not compared to the AVAQ concentrations.

WTC criterion

Following the events of September 11, 2001, a multidisciplinary team, comprising members of U.S. public environmental and health agencies established a benchmark concentration for indoor air of 0.0009 PCMe asbestos fibre/ml (COPC Committee of the World Trade Center Indoor Air Task Force Working Group, [COPC, 2003]; U.S. EPA, 2005). This criterion was employed during the cleanup of residences in the Lower Manhattan area most affected by dust from the towers (COPC, 2003). It was determined from the lifetime unit risk available in the U.S. EPA IRIS database, which is 0.23 $(f/ml)^{-1}$ (see Table 2). This reference value represents the asbestos concentration to which a continuous exposure (24 hours/day and 365 days/year) over 30 years would lead to not more than one excess cancer mortality per 10,000 persons.

The lower limit of the 95% CI of the concentration measured in five houses exceeds this reference value, meaning 19% of the samples. According to Lorber et al. (2007), the simple comparison of concentrations measured with a benchmark based on health effects is a screening of potential health impacts. When more than 10% of samples exceed a benchmark, it is appropriate to consider that a health impact could have occurred or could occur.

3.2 OUTDOOR AIR

Ambient air concentrations of asbestos in Thetford Mines have been measured for more than 35 years. Between 1973 and 1982, PCM analysis was employed by the *Association des mines d'amiante du Québec*, but the results of these analyses are not available (Lajoie et al., 2003). As point 2.2.2 indicates, this type of analysis was also utilized by the MDDEP.

TEM analyses have been performed in the region since the beginning of the 1980s. In 1984, Environment Canada and Environment Québec measured in Thetford Mines, using the indirect method, an average concentration of chrysotile fibres > 5 µm of 0.0737 f/ml[f] or 0.010 PCMe fibre/ml (n = 35); the samplers were installed on the roofs of public buildings (Sébastien et al., 1986 cited in Lajoie et al., 2003). In 1997, the *Association des mines d'amiante du Québec* reported an average concentration in the municipality of 0.0040 f/ml (Lebel, 1997 cited in Lajoie et al., 2003).

Then, in 2000 and in 2005, the MDDEP measured the asbestos concentrations above two sites in Thetford Mines backfilled with asbestos-containing mine tailings (Couture and Bisson, 2006; MENVQ, 2001). The mine activities had temporarily ceased at the time or were

[f] This is an estimated arithmetic mean.

in slowdown. The samplers were positioned between 1 and 2 metres from the ground to represent the potential exposure of children. The concentrations determined by the direct method were between 0.00041 and 0.00083 f/ml[g] in 2000 (n = 2) and < 0.0001 f/ml in 2005 (n = 2). Lastly, during the sampling campaign in 2004, the MDDEP analyzed by the direct method seven ambient air samples (see point 2.2.2)

Most of the asbestos fibres identified by TEM were chrysotile, but amphibole fibres were also found. In 1984, between 0.5 and 1% of the asbestos measured in Thetford Mines, Asbestos and Black Lake was tremolite (Sébastien et al., 1986 cited in Lajoie et al., 2003). In 2004, the MDDEP identified 34 amosite fibres and 17 chrysotile fibres in 51 asbestos fibres (Bisson and Couture, 2007).

3.2.1 Comparison with other settings

The airborne asbestos fibre concentrations measured in Thetford Mines in 2004 by the MDDEP are compared with those obtained, during the same study, in the urban areas of Montréal and Québec City as well as in proximity to an inactive tailings site located at Tring-Jonction, a locality near Thetford Mines (Bisson and Couture, 2007). A comparison with the concentrations obtained by Lebel (cited in Lajoie et al., 2003) and by Lee and Van Orden (2008) is also carried out (Table 9).

In 1997, Lebel utilized seven sampling stations in order to characterize the asbestos in the outdoor air of three mining towns in Québec: Thetford Mines, Black Lake (today a sector of the municipality of Thetford Mines) and Asbestos.

In the Lee and Van Orden study, outdoor air samples were taken all across the United States near the same buildings for which indoor air was sampled. The results are presented in Tables 7 and 8.

For these three studies, the authors utilized TEM to analyze their results. However, the counting criteria differ slightly in the three studies. The average of the concentrations measured by the MDDEP in Thetford Mines is calculated by giving to the only result below the DL a value equal to DL/2. The value attributed to the results below the DL in the study by Lebel was not available, while Lee and Van Orden attributed a value equal to zero to these results. The average concentrations for the city of Thetford Mines remain unchanged when a value of zero is applied to the result below the DL. Lastly, the concentrations measured in urban areas and at Tring-Jonction by the MDDEP are all below the DL.

The results in Table 9 indicate that the average asbestos concentrations found in outdoor air in the city of Thetford Mines are 7 times higher than the detection limit in the analytical method employed in the studies conducted by the MDDEP in urban areas in Québec and at Tring-Jonction (0.0006 f/ml). The average concentration in Thetford Mines is 215 times higher than the concentration found for all of the United States. As for the levels measured in 1997 in three mining towns in Québec, they are comparable to the level measured in 2004 in Thetford Mines.

[g] The MDDEP analyzed the fibres based on the following criteria: length > 5 µm, diameter < 3 µm and L/D ratio > 3:1.

Table 9: Comparison of asbestos fibre concentrations (f/ml) measured in Thetford Mines with those found in other settings

	MDDEP, 2004 (Bisson and Couture, 2007)			Mining towns in Québec, 1997 Lebel (cited in (Lajoie et al., 2003)			All of the United States, Lee and Van Orden (2008)
	Thetford Mines (2004)	Urban areas (Montréal and Québec City)	Tring-Jonction	Asbestos	Thetford Mines	Black Lake	
Counting criteria	L > 5 µm D < 3 µm L/D > 3:1	L > 5 µm D < 3 µm L/D > 3:1	L > 5 µm D < 3 µm L/D > 3:1	L > 5 µm D > 0,25 µm L/D ≥ 3:1	L > 5 µm D > 0,25 µm L/D ≥ 3:1	L > 5 µm D > 0,25 µm L/D ≥ 3:1	L > 5 µm D > 0,25 µm L/D ≥ 3:1
n	7	5	2	N/A	N/A	N/A	1,678
Detection limit	0.0006	0.0006	0.0006	N/A	N/A	N/A	N/A
Arithmetic mean	0.0043	-[a]	-[a]	0.004	0.004	0.007	0.00002

[a] All the results obtained are below the detection limit.

n: Number of samples.

N/A: Information not available.

Similarly, the total fibre concentrations that the MDDEP measured in 2004 in Thetford Mines, Montréal, Québec City and Tring-Jonction are compared (Bisson and Couture, 2007). Figure 1 illustrates the average total fibre concentrations analyzed by PCM by the MDDEP (Bisson and Couture, 2007). We observe that the total fibre concentration is approximately 3 to 4 times higher in Thetford Mines than in urban areas (Montréal and Québec City) and at Tring-Jonction.

The high number of samples, between 54 and 63 in each city, made it possible to perform a statistical analysis of the differences noted among the average concentrations. Since the results do not follow a normal distribution, the nonparametric tests of Kolmogorov-Smirnov (KS) and Mann-Whitney (MW) were used. The statistically significant level was set at 1%.

The differences in the average total fibre concentrations between the two stations of Thetford Mines and among the four urban stations (in Montréal and Québec City) were analyzed in a first phase. Then, the differences between the concentrations in Thetford Mines and those in urban areas were analyzed, as were the differences between the concentrations in Thetford Mines and Tring-Jonction.

Overall, the average total fibre concentrations of the two stations in Thetford Mines are not statistically different from each other; the same is true for the stations in Montréal compared to each other and the stations in Montréal and Québec City compared to one another (Table 10). However, the average total fibre concentration measured in Thetford Mines is statistically different from that measured in urban areas and from that measured at Tring-Jonction (Table 10).

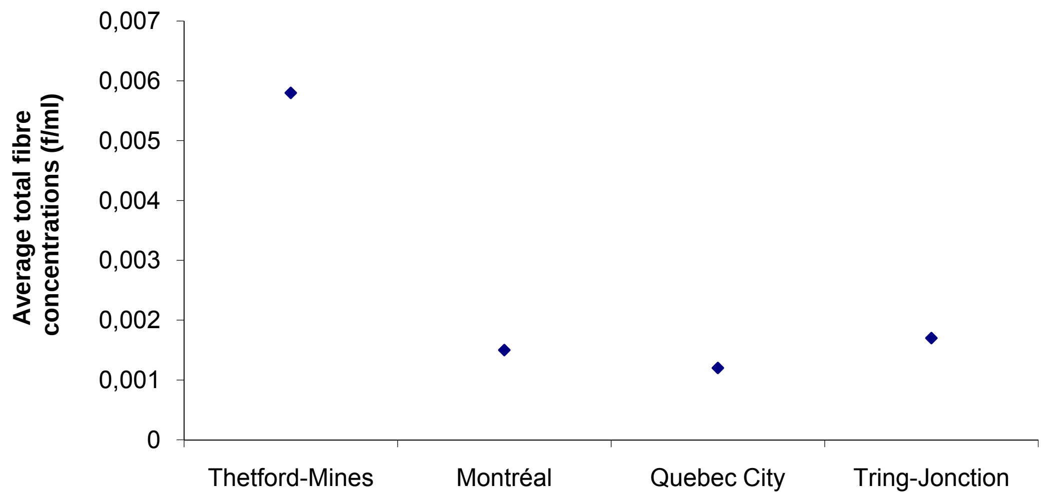

Figure 1: Average total fibre concentrations (f/ml) in ambient air analyzed by PCM by the MDDEP

Table 10: Results of statistical analyses of the average total fibre concentrations (f/ml) found by the MDDEP in different cities in Québec

Places compared (number of results compared)	Statistical significance	KS	MW
Thetford Mines: École Saint-Noël and Maison de la culture (n = 63 versus n = 62)	ns	p = 0.072	p = 0.042
Montréal: Ontario Street and Boulevard Châteauneuf (n = 31 versus n = 31)	ns	p = 0.253	p = 0.140
Montréal and Québec City (n = 62 versus n = 54)	ns	p = 0.712	p = 0.266
Urban areas[a] and Thetford Mines (n = 116 versus n = 125)	ss	p < 0.0001	p < 0.0001
Tring-Jonction and Thetford Mines (n = 58 versus n = 125)	ss	p < 0.0001	p < 0.0001

[a] Montréal and Québec City.
ns: Difference statistically not significant.
ss: Difference statistically significant.
KS: Kolmogorov-Smirnov test.
MW: Mann-Whitney test.

3.2.2 Comparison with air quality criteria

Ontario Ministry of the Environment

The Ontario Ministry of the Environment (OME) adopted an ambient air quality criterion for asbestos of 0.04 f/ml under Ontario Regulation 419/05 “Air Pollution – Local Air Quality” (Ontario Ministry of the Environment, 2005). In effect since 1976, this criterion takes into account fibres > 5 µm in length and with a L/D ratio of ≥ 3, and it establishes an average concentration not to be exceeded over a 24-hour period. It was proposed by the Ontario Health Minister at the time, who retained the workplace criterion of 0.4 f/ml recommended by the British Occupational Hygiene Society, and applied it to a safety factor of 10. The Ontario criterion is based on a 95% probability of having less than 1% risk of developing clinical evidence of asbestosis (A. Szakolcai, personal communication, March 12, 2008). It should be noted that ambient air concentrations that are compared to the Ontario criterion must be analyzed by TEM (C. Doehler, personal communication, September 6, 2007).

Since this criterion is based solely on a probability of onset of asbestosis, the outdoor air concentrations measured in Thetford Mines are not compared to the Ontario criterion in this report, in which it is the mortality risk of lung cancer and mesothelioma that is being assessed.

City of Montréal

The city of Montréal adopted an ambient air quality standard for asbestos of 0.05 f/ml under regulation 90 of the CUM (Montreal urban community) (modified by regulations 90-1, 90-2 and 90-3) (City of Montréal, 2008). However, the city does not specify the bases of this standard. Consequently, the concentrations found in Thetford Mines are not compared to the Montréal standard.

4 DISCUSSION

4.1 RISKS OBTAINED USING THE MSSS METHODOLOGY GUIDELINES

The risk assessment was first conducted using the approach adopted by the MSSS (2002) for carcinogenic substances. The results obtained are the following: the estimation of the lifetime excess mortality from lung cancer and from mesothelioma arising from a continuous lifetime exposure to the concentrations measured in indoor air and outdoor air in the city of Thetford Mines is between 72 and 125 per 100,000 persons exposed.

These risk levels were calculated using lifetime unit risks obtained from 3 organizations and using asbestos concentrations found in the indoor air of the 26 houses sampled by the AVAQ and those measured in the outdoor air by the MDDEP. They apply to the whole population (smokers and non-smokers as well as men and women combined). Also, the toxic potential of amphiboles and chrysotile is considered as being the same.

Uncertainties

This assessment contains several uncertainties. First, there are those related to the determination of the lifetime unit risks. In fact, the data obtained among workers are limited notably by the following factors: the difficulty of characterizing past exposures, the variations in the sampling and analysis methods (e.g.: fibre counting criteria), the mismatch between the subjects in the cohort and in the selected control population and the inadequate description of confounding factors such as smoking habits. Then, it must be assumed that the control population retained in the determination of the lifetime unit risks has the same smoking habits as the exposed population (Camus, Siemiatycki and Meek, 1998). According to Nicholson (1986), the entire population of the United States was comprised of approximately 67% male smokers and 33% female smokers at the time he published his report. According to Statistics Canada data, the percentage of smokers in the province of Québec and in the Chaudière-Appalaches region was approximately 24% in 2005 (Shields, 2007). As well, the risk during low-dose exposures could be less than what is predicted by the linear model. The statistics models utilized to extrapolate the results obtained from cohorts of workers exposed to high doses could have overestimated the dose-response relationship. A study by Camus et al. suggests that the lung cancer risks estimated on the basis of the K_L utilized by Nicholson, the U.S. EPA and the HEI-AR are 10 times higher than the risk established between 1970 and 1989 in a population of women in the regions of Thetford Mines and Asbestos, exposed to asbestos in their environment.

Second, there are also uncertainties regarding the concentrations employed to determine the average lifetime exposure dose. First, the results of the AVAQ study must be interpreted with caution, because the sampling conditions were not all complied with. As well, the residences in which a sample was taken were all located within 2 kilometres or less of the mine tailings sites. Moreover, the characterization studies of outdoor air concentrations conducted by the MDDEP, which were not performed to assess population risk, do not optimally reflect the real exposure of an individual, because the measurements for these studies were taken on building rooftops (see the section Points of clarification in Appendix 1). In addition, the UL of the 95% CI of the asbestos concentrations in outdoor air, which is to say the value retained as exposure datum, was estimated and not measured. Finally, almost all the indoor air and outdoor air samples were taken under the prevailing winds.

Third, in the specific context of this risk assessment, the fibre concentrations should be determined by PCM (U.S. EPA, 1993). In fact, the lifetime unit risks are derived from workplace data where concentrations have generally been analyzed by this type of microscopy, because the nature of the fibres is already known. However, concentrations analyzed by TEM have often been retained as exposure data in similar risk assessments (COPC, 2003; Lee and Van Orden, 2008; Lioy, Zhang, Freeman, Yiin and Hague, 2002; Lorber et al., 2007; Nolan et al., 2005; Weis, 2001). This is explained by the fact that several types of fibres are present in the environment, and TEM makes it possible to distinguish the asbestos fibres. When TEM is employed, it is preferable to count the PCMe fibres.

In Québec, the PCM counting criteria (IRSST 243-1) are the following: fibres > 5 µm in length, < 3 µm in diameter and with a L/D ratio > 3:1. In addition, PCM magnification does not permit distinguishing fibres thinner than 0.25 µm. In the AVAQ study, the fibres > 5 µm, with a diameter > 0.25 and < 3 µm and with a L/D ratio of > 3:1 were analyzed by TEM. Therefore, these are PCMe fibres. The MDDEP also utilized these same criteria in TEM, but in addition, analyzed fibres < 0.25 µm in diameter (Y. Couture, personal communication, June 19, 2008). Thus, the fibres counted are not exactly PCMe fibres, and this constitutes an additional uncertainty.

4.2 RISK OBTAINED USING THE BERMAN AND CRUMP MODEL

Lifetime excess mortality from lung cancer and from mesothelioma arising from a continuous lifetime exposure to concentrations measured in indoor air and outdoor air in the city of Thetford Mines corresponds to 8.2 per 100,000 persons exposed when it is determined using the Berman and Crump model.

Once again, this model targets the whole population (smokers and non-smokers and men and women combined). Its main advantage is that it permits the use of mortality rates that can apply to the appropriate control population. In addition, it is based on the dose-response models established by Nicholson, but it integrates more recent epidemiological data. In 2003, a group of experts from the U.S. EPA greeted favourably the analysis by Berman and Crump (Renner, 2007). However, the agency has not updated the information relative to asbestos in the IRIS database since that time, and it still uses the works of Nicholson to determine risks (U.S. EPA, 1993).

Uncertainties

The uncertainties mentioned in Section 4.1 with regard to the concentrations employed to determine the average lifetime exposure dose are also valid with this model. In addition, Berman and Crump calculated the potency factors in Table 6 based on an exposure to “pure” chrysotile. However, the AVAQ and MDDEP studies showed the presence of amphiboles, but it is not possible to know their exact concentration. Only Sébastien et al. reported tremolite concentrations between 0.5 and 1% in Thetford Mines (Lajoie et al., 2003). According to Berman and Crump, since the potential risk from amphiboles is approximately

3 times higher for lung cancer and 769 times higher for mesothelioma, the risk may be underestimated.

Finally, Berman and Crump recommend first to calculate the risks for sub-groups of smokers and non-smokers and then to apply them to the general population. Nevertheless, this type of data relative to the Québec population was not available at the time the analysis was performed. That is why the mortality rates among men and women in the Chaudière-Appalaches health and social service region were employed in order to estimate the risk for the whole population.

4.3 BACKGROUND RISKS

For comparative purposes, the risks associated with the background rate, meaning the asbestos fibre concentrations generally found in the environment[h], are estimated. For outdoor air, the HEI-AR indicates ambient levels on the order of 0.00001 f/ml in rural areas (with the exception of mining regions) and up to 0.0001 f/ml in urban areas. In Montréal, 10 samples were collected in the year 1984, and the average concentration obtained by TEM was 0.0009 f/ml (Sébastien et al*.,* 1986, cited in Lajoie et al*.*, 2003). Lee and Van Orden calculated an average of 0.00002 PCMe fibre/ml for samples taken across the United States (Table 9). The data on background concentrations inside residences are even more limited. As well, the available studies were conducted almost solely in residences having ACM. According to the HEI-AR (1991), the average concentration in these residences is 0.00019 f/ml. Lee and Van Orden mention an average concentration of 0.00005 PCMe fibre/ml for residences having ACM (Table 8).

Utilizing Lee and Van Orden's outdoor background rate of 0.00002 PCMe fibre/ml and the HEI-AR's indoor background rate of 0.00019 f/ml, the average lifetime exposure dose is equal to 0.00018 f/ml. That is 17 times lower than the average lifetime exposure dose calculated for the city of Thetford Mines. But the risks are also approximately 17 times higher. In fact, they range from 0.46 to 7.1 per 100,000 persons depending on the approach utilized (Berman and Crump model or MSSS guidelines). This is an approximate estimation and gives a general idea of the gap between the risks calculated in this study for the Thetford Mines population relative to those incurred by a population living in an environment where sources of asbestos exposure are limited.

4.4 RISK MANAGEMENT GUIDE VALUE

According to the MSSS guidelines (2002), when the lifetime unit risk is greater than 1 excess cancer per 1,000,000 persons exposed, an examination by government organizations is required. In addition, an environmental management of the contaminants is necessary. This environmental management involves:

- "[…] the implementation and application of the best ways to diminish at the source emissions, tailings or exposure to contaminants

[h] There are two types of background: naturally present concentrations and diffuse concentrations from human activities (U.S. EPA, 2008).

- the implementation and application of the most appropriate control methods
- […] the surveillance of affected areas and populations in order to ensure the integrity over time of the control measures” [translation]

This guide value was proposed mainly because it is important to reduce as much as possible exposure to carcinogenic environmental chemical contaminants. However, according to the lifetime unit risks shown in Table 2, the risk of 10^{-6} is reached at average lifetime exposure doses between 2.5 X 10^{-6} and 4.3 X 10^{-6} f/ml. Yet, according to the asbestos characterization studies consulted, such values are not detectable. Also, the background values mentioned above are at least one order of magnitude higher than 10^{-6} f/ml. Thus, these points illustrate that, in the specific case of asbestos, the guide value of 10^{-6} is not appropriate and that another value should be considered. Regulatory bodies sometimes retain a guide value that varies between 10^{-4} and 10^{-5}, for any substance (MSSS, 2002).

Lastly, each case should be discussed with the population and the groups concerned. In addition, the economic, technological, social, ethical, legal, cultural and political factors should be considered in the decisions to be adopted (MSSS, 2002).

4.5 COMPARATIVE ANALYSIS OF CONCENTRATIONS MEASURED IN THE CITY OF THETFORD MINES

The evaluation of asbestos concentrations in the ambient air of Thetford Mines is difficult, given the few studies available and the differences among the sampling and analysis methods employed in the studies.

The studies compared in this report have very similar sampling and analysis protocols and also comprise some dissimilarities; for example, the utilization or the non-utilization of a fan in the room where the sampling took place and the fibre counting criteria.

Overall, the average concentration of asbestos fibres or structures measured in the air of residences in the city of Thetford Mines is:

- between 4 and 46 times higher than those recorded in the United States in schools, residences and public and commercial buildings containing ACM;
- 232 times higher than the background measured in Upper Manhattan apartments in New York City;
- 1.4 times lower than that measured in two residences affected by dust from the collapse of the WTC towers a few days after September 11, 2001;
- 1.7 times lower than that found in Québec schools, which showed a high level of degraded ACM.

The average concentration measured by the AVAQ is also higher than the criterion adopted for the cleanup campaign of residences in New York City affected by the destruction of the WTC (0.0009 f/ml). This criterion was developed with the aim to protect the population against the risk that an exposure to asbestos might represent in the development of lung cancer and mesothelioma. When 10% of the samples are higher than a benchmark based on health effects, it indicates there might be a health impact (Lorber et al., 2007). Five samples out of twenty-six, or 19%, collected in residences in the city of Thetford Mines exceed this criterion. Since the other criteria for indoor air are not based on health effects, they are not compared to the AVAQ results.

The average asbestos fibre concentration, calculated using outdoor air samples taken by the MDDEP in the city of Thetford Mines:

- has remained stable since 1997;
- is 215 times higher than that measured in samples taken across the United States;
- is, relative to urban areas in Québec and at Tring-Jonction where no asbestos fibre was detected, 7 times higher than the detection limit of 0.0006 f/ml.

Similarly, the average total fibre concentration in the outdoor air of the city of Thetford Mines is statistically higher than that measured in urban areas in Québec and that obtained at Tring-Jonction. Lastly, these results were not compared with Ontario's ambient air criterion, because the present study evaluates carcinogenic risks while the Ontario criterion does not consider this effect. These same results were not compared with the Montréal criterion since the basis of the study is not available.

CONCLUSION

The main objective of this analysis was to assess the human health risk arising from the presence of asbestos fibres in the ambient air and indoor air of residences in the city of Thetford Mines. To do this, the concentrations measured by the AVAQ inside residences as well as those taken by the MDDEP in the ambient air were utilized. The cancer risk assessment was performed using two approaches, that proposed in the MSSS *Lignes directrices pour la réalisation des évaluations du risque toxicologique pour la santé humaine* (guidelines to assess toxicological risk for human health) and that of Berman and Crump. Next, the asbestos levels measured in the city of Thetford Mines were compared with those found during studies conducted in the same region at other periods and those obtained in other settings. They were then compared to asbestos criteria established by different organizations.

The lifetime mortality risk for (or lifetime excess mortality from) lung cancer and mesothelioma, which was estimated using the approach in the MSSS guidelines, is 72, 110 and 125 per 100,000 persons continuously exposed for 70 years, depending on the lifetime unit risk used. That estimated by the Berman and Crump model is 8.2 per 100,000 persons. This risk is approximately 17 times higher than that estimated from background concentrations. The asbestos concentrations in indoor air and outdoor air are also higher than those found in other settings (e.g.: other residences, public buildings, urban area). As well, more than 10% of the airborne samples taken in houses exceed a benchmark based on long-term health effects.

The conclusions of the cancer risk assessment must be interpreted with caution however, owing to the uncertainties and the methodological limitations discussed above. In both risk assessment approaches, the asbestos concentrations employed to estimate exposure doses come from air characterizations carried out by the AVAQ inside residences and from outdoor concentrations measured at ambient air stations sampled by the MDDEP. The risk levels estimated in this study cannot be extrapolated to the entire population of Thetford Mines except to the extent that the concentrations from these two data sources are representative of the concentrations to which the whole population of the city is exposed. It would be appropriate to test the risk estimated by the two approaches against recent epidemiological data on lung cancer and mesothelioma of the pleura in Thetford Mines to determine if there is an overestimation or underestimation of the risk, even though the epidemiological data available in the 2000s is derived from exposure that took place between the 1960s and the 1980s approximately. Notwithstanding the uncertainties and limitations mentioned above, the results of the risk assessment and of the comparative analysis of asbestos concentrations measured in the city of Thetford Mines suggest a health risk attributable to the presence of airborne asbestos in this region.

Finally, this procedure aimed to provide scientific information to the public health authorities in the Chaudière-Appalaches and Estrie regions and to the MSSS that are responsible for guiding public health decisions related to the management of environmental risks associated with asbestos exposure in Québec mining towns. This document does not attempt to pass judgement on the acceptability of the risks. However, it is important to point out that, according to the WHO, there is no evidence of a safe threshold for the carcinogenic effects of asbestos, and an increased cancer risk has been observed in populations exposed to very low concentrations of asbestos (WHO, 2006b). In light of this, it is desirable to reduce exposure as much as possible. Consequently, certain control measures must be considered such as prohibiting access to mine tailings sites, and halting the use of mine tailings for backfill and for abrasive or other purposes. In addition, it would be appropriate to take new measurements of airborne asbestos in Thetford Mines in order to monitor asbestos exposure over time, to ensure that is does not increase.

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APPENDIX 1

SYNTHESIS OF THE VARIOUS STUDIES RELATED TO ASBESTOS IN THE INDOOR AND OUTDOOR ENVIRONMENT IN THETFORD MINES

PREPARED BY GEORGES ADIB

SETTING THE CONTEXT

Between 2000 and 2005, four studies were conducted in relation to asbestos exposure in Thetford Mines.

Three of these studies were conducted by the Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP) between 2000 and 2005. The fourth was piloted by Marier et al., on behalf of the Association des victimes de l'amiante du Québec (AVAQ). It was carried out between 2003 and 2004 and published in the form of an article in the U.S. *International Journal of Occupational and Environmental Health* in December 2007.

Following the publication of the AVAQ study in December 2007 and in light of the three MDDEP studies, INSPQ received the mandate to assess the health risk arising from the asbestos levels found in the indoor and outdoor environment in Thetford Mines.

To do this, the INSPQ team performed a detailed analysis of the four studies with regard to the methodology adopted, the results obtained, and the conclusions and recommendations expressed by the authors.

This document is a summary of the parameters of the four studies. They are presented in the form of tables so the studies can be compared with one another (Tables 1 to 5).

The evaluation of the studies and the comments made by the INSPQ team are presented in Tables 6 and 7.

Lastly, we find it is important to make some clarifications that did not appear in the three MDDEP studies, but that the INSPQ team was able to obtain following a meeting with the professionals in this ministry in March 2008. These clarifications can be found at the end of this document.

Studies evaluated

1. **Concerning the sampling of asbestos fibres in Thetford Mines in relation to the utilization of asbestos tailings as backfill:**
   - First study carried out in 2000 (two documents):
     a. Centre d'expertise en analyse environnementale du Québec. *Échantillonnage et analyse de l'air ambiant: 26 juillet au 2 août 2000 (sampling and analysis of ambient air: July 26 to August 2, 2000).* (November 10, 2000).
     b. Ministère de l'Environnement du Québec, Service des lieux contaminés. *Rapport des travaux du comité directeur sur l'amiante - Dossier remblais d'amiante (report on the work of the asbestos steering committee – issue of asbestos backfill.* (November 27, 2000).
   - Second study carried out in 2005 (two documents):
     a. Memorandum sent by Mrs. Renée Gauthier of the MDDEP and Dr. Albert Nantel of the INSPQ, to Mrs. Ruth Drouin concerning the results of the asbestos fibre sampling in Thetford Mines (December 8, 2005).
     b. Couture, Y. and *Bisson*, M. *Rapport sur l'échantillonnage des fibres d'amiante à Thetford Mines (report on the asbestos fibre sampling in Thetford Mines)*. Québec: Ministère du Développement durable, de l'Environnement et des Parcs, Direction du suivi de l'état de l'environnement Québec. (April 2006).

2. **Concerning the sampling of asbestos fibres in the ambient air of Québec:**
   - Couture, Y. and Bisson, M. (November 2007). *Les fibres d'amiante dans l'air ambiant au Québec: analyse des données disponibles (asbestos fibres in the ambient air in Quebec: analysis of the available data)*. Québec: Ministère du Développement durable, de l'Environnement et des Parcs, Direction du suivi de l'état de l'environnement. [Study carried out in 2004].

3. **Concerning the sampling in residences in Thetford Mines:**
   - Marier, M., Charney, W., Rousseau, R., Lanthier, R. and Van Raalte, J. (2007) Exploratory sampling of asbestos in residences near Thetford Mines: the public health threat in Quebec. *Int J Occup Environ Health*, *13*, 386-397.

Table 1. Technical data on samplings

Title of the study	Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill		Asbestos fibres in ambient air in Quebec: analysis of the available data	Exploratory sampling of asbestos in the residences of Thetford Mines
	1st study	2nd study		
Author(s) / Organization(s)	Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP), in collaboration with the Centre d'expertise en analyse environnementale du Québec (CEAEQ)	Michel Bisson and Yvon Couture, MDDEP	Michel Bisson and Yvon Couture, MDDEP, in collaboration with the CEAEQ	Micheline Marier et al., Association des victimes de l'amiante du Québec (AVAQ)
Objective(s)	"To verify the potential risk specifically associated with lands containing asbestos backfill, without considering the potential contribution from mine tailings sites."	"To provide follow-up data to the data acquired in 2000 […] to verify if there exists a potential risk associated with lands containing asbestos tailings."	"To assess the general situation in Quebec (*levels of asbestos fibres in ambient air*) against the Ontario criterion (0.04 f/ml), rather than to determine short term concentrations in absolute value."	"(*To determine if*) asbestos is present in the environment of the mines and mine tailings sites in the region of Thetford Mines, to the point of posing a risk for residents."
Period / date	July 26 to August 2, 2000	October 4 to 12, 2005	January 31 to August 31, 2004	• August 12, 2003 • From November 7 to 9, 2003 • From July 30 to August 1, 2004
Placement	• Two sites in Thetford Mines: Centre communautaire (*St-Maurice*)[a] and near a schoolyard (*St-Gabriel*)[b] • A site in a rural area of Thetford Mines (*Chemin de la colline*)[c]	• Two sites in Thetford Mines: Centre communautaire (*St-Maurice*) and 10 metres south of the same schoolyard (*St-Gabriel*) • A site in a rural area of Thetford Mines (*Chemin de la colline*)	• Two sites in Thetford Mines: Maison de la culture[d] and a school (*St-Noël*)[e] • A site in a city with inactive mine and tailings sites (*Mine Carey, Tring-Jonction*)[f] • Three sites in urban areas (2 in Montréal, 1 in Quebec City)[g]	Indoor environment of 26 residences in the region of Thetford Mines[h]

[a] Site in a residential and recreational neighbourhood characterized by the presence of significant quantities of covered asbestos tailings.

[b] Site behind a residence bordering the schoolyard, in which a large part of the ground is constituted of uncovered tailings.

[c] Site where the presence of uncovered tailings seems to be limited to a few residential driveways.

[d] Site chosen to characterize a neighbourhood next to the mine and mill, influenced by the prevailing winds.

[e] Site chosen to represent a part of the city located a bit farther upwind from the mine and mill, influenced by the prevailing winds.

[f] Site chosen to characterize an area in which inactive tailings sites are found.

[g] One site is on Ontario Street in Montréal and another on boulevard Châteauneuf in Anjou to represent a downtown urban area and a neighbourhood influenced by traffic (brake wear); for Quebec City, the site is on rue des Sables, to represent a downtown urban area in which traffic and industrial influences are possible.

[h] The majority of the residences (24/26) were located within a 2-kilometre radius or less of mine tailings sites, of which 20 were in the direction of the prevailing winds and 4 were against the prevailing winds.

Table 1. Technical data on samplings (continued)

Title of the study	Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill		Asbestos fibres in ambient air in Quebec: analysis of the available data	Exploratory sampling of asbestos in the residences of Thetford Mines
	1st study	2nd study		
Specific conditions	• Activities on tailing accumulation areas reduced to a minimum • Minimal mining activities (5 workshifts/18) • Absence of school activities	• Mining operations halted • Normal school activities	• The site of the Maison de la culture in Thetford Mines is the site closest to the mine and mill; it is influenced by the prevailing westerly winds.	• Presence of earthwork materials, covered or not, outside 17 residences of 26. • Three residences with asbestos containing materials: stovepipe insulation (2), vinyl-asbestos linoleum (1). • One person in one residence exposed occupationally, sporadically, to asbestos (changing brake pads). • Use of a fan to put fibres back into suspension.
Number of samples	3 (+ 1 control sample)	3	299 (of which 14 analyzed by optical and electron microscopy simultaneously)	28 (of which 2 not retained by the authors for the results in fibres/ml)
Height of sampling trains relative to the ground (metre)	1.0 to 1.1[a]	1.75 to 2.0[b]	~ 9 (on building roofs)[c]	1.0 to 1.2
Meteorological conditions	• Average temperatures varying between 10 and 27 °C • Generally light winds, almost always in easterly or southerly directions • Relative humidity: data not available • 1/6 rain day	• Average temperatures varying between 3 and 26°C • Relative humidity varying between 70 and 95% • 4/9 rain days	Data not available	Data not available

a Heights chosen in order to sample the air breathed by the most sensitive receptors, namely children.

b Heights differ slightly owing to the different sampling material utilized in 2005; see the discussion at the end of the document (p. 62).

c Data obtained from the MDDEP.

Table 1. Technical data on samplings (continued)

Title of the study	Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill		Asbestos fibres in ambient air in Quebec: analysis of the available data	Exploratory sampling of asbestos in the residences of Thetford Mines
	1st study	2nd study		
Sampling method	• SKC® pumps (Universal PCXR model) • 25 mm diameter tube with cellulose ester filter (PALL® – Gelman Laboratory); pore diameter not specified	• Gilian® pumps (Aircon-2 model) • 25 mm diameter tube with cellulose ester filter; pore diameter 0.8 µm	• Gilian® pumps (Aircon-2 model) • 25 mm diameter tube with cellulose ester filter; pore diameter 0.8 µm	• Micro-Trap Inc® pumps (Micro-Max 1 model) • 25 mm diameter tube with cellulose ester filter; pore diameter 0.45 µm
Volume of air sampled (litre)	25,150 to 25,260 (10,000 for control sample)	24,975 to 25,520	~ 16,000 to ~ 31,000[a]	1,200
Duration (minutes)	10,000	9,990 to 10,208	4,320 to 8,640	80
Method of analysis	Transmission electron microscopy (TEM) and energy-dispersive X-ray spectroscopy (EDS): **NIOSH 7402 direct method**	TEM and EDS: **NIOSH 7402 direct method**	• Phase contrast microscopy (PCM): **IRSST 243-1 method** (299 samples) • TEM: **NIOSH 7402 direct method** (14 samples)	TEM and EDS: • **AHERA modified method** • **NIOSH 7402 direct method**
Comparison criterion	No criterion retained	No criterion retained	Ontario criterion for ambient air quality for asbestos: 0.04 f/ml[b]	• AHERA criteria of 70 structures/mm² of filter (equivalent to 0.022 structure/ml) • World Trade Center (WTC) criterion of 0.0009 f/ml
Laboratory	McGill University Occupational Health Department (Montréal)	Bodycote Testing Group (Montréal)	• *Centre d'expertise en analyse environnementale du Québec* (Québec) for PCM • Bodycote Testing Group (Montréal) for TEM	Lab/Cor Inc. (Seattle, U.S.A.)

a Volumes estimated using data transmitted by the MDDEP, by multiplying the duration, from 4,320 minutes (3 days) to 8,640 minutes (6 days), by a flow of approximately 3.6 litres/minute.

b In fact, the criterion appears in the Ontario Regulation 419/05 as being 0.04 f/cm3; we preferred to keep the information as it appeared in the MDDEP report (0.04 f/ml), knowing that 0.04 f/ml is equivalent to 0.04 f/cm3.

Table 2. Raw results

Title of the study	Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill					Asbestos fibres in ambient air in Quebec: analysis of the available data			Exploratory sampling of asbestos in the residences of Thetford Mines	
		1st study		2nd study						
Analysis by		TEM		TEM			PCM	TEM	TEM	TEM
Type of fibres		Totals	Asbestos	Totals	Asbestos		Totals	Asbestos	Asbestos structures	Asbestos
Fibre counting criteria		L ≥ 5 µm	L ≥ 5 µm	L ≥ 5 µm	L > 5 µm D < 3 µm L/D > 3:1		L > 5 µm D < 3 µm L/D > 3: 1	Not mentioned	L > 0.5 µm L/D > 5 : 1	L > 5 µm D: 0.25 µm-3 µm L/D > 3: 1
Number of samples	CC-SM É-SG RS-CC Laval*	1 1 1 1	1 1 1 1	1 1 1	1 1 1	MC É-SN CM-TJ Mtl-O Mtl-C Qc	62 63 58 31 31 54	4 3 2 1 2 2	28	26
Arithmetic mean‡ (or sole result) (f/ml)	CC-SM É-SG RS-CC Laval	0.00091 0.00041 < 0.00004 < 0.000075	0.00083 0.00041 < 0.00004 < 0.000075	0.0007 0.0002 0.0004	< 0.0001 < 0.0001 < 0.0001	MC É-SN CM-TJ Mtl-O Mtl-C Qc	0.0075 0.0042 0.0017 0.0017 0.0013 0.0012	0.0039 0.0049 0.0003 < 0.0006 0.0003 0.0003	126.15 s/mm² 0.051 s/ml	0.0019 (**0.0020**)**
Number and type of fibres	CC-SM É-SG RS-CC Laval	-	20(Ch)+ 2(S) 10(Ch) 0 0	-	7(G) 2(G) 4(G)	MC É-SN CM-TJ Mtl-O Mtl-C Qc	-	5-12(Ch)+9(Am)+9-18(G) 4-14(Am) + 5-9(G) 4(Sy) 0 9(Sy) 0	1-48 (Ch) 1(Ac) 1(Tr)	1-13(Ch) 1(Ac) 2(Tr)

L: Length of fibres.
D: Diameter of fibres.
* Site on a piece of land owned by the CEAEQ in Laval to assess background fibres: this is a control sample.
‡ Results below the detection limit were considered in the calculation of the averages such as DL/2.
s/mm² : Asbestos structures per square millimetre of filter.
s/ml : Asbestos structures per millilitre.
** Values in bold in parentheses are calculated without dividing the detection limit by 2.
Ch: Chrysotile; S: Silicates; G: Glass; Am: Amosite; Sy: Synthetic; Ac: Actinolite; Tr: Tremolite

CC-SM: Centre communautaire St-Maurice (Thetford Mines).
É-SG: École St-Gabriel (Thetford Mines).
RS-CC: Rural site, Chemin de la colline (Thetford Mines).
MC: Maison de la culture.
É-SN: École St-Noël (Thetford Mines).
CM-TJ: Carey Mine (Tring-Jonction).
Mtl-O: Ontario Street (Montréal).
Mtl-C: Boulevard Châteauneuf (Montréal).
Qc: Rue des Sables (Quebec City).

Table 2. Raw results (continued)

Title of the study	Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill					Asbestos fibres in ambient air in Quebec: analysis of the available data			Exploratory sampling of asbestos in the residences of Thetford Mines		
		1st study		2nd study							
Type of fibres		Totals	Asbestos	Totals	Asbestos		Totals	Asbestos	Asbestos structures		Asbestos
Median‡ (f/ml)	CC-SM É-SG RS-CC Laval	-†	-†	-†	-†	MC É-SN CM-TJ Mtl-O Mtl-C Qc	0.0046 0.0032 0.0016 0.00075 0.00075 0.00075	0.0041 0.0041 -† -† -† -†	82.70 s/mm² 0.027 s/ml		0.00083
Range of results	CC-SM É-SG RS-CC Laval	-†	-†	-†	-†	MC É-SN CM-TJ Mtl-O Mtl-C Qc	< 0.0015-0.056 < 0.0015-0.015 < 0.0015-0.0078 < 0.0015-0.0054 < 0.0015-0.0052 < 0.0015-0.0041	< 0.0006-0.007 0.0023-0.0082 < 0.0006 -† < 0.0006 < 0.0006	0-662.30 s/mm² < 0.004-0.311 s/ml		< 0.000553-0.010
Proportion of samples > comparison criterion (*see Table 1*)	CC-SM É-SG RS-CC Laval	N/A	N/A	N/A	N/A	MC É-SN CM-TJ Mtl-O Mtl-C Qc	0%	0%	**AHERA** **WTC**	54% (s/mm²) 57% (s/ml) -	- 50%
Detection limit (DL) (f/ml)	TM* Laval	0.00004 0.000075	0.00004 0.000075	0.0001 -	0.0001 -		0.0015	0.0006	0.004 (s/ml)		0.000553
Proportion of samples < DL	CC-SM É-SG RS-CC Laval	0% 0% 100% 100%	0% 0% 100% 100%	0% 0% 0%	100% 100% 100%	MC É-SN CM-TJ Mtl-O Mtl-C Qc	8% 13% 47% 55% 68% 67%	25% 0% 100% 100% 100% 100%	4%		35%

‡ Results below the detection limit were considered in the calculation of the medians such as DL/2.
† The median and the range were not calculated owing to the small size of the sampling (n ≤ 2 in each category).
N/A: Not applicable, no comparison criterion retained for these results.
*TM: Same detection limit for the three sites in Thetford Mines.

Table 3. Combined results (for asbestos fibres and structures only)

Title of the study	Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill		Asbestos fibres in ambient air in Quebec: analysis of the available data	Exploratory sampling of asbestos in the residences of Thetford Mines	
	1st study	2nd study			
Number of samples	(TEM) TM-C: 2 TM-RA: 1	(TEM) TM-C: 2 TM-RA: 1	(TEM) TM-C: 7 MA-IS: 2 UA: 5	(TEM) TM-R: 28 (asbestos structures)	(TEM) TM-R: 26 (asbestos fibres)
Arithmetic mean[‡] (or sole result) (f/ml)	TM-C: 0.00062 TM-RA: < 0.00004	TM-C: 0.00005 TM-RA: < 0.0001	TM-C: 0.0043 MA-IS: 0.0003 UA: 0.0003	126.15 s/mm² 0.051 s/ml	0.0019 (**0.0020**)[*]
Number and type of fibres	TM-C: 10-20(Ch) + 2(S) TM-RA: 0	TM-C: 2-7(G) TM-RA: 4(G)	TM-C: 5-12(Ch) + 4-14(Am) + 5-18(G) MA-IS: 4(Sy) UA: 9(Sy)	1-48 structures (Ch) 1(Ac) 1(Tr)	1-13(Ch) 1(Ac) 2(Tr)
Median[‡] (f/ml)	-[†]	-[†]	TM-C: 0.0041 MA-IS: -[†] UA: 0.0003	82.70 s/mm² 0.027 s/ml	0.00083
Range of results	TM-C: 0.00041-0.00083 TM-RA: -[†]	TM-C: < 0.0001 TM-RA: -[†]	TM-C: < 0.0006-0,0082 MA-IS: < 0.0006 UA: < 0.0006	0-662.30 s/mm² < 0.004-0.311 s/ml	< 0.000553-0.010
Proportion of samples > comparison criterion (*see Table 1*)	TM-C: N/A TM-RA: N/A	TM-C: N/A TM-RA: N/A	TM-C: 0% MA-IS: 0% UA: 0%	**AHERA** 54% (s/mm²) 57% (s/ml) **WTC** -	AHERA: - WTC: 50%
Detection limit (f/ml)	0.00004	0.0001	0.0006	0.004 (s/ml)	0.000553
Proportion of samples < DL	TM-C: 0% TM-RA: 100%	TM-C: 100% TM-RA: 100%	TM-C: 14% MA-IS: 100% UA: 100%	4%	35%

TM-C: City of Thetford Mines (between community, school, Maison de la culture)
TM-RA: Rural area in Thetford Mines
MA-IS: Mining area with inactive tailings sites
UA: Urban area (Montréal and Quebec City)
TM-R: Residences in Thetford Mines
[‡] Results below the detection limit were considered in the calculation of the averages and the medians by dividing the detection limit by 2.

[*] Values in bold in parentheses are calculated without dividing the detection limit by 2.
Ch: Chrysotile; S: Silicates; G: Glass; Am: Amosite; Sy: Synthetic; Ac: Actinolite; Tr: Tremolite
[†] The median and the range are not mentioned owing to the small size of the sampling (n ≤ 2 in each category).
N/A: Not applicable, no comparison criterion retained for these results.

Table 4. Authors' conclusion(s) about the studies

Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill		Asbestos fibres in ambient air in Quebec: analysis of the available data	Exploratory sampling of asbestos in the residences of Thetford Mines
1st study	2nd study		
• "The health risk assessment concluded that the level of exposure to asbestos fibres of the population in the region of Asbestos is higher than that observed in the ambient air of large North American cities. • The utilization of asbestos tailings on land surfaces leads to a low but real exposure to chrysotile asbestos fibres. • Although the health risk for children exposed to this concentration of fibres is low, this exposure adds to that of the known contamination in the ambient air of the municipality due to the mine operations and the mine tailings accumulation areas."	• "No fibre was detected in the samples of this study. In 2000, low concentrations had been observed on two sampling sites. We cannot explain with certainty the differences observed between the two series of results. • […] it is not improbable that another sampling would show fibre concentrations greater than 0 could be measured. Therefore, the recommendation to apply the principle of caution by covering the backfill with an uncontaminated material is upheld." (*Ref. Memorandum of 8-12-2005*)	• "The results of this study did not demonstrate the presence of asbestos fibres in the ambient air in Quebec for the urban area stations. • The mine tailings sites, in place for a certain period of time, do not seem to notably affect the air quality in the region of Asbestos. • We find airborne asbestos fibres in Thetford Mines; however, the total fibre concentrations are approximately 10 times below the Ontario criterion. If we consider only asbestos fibres, the difference is even greater."	• "The results of the analysis of the air, ground and dust lead us to consider that the residential environment in proximity to Thetford Mines is severely polluted by asbestos. • We believe that this pollution comes from the mining environment. In the few houses where there were asbestos-containing materials, the results were not necessarily higher. • The surrounding mine tailings sites, the asbestos tailings utilized in yards or alleys, and the dust released by trucks transporting tailings seem to us to be the main sources of pollution in the houses we visited."

Table 5. Principal recommendations of the authors of the studies

Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill		Asbestos fibres in ambient air in Quebec: analysis of the available data	Exploratory sampling of asbestos in the residences of Thetford Mines
1st study	2nd study		
• " Prioritize intervention in places where asbestos tailings are found on the surface and where children are the most exposed (schoolyards, playgrounds, recreational parks and daycares). • Have residence driveways (containing backfill) covered. • Control access to asbestos tailings accumulation areas."	• "As a precaution, exposure must be limited by covering backfills with an uncontaminated material." (*Ref. Memorandum of 8.12.2005*)	• No recommendations.	• "Immediate cessation of the use of mine tailings for earthworks. • Government assistance to residents to remove or cover tailings already in place around their homes. • Immediate prohibition of access to mine tailings sites. • Measure to stabilize and cover mine tailings sites to abate environmental pollution from asbestos. • Determination of a safety perimeter where it is reasonably impossible to control the pollution generated by tailings and relocation with compensation of residences beyond this safety perimeter. • Extensive sampling campaign to determine the extent of the residential pollution around mines and mine tailings sites, conducted without potential conflict of interest with the asbestos industry. • Professional cleaning of residences, businesses and public areas in these pollution zones. • Inform the public about risks related to mine tailings and about adequate prevention measures. • Support the region to eliminate dependence on asbestos exploitation."

Table 6. Strengths and weaknesses of the studies, identified by the INSPQ team

Title of the study	Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill		Asbestos fibres in ambient air in Quebec: analysis of the available data	Exploratory sampling of asbestos in the residences of Thetford Mines
	1st study	2nd study		
Strengths	• The analytical method utilized (TEM) is adequate for samples in a non-occupational environment. • The air volumes sampled conform to what is prescribed for TEM analysis to obtain optimal fibre densities.	• The analytical method utilized (TEM) is adequate for samples in a non-occupational environment. • The air volumes sampled conform to what is prescribed for TEM analysis to obtain optimal fibre densities.	• The air volumes sampled conform to what is prescribed for analysis by PCM and TEM.	• The analytical method utilized (TEM) is adequate for samples in a non-occupational environment.
Weaknesses	• Given the vast expanse of areas that might contain asbestos backfill, the representativeness of the three single samples at randomly chosen places is debatable. • The study does not satisfactorily meet the selected objective (see p. 1, Table 1) given the non-representativeness of the samples.	• The sampling conditions (period, mining and school activities, weather) were not similar to those in the 1st study.	• The majority of the samples were analyzed by PCM; this method is not adequate in a non-occupational environment where the predominant type of fibres is not known. • The results of the samples taken at Tring-Jonction indicate the situation that prevails in the presence of inactive tailings sites; the portrait might be different in the presence of active mine tailings sites. • Conclusions are drawn about the levels of airborne asbestos fibres in Quebec by assuming that all the fibres counted (total fibres) are asbestos fibres; however, there is no study that reports the existence of a correlation between these two measurements: depending on the case, asbestos fibre concentrations may be underestimated or overestimated in the environment under this assumption.	• The air volumes sampled, and indirectly the density of the fibres collected on the filters, are below what is prescribed in the NIOSH 7402 method for TEM analysis. • Samples are limited to a few residences, all located within a 1 to 2 kilometre radius of mine tailings sites, which does not make it possible to generalize the results to the whole city or the region of Thetford Mines. • The use of a fan to simulate air movements caused by the occupants and to release into circulation the asbestos that might have settled is not a recognized standard method in Quebec. • The authors' recommendations go beyond the scope of the results obtained.

Table 7. General comments on the studies, issued by the INSPQ team

<table>
<tr><th colspan="2">Sampling of asbestos fibres in
Thetford Mines in connection with the use of asbestos tailings as backfill</th><th rowspan="2">Asbestos fibres in ambient air in Quebec: analysis of the available data</th><th rowspan="2">Exploratory sampling of asbestos in the residences of Thetford Mines</th></tr>
<tr><th>1st study</th><th>2nd study</th></tr>
<tr>
<td>• The authors of the study put forward the hypothesis that in a period of slowdown of mining activities, activities on mine tailings sites are also reduced and that consequently, the emissions from mine tailings sites are minimal. However, we do not really know the scope of the emissions from mine tailings sites by natural erosion under the influence of winds or caused by human activities (use of all-terrain vehicles).
• It is believed that the activities of students in schoolyards containing backfill can cause the re-suspension of fibres in the air. However, this study was conducted in the absence of school activities. Therefore, the study cannot be used to measure the potential risk associated with lands containing asbestos backfill as mentioned in the objective (see p. 1, Table 1)
• Owing to these limitations, we consider that this study constitutes the least case scenario.</td>
<td>• This study, conducted in a normal school period, is possibly more representative of the real exposure.
• However, the rainy conditions during the sampling for this study probably downwardly influenced the exposure levels, which makes it more difficult to compare it with the study of 2000.
• We note the total absence of chrysotile fibres in the samples for this study although between 10 and 20 were counted in the 2000 study; this difference was not explained, but probably results from the rainy conditions.</td>
<td rowspan="2">• The study was conducted when mining activities were in a slowdown; it is very possible that the exposure levels are underestimated.
• The number of samples analyzed by TEM is insufficient to present a comprehensive portrait of the environmental exposure.
• In the absence of correlation between the results of the samples analyzed by PCM and those analyzed by TEM, the assumption that all the fibres counted by PCM are asbestos fibres cannot be utilized to draw conclusions on the real exposure to asbestos in the outdoor environment.
• The presence of amosite fibres in the samples remains inexplicable.</td>
<td rowspan="2">• We do not know if the residences were chosen randomly in order to ensure a statistically significant representativeness.
• The results of this study must be interpreted with caution because the volumes of air sampled, and consequently, the fibre densities collected on the filters, do not comply with the requirements of the sampling and analysis methods utilized.
• The comparison of the lower limit of the 95% confidence interval of the results to the criteria retained is not a sound method; it was used by the authors to offset the problem of the small volumes of air sampled.</td>
</tr>
<tr><td colspan="2">The data from these studies are not considered in the risk assessment process owing to:
1. the low representativeness of the samples due to their small number (3)
2. hypotheses supporting the sampling protocol</td></tr>
</table>

POINTS OF CLARIFICATION

The information presented in this section was obtained following a meeting with MDDEP professionals in March 2008. It concerns the three studies conducted by the ministry, which are:

- Sampling of asbestos fibres in Thetford Mines in connection with the use of asbestos tailings as backfill (studies from 2000 and 2005).
- Asbestos fibres in ambient air in Quebec: analysis of the available data (study from 2004).

a. Studies from 2000 and 2005

- The height of the sampling trains varied from 1 to 1.1 metre in 2000 and from 1.75 to 2 metres in 2005. This height variation is due to the different sampling material used in 2005. This variation would not affect the results obtained in the two studies, since experience shows that there is no difference in the levels measured at these heights relative to the distance from the source.
- Meteorological conditions may affect the results obtained; it is probable that dry conditions facilitate particle transportation, while in wet conditions, particles tend to settle; therefore there is less re-suspension of particles into the air.
- The presence of glass fibres in the samples from 2005 could not be explained, but since these two campaigns were limited in time, the MDDEP did not have the time to pursue the investigation.

b. Study from 2004

- The study on ambient air quality in Quebec was initially planned for 3 years, but it was carried out over 6 months owing to budget constraints; it therefore represents a time-limited portrait of the environmental exposure.
- The sampling sites chosen are those that are already in place and that are normally used in the sampling of different contaminants to observe the long-term trends; these sites are located above buildings at an average height of ± 9 metres.
- In general, the data from these sites are compared to current environmental criteria and are not utilized for the risk assessment.
- The devise utilized for the outdoor samples is adapted to temperatures between -20 °C and +45 °C; in addition, the sampling head was covered with a heated (from -5 °C) and ventilated (from 28 °C) cover.
- The term *inactive tailings site* refers to a mine tailings site where tailings are neither added nor removed; in contrast, a mine tailings site that "is unused" is a mine tailings site that is not used by an entrepreneur as a material supply source.
- It is not possible to judge the potential effect of natural erosion of inactive tailings sites on the increase in airborne asbestos concentrations.
- It is believed that the asbestos levels found in Thetford Mines include the contribution of mine tailings sites since it is difficult to distinguish between the asbestos levels from the mine and those from mine tailings sites.
- According to the MDDEP, mining activity (Black Lake and Bell mines) during the period covered by the study (February to August 2004) was in a slowdown; specifically, the Bell mine was in a slowdown from February to April 2004 and the Black Lake mine, from May 2004. The readings taken by the MDDEP when both mines were not operating indicate very low average concentrations of asbestos.
- The Ontario criterion for asbestos in the environment (0.04 f/ml) is derived from occupational standards and is therefore determined on the basis of a phase contrast microscopy (PCM) analysis.
- This criterion is cautious for long-term health effects, because it does not allow deviation around the average; it is a ceiling value not to be exceeded.
- The presence of amosite fibres found in the samples taken in Thetford Mines cannot be explained.

APPENDIX 2

LIFETIME UNIT RISKS ESTIMATION ACCORDING TO THE INSERM

Lung cancer

Lifetime excess lung cancer mortality at age t ($E_L(t)$), attributable to a continuous lifetime exposure to asbestos, is obtained by subtracting the expected lung cancer mortality in the population not exposed to asbestos ($I_{PnE}(t)$) from the lung cancer mortality in the exposed population ($I_{PE}(t)$) at the same age t, where t corresponds to the lifespan.

$$E_L(t) = I_{PE}(t) - I_{PnE}(t) \qquad \textbf{Equation 1a}$$

The value $I_{PE}(t)$ is calculated using Equation 2 of the report. The value $I_{PnE}(t)$ is obtained by dividing the sum of the expected number of lung cancer cases at each age grouping t_i ($\sum N_{PnE}(t_i)$) by a given cohort P_0 of the population at birth (100,000 persons for example) (Inserm, 1997). For the Inserm, each age grouping has a duration of 5 years.

The value $N_{PnE}(t_i)$ is obtained by multiplying the lung cancer mortality rate (number of cases/person*year) of each age grouping t_i by the cohort P_i of the population "at risk of dying" at this age grouping. The cohort P_i is itself based on the all-cause mortality rate of the age grouping t_i and of the cohort of the population "at risk of dying" at age t_i-1 (Inserm, 1997). Mortality rates vary based on several factors besides age, such as year in which they were established, sex, smoking habits and geographic location of the control population.

Lastly, it should be noted that the National Research Council (1984) calculated lifetime excess lung cancer mortality ($E_L(t)$) according to Equation 2a:

$$E_L(t) = I_{PnE}(t) * (K_L * f * d) \qquad \textbf{Equation 2a}$$

Mesothelioma

Lifetime excess mortality for mesothelioma at age t ($E_M(t)$), attributable to a continuous lifetime exposure to asbestos, is obtained by dividing the sum of the number of mesothelioma cases at each age grouping t_i ($N_m(t_i)$) by a given cohort P_0 of the population at birth (100,000 persons for example) (Equation 3a) (Inserm, 1997).

$$E_M(t) = \frac{\sum_{1}^{n=i} N_m(t_i)}{P_0} \qquad \textbf{Equation 3a}$$

The value $N_m(t_i)$ of a given age grouping is obtained by multiplying the mesothelioma mortality rate $I_M(t_i)$, estimated using Equation 3 of the report, by the cohort P_i of the population "at risk of dying." However, according to Nicholson (1986), when the time elapsed since the start of exposure (T) is less than 10 + d, where d equals the exposure duration, Equation 3 of the report can then be expressed in the following way (Equation 4a):

$$I_M(t_i) = K_m * f * \left[(T-10)^3\right]$$ **Equation 4a**

Given that, in the case of a lifelong exposure, T is always less than 10 + d, the values $I_M(t_i)$ can be calculated using Equation 4a.

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