

# **VERMICULITE IS NOT ASBESTOS**

**There are no real causes for concern about health risks from vermiculite: a review of the mineralogy of vermiculite and its fundamental differences to asbestos explains why.**

John Addison  
Addison-Lynch, Edingburgh  
February 1994

## **SUMMARY**

- Vermiculite is a sheet silicate mineral that is found as flaky crystals; it is not a fibrous mineral like asbestos. Fibres of vermiculite can be formed by breakage of the flakes or by curling of the edges of the flakes. Such mineral fibres do not constitute asbestos, and fibrous shape does not, by itself, mean that they will behave like asbestos.
- Vermiculite dusts, including these fibrous fragment forms, have demonstrated very few if any health effects, other than those that could be expected from any low toxicity silicate. Unlike asbestos, vermiculite has shown very few ill-effects in experimental testing with animals. Chemical testing suggests that it may not stay long enough in the lung to do serious damage.
- All vermiculite ores contain a range of other minerals that were formed along with the vermiculite in the rock. Vermiculite ores from some sources were even found to contain asbestos minerals but asbestos is not intrinsic to vermiculite and only a few ore bodies have been found to contain more than tiny trace amounts. Nevertheless serious public concern was generated because of the known occurrences of asbestos in vermiculite deposits such as those in Montana that were closed some years ago
- Asbestos is the name given to a number of naturally occurring fibrous silicate minerals that have been exploited for their useful properties such as thermal insulation, chemical and thermal stability, and high tensile strength. Chrysotile, known as white asbestos and a member of the Serpentine mineral group is the commonest having been used widely in asbestos cements, laggings and textiles. It is also becoming recognised as the least harmful of the asbestos fibres because of its lower chemical stability.

- The amphibole minerals form a very large group with a wide range of chemical compositions united by a common crystal structure. The normal forms for all of the amphiboles are prismatic, blocky, or rodlike crystals. However, certain of the amphiboles, for example grunerite (amosite), riebeckite (crocidolite), tremolite, actinolite and anthophyllite may occasionally occur in asbestos forms although these are rare in comparison to the normal varieties.
- Some confusion has arisen over the definition of amphibole asbestos which has led to the wrong impression that both forms of the amphiboles are the same and equally hazardous. It is now recognised that the prismatic mineral forms and the asbestos forms, even of the same amphibole, are mineralogically distinct, fracture in critically different ways, and the dusts formed by breakage have different effects on health. While asbestos dusts are carcinogenic in animals and humans, the prismatic amphibole dusts are very much less potent, and probably harmless to humans.
- No asbestos related diseases have been found among the workers in any of the vermiculite deposits except those in Montana where the asbestos exposure was known to be very high. Where the possible health effects from industrial exposure to prismatic amphiboles have been examined they have been mostly insignificant or ambiguous at worst.
- A wide range of regulations in Europe and the USA cover the supply, packaging and labelling of materials containing asbestos or other carcinogens, and their use in the workplace. All are relevant to the vermiculite producers, manufacturers and suppliers, who are required to provide health and safety data sheets. While the legislation trigger levels for all asbestos types are currently 0.1% of the bulk material and few vermiculite deposits would fail to meet this standard, recent research shows that a target level of no more than 0.001% for amphibole asbestos would be preferable for the vermiculite industry.

- Analytical techniques using optical and electron microscopy are available or are being developed now to identify and to quantify asbestos in mineral raw materials and products. Detection limits are below the suggested target levels so that it is possible to screen new and established supplies of vermiculite for their suitability.

# **CONTENTS**

## **1 Vermiculite the Mineral**

- 1.1 Vermiculite Fibres
- 1.2 Accessory Minerals in Vermiculite
- 1.3 Health Effects of Vermiculite
- 1.4 Experimental Evidence

## **2 Asbestos**

- 2.1 Chrysotile
- 2.2 Amphibole Minerals
- 2.3 Crystal Form and Cleavage of Amphiboles
- 2.4 Amphibole Asbestos Minerals
- 2.5 Commercial Amphibole Asbestos
- 2.6 Other Amphibole Asbestos Minerals

## **3 The Health Effects of Asbestos**

- 3.1 Asbestosis
- 3.2 Lung Cancer
- 3.3 Mesothelioma
- 3.4 Experimental Evidence of Carcinogenicity
- 3.5 The Importance of Fibre Durability
- 3.6 Health Risks from Other Minerals

## **4 The Regulatory Position**

- 4.1 Asbestos
- 4.2 Asbestos and Carcinogens Legislation
- 4.3 Suitable Action Levels

## **5 Analytical Methods for Asbestos Determination**

- 5.1 General Methods
- 5.2 Optical Microscopy
- 5.3 Scanning Electron Microscopy
- 5.4 Energy Dispersive X-ray Spectrometry
- 5.5 Transmission Electron Microscopy
- 5.6 Quantitative Microscopy

## **6 Conclusions**

## **7 References**

## **8 The Author**

# **VERMICULITE IS NOT ASBESTOS**

**There are no real causes for concern about health risks from vermiculite: a review of the mineralogy of vermiculite and its fundamental differences to asbestos explain why.**

## **1 VERMICULITE THE MINERAL**

Vermiculite is a naturally occurring sheet silicate mineral, usually formed by the hydrothermal alteration of mica minerals such as biotite and phlogopite (Harben and Bates 1990, Brindley and Brown 1980). It ranges in size from microscopic particles of clay mineral to lustrous brown sheets up to half a metre in diameter (MacEwan 1948) although they are usually in the range of 1mm to 1cm diameter. Most vermiculites when heated quickly to above about 230°C will lose their interlayer water and this results in the flakes exfoliating to form concertina shaped particles. Because of its light weight and resistance to thermal decomposition this exfoliated vermiculite is valuable as an insulation material and filler among many other uses.

### **1.1 Vermiculite "Fibres"**

Vermiculite is normally a platy mineral in its natural state. Processing of the ore can sometimes lead to the peeling off or "scrolling" of the surface layers at the edges of crystals forming fibres (Chatfield and Lewis 1980). Parallel fracturing and splitting of vermiculite flakes can also lead to the formation of fibre-shaped fragments. Vermiculite scrolls may be very fine (<0.1 µm diameter) but the vermiculite fragment fibres tend to be fairly coarse (1-2 µm diameter) ribbon-like forms. While all vermiculites may be capable of producing fibres in these ways, the "fibrous" proportions of the bulk material are usually very small, of the order of a few parts per million (by mass).

## **1.2 Accessory Minerals in Vermiculites**

Vermiculite ore deposits, like most other rocks, contain an assemblage of other minerals besides the vermiculite (Addison and Davies 1990). There may be major components such as feldspars, pyroxenes, amphiboles, carbonates, and quartz, as well as minor components such as phosphates, iron oxides, titanium oxides and zircon (Atkinson et al 1982). The full assemblage at any one mine is determined by the nature of the original rock types from which the vermiculite ores were formed. So the vermiculites formed from ultramafic rocks such as phlogopite pyroxenites and serpentinites may contain chrysotile, tremolite and anthophyllite in veins or as altered relics of olivine, pyroxene and mica. Vermiculite ores formed from gneisses or granites are more likely to contain feldspars and quartz; vermiculite formed from carbonates may contain magnesite, calcite and other carbonates, and phlogopite. The proportions of the different accessory minerals may vary depending upon which part of the ore body is being worked, and the proportions in the final product may also vary with the grade of the product. Indeed it may be possible to remove entirely some accessory components during ore treatment. Almost any asbestos type may be present in almost any type of vermiculite deposit just as they may in almost any other igneous or metamorphic rock. Even so, that asbestos would not constitute a measurable health risk if the amount was small.

## **1.3 Health Effects of Vermiculite**

There is very little direct evidence of any specific harmfulness in humans associated with inhalation of respirable vermiculite dust or of vermiculite fibres. Miners and mineral processors in South Africa and South Carolina have shown very few ill-effects even after many years of working history exposed to moderate airborne dust concentrations (Hessel and Sluis-Cremer 1989, McDonald et al 1988). This would seem to indicate that vermiculite itself has relatively low toxicity in comparison to minerals such as chrysotile or quartz.

The workers in these areas will also have been exposed to high cumulative concentrations of the vermiculite fibres without any apparent fibre-related diseases. However, because exposed working populations in the vermiculite epidemiology studies are small and most of the sites have not been working for very long (less than 60 years according to the production dates of Varley, 1952) it is not possible yet to exclude entirely a carcinogenic potential for the mineral or its fibres.

#### **1.4 Experimental Evidence**

Comparatively little biological testing of the health effects of vermiculite or vermiculite fibres has been carried out (Hunter and Thomson 1977, Swensson 1975, 1979). The results have all shown vermiculite to be of low toxicity in comparison to minerals such as quartz. There has been no specific testing of the chemical durability of vermiculite but its behaviour in acids is similar to that of chrysotile. Since the low chemical durability of chrysotile means that it does not persist in the lungs after inhalation over long periods of time it is fair to suggest that vermiculite would be no worse. Similarly if low durability is the reason why chrysotile is now considered to have low carcinogenicity in humans the same must also be said for vermiculite. This contrasts markedly with the highly durable amphibole asbestos minerals such as crocidolite and amosite which persist for many decades in the lungs of exposed persons and are highly carcinogenic (Churg et al 1984).

## **2 ASBESTOS**

Asbestos is the name given to the fibrous forms of a number of naturally occurring silicate minerals that have been exploited commercially for their useful properties of flexibility, high tensile strength, incombustibility, low thermal conductivity, and resistance to chemical attack. The predominant commercial variety is chrysotile (white asbestos), one of the serpentine group of minerals, which constitutes more than 95% of all asbestos that has ever been used.

The other asbestos varieties include amosite, crocidolite, anthophyllite asbestos, actinolite asbestos, and tremolite asbestos all of which belong to the amphibole group of minerals. Of these minerals only amosite and crocidolite have had wide commercial use (HSE 1993).

## **2.1 Chrysotile**

Chrysotile is the only asbestos mineral in the serpentine group, and is almost unique in the mineral world as a sheet silicate that attains its fibrous form because the silicate sheets are rolled into individual fibrils each one about 0.025 microns diameter. These fibrils usually grow parallel to each other, sometimes several centimetres long, across veins in the country rock. Most of the fibres released during working with chrysotile are actually bundles of fibrils (Hodgson 1979). Chrysotile is a very common mineral; it is found as an accessory mineral in a wide range of rock types all over the world, usually formed by secondary hydrothermal alteration of earlier minerals. Serpentine rock masses, some of them measured in kilometres, are found in almost every major mountain chain around the world, and most of these contain chrysotile as a major or minor component (Ross 1981). With the steady erosion of these rocks over millions of years and with the more recent industrial use of chrysotile there has been a continuous release of chrysotile into the air and water so that now it is ubiquitous in the natural environment (Bowes et al 1977, Kohyama 1989).

## **2.2 Amphibole Minerals**

The amphibole minerals are a group of silicate minerals with a wide range of chemical compositions but with the same fundamental crystal structure. The elements silicon and oxygen in minerals are usually arranged into tetrahedral shapes with the silicon atoms at the centre and oxygen atoms at each apex.

These tetrahedra are arranged in particular patterns in each of the main mineral groups; the tetrahedra share oxygen atoms and link together at the apices to form chains or sheets. In the amphiboles, the linked tetrahedra form pairs of chains which are then stacked together with the metal cations such as iron, magnesium, calcium, sodium and aluminum in the spaces between the chains (Deer, Howie and Zussmann 1963, Ross 1981).

### **2.3 Crystal Form and Cleavage of Amphiboles**

The normal crystal form for all of the amphibole minerals is as long six-sided prisms with a diamond shaped cross section and elongated in the direction of the silicate chains to form blocky or bladed crystals. All of the amphiboles have natural structural weaknesses within the crystal in the form of sets of parallel cracks in the crystals known as cleavage planes. The sets of cleavage planes in the amphiboles are always at angles of  $124^{\circ}$  (or  $56^{\circ}$ ) to each other, parallel also to the main crystal faces of the diamond shaped prisms, (Langer et al 1991). When crystals with strong cleavage planes, such as any of the amphiboles, are broken or ground to a dust, the commonest shape that the dust particles will adopt is determined by the cleavage planes. So when amphiboles are broken they form a wide range of particle shapes many of which will be elongate, diamond cross-section rods which are then described as amphibole cleavage fragment fibres. A proportion of these cleavage fragments will meet the size criteria for a regulatory fibre within the asbestos regulations of the United States or the United Kingdom. They would also be counted as fibres in any count of airborne fibres even though they are not asbestos (Langer et al. 1991).

## **2.4 Amphibole Asbestos Minerals**

Most of the amphibole minerals occur exclusively in nature as prismatic crystals or cleavage fragments broken from them, but a few can also occur in the fine fibrous forms typical of asbestos. The reason for the fibrosity, high tensile strength and other "asbestos" properties in these minerals is still the subject of research. The fibrous nature of the amphibole asbestos varieties is not just the extreme development of the amphibole cleavage since the crystallographic surfaces of the fibres are not those of the cleavage planes. Optical microscope and high resolution transmission electron microscope observations of amphibole asbestos minerals show that the true amphibole asbestos fibres are formed by crystallographic features such as multiple twin planes and multiple chain width variations (triple and higher number groups of chains rather than the normal paired chains) rather than the cleavage planes (Langer et al 1991, Veblen et al 1977). These novel planes tend to be free of defects and persistent over large distances within the crystals so leading to the high tensile strength and ease of splitting of the crystals into fibres. The asbestos mineral varieties of the amphiboles are usually found in particular geological environments. The asbestos forms are normally only found in metamorphic rock terrain where high fluid pressures, high temperatures and high stresses lead to the alteration and deformation of large rock masses with regrowth and conversion of original minerals to more stable asbestos varieties; the strain of deformation is accommodated with the unusual mineral forms, i.e. asbestos.

## **2.5 Commercial Amphibole Asbestos**

Amosite and crocidolite are the two main commercial amphibole asbestos types. They are also unusual in being comparatively rare outside the main commercial deposits in South Africa and Australia (Hodgson 1979). This is because the very iron-rich rocks, (FeO more than 40%) and physical (high stress) requirements to form them were geologically unusual and coincided in only these few places.

Because they are mineralogically rare, amosite or crocidolite will normally be found only where they have been deliberately used in the manufacture of a product, or as a contamination from some installation associated with manufacture.

## **2.6 Other Amphibole Asbestos Minerals**

The asbestos varieties of tremolite, actinolite and anthophyllite have never been found as large commercial deposits like those of chrysotile, crocidolite or amosite. However although the occurrences of tremolite, actinolite and anthophyllite asbestos are usually small, they are found throughout the world. The normal prismatic amphiboles with these compositions are fairly common for the simple reason that their metallic chemical constituents are simple and common. Deformation during mountain building processes and alteration of limestones, dolomitic limestones (Ca and Mg rich) and ultramafic rocks such as peridotites (magnesium and silicon) leads to the formation of tremolite and anthophyllite. More iron-rich rocks such as basalts are often the precursors to actinolite-bearing rocks. The stress and temperature conditions for the wholesale formation of the asbestos forms of the amphiboles are unusual, so while the normal tremolite, actinolite and anthophyllite are common the asbestos varieties are rare. Nevertheless any of these normal amphibole minerals may be converted partially to the asbestos form by stress and by secondary alteration. So if the normal amphibole is present in a rock or ore body then the asbestos form may be present, although by no means always. Asbestos varieties of amphiboles are almost always accompanied by their normal prismatic types (Ross 1981).

## **3 THE HEALTH EFFECTS OF ASBESTOS**

All asbestos minerals have been found to be capable of causing serious diseases in humans exposed to airborne dust containing them (Morgan and Seaton 1984). Those described below are the most important although there are other conditions which may also result from asbestos exposure.

### **3.1 Asbestosis**

Asbestosis is fibrosis of the lung parenchyma, in other words the development of fibrous scar tissue in the spongy area of the lung where the oxygen exchange between blood and air takes place. It results in reduced oxygenation of the blood, restricted breathing, and increased resistance to breathing in the small airways. The earliest complaint is usually coughing followed later by breathlessness. As the disease progresses the symptoms become more distinctive with the development of X-ray shadows, audible crackling of the lungs on examination, and increased breathlessness until the patient ultimately dies of cardio-respiratory failure. The severity of the disease is directly related to the extent of the exposure and it is progressive so that even if a patient is removed from further exposure the condition may still worsen. However, it is possible with modern dust control methods to operate an asbestos industry (particularly with chrysotile) within occupational hygiene standards which would ensure very low levels of asbestosis and probably none at all. There is good evidence now that on a fibre by fibre basis the health risks from crocidolite are greater than those from amosite and chrysotile in turn (Doll and Peto 1985).

### **3.2 Lung Cancer**

Bronchial carcinoma or lung cancer, a tumour on the epithelial cover of the lung airways is also strongly associated with exposure to asbestos. There is strong evidence that the degree of risk is related to the cumulative exposure but there is no evidence of a threshold level below which there is no risk. On the other hand there are increasing arguments which suggest that bronchial carcinoma can not be caused by asbestos without the prior development of asbestosis. This would imply that there is a de-facto threshold (Browne 1991). The risks of lung cancer are very much higher, by a factor of about ten, if the asbestos exposed person is also a cigarette smoker since the combined risks are apparently multiplied. It is however very difficult to attribute the cause of the lung cancer if the person was a heavy smoker with a casual, incidental or very low exposure to asbestos.

### **3.3 Mesothelioma**

Mesothelioma is a tumour which develops in the membranes which line the inside of the chest cavity and cover the lungs (pleural) or the intestines (peritoneal). It causes very few symptoms in the early stages but once the condition has developed to the point of correct diagnosis it almost invariably causes death within about two years (Morgan and Seaton 1984), and there is no treatment available which will change the prognosis (Ribak and Selikoff 1993). The disease usually takes between 20 and 50 years from first exposure to diagnosis and is difficult to predict from exposure. The risks are greatest for those with high cumulative exposure and a long working history, but there are cases attributable to asbestos where the exposure was very brief albeit possibly very high. The phrase "one fibre can kill" was used in the context of such a short term exposure but it is very misleading (Doll and Peto 1985) and it is now recognised that doses of many millions of fibres are usually necessary to cause mesothelioma. The amphibole asbestos crocidolite was the fibre involved in the first recognition of the association of the disease with asbestos exposure, (Wagner et al 1960) and that mineral is still seen as the most carcinogenic asbestos type, although other fine fibre amphibole asbestos types such as tremolite asbestos are probably equally hazardous. Amosite asbestos is considered to be less likely to cause mesothelioma, indeed there were no recorded cases at the amosite mines in South Africa (Transvaal) at the same time as the crocidolite exposed cases were discovered in Cape Province. Opinions about the ability of chrysotile to cause mesothelioma are now changing because chrysotile appears to break down or dissolve in the lungs of exposed persons. In this case it is unlikely to persist for the 20-50 years required for the mesothelioma to develop. The amphibole minerals in contrast are extremely durable and persist in the lungs of exposed persons for tens of years (Churg 1984).

### **3.4 Experimental Evidence of Carcinogenicity**

Many experiments have been carried out to understand the relative harmfulness of the asbestos minerals and the mechanisms of the asbestos diseases and the results have not always been easy to interpret or understand. Some of the most important of these have been related to understanding the importance of fibre length in the development of disease. A number of studies have now shown that certain lengths of fibres are more carcinogenic and more fibrogenic than others. Stanton et al (1981) and Pott et al (1989), using intraperitoneal inoculation experiments with differently sized fibres, showed that fibres longer than about 8  $\mu\text{m}$  and thinner than about 0.2  $\mu\text{m}$  were much more likely to cause tumours than short fibres. Davis and his co-workers also demonstrated that short asbestos fibres were less likely to cause disease than the longer ones and would suggest now that fibres longer than about 20  $\mu\text{m}$  were the most likely to be the cause of cancer and fibrosis ( Davis et al 1986, Davis and Jones 1988, Davis 1991). Intraperitoneal injection experiments with the same mass doses of a range of asbestos tremolites and of non-asbestos tremolites showed very much lower carcinogenicity for the latter. Fibre size differences alone could not explain the variation in carcinogenicity and some other properties, perhaps surface chemistry, were also important factors. It was strongly suggested from these experiments that the prismatic crystalline types of tremolite (non-asbestos) were very unlikely to be hazardous to the health of humans exposed to them (Davis et al 1990).

### **3.5 The Importance of Fibre Durability**

The relevance of results from chrysotile in animal experiments to human epidemiology has been difficult to understand because of apparent contradictions (Davis 1989). Most experiments testing chrysotile in animals have shown the mineral to be more fibrogenic and more tumorigenic than crocidolite or the other amphibole asbestos types in either inhalation or injection assays.

Similarly, chrysotile has always been found to be more toxic in cell studies and more haemolytic with red blood cells. Despite this evidence chrysotile has always been found to be the least harmful of the asbestos types in human epidemiology studies. It has become apparent now that overriding factors not previously taken into account were the duration of the animal experiments and the durability of the fibres. Tumours develop rapidly in experiments with animals relative to the rate at which they develop in exposed humans because of their different metabolic rates. So, while the low chemical stability of chrysotile is not a factor for the animal tests, it becomes increasingly important in humans to the extent that chrysotile is not now considered to be a major cause of mesothelioma. There is also important evidence from the asbestos mines of Quebec where tremolite was a natural accessory mineral in certain of the chrysotile deposits. Here, chrysotile miners were exposed to airborne dust clouds that contained not only fibres of chrysotile but also fibres of tremolite asbestos and cleavage fragments of tremolite (Nolan et al 1993). However, when the mineral dusts recovered from the lungs of miners who had died of mesothelioma were examined they were found to contain mostly tremolite fibres. The conclusion was that the chrysotile had either been preferentially cleared by the normal lung defence mechanisms or it had been dissolved, or partial dissolution had reduced the chrysotile toxicity allowing more rapid clearance (Churg 1984). The secondary conclusion was that the chrysotile was unlikely to have been the cause of the mesothelioma; this conclusion is however still not accepted by everyone.

### **3.6 Health Risks from Other Minerals**

The risks to the health of persons exposed to other silicate minerals depend to some extent on the nature of the minerals themselves; some minerals such as quartz are known to be toxic and capable of causing silicosis (pneumoconiosis) in moderately exposed workers, while others such as kaolinite are considered to be of low toxicity and only likely to cause disease in cases of very high exposure (Morgan and Seaton 1984).

Evidence for human carcinogenicity of silica and other minerals is weaker than for the asbestos minerals. Some minerals, such as quartz, are thought to be possible causes of lung cancer on the basis of animal inhalation studies (IARC 1987), although there is no evidence at all for others. There has been a great deal of research and debate on the carcinogenicity of minerals such as prismatic tremolite, actinolite, and anthophyllite and talc. The results of epidemiology studies have been ambiguous and contradictory in the talc industries, especially at those sites where tremolitic talc was exploited, and in other mineral extraction industries with amphiboles present. As a result, OSHA could not find enough justification in the evidence for regulating the nonasbestos minerals, tremolite, actinolite and anthophyllite as asbestos (Federal Register 29CFR Parts 1910 and 1926, June 1992). Indeed this lack of the epidemiological disease coupled with the abundance of normal non-asbestos amphiboles in very many mines and quarries, as well as in the general environment, is probably enough now to suggest strongly that these minerals are not carcinogenic. The contrast between this evidence and that from the mines which had genuine accessory amphibole asbestos is very striking indeed. In one mine, with tremolite and actinolite asbestos varieties at concentrations about 5% of the total ore, there were substantial excess numbers of deaths from respiratory cancer (more than double expected), and a number of mesothelioma cases (Amandus et al 1988).

## **4 THE REGULATORY POSITION**

### **4.1 Asbestos**

The asbestos regulations of the United Kingdom contain no reference to differences between asbestos amphiboles or normal prismatic (non-asbestos) amphiboles (Control of Asbestos at Work Regulations 1987). Instead the regulations simply refer to the specific minerals amosite and crocidolite and the "fibrous forms" of tremolite, actinolite, and anthophyllite, but without defining the term "fibrous".

The new draft HSE Method for the Determination of Hazardous Substances for asbestos identification establishes the clear distinction between the asbestos and the prismatic crystalline varieties of the same amphiboles, and describes in detail the optical properties of each type that may be used to distinguish them. In the United States of America the Occupational Safety and Health Administration (OSHA) recognised the difference between asbestos and non-asbestos amphiboles and in 1992 removed the non-asbestos tremolite, anthophyllite and actinolite from the scope of the asbestos regulations. This followed a very careful review of the evidence available at the time which included full scale judicial hearings covering every aspect of mineralogy, health effects, animal experimentation, toxicology and many other areas (Federal Register July 1992).

#### **4.2 Asbestos and Carcinogens Legislation**

There are a number of pieces of legislation which may be relevant to the issue of asbestos in vermiculites. The Asbestos Hazard Emergency Response Act (AHERA) identifies as asbestos containing materials (ACM) any material containing more than 1% of asbestos and uses this level as a trigger for the imposition of all relevant actions. This is only likely to be important for installations of old vermiculite product materials from mines that are no longer producing but which might have contained so much amphibole asbestos that they were classifiable as ACM. The carcinogens packaging and labelling regulations in the USA, and the equivalent legislation in the European Community, are certainly important for almost all supplies of vermiculite. Both of these pieces of legislation have trigger concentrations of 0.1% for requirement of labelling of any article or material as containing a carcinogenic substance. Although this standard is in place and is used for most carcinogens it is not being enforced for asbestos in Europe because of the lack of a validated method for quantitative analysis of asbestos at such a low level. When such a method becomes available then the standard will be enforced for asbestos.

A research programme for a suitable method has been the subject of a proposal to the EEC departments concerned, and work is likely to start in 1994. It is possible for 0.1% of asbestos to be present without being at all obvious to any supplier or user and testing according to the final method will almost certainly be required. It is very unlikely that any of the current supplies of vermiculite would fail to meet a 0.1% standard but that is not to say that all current supplies carry no asbestos health risk.

### **4.3 Suitable Action Levels**

The best information about the levels of asbestos content that would be unlikely to present an inadvertent health risk comes from a series of experiments with asbestos loosely dispersed in soils (Addison et al 1988). Airborne dust clouds were generated from mixtures of soils with different asbestos varieties in bulk concentrations ranging from 1% to 0.001% of asbestos. The dust concentrations were maintained at around  $5\text{mgm}^{-3}$ , the occupational exposure limit for a low toxicity dust, for around four hours and the airborne fibre concentrations were measured throughout. The experiments showed very clearly that even the lowest bulk amphibole asbestos content tested (0.001%) was still capable of producing measurable airborne asbestos concentrations (greater than  $0.01\text{fibres ml}^{-1}$ ). It would be necessary therefore to take action specifically to control for the asbestos emissions if soils containing higher levels than 0.001% asbestos were to be handled without significant health risks. Asbestos, if present in vermiculite, is likely to behave in a similar fashion; with the asbestos loosely dispersed and readily available for release into the air. Even relatively gentle handling of the vermiculite would abrade the friable asbestos, splitting fibre bundles, and adding to the released fibres. So, even though the carcinogens legislation may impose only a 0.1% limit for packaging and labelling, the vermiculite industries are advised to establish their own target limit of 0.001% for amphibole asbestos. Most current supplies of vermiculite could still meet this standard.

## **5 ANALYTICAL METHODS FOR ASBESTOS DETERMINATION**

### **5.1 General Methods**

Many different methods have been used for the analysis of the asbestos minerals and some have proved to be more useful than others. The main problem with the analysis of asbestos is that the definition of asbestos is basically morphological; it requires the distinction to be made between the asbestos form and the non-asbestos forms of the same mineral. Most of the instrumental analytical techniques such as X-ray diffractometry (Brindley and Brown 1980) and infrared spectrophotometry (Farmer 1974) respond very similarly for the two forms of the amphiboles and for any of the serpentine minerals (Addison et al 1992). None of these techniques alone can then be used for a quantitative or qualitative analysis of asbestos, unless the asbestos has first been identified by some other method and the asbestos is the only amphibole or serpentine present. Even then these instrumental techniques have detection limits, of about 0.5% for the amphiboles, and about 2% for chrysotile, that are far too high to be useful in real terms.

### **5.2 Optical Microscopy**

The most versatile and simple method for identification of asbestos, is polarised light microscopy with refractive index measurement by dispersion staining. Observations of morphological features such as curved fibres with easily split ends, flexibility and elasticity (amphiboles), colour and lustre, followed by careful evaluation of the optical properties of mineral fibres can rapidly provide an almost unambiguous identification of any of the asbestos minerals. With the appropriate care and controls the optical microscope methods can detect and identify asbestos in concentrations down to about 1 part per million. These methods are fully described in US EPA and UK HSE documents.

### **5.3 Scanning Electron Microscopy**

Scanning electron microscopy (SEM) generates a television image at magnifications up to about 200,000x by projecting a fine high-energy (20-30,000 volts) beam of electrons at the sample. The electron beam is scanned over the sample in a TV raster pattern which is synchronised to the raster of the image television. Electrons are bounced off the surface or from just beneath the surface and are detected electronically to give a final image intensity at each individual point in the raster image. The high magnification pictures are clear and sharp, with great depth of focus, allowing very detailed examination of fibre morphology. In addition, the techniques of energy dispersive X-ray spectrometry (EDXS) (Russel and Hutchings 1978), can produce a chemical analysis of individual fibres which, along with the morphology, may be enough for their identification in most situations (Asbestos International Association 1984, Addison 1992).

### **5.4 Energy Dispersive X-ray Spectrometry**

In EDXS, the fine electron beam is held steady at a single point and is directed to a position on the surface of a particle; the electrons may penetrate the particle where some of them may even collide with individual atoms. In the collision they may knock an electron out from one of the inner orbits of the atom and then an electron from an outer orbit will fall into the space. When it does this it emits an X-ray that has an energy specific to the atomic element and to the energies of the two electrons, the one knocked out and the one which replaced it (Russel and Hutchings 1978). The X-ray detector used for analysis not only detects the X-rays but also differentiates them by their energies. A computer builds the full energy spectrum from the thousands of X-rays collected and the calculates of the elemental proportions in the particle analysed. EDXS is a very powerful technique when coupled with scanning electron microscopy and can give a chemical "fingerprint" to particles as small as 0.2  $\mu\text{m}$  in diameter.

Even so, SEM with EDXS is limited to the analysis of fibres greater than about 0.2  $\mu\text{m}$  diameter, and gives no information about the crystalline form of the mineral under analysis. This means that false positive errors of identification could be made since there are other small fibre-shaped particulates with closely similar chemical composition to the asbestos minerals. Some of the pyroxene minerals, diopside, enstatite and hornblende for examples, would meet these criteria (Deer, Howie and Zussman 1967).

### **5.5 Transmission Electron Microscopy**

In transmission electron microscopy (TEM) a high energy (100-200,000 volts) electron beam is projected through the sample to form a shadow image of the mineral particles on a phosphorescent screen which is viewed directly by the microscopist. Images with magnifications of around 500,000 to 1,000,000 are routinely available so the detection of even the finest of asbestos fibres is readily achieved. The image contrast between the particles and the background image is also greater so visibility of fine fibres is easier than with SEM. The techniques of EDXS are also applicable to TEM and in this case the resulting chemical analysis is capable of being made fully quantitative so providing greater certainty of identification. With the appropriate electronic lens settings and aperture adjustment it is possible to present a fine electron beam towards a single particle and for the crystal lattice planes of the mineral particle then to diffract the electron beam. This produces an array of bright spots on a dark background in the image, the dimensions of which are directly related to the crystal lattice dimensions of the mineral particle. The combination of morphological data, fully quantitative chemical analysis, and crystallographic data can provide an unambiguous identification of an individual mineral particle with a mass of less than 10<sup>-15</sup> of a gram (Ledoux 1979, Chatfield 1980). These more advanced technologies improve the analytical certainty but increase the costs very dramatically.

A good optical microscope can be bought for a few thousand dollars; a good SEM costs about 100,000 dollars, but a suitable TEM might cost more than 300,000 dollars, and the EDXS equipment a further 50,000 dollars. So, the decision to perform an analysis, and the standards of analysis to apply both need careful consideration.

## **5.6 Quantitative Microscopy**

In the same way that optical and electron microscopy techniques have been used to quantify airborne fibre concentrations they can also be used to quantify the amphibole asbestos content of materials like contaminated soil or vermiculite. It is necessary first to prepare the sample by chemical treatment and to separate or segregate the fibres from the matrix (wet sedimentation is usually sufficient). An aqueous suspension is prepared and an aliquot of the suspension is then filtered through an appropriate filter and prepared for microscopy. Fibres of asbestos, previously established as present or identified in the course of the analysis, are then measured and counted. The volumes of the fibres are calculated from their measured dimensions and their masses calculated by the application of an appropriate specific gravity factor. The cumulated masses are then expressed as a proportion of the original mass in suspension. This is the basis of the analytical method proposed to the European Community, and it has been partially validated as capable of reproducible analysis at levels down to 0.001% by research at the Institute of Occupational Medicine in Edinburgh

## **6 CONCLUSIONS**

The vermiculite minerals usually contain fibrous vermiculite particles, some of which are in the size range similar to the asbestos minerals. These fibres have demonstrated apparent low toxicity in comparison to any asbestos, low durability in comparison to amphibole asbestos, and they usually constitute very small proportions of the bulk material. They are unlikely therefore to present a serious health risk to workers handling vermiculite or any measurable increase in health risks to normal occupants of buildings in which the vermiculite is installed. Most vermiculite ore bodies are free of asbestos minerals and any product made with vermiculite from these would be similarly unlikely to present any serious health risk. Some sources have been found to contain accessory amounts of amphibole asbestos that testing has shown to be in such low amount as to be insignificant in terms of health risks. Other ore deposits and products however have been found to contain asbestos at higher levels that would constitute a health risk to exposed persons. Appropriate assessment of ore bodies and testing of products should identify these and reduce the possibility of inadvertent uncontrolled exposure to the asbestos. Testing should take into account the mineralogical difference between the asbestos and non-asbestos varieties of the same amphibole minerals and should be sensitive enough to detect concentrations in bulk material down to 0.001%.

## **7 REFERENCES**

Addison J, Davies LST, Robertson A, Willey RJ. (1988) The release of dispersed asbestos fibres from soils. Edinburgh: Institute of Occupational Medicine, (IOM Report TM88/14).

Addison J, Davies LST. (1990) Analysis of amphibole asbestos in chrysotile and other minerals. *Annals of Occupational Hygiene*, 34: 159-175.

Addison J, Davies LST, McIntosh C, Porteous RH. (1992) Bulk asbestos reference minerals for optical microscope identification: preparation, evaluation and validation. Edinburgh, Institute of Occupational Medicine, IOM Report to client. HSE Contract No R2490/R48.44.

Amandus HE, Wheeler R, Armstrong BG, McDonald AD, McDonald JC, Sebastien P. (1988) Mortality of vermiculite miners exposed to tremolite. *Ann Occup Hyg*, 32: 459-467.

Asbestos International Association. (1984). Health and Safety Publication, Recommended Technical Method No.2 (RTM2); Method for the determination of Airborne Asbestos Fibres and Other Inorganic Fibres by Scanning Electron Microscopy. Asbestos International Association, London.

Armstrong BG, McDonald JC, Sebastien P, Althouse R, Amandus HE, Wheeler R. (1988) Radiological changes in vermiculite workers exposed to tremolite. *Ann Occup Hyg*, 32: 469-474.

Atkinson GR, Rose D, Thomas K, Jones D, Chatfield EJ, Going JE. (1982) Collection, analysis and characterization of vermiculite samples for fiber content and asbestos contamination. Midwest Research Institute, Final Report on EPA Prime Contract No 68-01-5915, US Environmental Protection Agency, Washington.

Basset WA, (1961) The geology of vermiculite occurrences. in *Proceedings, 10th Nat Conf on Clays and Clay Minerals*, Pergamon Press, New York, Monograph 12: 61-61.

Bowes DR, Langer A, Rohl A. (1977) Nature and range of mineral dusts in the environment. *Phil Trans Roy Soc Lond A286*: 593-610.

Brindley GW, Brown G. (1980) *Crystal Structure of clay minerals and their X-ray identification*; 3rd ed. Mineralogical Society Monograph No 5. Mineralogical Society, London.

Browne K. (1991) A threshold for asbestos-related cancer. In *Asbestos-Related Cancer*, Ed Sluysen M. Ellis Horwood, Chichester, UK, 218-40.

Chatfield EJ, Lewis GM. (1980) Development and application of an analytical technique for measurement of asbestos fibers in vermiculite. *Scanning Electron Microsc I*, 329-340.

Churg A, Wiggs B, Depaoli L, Kampe B, Stevens B. (1984) Lung asbestos content in chrysotile workers with mesothelioma. *Am Rev Respir Dis*, 130: 1042-1045.

Davis JMG, Addison J, Bolton RE, Donaldson K, Jones AD, Miller BG. (1985) Inhalation studies on the effects of tremolite and brucite dust in rats. *Carcinogenesis*, 1985; 5: 667-674.

Davis JMG, Addison J, Bolton RE, Donaldson K, Jones AD, Smith T. (1986) The pathogenicity of long versus short fibre samples of amosite asbestos administered to rats by inhalation and intraperitoneal injection. *Br J exp Path*, 67: 415-430.

Davis JMG, Jones AD. (1988) Comparisons of the pathogenicity of long and short fibres of chrysotile asbestos in rats. *Br J exp Path*, 69: 717-737.

Davis JMG. (1989) Mineral fibre carcinogenesis: experimental data relating to the importance of fibre type, size, deposition, dissolution and migration. In *Non-occupational exposure to mineral fibres*, eds Bignon J, Peto J, Saracci R, IARC Scientific Publications No. 90, International Agency for Research on Cancer, 33-45.

Davis JMG, Cowie HA. (1990) The relationship between fibrosis and cancer in experimental animals exposed to asbestos and other fibers. *Env. Health Persp*, 88: 305-309.

Davis JMG, Addison J, McIntosh C, Miller BG, Niven K. (1990) Variations in the carcinogenicity of tremolite dust samples of differing morphology. *Proceedings of the Collegium Ramazzini Symposium, New York, Annals of the New York Academy of Sciences*.

Davis JMG. (1991) Information obtained from fiber-induced lesions in animals. In *Mineral fibers and health*. Eds Liddell D, Miller K, CRC Press, Boca Raton.

Deer WA, Howie RA, Zussman J. (1966) *An Introduction to the Rock Forming Minerals*, Longmans, London.

Doll R, Peto J. (1985) *Asbestos. Effects on health of exposure to asbestos*. Health and Safety Commission, London, HMSO.

Dorling M, Zussman J. (1987) Characteristics of asbestiform and non-asbestiform amphiboles. *Lithos* 20: 469-489.

Farmer VC. (1974) *The Infrared Spectra of Minerals*, VC Farmer ed. Mineralogical Society Monograph No 4, Mineralogical Society, London.

Harben PW, Roberts RL. (1990) *Industrial Minerals Geology and World Deposits*. Metal Bulletin Plc, London.

Hessel PA, Sluis-Cremer GK. (1989) X-ray findings, Lung Function, and respiratory symptoms in black South African vermiculite workers. *Am J Ind Med*, 15: 21-29.

Hodgson AA. (1979) Chemistry and physics of asbestos. In Michaels L, Chissick SS, Eds *Asbestos, Vol 1, Properties, Applications and Hazards*, John Wiley and Sons, New York, 67-114.

Hunter B, Thomson C. (1973) Evaluation of the tumorigenic potential of vermiculite by intrapleural injection in rats. *Br J Ind Med*, 30: 167-173.

International Agency for Research on Cancer (1987) *Monograph on the Evaluation of the Carcinogenic Risk of Chemicals to Humans. Vol.42, Silica and Some Silicates*. IARC Lyon.

Kohyama N. (1989) Airborne asbestos levels in non-occupational environments in Japan. In *Non-occupational exposure to mineral fibres*, eds Bignon J, Peto J, Saracci R, IARC Scientific Publications No. 90, International Agency for Research on Cancer.

Langer AM, Nolan RP, Addison J. (1991) Physico-chemical properties of asbestos as determinants of Biological potential. In Liddel FDK, Miller K, eds. *Mineral Fibres and Health*; CRC Press, Boston 1991.

Langer AM, Nolan RP, Addison J. (1991) Distinguishing between amphibole asbestos and elongated cleavage fragments of their non-asbestos analogues. In: *"NATO Advanced Research Workshop on Mechanisms in Fibre Carcinogenesis"*. Brown RC, Hoskins JA, Johnson NF Eds. Plenum Press, New York.

Ledoux RL. (1979) *Mineralogical Techniques of Asbestos Determination*. Short Course Handbook Vol4, Mineralogical Society of Canada, Toronto.

Lockey JE, Brooks SM, Jarabek M, Khoury PR, McKay RT, Carson A, Morrison JA, Wiot JF, Spitz HB. (1984) Pulmonary changes after exposure to vermiculite contaminated with fibrous tremolite. *Am Rev Respir Dis*, 129: 952-958.

Lockey J, Jarabek A, Carson A, McKay RT, Harber P, Khoury P, Morrison JA, Wiot JF, Spitz HB and Brooks S. (1983) Pulmonary hazards of vermiculite exposure. In *Health Issues Related to Metal and Nonmetallic Mining*. Eds Wagner WL, Rom WN, Merchant JA.; Butterworth.

McDonald JC, McDonald AD, Sebastien P, Moy K. (1988) Health of vermiculite miners exposed to trace amounts of fibrous tremolite. *Br J Ind Med*, 45: 630-634.

Moatamed F, Lockey JE, Parry WT. (1986) Fiber contamination of vermiculites: a potential occupational and environmental health hazard. *Environ Res*, 41: 207-218.

Morgan WKC, Seaton A. (1984) *Occupational lung diseases*. 2nd Ed. Philadelphia, WB Saunders Co., Chapter 13.

Nolan RP, Langer AM, Oechsle GW, Addison J, Colflesh DE. (1991) Association of tremolite habit with biological potential: In "NATO Advanced Research Workshop on Mechanisms in Fibre Carcinogenesis". Brown RC, Hoskins JA and Johnson NF Eds. Plenum Press, New York.

Pott F, Roller M, Ziem U, Reiffer F-J, Bellmann B, Rosenbruch M, Huth F. (1989) Carcinogenicity studies on natural and man-made fibres with the intraperitoneal test in rats. In *Non-occupational exposure to mineral fibres*, eds Bignon J, Peto J, Saracci R, IARC Scientific Publications No. 90, International Agency for Research on Cancer.

Ribak J, Selikoff IJ. (1992) Survival of asbestos insulation workers with mesothelioma *Br J Ind Med*, 49: 732-735.

Ross M. (1981) The geological occurrences and health hazards of amphibole and serpentine asbestos. In *Reviews in Mineralogy*, vol 9A, Amphiboles and other hydrous pyriboles - mineralogy, ed D R Veblen, Mineralogical Society of America, Washington.

Russel PA, Hutchings AE. (1978) *Electron Microscopy and X-ray Applications to Environmental and Occupational Health Analysis*. Ann Arbor, Michigan 1978.

Sebastien P, Armstrong B, Case B, Barwick H, Keskula H, and McDonald JC. (1988) Estimation of amphibole exposure from asbestos body and macrophage counts in sputum: a survey in vermiculite workers. *Ann occup Hyg*, 32: 195-201.

Schoeman JJ. (1989) Mica and vermiculite in South Africa. *J S Afr Inst Min Metall*,89.1: 1-12.

Smith WE, Hubert DD, Sobel HJ, Marquet E. (1979) Biologic tests of tremolite in hamsters. In *Dusts and Disease*. Dement JA, and Lemen RA (eds) Pathotox Publishers, 335-339.

Stanton MF, Layard M, Tegeris A, Miller E, May M, Morgan E, Smith A. (1981). Relation of particle dimension to carcinogenicity in amphibole asbestoses and other fibrous minerals. *J Natl Cancer Inst*, 67: 965-975.

Swensson A. (1975) Experimental investigations on the fibro-genetic effects of the mica mineral vermiculite. *Work and Health*; Scientific pamphlet series 1975:11. The Worker Protection Department, Stockholm.

Swennson A. (1979) Personal communication to Mr F.E.Childs, Mandoval Ltd.

Varley ER. (1952) Vermiculite. Colonial Geological Survey, Mineral Resources Division. HMSO London.

Veblen DR, Buseck PR, Burnham CW. (1977) Asbestiform chain silicates: new minerals and structural groups. *Science*, 198: 359-366.

Wagner JC, Chamberlain M, Brown RC, Berry G, Pooley FD, Davies R, Griffiths DM. (1982) Biological effects of tremolite. *Br J Cancer* 45: 352-360.

Wagner JC, Sleggs CA, and Marchand P. (1960) Diffuse pleural mesothelioma and asbestos exposure in the North Western Cape Province. *Br J Ind Med*, 17: 260-271.

## **8 THE AUTHOR**

John Addison is a graduate in Geology from Glasgow University where he carried out research in geochemistry and mineralogy. From 1978 until 1993 he was senior mineralogist and latterly Head of Mineralogy Section at the Institute of Occupational Medicine in Edinburgh, one of the worlds leading centres in occupational health research. While there he gained an international reputation as an expert on asbestos and other minerals. He was directly involved in establishing the nature of differences between normal and asbestos types of amphibole minerals such as tremolite and actinolite and in demonstrating major differences in the carcinogenicity of the two types. His testimony at the U.S. OSHA judicial hearings was influential in the removal of non-asbestos varieties of actinolite, tremolite and anthophyllite from the asbestos regulations. He has been involved for a number of years in Health and Safety Executive working groups on asbestos identification and made important contributions to the U.K. recommended methods for asbestos analysis, UK asbestos reference materials, methods of survey and risk assessment in buildings, and methods of analysis for contaminated land. He has published over 40 articles in scientific journals and books relating to the mineralogy analysis and toxicity of materials such as asbestos, quartz, clay minerals and man-made vitreous fibres.

He is now a successful consultant based in Cottingham, near Hull, England and operating internationally in a wide range of fields.