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Identification and enumeration of asbestos fibers in the mining environment: Mission and modification to the Federal Asbestos Standard

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Abstract

Since the promulgation of the first Federal Asbestos Standard by the Occupational Safety and Health Administration in 1972, other federal agencies have modified the standard to better carry on their own unique missions. The instruments used to identify and measure asbestos, the sampling protocol, and the criteria used to define asbestos, have been modified to some degree. The Mine Safety and Health Administration regulates and controls asbestos dust in the mining and mineral commodity industries. However, crushed stone and processed ores contain mineral fragments that are frequently difficult to distinguish from asbestos. Mineral nomenclature, instruments for particle analysis, and sampling strategy must be accommodated to some degree to make asbestos control workable and meaningful. Precedent in other agencies has made consideration of these changes possible. Newly identified amphibole asbestos minerals have further complicated the agency's regulatory charge. Changes in its Asbestos Standard are now being considered. Crushed taconite ore in the Eastern Mesabi highlights many of these issues.

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Keywords: Amosite; Grunerite asbestos; Crocidolite; Riebeckite asbestos; Tremolite asbestos; Actinolite asbestos; Winchite asbestos; Richterite asbestos; Arfvedsonite asbestos; Fluor-edenite asbestos; Asbestos defects; Cleavage fragment; Mineral habit; Mesabi amphiboles

1. Introduction

The first national Asbestos Standard in the United States was promulgated through the Occupational Safety and Health Administration in 1972. The permanent standard, which superseded the initial emergency standard, was set at 5 fibers per milliliter of air (as a time-weighted average) in concert with a "hierarchy of controls". Exposure excursions were permitted as well. The membrane filter technique was introduced as a means of dust collection and asbestos was defined as one of six minerals (one serpentine mineral, and five amphibole minerals) that exhibited specific morphological characteristics. A fiber was defined on the basis of particle length (greater than 5 μm, less than 100 μm) exhibiting an aspect ratio (length-to-width) of 3:1 or greater. The instrument for asbestos assay was the phase-contrast light optical microscope employed at 430× magnification.

For mines, mills, fabrication plants, and places where asbestos-containing products were known to be present, handled, processed, or manipulated, the protocol and prescribed counting strategy in the standard could be successfully employed. Long, thin, objects were assumed to be asbestos without requiring further habit characterization or more positive mineral identification.

The Food and Drug Administration (FDA) followed OSHA's technique and protocol in their studies of "asbestos" in talc but found the identification criteria and assay instrumentation oversimplified and flawed. The issue...
central to their problems was the nature of the mineral itself. Were the recognized amphibole particles asbestiform or the result of crushing, i.e., cleavage fragments? The agency hosted a conference in 1976 in Pennsylvania State University where analytical issues and protocols were described and discussed. It is noted that the resulting publication carried many non-government laboratory protocols for tale analysis, e.g., Langer et al., 1977]. The Environmental Protection Agency (EPA) in their asbestos pollution studies of the outdoor ambient air found the OSHA instrumental protocol limited for their purposes. This agency concluded that transmission electron microscopy (TEM) was required. Modification of their Asbestos Standard followed and TEM became the analytical instrument in the agency’s indoor air pollution studies as well.

Mine Safety and Health Administration (MSHA) especially experienced difficulties in the application of the OSHA Asbestos Standard. The mining and mineral-processing environments were replete with fragments of minerals, especially fragments of minerals with the same amphibole name that appeared in the Federal Asbestos Standard. These difficulties were articulated in the MSHA proposed rule changes governing their asbestos exposure limit and instrumentation in 2005. Nowhere has this problem been highlighted better than along the Eastern Mesabi Range where the nature of the amphiboles in the taconite iron-ores has been an issue for more than 35 years. MSHA has proposed modifications to their existing asbestos protocol, including instrumentation change from light to analytical electron microscopy.

2. Early Asbestos Standard

The Occupational Safety and Health Act of 1970 established both the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) (Sunstein, 2002). The organizations were to collaborate in developing regulations regarding control of biologically active agents (toxic substances) in the workplace. The standards were to be based on existing science (NIOSH), epidemiological findings concerning the health experience of exposed workers (NIOSH), and available exposure data (OSHA). Asbestos was at the top of the OSHA “to be regulated” list. Data from consuming industries indicated hazards existed beyond those included in historical data sets (i.e., asbestosis). Of special concern were malignancies, which were occurring in numbers greater than those expected among the working populations studied. With asbestos applications on the rise, the size of the exposed populations increased correspondingly.

At the time of OSHA’s creation, there were approximately 5 million workplaces in the United States employing about 90 million workers. OSHA replaced the authority covered under existing federal and state legislation. The entire US workforce at that time experienced about 2 million injuries per year resulting in lost time, with about 14 thousand deaths. The figure for workers developing chronic disease was placed at about 100 thousand per year (Froines, 1996). The Asbestos Standard was to be devised to protect against pneumoconiosis (asbestosis), not malignancies. The issue facing OSHA was daunting.

Prior to this time, in the 1960s, the USPHS began to refocus on workplace exposure to asbestos. Its industrial hygiene group in Cincinnati was evaluating the British protocol for fiber assay. The United States at that time was using the midget impinger collection device and measuring total visible particulates in a dust cloud with bright field light optical microscopy. The British Occupational Hygiene Society’s position was that asbestosis was caused by the inhalation of asbestos fiber and not total dust (fiber plus particulates). The membrane filter protocol was beginning to be used for work place assay and came to be adopted in the US following a period of evaluation (read the membrane filter evaluation in the UK in Holmes, 1965 and US protocol in Edwards and Lynch, 1968). An overview concerning asbestos exposure, measured indices, and their biological relationships are outlined in Lynch et al. (1970).

Based on information provided by the BOHS, and the British asbestos industry, the USPHS agreed that the most convenient and practical exposure index was the greater than 5 μm fiber length. The asbestos-containing dust cloud was collected on a membrane filter and the phase-contrast optical microscope employed at a magnification of 430× was the recommended analytical tool for fiber count (Edwards and Lynch, 1968). The experience of the British industrial hygiene community, beginning in 1931, provided both the technical protocol and its rationale (Addingley, 1965; Addingley, 1966). The dust cloud was noted to vary among the asbestos consuming industries; included among the variables were fibers with differing length and width distributions, fiber number per mass unit of dust, and a variable ratio of fiber to particulate. The OSHA assay protocol, like all others, provided only an index of exposure.

The measurement of solid particles dispersed in a stable aerosol has always been an issue within the industrial hygiene community (Glenn and Craft, 1987). Drilling and blasting in mines, and crushing and grinding in mills, produce particulates that are visible to submicroscopic in size. Instruments for assay must necessarily vary.

The OSHA efforts regarding the development of a new Asbestos Standard replaced the provisions in the Walsh-Healey Public Contracts Act of 1960, the McNamara-O’Hara Act of 1966, and the Construction Safety Act of 1969. These regulatory attempts required employers engaged in business with the Federal Government to comply with “safety and health standards” developed by the Bureau of Labor Standards in the US Department of Labor (US DOL) (Froines, 1996). As Froines pointed out, these efforts were fragmented and, in retrospect, largely inadequate. Importantly, these acts did not specifically cover coal, metal and non-metal mines, railroads, or atomic energy installations.

OSHA supplanted the right of states to follow their own Asbestos Standard if they allowed higher exposures than
permitted in the Federal Standard. The states themselves had dissimilar standards. Dreessen et al.'s (1938) tentative standard of 5 million particles per cubic foot (mppcf) of air was adopted by many states but South Carolina's standard was 15 mppcf of air during this same time period. Some might regard this as ironic as both Drs. Lynch and Smith, pathologists in the state medical school in Charleston, were the first pathologists in the US to report primary carcinoma of the lung (found during routine autopsy) in two “asbestos-silicosis” cases who had worked in a Charleston South Carolina asbestos textile plant (Lynch and Smith, 1935). Their case report was prescient as lung cancer was to become the most prevalent malignancy setting at 12 fibers per milliliter of air based on data provided by the ACGIH. The data came from the Conference of Governmental Industrial Hygienists (ACGIH), the organization that focused on a permissible exposure level (PEL) for general industry in the United States since 1946 (Selikoff, 1980; Brownson, 1998). [Parenthetically, the ACGIH never had regulatory authority or enforcement power for any of its recommendations during the time period 1946-1972.] An overview of the mechanisms required for the establishment of a new standard or the modification of an existing standard was outlined by NIOSH (1976).

Changes in major provisions within the Asbestos Standard occurred over more than 35 years (Selikoff and Lee, 1978). Among the important modifications was the lowering of the permissible exposure level (PEL) over time. Other than the recognition of the differences in degree of hazard of cleavage fragments and their asbestiform analogues in the Asbestos Standard in 1994, the minerals regulated since 1971 have remained the same. The mineral names are given in Table 1. The instrument used for environmental assay has remained the same as well, i.e., the phase-contrast optical microscope (PCOM). However, other federal agencies, through necessity, have changed many of the analytical details of the Asbestos Standard to fit their unique charges and responsibilities.

### 3. The nature of asbestos

Assume that the name asbestos confers upon a mineral a specific set of physical properties (Speil and Leineweber, 1969; Ampian, 1976; Virta, 2001). Assume further that the six minerals cited in the OSHA Asbestos Standard usually display these specific properties to greater or lesser degree:

- They occur in nature as fibers. They require no unique processing or manipulation to produce fiber. Milling separates fiber from host rock, increases the concentration of fiber downstream in the process, and opens fiber bundles.
- The fibers are all polyfilamentous (they are composed of bundles of smaller, more narrow units called fibrils).
- Fiber bundles may be broken open (disaggregated) upon mechanical manipulation.
- Fibers removed from an ore seam often display splayed, unraveled, fiber ends.
- Most fibers are flexible to some degree (depending on the fiber type); some fibers may be woven into a mineral fabric.
- All fibers display high tensile strength that is diameter dependent.
- All fiber types possess stability in extreme chemical and thermal environments (stability in acidic or alkaline environments depends on fiber type as well).

Table 1

<table>
<thead>
<tr>
<th>Asbestos name in the OSHA Asbestos Standard</th>
<th>Mineral as defined by crystal structure</th>
<th>Asbestos name in mineral literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chrysotile</td>
<td>Serpentine</td>
<td>Chrysotile</td>
</tr>
<tr>
<td>Actinolite</td>
<td>Amphibole</td>
<td>Actinolite asbestos</td>
</tr>
<tr>
<td>Amosite</td>
<td>Amphibole</td>
<td>Grunerite asbestos</td>
</tr>
<tr>
<td>Anthophyllitea</td>
<td>Amphibole</td>
<td>Anthophyllite asbestos</td>
</tr>
<tr>
<td>Crocidolite</td>
<td>Amphibole</td>
<td>Riebeckite asbestos</td>
</tr>
<tr>
<td>Tremolitea</td>
<td>Amphibole</td>
<td>Tremolite asbestos</td>
</tr>
</tbody>
</table>

The earliest regulatory nomenclature did not reference specific mineral habit (“asbestos”) for actinolite, anthophyllite or tremolite. The minerals with separate names were grunerite asbestos (amosite) and riebeckite asbestos (crocidolite). OSHA specifically identifies six minerals as asbestos as these six were recognized as commercial asbestos fibers by the USBM since the 1930s (see Bowles, 1937).

Two additional amphibole asbestos minerals have been found in ore deposits in the United States, asbestiform winchite and asbestiform richterite. Both have been identified in association with vermiculite ore in Libby, Montana and both are thought to be present in some talc deposits in the Death Valley region of California. They have never been, nor are they now, listed in any US Agency Asbestos Standard.

**a** These minerals are not distinguished on the basis of habit. It is inferred by their appearance on the OSHA asbestos list that they are asbestos in habit.

Many of these properties are described in Speil and Leineweber (1969) and Virta (2001). The US Bureau of Mines (USBM) (Campbell et al., 1980) further characterized properties of commercial asbestos and non-fibrous tremolite. The USBM materials were prepared and characterized for use by the National Toxicology Program in its bioassay systems. The above “properties” are gross descriptive.

However, the asbestos minerals possess a set of crystallographic anomalies, most recently described in Verkouteren and Wylie (2002), which impart the mineral fiber with anomalous properties. These are produced by an abundance of crystal defects that are useful in distinguishing asbestos from non-asbestos mineral analogues. They are also important in explaining the biological properties of the asbestos dust cloud.

The six minerals that appeared in the 1972 standard were enumerated in early USBM documents, e.g., in Bowles’ (1937) report on asbestos. Interestingly, Bowles listed additional amphibole mineral names in the asbestos listing but were not considered commercially important, but as
“mineral curiosities”. Hornblende asbestos was among them. Today, the hornblende asbestos might be one of several newly described amphibole asbestos types, among them fluor-edenite asbestos, winchite asbestos, and richterite asbestos.

Based on the crystallographic properties that define asbestos, i.e., high frequency of closely spaced twinning and Wadsley defect structures involving chain dimensions (Chisholm, 1973; Hutchison et al., 1975; Champness et al., 1976; Franco et al., 1977; Harlow et al., 1985), fault offsets between adjacent twin planes (Seshan and Wenk, 1976; Crawford, 1980), disorientation of unit fibrils parallel to the long fiber axis (Franco et al., 1977), the amphibole asbestos minerals form thin fibrils within the fiber's composite bundle, with the fibrils randomly oriented around the c-axis. These features are summarized in Dorling and Zussman (1987) and Langer et al. (1991).

The non-asbestiform analogues also have twin plane defects as well as chain-width errors (Veblen et al., 1977). However, the frequency of occurrence of the defects is less and distances over which they repeat are far greater, as found by Harlow et al.'s (1985) study for amosite. But as noted in Verkouteren and Wylie, a fibrous particle lying on a twin plane can occur in non-asbestiform amphiboles as well.

The asbestos minerals that are mechanically manipulated generate dust particles that are longer and thinner and disproportionately higher in particle number as compared to non-asbestos minerals manipulated in the same way. This is especially true when comparing the non-asbestos analogues of the same mineral (Harlow et al., 1985; Wylie, 1988). Compare the mineral populations in Figs. 1 and 2. Consider for comparison a 1-μm diameter orthorhombic prism and a 0.125-μm diameter orthorhombic fibril with their c-crystallographic axes the same length. The same mass of mineral in the 1-μm prism would crush to yield 64 particles with 32 times greater surface area (chemical potential) if reduced to the sizes cited above.

Are these size differences biologically important? The smaller fibril diameter would form a more stable aerosol, would possess greater inhalation potential, could penetrate the pulmonary architecture to the pleura more easily, and could "hit" many more cell targets. The state of aggregation of dust controls its biological potential (Langer and Nolan, 1986).

Because of their unusual crystallographic properties, the asbestos minerals may be distinguished from their non-asbestiform analogues based on their anomalous optical behavior in polarized light (Wylie, 1979, 1988). Verkouteren and Wylie cautioned that the application of these characteristics would depend on the crystal symmetry of the particle, the size of the unit fibrils, and their crystallographic orientation with respect to the optical axis of the instrument. The physical behavior of these materials, and their resulting population following crushing, is therefore useful in assisting the analyst in distinguishing asbestiform from non-asbestiform mineral populations. It is when sin-
Fig. 2. (A) Tremolite asbestos fiber from a Mediterranean whitewash (stucco). Tremolite asbestos fiber bundle as seen in plane-polarized light (PLM). The fiber bundle is approximately 110 μm in length. From Langer et al. (1991). Some tremolite cleavage fragments are visible in the field as well. (B) Tremolite asbestos fibrils disaggregated from a fiber bundle by ultrasound as seen by transmission electron microscopy. Population of particles dominated by high aspect ratio amphibole fibrils.

gle isolated particles appear on a filter, or in a sample obtained in environments in which asbestos is not expected or thought to occur, that identification uncertainty increases.

4. Examples of Asbestos Standard accommodations

The US Environmental Protection Agency (EPA) required an assay instrument capable of resolving small airborne particulates in the ambient environment whose size was for the most part well beyond the resolution of the light microscope. The instrument of choice was found to be the transmission electron microscope (TEM). With time the TEM necessarily became an analytical instrument with chemistry and crystallographic data incorporated into the identification protocol. The diagnostics for single isolated particles were initially described in Langer and Pooley (1973).

The EPA eventually modified its counting protocol for the indoor air environment of schools so that fibers greater than 0.5 μm in length were included in the assay count with the length-to-width aspect ratio of the fibers increased from 3:1 to 5:1 and greater. It was noted at that time that these changes had limited biological relevance.

Historically, the EPA required a modified collection technique for airborne particulates. The initial studies of the asbestos content of ambient air in large urban areas required collection of particulates from very large volumes of air (many cubic meters) onto membrane filters. The first high volume filters were glass fiber pads that on consideration were deemed inappropriate for a fiber assay. The collection filters, made of methyl cellulose ester (MCE), were found overloaded with combustion products that obscured any asbestos that might be present. The direct technique for filter preparation (used in the workplace setting) was abandoned through necessity and the indirect filter preparation technique was introduced for environmental assay. The modified protocol required ashing or burning off of organic matter, re-dispersion of the heat-resistant residual particulate load into a material capable of forming a support film substrate for the particulates, sizing fiber length on the TEM screen, TEM identification of single, isolated particles, and assay based on conversion of fiber dimensions to mass. Fiber concentrations were expressed as mass units, nanograms of mineral per cubic meter of air. The fiber found in virtually every instance was chrysotile that exhibited a reasonably constant fibril diameter rendering mass calculation relatively straightforward (Nicholson and Pundsack, 1973). The rationale used by the investigators at that time (to report mass rather than fiber number and concentration) was based on concern that the manipulation of the filter load introduced fiber number artifact, and to a lesser extent fiber size artifact. Conversion to fiber units from units defining millions of particles per cubic foot of air was attempted in a range of occupational and environmental settings later in time (NIOSH, 1976).

5. Work hazards in mines and mills pre MSHA

Concern regarding mining hazards in the United States evolved in the latter part of the nineteenth century. Important legislation by Congress followed the Monongah Coal Mine disaster of 1907 in which 362 miners were killed in an explosion. That year no less than 20 mine disasters were reported with the loss of 4192 lives. Accidents, fires, explosions and other agents and factors accounted for the loss of life. Mining for mineral commodities and metals, other than coal, claimed many lives as well. That year, Congress established the US Bureau of Mines charged with mine safety.

The Federal Coal Mine Safety Act (1952) followed the Centralia disaster in Illinois and important legislative modifications to the Act was passed in 1969, spurred by the
6. The mine and mill environments

The higher PEL used for environment assay in mines and mills was in large measure based on the nature of the materials regulated by the agency. MSHA recognized that the earth's continental crust is formed of many petrologic zones (rock types) and scattered ore bodies, each reflecting very different mineral assemblages. Minerals in the amphibole group are estimated to constitute 5% of the earth's crystalline crust (Ronov and Yaroshewsky, 1969). Making up this 5% are 27 amphibole minerals that are considered "end-members" of 71 recognized compositional variants (Leake et al., 1998). Among these are amphibole minerals classified by mineral name as "asbestos" in the OSHA standard (Table 1).

Chemistry modifies mineral properties and new properties require a new mineral name (Table 2). Embracing the OSHA nomenclature for asbestos prior to 1994 required either change in assay instrumentation or a standard that would recognize the existence of cleavage fragments. PCOM was not an analytical tool and could not be used for mineral identification. OSHA's Physical Measurements Branch in Salt Lake City, charged with the analysis of bulk samples submitted to the agency, developed an analytical protocol utilizing polarized light microscopy among a number of other standard mineralogical instruments (Crane, 1992).

Among the amphiboles it is important to note that the names "amosite" and "crocidolite" are absent from the Leake report. The name "amosite" was formally "discredited" in the mineralogy community as the type mineral was later in time found to be a mixture of actinolite and cummingtonite (read commentary in Langer et al., 1979, and in Verkouteren and Wylie, 2002); amosite exists, but is technically grunerite asbestos, as crocidolite is technically riebeckite asbestos (Table 1). Separate mineral names for the same mineral occurring with different habit (form) are discouraged in the mineralogical community. The mineral name is therefore modified with a descriptive adjective reflecting habit (Table 1, Column 3). For example, tremolite occurring with an asbestiform habit is called tremolite asbestos.] The importance of distinguishing between asbestiform fibers and their non-asbestiform analogue fragments emerged in the mining community in the early 1970s (Amipan, 1976). The challenge was the ability to distinguish cleavage fragments from asbestos fiber. The minerals industry was perplexed.

However, because of the emergence of disease-prevalence among the miners and millers of vermiculite in Libby Montana (vermiculite associated with several amphibole asbestos fiber types), both the Department of Labor and the Office of the Inspector General required MSHA to re-evaluate their Asbestos Standard as it was modified from the OSHA standard. For example, the MSHA asbestos PEL was held at 2.0 f/ml of air. Admittedly, the OIG recognized that the diseases observed in the Libby workforce were in large part the result of exposures in the past. The Libby situation introduced more issues. The major asbestos fiber type in the vermiculite deposit had been reported to be tremolite with some actinolite, but Meeker et al. (2003) and Bandli et al. (2003), using modern electron microprobe technique, reported the presence of calc-sodic asbestiform amphiboles, winchite and richterite (Table 2). Neither mineral was cited in the Asbestos Standard.

7. The amphibole problem

The amphibole minerals are chain silicates with two distinct planes of perfect cleavage that produces elongated prismatic fragments when crushed. Tremolite is a common amphibole and crushes to yield prismatic fragments (Fig. 1a and b). Their asbestos analogues when crushed form
elongated fibers, generally with much higher aspect ratio (Fig. 2A and B). Amphibole asbestos fibrils are predominantly thinner in width than cleavage fragments of the same mineral formed by crushing (Wylie, 1988). Examination of the size distributions of these two aspect ratio (AR) populations shows that the higher values for the cleavage fragments (the tail of its distribution) and the lower values for the asbestos fibers (the tail of its distribution) overlap to some limited degree (Wylie, 1988). Study of populations of amphibole asbestos fibers indicates that Wylie’s initial observations hold for all fiber types Campbell et al. (1977). Amphibole asbestos fibril diameters (called widths, diameters, and thicknesses depending on who is writing and what they are describing) for the standard asbestos minerals (UICC Standard Reference Asbestos Minerals) and tremolite asbestos (from Libby Montana, as a standard UICC tremolite asbestos was not made) was published by Langer et al. (1974) (Table 3). Thin fibrils characterize the amphibole asbestos population.

With amphibole minerals making up some 5% of the crystalline continental crust, the mining and milling of ores and processing of mineral commodities is likely to be associated with a “mineral fiber” issue. Are the elongated objects that conform morphologically to the definition of asbestos actually asbestos? The OSHA Asbestos Standard prior to 1994 said “yes”. The modern standard says “no”. The issue today is whether or not you can distinguish between the forms on a small particle basis.

Consider the following comparative data from Wylie (1988) concerning tremolite asbestos associated with the vermiculite deposit in Libby, Montana and talc containing tremolite mined and milled in Gouverneur, New York. Wylie’s data showed that 88% of the tremolite from Libby had an AR greater than 10:1 while 8% of the tremolite from Gouverneur did as well; 52% of the Libby tremolite had an AR of 20:1 or greater whereas 4% of the Gouverneur tremolite did. Use of mineral name only and morphological criteria suggested that both deposits contained tremolite asbestos, with Libby to a much greater degree.

Comparison of the optical characteristics obtained by PLM (anomalous optical properties and size distribution of the particle populations) indicated that only the Libby tremolite occurs as asbestos. These observations illustrate the difficulties faced by MSHA. OSHA concluded in its published Asbestos Standard in 1994 that exposure to non-asbestiform cleavage fragments of the minerals cited in the Asbestos Standard was “not likely to produce a significant risk of developing the asbestos-related diseases” (Federal Register, 1992). Separation of forms of the same mineral appeared supportable on a biological basis. Parenthetically, our laboratory (the Environmental Sciences Laboratory, Mount Sinai School of Medicine) verified the presence of tremolite asbestos in the Libby vermiculite in the 1972 time frame. [Electron microprobe studies suggest winchite and richterite would be included among the fibers in the asbestos population as well as the cleavage fragment population.]

The issue regarding talc and its associated amphiboles is well described in Van Gosen et al. (2004). In their study, which focused on talc deposits in the Death Valley region of California, amphibole minerals tended to be plentiful. The likelihood of amphiboles occurring in association with talc was related to geological origin, rock type, and metamorphic history of the deposit. Further, geological processes controlled amphibole habit so that the presence of a specific amphibole did not guarantee that it exhibited the asbestos habit. Two of the amphibole minerals were identified as winchite and richterite.

**8. The Mesabi experience**

The exploitation of iron ore over the extent of the Mesabi Iron Ore Range has been carried out for more than a century (Langer et al., 1979). Mining and milling of ore within the Eastern Mesabi District, from the town of Mesabi eastward to Old Babbitt over a distance of about 19 miles, has produced particular problems for regulatory agencies here in the United States (both the EPA and

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Fibril width—as measured on TEM photomicrographs (units are in tenths of microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(N)</td>
</tr>
<tr>
<td>Crocidolite&lt;sup&gt;a&lt;/sup&gt;</td>
<td>552</td>
</tr>
<tr>
<td>Amosite&lt;sup&gt;b&lt;/sup&gt;</td>
<td>192</td>
</tr>
<tr>
<td>Anthophyllite&lt;sup&gt;c&lt;/sup&gt;</td>
<td>261</td>
</tr>
<tr>
<td>Tremolite&lt;sup&gt;d&lt;/sup&gt;</td>
<td>144</td>
</tr>
</tbody>
</table>

<sup>a</sup> *Crocidolite* specimen from the UICC Standard Reference Samples of Asbestos (SRSA). Republic of South Africa, northwestern Cape Province.

<sup>b</sup> *Amosite* specimen from the UICC SRSA, Transvaal, RSA.

<sup>c</sup> *Anthophyllite* specimen from the UICC SRSA, Finland.

<sup>d</sup> *Tremolite* specimen the reference samples did not contain a tremolite Asbestos Standard. This tremolite was obtained from the Libby Montana vermiculite deposit, collected by Walter Banks of the USBM, Denver, circa 1969–1970. The above data were presented at the international meeting “Biological Effects of Ingested Asbestos”, Durham, North Carolina November 18–20, 1973. See Langer et al. (1974).

<sup>e</sup> Some of these fibril widths exceeded 1.0 µm (by TEM examination).

<sup>f</sup> Average width of fibril is an arithmetic average. All distributions are log-normal; the anthophyllite distribution is poly modal suggesting the presence of anthophyllite-talc intergrowths (talcboles).
MSHA on the national level, and state authorities on the local level). Low-temperature iron silicate minerals that characterized the Biwabik Iron-Formation southwest of the Virginia bend had been transformed (“destroyed”) through contact and regional metamorphism with the Duluth Gabbro into high temperature assemblages that included amphiboles.

The taconite iron ore in the eastern Mesabi is principally magnetite and quartz, which is admixed with grunerite (grunerite-cummingtonite), actinolite, hornblende, riebeckite and a sodium hornblende. Amphibole intergrowths are common as well. These minerals are not homogeneously distributed through the stratigraphic members that define the Biwabik, but range in concentration outward with distance from the thermal and metasomatic effects of the gabbro body. These minerals have elemental compositions that are similar making it difficult to distinguish actinolite from some common forms of iron-rich hornblende (Gundersen and Schwartz, 1962). There are also issues involved in distinguishing between thin, acicular, grunerite cleavage fragments and grunerite asbestos (amosite). Descriptions of these mineral assemblages and characterization issues are in Gundersen and Schwartz (1962) and French (1968).

Matters changed dramatically in 1973. Crushed taconite ore examined by industrial hygienists was found to contain amphibole minerals a fraction of which were morphologically fibrous. Some argued that these particulates contributed to the then existing Federal definition of asbestos. In particular grunerite and actinolite were present with morphological traits that MSHA used to define asbestos—greater than 5 μm in length with an aspect ratio of 3:1 or greater. These fragments were eventually dumped as tailings (in slurry form) into a containment dam in Lake Superior following iron mineral extraction in a wet-magnetic process in Silver Bay, Minnesota (Langer et al., 1979). Questions arose as to whether these objects were actually asbestos and whether they constituted a health threat to those who breathed the air in Silver Bay or drank the water drawn from Lake Superior.

Analyses performed in the ESL-Mt. Sinai in New York were eventually published as several reports. The last of these reports, based on particle analysis by analytical electron microscopy (Langer et al., 1979), concluded that the number of particles of grunerite that were indistinguishable from amosite constituted only a very small fraction of the total amphibole particle population. Many of the papers presented at this symposium outline some of the difficulties involving mineral characterization encountered by analysts in their efforts to distinguish between asbestos fiber and cleavage fragment.

9. MSHA and its current Asbestos Standard

Based on the health outcome among the mine and mill workers at Libby Montana, MSHA has proposed changes to its existing Asbestos Standard. [Many of these same issues were observed during EPA’s investigation into the contamination of Lake Superior with taconite tailings in the early 1970’s (Langer et al., 1979).] In 2005, MSHA proposed that its PEL be lowered from 2.0 fl/ml of air to the current OSHA level of 0.1 fl/ml of air, its excursion level lowered to 1.0 fl/ml of air over a 30 min time period, and the instrument of assay, to improve mineral identification, would be the analytical transmission electron microscope. If followed, the ability to distinguish amphibole asbestos fibrils from cleavage fragments would be greatly improved.

As if the MSHA community did not have enough to consider, there has been a spate of new “asbestos” minerals found in places both inside and outside of the United States that have been implicated as possible agents of disease. Fibrous balangeroite and fibrous carlosturanite have been identified within the chrysotile deposits of the Piedmont in Italy where they are considered agents of disease causation (mesothelioma) rather than the chrysotile itself (Astolfi et al., 1991). Fluor-edenite asbestos (Bruni et al., 2006) and arfvedsonite asbestos (Shcherbakov et al., 2001), both minerals with amphibole structures, have been described. Arfvedsonite asbestos was mined and exploited in Russia in the northern Urals. The fluor-edenite occurs in a volcanic aggregate in Sicily and its fibers have been found in the lung tissue study of a person who died of pleural mesothelioma in the local town. The arfvedsonite asbestos is suspected as an agent in mesothelioma causation in the Urals (Shcherbakov et al., 2001). Winchite asbestos and richterite asbestos have been identified in ore deposits in the United States.

10. Conclusions and recommendations

Among its many responsibilities, MSHA is concerned with protecting the mineral industry workforce from the hazards associated with asbestos exposure. The agency recognizes that some amphiboles that are common rock forming minerals may, under special geological circumstances, form asbestos deposits. The agency also recognizes that when the massive non-asbestiform varieties of these common minerals are crushed during mining and milling a portion of the mineral particle population closely resembles asbestos. These are cleavage fragments and they have been found to possess far less biological activity than their asbestiform analogues. [OSHA removed cleavage fragments from their Asbestos Standard in 1994.] MSHA has grappled with this problem since its inception and analytical and counting strategies were modified to assist in distinguishing between habits of the same mineral.

Polarized light microscopy has occasionally been substituted for PCM in that it yields information regarding habit. Single crystal fragments (cleavage fragments) may be easily distinguished from polyfilamentous fiber bundles (asbestos) (Wylie, 1979). The PLM, when used with immersion oils, is a powerful analytical tool in the hands of an experienced microscopist (Crane, 1992). The anomalous optical behavior of amphibole asbestos, as compared to its non-asbestos...
analouges, was described in Wylie (1979). The crystallographic defects of the amphibole asbestos minerals, and the random orientation of the fibrils in the ab plane, impart parallel to sub parallel extinction to fibers and only two indices of refraction parallel to and across fiber length.

Single isolated fragments with widths or thicknesses greater than 1 μm are probably cleavage fragments (see the population data in Wylie, 1988). If the sample is amphibole asbestos, the population of particles will invariably contain fibrils with thicknesses much less than this value (Table 3). Langer et al.'s data (1974) obtained on the UICC Reference Asbestos standards also highlighted this characteristic of the amphibole minerals.

The MSHA assay for asbestos has in the past included X-ray diffraction analysis. In the continuous scan mode, with a high intensity X-ray source, minor concentrations of minerals may be detected, identified and quantified. This technique has been used in the Salt Lake City laboratory. Mineral identification is obtainable but morphological habit is not. The technique is rapid and assisted with powder diffraction file search programs.

MSHA proposed in 2005 that the analytical transmission electron microscopy (ATEM) be used as an assay tool. The microscopist would count only phase-contrast equivalent fibers, i.e., those greater than 0.2 μm in diameter. Mineral identification would be greatly improved with acquisition of structural data by means of electron diffraction studies.

Although the issue has been informally discussed, the chemistry of some amphiboles may be used to distinguish amphibole asbestos fibrils from thin diameter cleavage fragments. The aluminum content of some amphiboles has been considered important in this regard (Verkouteren and Wylie, 2002; Ross et al., 2008). An issue that has emerged is whether or not energy dispersive spectrometry can resolve the chemical differences as well as the standard probe crystal spectrometry technique.

The use of an analytical transmission electron microscope allows the assay for fibers that cannot be visualized by any light microscopy method (lying below the constraints imposed by physical nature of light, i.e., Abbe's Law).

ATEM also provides information regarding principal planes of separation of the amphibole particles. The ability of the analyst to obtain an interpretable diffraction pattern on an amphibole fragment requires a sufficiently thin plate that will allow passage of the diffracted electrons through the crystal (Whittaker, 1979; Dorling and Zussman, 1987). Thin twin planes, which lie on the (100) twin plane surface, are frequently expressed by amphibole asbestos fibrils. Diffraction nets and the planes on which fragments of minerals lie have been used to distinguish amphibole asbestos fibrils from cleavage fragments (Langer et al., 1991).

It might well be that each and every mineral deposit, processing mill, and aggregate quarry in the United States will require investigation for the presence or absence of asbestos. This was suggested by Walter Banks' report to the USBM (1980). The USEPA had also become involved in these issues because of asbestos fiber entering the general environmental. [It is important to note that the precursor organization to the US EPA initiated the studies concerning asbestos air pollution in major urban centers well before this time. The National Air Pollution Control Administration (NAPCA) held international conferences pertaining to air pollutants in the environment and their health effects. This writer presented a paper, co-authored with Dr. Selikoff, concerning chrysotile air pollution in New York City, chrysotile asbestos in the lungs of NYC residents (Langer and Selikoff, 1971).] With the Federal Asbestos Standard as a guide, the mining and mineral communities will continue to make modifications to its own standard.

MSHA might explore the implementation of a tier-system of analysis. Investigations have found that the study of asbestos begins with the determination of its presence or absence on a field inspection scale. The ATEM is not a universal solution to the identification problem. It is important to note that the number of laboratories equipped with ATEMs is limited, the personnel with the expertise required for the interpretation of diffraction data are small, the ability of real-time workplace assay (based on acquisition of all three particle diagnostics) for worker protection does not exist. Consider the time required for specimen preparation and analysis.

The report by Van Gosen et al. (2004) concerning the talc deposits in the Death Valley region of California found that the presence of amphibole minerals could be predicted on the basis of the geological process and rock type. Field survey by a member of MSHA's geology staff appears a reasonable first step. Is serpentine present? Are amphiboles present? The determination of mineral habit is a separate issue.

Conflict of Interest

The author declares that he has no conflict of interest.

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