Naturally Occurring Asbestos Resource Document

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Abbreviations

ACM	Asbestos-Containing Material
ATCM	Airborne Toxic Control Measure
AHERA	Asbestos Hazard Emergency Response Act
CARB	California Air Resources Board
CDC	Centers for Disease Control and Prevention
DOT	Department of Transportation
EDXA	Energy Dispersive X-Ray Analysis
EMP	Elongate Mineral Particle
f/cc	Fiber Per Cubic Centimeter of Air
FESEM	Field Emission Scanning Electron Microscopy
LNT	Linear No Threshold
MCL	Maximum Contaminant Level
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
NOA	Naturally Occurring Asbestos
NSSGA	National Stone, Sand and Gravel Association
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PLM	Polarized Light Microscopy
ppm	Part Per Million
REL	Recommended Exposure Limit
SAED	Selected Area Electron Diffraction
SEM	Scanning Electron Microscopy
SOP	Standard Operating Procedure
TEM	Transmission Electron Microscopy
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey

Executive Summary

1. What are EMPs? What is asbestos?

Elongate mineral particles (EMPs) are minerals particles with an aspect ratio of ≥3, meaning that the length of the particle exceeds its width by a factor of at least 3. This term does not address the length or width (other than in connection with the aspect ratio), habit, chemical composition, or other characteristics of a particle. EMPs include both non-asbestiform and asbestiform particles. In this document, a countable EMP is defined as having a length >5 µm.

Cleavage fragments[1] are created by breaking larger particles into smaller particles, usually by crushing, grinding, and other processes (both natural and industrial).

- **Most EMPs are not asbestos.** However, asbestos is one type of EMP.
- **Cleavage fragments and non-asbestiform EMPs are not asbestos.**
- Asbestos is a commercial term commonly applied to six "regulated" asbestiform minerals: chrysotile, crocidolite, amosite, anthophyllite asbestos, tremolite asbestos, and actinolite asbestos. Asbestos, and certain other asbestiform minerals, are the EMPs of health concern.

2. EMPs and Asbestos Health Risks

EMPs is a broad term, and the potential health risks associated with different EMPs differ. There are several potential health risks associated with the inhalation of asbestiform mineral fiber EMPs. Cleavage fragments have not been shown to pose the same health risks.

The primary health hazards caused by exposure to respirable asbestos are asbestosis (scarring of the lungs caused by the inhalation and retention of asbestos in the lungs), lung cancer, and pleural mesothelioma (cancer of the pleura, the lining surrounding the lungs). However, these diseases are almost always a result of repeated exposure to high levels of airborne asbestos (usually **occupational exposures** at work) over many years, and **not environmental (or ambient) exposures** that may be experienced by the general public, which are generally occasional, very low levels.

The health risks to humans presented by asbestos depend on several factors, including characteristics of the fibers and the concentration and duration of exposure:

- Respirability. The fibers must be **respirable**, that is, small enough to reach deep into the lungs.
- Fiber length and width. **Long fibers** (>5 µm) pose a greater risk than short fibers, and **thinner fibers** (<3 µm) pose a greater risk than wider fibers.

[1] Cleavage is breaking along planes of weakness inherent in a mineral structure and is found in all samples of a mineral. EMP fragments caused by longitudinal cleavage is the strict definition of a "cleavage fragment." However, minerals may also develop planes of weakness from structural defects, referred to as parting, which reflect conditions of formation and may also result in EMPs. Fracture is breakage unrelated to structure. In this document, for simplicity of nomenclature, the term cleavage fragment applies to any EMP formed by breakage, whether cleavage, parting, or fracture.

- Biopersistence. The **biopersistence** of fibers refers to how long the fibers remain in the lungs until they are cleared or removed. Fibers that stay in the lungs longer present a greater health risk.
- Exposure conditions. The exposure to asbestos must **exceed a certain concentration, referred to as a threshold, over a certain period of time**. If exposures are below the threshold, then no adverse health effects are expected. If exposure concentrations are above the threshold over a sufficient length of time, then there are health risks, which are expected to increase as the concentration increases above the threshold.

3. Measurement of EMPs

Asbestos exposure levels are generally reported as the number of airborne fibers per cubic centimeter of air (f/cc). To measure the number of asbestos fibers, scientists take air samples and analyze the materials collected on the filters. The measurement of asbestos is a highly complicated process and is discussed in detail in this report. The presence of EMPs in the form of cleavage fragments or non-asbestiform particles, which are not asbestiform fibers, can cause errors in the measurement of asbestiform mineral fibers.

4. Where EMPs Occur in Nature

EMPs are common in the U.S. and worldwide. Moreover, rocks and the soils overlying them that are likely to contain amphibole and serpentine minerals (some of which may be asbestos) are found in more than half the U.S. states. Asbestiform minerals are naturally occurring and are widely present in the Earth's crust. Asbestos encountered in this form in nature is referred to as naturally occurring asbestos (NOA).

NOA in trace amounts can occur anywhere, but is more likely to occur if the rock is metamorphic or igneous and unlikely to occur if the rock is sedimentary or in unconsolidated sand and gravel.

5. Other Issues Pertaining to EMPs

The question of whether asbestos or other asbestiform minerals are present in a particular deposit or rock type is best answered by a qualified geologist (*i.e.*, one who is knowledgeable about and experienced with NOA). The qualified geologist will know the local geology, how to inspect the site, how to obtain the correct types of samples to analyze, and so on.

If NOA is found at a site, the operator of a quarry or mine may have to implement additional exposure controls. There are many exposure control methods available, all of which are designed to limit exposure to respirable dust, and in general terms, may include: leaving certain areas with identified NOA undisturbed; restricting access to certain areas to authorized persons using personal protective equipment; maintaining buffers (especially with vegetation) around quarries so that dusts do not reach the surrounding communities; and using dust suppressants and other dust control technologies to minimize potential exposures to dust. This list is general and not exhaustive. A qualified engineer with knowledge and experience regarding quarries and dust control techniques and technologies should be consulted when determining the appropriate controls to use for a site.

Federal, state, and local governments regulate asbestos in the U.S. In general, the United States Environmental Protection Agency (U.S. EPA) regulates environmental matters and exposures and the United States Department of Labor, though the Occupational and Mine Safety and Health Administrations (OSHA and MSHA), regulates occupational exposures. There are also established state and local environmental regulations pertaining to NOA.

A Asbestos and Other EMP Basics

What is asbestos?

Asbestos is a general name given to a group of minerals that form naturally as fibers with certain shared properties, such as flexibility and high tensile strength, that were deemed commercially valuable (NIOSH, 2011). The characteristics of asbestos fibers also contribute to their ability to cause health effects in humans, such as various asbestos-related diseases.[2] The ability or inability of naturally occurring mineral fibers like asbestos to cause health effects in humans are the result of the crystal shape (also referred to as its habit) and size of the particles created when they were formed in the Earth, and the biopersistence of the fibers in the human body. Other mineral fibers that share these asbestos-like characteristics are said to be "asbestiform" fibers. U.S. regulatory policy for asbestos is limited to six asbestos types: a serpentine mineral called chrysotile asbestos and five amphibole minerals – amosite asbestos (also known as asbestiform cummingtonite-grunerite), crocidolite asbestos (also known as asbestiform riebeckite), anthophyllite asbestos, tremolite asbestos, and actinolite asbestos (Skinner *et al*., 1988; Strohmeier *et al*., 2010; NIOSH, 2011; Roggli, 2018). Each of the six types of asbestos has a non-asbestos analog – these are the same minerals, but they formed with non-asbestiform mineral habits[3] (*e.g*., prismatic or acicular, among others; see Table 1) (Harper *et al*., 2008; Bailey *et al*., 2004). There is sufficient evidence from studies of occupational exposure to asbestiform winchite and asbestiform richterite found in vermiculite from Libby, Montana (*e.g*., Montana State Board of Health, 1962), and to fluoroedenite from quarrying operations at Biancavilla, Italy (*e.g*., Bruni *et al*., 2014), among others, to conclude that all asbestiform amphibole fibers should be treated as if they are asbestos.

[2] The phrase "asbestos-related diseases" as used in this document means diseases or health conditions for which there is credible scientific evidence, published in the peer-reviewed literature, that supports a causal link between exposure to the asbestos in question and the diseases or health conditions. See Section B for more information.

[3] A mineral "habit" refers to the tendency of a crystal to grow in a specific shape based on its chemical structure and the geological forces that acted upon it during its growth.

Table 1 Asbestos Minerals and Their Non-Asbestos Mineral Analogs

Mineral Name (Mineral Group)	Name(s) When the Mineral Is Crystalized in the Asbestiform Mineral Habit (CAS No.)	Name(s) When the Mineral Is Crystalized in the Non-Asbestiform Mineral Habit (CAS No.)
Serpentine (Serpentine Group)	Chrysotile asbestos (CAS No. 12001-29-5)	Lizardite (CAS No. 12161-84-1) and Antigorite[1] (CAS No. 12135-86-3)
Riebeckite (Amphibole Group)	Crocidolite asbestos (or asbestiform riebeckite) (CAS No. 12001-28-4)	Riebeckite (or non-asbestiform riebeckite) (CAS No. 17787-87-0)
Cummingtonite-Grunerite (Amphibole Group)	Amosite asbestos (or asbestiform cummingtonite-grunerite) (CAS No. 12172-73-5)	Cummingtonite-Grunerite (or non-asbestiform cummingtonite-grunerite) (CAS No. 14567-61-4)
Anthophyllite (Amphibole Group)	Anthophyllite asbestos (or asbestiform anthophyllite) (CAS No. 77536-67-5)	Anthophyllite (or non-asbestiform anthophyllite) (CAS No. 17068-78-9)
Tremolite (Amphibole Group)	Tremolite asbestos (or asbestiform tremolite) (CAS No. 77536-68-6)	Tremolite (or non-asbestiform tremolite) (CAS No. 14567-73-8)
Actinolite (Amphibole Group)	Actinolite asbestos (or asbestiform actinolite) (CAS No. 77536-66-4)	Actinolite (or non-asbestiform actinolite) (CAS No. 13768-00-8)

Notes:
CAS No. = Chemical Abstracts Service Number.
Source: Thompson (1984).
(1) Rarely, asbestiform antigorite may be discovered.

What are EMPs?

The National Institute for Occupational Safety and Health (NIOSH) introduced the term "elongate mineral particles" (EMPs) in its 2011 "Roadmap for Research" on asbestos, defining an EMP as any mineral particle with a minimum length to width ratio (aspect ratio) of 3:1 (NIOSH, 2011).

EMPs are derived from minerals in two ways: (1) by forming naturally as mineral fibers, or (2) by the fragmentation of a non-fibrous mineral (for example, when a rock is crushed). The latter are termed "cleavage fragments"[4] (NIOSH, 2011). Minerals with different habits will generate EMPs with different characteristics. NIOSH (2011) created the term EMP in recognition of the fact that not all EMPs are fibers, and thus, not all EMPs are asbestos; in fact, the vast majority are not. However, EMPs formed by fragmentation are often (incorrectly) still referred to as fibers in many analytical protocols for EMPs (as can be seen in Section C of this document) (Harper, 2008).

[4] Cleavage is breaking along planes of weakness inherent in a mineral structure and is found in all samples of a mineral. Elongate fragments caused by longitudinal cleavage is the strict definition of a "cleavage fragment." However, minerals may also develop planes of weakness from structural defects, referred to as parting, which reflect conditions of formation and are not present in all occurrences, and these may also result in an elongate particle. Fracture is breakage unrelated to structure. In this document, for simplicity of nomenclature, the term cleavage fragment applies to any elongated particle formed by breakage, whether cleavage, parting, or fracture.

This distinction between NOA fibers and cleavage fragments, even of the same mineral, is important because they have different physical and toxicological characteristics (*i.e*., their ability, or lack thereof, to cause health effects in humans). Asbestiform minerals may appear as single fibers or as fiber bundles that contain numerous parallel fibers. Individual fibers may further subdivide under pressure into many very narrow single crystals (generally <0.5 μm in width), called fibrils (NIOSH, 2011). In contrast, cleavage fragments break under pressure into shorter pieces, or fragments. Fibrils are also characterized by outer surfaces that are smooth and relatively free from structural defects (NRC, 1984). As mentioned above, many asbestiform minerals that are not regulated as "asbestos" exist in nature. These include erionite (an asbestiform zeolite) and numerous asbestiform amphiboles (*e.g*., asbestiform winchite, asbestiform richterite, asbestiform fluroedenite; see Figure 1) (NIOSH, 2011).[5] Many of these non-regulated fibers, in part due to their form and physical characteristics, have been shown to be hazardous to humans (see Section B for more details).

In contrast to asbestiform fibers, EMPs derived by fragmentation of non-asbestiform minerals are typically wider, and their width increases with their length (Van Orden *et al*., 2016; Siegrist and Wylie, 1980). Cleavage fragments also have different surface properties, such as roughness (NRC, 1984), due to the way in which they are formed. Cleavage fragments are always non-asbestiform particles (Campbell *et al*., 1977). Exposure to cleavage fragments has not been shown to present similar health risks as exposure to asbestiform fibers (Gamble and Gibbs, 2008; Addison and McConnell, 2008; Mossman, 2008; Williams *et al*., 2013), including the non-asbestos analogs of the six types of asbestos regulated by the Occupational Safety and Health Administration (OSHA), United States Environmental Protection Agency (U.S. EPA), and Mine Safety and Health Administration (MSHA) as asbestos (see Section F for further information on these regulations).

[5] While this document addresses only amphibole and serpentine EMPs, if asbestiform zeolites are encountered during mining, they should be treated as asbestos.

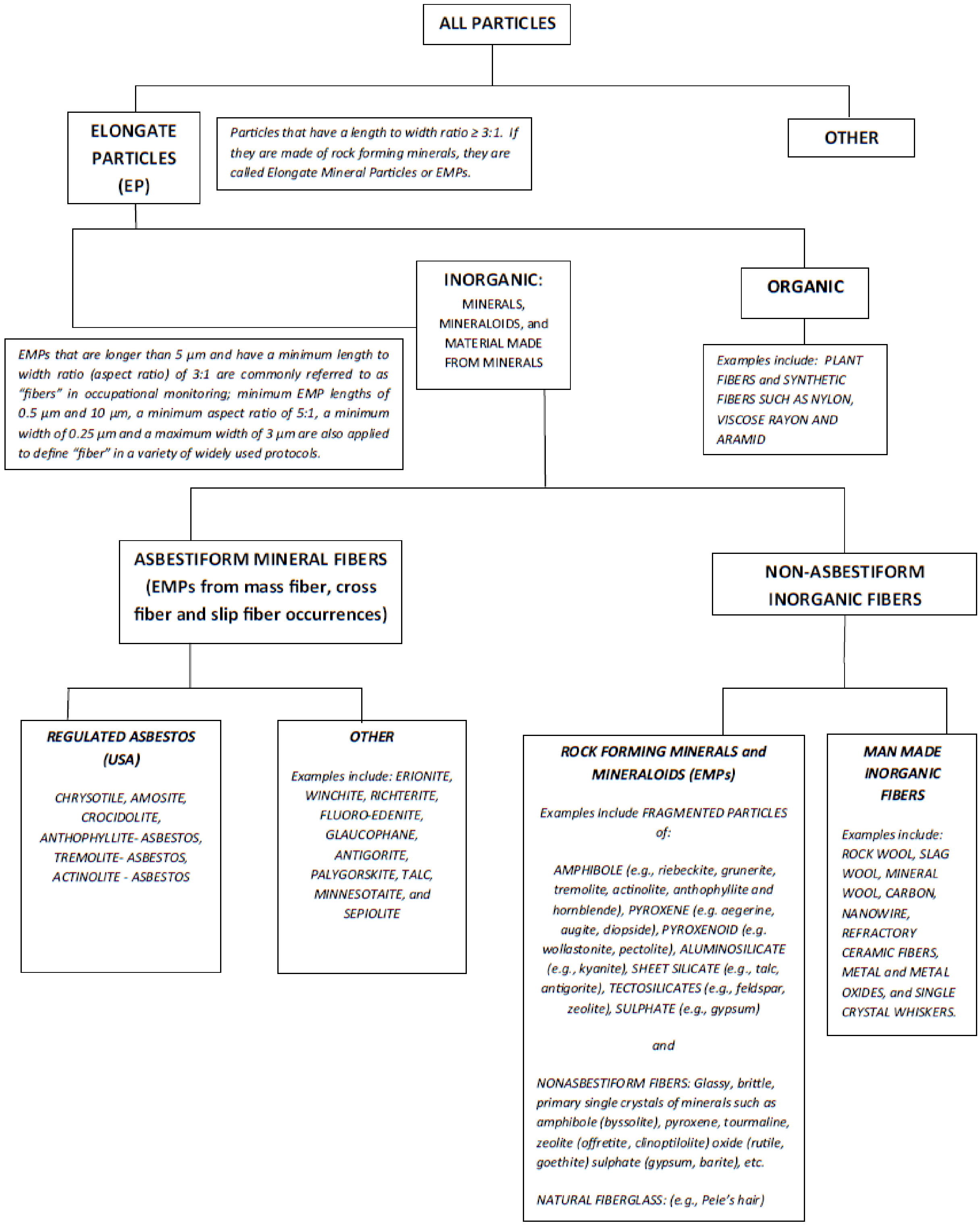

Figure 1 Universe of Particles. Source: Bailey *et al*. (2018).[6]

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In terms of their occurrence in nature, EMPs can be found in soils and mineral deposits, or suspended in water and air. For example, rocks containing 2% or more amphibole minerals, which usually form EMPs when crushed or broken, make up 6-15% of the rocks in the contiguous U.S. (Wylie and Candela, 2015). Figure 2 shows the distribution of rocks in the contiguous U.S. that may contain amphibole and/or serpentine minerals. Both types can exist in the asbestiform and non-asbestiform habit.

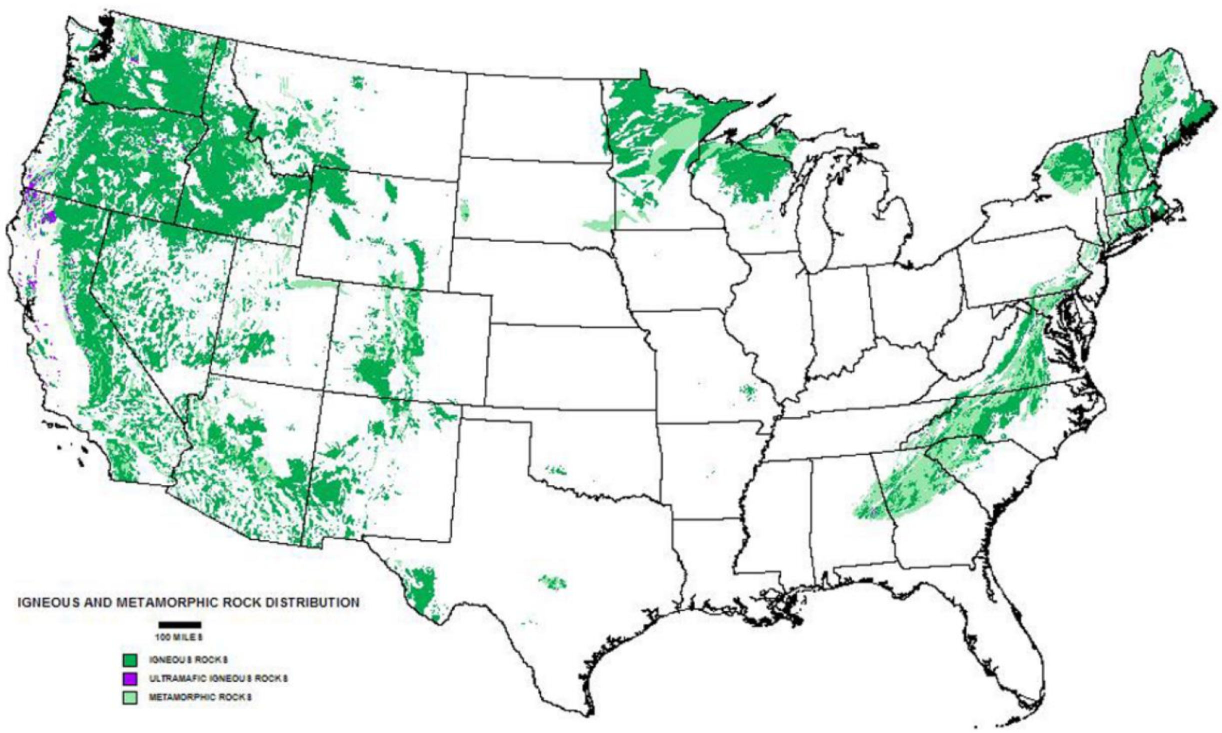

Figure 2 Igneous and Metamorphic Rock Distribution in the Contiguous United States. Rocks and soils in the areas shown in green have a higher probability of containing amphibole and serpentine minerals, some of which are minerals defined as asbestos. Source: U.S. EPA (1974). Note that the resolution is limited at this scale.

Asbestos fibers may become airborne and suspended in air as a result of natural processes such as erosion, and, for example, when asbestos or asbestos-containing rock is extracted and crushed in mining or quarrying operations. Asbestos-containing building materials can also release asbestos into the air during removal (typically called asbestos abatement) or with normal wear (Wylie and Candela, 2015). Asbestos fibers have been detected in air throughout the U.S., typically at very low levels. Wylie and Candela (2015) reviewed data on these "background" asbestos concentrations in air and found that they are typically <0.001 asbestos fiber per cubic centimeter (f/cc) and may be several orders of magnitude lower than 0.001 f/cc in rural areas.

What is "naturally occurring asbestos" (NOA)?

All asbestos is natural (*i.e.*, forms naturally and is not manmade), so "naturally occurring asbestos" (NOA) is a somewhat misleading term (Gunter, 2010). NOA is intended to mean instances of the regulated chrysotile and asbestiform amphibole minerals found in nature (where they originally form), rather than asbestos that has been used as or added to a commercial product (such as building insulation that contains asbestos). However, herein, we use the International Mineralogical Association (1997) definition for NOA, which, in addition to chrysotile, includes all compositions of asbestiform amphibole, although only five are formally regulated as asbestos in the U.S.

When present, NOA is typically found in only trace quantities in a rock unit, but its geographic distribution in rocks and soil is widespread (not just in the U.S., but globally). Wherever amphibole- and serpentine-bearing rock are found, there is potential for NOA to be formed (Bailey *et al*., 2004). Less common, erionite (an asbestiform zeolite) may be found where volcanic ash has weathered over millennia. As Figure 2 shows, rocks and the soils overlying them that are likely to contain amphibole and serpentine minerals (some of which may be asbestiform) can be found in more than half the U.S. states.

Usually, when NOA occurs, it is not homogeneously distributed in a rock unit (CARB, 2017). Instead, NOA normally exists in thin veins with sharp, visible edges running through the host rock. Average concentrations of NOA throughout an aggregate ore body are usually orders of magnitude less than 1% by weight if present at all (or else the ore body would be regulated as an "asbestos-containing material"; U.S. EPA, 1978, 1987). However, it is important to understand that the NOA content of a rock or ore does not provide any information about how much NOA may become airborne if disturbed. Inhalation of asbestos fibers is the way that asbestos presents a human health risk (see Section B).

NOA Encountered in Mining/Quarrying Operations

NOA is not present at the majority of mining and quarrying operations in the U.S. (NSSGA, 2019). However, asbestiform minerals are readily identifiable when present and can easily be distinguished from other mineral habits with the naked eye or with the use of a handheld magnifying lens (Campbell *et al*., 1977). Pressure from a fingernail or probe can readily dislodge asbestos fibers from the veins, and dislodged fibers of sufficient length will bend rather than break. These properties readily distinguish asbestiform EMPs from non-asbestiform EMPs in bulk samples, but microscopic analyses will be necessary to confirm their relative percentages in a given sample.

The heterogeneous distribution of NOA in rock as distinct veins means that it may be possible in certain circumstances to identify and isolate the NOA veins. Once identified, the NOA can be avoided or buried on-site. In addition, the quarrying or mining process itself blends all extracted materials, thereby reducing the concentration of any contaminants in the final product. The same mixing occurs when preparing samples for microscopic analysis (CARB, 2017).

Sections E and F describe protocols and processes for determining whether NOA is present at a mining/quarrying site, and controlling asbestos exposures at sites where NOA is found.

B Asbestos and Other EMP Health Risks

How is the health risk posed by a substance assessed?

Toxicology is the study of the potentially adverse health effects of biological, chemical, and physical agents on living organisms (Hayes and Kruger, 2014). It encompasses studies of human populations, experimental animals, isolated cells, and isolated molecules, including studies that describe how these substances cause observed effects. An understanding of toxicology is necessary for determining how much of a substance one can be exposed to, and under what conditions, without the likelihood of harm. In addition to an exposure assessment (*i.e.*, whether an individual had any contact with the substance in question and, if so, to what degree), a determination of dose (the amount of a substance taken into the body over time) is a key component of evaluating health effects from biological, chemical, and physical agents.

To characterize an agent's toxicity, it is necessary to understand the critical health effects it can cause and the exposure levels, or doses, at which these critical effects occur (*i.e.*, critical effect levels). Evaluating the relationship between health effects and exposure is referred to as a dose-response assessment. The dose-response assessment reflects a basic concept in toxicology – the type and severity of a substance's effects depend on both the magnitude of exposure (*e.g.*, the concentration of an agent inhaled or ingested) and the duration of exposure to the substance. There are levels of exposure to extrinsic substances below which adverse effects are highly unlikely or will not occur. This applies to all substances, even those that are necessary for maintaining one's health. In common parlance, "the dose makes the poison." For example, water intake is essential for humans, but drinking too much water can lead to water intoxication, with a potentially fatal outcome (Farrell and Bower, 2003). Other factors that can influence toxicity include the exposure magnitude, the frequency and duration of exposure, the route of exposure, and metabolism, as well as the genetics, nutritional status, and overall health status of the individual (Aleksunes and Eaton, 2019).

To characterize cancer risk, for example, hazards and the doses at which they occur are evaluated along with site-specific exposure information to determine the incremental risk of cancer above background risks (U.S. EPA, 2005). Risks are expressed as a unitless probability and are often based on the assumption that exposure occurs over a lifetime. U.S. EPA has established a target cancer risk range of 1 in 1,000,000 to 1 in 10,000 (*i.e.*, 1×10^{-6} to 1×10^{-4}) (U.S. EPA, 1990, 1991a). That is, U.S. EPA has determined an acceptable risk of excess cancer above background as 1 case of cancer per 1,000,000 or 10,000 persons. With respect to Superfund sites, U.S. EPA (2014) noted that "while the upper end of the risk range is not a discrete line at 1 in 10,000, EPA generally uses 1 in 10,000 in making risk management decisions. A specific risk estimate around 10^{-4} may be considered acceptable based on site-specific circumstances." Note that these calculated risks are based on deliberately conservative assumptions and thus overestimate the true risks. Also, this excess risk should be put into context of the absolute overall risk of cancer: 1 in 2 men and 1 in 3 women will develop some form of cancer in their lifetimes (ACS, 2020).

How are exposure levels of asbestos and other EMPs assessed?

Exposure levels of asbestos and other EMPs are typically determined in terms of "countable" particles per unit of media in which they are found. As discussed further in Sections C and D, concentrations of asbestos and other EMPs in air and water are calculated by counting the numbers of particles with certain characteristics observable using the chosen analytical method (*e.g.*, countable asbestos fibers per cubic centimeter of air), with different analytical methods providing different counting rules. NIOSH (2011) defined a "countable EMP" as an EMP longer than 5 µm (so, a particle with a minimum aspect ratio of 3:1 that is longer than 5 µm). When electron microscopy is used as the analytical method, NIOSH (2011) included a minimum width of 0.25 µm in its definition of "countable EMP" in an attempt to ensure there is parity between particle counts done with optical and electron microscopic analytical methodologies. Herein, "countable asbestos fibers" refers to countable EMPs from the asbestiform varieties of one of the six minerals regulated as asbestos in the U.S. and any other amphibole in this habit, unless we are discussing regulatory policy and practice, in which these terms are more narrowly defined.

What health effects can asbestos potentially cause?

EMPs is a broad term, and the potential health risks associated with different EMPs differ. There are several potential health risks associated with the inhalation of asbestiform fibers. Based on current evidence, cleavage fragments are not known to present asbestos health risks (Dell *et al*., 2021).

Based on current scientific knowledge, inhalation is the primary route of exposure associated with health effects associated with asbestos. Respiratory diseases associated with exposure to asbestos include asbestosis, lung cancer, and mesothelioma. Much of the evidence regarding these health effects has been obtained from studies of workers exposed to asbestos through their jobs, who were exposed to much higher levels of asbestos than the general public. For instance, asbestosis (a chronic disease characterized by the formation of scar tissue in the lungs) is associated with prolonged exposure to very high levels of asbestos and is therefore unlikely to be experienced by the general public (or by employees working with asbestos who adhere to proper safety precautions) (Mayo Clinic, 2019).

Exposure to some varieties of asbestos can also cause effects that appear on X-rays, such as pleural plaques (small areas of thickened tissue in the lung lining, or pleura). However, these effects are generally considered a sign of exposure and not disease (meaning that a person with pleural plaques will not necessarily ever develop diseases such as asbestosis or mesothelioma) (Zu *et al*., 2016; Kerper *et al*., 2015).

It is also worth noting that many studies of the health effects caused by asbestos exposures are focused on specific types of asbestos, *i.e*., countable asbestos fibers that were measured by phase contrast microscopy (PCM), discussed further in Section C. To determine the risks of experiencing health effects following exposure to asbestos at any particular location, one must consider the characteristics of the asbestos present at the location (*e.g*., fiber type, dimensions), as well as the amount of asbestos to which individuals were exposed, as described further below.

What determines the ability of EMPs to cause health effects?

Particle Characteristics

To cause a health effect in the respiratory system, an EMP must be able to enter the respiratory system and be deposited in the lungs, it must biopersist (*i.e*., remain in the respiratory system), and it must be capable of initiating a disease process. The ability of asbestos and other asbestiform mineral fibers to cause health effects can vary by their mineralogy, habit, length, width, and biopersistence (Wylie and Candela, 2015; Aust *et al*., 2011; Huang *et al*., 2011). Thus, it is important to consider these characteristics when assessing the likelihood of exposure to an EMP causing health effects.

Definitions of these characteristics and how they impact the risks of EMPs are as follows.

- **Habit:** As described in Section A, the two general habits of EMPs are asbestiform and non-asbestiform. Cells respond differently to different habits of the same mineral (Mossman *et al*., 2011; Langer and Nolan, 1994). For example cleavage fragments, which have very different physical properties than asbestos, do not pose the same health risks as asbestos (Davis *et al.*, 1991; Gamble and Gibbs, 2008; Addison and McConnell, 2008; Williams *et al*., 2013).
- **Length:** An EMP's length affects its ability to be deposited in the lungs and biopersist (ATSDR, 2001). Longer EMPs that are sufficiently narrow (see below) are more likely to be deposited in the lower airways after being inhaled, from which they are not readily cleared by the lungs' natural processes (Craighead, 2008; ATSDR, 2001; Bernstein and Hoskins, 2006; Coin *et al*., 1992; Bernstein and Pavlisko, 2017). In contrast, shorter EMPs are more readily engulfed and digested by large white blood cells called macrophages in the phagocytosis process, thus allowing them to be cleared from the lungs more easily (Bernstein and Pavlisko, 2017). Using time-lapse photography, Allison (1973) showed that "independently of asbestos type, short [fibers] (<5 µm) were readily taken up by phagocytosis, whereas long fibers (>25 µm) were never completely taken up…. Particles of intermediate size (5-25 µm) were sometimes completely ingested and sometimes not." NIOSH (2011) indicated that EMPs <5 µm in length did not contribute to lung cancer risk. Based on existing animal and human studies, Roggli (2015) concluded that "there is no convincing evidence for a pathogenic effect for [asbestos] fibers that are 5 µm or less in length." The scientific consensus following the Monticello Conference on EMPs also supported the conclusion that asbestos fibers ≤5 µm pose insignificant risk for asbestos-related cancer (Mossman, 2018; Chatfield, 2018; Weill, 2018). Occupational epidemiology studies of cancer and mesothelioma risk, and subsequent regulatory exposure limits derived using these studies, are all based on measurements of asbestos fibers that are longer than 5 µm (Chatfield, 2018).
- **Width:** An EMP's width affects its ability to be inhaled, deposit in the lungs, and biopersist (ATSDR, 2001). Much like longer asbestos fibers, those that are thinner than 3 µm are more likely to be deposited in the lower airways after being inhaled, from which they are not readily cleared (Craighead, 2008; ATSDR, 2001; Bernstein and Hoskins, 2006; Coin *et al*., 1992; Bernstein and Pavlisko, 2017). Asbestos fibers that are wider than 3 µm are not considered to pose human health risks (Boulanger *et al*., 2014; Lippman, 2014). Recently, Wylie *et al*. (2020) developed an approach to defining the dimensions associated with specific types of amphibole fibers' ability to induce mesothelioma. The authors reported that the proportion of countable asbestos fibers with widths ≤0.15 µm was a strong indicator of whether exposure to such fibers posed a mesothelioma risk, with that risk rising rapidly with small increases in the proportion of countable asbestos fibers <0.15 µm to which an individual is exposed. This is also supported by recent evidence that narrow fibers are able to make their way to the periphery of the lung (*i.e*., toward the pleural mesothelium) (Pooley, 2018).
- **Biopersistence:** Biopersistence refers to how long an EMP remains in lung tissue before it is cleared or dissolved. Biopersistence can be an important determinant of human health outcomes, as higher biopersistence of a substance leads to greater health risks posed by that substance (Feder *et al*., 2017; Bernstein *et al*., 1994). Amphibole asbestos fibers are more biopersistent than chrysotile asbestos fibers and also pose the greatest human health risks (Doll and Peto, 1985; Gibbs, 1994; Hodgson and Darnton, 2000, 2010; Berman and Crump, 2008a,b; Berman, 2011; Berman and Case, 2012).

Exposure Levels

As with any substance, the number of countable asbestos fibers (*i.e.*, with a minimum aspect ratio of 3:1 and >5 μm in length) to which an individual is exposed is an important factor to evaluate when assessing risk from exposure to them. In practice, the actual number of asbestos fibers to which the various tissues in the body have been exposed cannot be measured in a living person. While residual asbestos fibers can be measured in tissue samples, many will have been cleared from the body during the individual's life by natural bodily processes. Therefore, for practical purposes, the magnitude of an individual's exposure to asbestos is generally estimated by considering the measured asbestos concentrations in air or water weighted by the duration of an individual's exposure to those concentrations. In addition to the length and width of the EMPs to which an individual is exposed, the risk to a person experiencing adverse health effects increases with the number of asbestos fibers to which they are exposed (Pierce *et al*., 2016). However, exposure to asbestos likely does not increase an individual's risk of experiencing adverse health effects as long as the exposure does not exceed a minimum threshold. Above this threshold exposure level, risk then increases with increasing exposure and duration.

As noted above, most studies of health effects potentially caused by exposure to asbestos have been conducted in occupational settings in which workers were exposed to very high levels of asbestos. Exposures in these studies have generally been orders of magnitude higher than typical NOA exposures (*i.e.*, when present in nature, NOA is typically found in only trace quantities). When developing toxicity criteria for asbestos, regulatory agencies have extrapolated from these high occupational exposure levels to estimate risks at the much lower exposure levels typically experienced by the general public, using what is called a linear no-threshold (LNT) approach. Despite the likely existence of threshold doses below which specific types of asbestos fibers do not cause health effects, and the fact that every person is exposed to background levels of asbestos in ambient air (NRC, 1984; Bignon *et al*., 1989), the LNT approach assumes that there is no such threshold. This assumption is built into the risk model to ensure that the health risks of exposure to low levels of a substance are overestimated rather than underestimated (U.S. EPA, 2005). In addition, the LNT approach assumes that exposure to low levels of a substance over a lifetime (*i.e.*, chronic exposure) can have the same effect as exposure to high levels of that substance over a short period of time (*i.e.*, acute exposure).[7] This assumption is generally understood to overestimate risk, because cellular repair processes are able to mitigate some of the effects of low long-term exposures to a substance (Cox *et al*., 2020). Overall, the LNT approach is used to provide conservative overestimates of health risks posed by many substances, including EMPs, and particularly NOA (U.S. EPA, 2005).

[7] For example, as an analogy, this assumes that the impact of drinking a bottle of alcohol all at once is equivalent to the impact of drinking it over several weeks.

C Measurement of Asbestos and Other EMPs

What are the measures of EMPs?

Asbestos exposure levels are often given as numbers of fibers per cubic centimeter (f/cc, if levels in air are being measured) or per liter (if levels in water are being measured). However, NIOSH (2011) noted that the analytical methods used to measure asbestos levels, as described below and in Section D, cannot always distinguish between asbestos and cleavage fragments – thus, some of the latter may be counted when deriving asbestos exposure levels. Notably, health risks from the presence of NOA at a site are likely to be overestimated if cleavage fragment or other non-asbestiform EMPs are incorrectly included during microscopic analysis in the EMP counts meant to represent asbestos. Because NOA is typically found in only trace quantities in nature, cleavage fragments can sometimes dominate the particle counts in samples collected at a quarry or mine. If some, many, or all non-asbestos EMPs are counted as asbestos at a give site, the reported NOA exposure levels there may be skewed (incorrectly) high. Put another way, rock that contains no or essentially no chrysotile or asbestiform amphibole mineral could be incorrectly classified as NOA (*i.e.*, a false positive) due to an analyst incorrectly classifying cleavage fragment or other non-asbestiform EMPs as asbestos. This scenario could affect the controls deemed necessary to operate, mine, or quarry a site where NOA is present.

As discussed in Section B, while the habit of EMPs impacts their ability to cause health effects, there is also ample evidence that EMPs with certain dimensions pose more health risks than others. In acknowledgment of the limitations of the available analytical methods, NIOSH (2011) introduced the term "countable EMP," which, like the term EMP itself, is based on particles' dimensions, rather than solely their mineral habit and chemical makeup. This ensures that the EMPs that are most likely to cause health effects are counted when exposure levels are determined, even though EMPs that do not contribute to adverse health effects may also be counted. NIOSH (2011) defines a countable EMP as a particle with a minimum aspect ratio of 3:1 and a length >5 µm. It is overall preferable to use the NIOSH (2011) term "countable EMP," rather than "fiber" and to consider "fibers" as specified in most analytical methods or exposure limits to be "countable EMPs."

Fiber (countable EMP) numbers per gram, a common unit used by some laboratories to report the abundance of EMPs in bulk material, is not helpful in determining the risk or potential risk posed by the EMPs, because this measurement is not an invariant measure of the abundance of EMPs in the material. The same bulk sample can yield very different values in terms of fibers (countable EMPs) per gram, depending on the degree to which the sample is broken up. The only invariant measure of the abundance of EMPs in a material is weight percentage, which can be calculated from the length and width measurements of EMPs and the density of the EMPs in a sample of known weight, as described further below.

What methods are used to measure asbestos and other EMP levels?

Polarized light microscopy (PLM), the type of optical microscopy historically used to study minerals, can be used to determine the habit (asbestiform or non-asbestiform) of EMPs wider than 1 µm. The asbestiform habit produces optical properties that are distinctive and different from the non-asbestiform habit

(Verkouteren and Wylie, 2000). In addition, the mineral identity of asbestos can be determined by measuring indices of refraction, color, and other optical properties observed *via* PLM.

The most appropriate sample to analyze when determining the amount of asbestos in mine products is a sample from the mine product stockpile. That is because analyzing such a sample is likely to more closely represent the "average" level of asbestos in the mine product, due to the nonhomogeneous way in which asbestos is distributed in mineral deposits (CARB, 2017). In a mineral sample of known weight, the quantity of asbestos in the sample, as a percentage of weight, can be estimated by measuring the lengths and widths of asbestos in the sample. However, it is important to note that the percentage of asbestos in a single sample is likely to be meaningless for understanding how much asbestos a mineral deposit being mined contains and how its distributed in that deposit.

PLM can also be used to reliably estimate the weight percentage abundance of asbestos fibers in a deposit by the analysis of a large number of samples from that deposit, because the visible EMPs in samples taken from the larger mass of rock retain the mineral habit characteristics of that larger mass (U.S. EPA, 1993) and they contain the vast majority of the mass (Veblen and Wylie, 1993). Because transmission electron microscopy (TEM) is only able to analyze a very small amount of material at a time (sample weight of approximately 1 µg), as well as only relatively small particles, as discussed further below, we would not generally recommend using it over PLM for this purpose.

For determining the number of asbestos fibers in air, the lengths and widths of asbestos fibers should be measured by PCM, TEM, scanning electron microscopy (SEM), or field emission scanning electron microscopy (FESEM), and the dimensions and number of those determined to be countable EMPs should be recorded. Unlike TEM, SEM and FESEM provide information on EMPs' surface characteristics (cleavage planes, surface defects, *etc.*) in addition to their chemical composition. Also, SEM's field of view is larger than that of TEM. However, TEM is still the recommended instrumental technique to use for this purpose, because it can provide not only the chemical composition of each EMP, but also information on their crystal structure (by electron diffraction). Information on the EMPs' crystal structure enables differentiation between minerals of similar composition, which SEM and FESEM may not be able to do. TEM can also show smaller-width EMPs than these other analytical technologies.

For determining the amount of asbestos in water, TEM is also the recommended instrumental technique to use, because fibers longer than 0.5 µm can be measured *via* TEM (Chatfield and Dillon, 1983). However, the U.S. EPA Maximum Contaminant Level (MCL) for asbestos in drinking water is 7×10^6 fibers longer than 10 µm per liter (U.S. EPA, 2020a). This level was established based on the results of a large study of rats administered asbestos fibers >10 µm orally (NTP, 1985; U.S. EPA, 1991b, p. 3535). Given that U.S. EPA's concern regarding exposure to asbestos *via* drinking water relates only to fibers longer than 10 µm, the analytical method used to assess asbestos levels in water samples should be designed to address only fibers longer than 10 µm. A published method for this purpose is available from U.S. EPA (Brackett *et al*., 1994). If there is concern regarding the possibility of airborne EMPs being generated by the evaporation of water that contains EMPs, then the TEM analysis should be directed to determination of asbestos fibers longer than 5 µm (NIOSH, 1994).

The various electron microscopy analytical techniques can be used to measure the lengths and widths of EMPs. The width and aspect ratio abundances of EMPs in a sample can then be used to distinguish between asbestos and non-asbestos materials. If asbestos is present in a sample, it will have a modal frequency increase of EMPs with widths <0.5 µm (Wylie, 2016). In contrast, countable cleavage fragments (produced by non-asbestos materials) with widths <0.5 µm are quite rare (Wylie, 2016). In addition, because EMPs wider than approximately 3 µm cannot be inhaled and deposited in the lung (Craighead *et al*., 2008; ATSDR, 2001; Bernstein and Hoskins, 2006; Coin *et al*., 1992; Bernstein and Pavlisko, 2017), data on the widths of EMPs also provide a means of assessing the amount of respirable EMPs in a sample. Although the number of respirable EMPs per gram of bulk material may vary, we have found that the number of respirable EMPs longer than 5 µm per gram of *respirable dust* provides a more stable value that is characteristic of particular minerals (Chatfield, In Preparation). This is because, at some point in crushing a mineral sample, any further increase in the degree to which the mineral is broken up increases the number of countable EMPs, but also increases the total mass of respirable dust, and the ratio of these values tends to remain constant (Chatfield, In Preparation).

For crushed rock samples, there are no impediments to achieving detection limits for asbestiform amphibole that are lower than 0.001% by weight (ISO, 2014). The detection limit varies according to the amount of material examined and the presence of interfering minerals in a sample. A *theoretical* asbestos detection limit for PLM of 1 part per million (ppm), or 0.0001%, has been proposed based on PLM's ability to detect a single asbestos fiber 100 µm long and 2 µm wide in a few milligrams of crushed material (UK Health and Safety Executive, 1994). This assumes that asbestos fibers are minimally obscured by other mineral particles in the sample. The extent to which this low detection limit can be achieved depends on the optical characteristics of the minerals contained in the sample. It is important to recognize that the majority of the weight in a crushed rock sample is contributed by large particles, and because these are the particles that are detected by PLM, it can provide a reliable measurement of the weight percentage of asbestos and asbestiform amphibole in a sample. An advantage of PLM is that it can be used to examine relatively large samples weighing upwards of several milligrams, as opposed to electron microscopy methods, such as TEM, which are limited to analyzing samples weighing only about a microgram.

While electron microscopy methods such as TEM can also be used to determine the weight percentage abundance of EMPs in crushed rock samples by measuring the dimensions of EMPs in those samples, unless the largest dimension of an EMP or rock fragment in the sample is smaller than approximately 50 µm in length, this measurement will almost certainly be unreliable. TEM specimens are very thin carbon films that must be supported on metal meshes, and each open area available for analysis consists of a square that is usually approximately 100 µm in area (10 x 10 µm). When particles become too large, they may be only partially visible within the open area, and they can obscure other smaller particles and EMPs. Large particles also frequently cause the carbon film to break, rendering the TEM specimen grids unusable. Thus, if the maximum particle or EMP size is sufficiently small that intact specimen grids can be prepared and it does not have the potential to obscure countable EMPs, TEM measurement of the weight percentage abundance of asbestos and asbestiform amphibole in a sample of asbestos is possible.

However, using TEM for this purpose has two further limitations. The first is related to the fact that TEM can only analyze small samples (approximately 1 µg in weight). So, it is important to ensure that the 1 µg of material examined is representative of the entire rock sample (which can be difficult given the heterogeneity of rock). The other is that for the integrated mass of EMPs measured *via* TEM to be statistically valid, a counting protocol must be designed to ensure that infrequent large EMPs are properly represented in the number of countable EMPs. In this protocol, the counting magnification is determined by the size of the largest EMP that is found in an initial scan of the TEM specimens.

D Laboratory Analysis of Samples for Asbestos and Other EMPs

What methods and protocols are appropriate for determining the presence/ amount of EMPs in air or water under various conditions?

Table 2 summarizes the published standard analytical methods for the identification and quantification of asbestos fibers in air and water samples and what these methods are designed to measure. Although most of these methods refer to asbestos fibers as the analyte, the methods can be used to determine the concentrations of any type of EMP. The methods' counting rules, which include the specified dimensions for determination of which "fibers" should be counted apply to both fibers and cleavage fragments (*i.e.*, either type of EMP). While these methods can readily discriminate between asbestiform fiber **bundles** and cleavage fragments, this is not usually possible to do for individual smaller asbestos fibers and cleavage fragments (width < ~0.5 µm). However, because the widths of cleavage fragments are generally larger than those of asbestiform fibers with the same length, it is often possible to discriminate between these on the basis of the lengths and widths of a group of EMPs (Wylie, 2016).

Table 2 Summary of Analytical Methods for EMPs in Air and Water Samples

Sample Type	Analytical Method	Reference	Counting Rules[1]	Remarks
Personal Air Samples	PCM	NIOSH 7400 (NIOSH, 2019)	Length >5 µm Aspect Ratio ≥3:1	Used for routine EMP counts. Method does not provide ways to identify different types of EMPs or fibers.
Personal Air Samples	TEM	NIOSH 7402 (NIOSH, 1994)	Length >5 µm Width >0.25 µm Aspect Ratio ≥3:1	Intended to measure the ratio of asbestos fibers to total EMPs visible in a PCM count done by NIOSH 7400.
Area/Personal Air Samples	TEM	ISO 10312:2019 (ISO, 2019a)	Length ≥0.5 µm Aspect Ratio ≥5:1 **Annex E:** Length >5 µm Aspect Ratio ≥3:1 Width ≥0.2 to ≤3 µm	Annex E of this method describes counting procedures for PCM-equivalent "fibers" (*i.e.*, "fibers" able to be measured with PCM).
Area/Personal Air Samples	TEM	ISO 13794:2019 (ISO, 2019b)	Length ≥0.5 µm Aspect Ratio ≥5:1 **Annex F:** Length >5 µm Aspect Ratio ≥3:1 Width ≥0.2 to ≤3 µm	Indirect-transfer method for sample filters that are too overloaded for analysis by ISO 10312.
Area Air Samples	TEM	EPA AHERA (U.S. EPA, 1987)	Length >0.5 µm Aspect Ratio ≥5:1	Intended only for post-remediation clearance of school buildings. Does not require detailed recording of "fiber" dimensions.

Sample Type	Analytical Method	Reference	Counting Rules[1]	Remarks
Water Samples	TEM	EPA Method 100.1, EPA-600/4-83-043 (Chatfield and Dillion, 1983)	Length >0.5 µm Aspect Ratio ≥3:1	
Water Samples	TEM	EPA Method 100.2, EPA/600/R-94/134 (Brackett *et al.*, 1994)	Length ≥10 µm Aspect Ratio ≥3:1	

Notes:
AHERA = Asbestos Hazard Emergency Response Act; EMP = Elongate Mineral Particle; PCM = Phase Contrast Microscopy; TEM = Transmission Electron Microscopy.
(1) *i.e.*, Only EMPs with these dimensions should be counted.

For determining an individual person's exposures to airborne EMPs, the sampling and analytical method currently used in the U.S. is NIOSH Method 7400 (NIOSH, 2019). This method specifies that PCM be used to count EMPs with a length >5 µm and an aspect ratio ≥3:1 (countable EMPs). An important limitation of PCM is that it does not provide the mineral identity of an EMP (*e.g.*, whether or not it is asbestos) or even if it is mineral or non-mineral. Many air samples submitted for analysis by NIOSH 7400 today are very different from those analyzed when the PCM method was first introduced in the United Kingdom in 1968 (Asbestos Research Council, 1968) and when the NIOSH counting method was introduced in the U.S. a few years later (NIOSH, 1972). NIOSH 7400 is currently used to monitor a wide range of environments, such as asbestos abatement projects and occupational settings in which airborne EMPs may represent only a fraction of the total particle population present in the sample. It has been shown that the variability of EMP counts increases as the proportion of non-fibrous particulate in a sample increases (Crawford *et al*., 1982). For example, in terms of the different types of particles present, samples of airborne asbestos collected in asbestos textile operations during the late 1960s were much more homogenous compared with air samples collected in asbestos-cement manufacturing operations. Thus, PCM counts for the former samples would be much less variable than PCM counts for the latter samples. Crawford *et al.* (1982), who compared the results for contemporaneous samples analyzed using various EMP counting rules, determined relative standard deviations as high as 85% when using counting rules that are almost identical to those in NIOSH 7400.

Because NIOSH 7400 provides no means for determining the mineral identity of EMPs being counted, NIOSH developed Method 7402 (NIOSH, 1994), which is based on TEM analysis. This method allows EMPs to be identified by energy dispersive X-ray analysis (EDXA) and selected area electron diffraction (SAED). The definition of a countable EMP in NIOSH 7402 (length >5 µm, width >0.25 µm, aspect ratio ≥3:1) is intended to coincide with those EMPs that would be counted by PCM according to NIOSH 7400. Unfortunately, this minimum width criterion only applies to chrysotile fibers visible during PCM analysis. Amphibole EMPs and EMPs of other minerals with high refractive indices that have significantly narrower widths than 0.25 µm are also visible by PCM. However, in an analysis by NIOSH 7402, these EMPs are not included in the EMP count because their widths are narrower than 0.25 µm. Also, the use of NIOSH 7402 requires an EMP count for the sample that was previously analyzed *via* PCM according to NIOSH 7400. The results from analyzing the sample *via* NIOSH 7402 are used to apply a correction factor to the previous PCM count for the sample. This calculation procedure introduces many difficulties and potential errors, because the poor reproducibility of the PCM count, as described above, is combined with the lack of a 1:1 correspondence between EMPs that are visible by PCM and those that are visible by TEM. For example, in one study, a standard of 2 f/cc as measured by PCM (counting fibers greater than 0.3 µm in diameter) would have resulted in total fiber exposure concentrations to crocidolite, amosite, and chrysotile (during bagging) as measured using TEM and SEM combined of 351, 12, and 126 f/cc, respectively (Gibbs and Hwang, 1984).

For the analysis of airborne asbestos, the ISO 10312:2019 (Annex E) direct-transfer method for TEM analysis should be used (ISO, 2019a). This method allows for the determination of the concentration of asbestos fibers with lengths >5 µm and widths ≥0.2 to ≤3 µm (*i.e.*, PCM-equivalent fibers) in a sample. These dimensions are consistent with risk assessment methodologies for asbestos exposure, in which EMPs with lengths >5 µm and widths <3 µm are considered to be more hazardous (as discussed in Section B). This analysis does not require a prior PCM measurement; the EMP concentration can be calculated directly from the TEM data.

In some circumstances, air sample filters have too much particulate material on them, such that preparing TEM specimens by direct-transfer methods such as ISO 10312:2019 Annex E is not possible. ISO 13794:2019 is an indirect-transfer TEM method that allows such overloaded filters to be analyzed (ISO, 2019b). In this method, a portion of the sample collection filter is ashed in low-temperature plasma, the residual ash is dispersed ultrasonically in water, and aliquots of the suspension are filtered onto secondary filters. With an appropriately filtered aliquot, satisfactory TEM specimens can be prepared from one of these secondary filters. The TEM examination then follows the same procedure as that described in ISO 10312:2019 Annex E (ISO, 2019a). Although the ultrasonic dispersal used in the indirect preparation will cause chrysotile fiber clusters to disintegrate into individual fibers and bundles, it is our experience that the quantitative effect on the concentration of PCM-equivalent fibers of both chrysotile and amphibole materials is normally minimal. This indirect-transfer TEM method for the determination of asbestos fibers in ambient air is routinely used in France, under the name NF X43-050, for ambient air measurements of asbestos (AFNOR, 1996).

U.S. EPA developed the Asbestos Hazard Emergency Response Act (AHERA) TEM analytical method specifically for determining post-abatement clearance after the removal of asbestos-containing building materials from school buildings (U.S. EPA, 1987). The "clearance level" determined by this method has no health significance; it is intended as a cleanliness criterion only. In order to make the analysis more rapid and inexpensive, the AHERA method does not require the reporting of mineral identification. "Asbestos structures" are simply structures of all lengths >0.5 µm, aspect ratio ≥5:1. The concept of an "asbestos structure" is used to include fiber clusters and matrices that contain particles attached to (or overlapping with) asbestos fibers, as a measure of conservatism. We do not recommend that this method be used in for hazard or risk assessment.

For determining the concentration of asbestos fibers in a water sample, the appropriate analytical method to use is that described in EPA-600/4-83-043, which is now identified as EPA Method 100.1 (Chatfield and Dillon, 1983). In this method, all asbestos fibers with a length >0.5 µm and an aspect ratio ≥3:1 are counted. Also, recording the number of fibers with lengths >5 µm can be useful for determining the quantity of asbestos fibers present in water that, if the water were to evaporate, could become airborne. EPA Method 100.2 (Brackett *et al*., 1994) can be used for determining the concentration of asbestos fibers longer than 10 µm in water samples for comparison with the U.S. EPA MCL for asbestos (which, as noted in Section C, is specifically a maximum level of asbestos fibers longer than 10 µm; US EPA, 2020a).

E Site Inspections and Sampling for NOA

What methods and protocols are appropriate for determining whether NOA is present at a quarry or mine?

The presence or absence of NOA at a particular location is best evaluated by a qualified geologist (*i.e.*, one who is knowledgeable about and experienced with NOA). The inspection protocol for investigating whether NOA is present in aggregate mineral deposits depends upon the site being inspected, which generally fall into three basic categories: (1) sites where mining has not yet occurred, commonly referred to as greenfield sites; (2) sand and gravel deposits; and (3) active rock mines or quarries.

Before an inspection of any proposed or active mining site, some important questions need to be answered before the first sample is collected or even before visiting the site. The first is "What type of rock or sand/gravel is under investigation?" Deposits that are not composed of metamorphic or igneous rock are unlikely to contain NOA. The same is true for sand and gravel deposits formed from distant sources that are not metamorphic or igneous rocks. Generally, these types of deposits warrant no further investigation for the presence of NOA. The presence of metamorphic and igneous rocks can often be determined by reviewing the available information about the site's geology. For instance, previous investigators may have observed the presence of NOA at a given site, or documented the types of rock there in which NOA is commonly found (Bailey, 2004). If available, it is also prudent to review the available information about the presence of any asbestiform mineral (whether regulated or not) at a site, including mineral samples collected at the site. As mentioned earlier, nonregulated asbestiform minerals can pose health risks similar to asbestos (NIOSH, 2011) and warrant the same precautions. Possible sources of information about a site that should be reviewed include the following:

- United States Geological Survey (USGS) and state geological survey reports for the site and surrounding areas.
- United States Bureau of Mines publications on relevant local geology.
- Reports or studies of rock types present around the site by nearby university geology departments.
- U.S. EPA, state environmental protection agency, and MSHA reports and data for the site or nearby sites.
- Any geological or mineralogical studies already performed for the site (for instance, if the site is being acquired, any such studies available should be obtained from the seller).
- Reports of NOA found in nearby mining operations or during nearby construction activities.

All additional site investigation, such as visual observations, photographs, mapping, and collection of samples, will typically take place on-site.

Regarding sampling – the collection of a sample is just as important as its preparation for laboratory analysis and the analysis itself. For all samples, the specific location from which they were collected must be documented (plotted on a map or aerial photograph, as well as photographed), and they should be labeled with a clear identifier and the type of sample (core, grab, specific stockpile or conveyor belt, sediment, settled dust, baghouse, *etc.*) and photographed. Samplers must also record the depth from which core, pond sediment, and water samples were collected. In addition, any relevant field notes regarding the sample should be recorded, and chain of custody documentation for all samples should be completed. Laboratory results from the sample analysis should also be documented. Samples should be collected, and representative portions split with the testing laboratory, using standard methods such as ASTM C702 (ASTM International, 2018). ASTM C702 and the California Air Resources Board (CARB) Test Method 435 guidance document also specifically address sampling from mine/quarry stockpiles and conveyor belts to obtain a representative sample of a mineral deposit (ASTM International, 2018; CARB, 2017). The type of sample preparation by the analytical laboratory is equally important – improper sample preparation can destroy the characteristics of the asbestiform minerals that the analyst is trying to detect (Van Orden *et al.*, 2012a,b). Thus, knowing how the laboratory will process site samples for analysis is an important factor for interpreting the analytical results once they are received (*i.e.*, whether they are valid and can be relied upon for site characterization).

For greenfield sites, on-site inspections are limited to an examination of outcrops on or in the vicinity of the site and of any core samples that can be obtained. For sand and gravel operations, inspecting the upgradient aggregate source of the deposit is of most importance. The mineralogy of the aggregate in the sand and gravel deposit can point to whether it has an igneous or metamorphic origin (asbestiform minerals are formed from these types of rocks). Auger samples, hand-shoveled samples, or test pits can also be obtained from sand and gravel sites to assess the underlying deposit. In addition, sediments from ponds or lakes at the site can also be examined for NOA. If NOA is present at sand and gravel deposits, it will most likely be found in the fine sediments at the site (NSSGA, 2019). At an active mine or quarry, there are many more opportunities to examine the potential for NOA in a deposit. To maximize the assessment of the deposit's historical, present, and future mineralogy, samples should be collected that reflect different time periods over the life of the deposit. When an active mine or quarry is first examined, the goal should be to analyze samples that reflect the longest period of production time possible. If a review of the pertinent literature about the site does not indicate the presence of asbestiform minerals and samples reflecting past, current, and future mineralogy are negative for them, then NOA is less likely to be present in the mineral deposit under investigation. This does not mean that NOA will never be found at the deposit, but it does mean that it is less likely to be found.

Historical samples can represent the conditions of a sampled material many years in the past or in the previous day, week, month, or year. Some examples of historical samples, and protocols for their collection and analysis, include the following:

- Stored drill core of mined areas. After collection, these should be logged, and any suspect portions should be examined with a 200x stereomicroscope. Cutting thin sections for petrographic analysis by PLM should be considered if asbestiform minerals are found in the core.
- Inactive (*i.e.*, not currently mined) wall and floor samples where dikes, faulting, and shearing are apparent. These can be informative regarding whether the local mineralogy may support the formation of asbestos.
- Settling pond sediment samples. These can be representative of past mineralogy, depending on the sediment depth sampled. Such samples should be analyzed with a stereomicroscope and PLM at 400x to 1,000x to determine whether any asbestiform minerals are present. Serpentine settling pond sediments should also be examined using TEM.
- Settled dust samples from rafters and inside tunnels. These can reflect the mineralogy encountered over the past 3-12 months, depending on the amount of mining done in the sampled area and its dustiness. Such samples should be analyzed with a stereomicroscope, PLM, and, if necessary, TEM. Serpentine settled dust samples should always be analyzed by TEM.

- Samples of settled dust in a quality control laboratory, which can also reflect the mineral conditions encountered in the recent past.
- Stockpile samples. These reflect the mineralogy encountered in the past few weeks or months, depending on the sales and production volumes at the site. The height and depth from which stockpile samples are taken can reflect different timeframes. Properly collected stockpile samples represent the best reflection of the average mineralogy in a deposit over the period of time that the stockpile was created.

Samples reflecting the current mineralogy at a site are limited, but include the following:

- Drill cuttings from drilling and blasting activities. These samples should be examined in a similar fashion as settled dust samples.
- Muck pile (shot rock) samples. These samples should be analyzed in the same manner as core or stockpile samples.
- Crusher-run hand samples. These samples should be analyzed in the same manner as core or stockpile samples.
- Conveyor samples of crushed and screened rock product. These samples should be analyzed in the same manner as core or stockpile samples.

Samples reflecting future mineralogy can be collected from areas of a mine or site that are yet to be developed. These samples can represent many years into the future or next week, month, or year, depending on when they become active.

- Drill core of the mine's reserves. These should be examined in the same way as historical core samples.
- Rock samples from the active face and floor (*i.e.*, the next rock to be mined).

If rock samples collected by the geologist appear to indicate the presence of fibrous minerals, detailed PLM examination of the samples by a qualified mineralogist is the optimum analytical procedure to use. As discussed in Section C, PLM is recommended for the analysis of mineral samples because the bundles of narrow fibers that form asbestos have a distinctive habit and optical properties (UK HSE, 2020; Verkouteren and Wylie, 2002).

A continuing monitoring program at a site should be established for mines where igneous or metamorphic rock is present, even if the initial examination of the rock does not detect NOA (Bailey, 2004). An active quarry in igneous or metamorphic rock should establish a settled dust sampling program that can monitor the mined rock on a continuous basis, year in year out. Information about all the rock that has been mined over the sampling period can be obtained via this passive method of sampling. The sampling period used should be based on the amount of mining occurring at and the dustiness of the sampling point, and so will be specific to each site and area being monitored. A typical sampling frequency is quarterly. Sample collectors for settled dust should ideally be placed in surge tunnels, or a similar location, where they are protected from precipitation and other weather conditions and where all the mined material during each sampling period can be represented in the sample collected.

Quarry/mine personnel, especially in pit areas, should be trained on how to recognize suspect rock mineralogy and instructed to immediately inform management of its presence. Any rock samples of suspect minerals should be examined by a qualified geologist, and mining in the areas with such minerals should be stopped until a determination is made regarding their mineralogy. In addition, on a periodic basis, a qualified geologist should inspect the active face and floor of a mine/quarry for NOA.

If NOA is found in settled dust or in an active mining area, a qualitative geologic survey of the mine/quarry should be conducted by a qualified geologist. Such a survey should include an examination of the active wall and floor, as well as the collection of drill cutting, stockpile, conveyor belt, and other samples that reflect the current mining activities. If NOA is found to be present in the active mining area, the NOA should be safely extracted and properly disposed of if possible. A qualitative geologic survey should provide enough information regarding the NOA's presence to ascertain the most appropriate steps regarding active mining at the site. The steps involved in conducting a qualitative geologic survey of aggregate mining operations have been developed by the National Stone, Sand and Gravel Association (NSSGA, 2019).

F Determining and Mitigating Asbestos Risks

When does a quarry or mine need to put asbestos controls in place? What are those controls? What are the relevant regulations governing asbestos exposures?

The process for determining whether asbestos controls are necessary for a quarry or mine, and what the appropriate controls to use will be, is divided into the following steps:

1. Determine if EMPs Are a Hazard at the Site
2. Estimate Exposures to Asbestos
3. Compare Estimated Exposure Levels to Relevant Exposure Limits
4. Consult Other Relevant Regulatory Guidance
5. Determine Appropriate Exposure Controls

1. Determine if EMPs Are a Hazard at the Site

Asbestos controls only need to be considered for quarries and mines located in geologic formations that have NOA. The process for identifying the geological makeup of a site is described in Section E. Then, for sites located in the relevant formations, it should be determined whether the EMPs present at the site are capable of causing harm. If the specific types of EMPs present at a site are not known, samples must be collected, and they must be analyzed by a competent laboratory and an analyst who has training and experience with the full variety of EMPs and the various methods used to analyze them (as described in Sections C, D, and E).

A thorough analysis may show that the EMPs in question are cleavage fragments, which are not among the types known to be associated with asbestos-related diseases (as described in Section B). In that case, there would be no discernable EMP-related health reason to restrict or prohibit a quarry or mine from continuing to operate. On the other hand, asbestos or other durable asbestiform EMPs are usually known or assumed to be hazardous (see Section B), so their presence may warrant the use of additional dust controls utilized at quarries and mines.

2. Estimate Exposures to Asbestos

If NOA is found at a site, the next step is to quantify the exposures in the vicinity of the site by conducting an exposure assessment. Asbestos exposure assessments are typically focused on inhalation exposures (see Section B). This process typically includes air sampling at various points in and around the site (including collecting workers' personal air samples) and in any surrounding communities sufficiently nearby. Samples should be analyzed at a qualified laboratory, then the results compiled and reviewed. In some cases, computer-based models that account for factors such as source characteristics and wind direction and other meteorological conditions may help develop exposure estimates. If an exposure assessment has not been conducted by a competent party, any subsequent conclusions about the potential health risks of asbestos and decisions on whether and what exposure controls to use will rest on shaky ground.

3. Compare Exposure Levels to Relevant Exposure Limits and Guidelines

Once the exposure assessment results are in hand, it should be determined whether the measured or estimated airborne asbestos exposures at the site and in its vicinity reach or exceed a regulatory limit or a level known to be associated with asbestos-related diseases. If they do not, then there is no discernable EMP-related health reason to restrict or prohibit a quarry or mine from continuing to operate. Otherwise, it is appropriate to reduce asbestos exposures *via* controls.

The various regulatory and recommended limits for asbestos, described below, largely focus on airborne asbestos (because inhalation is the most relevant exposure route for asbestos-related diseases, as discussed in Section B). We know of no regulatory limits specifically for cleavage fragments.

U.S. EPA, OSHA, and MSHA regulations for asbestos apply to six specific asbestiform minerals: chrysotile asbestos, amosite asbestos (also known as cummingtonite-grunerite asbestos), crocidolite asbestos (also known as asbestiform riebeckite), anthophyllite asbestos, tremolite asbestos, and actinolite asbestos. However, as discussed in Section A, we recommend that erionite and all asbestiform amphiboles be treated as asbestos, whether regulated in the U.S. as asbestos or not. Regulatory limits generally focus on asbestos fibers longer than 5 μm and with an aspect ratio equal to or greater than 3:1 (*i.e.*, countable EMPs).

- OSHA and MSHA have issued regulations that focus on workplace exposures to asbestos, which are similar in many ways. MSHA asbestos regulations are at 30 CFR 56.5001 (surface mines) and 30 CFR 57.5001 (underground mines) (MHSA, 2008). OSHA asbestos regulations are at 29 CFR 1910.1001 (general industry), 29 CFR 1926.1101 (construction industry), and 29 CFR 1915.1001 (ship-related industries) (OSHA, 1995, 2011, 2019). OSHA (2019) and MSHA (2008) have set workplace exposure limits (called Permissible Exposure Limits, or PELs) for asbestos of 0.1 f/cc measured in the worker's breathing zone, as averaged over an 8-hour sampling period (*i.e.*, a full work shift). Both agencies have also set a short-term "excursion limit" of 1 f/cc measured in the worker's breathing zone, averaged over a 30-minute sampling period (OSHA, 2019; MSHA, 2008). These regulations also mandate that air samples collected for compliance purposes (*i.e.*, to be compared against the PELs) must be analyzed using PCM. PCM results potentially exceeding either the PEL or excursion limit must then be further analyzed using TEM (NIOSH Method 7402 or equivalent; for further details, see Section D).
- NIOSH, which is a research agency within the Centers for Disease Control and Prevention (CDC), does not set regulatory limits for hazardous substances, but does issue recommendations. Its Recommend Exposure Limit (REL) for asbestos is 0.1 f/cc (NIOSH, 2018). NIOSH (2018) does note that "airborne cleavage fragments from the non-asbestiform habits of the serpentine minerals antigorite and lizardite, and the amphibole minerals contained in the series cummingtonite-grunerite, tremolite-ferroactinolite, and glaucophane-riebeckite should also be counted as fibers provided they meet the criteria for a fiber when viewed microscopically." This inclusion of non-asbestiform EMPs in an asbestos exposure limit is contrary to the position of U.S. EPA, OSHA, and MSHA (which do not regulate any of the non-asbestiform habits of asbestos minerals) and is not supported by the vast majority of published literature on the subject (U.S. Congress, 2011; OSHA, 1992; MHSA, 2008).
- U.S. EPA has issued a Maximum Contaminant Level (MCL) for asbestos of 7×10^6 fibers longer than 10 μm per liter of drinking water (U.S. EPA, 2020a).

4. Consult Other Relevant Regulatory Guidance

When considering whether and what type of airborne asbestos controls are necessary for a site, operators should adhere to other applicable federal, state, and local regulations. Examples of these are listed below.

- U.S. EPA has not set specific airborne asbestos exposure limits for the general public.[8] However, U.S. EPA has issued a regulation for the protection of workers from asbestos exposure (40 CFR 763; U.S. EPA, 2007). Subpart G of this regulation extends the OSHA asbestos regulations to certain state and local government employees who were not previously covered by OSHA.
- The California Air Resources Board (CARB) has set state regulations that apply to the same six asbestos minerals defined in federal regulatory policy (CARB, 2021; BAAQMD, 2004). CARB has issued two Airborne Toxic Control Measures (ATCMs) that limit the concentration of asbestos in certain bulk materials or require dust mitigation when NOA is encountered.
    - The "Asbestos ATCM for Surfacing Applications" (17 CCR § 93106, adopted in 1990) limits the asbestos content of material used for unpaved surfacing to less than 0.25% as measured using its Test Method 435[9] (with certain exemptions) (CARB, 1990).
    - The "Asbestos ATCM for Construction, Grading, Quarrying, and Surface Mining Operations" (17 CCR § 93105, adopted in 2001) requires operators of such sites to employ the best available dust mitigation measures during road building and maintenance activities, construction and grading operations, and quarrying and surface mining operations if they are located in areas where NOA is likely to be found (CARB, 2001).[10]
- The Nevada Department of Transportation (DOT) specifies that the NOA and/or erionite level in rock, soil, and other mineral material obtained or produced for use in projects undertaken by Nevada DOT should not be ≥0.25% (Nevada DOT, 2019). Material in which the NOA and/or erionite content has been determined to be <0.25% may be used. This Nevada DOT policy specifies that CARB Test Method 435 (CARB, 2017) should be used for analyzing samples of the relevant materials.
- Fairfax County, Virginia, has issued an asbestos exposure control plan requirement for excavation and construction projects taking place in certain parts of the county where NOA may be located. It includes dust control measures, air monitoring, worker protection, and proper disposal or covering of ACMs (Fairfax County, Virginia, 2021).

5. Determine Appropriate Site-specific Exposure Controls

If it is determined that asbestos exposure controls are necessary for a given quarry or mine to continue operating safely, the type of exposure controls must be determined that will be most effective for mitigating risks from asbestos exposures. The exposure controls can be documented in an appropriate site guidance document (*e.g.*, as "Conditions of Use" in the quarry/mine's Master Use Permit). Such controls can include

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[8] A full list of laws and regulations regarding asbestos administered by U.S. EPA is available at the agency's website (U.S. EPA, 2020b).

[9] Test Method 435 includes highly detailed bulk-material sampling procedures/equipment and laboratory analytical methods that should be followed when mining in rock containing NOA (CARB, 2017).

[10] "Section 93105 applies to any road construction and maintenance, construction, grading, quarrying, and surface mining operations where a geographic ultramafic rock unit (GURU) may exist according to the Department of Conservation, Division of Mines and Geology maps that identify deposits of ultramafic rock in California; or where any area to be disturbed has naturally occurring asbestos, serpentine, or GURU as determined by the owner/operator or the Air Pollution Control Officer (APCO); or where naturally occurring asbestos, serpentine, or GURU is discovered by the owner/operator, a registered geologist, or APCO in the area to be disturbed after the start of construction, grading, quarrying, or surface mining" (CARB, 2001).

limiting access to a site, installing protective barriers or fencing, using dust suppression strategies, *etc*. Dust suppression is particularly important for quarries and mines regulated by federal and state air quality permits and occupational health regulations (as described above) that mandate the reduction of fugitive dust levels.

Some examples of the available asbestos control strategies for mines and quarries include the following:

- **Restrict Site Access**

  Members of the public should be restricted from entering the site without authorization from and accompaniment by responsible site authorities. Fencing or other barriers can be installed around the perimeter of the site, and warning signs against entering the site without proper authorization/accompaniment can also be posted on the site boundaries. This type of control is already typical of mines and quarries due to safety concerns.

- **Control Airborne Dust**

  - Quarries and mines are typically isolated from adjacent communities by operator-owned undeveloped buffer zones, berms, tree lines, and other natural or constructed barriers. These features reduce airborne dust in remote areas by increasing the distance that dust must travel to reach those areas, and by interfering with any natural wind patterns that could carry dust beyond site boundaries. It may be possible in some places to extend buffer zones in order to increase the distance between the site and any nearby communities.
  - Dust controls also include enclosing equipment, dust suppression by water spraying, and other effective engineering controls (*e.g*., heavy duty misters that create very fine water spray). Stationary equipment, such as crushers, screen towers, and conveyors, can be partially or completely enclosed, as well as ventilated to filter out airborne dust. Dust created by drilling equipment can be reduced by enshrouding the active drill stem and applying water spray to it. Water trucks can traverse haul roads and other accessible points inside the quarry or mine to help keep those surfaces damp, thereby reducing the amount of dust they generate.
  - Reducing the drop height between conveyor discharge points and stockpiles, and at transfer points between conveyors, can significantly reduce airborne dust generated from moving materials. Transfer points can also be enclosed with shrouds or sprayed with a fine water mist to reduce airborne dust.
  - Mandating low speed limits (15 mph or less) for all vehicles traveling on-site.
  - Covering customer truck loads of quarry/mine products with tarps, installing coarse aggregate track-out pads to scrub truck tires, and washing truck wheels at the site exit can reduce the amount of dust being transferred by these vehicles when traveling on adjacent public roads.
  - Use of street sweepers for paved roadways in the mine or for any material tracked out onto public roads.
  - Use of smaller blasting patterns to minimize dust.

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