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Review

Naturally occurring asbestos—A recurring public policy challenge

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Abstract

The potential environmental hazards and associated public health issues related to exposure to respirable dusts from the vicinity of natural in-place asbestos deposits (commonly referred to as naturally occurring asbestos, NOA) have gained the regulatory and media spotlight in many areas around the United States, such as Libby, MT, Fairfax County, VA, and El Dorado Hills, CA, among others. NOA deposits may be present in a variety of geologic formations. It has been suggested that airborne asbestos may be released from NOA deposits, and absent appropriate engineering controls, may pose a potential health hazard if these rocks are crushed or exposed to natural weathering and erosion or to human activities that create dust. The issue that needs to be addressed at a policy level is the method of assessing exposures to elongated rock fragments ubiquitous in dust clouds in these same environments and the associated risk. Elongated rock fragments and single crystal minerals present in NOA have been construed by some as having attributes, including the health effects, of asbestos fibers. However, the Occupational Safety and Health Administration (OSHA), Mine Safety and Health Administration (MSHA), and the Consumer Products Safety Commission (CPSC) found that the scientific evidence did not support this assumption. As in many environmental fields of study, the evidence is often disputed. Regulatory policy is not uniform on the subject of rock fragments, even within single agencies. The core of the issue is whether the risk parameters associated with exposures to commercial asbestos can or should be applied to rock fragments meeting an arbitrary set of particle dimensions used for counting asbestos fibers. Inappropriate inclusion of particles or fragments results in dilution of risk and needless expenditure of resources. On the other hand, inappropriate exclusion of particles or fragments may result in increased and unnecessary risk. Some of the fastest growing counties in the United States are in areas where NOA is known to exist and therefore this issue takes on national significance.

This ongoing national dilemma has raised public and business concerns. There has been continuing political and scientific debate and widespread miscommunication over perceived versus actual health risks, the validity of various analytical sampling and testing methods, the questionable necessity and escalating costs of remediation procedures, and the combined negative impact on numerous commercial and public interests. Thus, conflicting research and regulatory positions on the distinctions between and hazards of true asbestos and ordinary rock fragments is all that is presently available to the public until the differing scientific communities and government agencies arrive at a consensus on these issues. The risk assessment methodology and the analytical technology needed to support inferences drawn from existing research are available, but have not been organized and implemented in the manner needed to resolve the NOA controversy.

There should exist nationally adopted and peer-reviewed NOA standards (developed jointly by the scientific community, health risk professionals, and government regulators) that establish: (1) a scientific basis for risk evaluation and assessment of NOA and rock fragments; (2) accepted analytical protocols for determining if NOA actually exists in a given area and for separating NOA from related non-asbestos rock fragments and single crystal minerals; and (3) effective public policies for managing NOA, minimizing potential hazards, and protecting public health. This article will review some of the key issues involved with the current NOA debate, propose improved analytical methodologies, describe potential solutions for dealing with NOA, and outline the benefits to be gained by creating a practical national NOA public policy.

Keywords: Naturally occurring asbestos (NOA); Amphibole; Public policy; Health risk assessment; Mixed mineral dust

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Abbreviations: AHERA, Asbestos Hazard Emergency Response Act; APCD, Air Pollution Control Division; ASTM, American Society for Testing and Materials; ATCM, airborne toxic control measure; ATSDR, Agency for Toxic Substances and Disease Registry; BLM, Bureau of Land Management; CARB, California Air Resources Board; CCMA, Clear Creek Management Area; CPSC, Consumer Products Safety Commission; EPA, Environmental Protection Agency; FESEM, field emission scanning electron microscopy; HEI-AR, Health Effects Institute-Asbestos Research; IRIS, Integrated Risk Information System; ISO, International Organization for Standardization; MSHA, Mine Safety and Health Administration; NAS, National Academy of Sciences; NIOSH, National Institute for Occupational Safety and Health; NIST, National Institute of Standards and Technology; NOA, naturally occurring asbestos; NYC, New York City; OHV, off-highway vehicle; OSHA, Occupational Safety and Health Administration; P&CAM, physical and chemical analytical methods; PCM, phase contrast microscopy; PLM, polarized light microscopy; SEM, scanning electron microscopy; SUV, sport utility vehicle; TEM, transmission electron microscopy; μm, micrometers; USGS, United States Geological Survey.

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Contents

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1. Introduction

Asbestos is a generic commercial term given collectively to a group of six fibrous hydrated silicate minerals that occur in sufficient quantity and quality to be mined and processed for industrial and commercial applications. In this paper, we use the term asbestos to refer to the asbestiform habit of amphibole and serpentine minerals, without regard to their commercial potential. Despite its many desirable material properties, asbestos poses a serious potential health risk resulting from occupational exposure to ore-grade asbestos during certain mining, milling, manufacturing, installation, and post-use abatement activities. Asbestos typically occurs as fiber bundles, commonly with splayed ends, that are composed of extremely long and thin individual fibers that are flexible and can be easily separated from one another. The term "asbestiform" is used to describe the unusual crystallization habit (the actual shape assumed by a crystal or aggregate of crystals) of minerals when the crystals form as thin, hair-like fibers such as that which occurs with the six asbestos minerals [1]. Asbestiform describes a special type of fibrosity. The definition of asbestiform is often augmented to include a statement on the special properties of asbestiform fibers, i.e., shape, enhanced strength, diameter-dependent strength, flexibility, durability, and a unique smooth surface morphology [1]. Hence, asbestiform minerals are fibrous, but not all fibrous minerals are asbestiform. With amphiboles, however, the distinction between asbestiform and non-asbestiform varieties is being questioned even when examining samples with a light microscope. The vast majority of amphiboles occur as ordinary rocks that range in growth habit from blocky to acicular. Amphibole fragments separated, broken, or cleaved from these rocks during weathering, crushing, or grinding can occur in a variety of shapes ranging from blocky to prismatic to acicular [1]. Asbestos fibers on the other hand attain their shape by growth, not cleavage. However, long, thin "cleavage fragments," while rare, may resemble asbestos fibers [1]. Regardless, prismatic and acicular crystals or cleavage fragments do not have the strength, flexibility, or other unique properties of asbestiform fibers. Cleavage fragments can be distinguished from asbestos fibers by using polarized light microscopy (PLM) or high resolution tools like scanning electron microscopy (SEM) by their tendency to form particles with stepped sides and relatively small length to width ratios. In addition, unlike asbestos bundles, cleavage fragments do not display splayed ends. Cleavage fragments almost never show curvature. It should also be noted that cleavage fragments cannot form asbestos fibers by any type of mechanical force or weathering and asbestos fibers do not form cleavage fragments but only form finer fibers when broken apart.

Over the past several decades, the six asbestos minerals that have been mined, processed, and regulated in the United States include one serpentine and five amphibole minerals. Chrysotile asbestos, the only fibrous member of the serpentine mineral group, has been the most commonly used form of asbestos and accounts for approximately 90–95% of the worldwide historic asbestos production [1,2]. The five varieties of amphibole fibers that have been used commercially are crocidolite (riebeckite asbestos), amosite (cummingtonite-grunerite asbestos), anthophyllite asbestos, tremolite asbestos, and actinolite asbestos, see Table 1 [1–3]. While the asbestos minerals exhibit many desirable properties and were widely used, a conclusive association between asbestos exposure and lung cancer was not demonstrated until the late 1950s and early 1960s [4–6], prompting regulation of the six asbestos minerals by the Federal government [7].

Naturally occurring asbestos (NOA) is the general all-encompassing name given to asbestos minerals found in-place in their natural state. The term NOA is typically used in areas where the asbestos minerals are found in such low quantities that mining and commercial exploitation are not feasible. While large commercial deposits of asbestos minerals are rare, small non-economic occurrences of asbestiform minerals are more common. The link between asbestos minerals and disease

Table 1
The regulated asbestos minerals

Regulatory name	Mineral name	Mineral group	Ideal chemical formula
Chrysotile	Chrysotile	Serpentine	$Mg_3Si_2O_5(OH)_4$
Tremolite asbestos	Tremolite	Amphibole	$Ca_2Mg_5Si_8O_{22}(OH)_2$
Actinolite asbestos	Actinolite	Amphibole	$Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$
Anthophyllite asbestos	Anthophyllite	Amphibole	$Mg_7Si_8O_{22}(OH)_2$
Crocidolite	Riebeckite	Amphibole	$Na_2Fe^{2+}{}_3,Fe^{3+}{}_2Si_8O_{22}(OH)_2$
Amosite	Cummingtonite-Grunerite	Amphibole	$(Mg,Fe^{2+})_7Si_8O_{22}(OH)_2$

has generated fear of public exposure when small quantities of fibrous silicate minerals, or NOA, are discovered. There is a high probability of finding amphibole and serpentine minerals in many areas of the United States. Amphibole and serpentine minerals tend to occur in metamorphic, igneous, and ultramafic rock terrains, which are major constituents of approximately 30–40% of the continental United States. Under specific geological conditions, these minerals can form into long, thin fibers that may be classified as asbestos or NOA. In addition to the six regulated asbestos minerals, approximately 400 known minerals (including approximately 100 silicate and aluminosilicate species) may also occur in fibrous form [8,9]. Fig. 1 is a map of the United States showing regions where igneous or metamorphic rocks (green) can be found as well as the most current geographic distribution of asbestiform minerals (yellow) based on published literature [3,10,11]. The U.S. Census Bureau has projected that the United States population will surpass 360 million by the year 2030 with considerable growth projections in those states having significant incidences of ultramafic, igneous, and metamorphic rock formations (i.e., CA, AZ, NV, OR, WA, VA, NC, etc.) [12]. In addition, the Agency for Toxic Substances and Disease Registry (ATSDR) has recently released a map showing considerable overlap between the 100 fastest growing counties in the United States and known areas of NOA [13]. Therefore, more and more construction and community land development, including homes, offices, shopping centers, grocery stores, schools, road service facilities, and other human dust generating activities, will be taking place in previously unpopulated areas with the potential for NOA occurrences and potential airborne asbestos environmental health hazards.

2. The NOA debate

2.1. Science versus public policy

The NOA controversy arose because commercial asbestos minerals can also occur as elongated fragments in their non-asbestos form, in which case they would be referred to using the mineral names shown in Table 1 without the asbestos suffix. Elongated rock fragments and single crystal minerals present in NOA have been construed by some as having attributes, including the health effects, of asbestos fibers [14]. The current ambiguity in the definitions and health effects of asbestos and non-asbestos amphiboles has led to confusion about what particles should be counted as asbestos in the optical and electron microscope methods used to analyze asbestos. The issue is complicated by several factors; including: (1) only the five amphibole minerals commercially used are regulated as asbestos, while the

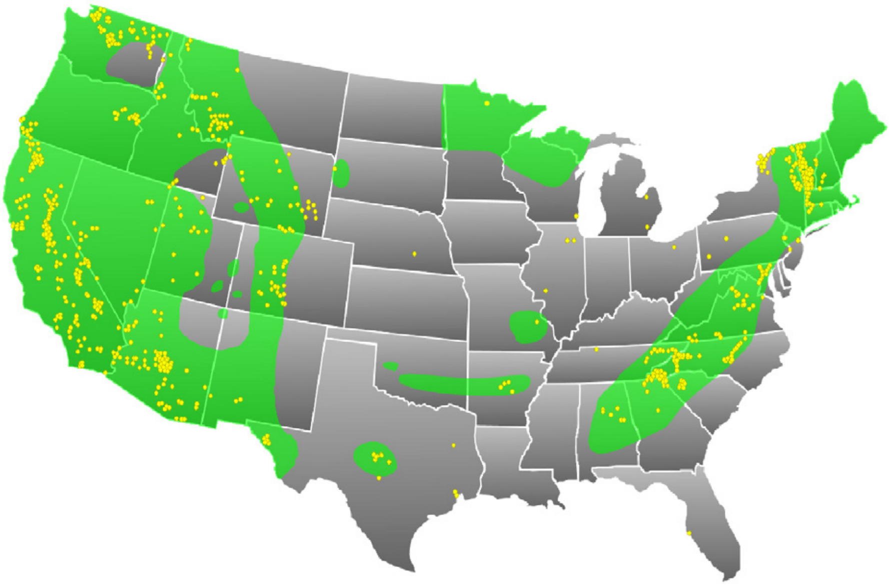

Fig. 1. Occurrences of amphibole minerals and asbestos in the contiguous United States. Green shaded areas illustrate regions of igneous and metamorphic rock terrains. Yellow dots represent possible locations where asbestiform minerals may occur according to the 2000 United States Geological Survey (USGS) database.

non-asbestos forms of these minerals are not; (2) other non-regulated amphiboles occur in the asbestiform habit, and in that form, likely present similar health risks as commercial asbestos minerals; and (3) an increasingly casual definition of asbestos fibers. Recently, the informal definition of asbestos has even gone as far as to classify any amphibole with an aspect ratio of 3:1 as asbestos. In a recent study of NOA in El Dorado Hills, California, this informal asbestos definition resulted in a significant portion of minerals to be classified as asbestos that were subsequently identified by another group as magnesiohornblende, a mineral with no known asbestos-related health effects [15].

Because asbestos is a recognized carcinogen [16], and deposits of amphiboles are widespread throughout the country, science and public policy are deeply entwined on the subject of NOA. In order to protect worker and public health, there should be rational public policy and strict regulation regarding potential harmful exposure to asbestos, whether it comes from handling commercially produced asbestos products or occurs in the natural environment [2,8,17–23]. Conversely, the misclassification of innocuous mineral dust, such as asbestos, generates widespread fear and needless waste of precious resources. Current evaluations of the health risks associated with exposure to non-asbestos minerals suggests that these minerals are innocuous or at worst pose risks that are much lower than those posed by commercially produced asbestos fibers, but no consensus on this issue has been reached [24,25].

Recently, the potential environmental hazards and related public health issues related to NOA deposits that have been exposed or disturbed during construction activities have been the subject of widespread concern that at times has reached near-hysterical levels. As in other circumstances, the public perception of and public policy for asbestos are largely driven by the popular media. Public fear of asbestos in the United States has undoubtedly had a major impact on regulations and restrictions associated with asbestos use and have led to many public misconceptions of the hazards related to asbestos.

One example of a common public misconception concerning asbestos is that occupants in asbestos-containing buildings may be subject to respiratory ailments. As a result, it has been estimated that by 1995 alone more than $50–100 billion had been spent on removal of asbestos-containing materials from schools, university buildings, public and commercial buildings, and private homes [8,21,22]. Unwarranted removal activity continues to this day, encouraged by those who profit from the abatement business, despite the publication of an advisory document in 1990 by the U.S. Environmental Protection Agency (EPA) that states most asbestos removal is unnecessary and even counterproductive both in terms of health protection and costs [26]. As an example of unwarranted removal, the New York City (NYC) school system responded to pressure from parent groups and spent nearly $100 million for asbestos removal in public schools [20–22]. During this time, many schools remained closed and parents were subjected to a massive media coverage that promoted the idea that school children might develop asbestos-related cancer in the future. However, based on fiber-in-air measurements conducted elsewhere, the calculated risk to NYC school children, using the most pessimistic models (or worst case scenario), was found to be less than six excess cancer deaths per million lifetimes, which is equivalent to smoking less than a dozen cigarettes in a lifetime [21]. This incident prompted 17 world-renowned experts on the subject of asbestos to issue a public statement criticizing the city's unnecessary and costly actions [19]. This group of scientists stressed that the public's fears could have been substantially allayed through education and that science, not unreasonable emotion, should guide both the administrative and the public response in these types of situations. Similar events fueled by public reaction include past media reports on purported asbestos in children's play sand and crayons [27,28]. In each instance, a report was made by a laboratory or "expert" that amphibole asbestos was observed in these products. Following the revelation and subsequent national publicity, tests on these products were performed by a number of scientists, including an Occupational Safety and Health Administration (OSHA) laboratory that showed there was no asbestos in these products, only non-asbestos mineral particles [29–31]. Little to no publicity followed these findings, leaving the public completely misinformed.

The examples cited above illustrate the need to avoid excess panic and rushed judgment over possible asbestos issues and the necessity of conveying the best possible scientific data to a concerned public. The general public's response to environmental risks like NOA is extremely variable. The general public has not exhibited concern regarding urban development on floodplains, near the ocean, and on active earthquake faults [8]. However, the general population has shown great concern for a variety of harmful substances found in our environment, such as lead [32–34] and mercury [35,36], as well as asbestos [22]. Risk imposed upon us is viewed much differently than risk we willingly choose to live with. The chosen risks of being killed by activities such as smoking and motor vehicle accidents are far greater than the risk imposed from exposure to asbestos [8,22]. However, we choose the former risks and the latter are imposed upon us. The inclusion of a reasonable margin of safety in a public health standard is scientifically justifiable, but the size of the margin of safety is a social and moral value. The Code of Federal Regulations states that acceptable exposure levels for toxins are concentrations to which the population may be exposed without adverse effects during a lifetime, or part of a lifetime, incorporating an adequate margin of safety [37]. This is an issue that puts the degree of risk imposed on the general public in direct competition with the degree of hardship imposed on commercial interests. Miscommunications can lead to unnecessary media hysteria and public alarm at one extreme to possible minimization of truly high risk environmental hazards at the other. Good public policies and regulatory practices must weigh the health risks of action and inaction as well as the associated financial costs. Environmental laws and regulations should be based on accepted scientific, engineering, and health principles. Scientists inform, but do not make the decisions as to acceptable risk. Scientists are obligated, however, to provide the best available data to the health and regulatory communities so that reasoned decisions can be made.

2.2. *What should be done about NOA?*

A national NOA public policy based on sound technical, scientific, and health standards is needed to ensure the proper use of land and natural resources while protecting the public. Standard evaluation programs that can determine acceptable land uses, risk associated with their use, and establish appropriate control measures need to be implemented. Such programs will ensure homeowners, schools, developers, product suppliers (i.e., mining and manufacturing companies), and construction companies that the building materials they are using and the sites they are building on are not asbestos contaminated. As before, progress in this endeavor must begin with a consensus on how to define and classify NOA and related elongated rock fragments. This also includes the evolution of appropriate testing methods to establish the safety of potential land development sites as well as the safety of sources of crushed stone and building materials. These goals can only be achieved by the accumulation, review, and debate of the best available knowledge by a panel of experts in a variety of scientific fields. Similar reviews were successfully implemented by the National Academy of Sciences (NAS) in 1984 [38] and the Health Effects Institute-Asbestos Research (HEI-AR) working groups in 1991 [39]. The NAS study investigated the health risks from non-occupational exposure to asbestos fibers. The HEI-AR group of experts examined the growing concern of human exposure to asbestos in public and commercial buildings. Both groups issued extensive reports that are now cited and referenced in most asbestos related research [38,39]. Such a panel could have a major impact on the ultimate goal of ensuring public health and safety in the most cost effective manner.

The responsibility of such a panel needs to include a charge to review the state-of-the-art in risk assessment and arrive at risk categories for classifying the hazards of airborne dust containing asbestos and elongated rock fragments. An understanding of the risk associated with asbestos and elongated rock fragments is important to properly protect the health of people living in proximity to construction zones or other dust generating activities. In risk assessment, it is important to characterize and count asbestos and rock fragments based on the properties that contribute to risk. Such research needs to achieve a consensus on the characteristics of asbestos that control risk and needs to be performed before designing analytical techniques and methods used to measure the particles of highest risk in mixed mineral dust environments.

The term "asbestos" has typically been defined and used in at least four different ways depending on the specific context [40]:

1. commercial definitions designed to highlight the properties of asbestos that impart commercial value, such as high tensile strength, low thermal and electrical conductivity, high heat resistance, and high mechanical and chemical durability;
2. geologic definitions that distinguish asbestiform materials from non-asbestiform particles (i.e., cleavage fragments) based on their mechanism of formation;
3. regulatory definitions, generally for occupational settings, that distinguish the minerals to be regulated from those that are not; and
4. analytical definitions that provide laboratories and analysts with the guidelines required to characterize, distinguish, and count appropriate structures to determine their concentration.

Unfortunately, according to Berman [40], the definitions developed for the purposes described above have been inconsistent and none have succeeded as a definitive measure that can be used to accurately support risk assessment. This is because the existing definitions do not coincide sufficiently with the chemical and physical characteristics of asbestos that contribute to biological activity. Berman and Crump point out that extrapolation of risk estimates from one population to another require that the portion of the study population measured have the attributes determined to be associated with risk in the reference population [41]. Although much is now known, Berman contends that there are still controversies concerning the asbestos characteristics that contribute to biological activity [40]. Berman has also stated that it is important that these controversies be addressed in order to better define and regulate asbestos in a risk-based manner that is "demonstrably health protective while avoiding incorporation of conservative assumptions that are so overwhelmingly broad as to preclude the ability to distinguish potentially risky situations from those that are clearly not" [40].

The National Institute for Occupational Safety and Health (NIOSH) has recently authored a White Paper outlining a roadmap for scientific research necessary to address current controversies related to the definition of asbestos, appropriate analysis techniques for asbestos and valid risk assessment methods [14]. The purpose of this proposed research will be to develop improved worker policies and practices related to occupational asbestos exposure. Similar policies are needed to address the same types of scientific issues related to mixed mineral environments and the health effects of NOA on the public at large.

While the national NOA guidelines need to be based on valid scientific evidence, a national public policy cannot be implemented without action at the congressional and regulatory level. This will be a difficult task for regulatory agencies due to inconsistent policy standards within different regions of the same agency. Not only is consensus needed at the scientific level, but at the regulatory and legislative level as well. Therefore, the development and implementation of an NOA policy will depend on the collaborative effort of people with expertise in various disciplines including geology, mineralogy, analytical methodology, medicine, toxicology, epidemiology, industrial hygiene, economics, risk assessment, and social and political science. The major issues and unanswered questions at the heart of the growing debate concerning NOA are: (1) the limitations of the current methods used to estimate the risk of exposure; (2) whether the mineralogical distinction between NOA and rock fragments extends to their biological effects; (3) whether aspect ratio (length:width) is a meaningful descriptor of fibers having the highest potential risk of disease; (4) determination of the appropriate dimensional characteristics used to assess fiber risk; and (5) defined analytical methods that provide cost effective discrimination between asbestos fibers and rock fragments, and/or between high risk, moderate risk, and low risk habits or forms. These issues will be discussed in more detail below.

3. Limitations of the processes used to estimate the risk of exposure

Asbestos is classified as a carcinogen by state, federal, and international agencies and all six types of asbestos shown in Table 1 are considered hazardous [1–3,8,16]. Humans may be exposed to asbestos by breathing airborne asbestos fibers, which can be deposited deep into the lungs where they persist for long periods. Medical studies have shown there is a strong association between certain diseases (asbestosis, lung cancer, and mesothelioma) and asbestos exposure [1–3,8,16]. Asbestos diseases have long latency periods (10–40 years) and have been related to the dose a person breathes (a combination of concentration and duration of exposure). In addition, several asbestiform varieties of other amphiboles (i.e., richterite, winchite, and others) have been identified that are suspected or known to pose a health risk similar to the regulated asbestos minerals [1]. As more information on the health effects of other asbestiform minerals becomes available, new regulations may be developed, or existing regulations modified, to include asbestiform minerals in addition to those currently regulated.

When discussing the health effects of asbestos minerals, it is also important to distinguish between fibers and the non-asbestiform cleavage fragment analogs of these minerals. Gamble and Gibbs [25], Mossman et al. [42], and Ilgren [24] have reviewed numerous studies demonstrating that cleavage fragments and amphibole asbestos fibers have fundamentally different properties and that these differences are biologically relevant. Cleavage fragments lack the strength, durability, flexibility, and acid resistance of asbestos. Several studies indicate that the toxicity of respirable cleavage fragments is so much less than that of amphibole asbestos that by any reasonable measure they are not biologically harmful [24,25,42]. OSHA conducted a review of the health effects of inhalation of non-asbestiform amphiboles and determined that the scientific evidence was insufficient to regulate cleavage fragments since such fragments were unlikely to produce a significant risk of developing asbestos-related disease [43]. However, there is still not a general consensus among the medical community about the potency of different fiber sizes (i.e., length, width, and/or aerodynamic diameter), the relative potency of different asbestos species, and the potential health effects of cleavage and other rock fragments versus fibers. For example, NIOSH continues to argue for the regulation of “fiber-like cleavage fragments” as asbestos until the potential health effects are better understood [14]. Current analytical methods do not provide specific guidance on how to discriminate between asbestos and other non-hazardous rock fragments in order to properly assess the hazards of exposure to them and evaluate risk assessment data. These controversies and limitations of the methods contribute to the overall complexity of evaluating potential asbestos risk sources of NOA.

Low concentrations of fibrous minerals are common in nature, but environmental disease related to mineral fiber is extremely rare and mainly due to a few types of amphibole asbestos and asbestiform erionite, a zeolite mineral [2]. Asbestos, left locked and undisturbed in its host rock, presents no threat to human health. According to Dusek and Yetman, placement of a cover of clean soil over asbestos-containing soil and/or rocks can provide an effective barrier against exposure because they claim there is no recognized transport mechanism for asbestos migration from underlying bedrock into the upper soil regions in the absence of mechanical disturbance [44,45]. However, it has been reported that asbestos materials buried above the frost line can eventually migrate to the surface through freeze–thaw cycles [46,47]. In any case, asbestos may potentially be released from NOA-containing rocks and soil when they are crushed or otherwise disturbed in some manner. Therefore, airborne asbestos could become an environmental health hazard in populated areas that contain NOA-bearing rocks or soil, especially where such ground materials are exposed to natural weathering and erosion or to various human activities that create dust (absent appropriate engineering controls), such as mining, excavation and development of natural outcroppings, driving automobiles on unpaved roads, outdoor sports and recreational activities, etc. A number of factors can influence the length of time asbestiform amphiboles and other mineral particles released from soil and/or rock may stay airborne and how far they may travel before settling. Important factors include the characteristics of the disturbed rock/soil (i.e., hardness, moisture content, particle size, etc.), the size and aerodynamic characteristics of the released particles, the nature and force of the disturbance activity, weather conditions at the time of the disturbance, and wind speed and direction [48]. The study of hazards associated with asbestos exposure has traditionally focused on ore-grade commercial products in occupational and indoor building settings. At present, no one has an approved or accepted test method or formula for extrapolating actual or even potential inhalation exposure levels from rock or soil containing asbestos. Berman [49] has proposed one potential method that was successfully used at a New Jersey quarry [50]; however, this procedure has not been widely adopted.

One recent statistical study by Pan et al. indicated that, after taking into account cases with possible occupational exposures, the risk of developing malignant mesothelioma in California was directly related to a person’s residential proximity to a source of ultramafic rock [51]. This study found that the odds of having mesothelioma fell by 6.3% for every 10 km farther a person lived from the nearest natural-occurring asbestos source. One of the study’s co-authors equated the risk of developing mesothelioma from exposure to NOA as about the same as the risk of developing lung cancer from exposure to secondhand smoke [52]. The results of Pan’s “residential proximity to NOA” study, however, have recently been called into question for several reasons [53,54]. One issue raised is the simple fact that the mere presence of NOA in geologic strata does not imply airborne fiber concentrations substantially above background levels nor does it take into account differences in fiber type. In fact, Pan et al. did not conduct any sampling or background level measurements near the vicinity of the study group's residences. Another issue is the fact that the most common type of asbestos in California ultramafic rock is chrysotile, which reportedly has low risk for mesothelioma [55]. Wind direction patterns are also an important variable, i.e., the closest NOA-bearing rock may not contribute as much asbestos exposure to a particular neighborhood as one somewhat further away. The study by Pan et al. lacked a lifetime residential history of the cohort subjects and may also have missed some potential occupational exposures. Use of a cohort's home address at the time of diagnosis does not consider residential location during the long relevant latency period, decades preceding diagnosis. As a final note regarding this study, to date there have not been any published studies reporting verified cancer clusters or epidemiological evidence of increased mortality in California that have been directly related to exposure to NOA.

Ross and Nolan reviewed several medical studies indicating a high incidence of mesothelioma, supposedly resulting from environmental exposure to tremolite NOA in soil, in several small rural villages in mainly agricultural areas of Turkey, Greece, Cyprus, Corsica, and New Caledonia [2]. In all of these studies, the villagers routinely quarried, ground, and used the tremolite asbestos-containing white soil to produce a whitewash or plaster material (i.e., white stucco), which was widely applied to the walls, floors, and roofs of houses. Other common uses of the tremolite-containing soil were as insulation and waterproofing materials in homes, in pottery, and even as a baby powder [56]. These studies represent unusual circumstances where villagers were repeatedly exposed to tremolite asbestos dusts from an early age both indoors and outdoors. Hence, it can be argued that clusters of mesothelioma attributable to NOA have been observed only in the unique cases where direct daily exposure to materials containing NOA is common.

With the potential for asbestos related disease, the determination of risk from asbestos is of critical importance to both public health officials and regulatory bodies. The EPA has reported there are four factors that increase the risk of contracting asbestos-related disease: (1) the concentration of asbestos fibers in the air; (2) the frequency of exposure; (3) the duration of exposure; and (4) the time that elapses after exposure [57]. Therefore, in areas containing NOA, it is possible that there will be some low level risk associated with background concentrations of asbestos. Regardless, it is unlikely that concentrations of airborne asbestos from NOA sources will ever produce sustainable elevated levels of airborne asbestos of the kind historically related to asbestos disease. The EPA has stated that the risk from NOA is similar to the everyday risk that everyone experiences from different environmental factors such as air pollution in urban areas or earthquakes in earthquake-prone areas [57]. However, existing asbestos risk models are based on a linear dose assumption, i.e. there is no threshold for development of disease. These models [58,59] were derived from epidemiology studies of comparatively high industrial exposures. The extrapolation of these models to low, ambient concentrations has not been validated. In the absence of such validation, the existence of a threshold air concentration for asbestos fibers cannot be discounted (not unlike the absence of threshold values for hydrocarbons in the early 1980s) and the extent that low concentrations of airborne fibers represent a health hazard cannot be precisely quantified [60]. Risk estimates can be made for low concentrations using the existing risk models, but the confidence intervals for such estimates will be comparatively large. As a result, it is even more difficult to understand the relationship between source concentration and the level of rock and soil disturbance necessary to generate harmful doses of airborne NOA-bearing dust and potential elevated risk. Although, as previously mentioned, Berman [49] has proposed one method for predicting exposure from soils and rocks that was successfully used at a New Jersey quarry [50]; however, this procedure has not been widely adopted.

The current EPA approved method of risk assessment is termed Integrated Risk Information System (IRIS), and is based on the evaluation of the risk of asbestos disease to a number of cohorts occupationally exposed to commercial asbestos [58]. The analytical method supporting the analysis is phase contrast microscopy (PCM) augmented by transmission electron microscopy (TEM) when the identity of fibers is in question. IRIS does not address any method for treating or considering non-asbestos rock fragments, and does not address the relative potency of different forms of asbestos.

EPA, recognizing the limitations of IRIS, commissioned an effort to modernize the risk methodology [61]. The result of this effort represents the latest science for measuring the risk posed by asbestos—the Berman–Crump Asbestos Risk Assessment Protocol (Berman–Crump Protocol) [41]. This protocol was the result of an EPA-funded, multi-year study which demonstrated that airborne amphibole asbestos fibers that are long and thin (longer than 10 μm and having widths that are less than 0.4 μm) are of most concern with respect to health risk and that different relative carcinogenic potencies should be applied for different fiber types when estimating risk. The EPA partially funded a collaborative study between NIOSH investigators and investigators from Duke University Medical Center and University of Chicago on the role of fiber size in predicting lung cancer or asbestosis in chrysotile textile workers at a single South Carolina textile plant [62]. The results of this study support the conclusions of the Berman–Crump Protocol. The study found that fiber length and width were highly statistically significant predictors of lung cancer and asbestosis mortality. Lung cancer was best predicted by long, thin fibers (i.e., >40 μm length; <0.3 μm width), although other sizes including those ≤ 5 μm length also provided good fits. This study also concluded that asbestosis was best predicted by shorter (≤ 1.5 μm), thinner (≤ 0.3 μm) fibers; length appeared to be unimportant.

A detailed review of the results from the Berman–Crump Protocol is beyond the scope of this article. In brief, the protocol defined appropriate procedures for evaluating asbestos-risk and developed optimum values for exposure–response coefficients for lung cancer and mesothelioma and a conservative set of potency estimates. To assess risk, depending on the specific application, either the best-estimate risk coefficients or the conservative estimates can be incorporated into described procedures for assessing asbestos-related risk in a given situation. Results presented in the study can be combined with appropriately determined estimates of exposure to develop estimates of risk in environments of interest.

The Berman–Crump Protocol was the subject of a peer-review consultation held in San Francisco on February 25–26, 2003 [63]. In general, the eleven-member expert panel endorsed the overall approach to risk assessment proposed in the report, although there are still some areas where controversies persist. At this time, the additional research and analyses recommended by the peer consultation panel are not yet completed, the protocol has not been independently peer reviewed, and the EPA has not officially adopted the protocol. However, the Berman–Crump method is in the process of being peer-reviewed and published [64–66]. Until the final version of the Berman–Crump Protocol is completed and officially adopted by the EPA as a valid risk assessment tool or other widely accepted risk models become available, assessment of asbestos exposure risk will depend primarily on the qualitative identification (i.e., the presence or absence) of NOA at a particular site, thereby placing this responsibility on geologists and trained asbestos analysts. Without well-defined standards and valid risk assessments, the ultimate risk from NOA exposure to humans under more typical circumstances during normal daily outdoor activities is still uncertain.

4. Sampling methodology

As the population grows and new land developments are initiated, potential NOA disturbances should be evaluated, a risk analysis performed, and a plan similar to or part of an environmental impact statement should become a standard part of the development protocol. Similarly, when suggestions or concerns are expressed about potential NOA in an existing area, a similar program should be put in place. Any evaluation of potential NOA environments must begin with a review of all available geological information. This should include all geological, topographical, and soil references, publications, and maps prepared by the United States Geological Survey (USGS), the local state and county agencies, or published in the literature. In addition, aerial photographs may provide information on geologic structures and recent and historic uses of a site [1]. Information on the geographic occurrence of unique plant species may also provide insight into the soil composition and distribution [1].

Regional reference samples that are representative of the area under study are essential in any mixed mineral or potential NOA investigation. They provide the laboratories with control samples that can be compared with the results obtained throughout the study. The reference samples should provide information on the general geology and mineralogy of the site, including the identification of any asbestiform minerals. While the current methods do not provide guidelines on the proper way to examine or collect samples in mixed mineral environments, several issues to consider in the sampling process are discussed below.

The USGS has recently published detailed maps showing the locations of historic asbestos mines, historic asbestos prospects, and natural asbestos occurrences in the Eastern and Central United States [67,68]. These maps and the associated digital data reports are intended to provide State and local government agencies and other stakeholders with the latest geologic information on natural occurrences of asbestos. These reports currently provide location, mineralogy, geology, and relevant literature information for 331 natural asbestos occurrences in the Eastern United States and 26 in the Central United States [67,68]. The California Department of Conservation has also issued a general state map and detailed reports and maps showing the location of ultramafic rocks and likely areas for NOA in three highly populated California counties (Western El Dorado, Placer, and Eastern Sacramento) [69–72]. The extensive mapping effort in California arose because of resident concerns over the potential health risks associated with NOA as land development increasingly moved into areas of serpentinite outcrops [73]. However, many available geologic maps and documents may not mention the occurrence of asbestos minerals if they were not an important part of the particular study. The original intent of the map or documents must always be considered when researching the geologic environment of a potential NOA site. It should also be remembered that while geographic conditions are more likely for asbestos formation in or near the designated areas on asbestos maps, its presence in a specific location is not certain by any means. For example, areas mapped as containing ultramafic rock may be extensively covered with soil and/or vegetation; hence, any NOA that may be present may not be in a state to be released unless disturbed.

Given the multiple purposes for the original generation of geological maps and the lack of standard protocols for surveys, the method recommended by the California Geological Survey for verification of the geologic conditions at a given location is through a detailed site-specific examination by a qualified geologist [1]. A site investigation involves walking the site and observing the mineralogy, paying close attention to structural features such as folds, faults, and cracks, including the orientation and degree of weathering. Asbestos occurs in veins, lenses, pockets, as aggregates of fibers, cross veins, slip fibers, or matted masses. The occurrence, distribution, and description (i.e. color, texture, friability) of any asbestos-containing or potentially asbestos-containing rock or soil should be documented in writing and with photographs. In addition, site areas containing fill or other imported earth material should be examined to determine if the materials contain asbestos since asbestos-containing materials and products have historically been used in construction and manufacturing in the United States. The California Air Resources Board (CARB) has already taken the lead in this area by adopting an Airborne Toxic Control Measure (ATCM) for construction, grading, quarrying, and surface mining operations that will take place in ultramafic rock regions [74]. In order to obtain an exemption from the regulation, a registered geologist must perform a geological survey prior to any excavation activities. The survey includes evaluation of geological maps and research, a site visit, and documentation of geologic features, rock and soil types that may be indicative of ultramafic rock or serpentine and amphibole mineralization. However, it is difficult to judge whether such regulations are adequate or necessary in the absence of scientific studies aimed at determining the effectiveness of these measures for protecting public health.

Depending on the scope of the project, sampling will typically be performed at the surface as well as below the surface [1]. In any case, the number of samples collected should be representative of the site. Geological sampling for NOA can be "targeted" or "unbiased" and can include hand and soil samples [1]. Targeted, or directed, sampling is used to verify field observations and confirm the presence or absence of asbestos in samples with potential fibrous minerals. Unbiased, or non-targeted sampling is used when there are no obvious locations or features on a site that suggest the presence of asbestos.

To confirm the presence of asbestos minerals, laboratory analysis is required to determine the morphology, crystal structure, and chemical composition of the particles present in bulk samples. Once the sources of potential asbestiform minerals have been sampled, as well as other rock types in the area, including non-asbestos amphiboles, the locations and potential for disturbance can be evaluated. If the potential for disturbance is likely, and the material friable, air testing and risk analyses should be performed. In the event that asbestiform materials are identified in soil samples, the releasibility of fibers under known conditions should be established. Assuming a substantial exposure potential exists, an air-monitoring program can be initiated, or a field-sampling program designed. Guidance on such sampling and measurement techniques can be found in the EPA Superfund Method [75].

There is a debate as to the suitability of the current accepted methodologies for mixed mineral environments [15]. An entirely new methodology and assessment procedure may be needed to properly address mixed mineral dusts and potential NOA-containing situations. Therefore, this paper does not recommend one analytical method over another, but touches on the advantages and disadvantages of a variety of analytical techniques that may be used in combination to evaluate mixed mineral environments.

5. Current methods for asbestos identification

As the surmised health effects of NOA continue to cause concern and fear in the general public, scientific and regulatory bodies are engaged in their own debate regarding the appropriate analytical methods and protocols for mixed mineral environments. Issues that have been raised concerning identification of asbestos include: (1) whether other asbestiform minerals should be included in the regulatory definition of asbestos; (2) whether the treatment of cleavage fragments of non-asbestiform amphiboles is appropriate; and (3) whether the current specified analytical dimensional criteria for fibers are appropriate [14]. Importantly, this debate centers on the amphibole asbestos minerals and the non-asbestos analogs and not the chrysotile mineral. Chrysotile is a recognized asbestiform mineral and is specified in the analytical methods. Thus, classification of its non-asbestos analog, antigorite, or other serpentine minerals such as lizardite, would violate the method, even if the particle met the nominal counting criteria (although it should be noted that NIOSH wants to regulate antigorite and lizardite as asbestos [14]). By inference, and because (with the exception of International Organization for Standardization (ISO) 10312 [76]) the methods are specific for asbestos, non-asbestos amphiboles should not be counted. However, some laboratories and agency groups take the position that unless the non-asbestos amphiboles are specifically excluded from the analytical protocol, they should be counted if the particle meets the nominal counting criteria [14,77].

This type of ambiguity in the research literature and public media as to the distinction between asbestos and non-asbestos minerals highlights the limitations of the current analytical methods and protocols. These limitations are magnified in the case of NOA and mixed mineral environments since typical exposure levels for NOA are much lower than traditional occupational exposure levels [39,78,79]. Due to the low fiber concentrations in typical mineral dust, non-asbestos amphiboles represent a much larger component of the total mineral particle population compared to commercial asbestos samples or airborne fibers generated from commercial sources, and therefore pose a greater analytical issue.

The historical development of current methods focused on the analysis of commercial-grade chrysotile asbestos found in the workplace and in consumer products, not the occurrence of amphibole asbestos found in mixed mineral environments [80]. The only current methods providing direct guidance for separation of the non-asbestos and asbestos amphiboles are the Yamate TEM method [81], which instructs the laboratory that asbestos minerals generally have a preferred orientation and electron diffraction pattern. The Yamate method cautions that some non-asbestos minerals will produce the same pattern, and indicates that ambiguity can only be resolved through the comparison of fiber morphology with standard reference minerals. The NIOSH 7402 TEM method [82] and the OSHA ID-191 PLM method [83] indicate that non-asbestos minerals represent an interference, and instruct the laboratory to separate asbestos from non-asbestos using the same characteristics as those used optically.

The issue of cleavage fragments is extremely important in mixed mineral environments due to the co-existence of serpentine and amphibole asbestos as well as their non-asbestos analogues. The identification of chrysotile with a microscope, for example, is straightforward due to the unique particle morphology and crystal structure not seen in non-asbestiform varieties of serpentine [3], even the non-asbestiform varieties with high aspect ratio. The distinction between amphibole asbestiform and non-asbestiform varieties, however, is not as obvious because amphibole particles can occur in a variety of shapes, ranging from blocky to prismatic to acicular to asbestiform [3]. A prismatic crystal has one elongated dimension and two other dimensions that are approximately equal. An acicular crystal is a special type of prismatic crystal that is extremely long and thin with a small diameter (i.e., needle-like) [1]. Amphibole particles can also break (or cleave) into smaller fragments when crushed or finely ground. Cleavage refers to the preferential splitting of crystals along planes of structural weakness (cleavage planes) [1]. Minerals with one cleavage plane will produce platy fragments, minerals with two distinct cleavage planes will produce prismatic or acicular fragments, and minerals with three or more cleavage planes will form polyhedral fragments [1]. The current PCM and TEM methods are designed to measure and identify asbestos but do not unambiguously define the nature of amphibole particles which should not be counted. Going forward, it is essential to reaffirm a consensus for an accurate risk-based mineralogical and regulatory definition of the term “asbestos” in order to develop improved cost-effective analytical methodology and provide proper risk assessment.

In the mineralogical sense, several studies and reference methods including the EPA 1993 PLM method [84], the American Society for Testing and Materials (ASTM) PLM method [85], and the National Institute of Standards and Technology (NIST) 1867 reference [86] define the asbestiform habit, under the light microscope, by the following characteristics [87,88]:

A fibrous silicate mineral comprised of fine, flexible, readily separable fibers, having a high tensile strength and the following characteristics as individual fibers or bundles:

1. mean aspect ratio ranging from 20:1 to 100:1 or higher for fibers longer than 5 μm;
2. very thin fibrils, usually less than 0.5 μm in width;
3. parallel fibers occurring in bundles; and
4. one or more of the following:

a. fiber bundles displaying splayed ends,
b. matted masses of individual fibers, and/or
c. fibers showing curvature.

These criteria are defined for optical magnifications, and a consensus definition should be defined for the SEM and TEM that incorporate these criteria, and any additional distinguishing characteristics not defined for the optical case such as parallel sides, type of ends, and electron diffraction characteristics. By definition, amphibole particles not meeting these criteria are not asbestos. Optically, the positive indicators of cleavage fragments and euhedral to subeuhedral crystals are stepped sides, visible cleavage planes, and blunt or angular terminations. Aspect ratios are generally less than 20:1 for particles longer than 5 μm, except in the case of byssolitic structures.

Another issue of debate regarding the analysis of mixed mineral dusts is what constitutes a “countable” fiber. The most notable differences in the definition of a countable fiber occur between the standard light and electron microscope methods for the determination of asbestos in air samples [88]. The NIOSH 7400 [89] and Physical and Chemical Analytical Methods (P&CAM) [90] PCM methods arbitrarily count as fibers all particles visible in the microscope that are at least 5 μm long and have a minimum aspect ratio of 3:1 [80,89]. In contrast, with the much higher resolution TEM, the analyst normally counts asbestos fibers greater than 0.5 μm in length with an aspect ratio greater than or equal to 5:1 [82]. The aspect ratio was chosen to improve precision and minimize the interferences from non-asbestos particles. In addition, the PCM and TEM methods were used to assess asbestos exposure levels and the estimating technology was based on counting “asbestos” particles of a certain size [91]. It is worth noting that the Asbestos Hazard Emergency Response Act (AHERA) method [92] was not intended for ambient air monitoring or exposure assessment, whereas the Yamate [81], ISO 10312 [76] and NIOSH 7402 [82] methods can be used for this purpose. In some laboratories, and even in some agency groups, aspect ratio has become the primary and sole means of identifying asbestos fibers. This practice is at odds with mineralogists, asbestos morphology, and with risk models that do not define asbestos according to simple shape characteristics. The use of a dimensionless parameter such as aspect ratio results in the loss of information about the actual size of the fiber and, therefore, is of little or no use when discussing exposure or toxicological outcome [18]. Defining asbestos fibers based on aspect ratio alone is unacceptable because it is not based on documented health effects or on unique physical characteristics of asbestos fibers. Asbestos is an elongated mineral, so although a predetermined aspect ratio will include most asbestos fibers, it will also include other elongated non-asbestos mineral particles.

5.1. Analysis of airborne fibers in mixed mineral dust

There is a tendency to regard fiber counting techniques as “locked in stone.” In reality, there has been tremendous evolution in the methodology, when as is the case today, the available methods failed to meet the need or adequately measure the exposure. The original procedures developed for asbestos dust measurements used a variety of techniques, such as entrainment or impingement, to capture the airborne particles. These dust collection tests were performed in locales where commercially produced asbestos was being manipulated or processed. Each of the early methods used a light microscopy method to count all particles that were at least 1 μm in size [93]. In the early 1960s, air filters began to achieve acceptance for the collection of airborne particulate [94]. These early studies were first conducted in the United Kingdom and later in the United States [95], but the PCM method was not developed until the late 1960s by the U.S. Public Health Service [94]. In 1970, the first regulatory PCM method for asbestos evolved that evaluated the airborne fibers in the workplace where commercial asbestos was in use and was intended as an assessment of industrial exposures [96]. In 1977, NIOSH issued their first PCM method [90], but published an updated method, NIOSH 7400 [89], in 1984 following studies that showed variability in results due in part to varying qualities of the microscopes. The NIOSH 7400 PCM method specified sample collection procedures, material (filter and microscope) qualities, and counting protocols.

As discussed above, the PCM method counts all visible fibers that are at least 5 μm long with an aspect ratio of 3:1 or greater. In general, the PCM technique is viewed as being unable to detect fibers less than 0.25 μm in diameter [97]. However, thinner fibers are visible in the PCM, but their diameters cannot be measured. The primary purpose of the standardized PCM methods was never to discriminate between asbestos and non-asbestos fibers, only to monitor and control the airborne commercial asbestos fibers in order to reduce the disease incidence [98,99]. The original dose response and risk assessment data were collected using midget impinger and thermal precipitator measurements [80,99,100]. Since its adoption, the PCM method has become the generally accepted technique used for exposure and risk estimates from which dose response assessments are derived [80,99,100]. In these workplace environments, it was a safe assumption that the majority of particles fitting the simple counting rules would indeed be asbestos. The PCM minimum 3:1 aspect ratio was not based on any scientific definition of asbestos characteristics or the toxicological significance of such characteristics, but simply reflected a need to improve consistency in exposure measurements by analysts. However, a technique that utilizes an "asbestos fiber" definition specifying a minimum aspect ratio of 3:1 for particles longer than 5 μm is not valid for the analysis of mixed mineral dusts simply because in most typical natural environments there are too many non-asbestos particles that would fit the aspect ratio definition [80].

The PCM technique can be extended beyond what is prescribed in the methods and additional information concerning airborne fibers in mixed mineral environments can be ascertained using the PCM. For example, current analytical techniques and risk protocols designed for the evaluation of airborne fibers in the workplace do not address the wide spectrum of particles that may be present in airborne mixed mineral samples. The particles can range from short, wide fibers to very long, thin fibers. There is a general consensus among health experts that long, thin fibers present more of a health risk than low to moderate doses of short, wide fibers. However, a controversy exists concerning the particles that fall in the middle of this length–width continuum. The risk of these intermediate sized fibers is not well understood. The fibers that are not counted in PCM (under 0.25 μm wide) fit the consensus that fibers long, and in this case, very thin, are more toxic; however, what is their contribution to the adverse outcome? Since the health effects of the intermediate sized fibers are not established and the contribution to disease from very thin non-PCM countable fibers is not quantified, there is uncertainty as to how to handle these particles during an analysis. Should the intermediate sized particles be differentiated from the long, thin asbestos fibers? If it is found that sorting of the particle population is necessary from a risk perspective, what is the most cost effective method to achieve this goal? It becomes apparent that some type of screening method is necessary as an initial step in the analytical process of mixed mineral environments. The ultimate goal of the screening step would be to provide information on the size distribution of the particles and fibers. If no high-risk fibers are detected, then no additional analysis may be necessary. If an elevated population of high-risk fibers is discovered, the most appropriate technique to accurately measure and unequivocally identify the presence of asbestos will need to be identified and used.

ASTM has recently implemented a screening method based on the PCM technique for determining an index of occupational exposure to airborne fibers in mines, quarries, or other locations where ore may be processed or handled [101]. ASTM recognized and addressed the complexity of analyzing asbestos in mixed mineral dust atmospheres with the development of this rapid screening optical protocol that preserves the information obtained in the conventional PCM analysis but added a discriminate analysis component to identify samples with significant numbers of long, thin fibers. The method provides an estimate of the fraction of counted fibers that may be asbestos by classifying the fibers (longer than 5 μm with an aspect ratio of 3:1 or greater) into three groups: (1) fibers that show curvature, splayed ends, or appearance of bundles; (2) fibers that are longer than 10 μm or thinner than 1.0 μm;[1] and (3) all other countable fibers. If an elevated content of long thin fibers is detected optically, the ASTM method recommends supplemental electron microscopy analysis. This type of approach that differentiates particles of different size ranges and different physical characteristics is the first step in screening mixed mineral samples.

Following the screening step in an analytical methodology for airborne fibers in mixed mineral environments, additional analyses may be necessary to accurately measure and unequivocally identify the presence of asbestos. While the complete chemical, morphological, and crystallographic analysis of every particle in a mixed mineral sample would be ideal, it is not realistic due to time and cost limitations. The resources, including time, money, and effort, need to be focused on the identification and classification of the particles that pose the most risk. More uncertainty is acceptable in the full identification of the particles that pose less of a risk. The challenge for scientists and policy makers will be streamlining and efficiently organizing the series of analytical steps most appropriate for analyzing fibers that present the most risk in airborne samples of mixed mineral dusts.

Either the TEM or SEM provides the necessary resolution and analytical capabilities to determine if the long, thin fibers are asbestos. In the United States, TEM is widely regarded as the most reliable technique for asbestos analysis due to the high image resolution, electron diffraction, and chemical identification capabilities [1,82,102]. However, as is the case with PCM, the focus of current TEM methods is to analyze known fibers in controlled environments, not unknown fibers in uncontrolled environments. Evaluation of ambient air samples for asbestos were first performed in the 1970s using electron microscopy and the first recognized EPA TEM procedure for air samples was written by Samudra et al. in 1977 [102]. The EPA developed a revised method, known as the Yamate Method [81], and though never officially published by the EPA, it "became the de facto standard analytical TEM procedure for airborne measurements in the United States" [39].

The first and fully promulgated air protocol produced by the EPA was a TEM method for testing the cleanliness of air in schools following abatement of asbestos-containing building materials. Under the AHERA authority, the EPA developed a rapid TEM method for use in clearance testing at abatement sites [92]. The method specified sample collection procedures and required a direct transfer preparation method. To reduce the analysis time, the method did not require recording of fiber dimensions, but did require listing the fibers as either greater than 5 μm or less than 5 μm in length. One important change over the Draft Yamate Method was the increase in minimum aspect ratio from 3:1 to 5:1. Many experts on the AHERA committee had argued for 10:1 or 20:1 as the minimum aspect ratio value, but the decision was deemed too great a change from historical data to be acceptable. In addition, a minimum length for asbestos fibers (0.5 μm) was specified for the first time to improve the reproducibility of fiber counts. Independently, recognizing that not all

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[1] The method is being revised to change "or" to "and".

airborne fibers are asbestos and that OSHA regulated asbestos fibers, NIOSH issued a TEM asbestos method in 1989, NIOSH 7402 [82], which was designed for use in conjunction with PCM (NIOSH 7400 [89]) to allow the determination of the asbestos proportion of countable PCM fibers. NIOSH 7402 specifies a magnification comparable to the magnification used in the optical microscope, counting fibers longer than 5 μm, wider than 0.25 μm, and which have an aspect ratio of at least 3:1. OSHA permits the use of the NIOSH 7402 method when analyzing air samples for OSHA compliance purposes (when performed in conjunction with PCM). An international analytical method, ISO 10312, was also developed for commercial mineral species [76].

The TEM methods described above are best suited for counting short fibers. There are several factors that contribute to the poor statistics on long, thin fibers that will be achieved when analyzing an asbestos population of fibers in the TEM. In an ambient airborne asbestos fiber population, the fiber length distribution can vary widely depending on the source, but typically from 1 to 10% of the fibers are longer than 5 μm in length and only 0.1–1% of the fibers are longer than 10 μm [103]. As a result, the measurement of all particles, as current TEM methods require, creates an intrinsically higher uncertainty for the concentration of long thin fibers than for the fibers less than 5 μm in length. In addition, as the magnification is decreased in the TEM, the visibility of thin fibers is reduced due to illumination issues [104]. This increases the probability of missing long, thin fibers at low magnifications in the TEM. There is also an increased likelihood that fibers 10 μm or longer in length will intersect a grid bar, making it difficult to accurately determine the total length [82,105]. This adds additional uncertainty to the proportion of fibers longer than 10 μm that may be missed during a routine analysis. Finally, in order to measure the length and width of long thin fibers with the same precision, multiple magnifications are needed. Low magnifications are required to measure fiber length and high magnifications are required to measure fiber width as well as characterize surface texture and the nature of the fiber ends [106]. This is accomplished much more readily in the modern digital SEM than TEM [107]. This inaccuracy in the concentration of long, thin fibers can lead to increased uncertainty in the risk estimates. To avoid the issues discussed above, the SEM can be used to search for fibers longer than 10 μm in length. The digital beam control in the SEM allows for easy multiple magnification imaging and the grid bars do not present interference during an analysis. The TEM can still be used to search for fibers less than 10 μm in length.

The usefulness of the TEM is also limited in mixed mineral environments due to the nature of the TEM image. A TEM image is a projection of the specimen created from the electrons that pass through the specimen [108]. The shape of the particle, as seen by TEM analysis, is the projection of the overall particle shape; however, the true particle shape may be very different from what is observed in the TEM image. In a typical TEM analysis, the identification of a fiber is often based on the general shape of the particle, including aspect ratio and substantially parallel sides. True particle shape and dimensions of mixed mineral dusts may become extremely important in fully characterizing the particles and may not be fully identified from a TEM image alone.

The SEM technique also has the potential of becoming a screening technique for the identification of long, thin fibers. The SEM has evolved over the past 35 years into a reliable and effective method for asbestos fiber identification [104,109]. Past concerns over the visibility of fibers in the SEM image have been alleviated by the advent of digital microscopy [104,107]. The development of the high-resolution field emission SEM (FESEM) makes the SEM an even more attractive technique for complex asbestos characterization. Measurements of both the length and width of long, thin fibers is easily accomplished by quickly changing between high and low magnifications. In addition, the SEM can produce high-resolution three-dimensional-like images on the nanometer to micrometer scale, as well as semi-quantitative chemical information [107]. A method similar to the ASTM optical procedure could be extended to the SEM as a supplemental analysis. Particles longer than 10 μm and less than 1 μm in diameter could be separated into those less than 0.4 μm in width and those wider than 0.4 μm. The three-dimensional-like SEM images can also be used to determine if the particle is asbestiform or non-asbestiform in many instances. The ratio of fine/coarse fibers and estimate of the asbestiform fraction would provide a reliable estimate of the asbestos content of samples from mixed mineral environments.

The SEM has previously been used in a variety of studies for morphological characterization of asbestos fibers [110–114], although few standard SEM analytical methods exist [115–119]. Lee et al. and Harris et al. described enhancing a standard airborne asbestos TEM method for the analysis of mixed mineral dusts by additional FESEM imaging of each particle found that had an aspect ratio of 3:1 or greater [120–122]. The developed protocol required the morphological, crystallographic, and chemical characterization of each particle including the collection of secondary electron FESEM images of the full structure, both structure ends, and the particle surface. Stereo pair images were also formed to provide depth perception information not obtainable from a single secondary electron image. The research showed that the FESEM relocation process and analysis are essential complementary elements to TEM for accurate particle-by-particle examination of mixed mineral dusts [120–122]. In addition to being more suitable for the analysis of long, thin fibers, the SEM is more cost-effective than TEM from an instrumental standpoint and can provide faster sample analysis. While there are no standard SEM protocols for NOA environments, the USGS did note in a recent report that “the emerging practice of fully characterizing all particles of potential concern, both chemically and morphologically, will aid in developing appropriate analytical procedures” [15]. SEM (FESEM in particular) is a capable method for developing such improved particle-by-particle analysis procedures.

The recent NIOSH White Paper proposal noted that the cost of using TEM and/or SEM for routine asbestos sample analysis would be considerably higher than PCM analysis and the turnaround time for sample analysis would be increased substantially [14]. While this argument has some merit, it should not prevent the development and regulatory adoption of such advanced electron microscopy methods. When dealing with matters of public policy and protecting the public health, it is vital that the best scientific methods be used to provide accurate measurements for risk assessments. This will require an extensive mineralogical characterization for evaluating the risks of NOA in a given area. In addition, the NIOSH proposal stated that any routine use of electron microscopy methods for counting and sizing fibers would require an analysis of inter-laboratory and inter-operator variability. Assessment of inter-laboratory and inter-operator variability should not pose a major problem to implementing improved electron microscopy methods since various laboratory accreditation organizations and round-robin testing protocols already exist to evaluate laboratory and analyst competence for the PCM and TEM existing methods. It will be important to develop techniques with improved resolution to visualize the smaller diameter fibers, which pose the highest risk, to assure the most complete and accurate fiber counts. The major challenge to scientists is to develop streamlined cost-effective screening techniques with the ability to accurately determine the fibers of highest risk with acceptable uncertainty and operator variability. This formidable task could possibly be accomplished with techniques that allow higher uncertainty in the measurement of lower to medium risk particles. As new methods are developed, it is important to point out that reported risk estimates for occupational asbestos exposure were generally determined by PCM methods. Hence, fiber counts obtained with improved microscope resolution capabilities would not be directly comparable to current occupational exposure limits for asbestos without developing meaningful conversion factors to relate the new results with the original risk data generated using the older PCM method.

5.2. Analysis of bulk samples of mixed mineral dust

While PCM, TEM, and SEM are strong potential analytical techniques for screening and analyzing air samples in mixed mineral environments, PLM can be a powerful tool for microscopic mineral identification and screening of bulk samples in mixed mineral environments. The early PLM analyses of large samples to determine the mineralogy of rock and ore samples dates back to the mid 1800s [123]. These evaluations utilized the polarized light microscope to examine thin sections of a rock or mounts of individual grains of minerals. Using the observed refractive indices of the minerals, unambiguous identifications of the mineral particles was possible. Responding to increasing demands to analyze building materials for asbestos content, the EPA published its first bulk analytical PLM protocol in 1982 [124]. Until then, microscopists used PLM techniques as they were generally taught in college courses. The 1982 EPA protocol, issued to be the standard procedure by which the asbestos content of bulk building materials was to be determined, was slightly modified in 1988 to allow for alternate quantification procedures [125]. In a 1992 letter from Michael Beard to Sally Sasnett, EPA officials acknowledged the issues related to the interpretation of the 1982 EPA PLM protocol, recognizing the difficulty in the identification of cleavage fragments and asbestos fibers of the same mineral, as well as the definition of asbestos, "asbestos fibers", and appropriate aspect ratios of asbestos fibers [126]. The Beard letter recommended the use of large aspect ratios (20:1–100:1) as a screening or identification tool for asbestos amphibole minerals.

Additional PLM analytical procedures have been issued by the EPA [84] and OSHA [83], with only the OSHA procedure being promulgated. The EPA has recommended the use of its more recent method but has not mandated such use. Other U.S. agencies and organizations, including NIOSH [127], ASTM [85], The New York Environmental Laboratory Approval Program [128], and CARB [129] have also written or published PLM analytical procedures.

As discussed above, PLM is routinely used to verify the presence of asbestos in bulk commercial products. Unlike bulk manufactured products, mixed mineral samples are not homogeneous because they have not been processed or refined for commercial purposes. Any serpentine or amphibole asbestiform minerals will be combined with other minerals common to ultramafic metamorphic rock formations, including non-asbestos particles of the same species. Therefore, the mineral quantification of homogenized bulk samples, as required by accepted PLM techniques, needs to be coupled with a macroscopic inspection of the original sample. A macroscopic inspection is necessary to identify specific locations for further PLM analysis.

The PLM technique can potentially identify both the mineral species and the crystal habit of asbestos containing materials. Specifically, the extinction angle can be used to differentiate asbestiform amphiboles from non-asbestiform amphibole minerals that are often found in mixed mineral environments. Under cross-polarized light, an anisotropic mineral (one having different physical properties in different directions) will change color as the stage is rotated. The grain will turn black at four positions during a full rotation and is said to have reached extinction [130]. When a mineral goes extinct in a straight up-down or sideways orientation, the mineral is said to have parallel extinction. When parallel extinction occurs, the extinction angle is measured to be nearly zero degrees.

Orthorhombic amphibole particles, such as anthophyllite, will always exhibit parallel extinction regardless of the crystal habit of the particle. However, in monoclinic amphiboles, the extinction angle can be used to distinguish asbestiform from non-asbestiform particles. Non-asbestiform monoclinic amphiboles typically show non-parallel or oblique extinction greater than 10°. However, the asbestiform monoclinic amphibole particles do exhibit parallel extinction [131,132]. Due to the resolution limits of the microscopes, individual asbestiform fibrils are not visible in some orientations in the optical microscope. However, bundles of individual fibrils that are tightly packed and randomly oriented around one axis are readily visible [131]. This uniaxial-like property produces parallel extinction in monoclinic asbestiform amphiboles and makes them distinguishable from non-asbestiform particles [132].

6. The impact of NOA on the United States

Public, business, and government concerns involving NOA are currently widespread throughout the United States. NOA contamination in various geographic locations has generated great fear and worry and has prompted, in some instances, very costly and controversial remedial actions. The following examples illustrate the types of problems that can occur as a result of the various issues involving NOA discussed above and the fact that the United States has no clear national public policy for dealing with NOA in a straightforward manner. A few cases discussed below also offer examples for improvements and potential solutions for solving issues associated with NOA.

6.1. Libby, MT

Libby is a small town in northwest Montana within the Rainy Creek Complex—an igneous alkaline-ultramafic body. Libby was at one time the site of the world's largest vermiculite mine accounting for almost 80% of the world's vermiculite production [3]. The unprocessed vermiculite ore reportedly contained an estimated 0–5% amphibole, both asbestiform and non-asbestiform varieties [2,3,114,133–135]. Epidemiological studies conducted in the 1980s found a high incidence of asbestos-related disease among the mine workers. National attention turned to the small town in late 1999 when the media reported a high incidence of asbestos disease among Libby residents [2].

Within days of the first media reports, the EPA began an investigation and remediation effort. The area is now designated as a Superfund site. The Superfund action at Libby ranks among the largest and most costly in the history of the EPA [2]. A 2003 study in the Libby area conducted by the USGS stated that "the ultimate resolution . . .will be years in coming, and the final costs. . . may be enormous" [114]. Confirming this prediction, a report issued by the EPA Office of Inspector General in December 2006 stated that the EPA still cannot verify the effectiveness of its efforts to clean up amphibole asbestos contamination in Libby after 7 years of work on more than 700 homes and more than $100 million spent [136].

The mineralogy in the Libby area is complex. Nearly all of the amphiboles found in Libby are not regulated minerals, and at a minimum, the vast majority of the amphiboles in the soil and air are not asbestiform [114,134,135]. A recent study conducted by the USGS in Libby noted that the amphibole minerals in Libby continue to present formidable challenges to the analyst, to anyone attempting to classify these materials using existing regulatory definitions, and particularly to those attempting to extrapolate those morphological features and chemical compositions to potential health risks [114]. Regardless of whether they are asbestiform, average ambient concentrations of airborne amphibole particles longer than 10 μm and thinner than 0.4 μm range from 0.0002 structures per milliliter (s/cc) to below detectable limits in the community [137]. Estimates of asbestiform concentrations range from 1 to 10% of the ambient concentrations [138]. Thus amphibole concentrations are similar to background concentrations for total asbestos (primarily chrysotile) in urban environments.

The potential asbestos exposure pathways in Libby include individuals with occupational exposure, family members exposed through worker take-home contamination, community members exposed through ambient environmental levels, and residents exposed through the use of vermiculite as insulation or as a soil additive. Because of the multiple potential exposure scenarios, causes of disease among the non-mining population are confounded and in dispute [139–141]. Much of the debate stems from the lack of a coherent national policy and scientific consensus on the definition of asbestos, methods of identifying and classifying asbestos fibers and rock fragments, and the appropriateness of using risk models based on exposures to commercial asbestos fibers in a situation where only a portion of the counted fibers have the characteristics of asbestos.

6.2. El Dorado County, CA

El Dorado County, California is located within the Great Valley ophiolite belt, which includes numerous outcrops of serpentinite and other ultramafic rock as a result of tectonic activity [2]. The region formerly contained numerous chrysotile asbestos mines. El Dorado County attracted many new residents in recent years, so many that the population has increased nearly six-fold since 1960 [142]. During excavation for housing sites in El Dorado County in 1998, reported occurrences of tremolite asbestos were found at some of the sites, alarming the homeowners over health concerns and potential lowered home values. The local media produced a series of articles that suggested that the county residents' exposure to asbestos was endangering their health and the county has been in turmoil over the issue of NOA ever since. The media stories have focused on asbestos found in homes near mining and construction activities, animals from the region that had high levels of asbestos in their lungs, and testing at three schools and a community center: Rolling Hills Middle School, Silva Valley Elementary School, Oak Ridge High School, and El Dorado Hills Community Center [142].

In 2003, the EPA conducted a series of tests at schools and other public areas in the community of El Dorado Hills to assess potential asbestos exposure [143,144]. The testing included simulated activities that can create dust including: baseball, basketball, and soccer games at schools, running and biking on nature trails, playground activities, and gardening. The study reported asbestos fibers in almost all of the air samples collected during these tests and indicated that personal exposure levels were significantly higher during most sports and play activities compared to nearby levels taken outside the areas of activity. The results of the study led to extensive mitigation efforts in the county. The EPA study was later challenged, however, by another scientific report that claimed, after a careful and thorough particle-by-particle review of the EPA data and additional analysis of split samples, that the materials identified as asbestos by the EPA and its contract laboratories were not asbestos, based on chemistry and morphology, but were amphibole cleavage fragments and therefore should not be considered a major health risk [145]. The conclusions made in the critical review were supported by a number of mineralogical and asbestos experts [146–148]. A lengthy debate has ensued, highlighting the lack of consensus on the definition of asbestos, the relative risk posed by cleavage fragments, and the methods for distinguishing them.

The most recent study in the El Dorado area was conducted in 2006 by the USGS on behalf of the EPA [15]. Similar to the Libby case, the study found that the types of amphiboles in the El Dorado Hills area are not easily characterized using standard commercial asbestos test methods. In fact, the USGS report stated that if the EPA study had been conducted as an enforcement action, it would be inappropriate to classify the amphibole particles in El Dorado Hills as an actionable material because: (1) the majority of the particles were prismatic, not fibrous; and (2) approximately 40% of the particles were magnesiohornblende, a non-regulated mineral. The USGS study noted that the emerging practice of fully characterizing all particles of potential concern, both chemically and morphologically, will aid in developing appropriate analytical procedures, interpretation of epidemiological data, and development of regulatory policies to deal with situations such as the one in El Dorado Hills. The USGS report also concluded with a recommendation that the health, mineralogical, and regulatory communities consider a thorough evaluation of the existing asbestos definitions and analytical methods for application to NOA problems.

As a result of the EPA testing at Oak Ridge High School, mitigation efforts were completed by the school district that had a cost of over $1.7 million [149]. The cost related to mitigation efforts has been in excess of $1.8 million for a new elementary school built in El Dorado Hills [149]. Data from the adjoining community of Folsom, California indicates that their cost will be in excess of $5 million to mitigate alleged NOA concerns during the construction of a new high school [149]. The necessity for these costly remediation actions is still very much in debate as a result of unanswered questions over testing methods and risk assessments. The manner in which NOA has been addressed in El Dorado Hills has had a tremendous impact on the local government and the schools, but the potential impact extends to the entire State of California and the nation as similar conditions and events arise elsewhere.

6.3. New Idria, CA

The New Idria serpentinite is a mountainous 44 square mile (114 km^2) area located near Coalinga, California that consists of a large amount of highly sheared and pulverized rock fragments and powders, as well as boulders of partially altered serpentine-rich rock [2,150]. New Idria is one of the largest NOA deposits in the world. Asbestos-bearing dust and debris has been entering the air and the stream valleys in this area for millions of years and the bulk material contains up to 60% chrysotile [2]. The vast majority of the asbestos found in this region has been described as "short-fiber" chrysotile and is reported to be amphibole-free because of the absence of igneous intrusions within the serpentinite body [2]. The New Idria serpentinite area is the site of three chrysotile mines, two of which (Atlas and Johns-Manville) ceased operations many years ago. The third mine, operated by King City Asbestos Corporation, was the last active asbestos mine in the United States and was closed in 2002. In the mid-1990s, the EPA designated the two closed mines as Superfund sites because of concerns about the health hazards of water- and air-borne chrysotile asbestos emissions from the mines [151–153]. Because of these concerns, valuable agricultural land was condemned, restrictions on the use of public lands were proposed, large sums of money were requested for asbestos mitigation, and local residents were fearful for their safety. In this case, the EPA chose to focus on only a small fraction of the total asbestos releasing area as the two Superfund sites cover only a few percent of the total 28,000 acres that encompass the New Idria serpentinite [2,150].

The actual health risks to humans from NOA in the New Idria serpentinite have been questioned. Numerous studies indicate there is no evidence that ingestion of chrysotile asbestos (in water or food) causes harm in humans or animals, or that inhalation of short chrysotile asbestos fibers in the quantities found in the New Idria area cause disease [2,150,154]. Ross claimed that the New Idria Superfund sites, even by expenditure of huge sums of money, will have no measurable effect on human health, particularly in view of the fact that most of the asbestos emissions come from surrounding areas outside the Superfund sites, through naturally occurring processes [2,150]. Essentially confirming this claim, the EPA recently reported that the Atlas mine site has been cleaned up and no longer pose a risk to human health, but the health risks posed by NOA outside the mine site boundary still need to be assessed before the site can be removed from the National Priorities List [155]. Ross contends that the actual health risks in the New Idria serpentinite, if any, would have been better addressed by a scientifically based policy that addressed the entire outcrop area [2].

6.4. Clear Creek management area, CA

The Clear Creek Management Area (CCMA), located in San Benito and Fresno Counties, California is a popular 50,000 acre recreational area managed by the Bureau of Land Management (BLM). It provides 400–600 miles of unpaved vehicle routes and almost 3000 acres of barren hill climbs for off-highway vehicle (OHV) users, as well as other recreational opportunities such as hiking, camping, hunting, and rock collecting.

The CCMA is located on and around the New Idria ore body discussed above and is part of the Atlas Asbestos Mine Superfund site. The CCMA also borders the Johns-Manville Mine Superfund site. Most of the CCMA is designated as an asbestos hazard area and warning signs are posted at entry points and on bulletin boards. The EPA and BLM have long been concerned about potential health hazards associated with the generation and inhalation of airborne asbestos fibers by users of the CCMA, particularly those operating OHV on unpaved roads. Because of concerns over public health hazards, EPA and BLM conducted several risk assessment studies beginning in 2004 to update a study conducted by BLM in 1992 and to estimate asbestos exposure at the CCMA as a basis for determining appropriate managing strategies and mitigation measures that will minimize human health risk to users and maintenance workers [155–157].

Air samples were collected during both dry and wet seasons by individuals wearing personal monitors, while engaged in typical recreational activities including motorcycle riding, all terrain vehicle riding, sport utility vehicle (SUV) driving, hiking, camping, and washing and vacuuming dusty vehicles. The exposure of child users was also evaluated by positioning monitors to mimic a child's breathing zone. Results of the sampling indicated that the concentrations of chrysotile asbestos fibers to which CCMA recreational users are exposed is very high when compared with occupational health standards, particularly for trailing motorcyclists and SUV drivers, since these people would be exposed to greater amounts of dust compared to lead drivers. The EPA reported that the highest asbestos exposure levels measured in the CCMA studies were about 10 times higher than the highest values measured in El Dorado in 2004; however, the important differences in the types, sizes, and relative health risks of asbestos present in the CCMA and El Dorado studies were not mentioned in that report [157]. The asbestos type in the CCMA is chrysotile, whereas, the asbestos reported in El Dorado was amphibole. As mentioned above, the health risks of the chrysotile in the CCMA/New Idria areas have been questioned; therefore comparing “asbestos levels” in the CCMA to those in El Dorado may not be appropriate [2,150,154]. However, it should be acknowledged that the current EPA paradigm for assessing asbestos-related risks considers all types of asbestos as having similar potencies [61,158]. Results from the CCMA studies are currently being analyzed by the EPA, which has promised the issuance of technical memos and a final summary report sometime after the final sampling event, which had a scheduled date in mid-2006.

6.5. *Fairfax County, VA*

During the late 1980s building boom, large deposits of asbestos-containing rock were discovered at a construction project for an underground parking garage in Fairfax County, Virginia [2,44,45]. As a result of the rock being drilled and crushed, dust covered the entire construction project and several air drill operators experienced itching and skin irritation. Medical and geological investigations determined that the irritation was caused by tremolite fibers in the dust. Geological studies also found large veins of tremolite and actinolite asbestos in Fairfax County and other nearby areas. Construction and development in these NOA deposits presented considerable problems regarding public and employee safety.

The Air Pollution Control Division (APCD) of the Fairfax County Health Department immediately launched an extensive investigation to determine the extent of the NOA and the potential for airborne exposure to construction workers and the public. Air monitoring data confirmed that construction activities posed a significant potential health hazard to workers and the public. Media reports to the public made factual statements about the NOA in Fairfax County, but did not promote undue alarm, which allowed County officials to properly address the problem. As a result, the Fairfax County Health Department initiated appropriate dust control procedures and published a dust control advisory [44]. The advisory requires contractors to use: (1) proper dust control practices at all times; (2) personal and ambient air monitoring of the construction site during all phases of earthwork involving NOA; (3) safe waste rock disposal practices with all final disposal sites being covered with 6 in. of clean, compacted, NOA-free soil; and (4) requires that sufficient notice of possible asbestos contamination be given to all employees and contractors in compliance with existing OSHA asbestos standards and they must be given asbestos awareness training. If air monitoring determines a violation of permissible airborne asbestos limits has occurred, a report must be filed with the APCD outlining the suspected cause of the violation and the actions that will be taken to prevent future violations. As discussed above, CARB has also developed a similar detailed regulatory document on asbestos control procedures for construction, grading, quarrying, and surface mining activities in the State of California [74].

Due to this well-reasoned regulatory initiative in Fairfax County, home and commercial construction continued on some of the most valuable land in the eastern United States, while at the same time protecting workers and the public from an avoidable risk of asbestos-related disease. Fairfax County did not ban construction in the asbestos vein because it was demonstrated that common sense controls can work when dealing with NOA. Economics in the Washington, DC metropolitan area made it possible to develop this land even with the added expense of NOA controls. It was estimated that the expense of reasonable controls can add 10–20% to construction costs [44].

6.6. *Sparta, NJ and similar mining communities*

The Southdown marble quarry located a few miles from Sparta, New Jersey became locked in a legal battle with the community in 2000 over whether the mine was releasing asbestos in the air [159]. The quarry had been in operation for almost 100 years and the workings were associated with very low levels of tremolite cleavage fragments. The issues ranged from differing scientific reports concerning the possible presence of tremolite fibers, debate about conflicting state and federal standards for the definition and measurement of asbestos, debate among doctors as to what size fibers are hazardous, and differing attitudes among the town’s newcomers and long time residents, many of whom had worked at the quarry [159,160]. The quarry was eventually fined $246,350 for violations of state and federal air pollution laws and regulations and was required to implement a dust management plan, which included installation of asbestos monitoring devices, with an estimated cost of $700,000 [99,159]. The EPA and the New Jersey Department of Environmental Protection, using a panel of recognized experts in asbestos measurement and risk assessment, developed a work plan for measuring asbestos contamination from the quarry using TEM [50]. The peer-reviewed plan recognized a method for sorting asbestos and cleavage fragments into different categories and this allowed separate risk estimates to be refined [161]. According to Ilgren, no reliable scientific evidence was ever reported to indicate an attributable risk of asbestos-related disease in either the workforce or the residents of the town of Sparta [24].

Ilgren reviewed studies involving a variety of mining communities, including taconite, talc, gold, dolomite limestone, vermiculite, and copper mines, where workers and nearby residents may have been exposed to trace levels of amphibole cleavage fragments that were present as impurities within the main mining product of interest [24]. These studies included taconite mining towns in Minnesota where the taconite (a low grade iron ore) typically had elevated levels of grunerite cleavage fragments and various talc mines in New York, Vermont, Italy, and Norway where the talc contained substantial levels of tremolite cleavage fragments. The taconite and various talc mining studies concluded that the permeation of the residential areas near the mines by non-fibrous amphibole cleavage fragments did not result in a pandemic of asbestos-related disease among workers or residents. These studies also demonstrated that not all occurrences of amphibole minerals are necessarily a public health hazard.

7. Benefits of a national NOA public policy

NOA has existed in the environment for millions of years. However, asbestos, whether it exists naturally in the ground or in manufactured products, is still asbestos and poses a serious potential health hazard if released into the air. The nation should develop a rational NOA public policy that is based on scientific, engineering, and medical principles to ensure that the public health is properly protected. The ultimate consequence of not correcting the current issues and controversies discussed above surrounding proper NOA identification and exposure risk will be inaccurate environmental asbestos concentrations and scientifically inaccurate risk assessments, which will mistakenly alarm the public and adversely impact local government bodies and economies. Conversely, underestimation of asbestos levels and/or risk can result in failures to protect the public health. Good regulatory policies must weigh the health risks of action and inaction as well as the financial costs. Over-regulation and flawed public policies based on incorrect science can be extremely costly, address minimal health risk, and divert attention from more socially important endeavors. Public funds misdirected towards unnecessary mitigation efforts will have a negative impact on local government's ability to provide quality educational facilities and other important social programs and services.

Common sense regulations such as those employed by the county government of Fairfax, Virginia, can serve as a model for using science as a basis for risk management decisions to control mineral dust exposures to the public, while still allowing commercial land development and mining activities. In the past, public panic has been fueled by unsupported concepts, such as the "one fiber theory," which maintains that one fiber of inhaled asbestos will cause cancer. An adult male, breathing at a resting rate, will breathe in one million fibers/year using the background asbestos concentration reported in the NAS 1984 report on non-occupational exposure to asbestos [38]. Or, as an extreme, under the currently accepted IRIS risk model, if a person breathes a single asbestos fiber over his lifetime, there is a calculatable risk for that exposure. However, the scientific and medical information available does not justify the claim that exposure to any amount of any asbestos fiber presents an unacceptable health risk [162]. If such a claim were true, all rocks and soil containing any concentration of any type of fibrous mineral would be regulated, and thus prevent mining or other commercial development of vast areas of valuable land. It obviously is not necessary or cost-effective to mitigate every stretch of land that contains some trace level of NOA. NOA public policy should recognize and assess the risks of using our land and its natural resources and implement control measures without putting unfounded fear into the population. Legal reform and education of the media and general public are needed to bring a scientific basis to public policies regarding exposure to NOA.

The development of an effective NOA policy that protects the public health, but also allows for the proper use of scarce land and optimum utilization of other marginal public resources, is essential for the United States to maintain a sustainable economy in the face of a growing population. Achieving this formidable goal will require greater cooperation between the scientific, health, and regulatory communities. There is an urgent need for the Federal government and the EPA to commission a comprehensive, independent, national review of the science addressing the definitions and measurement of NOA so the nation can develop an accurate standardized risk assessment method to ensure that the public health is protected and unwarranted economic chaos is avoided. A national peer-reviewed study would be the most effective way to: (1) establish a consensus among the medical community as to the health effects of asbestos and non-asbestiform minerals, particularly in mixed mineral dust environments; and (2) develop reliable analytical testing methods for NOA that are reproducible, follow sound scientific and laboratory practices, and result in remediation actions that are only conducted when they are truly necessary. Successful models for such a national NOA review can be taken from the work of the previous EPA supported asbestos-related working groups from the Health Effects Institute, which has a 25 year history of working with EPA on a variety of issues effecting public health, and the National Academy of Sciences. Failure to commission a scientific analysis of NOA will compromise the public health and negatively impact government and commercial interests in large areas of the United States for many years to come.

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