American Journal of Industrial Medicine 27:641–660 (1995)

Occupational Exposures to Fibers and Quartz at 19 Crushed Stone Mining and Milling Operations

Gregory J. Kullman, MS, Alice L. Greife, PhD, Joseph Costello, MS, and Frank J. Hearl, SMChE, PE

From 1979 to 1982, the National Institute for Occupational Safety and Health (NIOSH) conducted a cross-sectional exposure assessment and mortality study of selected crushed stone facilities in the United States. This study was undertaken in part to address concerns that asbestos exposures could be occurring in some crushed stone operations due to the presence of amphibole and serpentine minerals. The investigation was also designed to characterize exposures to crystalline silica and other mineral compounds. Nineteen crushed stone operations, mining limestone, granite, or traprock were surveyed to assess exposures to respirable and total dusts, mineral compounds including crystalline silica, asbestos, and mineral fibers. At the initiation of the study, crushed stone operations were selected from a Mine Safety and Health Administration (MSHA) listing of the active industry in 1978. With the exception of requiring inclusion of the traprock operation in Maryland where asbestos fibers were initially discovered, a stratified sample of operations was randomly selected by rock type (granite, limestone, traprock, or sandstone). However, because of reluctance or refusal of some companies to participate and because of the closures of some of the selected operations, replacements were randomly selected. Some replacement selections were likewise replaced due to lack of cooperation from the companies. The studied sample included only 10 of the 27 randomly selected operations in the original sample. Asbestos fibers were detected at one traprock facility, the Maryland operation where asbestos was originally found. Measured personal exposures to fibers exceeded the NIOSH Recommended Exposure Limit (REL) for two out of 10 samples. All of the samples were below the MSHA Permissible Exposure Limit (PEL), which was in effect at the time of the survey. However, due to the presence of nonasbestos mineral fibers in the environment, it could not be stated with certainty that all of the fibers counted by phase contrast microscopy were asbestos. A variety of silicate mineral fibers (other than those classified by NIOSH as asbestos) were detected in the traprock operations and at one granite operation. Crystalline silica was detected at 17 of the 19 surveyed crushed stone operations. Overexposures to crystalline silica were measured at 16 of the crushed stone operations; approximately one in seven personal-respirable dust samples (14%) exceeded the MSHA PEL for crystalline silica. Approximately 25% of the respirable dust samples exceeded the NIOSH REL for crystalline silica. Mill operators and mill laborers consistently had the highest and most frequent overexposures to crystalline silica.

Environmental Investigations Branch, Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Morgantown, WV.
Address reprint requests to Gregory J. Kullman, Environmental Investigations Branch, Division of Respiratory Disease Studies, NIOSH, Centers for Disease Control and Prevention, 1095 Willowdale Rd., Morgantown, WV 26505-2845.
Accepted for publication September 2, 1994.

Key words: crystalline silica, quartz, crushed stone mining, fibers, asbestos, occupational exposure

INTRODUCTION

During the mining and milling of stone deposits, crushed stone miners are exposed to airborne dusts containing a variety of minerals. Some of the mineral dusts generated during crushed stone production can cause respiratory disease in exposed workers [Stern et al., 1947; Key and Ayer, 1972; NIOSH, 1975, 1980; U.S. EPA, 1979]. During the mid-1970s, asbestos fibers were discovered in a crushed stone quarry in Maryland [Carter, 1977]. This discovery, along with the potential for crystalline silica overexposures, focused attention on the potential occupational health problems in the crushed stone industry. From 1979 to 1982, the National Institute for Occupational Safety and Health (NIOSH) conducted a cross-sectional industrial hygiene study of selected crushed stone quarries in the United States. This study was undertaken to address concerns that asbestos fiber exposures could be occurring in some crushed stone operations due to the presence of amphibole and serpentine minerals. This investigation was also done to characterize exposures to crystalline silica and other mineral compounds. A mortality study of crushed stone workers at these plants was also conducted and was reported separately [Costello et al., 1992; Costello et al. 1995].

Airborne asbestos fibers are defined as those particles having (1) an aspect ratio of 3 to 1 or greater, and (2) the mineralogic characteristics (i.e., the crystal structure and elemental composition) of the asbestos minerals and their nonasbestiform analogs. Asbestos minerals are defined as chrysotile, crocidolite, amosite (cummingtonite-grunerite), anthophyllite, tremolite, and actinolite. In addition, airborne cleavage fragments from the nonasbestiform habits of the serpentine minerals antigorite and lizardite, and the amphibole minerals contained in the series cummingtonite-grunerite, tremolite-ferroactinolite, and glaucophane-riebeckite are also counted as fibers provided that they meet the criteria for a fiber when viewed microscopically [NIOSH, 1990].

Crushed stone is size-reduced rock used primarily for building and construction purposes [U.S. Dept. of the Interior, 1980]. Mechanized crushed stone production has taken place since the early 1900's in the United States, which is one of the world's largest producers of crushed stone. The crushed stone industry is widespread; at the time this study originated (1979), crushed stone was produced in all but two U.S. states, Delaware and North Dakota. The United States produces several different types of crushed stone. The breakdown of production by type of stone (1978) includes: limestone 74%, granite 11%, traprock 9%, sandstone 3%, marble 2%, and shell 1% (U.S. Dept. of Interior, 1980). (The coarser grained igneous rocks are usually called "granite"; the term "traprock" is used to describe all dense, dark, fine-grained igneous rocks.)

Crushed stone production is a physical/mechanical process. The stone is produced by mining stone deposits and processing the stone to desired size specifications through crushing and sizing activities in the mill (Figure 1) [Lefond, 1975]. Most crushed stone is mined from open pit quarries by workers using bench mining methods. The first step in the mining process is the removal (stripping) of the overburden

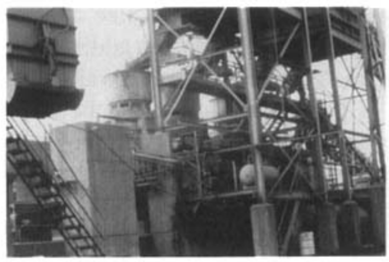
A

B

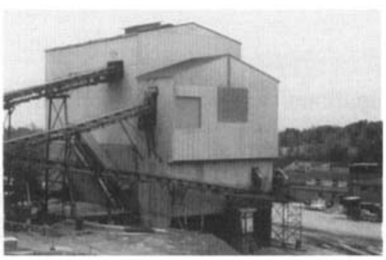
C

D

E



F



G

H

I

Fig. 1. Crushed Stone Production: **A)** Open pit crushed stone mine. **B)** Removal of overburden in the mine. **C)** Drilling operations in the mine. **D)** Secondary breakage with drop ball hammer in mine. **E)** Loading operations in the mine. **F)** Secondary stone crushers in the mill. **G)** Mill screening house. **H)** Conveyor transport of crushed stone in the mill. **I)** Loading crushed stone product at mill stockpiles.

materials (vegetation, soil, clay, etc.) that cover the stone. This is generally done by miners operating a variety of earth-moving equipment, including trucks, shovels, front-end loaders, scrapers, draglines, and hoe-type stripping equipment. After the overburden has been removed, drilling and blasting are done to fragment the stone into workable dimensions. Following blasting, secondary breakage is often done in the mine by workers operating drop-ball or drop-hammer cranes. Next, the stone is loaded and transported to crushing sites. Loading equipment can include dragline excavators, shovels, and front-end loaders. Dump trucks or other tire-mounted, earth-moving equipment are commonly used to transport quarried stone from the mine to crushing operations. Diesel-powered equipment is widely used for loading and hauling activities in the mine [Lefond, 1975; U.S. Dept. of Interior, 1980].

After mining, the stone is reduced to the desired size specifications by crushing and screening processes in the mill. The crushing and screening activities are frequently conducted in a series of stages using several different types of milling equipment. Primary crushing is done first to reduce the run-of-mine stone to a manageable, uniform size. Primary crushers generally reduce stone by compression or rapid impaction. Secondary and tertiary crushing is done next to further reduce the physical dimension of the crushed stone to desired specifications; cone crushers are typically used. Gradation specifications of crushed stone are controlled in the mill by screening and, in some cases, washing the stone. The screening process is used to separate the crushed stone into various size categories. Many types and arrangements of screen classifiers are available. In addition to crushing and screening, some crushed stone operations clean the stone in wash plants to remove dirt and clay materials. Crushed stone is generally transported between different crushing, screening, and washing operations in the mill by conveyor belts. The finished crushed stone product is transported to stockpile storage areas or to load out bins. This is usually done by conveyor belts or by trucks. At the bin and stockpile areas, crushed stone is loaded into trucks, railroad cars, or other vehicles for transportation to market [Lefond, 1975; U.S. Dept. of the Interior, 1980].

MATERIALS AND METHODS

Site Selection

This study was designed to assess occupational exposures generated during crushed stone handling and production. Industrial hygiene field surveys were conducted at 19 different crushed stone operations that processed three rock types: limestone, granite, and traprock. These facilities were selected to reflect general geographical (location east or west of the Mississippi River) and rock-type distributions of U.S. crushed stone operations. These facilities do not constitute a random, representative sample of the crushed stone industry. At the initiation of the study, crushed stone operations were selected from a Mine Safety and Health Administration (MSHA) listing of crushed stone mines active in 1978. With the exception of requiring inclusion of the traprock operation in Maryland where asbestos fibers were initially discovered, a stratified sample of operations was randomly selected by rock type (granite, limestone, traprock, or sandstone). However, because of reluctance or refusal of some companies to participate and because of the closures of some of the selected operations, replacements were randomly selected. Some replacement selections were likewise replaced due to lack of cooperation from the companies. The

TABLE I. Industrial Hygiene Survey Sites

Plant # (Study #)[a]	Rock type	Location	Size of work force[b]
L1 (1)	Limestone	Georgia	57
L2 (2)	Limestone	Georgia	31
L3 (3)	Limestone	Tennessee	38
L4 (5)	Limestone	Pennsylvania	17
L5 (6)	Limestone	West Virginia	85
L6 (9)	Limestone	Illinois	168
L7 (13)	Limestone	Michigan	26
L8 (14)	Limestone	Iowa	15
L9 (15)	Limestone	Iowa	15
G1 (4)	Granite	Georgia	32
G2 (7)	Granite	South Carolina	58
G3 (8)	Granite	North Carolina	50
G4 (10)	Granite	North Carolina	33
G5 (12)	Granite	Minnesota	38
T1 (11)	Traprock	Maryland	60
T2 (16)	Traprock	Connecticut	18
T3 (17)	Traprock	Connecticut	22
T4 (18)	Traprock	Pennsylvania	72
T5 (19)	Traprock	California	39

[a]Original operation number.
[b]Approximate number of workers at the time of the survey.

studied sample included only 10 of the 27 randomly selected operations in the original samples. Nine limestone operations, five granite operations, and five traprock operations were surveyed in 13 different states. These rock types were selected since they comprised > 90% of the crushed stone produced in the United States. Table I lists these crushed stone operations by state, rock type, and size of work force.

Sampling Strategy

At each crushed stone operation, 1–4 days were spent collecting industrial hygiene data from both mining and milling processes. Area and personal samples were collected. At the smaller crushed stone operations, personal samples were collected from every worker. At larger operations, a sample of workers was selected from the different job exposure zones. Airborne samples were taken for respirable and total dusts, crystalline silica, asbestos, and other mineral fibers. Bulk samples of settled dust were collected for qualitative mineral identification.

Job exposure zones were established to assure that personal exposures were sampled in a consistent manner at each facility. An exposure zone is a specified, consistent grouping of workers selected for their potential similarities in environmental exposures. The exposure zone concept is used to characterize the type of work with respect to the personal exposure of the workers [Corn and Esmen, 1979]. Generally, exposures in an exposure zone should be more similar and less variable than those for the entire work force. The crushed stone workers in this study were assigned to job exposure zones based on job category criteria including: (1) work similarity, (2) environmental similarity, (3) similarity in the potential for exposure to particular hazardous agents, and (4) identifiability. Twenty-seven different job ex-

TABLE II. Environmental Job Exposure Zones for Personal Sampling

1. Mill operator	15. Mine drilling
2. Mill laborer	16. Mine maintenance/construction
3. Mill foreman	17. Mine blasting
4. Mill maintenance/construction	18. Mine foreman
5. Mill truck driver	19. Mine stripping
6. Mill heavy equipment operator	20. All-laborer
7. Shop worker	21. All-maintenance/construction
8. Shop welder	22. All-water/fuel truck driver
9. Office worker	23. All-foreman
10. Scalehouse worker	24. All-lab worker
11. Mine truck driver	25. All-truck driver
12. Mine heavy equipment operator	26. All-heavy equipment operator
13. Mine shovel/dropball operator	27. Mill railroad worker
14. Mine laborer	

posure zones were established to evaluate personal exposures in the crushed stone industry. Table II lists these job exposure zones.

Asbestos and Mineral Fibers Sampling and Analysis

Airborne asbestos and mineral fiber samples were collected on a 37-mm cellulose ester filter with an 0.8-μm pore size. The filter, supported on a back-up pad, was contained in a three-piece, open-faced filter cassette. The asbestos and mineral fiber samples were collected using a portable sampling pump calibrated to 1.5 L/min. Mill locations were sampled using partial-period area sampling methods. The samples were collected over a 15–90-minute sampling period depending on the perceived dustiness of the work environment and observed dust loading on the filter. Although area and bulk samples were collected and analyzed from all of the studied facilities, personal exposure to asbestos was quantified only at the one crushed stone operation known to contain asbestos minerals in the bedrock (Plant T1). Approximately three to six consecutive, partial-period samples were collected from each worker to quantify fiber exposures.

The asbestos and mineral fiber samples were analyzed for fiber count and fiber identification by several different methods, including phase contrast light microscopy, polarizing light microscopy with dispersion staining, and transmission electron microscopy. The samples were analyzed for fiber count by phase contrast light microscopy according to NIOSH Method P & CAM 239 [NIOSH, 1977a]. Since completion of these field surveys, the NIOSH method for asbestos fiber analysis by transmission electron microscopy has been revised to NIOSH Method 7402-Asbestos Fibers, which is designed for use with Method 7400 (phase contrast light microscopy) to determine the asbestos fraction in the optically visible range in samples of mixed mineral fibers. The polarized light microscopy methods described in this report are also described in NIOSH Method 9002: Asbestos (bulk) [NIOSH, 1986].

With the NIOSH method P & CAM 239, a portion of each filter was removed and mounted in a clearing solution on a microscope slide. The fibers in a predetermined field were then counted at 400–450 magnification and phase contrast microscopy. All particles longer than 5 μm with a length-to-width ratio (aspect ratio) of 3 or greater were counted as fibers. Counting was continued until 100 fibers or 100 fields had been counted. This method provided an index of airborne fiber concentration only. It cannot be used to differentiate between fiber types, and it cannot detect fibers with diameters <0.2 μm. Some of these samples were analyzed qualitatively for fiber identification by polarizing light microscopy and dispersion staining [NIOSH, 1977b; McCrone, 1987].

Transmission electron microscopy (TEM) with selected area electron diffraction (SAED) and energy dispersive X-ray analysis (EDAX) was also used to analyze the samples for fiber count and identification according to the Zumwalde and Dement methods [NIOSH, 1977b]. Before analysis, a portion of each filter was removed, deposited on an electron microscope grid, and carbon coated. The filter matrix was then dissolved with acetone leaving the particulate adhering to the carbon film on the grid. After preparation, each sample was analyzed using TEM for fiber count. All particulates in a predetermined grid area with an aspect ratio of 3 or greater were counted as fibers. A minimum of 10 grid openings or 50 fibers were counted from each sample to optimize analytical accuracy. Fiber identification was accomplished using SAED, EDAX, or both methods in combination with TEM. SAED was used in conjunction with TEM to measure the diffraction of an electron beam incident on the sample. The crystalline structure of mineral compounds in the sample produces an electron beam diffraction pattern characteristic of the mineral compound. These diffraction patterns were used for mineral identification based on predicted patterns for a particular mineral compound. Using EDAX, a beam of high energy electrons, incident upon a fiber, generated X-rays characteristic of the elements in the fiber. The X-rays were detected using a lithium-drift silicon detector in the electron microscope column. Fiber identification was accomplished by comparing the sample's X-ray spectrum to known X-ray spectrum for different mineral fiber types. When used together, these two analytical methods (SAED and EDAX) provided a greater rate of fiber identification than possible when used separately [NIOSH, 1977b].

Respirable Dust, Total Dust, and Crystalline Silica Sampling and Analysis

Airborne dust concentrations were measured at each of the crushed stone operations surveyed. Respirable and total dusts for gravimetric analysis were collected on 37-mm polyvinyl chloride filters using a two-piece filter cassette. The respirable dust samples were collected with a 10-mm nylon cyclone using a portable sampling pump calibrated to 1.7 liters per minute (L/min). Under these operating conditions, the nylon cyclone has a 50% collection efficiency for particles with an aerodynamic diameter of 3.5 μm [Hinds, 1982]. Total dust samples were collected directly into the filter cassette without using the cyclone preseparator at a flow rate of 2.0 L/min.

Both personal and area samples were collected to measure respirable and total dust exposures and concentrations. Personal samples were collected by attaching the sampler to the worker and operating it throughout the work shift. The sampling orifice was positioned in the worker's breathing zone. Area samples were positioned at select locations to represent exposure zones in the facility and were operated throughout the work shift.

Each respirable and total dust sample was analyzed gravimetrically for filter weight gain using an electrobalance with an instrumental precision of ± 0.01 mg. Before sampling, each filter was pre-weighed to the nearest 0.01 mg and then re-weighed after sampling. The difference in filter weight divided by the total volume sampled yields the measured concentration in mg/m^3. The respirable and total dust samples were analyzed by X-ray diffraction (NIOSH Method P & CAM 259) for three

TABLE III. Mineral Fibers Identified in Personal Total Dust Samples Using Electron Microscopy With Energy Dispersive X-Ray Analysis[1]

Mineral identification	Percentage of fibers identified
Serpentine	68.2
Tremolite	19.1
Hornblende	1.9
Olivine	7.0
Magnesite	3.8

[1]Samples from plant T1 only.

different crystalline silica polymorphs: α-quartz, cristobalite, and tridymite [NIOSH, 1977a]. Since completion of these field surveys, the NIOSH analytical method for respirable crystalline silica has been revised to NIOSH Method 7500—silica, crystalline, respirable [NIOSH, 1986].

Each sample was dissolved in tetrahydrofuran and the residue was deposited on a silver membrane filter. The filter samples were scanned by X-ray diffraction to determine the presence of crystalline silica and other minerals that may cause analytical interference. The mass of crystalline silica was determined by measuring the diffraction peak intensity for a particular polymorph and comparing this value to an external calibration curve prepared using a 5-μm Minusil standard. The analytical precision of this method was ~10% for a 50-μg sample of quartz.

RESULTS

Asbestos and Mineral Fibers

Mineral fibers were detected at several crushed stone operations in the study. Fibers that were classified as asbestos were present at one traprock operation located in Maryland (Plant T1). Both tremolite and chrysotile fibers were detected at this operation along with a variety of other mineral compounds with fibrous morphology. Five types of fibrous minerals were detected in airborne samples: serpentine (including chrysotile), tremolite, hornblende, olivine, and magnesite. Approximately 45% of the fibers in these samples were longer than 5 μm, and 43% of the fibers were below 1 μm in diameter. Based on microscopic observations, most of these mineral fibers were rod-shaped and appeared to be elongated cleavage plane mineral fragments. A glossary of terms relevant to these descriptions is provided in Appendix A. A portion of the serpentine, tremolite, and magnesite minerals appeared asbestiform by electron microscopy analysis. These microscopic methods do not always permit true resolution between asbestiform and nonasbestiform mineral habits (in individual particles/fibers). These differences are more accurately measured by physical properties at the macroscopic level.

Table III presents the types of mineral fibers identified at Plant T1. The analyses presented in this table are electron microscopy results from five personal air samples. The fibers detected in these samples are classified by mineral identification according to their relative percentages in the samples.

The NIOSH Recommended Exposure Limit (REL) for asbestos is 0.1 fibers >5

TABLE IV. Mineral Fiber Concentrations From Area Total Dust Samples Plant T1—Mill, Crusher

Location	Concentration fibers/cm^3
Secondary crusher	0.36
	0.39
	ND[a]
	0.21
	0.30
	ND[a]
	0.10
Tertiary crusher	ND[a]
	ND[a]
	ND[a]

[a]Below detectable limit (0.02 fibers/cm^3).

μm in length per cubic centimeter (fibers/cm^3) collected over any 100-minute period and was established based on the analytical limitations of using phase contrast microscopy [NIOSH, 1990]. The MSHA Permissible Exposure Limit (PEL) for asbestos for surface and underground metal and non-metal mines, the classification that includes the mines surveyed by this study, states that the 8-hour, time-weighted average (TWA) airborne concentration of asbestos to which employees are exposed shall not exceed 2 fibers/cm^3 >5 μm in length as determined by the membrane filter method with particle counting by phase contrast microscopy. Additionally, the MSHA PEL limits exposure concentrations to 10 fibers/cm^3 when determined over a minimum sampling period of at least 15 minutes [U.S. Dept. of Labor, 1991a].

Mineral fiber concentrations from the 10 area samples collected at Plant T1 ranged from below the detection limit to a high of 0.39 mineral fibers per cubic centimeter of air (fibers/cm^3). Five of the 10 samples had detectable concentrations of mineral fibers as shown in Table IV. Personal mineral fiber exposure measurements were collected from 10 of the workers. The TWA mineral fiber exposure concentrations ranged from nondetectable to 0.31 fibers/cm^3. Eight of the 10 workers sampled had mineral fiber exposure concentrations above the detection limit as shown in Table V. In cases where mixed mineral fiber types occur in the same environment (including asbestos and nonasbestos fibers), the phase contrast microscopy fiber count results may be adjusted by a factor developed from supplemental analysis by electron microscopy using electron diffraction and microchemical analysis to improve specificity [NIOSH, 1977b, 1990]. For example, the data from Table III could be used to adjust the mineral fiber results to yield a specific asbestos fiber concentration by using only those fibers identified as serpentine and tremolite.

Mineral fibers other than asbestos were detected in bulk and airborne samples from some of the crushed stone operations studied, other than plant T1. These data are summarized in Table VI. The traprock operations had the greatest and most varied mineral fiber content. Albite, hornblende, labradorite, and sphene were some of the most frequent mineral fibers detected in the traprock operations. Mineral fibers were identified at only one of the granite operations, whereas no mineral fibers were detected in the limestone operations. Airborne mineral fiber concentrations from partial-period area samples collected from traprock (excluding plant T1) and granite

TABLE V. Personal Mineral Fiber Exposure at Plant T1

Exposure zone	Shift	Mineral fiber exposure concentration (fibers/cm^3)
Mill operator	1	0.02
Mill operator	1	0.02
Mill laborer	1	0.07
Mill laborer	1	ND[a]
Mill operator	1	0.07
Mine driller	1	0.03
Mine truck driver	1	ND[a]
Mine heavy equip op.	1	0.02
Mill maintenance	2	0.31
Mill laborer	2	0.18

[a]Below detection limit (0.02 fibers/cm^3).

operations ranged from nondetectable to 3.6 fibers/cm^3. Asbestos fibers were not detected in these samples. Most of the mineral fibers were rod-shaped or acicular particles with a 3-to-1 or greater aspect ratio and appeared to be elongated cleavage plane fragments based on appearance at the microscopic level. There are no current exposure standards or guidelines for these mineral fibers.

Mineral Dust Constituents

The mineral content of the dusts generated through crushed stone production varied among the three rock types (limestone, granite, and traprock) sampled during the study. In limestone operations, the carbonate minerals including calcite and dolomite were the dominant minerals. Silicate minerals including α-quartz were detected at most of the limestone operations. In samples from the granite segment, the silicate minerals were predominant. The tectosilicates, phyllosilicates, and inosilicates comprised most of the major silicate minerals. The feldspar and quartz minerals were predominant in the tectosilicate group. Traprock operations contained the greatest and most varied mineral content. The silicate minerals were predominant in traprock.

The phyllosilicates, tectosilicates, and inosilicates comprised most of the major silicate minerals in the traprock operations. The nesosilicate and sorosilicate minerals were also detected at some of the traprock operations. The traprock operations generally had a lower free silica content than the granite operations. Cristobalite was detected at most of the traprock operations in trace amounts.

Respirable Dust

Table VII presents TWA personal respirable dust concentrations by rock type. A total of 603 personal samples for respirable dust were collected. The geometric mean (GM) respirable dust concentration for all operations was 0.28 mg/m^3 with respirable dust concentrations ranging from nondetectable to 8.31 mg/m^3. Workers in the limestone operations had the highest GM respirable dust exposure concentration, 0.39 mg/m^3. The traprock workers had a GM exposure concentration of 0.23 mg/m^3, whereas granite workers had the lowest GM exposure concentration, 0.17 mg/m^3.

Figure 2 presents personal, TWA, respirable dust concentration by plant. Geometric mean concentrations by plant ranged from a low of 0.12 mg/m^3 to a high of

TABLE VI. Mineral Fibers Identified at the Other 18 Crushed Stone Operations* in Bulk and Airborne Samples

Rock type	Mineral identification	Morphology	Number of facilities containing fibers
Limestone	ND	—	0
Granite	Hornblende	Rod-shape	1
		Asbestiform-shape	1
	Microline	Rod-shape	1
	Albite	Rod-shape	1
	Olivine	Rod-shape	1
Traprock	Albite	Rod-shape	2
	Apatite	Rod-shape	1
	Augite	Rod-shape	1
	Biotite	Rod-shape	1
	Calcite	Rod-shape	1
	Garnet	Rod-shape	1
	Gypsum	Rod-shape	1
	Hornblende	Rod-shape	2
		Asbestiform-shape	1
	Labradorite	Rod-shape	3
	Olivine	Rod-shape	1
	Orthoclase	Rod-shape	1
	Quartz	Rod-shape	1
	Rutile	Rod-shape	1
	Sphene	Rod-shape	2

*Operations other than Plant T1, which was the only plant where asbestos was found.

TABLE VII. Personal Respirable Dust Exposure Concentration by Rock Type Geometric Mean Concentrations in mg/m³

Rock type	Samples	Geometric mean,[a] mg/m³	Geometric standard deviation	Range mg/m³ Low	Range mg/m³ High
Limestone	295	0.39	2.88	ND[b]	8.31
Granite	143	0.17	2.58	ND[b]	1.46
Traprock	165	0.23	2.86	ND[b]	6.50
All rock types	603	0.28	2.96	ND[b]	8.31

[a]Samples below the detection limit were set at the detection limit to calculate GMs.
[b]Limit of detection for respirable dust, 0.01 mg/sample, or about 0.01 mg/m³ depending on sample volume.

0.68 mg/m^3. The figure presents the plant GM respirable dust concentration along with the 95% confidence limits indicated on the figure by the range bars.

Area respirable dust sampling results are presented in Table VIII. The area samples were generally taken from "worst case" locations in the mill. Some area samples were also collected from office/scalehouse locations. The limestone operations had the highest GM concentrations from area samples collected in the mill, 0.87

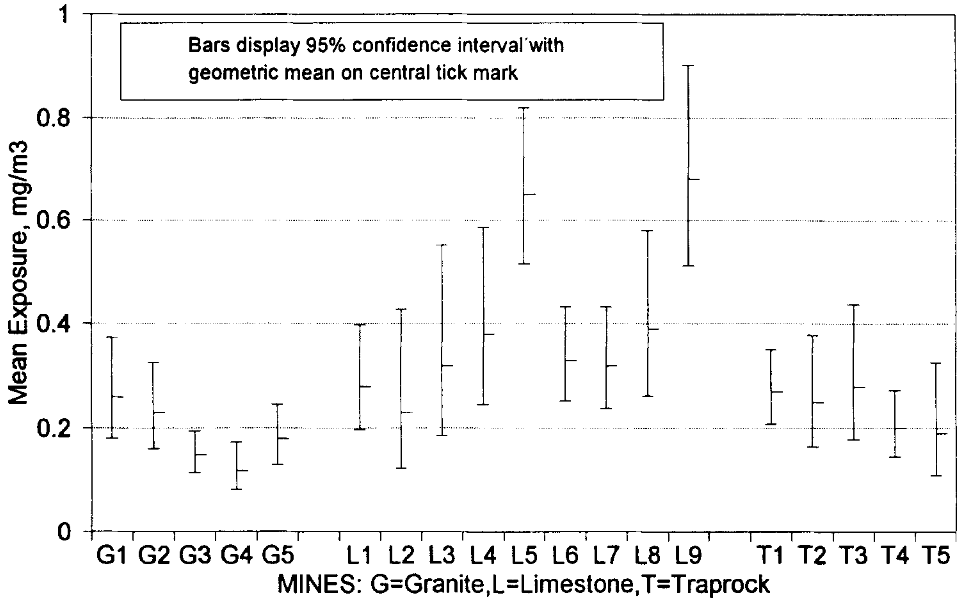


Fig. 2. Personal respirable dust exposures by plant.

mg/m^3. The granite and traprock operations had GM concentrations of 0.22 mg/m^3 and 0.15 mg/m^3, respectively.

Total Dust

Personal TWA total dust exposure concentrations are presented by rock type in Table IX. The GM concentration of the 79 total dust samples is 1.48 mg/m^3 with a geometric standard deviation of 3.50. The total dust concentrations ranged from 0.15 mg/m^3 to 35.6 mg/m^3.

Crystalline Silica

Crystalline silica was detected in the respirable dust at 17 of the 19 crushed stone operations surveyed. The α-quartz was the principal polymorph of crystalline silica found; cristobalite was detected at four of the traprock operations in ~6% of the personal respirable dust samples. Tridymite was not detected at any of the study sites. Table X presents the α-quartz sampling results by rock type. The granite operations had the highest α-quartz content; ~37% by weight in those samples with detectable concentrations of α-quartz.

The limestone and traprock samples contained lower average percent by weight α-quartz content, ~11% and 15%, respectively. In Table XI, GM personal respirable α-quartz exposure concentrations are presented by rock type. The granite operations had the highest α-quartz concentrations with a GM of 0.06 mg/m^3. The traprock and limestone operations each had GM α-quartz concentrations of 0.04 mg/m^3.

Figure 3 presents personal, respirable quartz exposure concentrations by plant. GMs are used and concentrations are reported in mg/m^3. At two of the traprock operations, all the personal exposure measurements were below the analytical limit of

TABLE VIII. Area Respirable Dust Geometric Mean Concentrations in mg/m^3

Area	Samples	Geometric mean, mg/m^3	Geometric standard deviation
	Limestone		
All mill areas	37	0.87	2.02
Primary crusher	11	0.71	2.68
Secondary crusher	19	1.16	1.61
Office or scalehouse	4	0.08	10.00
	Granite		
All mill areas	10	0.22	2.14
Primary crusher	8	0.26	2.13
Secondary crusher	0	—	—
Office or scalehouse	0	—	—
	Traprock		
All mill areas	18	0.15	6.61
Primary crusher	6	0.08	4.74
Secondary crusher	9	0.24	10.44
Office or scalehouse	3	0.09	2.29

TABLE IX. Personal Total Dust Exposure Concentration by Rock Type Geometric Mean Concentrations in mg/m^3

Rock type	Samples	Geometric mean, mg/m^3	Geometric standard deviation	Range mg/m^3	
				Low	High
Limestone	16	3.49	4.39	0.22	35.6
Granite	7	1.56	2.71	0.65	12.0
Traprock	56	1.15	3.04	0.15	15.1
All rock types	79	1.48	3.50	0.15	35.6

detection (LOD). The highest GM exposure level (0.11 mg/m^3) was observed at a limestone operation.

The personal samples for respirable crystalline silica were compared to existing occupational exposure control limits. The following were considered.

1. The NIOSH REL: 0.05 mg/m^3 for the sum of α-quartz, cristobalite and tridymite. Additionally, NIOSH has determined that exposure to crystalline silica presents a potential lung cancer risk [NIOSH, 1988].

2. The ACGIH Threshold Limit Value (TLV) [ACGIH, 1994]: 0.10 mg/m^3 for α-quartz, and 0.05 mg/m^3 for cristobalite and tridymite.

3. The MSHA PEL:

$$\text{PEL} = \frac{10.0\ \text{mg/m}^3}{(2 + \%\text{Q})}$$

where %Q is the percentage quartz in the sampled dust, the PEL is the measured respirable dust concentration. The formula represents a quartz PEL at 0.1 mg/m^3

TABLE X. α-Quartz Content of Personal, Respirable Dust Samples

Rock type	Samples	Percentage below LOD[a]	Mean α-quartz percentage[b]	Standard deviation, percentage
Limestone	295	72	11	8.6
Granite	143	36	37	20.0
Traprock	121*	82	15	10.0

[a]Percentage of samples for which concentration was below the limit of detection (LOD).
[b]Arithmetic average of percentage by weight α-quartz in those samples above the LOD.
*Due to interfering mineral compounds, α-Quartz could not be quantified in a portion of the respirable dust samples from one traprock operation. These samples were excluded from α-Quartz analysis.

TABLE XI. Personal Respirable α-Quartz Exposures by Rock Type Geometric Mean Exposures in mg/m^3

Plant type	Samples	Geometric mean,[a] mg/m^3	Geometric standard deviation	Range (mg/m^3) Low	Range (mg/m^3) High
Limestone	295	0.04	1.88	ND[b]	0.43
Granite	143	0.06	1.94	ND[b]	0.28
Traprock	121	0.04	1.62	ND[b]	0.48

[a]Samples below the detection limit were set to the detection limit for the purposes of calculating GMs.
[b]Below limit of detection for respirable α-quartz analysis, 0.03 mg/sample, or ~0.03–0.04 mg/m^3 in air depending on sample volume.

combined using the additive-mixture formula [U.S. Dept. of Labor, 1991a] with a respirable dust PEL of 5.0 mg/m^3.

Table XII reports that 17 of the 19 plants studied had at least one respirable quartz sample in excess of the NIOSH REL. Of these, 16 had at least one exposure measurement in excess of the MSHA PEL, and 15 had at least one measurement over the ACGIH TLV. For the purposes of regulating general industry, the Department of Labor (OSHA) uses a PEL equivalent to the ACGIH TLV.

The overall distribution of samples exceeding these limits is presented in Table XIII. Overall, out of 559 samples, 25% exceeded the NIOSH REL, 14% exceeded the MSHA PEL, and 13% exceeded the ACGIH TLV. Although both the ACGIH TLV and the MSHA PEL nominally control quartz exposures to a 0.1 mg/m^3 limit, it is possible to reach different compliance decisions based on a particular sample. The ACGIH TLV is compared to the absolute amount of quartz analyzed for each individual sample. The MSHA PEL is established by computing a respirable dust PEL from an airborne bulk quartz concentration in the dust, %Q. If that concentration varies for the respirable dust samples, it is possible to reach different conclusions relative to the control limit. Note in Table XIII that the percent exceeding the MSHA PEL is greater than the percent exceeding the ACGIH TLV for limestone and traprock mines; however, the reverse is true for the granite mines.

Workers in certain job exposure zones, mill operators and mill laborers, consistently had the highest and most frequent overexposures to crystalline silica. The risk of silicosis would be greatest in these work groups. Other job exposure zones

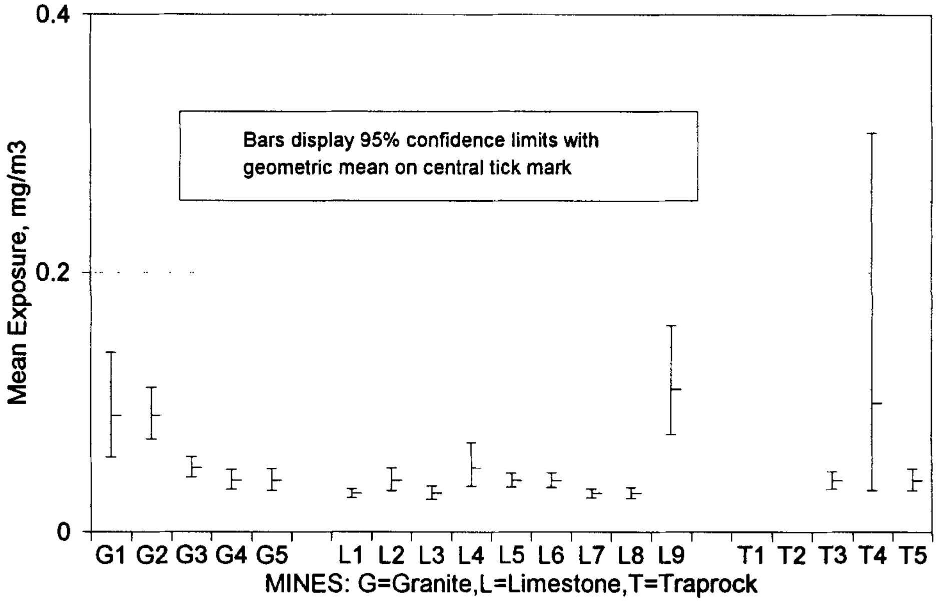


Fig. 3. Personal respirable quartz exposures by plant.

TABLE XII. Number of Operations With Crystalline Silica Overexposures*

	Number of plants surveyed	Plants with exposure(s) above the NIOSH-REL	Plants with exposure(s) above the MSHA-PEL	Plants with exposure(s) above the ACGIH-TLV
Limestone	9	9	8	7
Granite	5	5	5	5
Traprock	5	3	3	3
All rock types	19	17	16	15

*Includes all plants with one or more personal overexposures.

with higher and more frequent crystalline silica overexposures include truck drivers—mine and mill, heavy equipment operators—mine/mill and mine drilling.

DISCUSSION

This study was initiated in response to concerns about the potential for asbestos exposures at crushed stone quarries and mills. This perception followed the identification of asbestos in the product from one traprock quarry in Maryland, which contained serpentine minerals. A group of mines in three crushed stone mining segments (granite, limestone, traprock) was selected for study. After replacing uncooperative (or closed) mining operations with willing participants, the mines were surveyed by a team of industrial hygienists with the intent of characterizing exposures to fibrous minerals including asbestos in its various forms, as well as to document exposures to other minerals including crystalline silica.

TABLE XIII. Respirable Crystalline Silica Samples With Overexposures by Rock Type

Rock type	Samples	Percentage below LOD[a]	Percentage exceeding NIOSH-REL	Percentage exceeding MSHA-PEL	Percentage exceeding ACGIH-TLV
Limestone	295	72	20	14	10
Granite	143	36	45	21	22
Traprock	121	82	12	8	7
All types	559	65	25	14	13

[a]Limit of detection (0.03 mg/sample) for each crystalline silica polymorph or ~0.03–0.04 mg/m^3 in air depending on sample volume.

The selection process used to choose mines participating in this study might have introduced bias when the randomly chosen sites that declined to participate in the study were replaced with alternate sites. Although the sites ultimately surveyed include geographically stratified facilities mining in three different rock-type strata, due to the potential selection bias the results of these surveys cannot be considered ''representative'' of the crushed stone mining industry in general.

Analysis of the bulk samples collected at the sites revealed that amphibole minerals, a major asbestos-containing mineral category, were present at all granite and traprock operations in this study. However, asbestos fibers including both chrysotile and tremolite were detected only at one of the traprock operations studied—this was the Maryland traprock mine (Plant T1) where the asbestos was first detected. In addition to the chrysotile and tremolite asbestos fibers, there were several other minerals present in the ore body at this mine that had a fibrous shape (aspect ratio ≥ 3:1, longer than 5 μm). These included: albite, hornblende, labradorite, and sphene. Since the analytical method prescribed for fiber exposure quantitation, phase contrast microscopy, does not distinguish between asbestos and nonasbestos fibers, but rather counts all fibers, some adjustment to the total mineral fiber counts may be necessary. In the absence of qualitative data that can be used to determine the percentage of asbestos fibers in each sample collected, all fiber concentrations derived from phase contrast microscopy analysis should be compared to the NIOSH REL and MSHA PEL for asbestos without adjustment for fiber type. Taking this approach, several samples collected at the secondary crusher area of this facility exceeded the NIOSH REL for asbestos fibers of 0.1 fibers/cm^3, reaching as high as 0.39 fibers/cm^3. However, eight out of 10 personal samples collected on mill workers were below the 0.1 fibers/cm^3 REL. The two samples that exceeded the REL were collected on a mill maintenance worker and a mill laborer. Other mill laborers and mill operators were below the REL. All of the fiber sample concentrations were below the 2.0 fibers/cm^3 MSHA PEL.

The focus of the industrial hygiene sampling protocol was to obtain sufficient data for an exposure assessment relevant to potential asbestos exposures. In addition to that, other minerals were characterized. At 17 of the 19 facilities studied, there were significant overexposures to crystalline silica, where measured personal exposures exceeded the NIOSH REL. At 16 of these facilities, at least one sample was observed with exposures exceeding the MSHA PEL. Overall, one in seven respirable dust samples (14%) exceeded the MSHA PEL. Certain job exposure zones had the highest and most frequent overexposures to silica. They were: mill operator, mill laborer, truck drivers—mine/mill, heavy equipment operators-mine/mill, and mine drilling. The greatest silicosis risk exists for these groups of workers.

Cross-sectional exposure data describe conditions at a facility or job location at a single point in time. Attempts to obtain historical industrial hygiene data for all the crushed stone operations in this study were unsuccessful. Such data were available for only one of the 19 operations in this survey. MSHA compliance inspection data were available for most of the studied mines. However, the collection period was coincident with the field data collection phase for this study. Older historical records were not available.

CONCLUSIONS

Workers at crushed stone quarries and mills are exposed to a variety of minerals including asbestos and silica. This investigation documented asbestos exposures at one facility where the exposure occurred as a result of mining an ore body contaminated with serpentine chrysotile asbestos and amphibole tremolite asbestos. Other mineral fibers were discovered at other facilities in this study; however, these were not in the category classified as asbestos. Where mineral fibers were found, some personal exposures were observed in excess of the 0.1 fibers/cm^3 NIOSH REL that would be applied to asbestos exposures.

Exposures to crystalline silica were pervasive in the crushed stone facilities in our study. With 14% of all samples collected on these surveys found to be in excess of the MSHA PEL, and with 25% exceeding the NIOSH REL, it can be concluded that a significant silicosis hazard and a potential lung cancer risk from silica exposure existed in the facilities during the period of the study. The rate of overexposure revealed in MSHA compliance data for the crushed stone industry, shows that during the period 1988 to 1992, approximately 25% of all respirable quartz samples (contaminant code 523) exceeded the MSHA PEL; combining samples in other MSHA respirable dust contaminant codes (121, 131, 521, and 523), approximately 12% of the MSHA compliance samples exceeded the PEL [MSHA, 1994]. Based on these findings, it is likely that a significant silicosis risk and a potential lung cancer risk still exists for workers in this industry.

REFERENCES

ACGIH (American Conference of Governmental Industrial Hygienists) (1994): "Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices." Cincinnati; ACGIH. Ohio.

Carter LJ (1977): Asbestos: Trouble in the air from a Maryland rock quarry. Science 197:237–240.

Corn M, Esmen NA (1979): Workplace exposure zones for classification of employee exposures to physical and chemical agents. Am Indus Hygie Assn Jo 40:47–57.

Costello J, Castellan RM, Swecker GS, Kullman GJ (1992): Mortality of a cohort of U.S. workers employed in the crushed stone industry, 1940–1980. Final Report: NIOSH, July 13.

Costello J, Castellan RM, Swecker GS, Kullman GJ (1995): Mortality of a cohort of U.S. workers employed in the crushed stone industry, 1940–1980. Am J Ind Med (this issue).

Hinds WC (1982): "Aerosol Technology." New York: John Wiley & Sons.

Key MM, Ayer HE (1972): Silicosis in hard rock mining. J Occup Med 14:863–864.

Lefond SF, (ed). (1975): "Industrial Minerals and Rocks, 4th ed. " Baltimore: Port City Press.

McCrone W (1987): "Asbestos Identification." Chicago: McCrone Research Institute.

MSHA (Mine Safety and Health Administration). (1994): Data available from the Mine Inspection Data Analysis System. MSHA, Arlington, Virginia.
NIOSH (National Institute for Occupational Safety and Health) (1975): Occupational Exposure to Crystalline Silica, U.S. Department of Health, Education and Welfare, DHEW Publ No. (NIOSH) 75-120.
NIOSH (National Institute for Occupational Safety and Health) (1977a): "NIOSH Manual of Analytical Methods," Vols. 1–7. DHEW Publ No. (NIOSH) 77-157-A.
NIOSH (National Institute for Occupational Safety and Health) (1977b): "Review and Evaluation of Analytical Methods for Environmental Studies of Fibrous Particulate Exposures." DHEW Publ No. (NIOSH) 77-204.
NIOSH (National Institute for Occupational Safety and Health) (1980): Workplace Exposure to Asbestos, U.S. Department of Health, Education & Welfare, DHEW Publ No. (NIOSH) 81-103.
NIOSH (National Institute for Occupational Safety and Health) (1986): NIOSH Manual of Analytical Methods, 3rd ed. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publ No. 84-1000.
NIOSH (National Institute for Occupational Safety and Health) (1988): Testimony of the National Institute for Occupational Safety and Health on the Occupational Safety and Health Administrations Notice of Proposed Rule on Air Contaminants, 29 CFR Part 1910, Docket No. H-020, Washington, DC, August 1.
NIOSH (National Institute for Occupational Safety and Health) (1990): Testimony of the National Institute for Occupational Safety and Health on the Occupational Safety and Health Administrations Notice of Proposed Rulemaking on Occupational Exposure to Asbestos, Tremolite, Anthophyllite, and Actinolite, Washington, DC May 9.
NIOSH (National Institute for Occupational Safety and Health) (1991): Work Related Lung Disease Surveillance Report. DHHS (NIOSH) Publ No. 91-113.
Stern AC, Baliff J, et al. (1947): Dust concentrations in stone crushing operations. Monthly review. New York State Department of Labor. Division of Industrial Hygiene and Safety Standards, November 1.
U.S. Department of the Interior, Bureau of Mines (1980): "Stone." Washington, DC: U.S. Government Printing Office.
U.S. Department of Labor (1991a): Code of Federal Regulations, Title 30, Part 56 Safety and Health Standards—Surface Metal and Nonmetal Mines. Section 56.5001, Exposure Limits for Airborne Contaminants.
U.S. Department of Labor (1991b): Code of Federal Regulations, Title 30, Part 57 Safety and Health Standards—Underground Metal and Nonmetal Mines. Section 57.5001, Exposure Limits for Airborne Contaminants.
U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards (1979): Asbestos, Rock Quarries—Mineralogical Analysis of Crushed Stone Samples, EPA-450/3-79-031, July.

Appendix: GLOSSARY OF TERMS*

Asbestos

A generic term for a number of silicate minerals with a fibrous crystalline structure. The quality of commercially used asbestos depends on the mineralogy of the asbestiform variety, the degree of fiber development, the ratio of fibers to acicular crystals or other impurities, and the length and flexibility of the fibers. The asbestiform varieties of these minerals can be found in both the amphibole and serpentine mineral groups. The asbestiform varieties occur in veins or small veinlets within rock containing or composed of the massive (nonasbestiform) variety of the same mineral. The major asbestiform varieties of minerals used commercially are chrysotile, trem-

*Quoted from NIOSH [1990] testimony.

olite-actinolite asbestos, cummingtonite-grunerite asbestos, anthophyllite asbestos, and crocidolite. Asbestos is marketed by its mineral name (e.g., anthophyllite asbestos), its variety name (e.g., chrysotile or crocidolite), or its trade name (e.g., Amosite).

Serpentine Minerals

The serpentine minerals belong to the phyllosilicate group of minerals. The commercially important variety is chrysotile, which originates in the asbestiform habit. Antigorite and lizardite are two other types of serpentine minerals that are structurally distinct in mineral habit. The fibrous form of antigorite is called picrolite.

Chrysotile. Generally occurs segregated as parallel fibers in veins or veinlets and can easily separate into individual fibers or bundles. Often referred to as "white asbestos," it is used commercially for its good spinnability in the making of textile products and as an additive in cement or friction products.

Amphibole Minerals

Minerals in the amphibole group are widely distributed in the earth's crust in many igneous or metamorphic rocks. In some instances, the mineral deposits contain sufficient quantities of the asbestiform minerals to be economically minable for commercial use. The minerals and mineral series of the amphibole group have variable compositions with extensive elemental substitutions. They are found in forms ranging from massive to fibrous. The most common commercially exploited asbestiform varieties of this mineralogical group include crocidolite, amosite, anthophyllite, tremolite, and actinolite. Crocidolite, amosite, and anthophyllite are selectively mined for commercial use, whereas tremolite and actinolite are most often found as contaminants in other mined commodities such as talc and vermiculite. The amphiboles have good thermal and electrical insulation properties, and they have moderate to good resistance to acids.

Crocidolite. A varietal name for the fibrous habit of the mineral riebeckite, in the mineral series glaucophane-riebeckite, in which both asbestiform and nonasbestiform habits can occur. This mineral type is commonly referred to as "blue asbestos."

Amosite. Commercial term derived from the acronym "Asbestos Mines of South Africa." Amosite is in the mineral series commingtonite-grunerite, in which both asbestiform and nonasbestiform habits of the mineral can occur. This mineral type is commonly referred to as "brown asbestos."

Anthophyllite. Can occur in both the asbestiform and nonasbestiform mineral habits. The asbestiform variety is often referred to as anthophyllite asbestos.

Tremolite. Can occur in both the asbestiform and nonasbestiform mineral habits and is in the mineral series tremolite-ferroactinolite. The asbestiform variety is often referred to as tremolite asbestos.

Actinolite. Can occur in both the asbestiform and nonasbestiform mineral habits and is in the mineral series tremolite-ferroactinolite. Mineral series such as cummingtonite-grunerite and tremolite-ferroactinolite are created when one cation is replaced by another in a crystal structure without significantly altering the structure. There may be a gradation in the structure in some series, and minor changes in physical characteristics may occur with elemental substitution. Usually a series has two end members with an intermediate substitutional compound being separately-named, or just qualified by being referred to as members of the series. Members of the tremolite-ferroactinolite series are hydroxylate calcium-magnesium, magnesium-iron, and iron silicates, with the intermediate member of this series being named actinolite. The asbestiform variety is often referred to as actinolite asbestos.

Asbestiform habit. A specific type of mineral fibrosity in which the growth is primarily in one dimension and the crystals form naturally as long, flexible fibers. Fibers can be found in bundles that can be easily separated into smaller bundles or ultimately into fibrils.

Cleavage fragments. Mineral particles produced by the breaking of crystals in directions that are related to the crystal structure and are always parallel to possible crystal faces. Minerals with perfect cleavage can produce perfect regular fragments. Amphiboles with prismatic cleavage will produce prismatic fragments. *Note:* These particles can be elongated and may meet the NIOSH definition of a fiber upon microscopic examination.

Fiber. An acicular single crystal or similarly elongated polycrystalline aggregate particle. Such particles have macroscopic properties such as flexibility, high tensile strength and aspect ratio, and silky luster, and axial lineation. These particles have attained their shape primarily because of manifold dislocation planes that are randomly oriented in two axes but parallel in the third. *Note:* Upon microscopic examination, particles that have a 3:1 or greater aspect ratio are defined as fibers by NIOSH. Other macroscopic properties (e.g., flexibility, tensile strength) used to mineralogically define fibers cannot be ascertained for individual fibers examined microscopically.

Nonasbestiform habit. Each of the six commercially exploited asbestiform minerals also occurs in a nonasbestiform mineral habit. These minerals have the same chemical formula as the asbestiform variety, but have crystal habits where growth proceeds in two or three dimensions instead of one dimension. When milled, these minerals do not break into fibrils but rather into fragments resulting from cleavage along the two or three growth planes. *Note:* Particles formed by the comminution of these minerals are referred to as cleavage fragments and can meet the NIOSH definition of a fiber for regulatory purposes when viewed microscopically.

Mineral. A homogeneous, naturally occurring, inorganic crystalline substance. Minerals have distinct crystal structures and variation in chemical composition and are given individual names.

Mineral series. A mineral series includes two or more members of a mineral group in which the cations in secondary structural position are similar in chemical properties and can be present in variable but frequently limited ratios (e.g., cummingtonite-actinolite). The current trend in referring to a mineral series is to simplify long series names by using the mineral name of only one (end or intermediate) member (e.g., tremolite for tremolite-actinolite-ferroactinolite). *Note:* The microscopic analysis of individual particles or fibers from the asbestiform and nonasbestiform habits often exhibit chemical ratios within a mineral series rather than that of a particular end member.