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NOTES

Asbestos Fiber Type Description

Asbestos E.L. Mann
3/30/88 memo From B. Lewis
- Canadian Asbestos Industry E.J. Bonkoff SS
4/8/90 Memo from REM
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3103 cont'd		Kim Peters

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FREEBORN & PETERS

Attorneys at Law

Asbestos Fiber
- Types, Description & Miscellaneous

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MTC 000003

ASBESTOS

E. L. MANN

Reprinted from

INDUSTRIAL MINERALS AND ROCKS

5th Edition, 1983

MTC 000004

Asbestos *†

E. L. MANN ‡

Asbestos is the generic name given to a group of fibrous mineral silicates found in nature. They are all incombustible and can be separated by mechanical means into fibers of various lengths and cross sections, but each differs in chemical composition from the others. The commercial grades of asbestos consist of a spectrum of lengths and sizes and are not definitive as are most organic fibers.

It is generally recognized that there are two main groups of asbestos. The first only contains the fibrous serpentine called chrysotile and comprises about 94% of the world production of asbestos. The second group contains five minerals in the amphibole series—crocidolite, amosite, anthophyllite, tremolite, and actinolite. The latter two have no commercial importance.

Properties

Physical

The structures of asbestos fibers have been studied intensively over a number of years. X-ray diffraction patterns have been used as a means of identification and classification. Low angle X-ray scattering techniques have shown that chrysotile fibers are "hexagonally close packed" and parallel to each other, having cross-sectional diameters varying from 180Å to 300Å units, while the amphibole fibers are many times larger in cross section, have considerably smaller surface areas, and the fibers are less symmetrical than those of chrysotile. Electron micrographs of the more common types of asbestos are shown in Figs. 1–4. Fig. 1 illustrates the softness and flexibility of chrysotile which make it suitable for textile-type products.

For a number of years there was considerable controversy over the exact nature of chrysotile fiber, but the photographic evidence in Figs. 5–7 clearly show that it is tubular in structure. The curvature is the result of the mismatch in the dimensions of the silica [Si_2O_5] and brucite [$Mg(OH)_2$] layers which are on the inside and outside, respectively, of a double sheet. This curvature had been predicted by Pauling (1930) years ago based on the molecular dimensions of the two component structures.

In contrast to this, the structure of the amphiboles consists of two ribbon chains based on Si_4O_{11} units separated by a band of seven cations with two hydroxyl groups attached to

* Previous editions—1937, 1949, 1960, and 1975—have developed a format describing the general physical properties of asbestos; the distribution of deposits throughout the world; description of mining and milling methods; tests and specifications; grades produced; prices, uses, and markets.

In the 4th and 5th editions certain phases are discussed in more detail. The sections relating to world occurrences, geology of deposits, and methods of evaluation are covered more fully. Statistics have been augmented and updated whenever possible and the bibliography enlarged.

† The 4th edition was coordinated by R. W. Winson formerly Mine Project Manager, Canadian Johns-Manville Co., Ltd., Asbestos, Quebec, Canada (now deceased) with assistance from J. W. Axelson (Properties), E. L. Mann (Geology; World Deposits; Production; Exploration and Evaluation), J. N. Gauthier (Mining), E. B. McKenna (Milling), D. P. R. Smyth (Tests and Specifications; Uses) and R. T. Hughes (Markets).

Grateful acknowledgement for assistance in reviewing the latest edition is given to the following: W. C. Streib, Research and Development Center, Manville Products Corp., Denver (Properties), F. J. Evelegh (Deposits and Production) and E. J. Day (Exploitation), both of Johns-Manville Canada Inc., and Margaret Cole (Production and Uses) and D. M. Kelleher (Markets), both of Manville Products Corp., Denver, CO.

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FIG. 3—*Amosite, Penge, South Africa. X5000. Reduced approximately 33% in reproduction.*

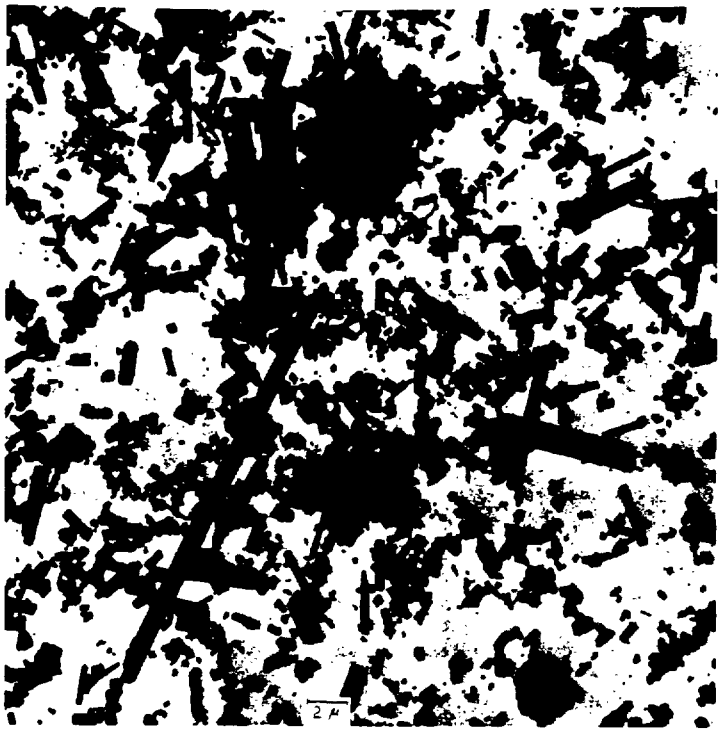

FIG. 4—*Anthophyllite, Georgia. X5000. Reduced approximately 33% in reproduction.*

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FIG. 5—*Chrysotile, X150,000. Reduced approximately 33% in reproduction.*

staining technique for the detection of chrysotile fibers.

Chrysotile is unique as compared to the other types of asbestos and most materials of a similar nature such as clays and talcs, since it carries a positive charge or has a plus zeta potential in a water slurry. The magnitude will vary with chrysotile from different deposits. Similarly, the isoelectric point or pH for zero potential will be different for chrysotiles from various sources. The isoelectric point for chrysotile will vary from 10.5 to 11.3 depending



FIG. 6—*High resolution electron micrograph of chrysotile. Reprinted with permission from "Acta Chrystalogica," (Yada, 1967). Reduced approximately 38% in reproduction.*

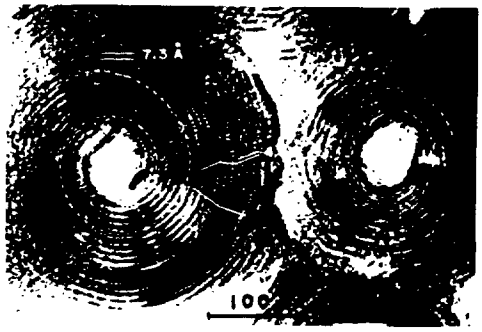

FIG. 7—High resolution electron micrograph of chrysotile. Reprinted with permission from "Acta Chrystalogica," (Yada, 1967). Reduced approximately 38% in reproduction.

TABLE 1—Types of Asbestos

Type	Theoretical Formulae
Chrysotile Hydrated magnesium silicate	$Mg_6[(OH)_4Si_2O_5]_2$
Crocidolite Complex sodium iron silicate (riebeckite) commonly called Blue Asbestos	$Na_2Fe_5[(OH)Si_4O_{11}]_2$
Amosite Iron magnesium silicate (grunerite)—same as anthophyllite except for high iron content	$MgFe_6[(OH)Si_4O_{11}]_2$
Anthophyllite Magnesium silicate with varying amounts of iron in the lattice	$(Mg,Fe)_7[(OH)Si_4O_{11}]_2$
Tremolite Calcium magnesium silicate	$Ca_2(Mg,Fe)_5[(OH)Si_4O_{11}]_2$
Actinolite Calcium magnesium silicate with varying amounts of iron	$Ca_2(Mg,Fe)_5[(OH)Si_4O_{11}]_2$

on the source of the fiber and the method of measurement.

Careful density measurements (Pundsack, 1956) of chrysotile have shown values ranging from 2.53 to 2.58 with 2.56 most typical.

The surface area determination of chrysotile depends upon the type of measuring apparatus employed. The industry generally uses an air permeability method (Badollet, 1951) for measuring the degree of openness of the fiber. If the true surface area is desired, it is necessary to employ gas adsorption techniques. Specific areas by air permeability will range from about 0.4 to 5 m^2/g whereas comparable gas adsorption areas will vary by a factor of 10 from 4 to 50 m^2/g depending on the source of the fiber and the degree of openness.

Effect of Heat on Asbestos

The weight loss for different types of asbestos when heated for 2 hr each at successive temperatures from 400° to 1800°F is shown in Table 4 (Badollet, 1951; Badollet and Streib, 1955). As expected, the weight loss for the amphiboles is considerably less than for chrysotile because of much less available ^-OH to be driven off as water. In spite of this, the amphiboles after heating at 800°F will still be more brittle than a chrysotile heated at 100° to 1100°F.

Table 5 shows the effect of heating chrysotile on the tensile strength of the fiber. The fiber bundles tested for tensile strength were very small so heat transfer would be effected in the 3-min heating time. Even after heating at 1200°F chrysotile retains 32% of its strength.

Structural changes in chrysotile can occur under conditions of intense grinding. This causes the structure to become amorphous with a loss of recognizable X-ray diffraction or electron microscope images. This apparently occurs because of localized temperature surges within the fibrils which produces dehydroxylation as the tremendous impact energies are absorbed.

Amphibole asbestos fibers also decompose at higher temperatures. This is particularly true when ferrous iron is present as it causes complex decomposition or thermal analysis determinations which are extremely dependent on atmospheric compositional variations.

TABLE 2—Approximate Chemical Analysis of Asbestos

	Chrysotile	Crocidolite	Amosite	Anthophyllite	Tremolite
SiO_2, %	37-44	49-53	49-53	56-58	53-62
MgO, %	39-44	0-3	1-7	28-34	0-30
FeO, %	0-6	13-20	34-44	3-12	1.5-5
Fe_2O_3, %	0.1-5	17-20	–	–	–
Al_2O_3, %	0.2-1.5	–	2-9	0.5-1.5	1-4
H_2O, %	12-15	2.5-4.5	2-5	1-6	0-5
CaO, %	tr-5	–	–	–	0-18
Na_2O, %	–	4.0-6.5	–	–	0-9
$CaO + Na_2O$, %	–	–	0.5-2.5	–	–

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TABLE 3—Properties of Asbestos Fibers (Badollet, 1951)

Property	Actinolite	Amosite	Anthophyllite	Chrysotile	Crocidolite	Tremolite
Structure	Reticulated long prismatic crystals and fibers	Lamellar. Coarse to fine fibrous and asbestiform	Lamellar. Fibrous asbestiform	Usually highly fibrous fibers fine and easily separable	Fibrous in ironstones	Long. Prismatic and fibrous aggregates
Mineral association	In limestone and in crystalline schists	In crystalline schists, etc.	In crystalline schists and gneisses	In altered peridotite adjacent to serpentine and limestone near contact with basic igneous rocks	Iron rich silicious agrillite in quartzose schists	In Mg limestones as alteration products of highly magnesian rocks. Metamorphic and igneous rocks
Origin	Results of metamorphism	Metamorphic	Metamorphic. Usually from olivine	Alteration and metamorphism of basic igneous rocks rich in magnesian silicates	Regional metamorphism	Metamorphic
Veining	Slip or mass fiber	Cross fiber	Slip. Mass fiber unoriented and interlacing	Cross and slip fibers	Cross fiber	Slip or mass fiber
Essential composition	Ca·Mg·Fe·Silicate water up to 5%	Silicate of Fe and Mg higher iron than anthophyllite	Mg silicate with iron	Hydrosilicate of magnesium	Silicate of Na and Fe with some water	Ca and Mg silicate with some water
Crystal structure	Long and thin columnar to fibrous	Prismatic. Lamellar to fibrous	Prismatic. Lamellar to fibrous	Fibrous and asbestiform	Fibrous	Long and thin columnar to fibrous
Crystal system	Monoclinic	Monoclinic	Orthorhombic	Monoclinic (pseudo-orthorhombic?)	Monoclinic	Monoclinic
Color	Greenish	Ash gray or brown	Grayish white. Brown-gray or green	White. Gray. Green. Yellowish	Lavender-blue. Metallic-blue	Gray-white. Greenish Yellowish. Bluish
Luster	Silky	Vitreous. Somewhat pearly	Vitreous to pearly	Silky	Silky to dull	Silky
Hardness	6±	5.5-6.0	5.5-6.0	2.5-4.0	4	5.5
Specific gravity	3.0-3.2	3.1-3.25	2.85-3.1	2.4-2.6	3.2-3.3	2.9-3.2
Cleavage	110 perfect	110 perfect	110 perfect	010 perfect	110 perfect	110 perfect
Optical properties	Biaxial negative extinction inclined	Biaxial and positive extinction parallel	Biaxial positive extinction parallel	Biaxial positive extinction parallel	Biaxial ± extinction inclined	Biaxial negative extinction inclined
Refractive index	1.63± weakly pleochroic	1.64±	1.61±	1.51-1.55	1.7 pleochroic	1.61±

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TABLE 3—Continued

Length	Short to long	2 to 11 in., varies	Short	Short to long	Short to long	Short to long
Texture	Harsh	Coarse but somewhat pliable	Harsh	Soft to harsh. Also silky	Soft to harsh	Generally harsh. Sometimes soft
Specific heat, Btu per lb per °F	0.217	0.193	0.210	0.266	0.201	0.212
Tensile strength, psi	1000 and less	16,000 90,000	4000 and less	80,000 100,000	100,000 300,000	1000 8000
Temperature at maximum ignition loss, °F	–	1600 to 1800	1800	1800	1200	1800
Filtration properties	Medium	Fast	Medium	Slow	Fast	Medium
Electric charge	Negative	Negative	Negative	Positive	Negative	Negative
Fusion point, °F	2540	2550	2675	2770	2180	2400
Spinnability	Poor	Fair	Poor	Very good	Fair	Poor
Resistance to acids and alkalies	Fair	Good	Very good	Poor	Good	Good
Magnetite content	–	0	0	0-5.2	3.0-5.9	0
Mineral impurities present	Lime, iron	Iron	Iron	Iron, chrome, nickel, lime	Iron	Lime
Flexibility	Poor	Good	Poor	High	Good	Poor
Resistance to heat	–	Good. Brittle at high	Very good	Good. Brittle at high	Poor, fuses	Fair to good
Ionizable salts, μmhos (relative electrical conductance)	–	1.34	0.58	1.82	0.84	–

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TABLE 4—Effect of Temperature on Loss in Weight of Asbestos Fibers

°F	Time, Hr	% Loss in Wt				
		Amosite	Anthophyllite	Chrysotile	Crocidolite	Tremolite
400	2	0.23	0.05	0.30	0.08	0.04
600	2	0.57	0.24	0.85	0.25	0.08
700	2	0.80	0.30	1.78	0.49	0.13
800	2	0.98	0.38	2.17	0.73	0.22
900	2	1.07	0.41	2.83	0.83	0.26
1000	2	1.16	0.44	3.99	0.86	0.29
1100	2	1.36	0.52	10.38	1.00	0.37
1200	2	1.39	0.54	12.75	1.04	0.37
1400	2	1.43	0.54	13.43	1.03	0.47
1500	2	–	0.64	–	–	0.56
1600	2	1.52	1.12	13.62	0.93*	0.67
1700	2	–	1.73	–	–	1.40
1800	2	1.53	2.39	13.77	0.77*	2.18

* Iron changing in weight due to oxidation.

Chemical Resistance

Asbestos is often used in chemical service where resistance to chemicals is of paramount interest. Table 6 gives data on the effect of various acids and caustic soda on asbestos after long exposure at room temperature and for short exposure at boiling temperatures. Because of the basic nature of chrysotile, it is seriously attacked by strong acids and should not be exposed to them. It is resistant to 25% caustic but recent data show that it is attacked by strong caustic (70%) at its boiling temperature.

TABLE 5—Effect of Heat on Tensile Strength of Canadian Chrysotile Crude

	Tensile Strength, Psi	% of Original Tensile Strength
Original crude, no heat	131,000	–
Heated 3 min at 600°F	120,000	91.6
Heated 3 min at 800°F	96,000	73.3
Heated 3 min at 1000°F	78,000	59.5
Heated 3 min at 1200°F	42,000	32.0

TABLE 6—Solubility of Asbestos

	% Loss in Wt, Refluxing 2 Hr, 25% Acid or Caustic				
	HCl	CH_3COOH	H_3PO_4	H_2SO_4	NaOH
Actinolite	20.31	12.28	20.19	20.38	9.25
Amosite	12.84	2.63	11.67	11.35	6.97
Anthophyllite	2.66	0.60	3.16	2.73	1.22
Chrysotile	55.69	23.42	55.18	55.75	0.99
Crocidolite	4.38	0.91	4.37	3.69	1.35
Tremolite	4.77	1.99	4.99	4.58	1.80

	% Loss in Wt, Room Temperature 26°C for 528 Hr, 25% Acid or Caustic				
	HCl	CH_3COOH	H_3PO_4	H_2SO_4	NaOH
Actinolite	22.55	12.14	20.10	20.60	9.43
Amosite	12.00	3.08	11.83	11.71	6.82
Anthophyllite	2.13	1.04	3.29	2.90	1.77
Chrysotile	56.00	24.04	56.45	56.00	1.03
Crocidolite	3.14	1.02	3.81	3.48	1.20
Tremolite	4.22	1.41	4.89	4.74	1.65

Most amphibole fiber varieties are more acid resistant than those of chrysotile. However, they are not entirely acid resistant and can exhibit weight losses of 2 to 20% when subjected to boiling concentrated acids.

Geology

General

Chrysotile constitutes about 94% of the current world production of asbestos and, of this amount, all but a fraction of a percent is derived from deposits whose host rocks are ultrabasic in composition (Berger, 1963; Bates, 1969; Keith and Bain, 1932). This other fraction of the chrysotile production is derived from serpentinized dolomitic limestone. Among the other varieties of asbestos, amosite and crocidolite are found in certain metamorphosed ferruginous sedimentary formations and, together, account for some 5.3% of world production. Tremolite and anthophyllite make up the balance of the production and are generally found in association with highly metamorphosed ultrabasic rocks.

The bulk of world chrysotile production comes from the USSR and Canada. Southern Africa, including Zimbabwe, Swaziland, and South Africa, is the third largest producer with the balance coming from other parts of the world.

Of the Canadian production, by far the greatest amount comes from the Eastern Townships of Quebec (Fig. 8) with northern British Columbia, Ungava, Newfoundland, and Ontario contributing the balance. Russian production comes mainly from the Bazhenovo district in the central Urals, the Dzhetygara area of northwest Kazakhstan, the Kiembay area in the southern Urals and from Ak-Dovurak near the Yenesei River west of Lake Baikal.

The age of asbestos deposits varies greatly from earliest Precambrian in Zimbabwe and Swaziland to Upper Jurassic in California. The Ontario, Ungava, and Brazil deposits are all Precambrian, while those of the Eastern Townships, Vermont, and Newfoundland are all ascribed a Mid-Paleozoic age, associated with early folding in the Appalachian Mountain belt. The deposits of western Canada are connected with mountain building in the Late Paleozoic while the Russian deposits vary from Early Paleozoic to Late Paleozoic or Triassic in age.

Structures

General deformation in the form of faulting, folding, or shearing evidently plays a major role in the localizing of asbestos deposits (Cooke, 1937). The introduction of swarms of small intrusive dikes of acidic to intermediate composition also contributes to the general fracturing and opening up of the rock which, in turn, leads to serpentinization and the formation of chrysotile fiber.

The majority of chrysotile ore deposits tend to occur in serpentinized peridotite rather than dunitic host material. This is probably due to the fact that serpentinized dunite bodies tend to flow when subjected to stress, thereby aiding in the development of fracturing in the surrounding more brittle peridotite.

Asbestos Veining

Chrysotile asbestos is referred to as cross fiber where the fibers lie transverse to the vein, and as slip fiber where the fiber lies in the plane of the vein (Gold, 1967; Cooke, 1937). In the case of cross fiber, the orientation may be anywhere from normal to sharply inclined to the vein walls, in which case it can be referred to as oblique fiber. The fiber in the veins may be straight, gently curved, or contorted. Fiber containing sharp flexures is apt to break easily.

The quality of the fiber ranges from soft and silky to harsh; from highly flexible to brittle; and from strong to weak.

Partings are often present in the veins, either as microscopic discontinuities or as irregular shaped inclusions composed of picrolite, serpentine, brucite, and magnetite, or combinations of these. The veins may be relatively persistent or short and lenticular, occurring in the form of stockworks or in parallel systems known as ribbon fiber. They may be fissure fillings, replacements, or stress-relief features, and are often the result of a combination of these processes.

Some very short fiber is derived from a variety referred to as "mass" fiber. Mass fiber consists of either the complete replacement of most of the original mineral constituents to fiber, each grain of which has a different fiber orientation, or a dense network of fine reticulating replacement veins. Both varieties result in a very high content of short fiber and the rock, which appears to be largely fibrous, is sometimes referred to as "fur" rock.

Other varieties of mass fiber include "platy"

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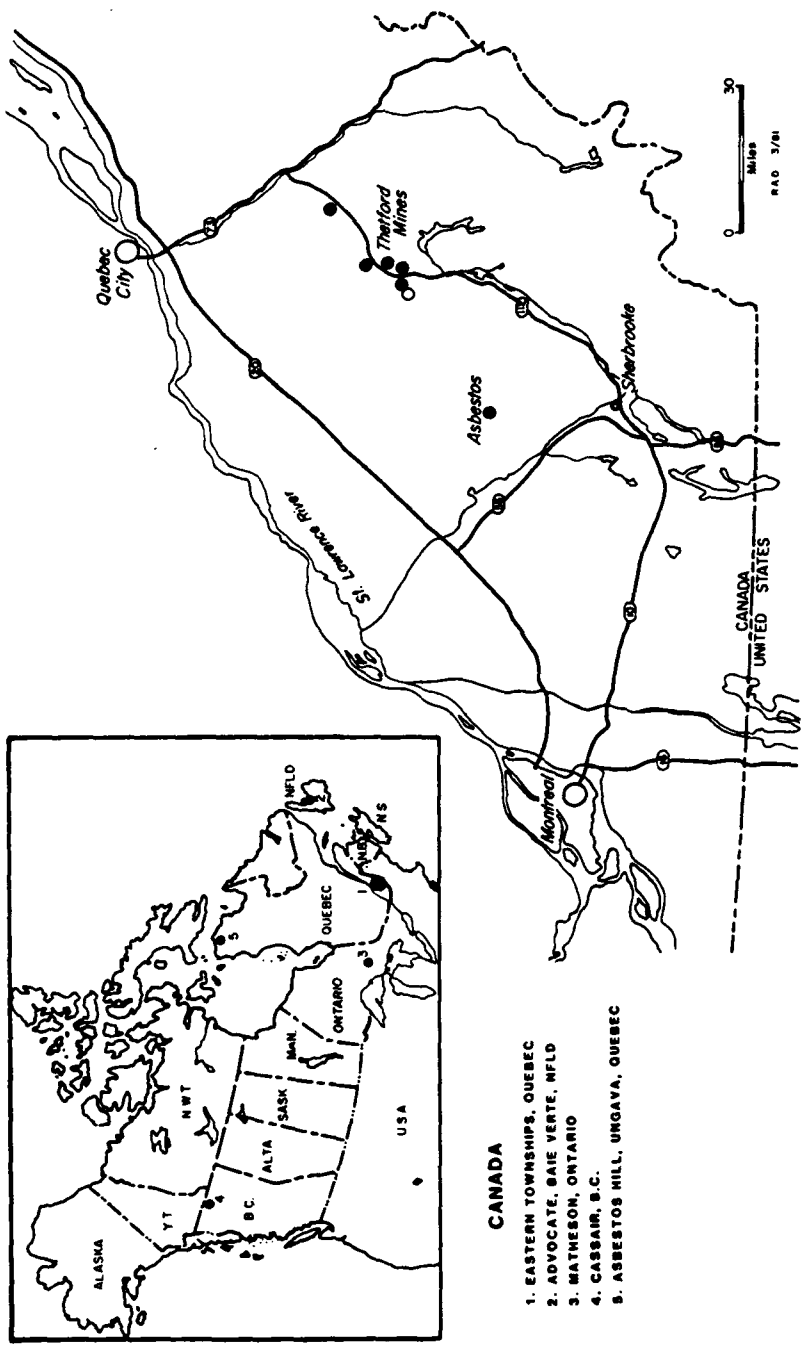

FIG. 8—*Asbestos mining areas in Canada. At right, the Eastern Townships of Quebec.*

fiber, of which the Coalinga deposit is unique. A similar, but less important, variety is known as "mountain leather."

World Asbestos Deposits (Fig. 9)

North America

Canada: *Eastern Townships, Quebec*—Chrysotile asbestos was discovered in two localities in the Eastern Townships in 1878 and has been actively mined at Thetford Mines and Asbestos for over 100 years. The chrysotile deposits of Quebec's Eastern Townships occur intermittently along a major serpentine belt which arcs northeastward into the Gaspé Peninsula in one direction and southward into the Appalachian Mountain belt of Vermont in the other (see Fig. 8).

The area yields over 80% of Canada's fiber production and some 30% of the world total, thereby vying closely with the Bazhenovo district of the Soviet Union for first place in world production. Most of the major occurrences are located along a sector 55 miles long which lies parallel to, and 50 miles southeast of, the St. Lawrence River extending from a point near East Broughton, 50 miles south of Quebec City, southwestward past Thetford Mines and Black Lake to Asbestos and Danville which lie approximately 85 miles east of Montreal.

This serpentine belt is a typical ophiolitic complex of gabbroic and dioritic rocks, and of pyroxenite, peridotite and dunite, serpentinized to various degrees with associated granite, rodingitic, and talc-carbonate rocks. This belt has been described in the past as a partially serpentinized ultrabasic intrusive emplaced in the crust along faulted zones of weakness. More recent study would indicate that this giant complex has been extruded onto or just under unconsolidated aluminous and silicious sediments in a eugeosynclinal ocean basin. Magmatic differentiation within the ultramafic magma is thought to be responsible for the formation of the various pyroxenite, peridotite, and dunite phases found in the complex.

The small granitic masses found within the ultramafic complex have been considered intrusive but may be the result of the ingestion and digestion of fragments of underlying sea floor sediments. Subsequent faulting and shearing has resulted in numerous dislocations within and adjacent to the ultramafic complex.

Consideration of this complex as a submarine extrusive simplifies the problems of water for serpentinization, allowance for large volume change, the occurrence of fiber as open fracture fillings in stockworks, and banded fiber in ribbon zones. It also explains the presence of "pillows," usually gradationally serpentinized from the surface inward.

The fiber occurs mainly in highly serpentinized peridotite (harzburgite containing 10–15% enstatite) and is found in numerous occurrences along the strike of the complex.

There are presently six deposits being mined in the Eastern Townships and numerous others are either dormant or completely mined out. For purposes of description the deposits may be grouped on the basis of their distribution within the belt, i.e., the Pennington dike deposits, those of Thetford Mines area, the Black Lake deposits, and those of Asbestos.

Pennington Dike, Thetford Mines-East Broughton Area (Anon., 1972; Merrill, 1957; Riordan, 1957; Rowbotham, 1970)—Separated from the main Thetford ultrabasic intrusive and extending northeastward for some 17 miles or more is the Pennington "dike" which has supported a number of asbestos mining operations, both past and present, over much of its length. This serpentinite body is actually tabular and more sill-like in form, being closely conformable with the country rocks which dip up to 60°SE. Shearing is conspicuous throughout its length. This is interpreted as being a major thrust fault, the plane of which occurs at the base of the sill. Where the sill is narrow, shearing extends from wall to wall and much of the rock is steatized, but the wider portions which reach a thickness of up to 800 ft are less affected. It is these wider bulges which contain most of the major ore zones. Slip fiber predominates in all the deposits, though some cross fiber is found in the wider, less sheared sections, particularly toward the southwest.

The narrowness of the ore bodies and the attitude of the sill are obstacles to mining any appreciable depth. Only two mines, National Asbestos and Carey-Canadian, are presently operating on the Pennington dike.

Thetford Mines Area (Cooke, 1937; Riordon, 1957, 1957a, b; Riordon and Laliberté, 1957)—A large mass of periodotite is host to the Thetford Mines and Black Lake deposits. The Thetford group lies at the northeast end of this mass and contains four closely connected deposits, all of which lie in a well-defined zone along the hanging-wall side of a prominent fault structure marked by the presence of intensive talc-carbonate alteration. The

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zone has a length of 6000 ft and a width of 1500 ft with the largest and deepest deposits, the King-Bell-Johnson complex, extending to a depth of 1500 ft or more. These deep zones are mined by underground methods. The other deposits are the Bennett-Martin, the Beaver-Consolidated, and the Beaver "C." The first two are now exhausted.

A number of subsidiary shears, most of which have dips in the opposite direction to the main fault and strikes that roughly parallel it, tend to break the ore zone into segments. Most of these subsidiary shears are accompanied by numerous bodies of syenite, and evidently developed along the original zones of weakness into which these acid rocks were introduced. Some large bodies of serpentinized dunite situated within the ore zone contributed to the fracturing in the surrounding peridotite by behaving as relatively incompetent masses which tended to flow under stress.

Black Lake Area (Anon., 1972; Riordon, 1957a, c, d; Riordon and Laliberté, 1957)—There are three major ore bodies in the general vicinity of Black Lake. The British Canadian-Megantic mine is over 1 mile long and ½ mile wide, and occupies a position adjacent to a pronounced flexure in the peridotite contact immediately east of the town of Black Lake. This ore body is cut up into ore shoots by a series of roughly parallel shear zones and syenite dikes striking tangentially to the folded contact. Large bodies of serpentinized dunite are also found within the ore body and produce low grade to barren sections.

Southwest of the town of Black Lake are the ore bodies which comprise the Lake Asbestos mine, the lake having been drained to permit mining of the deposit beneath. The easternmost of these ore zones is situated along the hanging-wall side of a northwest-southeast transverse fault which dips to the northeast. Like the major fault in Thetford this zone has also undergone intensive steatization. Another ore body to the west was located beneath a large, flat-lying acid dike which evidently localized the fracturing in its vicinity and no doubt was responsible for the formation of fiber in the vicinity.

The Normandie mine is located about a mile to the west of Lake Asbestos and two miles southwest of the town of Black Lake. This deposit consists of at least three separate ore bodies lying along a northeasterly plunging fold axis which manifests itself in a pronounced *Z* bend in the peridotite-Caldwell schist contact in the vicinity. The old Vimy Ridge deposit which is now completely worked out is the most southerly of these and occurred close to surface, with much of the upper portions of the ore body truncated and removed by erosion.

The central zone lay completely buried beneath a capping of drift and overburden, and was only discovered by regular grid pattern diamond drilling in the peripheral areas surrounding the old Vimy Ridge mine. The Normandie open pit mine, a very productive operation in its day, has now been mined out.

Further deep drilling on the downdip extension of the Normandie ore body led to the discovery of a deep ore zone lying well beneath the overfolded capping of Caldwell quartzites. This deposit, the Penhale ore body, has been explored by underground methods and is now being considered for production.

The origin of these three ore bodies is closely related to the folding but may also be dependent on a fault zone trending southwest which parallels the fold axis to the east of the ore bodies.

Whereas the other deposits in the Eastern Townships are made up of a stockwork of asbestos veins, the Normandie, Vimy Ridge, and Penhale ore bodies are composed predominantly of a prominent system of parallel veins of ribbon fiber. These veins form a conjugate pattern but dip predominantly to the northeast with the rake of the ore zone.

The Vimy Ridge and Normandie ore bodies are separated by numerous large syenite dikes and some shearing, whereas the Normandie and Penhale deposits are separated by a zone of low grade to barren material.

Asbestos-Shipton Area (Allen et al., 1957; Bourassa, 1957; Rowbotham, 1970; Riordon and Laliberté, 1957)—The Jeffrey and the now-exhausted Nicolet ore bodies occur along the north and footwall side of a peridotite-dunite intrusive. The Jeffrey deposit, discovered over 100 years ago, has been producing since the early 1880s and is now the largest asbestos mine outside the USSR. The ore body itself has an ellipsoidal to cylindrical or roughly pipe-like form, having an average diameter of about 2000 ft and its major axis plunging about 55° to the southwest. The ore zone is bounded on both the footwall and hanging-wall contacts by major faults or zones of shearing which dip south-southeast at about 65° to 70°. The ore body is also cut by several irregular shears which trend roughly parallel to the footwall contact and divide the deposit into five major ore zones. Numerous acid dikes of dioritic to

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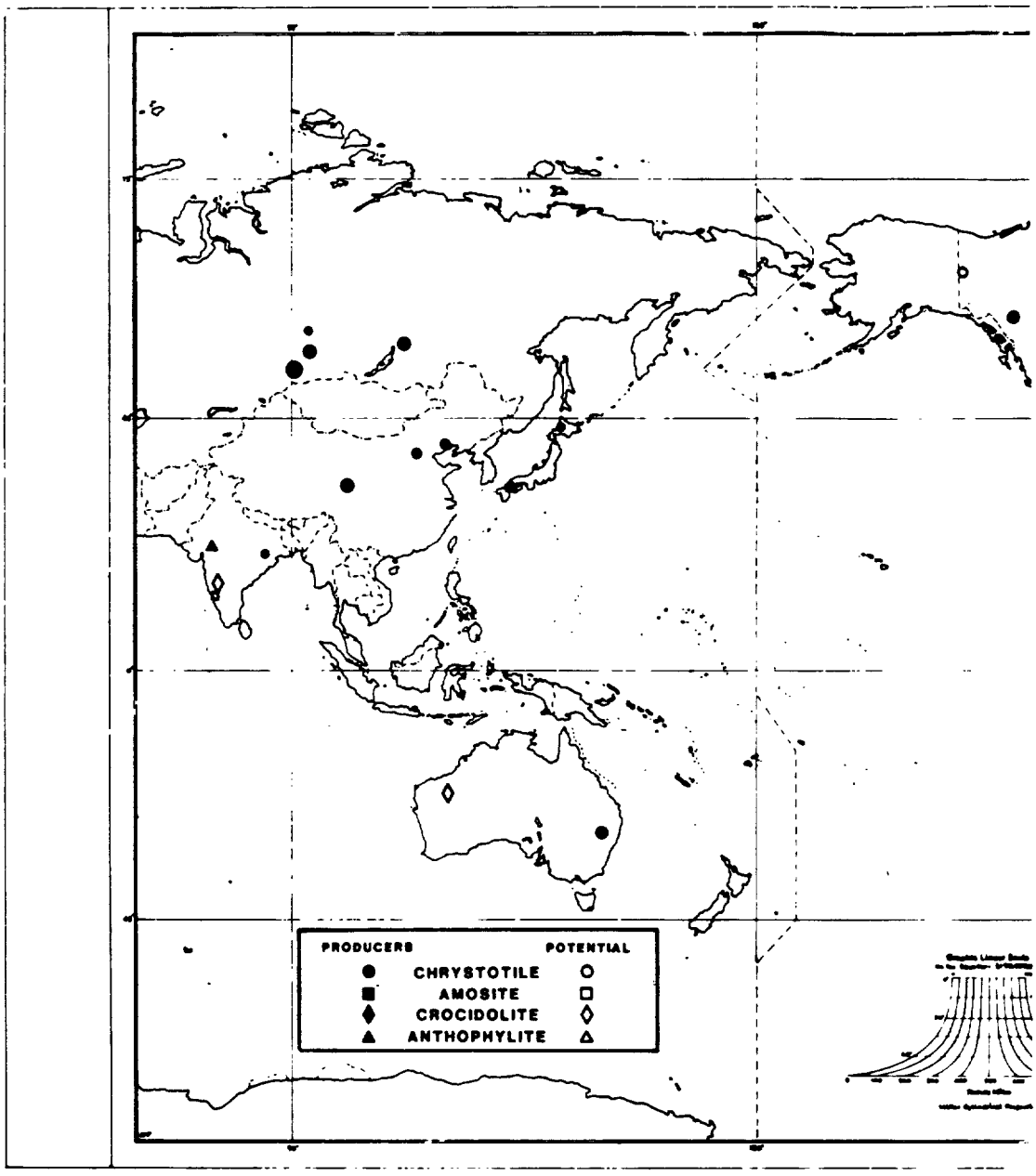

FIG. 9—*World asbestos deposits.*

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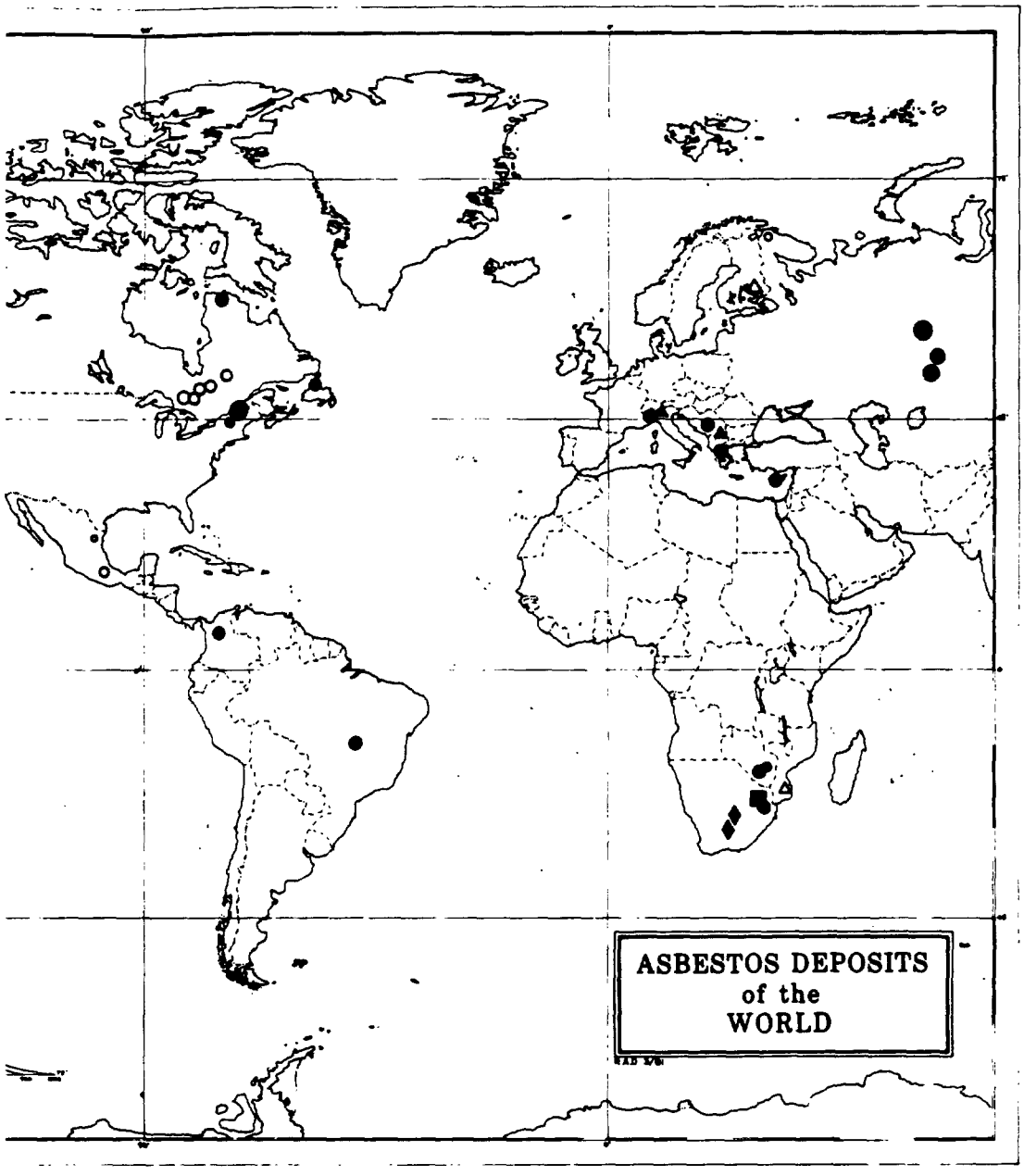
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syenitic composition tend to follow the shear zones but a few exhibit later cross-cutting tendencies. The fiber is generally of good- to medium-grade cross fiber, though sections of slip fiber and mass fiber also occur.

The Nicolet ore body occurred as a narrow zone along the footwall contact, being bounded on its south side by a prominent zone of shearing. This deposit has now been exhausted.

Baie Verte, Newfoundland—Asbestos is currently mined near Baie Verte (Straw, 1961) on the north shore of Newfoundland. The Advocate ore body forms a continuous fiber zone within the highly serpentinized periphery of a massive elliptical pyroxenite body, 1 mile long by ¼ mile wide. The inward dipping fiber zone surrounds the massive pyroxenite core and is in turn surrounded by highly sheared serpentinite. The serpentinite is part of the 55-mile belt of ultrabasic rocks that separate the schists of the Ordovician Fleur de Lys group from the volcanics to the east.

The massive pyroxenite core shows strong parallel, nearly vertical bands of pyroxene-rich and pyroxene-poor phases, suggesting that it is a fragment of differentiated oceanic crust caught up in a subsequent ultramafic flow. The fiber probably formed in fractures on the highly stressed, highly serpentinized periphyry of this peridotite core.

The fiber occurs as a stockwork of good quality fiber veins averaging ¼ to 5/16 in. in length. After mining and milling the fiber is loaded directly at the nearby terminal for shipment to overseas markets.

Reeves Township, Timmins, Ontario—Chrysotile asbestos occurs at Reeves (Douglas, 1970; Rowbotham, 1970; Hendry and Conn, 1957) 40 miles southwest of Timmins. This deposit lies near the northern tip of a large serpentine mass in contact with Precambrian metavolcanics. The south or footwall side of the ore body is bordered by a major east-west fault that dips 45°N in the serpentine. Extensive talc-carbonate alteration is common along this fault. Two north-south diabase dikes cut the ore zone. These have caused pronounced alteration of the fiber along their contacts.

The deposit was mined for a number of years but finally closed in 1974 due to marginal grades and pervasive alteration of the fiber.

The deposit in Munro Township in eastern Ontario has long been exhausted by mining. This deposit occurred within a narrow ultrabasic dike bounded by faults containing pronounced talc-carbonate alteration. The ore zone was also offset by cross faulting.

Cassiar, Northern British Columbia—The Cassiar asbestos deposit (Douglas, 1970; Smitheringale, 1957) occurs at an elevation of over 6000 ft near the peak of Mount McDame in the Cassiar Range. Fiber in the Cassiar deposit is long and of exceptional grade and quality and is associated with an ultrabasic sill intruded into a folded succession of volcanic flows and sediments of Devonian age. The asbestos occurs as cross fiber veins in dark green serpentine commonly ½ to 1 in. wide and up to 15 ft long. This fiber is shipped in special containers by road to Whitehorse, then by narrow-gauge railway to Skagway and from there by ship to overseas markets.

Clinton Creek, Yukon Territory—Mining of asbestos at Clinton Creek (Douglas, 1970) near the Canada-Alaska boundary was short-lived and the relatively small deposit is now closed.

The deposit lies just south of the Yukon River within 150 miles of the Arctic Circle. Here cross fiber averaging close to ¼-in. in length occurred in a small ultrabasic body enclosed by phyllites, argillites, and quartzites of Paleozoic age. A portion of the deposit has also undergone strong talc-carbonate alteration. This remote location necessitated costly road, rail, and shipping transportation similar to that of Cassiar asbestos which decreased the margin of profit considerably.

Asbestos Hill, Putunig, Ungava, Quebec—Situated some 40 miles from tidewater on Quebec's Hudson Strait (Mann, 1962; Stewart, 1978) on the western margin of a large ultrabasic to basic intrusive, is one of Canada's newest and richest asbestos producers, Asbestos Hill. This deposit, about 2500 ft long and up to 200 ft wide, occurs at a point where the dip of the serpentine changes from gently inward-dipping through vertical to steeply outward dipping from the intrusive complex. There is also evidence of a small drag fold where the dip changes most abruptly that appears to form the locus of the ore zone. Talc alteration is present in some zones. The ore is exceptionally high grade with the bulk of the fiber ranging from 5/16 to 7/16 in. in length and a minimum amount of short fiber. This produces a good Group 4 asbestos-cement fiber. The ore near the surface was, until recently, mined by open pit but the deeper parts are now being considered for development by underground methods. The fiber is partially concentrated at the mine site before being transported to Deception Bay and thence by sea during a 3½ to 4-month shipping season to Nordenham, Germany, for final processing.

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Other Potential Deposits—Several other deposits have been considered at various times for possible production. These include the Abitibi deposit situated 50 miles north of Amos; the McAdam deposit 17 miles east of Chibougamau, both in Quebec; the Lloyd Lake Midlothian Township deposit 40 miles south of Timmins, Ont.; and the Garrison deposit 70 miles east of Timmins. An attempt was made to develop the Midlothian deposit at Lloyd Lake but the project encountered serious financial problems and has been halted.

United States of America: Chrysotile asbestos is mined near Eden, VT, and in two localities in California. Small quantities of chrysotile are also recovered from dolomitic limestones in Arizona.

Pacific Asbestos, Copperopolis, California—The Pacific Asbestos deposit (Leney and Loeb, 1972) is located between Copperopolis and Sonora in the foothills of the Sierras about 125 miles east of San Francisco. This deposit occurs within a belt of ultrabasic rocks which trend northwest for 20 miles and reach a maximum width of 4 miles. Strike faulting is common and the peridotites and dunites have been variously altered to serpentine. The ore body occupies a zone about 2000 ft wide between two bands of antigorite schist which are believed to represent zones of shearing within the intrusive. Fiber occurs as cross fiber up to 1 in. in length but most of the fiber is ¼ in. or less. The ore body is cut by narrow dioritic dikes. Talc-carbonate alteration is also prevalent in some portions of the pit.

New Idria-Coalinga, California—The recognition of "platy chrysotile" in the New Idria ultrabasic intrusive led to the successful mining of this fiber in two or three operations northwest of Coalinga (Munro and Reim, 1962) in Fresno County. The ultrabasic body trends northwestward and covers an area some 15 miles in length and 3 to 5 miles wide, having been intruded into Jurassic sediments in Late Jurassic or Early Cretaceous times. The intrusive is composed of highly sheared serpentinite characterized by its extremely platy, slickensided nature. "Boulders" of massive serpentinized material occur scattered through the loose platy serpentine. There is also evidence of abundant landslide material, a factor which may have contributed to the extreme deformation of the serpentine.

The ore contains abundant short chrysotile fiber similar to the Canadian variety but low prices and severe safety and health regulations caused the closing of two of the three producers in the area.

Eden, Vermont—The southern extension of the Eastern Townships serpentine belt of Quebec continues intermittently southward down the Appalachian chain into northern Vermont (Rowbotham, 1970). Fiber occurrences have been known for many years over a considerable area in Lamoille and Orleans Counties. The deposit which has been producing for a number of years lies near the village of Eden. Here a substantial ore body, some 3000 ft wide, is being mined at the foot of Mount Belvidere between elevations of 1000 and 1500 ft.

Slip fiber is the more predominant variety mined but some good quality cross fiber is also recovered. The host rock is a highly serpentinized peridotite with the fiber occurring along a contact between gneiss and amphibolite schist.

Mexico: *Cuicatlan, Oaxaca*—A large occurrence of slip fiber has been discovered at Concepcion Papalo east of Cuicatlan, and about 50 miles north-northwest of Oaxaca in Mexico. The Pegaso occurrence is exposed on two sides of a ridge in highly dissected terrain and appears to be part of a tabular serpentinite body which forms the core of a highly folded and sheared sequence of rocks.

The occurrence is presently under study for possible production but the lower tensile strength and the fact that the fiber is slip variety render the deposit very marginal.

Ciudad Victoria, Tamaulipas—Occurrences of chrysotile fiber are known to occur in the Sierra Madre Oriental Mountains west of Ciudad Victoria (Rowbotham, 1970) in the State of Tamaulipas. These are generally small, discontinuous zones of ribbon fiber and are of little economic significance.

South America

Cana Brava, Goiás, Brazil: The Cana Brava asbestos deposit is located some 120 miles north of Brasilia and 60 miles northeast of Uruaçá in the State of Goiás. Little is known about the deposit except that it occurs in a large ultrabasic body which intrudes gneisses of the Brazilian Precambrian Shield. The ore is apparently a good quality cross fiber of medium length which occurs in two separate zones 1800 ft long and roughly 200 ft wide. The bulk of this fiber is utilized by local Brazilian manufacturers.

Las Brisas, Antioquia, Colombia: A deposit

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of chrysotile asbestos is at present being readied for production at Las Brisas, Antioquia, in central Colombia (Harris, 1973). This property lies about 80 miles north of Medellin or roughly midway between Bogota and the Caribbean port of Cartagena. The deposit is reported to comprise at least two separate zones containing fiber of distinctly different grade.

Europe

Balangero, Northern Italy: The bulk of the Italian chrysotile production comes from Balangero (Rowbotham, 1970), a large, low grade slip fiber deposit located near San Vittore about 20 miles north-northwest of Turin. The ore zone occurs in a highly sheared serpentine body about 1500 ft wide which trends north-south and is intrusive into paragneisses in the foothills of the Alps in Western Italy.

Zidani, Kozani, Northern Greece: Situated about 75 miles southwest of Thessaloniki and 20 miles due south of Kozani is a large, low grade slip fiber deposit which currently is being developed for production. The deposit occurs in a highly sheared and fractured serpentinite, probably of dunitic composition which is flanked by crystalline marble to the west. The property was in production in 1981.

Troodos, Cyprus: Cyprus (Bear, 1963; Vokes, 1964) is an ancient source of asbestos, as it was known and exploited by the ancient Greeks and Romans. These deposits are some of the largest occurrences of chrysotile in the European area.

Asbestos has been mined for the past 70 years near Amiandos in the Troodos Mountains in the south-southwestern portion of the island. The chrysotile occurs in a body of bastite-serpentinite covering an area some 3½ miles north-south and 2½ miles wide, being roughly oval in plan. The best fiber is confined to the southern part of the area near the faulted eastern margin of the peridotite where deformation was most intense. The fiber occurs in small discontinuous lenticles or in larger composite veins of cross fiber and picrolite up to ½ in. wide and several feet long. The fiber seldom exceeds ¼ in. in length. These deposits are probably Upper Cretaceous in age.

The Troodos mine is at an altitude of 5000 ft and the crude ore is transported to Limassol by a 19-mile-long aerial ropeway for further processing.

Yugoslavia: Short fiber chrysotile has been produced from a number of mines in Yugoslavia (Rowbotham, 1970) for many years. Many of these mines have undergone expansion recently and this is reflected in the latest production figures. Deposits are mined at Korlace in Serbia and near Tuzla, Bosnia. Details of the geology of these deposits are not available.

USSR: Russia (Nalivkin, 1960; Rowbotham, 1970; Smirnov, 1971; Stenho and Fronek, 1977; and Petrov and Znamensky, 1978) is now considered to be the largest producer of asbestos in the world with an estimated production of 3,197,000 short tons of fiber in 1978 and 2,723,000 tons in 1979.

The USSR's known reserves are vast and are considered to surpass those of any other country.

There are four major areas of asbestos production in the USSR: the Bazhenovo deposits of the Central and Northern Urals, the Dzhetygara district in the Southern Urals of western Kazakhstan, the newly opened Kiembay district also in the southern Urals and the Ak-Dovurak deposits in Tuva ASSR some 600 miles west of the southwest end of Lake Baikal.

Bazhenovo (Bajenovsk) District—According to its production and reserves, the Uralian deposits of Bazhenovo occupy first place in the USSR and rival the Eastern Townships of Quebec for the leading asbestos district of the world. These deposits are affiliated with the Bazhenovo-Alapajevsk or eastern serpentine belt which extends for a distance of about 110 miles in the Central Urals. Most of the deposits are centered around the new town of Asbest which is 50 miles northeast of Sverdlovsk and 900 miles east of Moscow.

The deposits are associated with fault zones in serpentinites which formed predominantly as the result of alteration of peridotites and, to a lesser extent, pyroxenites. Formation of the veins of chrysotile is thought to be by filling of fissures in a massif of ultrabasic rocks.

Mines in the Asbest area and others at Alapajevsk, Novaja and Lesnoje, together with the deposits at Rez (East Aninsk) Krasnouralsk, Lukosk and Krivisk have an annual capacity of at least 1.5 million tons of fiber.

Besides the Bazhenovo group, a number of other deposits of asbestos are known.

Dzhetygara District, Northwest Kazakhstan—This constitutes the second largest area of production in the USSR and has been in production since 1965. The district has a planned annual production of about 800,000 tons.

The Dzhetygara district lies some 140 miles southwest of Kustenay. Little is known of the geology of the deposits except that they occur

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in serpentinized peridotites of Early Hercynian (Middle Devonian) age.

Kiembay (Kijembai), Southern Urals—This deposit, the third largest in the USSR, is located some 90 miles east of Orsk in the Orenburg Administrative Region. The deposit occurs in a completely serpentinized ultrabasic intrusive. Severe weathering 150 to 200 ft deep has caused the surface fiber to become weaker and relatively brittle. The deposit has been developed recently by a collective combine with Czechoslovakia, Poland, Hungary, East Germany, Romania and Bulgaria participating with the USSR to bring it to its planned productive capacity of 550,000 tpy.

Ak-Dovurak (Aktovrak), Tuva ASSR—Important deposits of asbestos have recently been developed near Ak-Dovurak, Tuva, near the Yenesei River to the west of Lake Baikal. These deposits are associated with a belt of serpentinized ultrabasic rocks of the Salair complex which forms part of the Lower Hercynian of the eastern Altai-Sayan Province. The ultrabasic intrusions occur intermittently in belts which extend along major faults.

At least six significant deposits have been discovered and the district is reported to contain vast reserves near the village of Kyzyl-Mazalyk and the Kedrovsk deposit 30 miles to the south.

Other Deposits—Chrysotile asbestos deposits are known at Molodeznoje (Molodjezhnoje) some 130 miles east of the northern end of Lake Baikal. The deposit is of excellent grade but will have to await development until the Baikal-Amur railway is constructed.

The Ilcirsk and Sajan deposits in the same general area also have good potential for future production.

A peculiar fiber deposit is located near Pechenge close to the Norwegian border. Although the deposit is large, the high iron content is very detrimental to the value and it is doubtful whether the deposit will ever prove to be economic.

Africa

Shabani, Zimbabwe: The Shabani mine (Laubscher, 1964; 1968; Oldham, 1968; Wilson, 1968), situated some 100 miles east of Bulawayo, has the largest reserves of fiber in southern Africa. The deposit occurs near the base of a lenticular ultrabasic sill 9 miles long and 1½ to 3 miles wide which intrudes Early Precambrian gneisses. The sill strikes northwest and dips about 40° SW and is composed of dunite at the base, overlain by peridotite, pyroxenite, and gabbro. A swarm of younger diabase dikes cut the ore zone but these are themselves truncated by strong zones of shearing, both parallel and oblique to the basal contact. The intrusion and shearing has caused strong serpentinization of the dunite and heavy talc-carbonate alteration, particularly along the footwall shear zone. The fiber occurs as a stockwork of cross fiber veins described as "stress-controlled dilation seams." The quality is good and the length of the fiber up to 1½ in. in places.

Fiber is also mined at other localities in Zimbabwe, notably in the Mashaba, Belingwe, and Filabusi districts.

Msauli, South Africa: The Msauli mine (Hall, 1930; Pelletier, 1964; Van Biljon, 1964) is located 16 miles south-southeast of Barberton in the eastern Transvaal and only six miles southwest of the Havelock mine across the Swaziland border. The serpentine in which this ore body occurs is very similar to that of the Havelock deposit in what appears to be the faulted continuation of the same sill-like ultrabasic intrusive. The serpentine body averages 450 ft wide and dips about 65° to the east. The best fiber is reported to occur to the north in association with major faulting. The fiber occurs as a stockwork of veins from 1/32 to ¾ in. and is of the same general high quality as that of Havelock. However, some sections contain a higher percentage of magnetite.

Havelock, Swaziland: The Havelock mine (Pelletier, 1964; Van Biljon, 1964) is located within ½ mile of Swaziland's western border with the Republic of South Africa, and lies some 12 miles south-southeast of Barberton in the eastern Transvaal. Here, a sill-like body of serpentine of the ancient Jamestown Complex is intercalated in the Early Precambrian Fig Tree sedimentary sequence, all of which dip south at 55°. The ore zone has a strike length of 5000 ft and widths from 60 to 350 ft averaging about 110 ft. The ore body is traversed by a longitudinal fault zone with associated transverse faulting. Talc-carbonate alteration is prevalent in the western portion of the mine. The fiber occurs as a stockwork of high quality cross fiber seams, which average ½ in. or more in length and comprise 3% to 4% of the rock. Mining of the upper portion of the ore body was by open cast workings, the deeper portions now being mined by underground methods. The ore is transported by aerial cableway to Barberton for processing.

Other Deposits: Many small deposits of

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chrysotile asbestos occur at many locations in northern and eastern Transvaal but their combined production has never been appreciable. Most of these are elongated ribbon fiber zones which are in ultrabasic rocks or associated with dolomitic limestones.

Occurrences of chrysotile fiber are also reported from the Ingessana Hills and Qala en Nahl districts of eastern Sudan. Both areas have been explored extensively and several small deposits have been indicated, but the total potential remains relatively small.

Australia

Woodsreef (Transpacific Asbestos), New South Wales: The Woodsreef (Straw, 1964; Butt, 1978) asbestos deposit is located just east of Barraba approximately 340 miles north of Sydney in northeastern New South Wales. The deposit occurs in a lens of serpentinite approximately 5 miles long and 1½ miles wide which forms part of the Great Serpentine Belt of New South Wales. The ore body occurs in a layered peridotite-dunite complex which has intruded sediments of Mid-Paleozoic age, and is approximately 2300 ft long and 250 ft wide. It is bounded on the western margin by prominent faulting and shearing. Strong shear zones are also prevalent within the fiber zone. The fiber occurs mainly as a stockwork of cross fiber seams and is generally short to medium in length. Although production commenced in 1972, the mine has encountered serious fiber recovery problems and the long-term viability of the deposit is still in question. Most of the fiber is exported to Japan but some is consumed locally.

New Zealand

Pyke Asbestos, South Island: A small occurrence of chrysotile fiber is reported near the headwaters of Pyke River (Babcock, 1978) high in the Southern Alps some 50 miles northeast of Milford Sound on the South Island of New Zealand. Due to its isolated location and relatively low grade, it is not expected to be exploited in the near future.

Asia

China: Little is known about the geology of Chinese asbestos deposits apart from a few short reports written by various mining and trade delegations (Mamen, 1973). However, various production estimates indicate that China ranks fourth in world production with 231,000 tons of fiber produced in 1978.

The Lai-yüan district of Hopeh, situated approximately 100 miles southwest of Peking, was for many years the only source of chrysotile in China.

Emphasis has recently shifted to the Shihmien area which is located about 250 miles west of Chungking in southwest Szechwan (the word *Shihmien* is translated as *rock cotton*). At least a dozen projects now contribute to the production from this area which totals more than 50,000 tpy of long and short chrysotile fiber.

A small amount of fiber is also recovered from the Chin-chou mine in Liaoning which lies some 265 miles east-northeast of Peking.

India: Indian asbestos production (private communication) is small and includes chrysotile of both ultrabasic and limestone origin, together with some amphibole varieties.

The small Roro deposit, located in southern Bihar State, about 175 miles west of Calcutta, is an example of chrysotile production. Here the ribbon fiber occurs in five separate discontinuous zones along highly serpentinized contact zones between massive serpentinized peridotite bands and massive to sheared "clot" peridotite. One of these, the Upper Zone, is economic and contains from 7% to 15% fiber over minimum mining widths. The ore is hand-cobbed and sorted for milling.

Japan: Chrysotile asbestos is mined at two localities in the Yamabe district of Hokkaido, Japan (Rowbotham, 1970). The fiber is generally short and all of the production is utilized locally.

Chrysotile in Dolomite

In addition to the large deposits of chrysotile asbestos found in serpentinized peridotite there are comparatively small tonnages mined from serpentinized dolomitic limestones (duToit, 1946; Hall, 1930; Pelletier, 1964; Rowbotham, 1970; Van Biljon, 1964). Such fiber is often of high quality and is free of the magnetite found associated to a varying degree with deposits where the original host rock is of ultrabasic igneous origin.

Chrysotile of this type has been mined from the Carolina district in the Transvaal and in the Salt River and Sierra Ancha regions in Arizona where it is found in narrow bands associated with diabase sills. The only chrysotile of this variety known in the USSR occurs near Aspa-

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gash just south of Krasnovask on the Yenesei River.

Crocidolite and Amosite

Both crocidolite and amosite occur in South Africa (Cilliers and Genis, 1964; Cilliers et al., 1964; duToit, 1946; Frankel, 1953; Hall, 1930; Keep, 1961; Pelletier, 1964) in bedded metamorphosed sedimentary formations known as banded ironstones, that may be classed as ferruginous quartzite or probably more exactly as an iron-rich silicified argillite. Cross fiber veins are found as closely spaced ribbons roughly conformable with the bedding which in some localities is distorted and steeply dipping. Crocidolite veins are generally less than 2 or 3 in. thick with the bulk of the fiber between ¼ to ¾ in. in length. Amosite veins on the other hand often range up to 10 or 12 in. thick.

Crocidolite is found over a large area of Cape Province occurring in a belt of the Lower Griquatown series of the Transvaal system. One of the oldest producing areas is in the vicinity of Prieska on the Orange River with notable production coming from Westerberg and Koegas, located a few miles down the river. Another producing area of blue asbestos in the Cape Province is farther north in the Kuruman district, and at Pomfret, just south of the Botswana border.

Approximately 200 miles northeast of Johannesburg both crocidolite and amosite are found in similar formations in the vicinity of Pietersburg in northern Transvaal. In some places here the two varieties have been known to occur side by side in the same vein. Such a vein, having fibers composed of crocidolite at one end and amosite at the other, is referred to as a "doublet." It is interesting to note that there is generally no weakening of the fibrils at the point of contact of the two varieties of fiber.

In the Pietersburg area a quite silky-fibered phase of amosite called *montasite* is found which is often a dusty blue in color and has sometimes been confused with crocidolite.

Widespread occurrences of amosite and crocidolite are known to occur in the Bababudan Hills north of Chikmagalur in Mysore, India. Both varieties of fiber occur in an assemblage of banded ironstones and shales similar to those of northeastern Transvaal but the amosite in particular is noticeably shorter. However, one area of amosite has been intensively investigated for possible production.

Deposits of crocidolite are found in the Hammersley range of western Australia, as well as in Bolivia and elsewhere.

Amosite-bearing banded ironstone crops out for a distance of over 20 miles near Penge in the Lydenburg district of the Transvaal. The fiber-bearing "reef" is being worked at three points along the strike, at Penge, and at the Weltevreden and the Kromellenboog mines. A good cross section of the country rock has been exposed by diamond drilling to 1000 ft in depth. The fiber-bearing banded ironstones and associated sedimentary members dip southwestward at about 20°. This sequence has been intruded by thin persistent sills of dolerite which are conformable with the bedding.

The following column is from a 1200-ft diamond drill hole intersecting the fiber-bearing horizon at a depth of 1000 ft below the surface at the "Amosa" mine which is part of the Penge property:

Shales
Dolerite sills
Shales
Bevetts conglomerate
Banded ironstone (main fiber zone)
Dolerite sill
Banded ironstone (sometimes fiber-bearing)
Dolomite

The Bevetts conglomerate is considered an important "marker" for the fiber-bearing formation.

In addition to the rock series in the foregoing, diabase cuts vertically across the whole formation at intervals. Evidence as to possible relationship of these dikes to the genesis of the amosite mineralization is inconclusive.

With the steady depletion of known amosite ore reserves, extensive exploration for additional ore was initiated a few years ago. Considerable success was achieved by utilizing a novel structural approach developed by the Cape Asbestos Group (private communication).

Careful mapping of the main marker horizons with respect to detailed topographic contours disclosed a system of broad, gentle north-south folds having amplitudes of about 50 ft and wavelengths of 4000 to 5000 ft between crests. A second, superimposed pattern of east-west cross folds was also detected having similar amplitude and a wavelength approaching 7000 ft. Careful structural mapping further indicated that each of the known or producing deposits was located on the loci of intersections of either anticlinal or synclinal structures.

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Consequently, by drilling similar loci, at least five new fiber occurrences were discovered and the sixth failed only because the precipitous terrain in the area prevented drilling directly on target. Nevertheless, a drill hole angled toward the target from the nearest accessible location did disclose traces of fiber on the periphery of the target.

This record of successful drilling gives considerable weight to the hypothesis of a structural control for the genesis of amosite fiber. Similar patterns of cross-folding have been noted in many crocidolite deposits in the Northwest Cape and elsewhere.

It should be remembered, however, that the main prerequisite for any fiber development is to have the necessary chemical components for a specific fiber variety. Without the required chemical constituents, no amount of folding, faulting, or alteration can produce any fiber.

It is interesting to consider this structural origin for the genesis of chrysotile fiber as well, because the effects of faulting, folding, and dilation by shearing or intrusion almost invariably occur in close proximity to fiber occurrences.

Anthophyllite, Tremolite, and Actinolite

Production of amphibole asbestos (Rowbotham, 1970), other than crocidolite and amosite, includes significant amounts of anthophyllite, a small quantity of tremolite, and token amounts of fibrous actinolite.

Of the world's known anthophyllite deposits, Finland has been by far the most important producer. However, the famous deposits at Paakkila in the parish of Tuusniemi near Outokumpu in eastern Finland, as well as those of Maljasalmi in Kuusjarvi Parish some 10 miles to the east have now been mined out and no further production is anticipated.

The anthophyllite occurred as a series of lenses of amphibolitized and serpentinized ultrabasic material originally thought to be dunitic in composition. These lenses appear to have become detached from larger bodies during an early period of severe deformation. The serpentinized amphibolite lenses occur in a biotite gneiss which is intruded by Late Karelian granites and pegmatite.

The size of these bodies was generally small, varying from 125 to 200 ft in length and 30 to 80 ft in width with a potential of 40,000 to 100,000 tons of anthophyllite asbestos in each pod.

Exploration for these isolated bodies is difficult and often costly as the area is drift-covered and most of the ore lenses are not exposed at surface.

Present mining of these ore bodies is by open pit with the ore being processed at a centrally located mill.

Other amphibole asbestos is reported from many countries including Yugoslavia, Bulgaria, Brazil, Japan, India, and Taiwan. Little is known of the mode of occurrence of these deposits or their present production status.

A small quantity of anthophyllite is mined near Greenmountain, Yancey County in North Carolina. Production has been small and erratic but is reported to be increasing slightly. Similar material is known to occur in the nearby state of Georgia.

Italy continues to produce a limited quantity of long-fibered tremolite from small deposits located at Val Malenco, in the Sondrio district some 60 miles north of Milan. Reports of tremolite fiber are also known from the Aosta district north of Turin in the Italian Alps.

The Mavita anthophyllite mines of Mozambique, closed since 1975, are expected to reopen shortly pending the testing of a pilot plant (*Asbestos*, 1980).

Although some occurrences of fibrous actinolite are reported, production is extremely limited and of negligible value.

Principal Deposits

In the foregoing sections, the major asbestos deposits of the world have been briefly described. Global distribution of these deposits appears to be rather haphazard, but closer examination reveals that their occurrence generally coincides with the earth's major chains of mountain building of all ages. This is particularly true of the Urals, the Appalachians, and Rocky Mountains, but the relationship is more difficult to recognize in Precambrian fold belts.

Production

Of the world's two leading producers, both the USSR and Canada (Hendry, 1972) have vast reserves of chrysotile fiber; though, from the limited information available, it would appear that Russia has more reserves than Canada. Elsewhere in the world, reserves seem to be fairly evenly distributed among those countries presently producing, or those in which potential deposits are known (Table 7).

The production of fiber, including both

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chrysotile and the various types of amphibole asbestos, increased steadily to a peak in 1978, but has declined since (Fig. 10). Of particular note is the lead taken by the Soviet Union in the mid-sixties. However, it is interesting to note that some authorities consider this figure to be biased by the inclusion of a greater proportion of very short fiber grades not presently recovered in Canada.

Russian production of medium and short fiber chrysotile is concentrated in the Central Urals where the large "Asbest" combine, together with smaller mines and mills at Alapajevsk, Nizhnitagil, Kiyembay, and south of Sverdlovsk, are capable of producing about 1.5 million tpy of fiber. Production has been steadily increasing over the last 25 years, both at existing mines and at new mills at Dzhetygara in northwest Kazakhstan and Ak-Dovurak in the Tuva ASSR. Other deposits such as Molodezhnoe and Ilchirsk in the Buryat SSR and those discovered at Bugetsaysk in Kazakhstan await development.

There are no less than six large mills in the "Asbest" combine, the sixth being commissioned recently. Combined capacity of these mills is now well over 1 million tpy. The first stage of the Dzhetygara combine in Kazakhstan was completed in 1965 with a productive capacity of 500,000 tpy. Since then a second stage of development and expansion has been completed.

The first stage of the "Tuvaasbest" combine at Ak-Dovurak came into operation in 1966. This was followed by further expansion to give a potential capacity of over 500,000 tpy of fiber.

The graph showing Canadian production has been climbing steadily over the last 20 years. This has been brought about by the enlarged capacities of many plants and the opening of several new mines such as Advocate, Reeves, Clinton Creek, and Asbestos Hill. During this same period several deposits have been depleted resulting in the closing of several properties including Munro, Nicolet, Flintcote, Reeves, Normandie, and Clinton Creek.

According to the latest statistics, the Eastern Townships of Quebec (which have been producing asbestos for the past 100 years) and Ungava now account for 1.482 million tpy of fiber. This represents approximately 89% of Canadian production, with the balance coming from British Columbia (7.8%) and Newfoundland (3.2%). The Jeffrey mine at Asbestos is the largest single producer, accounting for some 600,000 tpy of fiber. The balance of the production, amounting to approximately 750,000 tons, comes from a number of mines located in and around Thetford Mines.

African production ranks third in world production statistics. It should be remembered, however, that this production comprises 430,000 tons of chrysotile produced in Zimbabwe, the Republic of South Africa, and Swaziland, as well as 207,000 tons of crocidolite and 64,000 tons of amosite produced in South Africa. Zimbabwean production has increased appreciably in the last few years since the completion of a large expansion program at Shabani.

Recent mining of these ore bodies was by open pit with the ore being processed at a centrally located mill.
and 231,000 tons in 1978.

European production has shown only minor fluctuations over the past 15 years. Most of the mines are relatively small and production tends to fluctuate. Italy leads European production with 146,000 tons of fiber, most of which is mined at Balangero. French production has all but ceased with the closing of the Corsican asbestos mines.

The United States ranks eighth in world production with 103,000 tons in 1978 and a similar amount in 1979. Most of this production comes from California and Vermont with a small amount from chrysotile in dolomites mined in Arizona. Overall production took a noticeable increase in 1963 and 1964 when the Coalinga-New Idria deposits were first developed but this has dropped again with the closing of two of the mines in this area.

Most other countries show little change in overall production. Brazil, however, has risen to seventh in world production due largely to the opening of Cana Brava mine north of Brasilia at Uruaçú.

Australia ranks ninth in world production with all of its tonnage coming from the Woodsreef deposit near Barraba in New South Wales.

The production of crocidolite and amosite comes solely from the Republic of South Africa. Most of the crocidolite production comes from a number of small mines in the Prieska, Griquatown, and Kuruman districts of the Northern Cape but some production is also mined in the Pietersburg district of the northeastern Transvaal.

Varieties of amphibole asbestos, other than crocidolite and amosite, have a comparatively limited production. Of this, anthophyllite dominates the field, leaving a very limited quantity of tremolite and negligible amounts of fibrous actinolite.

Of the world's known anthophyllite deposits,

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TABLE 7—Asbestos—World Production (1000 St)

	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
North America:												
Canada	924	1064	1014	1046	925	1050	1118	1174	1216	1277	1421	1388
United States	48	45	41	44	44	45	45	53	53	66	101	118
Mexico	—	—	—	—	—	—	—	—	—	—	—	—
Total	972	1109	1055	1090	969	1095	1163	1227	1269	1343	1522	1506
South America:												
Argentina	Tr	1	Tr	Tr	Tr	Tr	—	—	—	Tr	1	Tr
Bolivia	Tr	—	Tr	Tr	—	Tr	Tr	Tr	Tr	Tr	Tr	—
Brazil	3	3	4	3	4	4	4	3	5	1	—	1
Venezuela	1	2	5	8	9	5	4	1	—	—	—	—
Total	4	6	9	11	13	9	8	4	5	1	1	1
Europe:												
Austria	—	—	—	—	—	—	Tr	1	1	1	—	—
Bulgaria	1	1	1	1	1	1	1	1	1	1	1	1
Finland	8	19	8	10	8	10	11	10	11	10	12	13
France	14	14	9	16	21	23	29	31	28	27	24	11
Greece	Tr	Tr	Tr	Tr	—	—	—	—	—	—	—	—
Italy	26	35	39	38	40	53	61	63	61	63	76	79
Portugal	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	—	Tr	—	Tr
Spain	Tr	—	—	—	—	Tr	Tr	Tr	—	—	—	—
USSR[e]	375	450	500	500	550	600	660	880	1100	1200	1300	1500[e]
Yugoslavia	4	4	4	5	6	5	6	7	7	9	9	11
Total	428	523	561	570	626	692	768	993	1209	1311	1422	1615
Africa:												
Botswana	1	1	1	2	2	1	1	2	2	2	2	1
Eritrea	—	—	—	Tr	Tr	—	—	—	—	—	—	—
Kenya	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Morocco	1	1	Tr	Tr	—	—	—	—	—	—	—	Tr
Mozambique	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	—	—
Zimbabwe	90	105	119	132	127	120	134	162	142	142	153	185[e]
South Africa	109	120	137	157	176	182	176	195	221	206	216	241
Swaziland	30	33	30	31	25	25	32	31	33	33	40	41
United Arab Republic	Tr	—	—	Tr	Tr	1	Tr	Tr	1	Tr	2	3
Total	231	260	287	322	330	329	343	390	399	383	413	471
Asia:												
Afghanistan	—	—	—	—	—	—	—	—	—	—	—	—
China[e]	15	23	26	33	66	90	90	100	100	110	130	140
Cyprus	15	15	15	15	16	14	23	16	22	20	14	18
India	Tr	2	1	2	1	1	2	2	2	3	3	5
Iran	—	Tr	2	Tr	Tr	—	—	—	—	—	—	—
Japan	7	7	10	13	11	14	17	19	15	18	18	16
Korea	Tr	Tr	Tr	Tr	Tr	Tr	1	Tr	1	2	1	2
Philippines	—	—	—	—	—	Tr	Tr	Tr	1	Tr	1	—
Taiwan	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	1	1	1	1
Turkey	Tr	Tr	1	Tr	1	Tr	Tr	Tr	1	Tr	1	1
Total	37	47	55	63	95	119	133	137	143	154	169	183
Australia	5	6	10	15	16	18	16	17	18	13	14	12
New Zealand	—	Tr	Tr	Tr	Tr	1	Tr	Tr	Tr	Tr	—	—
Total	5	6	10	15	16	19	16	17	18	13	14	12
Total World[e]	1677	1951	1977	2071	2049	2263	2431	2768	3043	3205	3541	3788

Source: 1954–1969, 1979 compiled from *US Minerals Yearbook*, US Bureau of Mines; 1970–1971 compiled from British Institute of Geological Sciences, and various trade journals; 1972–1978 compiled from Johns-Manville records and various trade journals.

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1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979*
1489	1452	1510	1577	1662	1635	1629	1810	1824	1260	1664	1598	1568	1655
126	123	121	126	126	131	132	150	112	99	115	109	103	103
—	—	—	—	—	—	—	—	—	—	—	—	—	—
1615	1575	1631	1703	1788	1766	1761	1960	1936	1359	1779	1707	1671	1758
Tr	Tr	Tr	Tr	Tr	Tr	Tr	—	Tr	Tr	Tr	Tr	Tr	Tr
—	—	—	—	—	—	—	—	—	—	—	—	—	—
2	2	5	10	14	22	36	48	71	77	77	103	135	132
—	—	—	—	—	—	—	—	—	—	—	—	—	—
2	2	5	10	14	22	36	48	71	77	77	103	135	132
—	—	—	—	—	—	—	—	—	—	—	—	—	—
1	2	2	3	4	3	3	14	27	24	Tr	Tr	Tr	Tr
13	12	14	15	15	16	7	7	7	3	—	—	—	—
Tr	Tr	—	1	1	—	Tr	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—
91	111	114	124	131	132	146	165	163	162	184	165	154	143
Tr	Tr	Tr	Tr	Tr	—	Tr	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—
1720	1980	1980	2000	2100	2200	2425	1698	2205	2955	3080	3197	3197	2723
8	10	11	13	13	17	12	9	12	15	13	9	11	12
1833	2115	2121	2156	2264	2367	2593	1893	2414	3159	3277	3371	3362	2878
—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—
Tr	Tr	—	—	—	—	—	—	—	—	—	—	—	—
1	1	Tr	1	—	—	Tr	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—
175	107*	95*	88*	88*	88	88	259	264	270	182	221	221	259
277	268	261	285	317	352	356	369	364	391	402	408	386	275
36	40	43	43	36	39	39	39	41	41	43	47	41	42
2	NA	3	—	—	—	—	—	—	—	—	—	—	—
491	416	402	417	441	479	483	667	669	702	627	676	648	576
—	—	—	—	—	—	—	—	—	—	15	14	14	4
150	165	165	180	190	176	220	138	198	199	232	231	231	276
24	19	21	24	28	25	31	35	31	35	37	39	39	40
8	8	10	11	11	12	14	8	8	5	5	5	8	22
—	—	—	—	—	—	—	—	—	—	—	—	—	—
21	27	24	23	24	24	16	9	5	5	9	8	7	9
1	2	4	7	2	—	2	7	7	7	5	7	15	15
1	Tr	Tr	Tr	1	—	—	—	—	—	—	—	—	—
1	1	1	3	3	—	3	5	4	2	2	3	2	3
1	2	4	6	2	2	4	5	18	18	11	9	11	11
207	224	229	254	261	239	290	207	271	271	316	316	327	380
13	1	1	1	1	1	1	49	37	61	66	56	69	77
—	—	—	—	—	—	—	—	—	—	—	—	—	—
13	1	1	1	1	1	1	49	37	61	66	56	69	77
4161	4333	4389	4541	4769	4874	5164	4824	5398	5629	6142	6229	6212	5801

NA Not Available
e estimate
Tr Trace

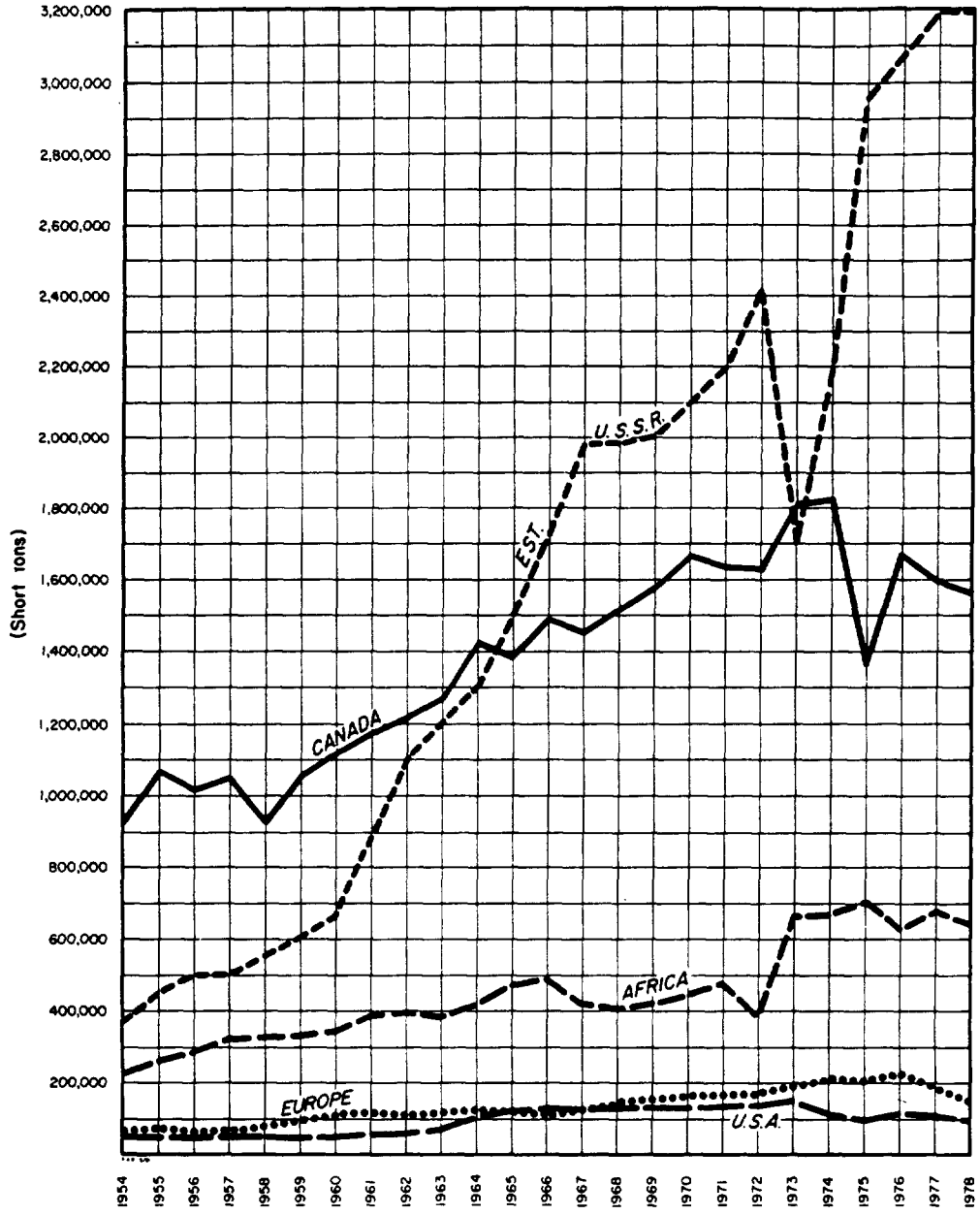

FIG. 10—*Asbestos production, major areas.*

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Finland dominated the field with an annual production of 15,000 tons in 1971, but over the next four years production dropped progressively until the mines closed in the mid-seventies. Yugoslavia, Bulgaria, Brazil, Japan, and India are all reported to have some amphibole asbestos production, but details of these deposits and pertinent statistics are unavailable.

A small quantity of long-fibered tremolite is produced from small deposits in the Sondrio and Aosta districts in northern Italy.

Table 8 gives the total world production of all types of asbestos by countries for the years 1977–1980. Similar statistics for crocidolite and amosite are also shown but comparative figures for anthophyllite production are unavailable.

Exploration and Evaluation

The following observations concerning exploration and evaluation apply mainly to chrysotile deposits and to those, in particular, which occur in ultrabasic rocks, and are essentially a review of current methods employed in Canada.

Geophysical

Owing to the lack of outcrop within areas of ultrabasic rocks, or within a belt in which these rocks are expected to occur, both aeromagnetic and ground magnetic surveys (Conn, 1967; Low, 1951) are often employed in the early stage of exploration for asbestos. Ground magnetic surveys may be used to check and define

TABLE 8—Approximate Production of All Types of Raw Asbestos by Countries (St)

	1977	1978	1979	1980
USSR	2,899,000	2,689,600	2,524,300	2,645,500
Canada	1,663,400	1,571,900	1,654,600	1,410,900
Republic of South Africa	419,100	284,400	274,500	295,400
People's Republic of China	275,600	275,600	275,600	275,600
Zimbabwe	300,900	274,500	286,600	289,900
Italy	165,300	154,300	148,800	134,500
Brazil	102,500	135,600	152,100	159,800
United States	101,400	102,500	98,100	97,000
Australia	56,200	69,400	87,100	91,500
Swaziland	49,600	40,800	37,500	37,500
Cyprus	40,800	37,500	39,700	44,100
Korea	6,600	15,400	16,500	15,400
Afghanistan	15,400	15,400	4,400	*
Yugoslavia	9,900	11,000	11,000	11,000
Turkey	12,100	14,300	11,000	11,000
Japan	7,700	6,600	4,400	4,400
India	5,500	6,600	6,600	6,600
Taiwan	3,300	2,200	3,300	2,400
Total	6,134,300	5,707,600	5,636,100	5,532,500
Amphibole Asbestos Production Included in Above Tabulation				
Amosite				
Republic of South Africa: Transvaal	73,800	44,700	43,100	56,900
Crocidolite				
Republic of South Africa: Cape Province, Transvaal	221,600	151,300	130,400	120,800
Tremolite, Actinolite, and Anthophyllite				
Republic of South Africa	600	—	—	—
Finland, Yugoslavia, US, Japan, Brazil, Bulgaria, India, Italy	16,500•	16,500•	13,200•	13,200•
Total, All Amphiboles	312,500	212,500	186,700	190,900

* No production figures available.
• Estimate.

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in more detail anomalies obtained by an airborne survey of a large area, or the ground survey alone may be used for the purpose of exploring a small area.

In the case of an airborne survey, flight lines are normally spaced at ¼-mile intervals, and flown as close to 500-ft elevation as possible. Where the terrain is rugged, helicopters are used which are capable of maintaining a constant altitude of 300 ft above ground level. The spacing between profiles on a ground survey is usually 200 or 300 ft and readings are taken at intervals of 50 or 100 ft.

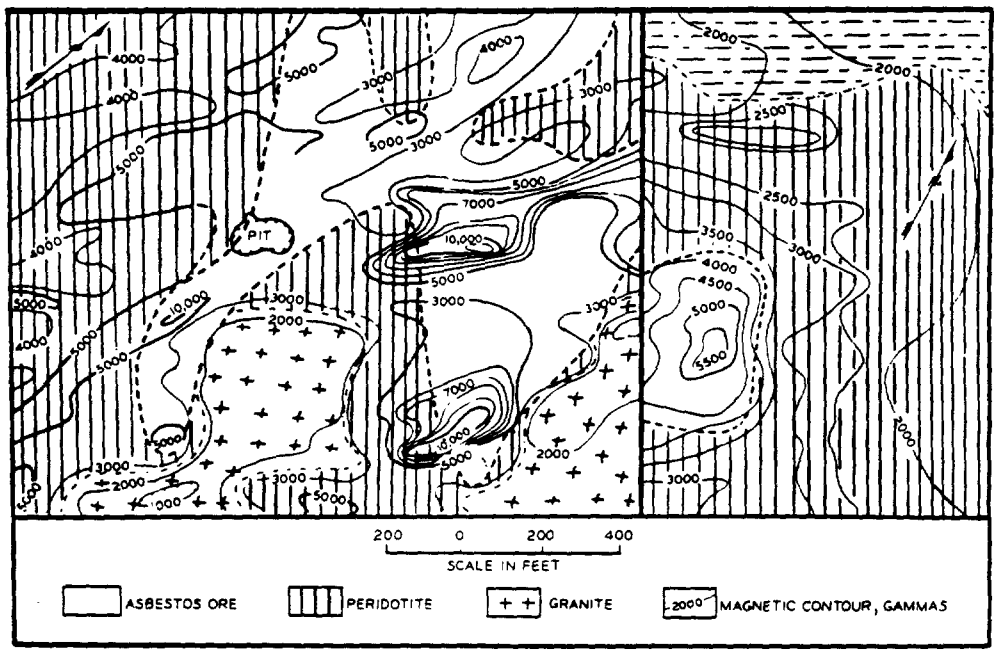
Magnetic surveys are used to locate and define the areas of ultrabasic rocks and, within these, the areas which have been subjected to extensive serpentinization. This is possible because this type of alteration produces a higher content of secondary magnetite. Asbestos deposits in ultrabasic rocks are a result of intensive serpentinization, and for that reason asbestos veining is usually accompanied by a higher concentration of magnetite than is normally found in the barren serpentine. It follows, therefore, that magnetic anomalies obtained over an area of ultrabasic rocks are favorable places to explore for asbestos. Figs. 11 and 12 show the results of ground magnetometer surveys carried out over two known ore bodies.

Modern instrumentation has made great strides in recent years, and it is now possible to conduct precise surveys with small lightweight magnetometers, in contrast to the cumbersome equipment used in the past.

Diamond Drilling

Diamond drilling is normally employed to probe beneath the overburden to assess and define the limits of an asbestos deposit. As asbestos ore bodies are usually large in volume, it is customary to drill vertical holes on a grid pattern. In the initial stages of exploration an interval of 400 ft and sometimes more may be used, filling in to an interval of 100 ft or even less, where an asbestos-bearing zone is encountered. In cases where a deposit is elongated in one direction, holes are generally spaced at closer intervals across the strike. Narrow, tabular targets are best explored by angle holes planned to give the attitude and true thickness of the body.

Care should be exercised to test the area with one or two preliminary drill holes to determine



FIGS. 11 and 12—*Results of ground magnetometer surveys of two known ore bodies.*

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whether the fiber has a preferential vein angle or not. If the angles of the vein intersections appear random, no changes need be made to the program. If, on the other hand, the deposit exhibits prominent vein angles which diverge from the average 45°, then the attitude of all later drill holes should be changed to correct for this variation.

In the past, drill evaluation programs frequently used small diameter, AX (1$^{9}/_{32}$ in.) or EX ($1^{3}/_{16}$ in.), core sizes for evaluating any deposits where shearing was minimal and where holes did not exceed 300 ft. Experience has shown, however, that large core sizes such as NX (2⅛ in.) or BX (1⅝ in.), are preferable for better depth penetration, more geologic data, and to aid in fiber logging and dry milling of the core.

Wire-line drill equipment and the use of nonrotating core barrels are also recommended to minimize fiber loss by grinding of the core during drilling.

Steps are taken to recover the sludge only where core recovery is poor, which is generally the case with slip fiber occurrences. Because of the tendency of the fiber to fluff up and remain in suspension, much greater settling tank capacity is required than is the case when recovering sludge from other minerals. Care must also be taken to avoid contamination by grease and vegetable matter as these cannot be burned off without damaging the fiber.

In regions where permafrost conditions are expected, every precaution should be taken to avoid freezing the string of drill rods down the hole. The use of suitable low-freezing drill lubricant media such as a concentrated brine solution is adequate to allow drilling in most areas of permafrost. However, due to the high percentage of fiber cuttings in the water return, the brine solution has to be renewed at frequent intervals—a factor which considerably increases the cost of drilling asbestos prospects in permafrost areas. A number of successful drill ventures under permafrost conditions have been completed, including Asbestos Hill which showed the frozen ground to persist to at least 1000 ft below surface.

In areas where drilling is impractical, exposure by trenching or exploration beneath the surface by adit or shaft and lateral workings may offer the only means of assessing a deposit.

Evaluation

The evaluation (Conn and Mann, 1971; Dean and Mann, 1968; Oughtred, 1952) of any asbestos deposit entails the determination of its size, as well as the grade and quality of its fiber. Dimensions of a mineral zone are established by conventional methods, such as mapping, magnetic surveys, trenching, and diamond drilling. The value of the contained asbestos fiber is dependent on numerous physical properties such as fiber length, strength, flexibility, harshness, and color, besides the actual amount of fiber present.

The determination of grade cannot be based on a simple chemical analysis as both the fiber and the wall rock have essentially the same chemical composition. To avoid the complete crushing of the rock and physical separation of the fiber into different lengths, a method of visual evaluation has been developed which requires careful enumeration of the total number of fiber veins, together with the average length of fiber in each vein. These fiber lengths, if expressed in sixteenths of an inch, give an approximation of the grade, each 1/16 in. vein of fiber in a 5-ft section being approximately 0.1% fiber.

As the price of fiber varies considerably depending on its length, the use of grade based solely on its percentage fiber content is of little significance. Instead, the product of these two variables, expressed in dollars per ton of rock, offers a far more meaningful value which can be used for direct comparison in the final evaluation.

Drill Core: The method of visual evaluation is ideally suited to the evaluation of drill core.

Each vein of cross fiber is logged and the length carefully measured and recorded in multiples of 1/16 in. (Adoption of the metric system based on multiples of 1 mm is also acceptable.) As veins are often of irregular width, the average width of each vein should be estimated. Some veins are of a composite nature carrying partings, or the fiber may have kinks which cause it to break into shorter lengths. The fiber in some veins may be at right angles to the vein walls, in others sharply inclined. Allowance must be made for these conditions in arriving at the true lengths of fiber.

The more precise determination of fiber content calls for the measurement of each vein angle in the core to permit individual volume corrections. However, in practice it is usually assumed that the random angle is 45° and a factor of 1.414 (inverse of the sine of 45°) is used. However, this can be quite misleading if the average angle is rather small, so logging results should be checked against laboratory recovery and bulk sampling wherever possible.

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As a rule, the visual reading gives an indicated lower yield of a higher value fiber than a corresponding mill test. This is to be expected as the visual readings disregard fiber lengths of less than 1/16 in. which are, of course, recovered in milling and are important in grading. Furthermore, a certain amount of pulverized host rock adheres to the fiber, further reducing the grade and increasing the yield by 20% or more. On the other hand, there may be some loss of veins in the core and the veins themselves contain foreign material such as nonfibrous serpentine, picrolite, and magnetite. There is also a tendency, on the one hand, for some breaking of fibers to occur in the mining and milling process while, on the other hand, the fluffed up milled product tends to remain on a screen which an unopened fiber would pass through. For most practical purposes, the discrepancies are compensating and, when a suitable volume correction factor is used, the ore values found by the two methods are generally quite close.

Slip fiber is often associated as a minor constituent in deposits made up mainly of cross fiber, and in others the slip fiber may be the predominant type. It is not easy to determine the slip fiber length by the normal visual methods of logging core; however, its presence may be recorded separately by vein widths and the percentage slip fiber determined in the same manner as used for cross fiber. Laboratory assistance is almost essential in evaluating slip fiber deposits.

Regardless of the method used in evaluating asbestos ore, the final answer should give the value of the fiber, the yield and, from this, the value of the ore in dollars per ton. A bulk sample properly milled and graded readily supplies the answer, whereas a laboratory test normally gives only the yield of an ungraded fiber and, therefore, of unknown value. The visual method, after due allowance for vein angles, gives the yield only and further calculations are required in order to approximate the fiber and ore value.

In order to place a value on the ungraded fiber resulting from laboratory extraction a graph is used (Fig. 13). The curve on this graph is derived from the Quebec Standard Tests (described elsewhere in this chapter) for average test production of all standard grades by weighting the fractions found in each box to give each grade a "point rating." The prices for Quebec asbestos are based on a minimum shipping test but for practical purposes the average test of production is about 20% higher. Weighting factors for the fraction are 100 for +½ in., 40 for −½ + 4 mesh, 10 for −4 + 10 mesh, and 1 for −10 mesh. These have no real significance and have been chosen only to control the shape of the curve.

As an example, a fiber testing 5.7 oz on the ½ in., 7.5 on the 4 mesh, and 2.3 on the 10 mesh with 0.5 in the pan would have a point rating of:

$$\begin{aligned} 5.7 \times 100 &= 570 \\ 7.5 \times 40 &= 300 \\ 2.3 \times 10 &= 23 \\ 0.5 \times 1 &= — \\ &\overline{\quad\quad} \\ &893 \text{ points} \end{aligned}$$

and from the curve the fiber value would be about $455 per ton (1973 prices).

In applying this same procedure to the visual method, it is necessary to correlate the observed lengths with the corresponding Quebec Standard Test. In order to do so, it is assumed that fibers of ½ in. length and more will stay on the ½ in. screen, ¼ to 7/16 on the 4-mesh screen, and ⅛ and 5/16 in. on the 10-mesh, whereas the 1/16 is assumed to end up in the pan. A synthetic Standard Test can then be arrived at by simple arithmetic.

To illustrate this procedure, assume that a core length of 85 ft contains four veins of ½ in. length, two of 5/16 in., one of ⅝ in., two of ⅞ in., and one of 1 in.; 16 of ¼ in., three of

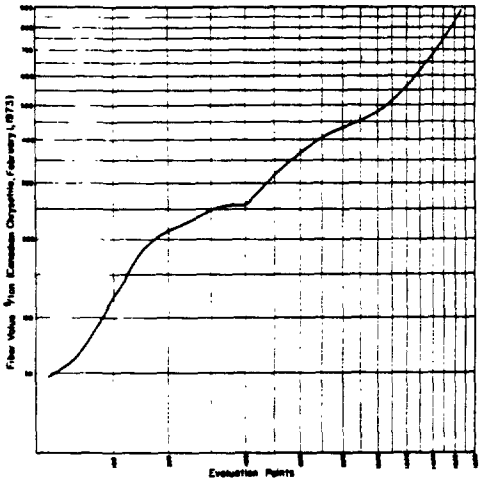

FIG. 13—*Graph for evaluating ungraded fiber based on 1973 prices. (Reproduced by permission of Asbestos Corp. Ltd.)*

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$\frac{3}{16}$ in., two of $\frac{3}{8}$ in., and two of $\frac{7}{16}$ in.; 23 of $\frac{1}{8}$ in. and 10 of $\frac{3}{16}$ in.; 74 of $\frac{1}{16}$ in.

Reducing everything to a common denominator of $\frac{1}{16}$th, there would be 104 such sixteenths of $\frac{1}{2}$ in. and over, 105 of $\frac{1}{4}$ to $\frac{7}{16}$ in., 76 of $\frac{1}{8}$ and $\frac{3}{16}$ in., and 74 of $\frac{1}{16}$ in., totaling 359 in all.

In 85 ft there are $85 \times 12 \times 16$ sixteenths; therefore, the uncorrected yield is

$$\frac{359}{85 \times 12 \times 16} \times 100 = 2.2\%.$$

A correction must be made next for the average vein angle which here will be assumed at 45°:

$$\text{Corrected yield} = \frac{2.2}{\sin 45^\circ} = 3.1\%.$$

Next to arrive at the synthetic Standard Test:

½ In.	4 Mesh	10 Mesh	Pan	Total
104	105	76	74	359 sixteenths
104/359 × 100	105/359 × 100	76/359 × 100	74/359 × 100	100%
4.6	4.7	3.4	3.3	16.0 oz

Then to find the fiber value from the graph:

$$\begin{aligned} 4.6 \times 100 &= 460 \\ 4.7 \times 40 &= 188 \\ 3.4 \times 10 &= 34 \\ 3.3 \times 1 &= 3 \\ &\overline{685 \text{ points}} \end{aligned}$$

From the graph the fiber value is found to be $400 a ton, and from this the indicated ore value is calculated to be 3.1% of $400 or $12.40 per ton (1973 prices).

Face Readings

On the surface or in underground workings, channel sampling may be employed. On the other hand, it is also possible to log these surfaces in a similar manner to that used for drill core. One method is to take a linear reading along either wall of a drift or crosscut and another is to take cross sections at intervals of 5 ft on the back and both walls to ensure that veins running parallel to the drive are not excluded.

An alternative method is to record all the veins in the face, walls, and back after each round. In order to arrive at a percentage, a factor based on the area involved is applied to the reading for each surface, and an average percentage for the round is determined in this manner.

The fact, however, that the rock tends to break along one or more of the numerous fault planes present rather than across the fault bounded blocks to expose the veins within them, makes it difficult to obtain representative results.

Bulk Sampling

The various methods of logging and sampling outlined seldom give entirely dependable results. The visual methods of logging will usually produce dependable results only where there is a relatively low content of shorts. Slip fiber, as already noted, presents a problem in this connection. Even laboratory results, which are dependent on complete extraction, usually give an appreciably higher fiber value than that obtained in a conventional mill. It is not easy to simulate in a laboratory the conditions to be found at an operating mine where the fiber from the time of blasting to the final product is subjected to a good deal of handling, some of which is rather severe. The fibers, as a consequence, suffer some breakage in the process.

Bulk sampling is often resorted to as a means to check and to arrive at a suitable factor to be applied to drill core data. This may be done by diamond drilling a block of ground at close intervals prior to mining and milling. The core is then read visually and treated in the laboratory. Provided precautions are taken to avoid contamination and the sample is sufficiently large, results should be reasonably reliable despite the erratic distribution of fiber in the rock.

A 12,000-ton bulk sample from one deposit indicated that a yield factor of two would be necessary to bring the "visual" ore value in line with that found by milling. In this deposit there were approximately equal amounts of slip and cross fiber and it is observed that the visual determined yield is low and the fiber value exaggerated.

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	Fiber Value per Ton, $	%	Ore Value per Ton, $	Yield Correction Factor
Mill recovery	111	6.80	7.53	1.00
Laboratory recovery	164	4.59	7.70	0.98
Visual analysis	202	1.87 *	3.78	1.99

* No correction for vein angles.

A 50,000-ton sample assessed in the same manner also indicated a factor of two but showed that the fiber value determined visually was fairly close to that found in milling. This is attributed to the absence of slip fiber which, when present, makes the estimation of fiber value more difficult.

	Fiber Value per Ton, $	%	Ore Value per Ton, $	Yield Correction Factor
Mill recovery	153	2.75	4.20	1.00
Laboratory recovery	160	2.52	4.03	1.04
Visual analysis	148	1.37 *	2.03	2.07

* No correction for vein angles.

Tensile Strength

In considering the preceding paragraphs, it is important to point out that the measurements made and the evaluations so obtained are based entirely on the length of the fiber which is today a secondary factor in fiber value. Most asbestos-cement fiber grades sold today are valued for the strength they lend to cement or other mixes and a standard scale of Strength Units has been established.

It is imperative then that any evaluation of a chrysotile deposit include Strength Unit evaluations which are laboratory tests involving the testing of an asbestos-cement tile made with the subject fiber. Once the inherent strength of the fiber from a particular ore body has been determined it is usually possible to equate strength to length distribution and dust content measurements.

Tonnage and Grade

To estimate the tonnage and grade of a deposit from diamond drill core data, individual drill holes may be weighted according to their interval using the polygonal method. An alternative procedure is to use cross sections, or groups of cross sections and, by weighting the individual holes in each section, determine the average grade for each section.

A third method employs contoured cross sections, wherein the contouring is based on a reasonable interpolation of the intervening area between drill holes. This method permits the estimator to make use of all available geological information in his interpolation. In open pit operations contoured horizontal sections may be prepared in this manner to correspond with expected mining level intervals, and these serve as a useful guide to mining. Separate horizontal sections contoured for rock value and fiber value per ton permit the mine operator to produce a more balanced mill feed with respect to both fiber content and grades.

Exploitation

Mining

The development of asbestos mining in Canada has been accompanied by a succession of mining practices and equipment. The simplest hand methods were, quite naturally, first employed in shallow open pit workings. During one period, when pits were reaching considerable depth, quite elaborate overhead cableway derricks were popular. Modern power shovels loading into heavy-duty trucks have now supplanted all other loading and transporting equipment where open cast methods are employed. Underground methods which have been used in the past include glory holes, shrinkage and sublevel stoping, and block caving.

In some cases, scraper hoists drag the broken ore from the underground drawpoints and in others it is passed directly through grizzlies. Large primary crushers may be located underground. The trend that prevailed in Canada, in the late 1940s and early 50s when most of asbestos was mined by underground methods, has been reversed and now open pit mining prevails.

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It is generally considered that surface mining is more advantageous in recovery, grade control, economy, and safety. The reversing of that trend is mostly due to the technological innovations in mining equipment: shovel size varies from 2½ to 15-cu-yd capacity, truck size goes from 25 to 200-ton payload, rock drilling equipment has improved considerably, and new blasting agents and techniques have been introduced. These innovations permit increased waste to ore ratio up to 3:1 or more, thus lengthening the economic life of open pits.

In Africa a large part of all the chrysotile is mined by underground methods. The ore bodies are generally tabular in shape with a pronounced dip, with the result that the economic limit for quarry mining was reached at a comparatively early stage. Ore widths in the larger mines commonly range from 80 to 200 and up to 400 ft. Some ore bodies, notably in the Shabani district of Zimbabwe, are quite extensive in length; in one case, development has extended for three miles along the strike, and is being developed or diamond drilled to over a thousand feet in depth. Several underground methods have been used including cut and fill. Presently, sublevel stoping and caving accounts for most of the tonnage extracted. Caving may be initiated by blasting holes drilled upward from sublevel crosscuts, starting first on the hanging-wall side and retreating over a considerable width toward the footwall, or the development and retreat may be along the strike of the ore. In some cases high pressures have developed from an arching effect but these pressures have been largely released by mining a vertical slot which may extend through to surface and toward which the ore is allowed to cave. In the sublevel stoping method a slot may also be opened across the center of the ore body. The long holes which are fanned out from the sublevel drifts are then blasted toward the slot, and mining proceeds as a systematic retreat in two directions away from the opening thus made.

Drilling in the softer portions of these South African chrysotile mines is now frequently accomplished by rotary drills employing bits in which tungsten carbide cutting lugs are set. In drilling long holes, which may be up to 70 ft or more for sublevel mining, short lengths of jointed rods are used. With percussion type drills, which are generally used for harder rock than the rotary drills, flexible ribbon steel with a chisel bit of tungsten carbide has proven useful and efficient.

Much of the amosite and crocidolite in Africa has been mined from small, narrow open cuts or adits following the fiber-bearing band. In the Penge area the operations have been developed for larger scale and deeper mining. The main ironstone "reef" runs quite consistently at around 54 in. thick with a dip of about 20°. A sloping face is advanced along the strike by drilling rounds of about 6 ft with jackhammers. The broken material is shoveled back from the face into temporary pillars for roof support. The remaining material is hand-loaded into small cars, hoisted to a haulage level, and transported to a sorting plant for further removal of waste rock before being sent to the cobbing plant and mill. Formerly the fiber-bearing portion was hand-sorted underground which resulted in excessive values being left behind in the pillars. The ironstone fractures into rectangular blocks which lend themselves well to being built up in this way. The main fiber-bearing reef commonly contains up to 30% asbestos, so that the proportion of waste to barren works out well for the system used. The method is locally referred to as shrinkage stopage but should not be confused because of this nomenclature with the latter system as commonly practiced in other areas.

Milling

Mill flow lines are designed to suit the characteristics of a given ore body. The basic steps are similar for most flow lines. The raw fiber is recovered using the dry process which has been used almost exclusively since the inception of asbestos milling in Canada some 90 years ago. However, in certain cases, wet processing of at least some of the fiber has occurred. This method of processing may be examined more closely in the future.

There have been few major changes in the basic process since the last volume of this series was published in 1975. The major improvements have evolved around material handling, packaging, and shipping methods. The improved methods developed by the asbestos mining industry have made it possible for both the producer and customer to store, ship, receive, and use fiber in a relatively dust-free environment.

The major portion of the production is being packaged in woven polylaminate 50 kg pressure-packed bags for the domestic and export markets.

Fiber in water-soluble unsized kraft paper bags is also provided to some customers who

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consume the bag, along with the fiber in wet paper-making production processes.

Recent developments in packaging equipment have permitted the packaging of fiber in high density blocks, approximately 1 cu ft in volume, containing 45 kg. Some producers are supplying small tonnages of limited grades in these blocks which, because of their size, offer some economics in transportation and storage.

Unitized bags, with coverings of stretch or shrink wrap plastic film for additional stability and protection in rail and container shipments, are supplied by some producers. The present trend is toward 100% mechanical handling of the asbestos at both the mines and point of use.

The flowsheet shown in Fig. 14 is a generalization of the essential steps and equipment used in a Canadian chrysotile asbestos mill producing the full range of raw asbestos fiber grades Group 3 to Group 7.

Fig. 15 shows a section of a Canadian asbestos mill primary rock and fiber cleaning circuit.

Fig. 16 illustrates a schematic flow line of a two-product Canadian asbestos mill.

Fig. 17 illustrates a recent Canadian installation of a primary and secondary crushing, drying, and ore concentration system.

The description that follows of the essential steps of a milling operation is based on Figs. 14 and 17.

Mill feed is derived from the underground or pit operation. Primary crushing may be done in underground stations in the case of an underground mine or surface plant when treating open pit ore.

Large jaw crushers (the 48 x 60-in. size is the most popular) are used in the majority of the Canadian plants either underground or on surface. Heavy-duty pan feeders have proven quite practical and comparatively trouble-free, particularly for handling open pit ore containing large unbroken pieces which are likely to cause blockages. Lately the trend has been toward large capacity gyratory crushers which eliminates the need for feeders and bins.

In countries where relatively cheap labor is still available a certain amount of hand sorting continues to be done before or after (or both) primary crushing for the purpose of removing barren rock and also to recover pieces of the larger asbestos veins to be used in the production of No. 1 or No. 2 crudes. Reduction in primary crushers of the size mentioned is normally to about 7 in., and is followed quite commonly by 7-ft or smaller cone crushers with settings ranging from ¾ to 2½ in.

Ore concentration is an important step in the milling of asbestos ore and is particularly important to the lower grade ore bodies. It is not uncommon to discard up to 40% of the mine ore through selective impacting and screening in the primary and secondary crushing circuits. Nearly all producers are able to accomplish beneficiation of this type to some degree. The use of magnetic pulleys is a relatively new approach being used by some producers for upgrading the mine ore. Not all asbestos ore bodies are amenable to this type of separation.

The next step is to dry the ore. It is considered good practice to provide a storage large enough for one shift's production of mine ore to assist in regulating the flow rate to the dryers.

Most of the moisture is contained in the −1½ in. fraction. At some plants this fraction is screened and dried separately from the oversize (1½ to 7 in.).

In all stages of beneficiation it is important to minimize abrasion and cutting of the fiber particularly in the earlier stages before the longer and more easily released fiber fractions are separated from the gangue.

The selection of a dryer is largely based on local preference. The two more commonly used are the rotary and vertical dryers. Recently an installation has been made using fluid bed dryers.

The chief advantage of the vertical tower and fluid bed over the rotary kiln-type dryer is normally a lesser degree of mechanical damage to the fiber. On the other hand, the rotary dryer is preferable and is also more effective for open pit ores containing snow and pieces of ice.

Where conditions permit, oversize (say, +1½ to 3 in.) material may be separated before drying, and bypassed to lessen the pebble-milling action of rotary dryers. Where vertical dryers are used the feed should not be much coarser than a 1½ in. grizzly opening size in order to avoid blockages in the gridwork of arresting bars with which the dryers are fitted.

There is a limit to the air velocity which may be used in the counterflow vertical-type dryer where the products of combustion from an oil or coal-fired furnace rise through the falling ore. Near the bottom of the tower, where the hot gases enter, fluffed particles of fiber may be temporarily held in suspension in a damaging temperature environment.

One solution to this objectionable feature is to have at least part of the hot gases introduced at the top of the tower and to be drawn downward with the falling material.

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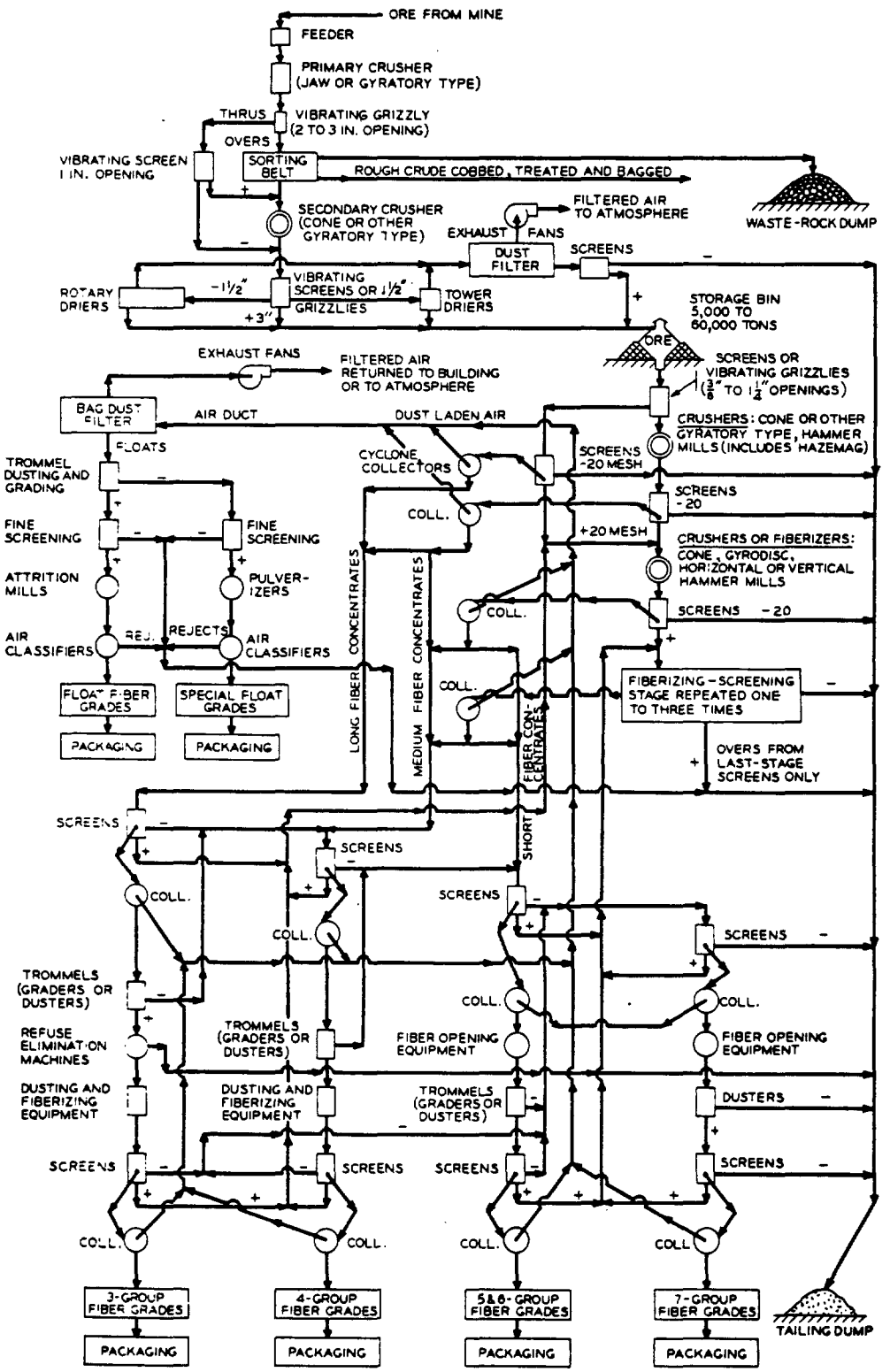

FIG. 14—*Flowsheet of a Canadian asbestos mill.*

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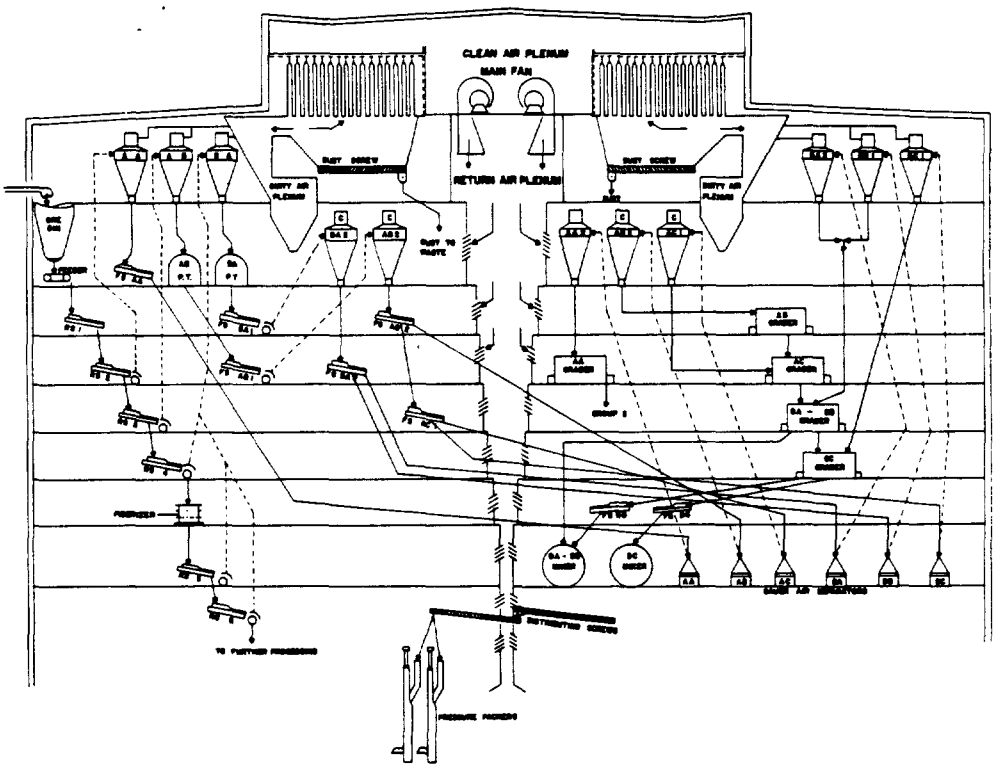

FIG. 15—*Section of a Canadian asbestos mill showing the primary rock line and fiber cleaning circuit.*

Dryers using the practical application of this principle have the discharge gas takeoff at a point midway up the height of the dryer, thus keeping air velocities and temperature within permissible limits toward the bottom of the tower. An after-cooling device may also be used in which cool air is blown through the discharged hot ore to remove further moisture before the ore is discharged onto conveyor belts. The air from this operation may be used as preheated makeup air in the dryers.

The air and products-of-combustion as discharged from the dryers carry a considerable volume of dust. It is desirable, therefore, to provide filtering equipment in order to keep the plant area clean. Bag filters using various fabrics have operated successfully and are certainly the most positive means of removing the dust. Care must be exercised, however, to guard against condensation.

An alternative filter which has been used is known as the Impingo. This employs an ever-changing layer of cold moist aggregate, or the ore itself screened to, say, +1-in. size. Some moisture is precipitated from the gases and dust adheres to the surfaces of the crushed stone or pebbles. This system has proven ineffective in most applications.

It has been found desirable to have substantial storage capacity between drying and the main stage of milling. Besides assuring an adequate and more uniform supply of ore to the mill, further drying (up to 1% moisture loss) takes place during the storage. The size of storage facilities will vary with mill capacity.

As will be apparent from the flowsheet (Fig. 14) the release and separation of fiber from gangue is accomplished by successive stages of crushing or comminution by impact. Impactors are designed to release the fiber from the host rock and at the same time produce a minimum of fines.

Fiber in the form of cross-fiber veins or slip fiber thus released is at the same time sufficiently "teased out" so that the portion so freed may be lifted by air suction, leaving most of the

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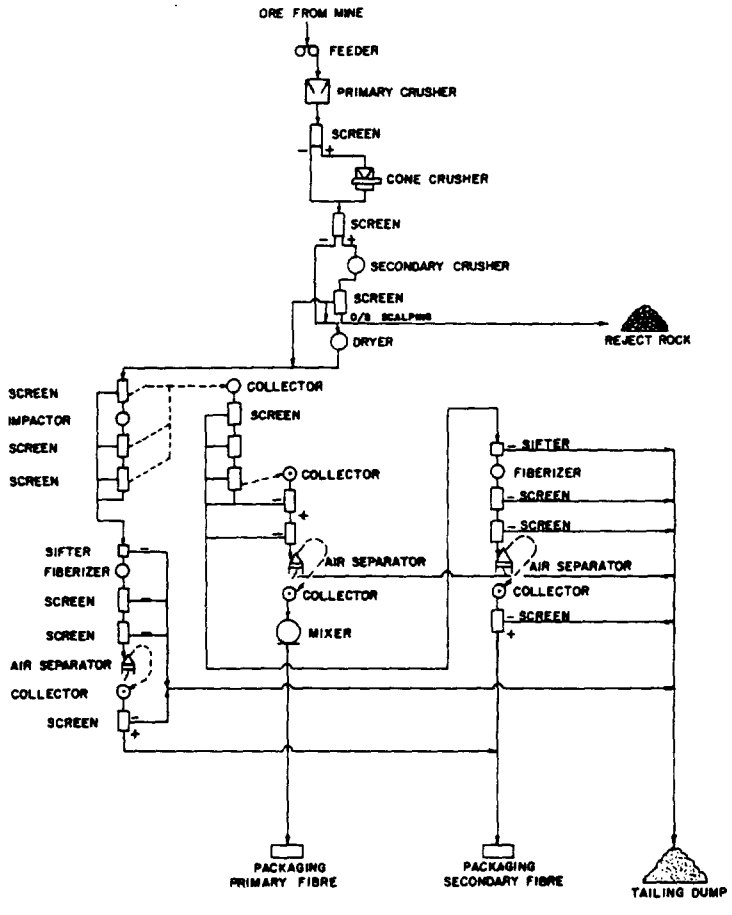

FIG. 16—*Schematic flow of a two-fiber-product Canadian asbestos mill.*

rock as a reject to go to the next stage of impacting and eventually to tailings.

Finer fractions are generally screened out prior to air separation. Otherwise a large portion of rock fines would be aspirated with the fiber. Rotary aspirators designed to present a uniform layer of material to the aspirating hood are commonly used to improve the aspirating efficiency. The products of these first stages of separation may be considered as concentrates. They contain a large percentage of rock particles and must be further treated in the fiber grading division of the plant.

Here the concentrates are further graded and undergo a series of cleaning operations for the purpose of removing sand and dust. Screens, trommels, specific gravity air separators, and modified forms of these such as graders and dusters, further clean the fiber and separate it into standard grade lengths.

In the grading mill the fiber is further separated into the approximate quality brackets required for specific grades and is subjected to several stages of screenings using shaking screens, rotating screens, conventional trommels, trommel-like graders, and rotary dusters.

When well opened or fluffed out grades are called for, the fiber is subject to special treatment in one or more of a variety of machines ranging from graders or Willows (fixed shell trommels having a rotating center shaft to which beater arms are attached) to one of several types of high-speed hammer mills, disk grinders, or pulverizers. The type of machine or machines used depends upon the length and type of fiber to be processed and the degree of opening or fluffing up required. This additional treatment is generally given to the shorter fibers.

A large volume of air is used in an asbestos

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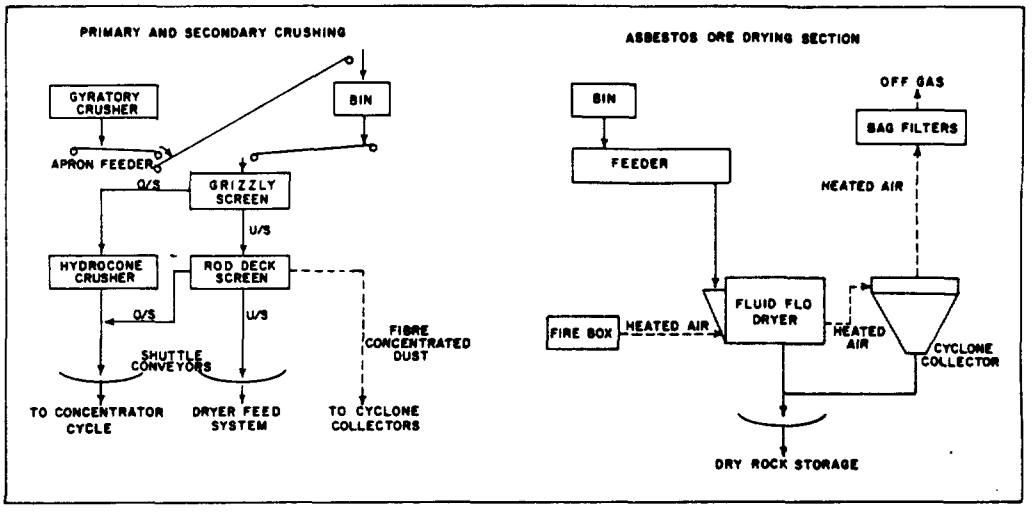

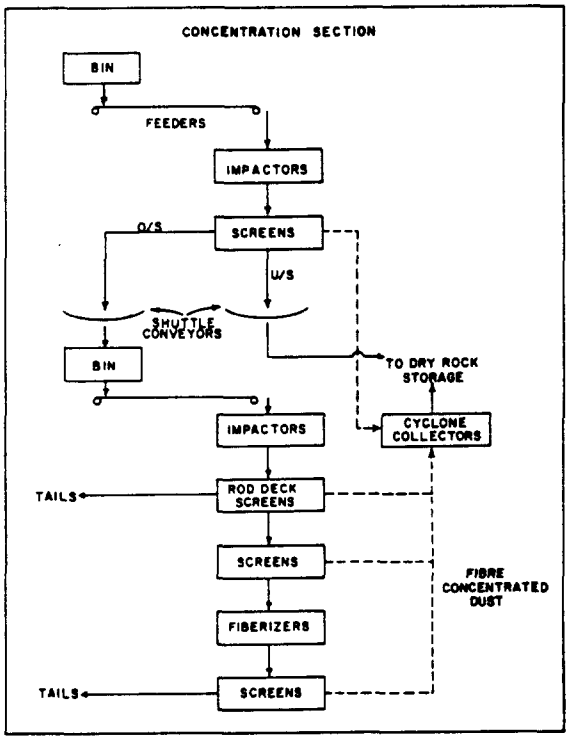

FIG. 17—*Recent Canadian installation of a primary and secondary crushing, drying, and ore concentration system.*

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mill, most of which is for the primary purpose of separating fiber from rock, and dust by air suction and classification.

An additional quantity is also required for dust elimination at many points within the building to keep the dust content of air in the building to a minimum. It is estimated that mills having a capacity of, say, 5000 tpd of ore, use from 500,000 to over 800,000 cfm of free air.

The average consumption in Canadian mills is something in the order of 7 to 14 tons of air per ton of ore treated (Kula and Wiser, 1970; Rozovsky, 1957).

Modern practice requires all this air to be filtered before being discharged from the mill into the open. This has led to extensive bag filter units being installed in nearly all mills in recent years.

In Zimbabwe, South Africa, and Swaziland, where there are several modern mills, one finds that the general approach to the beneficiation of chrysotile does not differ greatly from Canadian practice.

One feature of African milling is careful control of moisture content as this may actually fall too low, particularly during the dry season. Fiber may be more easily broken or damaged under extremely dry conditions.

In Zimbabwe the small pan crusher or Chilean mill was one in extensive use. This is no longer widely used for general milling but has been adopted to some extent in Canada for the preparation of crudes.

African practice, for the preparation of crocidolite and amosite, is generally very simple, consisting to a large degree in hand sorting, crushing, and screening as with the "crude" grades in Canada. However, in the Penge area of the Transvaal, milling practice is somewhat more elaborate and several milled grades of amosite are produced.

In addition to the more or less conventional sorting and some very difficult cobbing due to the extreme toughness of the rock, the fiber is treated in different mill circuits variously equipped with jaw crushers, cone crushers, rolls, hammer mills, and trommels. As an example the longest grade, D_3, is prepared essentially as follows:

3 x 14 in. grizzly
↓
Reduction to 1½ in. in small jaw crusher
↓
Crushing rolls (24 x 48 in.) to ¾ in.
↓
Trommel—1½ in.—undersize to next shorter grade circuit
↓
Crushing rolls (12 x 36 in.) to ½ in.
↓
Trommel—¾ in. (as above)
↓
Degritting trommels (2 in parallel)—¼ in.
↓
Bagging

In the circuits for shorter grades, cone crushers, hammer mills, and other fiberizing and cleaning equipment is now used. Trommels have proven effective as a cleaning device for medium as well as the long grades.

For the very short fibers high-speed vibrating screens are found more efficient. Air separation is practiced in various forms such as air traps, suction hoods, and screens, depending on the fiber grade being treated.

Tests and Specifications

The only test that is generally recognized by the government in Canada is the Quebec Asbestos Mining Association classification known as the Quebec Standard (Q.S.) Test. (This test is performed in the Quebec Standard Testing Machine which consists of a nest of three sieve boxes with ½ in. screen, 4-mesh, and 10-mesh screens, respectively, and a bottom box serving as a pan. A test is made with 16 oz of asbestos and the whole mechanically shaken for 600 revolutions at 328 rpm. The equipment is made to exact standard specifications, and can be purchased through the secretary of the Quebec Asbestos Mining Assn., Quebec City, Prov. of Quebec, Canada, G1R 2K2. The Quebec Asbestos Mining Assn. has set specifications for the various fiber grades showing the minimum limits for the quantities of fiber that should remain on each screen. It is used as a production control and serves as a specification of the grade of fiber for sale.

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This type of test has also been partially adopted by other countries, and in some cases the results are expressed in percentages instead of ounces.

Other variations of the Quebec Standard Test at some localities involve the Ro-Tapping of the Q.S. fractions for further evaluating purposes, because it was believed that the Ro-Tap would give a better distribution of the fiber lengths.

The Ro-Tap test is used by many asbestos mill operators to obtain a fiber distribution impossible to get by the Quebec testing machine. The use of the Ro-Tap differs with operators at different plants. It is not a standardized test accepted by the industry, and therefore the type and size of screens vary, as well as the lengths of time of Ro-Tapping and the quantity of fiber used in making a test.

In many cases, a cubic-foot box or a fraction of a cubic-foot box is used for obtaining the density of fibers. When the box is filled with the fiber, it is weighed and the values expressed as pounds per cubic foot. Many customers make density measurements as a guide for the introduction of the fiber in a specific product.

Wet classification and screening have been employed to an increasing extent in recent years. Equipment such as the McNett or the Clark wet testing machine may be used for production purposes permitting the operator a much closer check on fiber lengths, nonfibrous fractions, and dust content.

Many tests are made at the special request of customers who in turn may evolve their own best methods to evaluate the fiber in terms of their finished products. This has resulted in tests such as: viscosity, absorption, grit, troweling, bulk, penetration, soluble salts, magnetite content, compressibility, flexing, tensile strength, color, strength units, surface area, and others being made.

Fiber producers in other countries such as Zimbabwe, USSR, Australia, Cape Province, and Transvaal, South Africa, have evolved their own testing methods for grading and classifying fibers, but do use the Quebec Testing Machine to a certain degree.

The classifications for various grades from the more important producing areas are given in Tables 9–14.

Uses of Asbestos

The uses of asbestos are numerous and at least 3000 different products are being manufactured in the world today which take advantage of its unique properties. Some of the major

TABLE 9—Quebec Grading as Set Forth by the Quebec Asbestos Mining Assn.

SPECIFICATION	Guaranteed Minimum Shipping Test			
	1/2 In., Oz	4 Mesh, Oz	10 Mesh, Oz	Pan, Oz
Group No. 1 — No. 1 Crude-cross-fiber veins having 3/4-in. staple and longer.				
Group No. 2 — No. 2 Crude-cross-fiber veins having 3/8-in. staple up to 3/4-in. Run-of-Mine Crude consists of unsorted crudes. Sundry Crudes—consist of crudes other than above specified.				
Group No. 3 (Commonly referred to as textile or shipping fibers)				
3F	10.5	3.9	1.3	0.3
3K	7	7	1.5	0.5
3R	4	7	4	1
3T	2	8	4	2
3Z	1	9	4	2
Group No. 4 (Commonly referred to as asbestos cement fibers)				
4A	0	8	6	2
4D	0	7	6	3
4H	0	6	8	3
4H	0	5	7	4
4K	0	4	9	3
4M	0	4	8	4
4R	0	3	9	4
4T	0	2	10	4
4Z	0	1.5	9.5	5
Group No. 5 (Often referred to as paper stock grades)				
5D	0	0.5	10.5	5
5K	0	0	12	4
5M	0	0	11	5
5R	0	0	10	6
5Z	0	0	8.5	7.4
Group No. 6 (Paper and shingle fibers)				
6D	0	0	7	9
6F	0	0	6	10
Group No. 7 (Shorts and floats)				
7D	0	0	5	11
7F	0	0	4	12
7H	0	0	3	13
7K	0	0	2	14
7M	0	0	1	15
7R	0	0	0	16
7T	0	0	0	16
7RF and 7TF Floats	0	0	0	16
7W	0	0	0	16
Group No. 8 & 9 (Sands and gravels)				
8S	0	0	0	16
	Minimum 50 lb per cu ft			
8T	0	0	0	16
	Minimum 75 lb per cu ft			
9T	0	0	0	16
	More than 75 lb per cu ft			

TABLE 10—Cassiar Asbestos Grades, Northern British Columbia

C-1	Crude 3/4-in. staple and longer.	
AAA	Extra long spinning fiber	– Canadian Group 3
AA	Long spinning fiber	– Canadian Group 3
A	Spinning fiber	– Canadian Group 3
AC	Spinning fiber	– Canadian Group 3
CC	Spinning fiber	– Canadian Group 3
AK	Asbestos-cement fiber	– Canadian Group 4
CP	Asbestos-cement fiber	– Canadian Group 4
AS	Asbestos-cement fiber	– Canadian Group 4
CT	Asbestos-cement fiber	– Canadian Group 4
AX	Asbestos-cement fiber	– Canadian Group 5
AY	Asbestos-cement fiber	– Canadian Group 5
CY	Asbestos-cement fiber	– Canadian Group 5
AZ	Asbestos-cement fiber	– Canadian Group 6
CZ	Asbestos-cement fiber	– Canadian Group 6

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TABLE 11—Classification of African Chrysotile*

C&G1 Long, crudy textile fiber C&G2 Textile fiber C&G3 Long shingle fiber C&G4 Shingle fiber C&G5 Short shingle fiber or paper stock	From mines in the Shabani district of Zimbabwe
VRA-2 Textile fiber VRA-3 Long shingle fiber VRA-4 Shingle fiber	From the Mashaba district of Zimbabwe
HVL2 Textile fiber HVL3 Long shingle fiber HVL4 Shingle fiber HVL5 Short shingle or paper stock	From the Havelock mine in Swaziland
Msauli – Grade 4 Shingle fibers Msauli – Grade 5	From the Msauli mine near Swaziland border in the Transvaal
Amianthus 1 and 2 – Textile fibers F – Long shingle fiber AA – Shingle fiber	From the Barberton district of the Transvaal
Munnik-Myburgh M1 – Textile fiber M3 – Shingle fiber M4 – Short shingle fiber	From the Barberton district near Nelspruit of the Transvaal

*In the absence of a current listing of Zimbabwean, South African, and Swaziland grades, this list from the 1975 edition is included to indicate type and source.

ones are listed, along with a brief discussion of the products involved (Badollet, 1948).

Crudes No. 1 and No. 2—Chrysotile crudes are usually processed by the customer to produce a long spinning fiber for use in textiles. A desirable fiber for textiles is one that has good flexibility, is soft, low in soluble salts and magnetite, and easily carded without an excess drop in shorts. It should also be free from wood and blasting wire or fuse wire! Fiber of this quality would be desirable for all textile uses, including those for the electrical industry. In some cases, this grade of fiber is used as felts in laminates along with resins to form a strong molded sheet for use in airplanes, boats, etc.

Crocidolite crudes must be carefully processed to produce long fibers which can be used in textiles, gaskets, ropes, or in laminates with resins.

Amosite crudes, after reprocessing, will give a long bulky fiber that is used in blanket insulation or in products requiring a low density and good insulation value. Spinning of amosite can be accomplished, but is difficult.

Group 3 Milled Fibers—Chrysotile fibers that meet this classification are generally used in textiles. Some are used in long fiber asbestos papers, packings, gaskets, brake linings, clutch facings, electrolytic diaphragms, pipe coverings, and insulating blocks. Some of the fibers of this group are now being used in laminates with resins.

Crocidolite may be used for most of the purposes listed previously, providing color is not an objection. It should generally be carefully prepared in a well-opened condition.

Group 4 Milled Fibers—Many grades of fibers in this classification are used in asbestos-cement processes to produce pipe, jackets, boards, sheets, and a variety of hand-molded articles. Other uses are for papers, pipe coverings, packings, gaskets, millboards, and plastics.

Crocidolite, similar to Group 4 chrysotile, is used in asbestos-cement pipes, in some packings and in some gaskets.

Amosite is used in magnesia blocks, pipe coverings, and other insulation compositions when a light density is desired. It is also used in acetylene cylinders to give strength to the calcium silicate mix during curing.

Group 5 Milled Fibers—Fibers of this group sometimes are used as replacements for Group 4 fibers, and therefore the products made with these fibers would include asbestos-cement sheets, corrugated or flat boards, pipe, electrical panels, papers, millboards, pipe coverings, gaskets, packings, brake linings, and plastics.

Crocidolites of this classification are used in asbestos-cement pipes.

Group 6 Milled Fibers—Chrysotile fibers of Group 6 are used in asbestos-cement shingles, flat sheets, corrugated sheets, boards, brake lining, papers, millboards, and plastics.

Crocidolite of this grading is used in the

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TABLE 12—Classification of Russian Chrysotile (Condensed)

Grade	Type	Texture	Mark according to USSR Standards, 1972
0	Spinning fiber	Harsh, crudy	DV-0 80, DV-0 55
1	Spinning fiber	Harsh, crudy Semi-crudy	J-1-50, J-1-38 PRJ-1-75, PRJ-1-50
2	Spinning fiber	Harsh, crudy Semi-crudy Semi-open	J-2-20 PRJ-2-30, PRJ-2-15 P-2-30, P-2-15
3	Asbestos-cement fiber	Harsh, crudy Semi-open	J-3-40 P-3-70, P-3-60, P-3-50 M-3-70, M-3-60
4	Asbestos-cement fiber	Semi-open Open, soft	P-4-40, P-4-30, P-4-20, P-4-5 M-4-40, M-4-30, M-4-20, M-4-5
5	Paper fiber	Semi-open Open, soft	P-5-67, P-5-65, P-5-52, P-5-50 M-5-65, M-5-50
6	Paper and shingle Fiber and shorts	Semi-open Open, soft	P-6-45, P-6-30 M-6-40, M-6-30 K-6-45, K-6-30, K-6-20, K-6-5
7	Unguaranteed		7-300 7-370 7-450 7-520

production of asbestos-cement ML6 products. The balance would be classed as a filler and used wherever its physical properties could be employed to advantage.

Amosite of this classification is considered quite short for most purposes, and would probably be used as a cheap filler to free up asbestos-cement slurries prior to pressing.

Group 7 Milled Fibers—These fibers find usage in certain papers, cements, asphalt roof coatings, paints, welding rods, floor tile, and plastics.

TABLE 13—Classification of African Amosite

Grade	Approximate Range Average Fiber Length, In.
S 11	1–1 1/2
W 3	1/2–1 1/2
K 3	1/2–1 1/2
SK	3/16–3/4
S 33	1/8–1/2
S 33/66	1/8–1/2
GW	1/8–1/4
GK	1/8–1/4
S 44	1/8–1/4
RK	1/8–1/4
6605	1/16–1/8

The grades listed above are produced in the Penge area from the Penge mine and the Weltevreden and Kromellenboog mines. The fiber lengths shown are not necessarily exact, but have been included in order to give some indication of the relative lengths of fibers of the different grades.

Crocidolite and amosite fibers of a length equivalent to Group 7 chrysotile are not known to be used in commercial products unless as a cheap filler where color is not objectionable.

Floats—Chrysotile floats (Badollet, 1952, 1956) are used extensively in plastics and coatings.

The selection of asbestos fiber for a particular application will depend upon the processing method, as well as the desired properties of the end product. The following examples outline some of the major uses for asbestos fiber and illustrate pertinent factors which influence the choice of fiber grade and type.

Asbestos-Cement Products—Pressure pipe which must conform to hydrostatic test speci-

TABLE 14—Cape Blue (Crocidolite)

Grade	Approximate Range Average Fiber Length, In.	Typical Values Surface Area (Rigden), Cm^2/g
C	1 1/4–1 3/4	1,500
S	1/4–3/4	5,500
S 80	1/4–3/4	9,500
P 25	1/4–3/4	8,300
H	1/8–1/2	7,500
H 80	1/8–1/2	10,000
713	1/8–1/2	13,000
WDS	1/8–3/8	9,000

Cape Blue Mines (Pty) Ld. produce most of the Blue asbestos. Among other producers grading practice is to refer to "long" and "short" for the bulk of their production.

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fications is produced from high quality Group 4 fiber, usually a blend of chrysotile and crocidolite, to ensure a good modulus of rupture. On the other hand, the flexural and impact strength requirements for asbestos cement sheets can usually be met by using a Group 6 fiber. Formulations for corrugated sheets generally include some Group 5 material to improve adhesion of the wet sheets during the forming process.

In all asbestos cement products made by the wet machine process, drainage is an important fiber characteristic since it has direct bearing on the production rate. For this reason, preference may be given to fast filtering fibers and amosite may be included in the formulation as a filter aid.

The requirements for shingles made by a dry process are not so exacting from either the strength or drainage point of view and can be satisfied with a lower quality 6 or 6–7 blend.

Asbestos Paper—Traditionally asbestos fiber in conjunction with an organic binder has been used for the manufacture of paper and millboard which, in turn, were converted to roofing felt, pipe coverings, electrical insulations, and many other products. Various blends of Groups 4, 5, and 6 fibers are used for this application, depending upon the desired strength and porosity of the paper.

More recently, a latex-asbestos process has been developed in which a long clean Group 7 fiber having a high surface area is coated with latex rubber by a chemical precipitation method and the resulting finish formed into a continuous sheet on a paper machine. A large proportion of this latex asbestos paper is used as an underlayment for vinyl-rolled floor covering. A lesser amount is used in the manufacture of gaskets.

Friction Materials—This product line cannot be related to any particular fiber group, since it spans the complete spectrum from Group 3 spinning grades to the shorter Group 7.

The explanation lies in the wide variety of products, which fall within the general classification of "friction materials," and the equally diversified manufacturing processes involved.

Clutch plates are made from an asbestos open-weave cloth impregnated with resin and bonded to a steel disk. A similar product can be manufactured by molding a dry resin-fiber blend under conditions of high temperature and pressure onto a packing plate. For the first method, a Group 3 fiber is required, whereas the molding process utilizes a Group 5.

Automobile brake linings bonded to a steel shoe are usually made from Group 7 fiber in a semi-wet extrusion process while heavy blocks for railcars and large vehicles use Group 5 or 6 fiber dry-molded and machined to finished dimensions.

Group 5 fiber is also used extensively in disk brake pad formulations.

Sheet Packing—Latex asbestos paper made from Group 7 fiber can be densified and used for gasketing, but most sheet packing material is formed on a sheeter machine by a calendering process. This latter method requires a longer fiber in the Group 4 to 5 range, which has been cleaned and opened. The fiber is blended with natural or synthetic rubber, plasticizers, and other ingredients in a high shear mixer to form a dough which is later calendered into sheets of various thicknesses.

Floor Tile—A large volume of Group 7 fiber is supplied to manufacturers of vinyl floor tile. This product requires a short, clean, well opened Group 7 fiber having a high degree of uniformity in such properties as length distribution, absorption, and color. This latter feature is particularly important to the industry because of the need for matching of shades from different production runs.

Asphalt Products—Group 7 asbestos fiber in combination with asphalt and various solvents form the basis of a wide variety of products often classified under the catchall heading of "Blackline."

These include spray or brush-on roof coatings, sound deadeners for automobile body panels, and caulking components.

In recent years, automobile underbody protective coatings applied by airless spray equipment have provided an outlet for Group 7 fiber. Since the finished compound must pass through an orifice 0.021 to 0.028 in. in diameter under high pressure during application to the automobile, the fiber used must meet strongest specifications on fineness and viscosity building properties.

Short Group 7 chrysotile asbestos added to hot asphalt paving mix helps to improve characteristics of toughness, flexibility, and water impermeability. Asbestos modified pavements have proved successful in high traffic density areas, such as busy street intersections, bus stops, and bridge decks.

Caulking Compounds—Combinations of long asbestos with cement and other ingredients. along with waterproofing resins, are used to produce special types of caulking compounds.

In many cases, short asbestos and floats are also combined with various types of resins and

TABLE 15—Asbestos Prices—Canada, US

Standard Grade Designation	
Quebec, Canada	**Per Ton of 2000 Lb, f.o.b. Mine Canadian Dollars**
Grades 3Z to 3F spinning fiber	$ 1202 to $ 1995
Grades 4T to 4A asbestos cement fiber	850 1256
Grades 5Z to 5D paper fiber	497 687
Grade 6D paper and shingle fiber	408 426
Grades 7TS to 7D shorts	125 253
Paperbestos No. 1 to 5 H.D. Blocks	237 782
Cassiar, B.C. Canada	**Per Ton of 2000 Lb, f.o.b. North Vancouver, B.C. Canadian Dollars**
AAA nonferrous spinning fiber: Canadian Group 3	$ 2000
AA nonferrous spinning fiber: Canadian Group 3	1600
A nonferrous spinning fiber: Canadian Group 3	1265
AC nonferrous spinning fiber: Canadian Group 3	1155
AK asbestos cement fiber; Canadian Group 4	1075
AS asbestos cement fiber; Canadian Group 4	1000
AX asbestos cement fiber; Canadian Group 4	930
AY asbestos cement fiber; Canadian Group 5	660
AZ asbestos cement fiber; Canadian Group 6	430
Specialty Grades AK100, AS100, AX100 and AY120 are increased an additional $25 per ton above list price of base grade.	
Vermont, US	**Per Ton of 2000 Lb f.o.b. Morrisville, VT US Dollars**
Grade 3Z fiber	$ 1135
Grades 4T to 4D fiber	$ 754 to 833
Grades 5R to 5K fiber	495 to 584
Grade 6D waste	363
Grades 7R to 7D shorts	113 to 215
Hooke No. 1	1520
Hooke No. 2	880
California, US (Calidria Asbestos)	**Per Ton of 2000 Lb, f.o.b. King City, CA US Dollars**
SG-103 pellets in bags; vinyl-asbestos floor tile	$ 136
SG-104 pellets in bulk; vinyl-asbestos floor tile	116
SG-130 open fiber in bags; general	194
SG-200 pellets in bags; rubber	176
SG-210 open fiber in bags; general	250
HPP pellets in bags; rubber reinforcement	224
HPO open fiber in bags; asphalt	250
RG-110 open fiber in bags; roofing	270
RG-144 open fiber in bags; resin viscosity control	700
RG-244 open fiber in bags; resin viscosity control	3300
Arizona, US	**Per Ton of 2000 Lb, f.o.b. Globe, AZ US Dollars**
No. 1 crude (soft)	$ 3000
AAA	2000
Grade 3Z nonferrous filtering-plastic	$ 1350 to 1400
Grade 4T nonferrous filtering-plastic	700 1350
Group 7 white shorts	50 200

Source: Asbestos, January 1981.

TABLE 16—Annual Exports of Asbestos from Canada by Areas*
(St)

	1977	1978
United States	545,500	544,200
Europe including United Kindgom	1,006,400	898,700
South and Central America	39,200	37,700
Africa and Asia	472,100	392,600
Others	417,900	220,100

*Dollar value not available.

other materials to produce a soft plastic caulking compound that remains soft or it may be controlled so as to set up as a hard mass.

Plastics—Structural materials using plastics reinforced by asbestos or as a combination of asbestos and glass are now of considerable importance commercially. The asbestos may be in the form of a mat, or as paper or cloth to form laminates with resins such as polyesters, phenolics, thermosetting silicones, melamines, and furanes.

The use of long fiber chrysotile, crocidolite, and in some cases amosite, in the form of felts or papers and impregnated with resins produces a tough product of high strength and good heat resistance. These products have been used in aeroplane wings in England and in small sailing boats, radar scanner aerials, aircraft tanks, automobile bodies, and other products including rocket tubes, missile nose cones, and other parts.

In some cases, asbestos in the form of cloth or a millboard type is impregnated by resins to obtain a strong sheet for structural use.

Short Group 7 fiber and floats are also used extensively as a fibrous filler for the production of molded phenolic resin and polyester parts, such as automobile heater and air conditioner housings, electric kettle bases, and other appliance parts. In such applications, freedom from abrasive particles is especially important to hold die wear at minimum level.

Joint Filler—Another interesting use for short Group 7 fiber and floats is in the manufacture of joint filler cements and texture paints. Here again, fineness, and whiteness are critical properties of the fiber. Also, since the viscosity of the mix after the addition of a prescribed amount of fluid must be consistent from batch to batch, the absorptive capacity of the asbestos must be controlled within very narrow limits.

Prices for fibers from the major Canadian and American producing areas are listed in Table 15. Russian fiber prices vary with fiber

TABLE 17—Russia: Exports of Asbestos to Countries Importing over 1,000 t in Any One Year, 1974, 1975

	1974		1975	
	t	1,000 Roubles	t	1,000 Roubles
Austria	7.9	0.79	10.0	1.54
Belgium-Luxembourg	14.9	1.62	14.2	1.98
Bulgaria	32.6	4.23	28.8	4.55
Cuba	14.0	2.08	8.8	1.40
Czechoslovakia	28.0	4.15	31.2	5.53
France	54.4	5.86	63.2	9.23
East Germany	44.7	5.14	59.4	9.35
West Germany	18.5	2.19	17.9	2.60
Hungary	26.0	3.32	27.9	4.44
India	35.4	5.09	29.2	4.62
Italy	1.2	0.15	13.4	2.38
Japan	66.5	8.01	68.3	10.68
Poland	74.9	9.61	76.2	12.50
Romania	21.9	2.94	34.3	5.80
US	—	—	10.7	2.56
Yugoslavia	32.0	4.49	33.7	6.31
Others	55.3	6.89	89.3	11.05
	528.2	66.56	616.5	97.63

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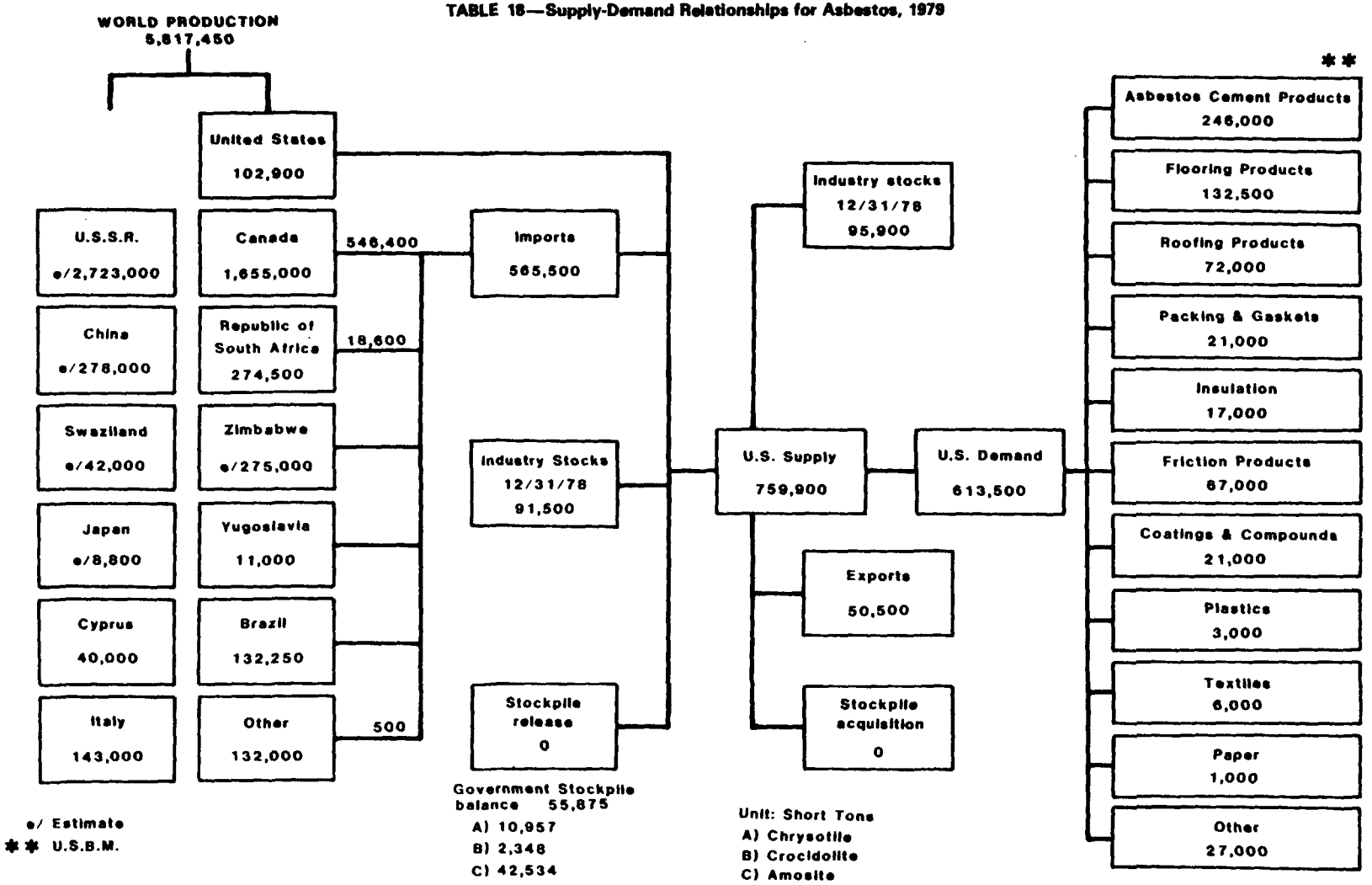
TABLE 18—Supply-Demand Relationships for Asbestos, 1979



availability, and only certain grades are offered for sale.

Markets

In the late 1960s and early 1970s the consumption of asbestos fiber increased at the rate of 3 to 4% yearly. The US, Western Europe, and Japan have remained the major outlets for asbestos fiber exports. In recent years some of the developing countries have become a major factor in the rate of asbestos fiber consumption.

On a worldwide basis, estimated consumption is approximately 6 million tons, of which Canada supplies about 28% of world requirements. As indicated in Table 16, Western Europe accounts for 40% of total Canadian exports.

The largest producer is Russia which produces 50% of the world requirements. Russia exports from 330,000 to 660,000 short tons per year (see Table 17).

The major end uses for asbestos fiber are asbestos-cement sheet, asbestos-cement pipe, cushion vinyl floor backing, floor tile, friction materials, rolled roofing, asbestos-filled asphalts, plastics, coatings and other lesser uses. A breakdown of US 1978 end use consumption shows asbestos-cement products consuming 41% of total fiber, and floor tiles 20% (Table 18).

However, due to the slower increase in consumption for asbestos-cement pipe and sheet and continued increase in the use of substitutes, the overall world growth rate will decline in the coming years.

Health Hazards

In the area of health hazards, the asbestos industry has taken measures to answer statements on the usage and safe application of asbestos by setting up the Asbestos Information Assn./North America, whose basic objectives are to: (1) provide an authoritative channel of communication, (2) rebut irresponsible statements, (3) disseminate information on the safe uses of asbestos in our modern technological society.

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new requirements was the use of amosite. R. T. Land, a government consultant on miscellaneous materials, stated in 1941 about amosite that "if Canadian fibers were substituted, thicker, heavier, and less efficient products would be made, and such products would not comply with current specifications. This type of fiber is essential for bulky lightweight insulation." Considering that during this period the government was controlling the insulation market, it would have been impossible not to use amosite.

However, I will now turn Devil's Advocate and explore other reasons for using amosite that I have encountered. First and foremost would be the shortage of suitable Canadian fibers. One of Manville's own Inspection and Control reports specifically gave this reason for experimenting with amosite in 85% magnesia.

The second reason is that the market price of amosite, including overseas freight, was generally comparable, if not favorable, to the price of long fiber chrysotile. This is also consistent with the previously stated reason concerning the shortage of suitable Canadian fiber.

The third reason would be that by adding amosite you simply made a better product in some instances. And this can lead to lowered production costs due to fewer rejects and less material usage.

Finally, inasmuch as this research is for the benefit of the trust, I have collected a number of documents which can provide background on these matters in greater detail. I have included an excerpt from our Claims Court appeal, discussing our arguments on the specifications issue, as well as documents covering amosite and crocidolite use in general, government requirements for amosite, and some of Manville's attempts to provide the required amosite products. Some of these documents I think are so pertinent that I'm only sorry they didn't surface before - they would have been very supportive of Don's testimony.

Should you require any further information on this issue, please let me know.

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