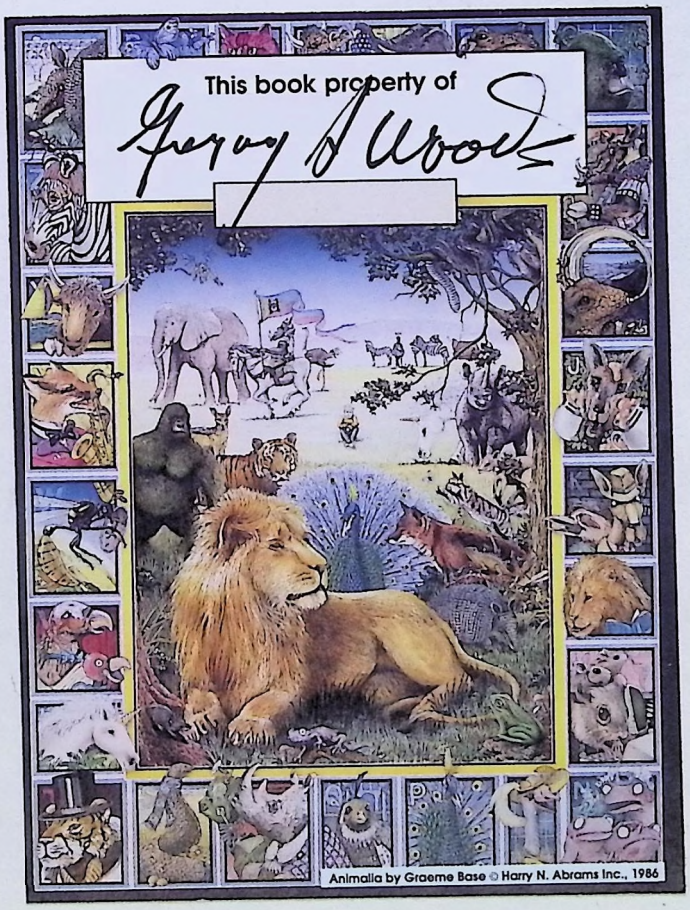
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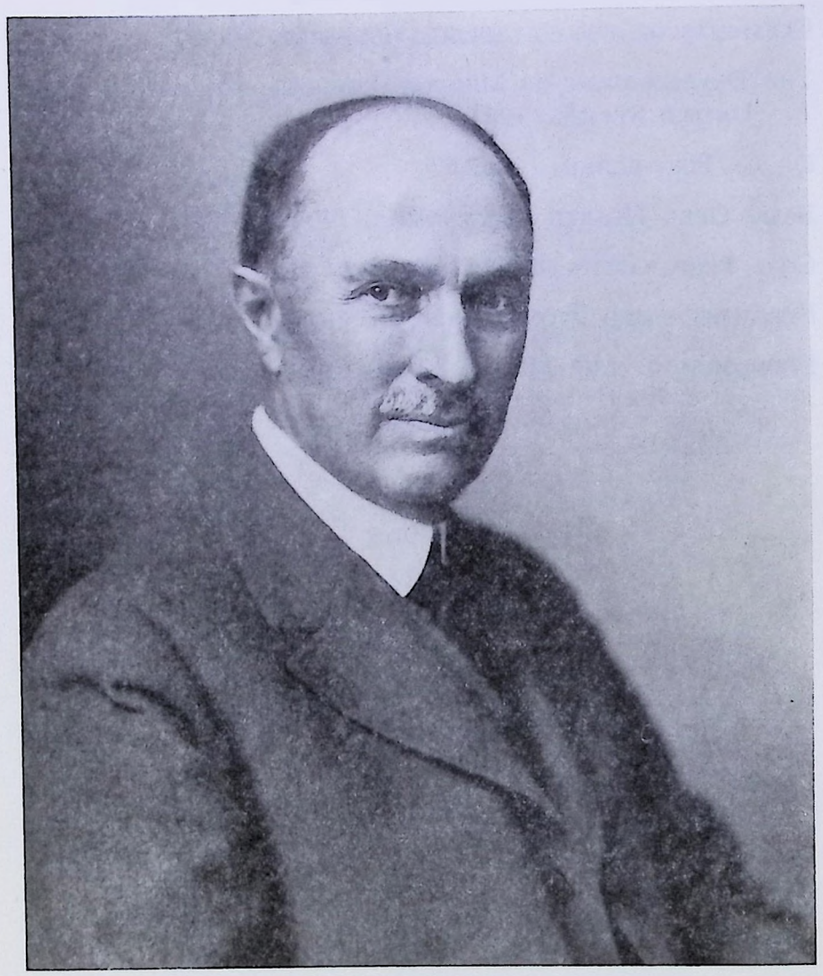
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Industrial Minerals and Rocks

(Nonmetallics other than Fuels)

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Third Edition Completely Revised

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Third Edition

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Preface to the Third Edition

Now, after a period of ten years of intensive activity in the field of industrial minerals, this third edition of this volume on Industrial Minerals and Rocks is published. The first edition was printed in 1937, the second in 1949. Just as the second was an almost entirely rewritten version of the first, bringing up to date the many advances in that dynamic field that had taken place in the 12 years, now this third edition is also almost entirely rewritten in an attempt to keep pace with the rapid changes that have occurred in the technology, industrial applications and usefulness of the industrial minerals.

Just as this book is a measure of, and a monument to the vitality and strength of the industry itself, it is also a measure of the vitality and strength of the Industrial Minerals Division of the Society of Mining Engineers of AIME. It was in 1920 during the term of Herbert Hoover as president of AIME that the Nonmetallic Minerals Committee was formed, which in 1935 became the Industrial Minerals Division. Two of the men who were active in the organization of that committee were active in the writing and editing of each of these three editions, Oliver Bowles and Raymond Ladoo. Each has served as Chairman of the Division. Each has written two chapters in the current volume. Unfortunately Dr. Bowles passed on before this third edition could appear, but his great contributions to the Industry were recognized by the Division which made him the first recipient of its Hal Williams Hardinge Award. Samuel H. Dolbear, the first Chairman of the Division, inspired the first two editions, and served as the Editor-in-Chief of them. Although still active, he asked to be relieved from responsibility in this third edition.

That this present volume is truly the collective achievement of the Industrial Minerals Division is indicated by the fact that its editor-in-chief and seven members of its editorial board are past Chairmen of the Division. The other four are equally outstanding in the Industrial Minerals Field—J. E. Lamar, head of the Industrial Minerals Division of the Illinois Geological Survey; M. F. Goudge, just retired as head of the Industrial Minerals Division of the Canadian Department of Mines and recipient of its Blaylock medal of CIM and the McCharles Prize from the University of Toronto; George C. Lindsay, Editor of that active journal in the Industrial Minerals Field, Rock Products; and George Josephson, of the Statistical Division of the U. S. Bureau of Mines.

Like the second edition, publication of this volume was made possible by an appropriation from the Seeley W. Mudd Memorial Fund, now administered by a

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committee of which J. M. Lovejoy is Chairman, with H. T. Mudd, J. T. Duce, Howard C. Pyle, and E. O. Kirkendall as members. To the foresight and generosity of Colonel Mudd, the Industrial Minerals Industry must be obligated forever.

To each of the authors who contributed so generously of their time and experience in the preparation of these chapters, the members of the Editorial Board are sincerely grateful. To Mr. E. J. Kennedy, Jr., a former Assistant Secretary of the Institute, credit must be given for bringing the manuscripts through to publication. Thanks are also extended to Mr. E. H. Robie, Mrs. W. D. Gifford, Miss M. Snedeker and R. Beals who assisted in publication and to Mr. John Herling who indexed the volume.

Wilmington, Delaware
June 29, 1959

JOSEPH L. GILLSON

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Asbestos*

G. F. JENKINS†

The word asbestos is a broad term that has been accepted and applied to a number of fibrous mineral silicates found in nature. They are incombustible and can be separated by mechanical means into fibers of various lengths and thicknesses, but differ in chemical composition and other properties.

It is generally recognized that there are six varieties of asbestos; the finely fibrous form of serpentine known as chrysotile, and five minerals of the amphibole group, i.e., amosite (not fully recognized as a mineral species name but accepted in asbestos terminology), anthophyllite, crocidolite, tremolite and actinolite. (Figs 1–4.)

Physical and Other Properties

The structures of asbestos fibers have been studied intensely in recent years. X-ray diffraction patterns[1 to 15] have been used as a means of identification and classification. The amphibole group structures have been fairly well established while the serpentine group has been the subject of many investigations during the past six years.

Low-angle X-ray scattering techniques[5] have shown that the chrysotile fibrils are "hexagonally close packed" and parallel to each other, having cross-sectional diameters varying from 180Å* units to 300Å units, while the amphibole fibers are many times larger in cross section. The electron micrographs of chrysotile asbestos (Figs 1–4) have also indicated that the fibrils might be in the form of a hollow tube. This point has been the subject of considerable controversy by a number of investigators.[7 to 16] Density measurements[17] made on a sample of high quality Arizona fiber did not indicate that the fiber had a hollow tube structure; however, the so-called "sheet structure" of the fibril could be distorted in such a way that it gives the appearance of a hollow tube in the electron microscope. It is of interest to quote one investigator, F. L. Pundsack,[17] in this connection:

> Although the empirical composition of chrysotile is $3MgO.2SiO_2.2H_2O$, the true unit cell‡ composition is best represented as $Mg_{12}(OH)_{16}Si_8O_{20}$. This cell has dimensions of a = 5.3Å, b = 9.2Å, and c = 14.6Å where the "a" direction is the fiber axis. The calculated density of this unit is 2.56 g/cc, a value in close agreement with experimentally determined density values for chrysotile.
>
> The exact manner in which the unit cells of asbestos are stacked together to build up a single fiber of chrysotile is not known, but from various

* Angstrom units = 0.0000001 mm.

* This chapter in previous editions (1937 and 1949) described the general properties of asbestos, the distribution of deposits throughout the world as known at the time of writing, a description of mining methods, beneficiation and preparation for market, production statistics, tests and specifications, uses and prices. In the present edition certain phases of the subject are covered in greater detail than previously, while other aspects are dealt with more briefly, using references to assist readers in search of more detailed information. It will be found that the physical properties of the various asbestos minerals are itemized and described much more fully here; likewise there is new information on prospecting methods and evaluation of deposits. Statistics are brought up to date and mention is made of newly developed occurrences.

† General Manager, Asbestos Corporation Ltd., Thetford Mines, Quebec, Canada.

The author wishes to acknowledge the help given him by M. S. Badollet, Research Center, Johns-Manville Corporation, Manville, N. J., with the section on basic properties and uses; also the help of Dr. P. H. Riordan, Exploration Manager, Asbestos Corporation Ltd., Thetford Mines, Quebec, with sections on geology of Canadian deposits, exploration, and evaluation.

‡ The unit cell is the smallest possible subdivision of structure which by repetition of itself in all directions, builds the visible macrocrystal.

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FIG 1—*Electron micrograph of chrysotile asbestos. 4000×.*



FIG 2—*Electron micrograph of amosite asbestos. 4000×.*



FIG 3—*Electron micrograph of crocidolite. 4000×.*



FIG 4—*Electron micrograph of chrysotile asbestos. 45,000×.*

lines of experimental evidence it can be estimated that stacking in the "b" direction probably does not exceed a "width" of about 1000Å. Stacking in the "c" direction probably is limited to a "thickness" of not more than 200Å, whereas stacking in the "a" direction may extend to a "length" of many millions of angstrom units. Because of the nature of the X-ray diffraction pattern of chrysotile it is generally accepted that a single fiber of chrysotile does not exist as a flat lathlike structure, but instead the fiber must be distorted in some way. Efforts to account for this distortion have ranged from depicting the single fiber as a slightly curved lath all the way to viewing it as a completely curved structure which forms a hollow tube. Recent evidence seems to mitigate against a simple hollow tube structure, but as yet no completely satisfactory structure has been evolved.

Chemical analyses of asbestos fibers do not give the entire story of the fibers under investigation, and additional tests are necessary in order to obtain more complete information in respect to various properties for identification purposes. Such tests include differential thermal analysis,[18] surface area,[19] conductivity,[20] solubility, spectrographic analysis, magnetic ratings, flexibility, tensile strength, basicity[19] of fiber, and reactivity of fiber with other electrolytes.

In many cases, a study of the chemical analysis data of a given asbestos fiber indicates the possibility of other minerals being present. This can be verified by the spectrographic and petrographic analyses and X-ray diffraction patterns. Then again, chrysotile fibers from different areas may have minor differences in thermal analyses and surface areas that may account for certain peculiar characteristics of the fiber when used in some particular product.

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TABLE 1—*Properties of Asbestos Fibers*

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 iron-stones	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 argillite in quartzose schists	In Mg limestones as alteration products of highly magnesian rocks. Metamorphic and igneous rocks
Origin	Results of contact 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 pct	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
Theoretical formula	$Ca(Mg.Fe)_3(SiO_3)_4 \times H_2O$	$(Fe.Mg)SiO_3$. 1–5 pct H_2O	$(Mg.Fe)_7Si_8O_{22}(OH)_2$	$3MgO.2SiO_2 2H_2O$	$NaFe(SiO_3)_2FeSiO_3 \times H_2O$	$Ca_2Mg_5Si_8O_{22}(OH)_2$
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
Lustre	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±
Length	Short to long	2″ to 11″ 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

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TABLE 1—*Properties of Asbestos Fibers (Continued)*

Property	Actinolite	Amosite	Anthophyllite	Chrysotile	Crocidolite	Tremolite
Specific heat B.t.u./lb/°F	0.217	0.193	0.210	0.266	0.201	0.212
Tensile strength, lb/sq in	1,000 and less	16,000 90,000	4,000 and less	80,000 100,000	100,000 300,000	1,000 8,000
Temp. at max. ignition loss, °F	—	1,600 to 1,800	1,800	1,800	1,200	1,800
Filtration properties	Medium	Fast	Medium	Slow	Fast	Medium
Electric charge	Neg.	Neg.	Neg.	Pos.	Neg.	Neg.
Fusion point, °F	2,540	2,550	2,675	2,770	2,180	2,400
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 temp.	Very good	Good. Brittle at high temp.	Poor, fuses	Fair to good
Ionizable salts, micro-mhos (Relative elec. conductance)	—	1.34	0.58	1.82	0.84	—

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Since chrysotile asbestos is the result of hydrothermal reactions under certain conditions within the serpentine rock, whether it be peridotite, dunite, pyroxenite or serpentinized dolomitic limestone, it is only natural to expect imperfections within the crystal structure and the inclusions of impurities between fiber bundles as well as at the end of the bundle nearest the wall rock. Consequently, it is difficult to remove these impurities by mere mechanical means, and therefore it is necessary to measure their detrimental effect by obtaining the conductivity, solubility, basicity, reactivity, and magnetic rating. In some commercial products, this type of information is not necessary; however, if the fiber is to be used in electrical products or for certain filtration purposes, it is then desirable to have this additional information.

Crocidolite and amosite occur in metamorphosed siliceous-ferruginous sediments. The fibers are often comparatively long, ranging up to several inches, which, however, is of no advantage for most purposes, and may detract from the value since the greatest use for these varieties is in the manufacture of asbestos cement products where fibers of one-eighth to three-eighths inches in length are more suitable.

Anthophyllite[21] has a low ignition loss comparable to that of tremolite. It is never known to occur, however, with fibers sufficiently flexible to be spun nor with the tensile strength required to make them of value to the asbestos cement industry. Resistance to chemical reaction, nevertheless, opens a specialized field for this fibrous mineral as a filter medium and as a filler.

A comparison of the properties[21] of the six varieties of asbestos is shown in Table 1.

Recent thermal analyses[18] for chrysotile show a broad endothermic peak between 600° and 720°C, which corresponds to loss of structural water with an exothermic peak at 800°C, probably associated with a phase change to fosterite. This type of pattern agrees with other patterns reported in the literature.

The surface area determination of chrysotile depends upon the type of measuring apparatus employed. For example, if measurement of the degree of opening of the fiber bundles is desired, then an air permeability[21] method is quite satisfactory. However, if it is desired to measure all the available pore space between the fibers, it is necessary to resort to a method employing gas absorption techniques. The specific surface areas[18] reported by nitrogen absorption show an extreme range of values apparently due to the method of opening the fiber bundles. These values range from 4 to 12 m^2/g when carefully opened by hand, or from 30 to 50 m^2/g when special mechanical equipment and chemical dispersing agents are used.

The hydrogen ion concentrations[18] of chrysotile fibers have been reported to vary from 9.0 to 10.3, depending upon the method of preparing the sample and its measurement. The hydrolysis of the chrysotile molecule in distilled water free from carbon dioxide resembles the action of magnesium hydroxide in water.

Recent careful density measurements[17] of chrysotile asbestos have shown values varying from 2.53 to 2.58.

The electrical conductivity[19] of a number of aqueous suspensions of chrysotile fibers from eight different sources is shown in Table 2, and the excess soluble electrolyte content is expressed as equivalent sodium chloride.

TABLE 2—*Specific Conductivity of Chrysotile Asbestos Aqueous Suspensions*[19]
($Ohms^{-1}\ cm^{-1} \times 10^5$)

Sample	Percent chrysotile in suspension				Percent NaCl equiv.[d]
	0.20	1.00	2.00	2.90	
Danville[a]	—	12.5	17.5	23.4	0.24
Arizona Soft[b]	6.0	10.9	17.1	22.2	0.27
Arizona Harsh	5.3	7.4	9.7	11.9	0.10
Munro	3.5	5.4	6.4	7.7	0.05
Vimy	4.8	7.8	10.9	13.5	0.13
Normandie[c]	5.0	9.8	13.9	17.8	0.19
Shabani	4.8	10.5	16.3	20.6	0.24
Transvaal	6.1	11.3	17.0	21.8	0.25

[a] Additional points 0.07 pct = 3.0×10^{-5}, 0.13 pct = 4.7×10^{-5}, 0.40 pct = 8.4×10^{-5}.
[b] 0.3 pct = 6.7×10^{-5}.
[c] 0.5 pct = 6.7×10^{-5}.
[d] Hypothetical NaCl in the sample required to account for that portion of the conductivity not due to $Mg(OH)_2$ ionized from the fiber surface.

The data from Table 2 show that the chrysotile fibers from different sources contain soluble electrolytes as well as the magnesium and hydroxyl ions dissociated from the fibrils. If we take the column showing 2.90 pct chrysotile in suspension, then the fibers would

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TABLE 3—*Effect of Temperature on Loss in Weight of Asbestos Fibers*

Temp. °F	Time	Loss in weight				
		Amosite, pct	Anthophyllite, pct	Chrysotile, pct	Crocidolite, pct	Tremolite, pct
400	2 hr	0.23	0.05	0.30	0.08	0.04
600	2 hr	0.57	0.24	0.85	0.25	0.08
700	2 hr	0.80	0.30	1.78	0.49	0.13
800	2 hr	0.98	0.38	2.17	0.73	0.22
900	2 hr	1.07	0.41	2.83	0.83	0.26
1,000	2 hr	1.16	0.44	3.99	0.86	0.29
1,100	2 hr	1.36	0.52	10.38	1.00	0.37
1,200	2 hr	1.39	0.54	12.75	1.04	0.37
1,400	2 hr	1.43	0.54	13.43	1.03	0.47
1,500	2 hr	—	0.64	—	—	0.56
1,600	2 hr	1.52	1.12	13.62	0.93*	0.67
1,700	2 hr	—	1.73	—	—	1.40
1,800	2 hr	1.53	2.39	13.77	0.77*	2.18

* Iron changing in weight due to oxidation.

have the following ranking according to conductivity:

Rank No. 1 (best)	Munro
Rank No. 2	Arizona Harsh
Rank No. 3	Vimy
Rank No. 4	Normandie
Rank No. 5	Shabani
Rank No. 6	Transvaal
Rank No. 7	Arizona Soft
Rank No. 8 (poorest)	Danville

Conductivities of suspensions or aqueous extracts of asbestos are an index of dissolved salts or electrolytes, but do not necessarily correlate closely with the electrical insulating properties of the same fibers in the dry state. For instance, in addition to electrolytes, other impurities such as magnetite may effect the electrical insulating value. Further, there is strong evidence that differences in hydroxyl ion arrangement at fiber surfaces is responsible for electrical leakage along and around the fiber surfaces.[20]

Effect of Heat on Asbestos[21,25]

Varieties of asbestos subjected to temperatures ranging from 400° to 1800°F, as given in Table 3, and for a period of two hours for each test, first showed the effect by a loss of molecular water content. The later gain in weight in the case of crocidolite at higher temperatures is accounted for by oxidation of molecular iron.

It will be noted that at elevated temperatures the ignition losses for the amphiboles is far less than that for chrysotile. It should not be assumed, however, that the amphibole fibers are less or even relatively less brittle under these conditions. An anthophyllite, for example, heated at 800°F for two hours is far more brittle and friable than a chrysotile heated for two hours at 1000° to 1100°F.

TABLE 4—*Effect of Heat on Tensile Strength of Canadian Chrysotile Crude*

	Tensile strength lb/sq in.	Percent 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

In 1956 H. M. Woodrooffe[22] made a study on the pyrolysis of chrysotile asbestos using the Chevenard Thermobalance with a modified control system. The decomposition of chrysotile occurred in three distinct stages represented empirically in Table 5 by points T_a, T_b, and T_c. The first stage represented a surface phenomenon, a second stage of rapid change from 400° to 500°C and a third stage around 700°

to 1000°C where the decomposition is rather uniform and the weight loss is small. The pyrolysis curves for fifteen different specimens show weight losses from 12.60 to 14.65 pct. At the higher temperature weight losses will include decomposition other than water and must be considered.

The pyrolysis data and chemical analyses of fibers under observation are shown in Tables 5 and 6.

Brindley and Zussman[23] have recently shown on the basis of X-ray diffraction studies that after chrysotile loses its water at about 500°C, the chrysotile structure begins to undergo rearrangement to form forsterite, and at 600°C or slightly higher no trace of chrysotile structure remains.

TABLE 5—*Pyrolysis Data*

Sample No.	T_a	T_b	T_c	Percent weight loss			
				100°C T_a	T_a T_b	T_b T_c	Total
1 Vimy	545°C	718°C	885°C	0.90	10.65	1.05	12.60
2 Abitibi	545	715	885	1.25	10.15	1.30	12.70
3 C and G3	460	697	885	1.10	13.30	1.05	15.45
4 Munro	515	720	900	0.55	11.35	1.05	12.95
5 Kilmar	440	675	885	0.85	11.55	1.15	13.55
6 Deloro	425	740	920	0.35	13.15	1.15	14.65
7 Cassiar	520	705	900	0.85	11.55	1.15	13.55
8 Newfoundland	460	690	905	0.75	11.95	1.10	13.80
9 Carey	490	680	870	0.95	11.40	1.10	13.45
10 Normandie	460	715	895	0.80	11.60	1.10	13.50
11 Thetford	480	680	870	0.80	10.90	0.95	12.65
12 Papineau Co	450	705	1000	1.05	11.50	1.10	13.65
13 Black Lake	455	705	885	0.65	11.45	1.10	13.20
14 C.J.M.	455	695	895	0.95	11.95	1.10	14.00
15 Picrolite	595	735	885	0.65	10.10	1.20	11.95
16 Kilmar Serpentine	315	660	855	0.70	12.90	0.95	13.85

TABLE 6—*Chemical Analysis of Some of the Samples[1] of Table 5*

Sample No.	MgO	SiO_2	Al_2O_3	Fe_2O_3	CaO	+105 H_2O
1	38.49	41.66	1.67	4.25	None	12.28
2	39.67	42.02	2.17	3.75	None	11.98
3[2]	40.15	37.28	0.71	2.29	1.00	14.01
4	40.87	41.96	1.10	2.36	0.55	13.18
5[3]	41.48	41.68	0.11	0.43	1.15	14.02
6	39.53	36.52	1.69	3.80	0.90	12.13
7	40.23	41.22	0.40	2.18	1.20	14.08
8	42.43	40.64	0.34	1.66	Nil	13.40
9	42.48	42.40	N.D.	0.68	0.13	13.68
11	41.20	41.56	0.12	1.96	1.05	13.84

[1] Dry weight basis.
[2] This sample contained 2.69 pct CO_2.
[3] This sample contained 5.57 pct CO_2.

A convenient table of data showing the effect of acids and caustic soda is given in Table 7. Apparently when the fibers stand in acids or sodium hydroxide solution for 528 hr at 26°C, the solubility is about the same as at boiling for two hours. Acids such as hydrochloric, phosphoric, and sulfuric, attack the

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TABLE 7—*Solubility of Asbestos*

Percent Loss in Weight, Refluxing Two Hours
25 pct 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

Percent Loss in Weight, Room Temperature 26°C for 528 Hr
25 pct 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	3.91	3.48	1.20
Tremolite	4.22	1.41	4.89	4.74	1.65

fibers to about the same extent. Acetic acid, on the other hand, is not so severe, while caustic does only a little damage to the fiber structure. Chrysotile is readily attacked by mineral acids and should not be used in the presence of these.

A review of literature shows that the chemical analyses of asbestos fibers vary, depending upon the location of the deposit. The following analyses (Table 8) give a general idea of the chemical elements that are found in asbestos fibers from various parts of the world.

Geology

Chrysotile constitutes about 93 pct 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. This other fraction of the chrysotile production is derived from

TABLE 8—*Chemical Analyses of Asbestos Fibers*
(Oven dried basis in percent)

	MgO	SiO_2	Al_2O_3	FeO	Fe_2O_3	MnO	CaO	Na_2O-K_2O	H_2O
Actinolite (1)	4.7	52.4	Tr.	23.1	6.4	0.1	9.3	0.4	3.1
Actinolite (2)	5.0	47.0	7.0	26.1	2.4	0.1	10.8	Tr.	1.0
Chrysotile (3)	40.9	43.1	0.9 (-TiO_2)	—	1.1	—	Nil	0.1	13.6
Chrysotile (4)	41.4	38.9	0.8	1.7	2.6	—	Tr.	0.3	13.9
Chrysotile (5)	42.3	40.1	0.3	1.2	2.3	—	—	—	13.1
Chrysotile (6)	40.8	41.2	0.1	0.4	3.8	—	—	—	13.3
Chrysotile (7)	40.1	39.0	3.7	0.9	1.5	—	—	—	14.5
Chrysotile (8)	43.8	40.3	1.0	0.1	0.7	—	—	—	13.9
Chrysotile (9)	43.3	42.6	0.1	0.2	1.0	—	0.1	—	12.6
Chrysotile (10)	40.7	42.4	1.6	(2.1)		—	—	—	14.0
Montasite* (11)	6.4	49.9	Tr.	33.5	6.8	0.1	0.1	0.3	2.6
Montasite* (12)	5.2	47.6	1.8	31.7	7.4	0.9	0.1	2.0	2.2
Amosite (13)	6.2	48.5	0.6	34.9	4.3	—	0.8	0.4	Nil
Montasite (14)	5.9	50.0	Tr.	25.8	12.1	—	0.2	2.8	3.2
Montasite (15)	4.2	56.0	Tr.	17.3	18.4	—	Nil	1.8	1.6
Australian Blue (16)	5.2	51.5	1.0	14.5	18.5	—	0.1	5.8	1.5
Cape Blue (17)	2.7	46.7	0.6	14.0	25.0	—	2.4	3.9	3.7
Bolivian Blue (18)	14.5	56.1	0.7	4.1	15.6	—	1.1	5.8	2.2
Anthophyllite (19)	30.1	57.2	2.0	4.6	2.7	—	0.2	Tr.	3.3

* Amosite having a grayish blue color.

Reported by:

(1) Frankel
(2) Peacock
(3) Krugersdorp
(4) From Danville, P.Q.
(5) From Black Lake, P.Q.
(6) From East Broughton, P.Q.
(7) From Thetford Mines, P.Q.
(8) From Arizona
(9) From Deloro Township, Ont.
(10) From Western Australia
(11) From Pietersburg Transvaal
(12) From same as above
(13) From Transvaal
(14) From Pietersburg
(15) From same sample as 14
(16) From Australia
(17) From Cape Province
(18) From Bolivia
(19) From Georgia, U.S.A.

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 5.4 pct 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 the chrysotile production comes from three principal areas: the Eastern Townships of Quebec in Canada (Fig 5), the Bajenova District in the Urals of the U.S.S.R.,

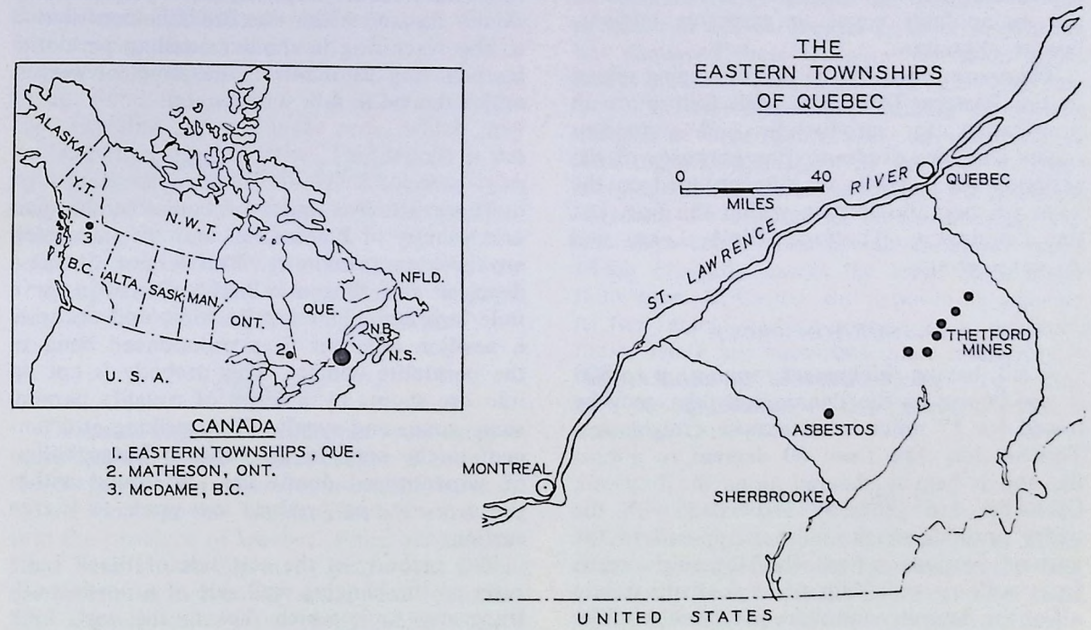


FIG 5—*Asbestos mining areas in Canada.*

and, from Southern Rhodesia, Swaziland and the Transvaal in Africa. The Quebec deposits are mid-Paleozoic in age, those in the Urals are of late Paleozoic or Triassic and those in Africa are Precambrian in age.

EASTERN TOWNSHIPS, QUEBEC

The chrysotile deposits found in the Appalachian belt passing through the Eastern Townships of Quebec yield close to 44 pct of the total world fiber production. These deposits occur over a length of some 55 miles in association with the peridotite facies of a belt of ultrabasic rocks. A major unconformity, probably faulted in places, served as a zone of weakness along which these eruptives moved upward through the crust. The peridotite was originally a harzburgite containing 10 to 15 pct enstatite and small bodies of dunite, having dimensions of a few feet to several hundred feet, are scattered through the peridotite as local segregations. Deuteric alteration resulted in the uniform and partial serpentinization of the peridotite and complete serpentinization of most of the dunite.

Soon after the emplacement of the ultrabasic rocks, and quite possibly while these rocks were still cooling, minor adjustments caused a moderate amount of fracturing which was followed by the intrusion of acid magma. This last intrusive activity produced numerous small, irregular shaped, bodies of granite and swarms of even smaller bodies of syenite which resulted in complete serpentinization of the ultrabasic rocks in their immediate vicinity. In some of the smaller ultrabasic bodies these acid intrusives apparently failed to gain access as they are not always in evidence.

Major adjustments, which took place soon after the emplacement of the granite and syenite, were confined for the most part to those margins of the peridotite that were in

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contact with the country rocks, in preference to those contacts with other facies of the intrusive complex. Contact faults of this character are common, and where irregularities were present in the contact these faults or branch faults continued out into the main body of the peridotite. In addition there are a number of significant transverse faults.

This period of major faulting was accompanied by the development of numerous subsidiary faults and fractures. It was in conjunction with these adjustments that intensive serpentinization of the peridotite occurred and culminated in the formation of asbestos veins. Subsequently there was a final period of hydrothermal activity which gave rise in some of the major fault zones to extensive talc-carbonate alteration.

There are presently ten deposits being mined in the Eastern Townships with four more in preparation for production and numerous others that are dormant. For purposes of description the deposits may be grouped on the basis of their distribution within the belt, i.e., the Pennington, Thetford, Black Lake, and Asbestos groups.

PENNINGTON GROUP

A sill, having thicknesses ranging up to 800 ft and known as the Pennington dike, may be traced for 17 miles in an almost straight line. This sill has dips from 60 degrees to almost flat and is heavily sheared along the footwall. Orebodies are generally associated with the wider portions of the sill, as opposed to the narrow portions where the shearing occurs from wall to wall. Slip fiber predominates in all of the deposits, and there is more cross fiber at the southwest than at the northeast end of the sill. The narrowness of the orebodies and attitude of the sill are obstacles to mining to any appreciable depth. The footwall shear along much of its length has been converted in part to steatite.

There are presently two deposits being mined and two others under development, in addition to four that are dormant or exhausted.

THETFORD GROUP

A large mass of peridotite is host to the Thetford and Black Lake groups. The Thetford group lies at the northeast end of this mass and contains four producing 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 zone has a length of 6000 ft and a width of 1500 ft with the largest and deepest deposit, the King-Bell-Johnson, extending to a depth of 1500 ft or more. The other deposits are the Bennett-Martin, the Beaver Number 1, and the Beaver Number 2.

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 GROUP

There are five major orebodies in the general vicinity of Black Lake, only two of which are in close proximity. The largest of these deposits, the Megantic-British Canadian, is a mile long by a half a mile wide, and occupies a position adjacent to a pronounced bend in the peridotite contact. This orebody is cut up into ore shoots by a series of roughly parallel shear zones and syenite dikes striking at a tangent to the bend in the contact. Large bodies of serpentinized dunite are also found within the orebody and produce low grade to barren sections.

The orebody at the east side of Black Lake rests on the hanging wall side of a north-south transverse fault which dips to the east. Like the major fault in Thetford this zone has also undergone intensive steatitization. Another orebody on the west side of the lake lies beneath a large, flat lying, acid dike, which evidently localized the fracturing in its vicinity and no doubt served as a barrier to rising solutions.

Two miles west of Black Lake the Normandie and Vimy Ridge deposits are situated just south of a sharp "s" bend in the peridotite contact. Displacement along a transverse fault is probably responsible for this marked irregularity in the contact. The Normandie orebody lies to the south or on the footwall side of the transverse fault and is separated from the Vimy Ridge orebody to its south by a shear which is associated with numerous large syenite dikes. Both orebodies are bounded on the east by a fault zone which is a southward continuation of a fault paralleling the peridotite contact to the northeast. Both orebodies fall within a zone which rakes flatly north beneath the contact. Whereas the other deposits in the Eastern Townships are made up of a stock work of asbestos veins, there is a prevalent system of parallel veins in the Normandie and Vimy Ridge orebodies which dip flatly to the north with the rake of the ore zone.

DANVILLE GROUP

The Jeffrey and the very much smaller Nicolet orebodies occur on the North and footwall side of a large peridotite dike. The Jeffrey orebody is pipelike in form, having a diameter of 2000 ft, an undetermined depth, and a steep dip to the south. The deposit is bounded by faults on three sides, one of these being along the contact, the others between the peridotite and a dunitic rock, which may be later than the peridotite. The deposit is cut by numerous irregular shears associated with acid intrusives, and having a prevalent trend paralleling the footwall contact.

The Nicolet orebody occupies a narrow zone along the contact and is bounded on its south side by a pronounced zone of shearing.

VERMONT

The most important chrysotile orebody presently known in the United States is found in the serpentine formation of northern Vermont which is part of the Appalachian belt extending into the province of Quebec. Fiber occurrences have been known for many years over a considerable area in Lamoile and Orleans counties. The deposit which is currently being worked lies near the village of Eden. Here a substantial orebody some 3000 ft wide is being mined at the foot of Mount Belvidere between elevations of 1000 to 1500 ft.

Slip fiber is the more predominant variety but some good quality cross fiber is also found. The host rock is a highly serpentinized peridotite with the fiber occurring in the vicinity of a contact with gneiss on the east side and amphibolite schist on the west side.

STRUCTURES

Major faults, along with subsidiary faults have evidently played an important part in localizing the formation of the asbestos deposits in the Eastern Townships. Irregularities in the periodotite contact were in some instances responsible for the form and distribution of these faults. Serpentinization, caused by the introduction of the swarms of small acid intrusives, influenced the formation and configuration of the subsidiary faults, and where these intrusives were large they probably tended to trap the asbestos vein-forming solutions. The serpentinized dunite bodies tended to flow when subjected to stress, and thus aided in the development of fracturing in the surrounding more brittle peridotite.

OTHER DEPOSITS

The Munro deposit in Eastern Ontario lies within a narrow ultrabasic dike that is bounded by contact faults which are marked by the presence of talc-carbonate. Later cross faulting has displaced these marginal alteration zones and is evidently post-asbestos in age. Near Baie Verte in Newfoundland, faulting along the margins of a peridotite body appears to have localized the formation of deposits to these margins. In the Belingwe district of Southern Rhodesia the deposits lie on the hanging wall side of a broad zone of talc-carbonate schist which evidently marks the locus of a major fault zone. In Cyprus the deposits lie adjacent to the faulted eastern margin of a peridotite mass. There are numerous other references in the literature on asbestos deposits which indicate the significance of the structural environment.

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. In the case of cross fiber the orientation may be anywhere from normal to sharply inclined to the vein walls, and the fibers may be straight, gently curved or contorted. Where sharp flexures are present the fiber is inclined to break. 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 picrolitic serpentine and magnetite or one or other of these constituents. The veins may be relatively persistent or short and lenticular, occurring in the form of stock works or in parallel systems. They may be fissure fillings or replacements, and are often the result of a combination of these two processes.

Some very short fiber is derived from a variety referred to as mass fiber, which occurs in

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the form of a dense network of fine reticulating replacement veins. The close spacing of these veins has resulted in a very high content of fiber, and the rock appears to be largely fibrous, sometimes being referred to as "fur" rock.

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. 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 was of 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 intrusive diabase sills.

Crocidolite and Amosite

Both of these varieties occur in South Africa in bedded metamorphosed sedimentary formation known as banded ironstones, which 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 in the bracket between ¼ and 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, points a few miles down the river. Another producing area in Cape Province is farther north in the Kuruman district where blue asbestos is mined at points near the headwaters of the Kuruman river and not far from the town by that name, and at Pomfret, just south of the Bechuanaland border. To the east and north of these areas 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. In the Pietersburg area there is also a quite silky-fibered phase of amosite called montasite which is often a dusty blue in color and has sometimes been confused with crocidolite. The only other known important deposits of crocidolite are found in the Hammersley range of Western Australia, although there are occurrences in Bolivia and elsewhere.

Amosite-bearing banded ironstone outcrops for a distance of over twenty 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 itself, the Weltevreden and the Kromellenboorg 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 dip at an angle of about 20 degrees with associated sedimentary formations and thin sills of dolerite being quite persistent and conformable. 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 above, diabase dikes cut vertically across the whole formation at intervals. Evidence as to possible relationship of these dikes to the genesis of the amosite mineralization is apparently inconclusive.

Principal Deposits

In discussing, in the preceding paragraphs, the mode in which the more important varieties of asbestos occur, specific mention has been made of several of the principal producing areas and deposits. It may also be stated that Canada produced about 50 pct of the world supply of chrysotile, mostly from the province of Quebec.

The known ore reserves of the latter area are great, and productive capacities continue to be enlarged. Figure 6 reflects the growth of Canadian production over the past nine years, showing an increase of some 57 pct in tons produced. There are further new plants under construction which came into production in

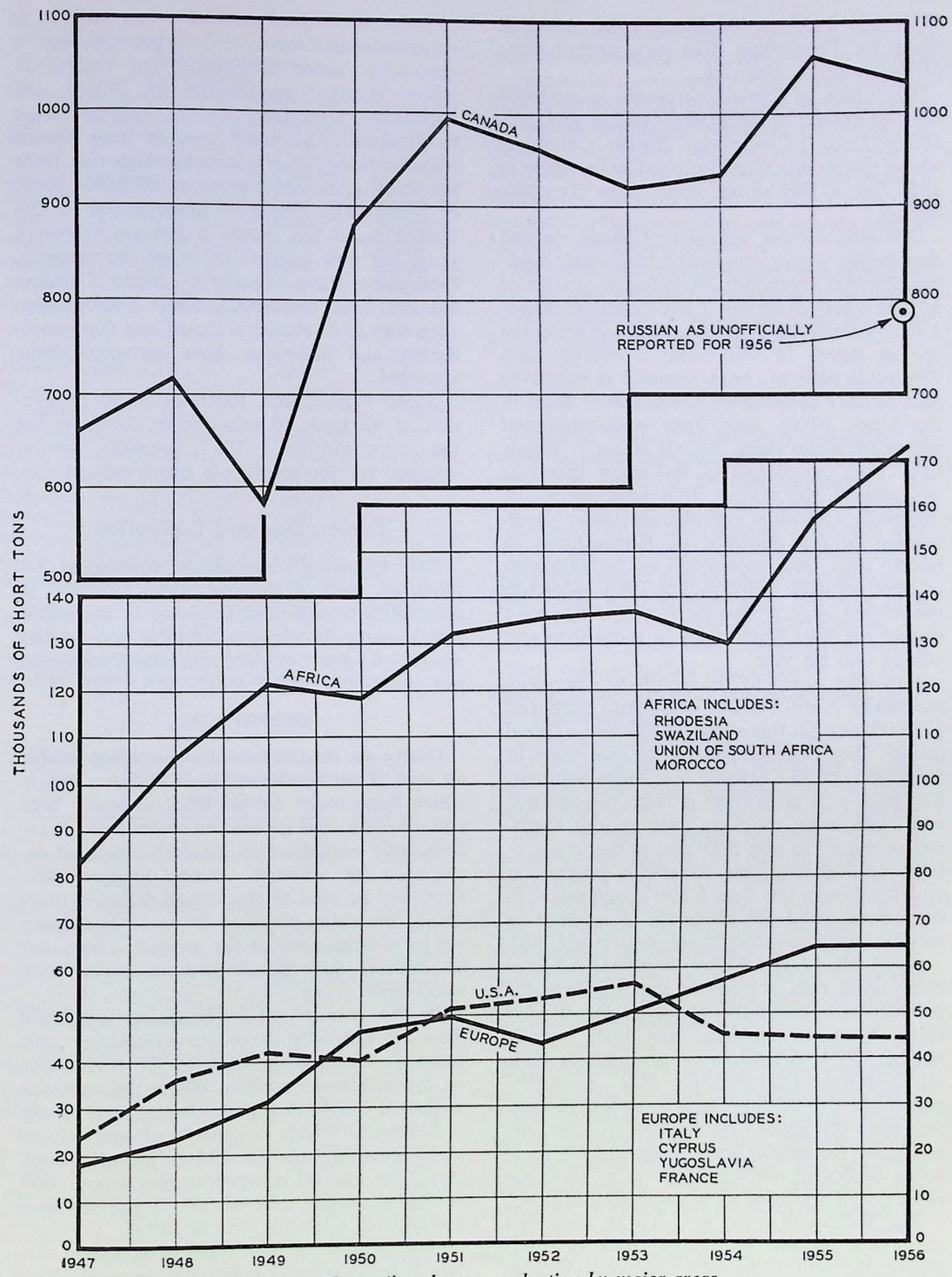


FIG 6—*Chrysotile asbestos production by major areas.*

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1958 and 1959 in the Black Lake area and along the Pennington dike with further plans for expansion at Danville.

Elsewhere in Canada chrysotile is produced near Matheson in Northern Ontario and McDame Lake in Northern British Columbia, where operations started at the Cassiar mine in 1953 on a high grade long fiber chrysotile deposit.

Running a close second to Canada we find that Russia is now reporting a production totaling 790,000 short tons, including a quarter of a million tons of groups 7 and 8, with plans for a very substantial increase which will bring the annual figure to well over a million tons. Chrysotile fiber has been reported as occurring in a number of localities in addition to those in the Urals which have been recognized and mined for many years. Several places in Siberia have been mentioned in the scant literature available on the subject. It is understood that important chrysotile deposits are under development in the Province of Khazakhstan in middle Asia with production of 500,000 tons of fiber annually slated before 1960. Added to the present large production from the Bajenova district the total would then be more than one million tons per year.

Referring again to the graph of chrysotile production it will be seen that Africa produced 172,000 tons. Of this about 30,000 tons of good quality fiber is accounted for by one mine in Swaziland. Of the 119,000 tons from Southern Rhodesia, a large portion is from the Shabani area, with lesser tonnages from nearby Mashaba to the north and Belingwe to the south. A large proportion of the Rhodesian production is derived from less than a half dozen mines in the above areas but there are a number of smaller properties which are well established.

The United States with its Vermont Asbestos Mine ranks next in order of importance in the production of chrysotile. Here the deposit near Eden, Vermont, supplies some 3,000 tons of ore per day to a modern plant producing some 40,000 tons of fiber per year with a good proportion in the medium length grades. Production from this deposit commenced in 1908, and continued for several years. Then in 1929 there was a revival of activity in the area. The present modern facilities were completed in 1949.

The Balangero mine near Turin, Italy, has an annual output of 32,000 tons of short fibered chrysotile. The total production is from one low grade massive deposit of serpentine some 1500 ft wide apparently intruding a paragneiss.

Production of the amphibole varieties of asbestos other than crocidolite and amosite is comparatively limited. The largest quantity is apparently mined in Finland and Yugoslavia which reported productions of 18,000 and 8,000 tons respectively in 1956. Italy continues to produce some 1,000 tons of long fibered tremolite every year at a rather high cost from the mine at Sondrio which is 50 miles north of Milan. The output of anthophyllite in the United States has shown a decrease in recent years but now appears to be on the increase. Production from deposits in North Carolina has not been continuous. Some anthophyllite continues to be mined in Brazil and deposits in Kenya and elsewhere have attracted some attention.

Table 9 gives first, the total world production of all types of asbestos by countries for the years 1956 and 1957; secondly, similar statistics for the amphibole fibers only.

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 rock outcrop within an area of ultrabasic rocks, or within a belt in which these rocks are expected to occur, both aeromagnetic and ground magnetic surveys are frequently employed in the early stage of exploration for asbestos. Ground magnetic surveys may be used to check, and define in more detail, anomalies obtained by an air-borne survey of a large area, or the ground survey may be initiated for the purpose of exploring a small area.

In the case of an air-borne survey, flight lines are normally spaced to one-quarter mile intervals, and flown as close to 500 ft elevation as is possible to maintain. Where the terrain is rugged it has been found advantageous to use a helicopter which is capable of maintaining a constant altitude of 300 ft above ground level. The interval between profiles on a ground survey is usually 200 or 300 ft and readings are taken at intervals of 50 or 100 ft.

The purpose of both types of magnetic survey is to locate and define the areas of ultrabasic rocks, and, within these, the areas which have been subjected to extensive serpentinization as this type of alteration produces a higher content of secondary magnetite. Asbestos deposits in ultrabasic rocks are a result of intensive serpentinization and asbestos veining is frequently accompanied by a higher concentration of magnetite than is normally found in the barren serpentine. Therefore it follows that magnetic anomalies obtained over an area of ultrabasic rocks are favorable places to explore further for asbestos. Figures 7 and 8 show the results of ground magnetometer surveys carried out over two known orebodies.

Dip needle surveys have also been employed with success. However, the degree of sensitivity of this instrument is appreciably less than that of the Askania type magnetometer.

TABLE 9—*Approximate Production of all Types of Raw Asbestos by Countries*
Short Tons

	1956	1957
Canada	1,050,000	1,061,400
Russia	790,000*	790,000*
Union of South Africa	135,000	157,300
Rhodesia	119,000	132,100
U.S.A.	41,300	43,700
Italy	36,500	37,800
Swaziland	29,900	30,700
Cyprus	15,400	13,300
Yugoslavia	15,000	15,000
Japan	9,900	13,300
Australia	9,800	13,800
France (Corsica)	9,400	15,400
Finland	8,300	10,000
Venezuela	5,000	7,700
Brazil	3,700	3,300
India	1,300	700
Bechuanaland	1,300	1,300
Bulgaria	1,100	1,100
Turkey	600	—
Morocco	400	—
Kenya	200	100
Formosa	100	300
Total	2,283,200	2,348,300

* This figure is an unofficial and unverified estimate, it includes 273,000 tons of grades 7 and 8, and is thought to represent possible production at maximum capacity.

Amphibole Asbestos Production Included in Above Tabulation for 1957
Short Tons

Amosite	1956	1957
Union of South Africa, Transvaal	50,000	56,800
Crocidolite		
Union of South Africa, Cape Province	47,700	59,500
Transvaal	14,400	15,300
Australia	8,000	12,200
	70,100	87,000
Tremolite, Actinolite and Anthophyllite		
Finland	8,300	10,000
Yugoslavia	8,000	8,000
U.S.A.	2,000†	2,000†
Japan	1,500†	4,900†
Brazil	1,300†	1,300†
Bulgaria	1,100	1,100
India	1,100†	500†
Italy	1,000	1,000
Kenya	200	100
	24,500	28,900
Total: All amphiboles	144,600	172,700

* This figure represents an unofficial and unverified estimate. It includes 273,000 tons of grades 7 and 8.
† Estimate.
‡ Exports.

DIAMOND DRILLING

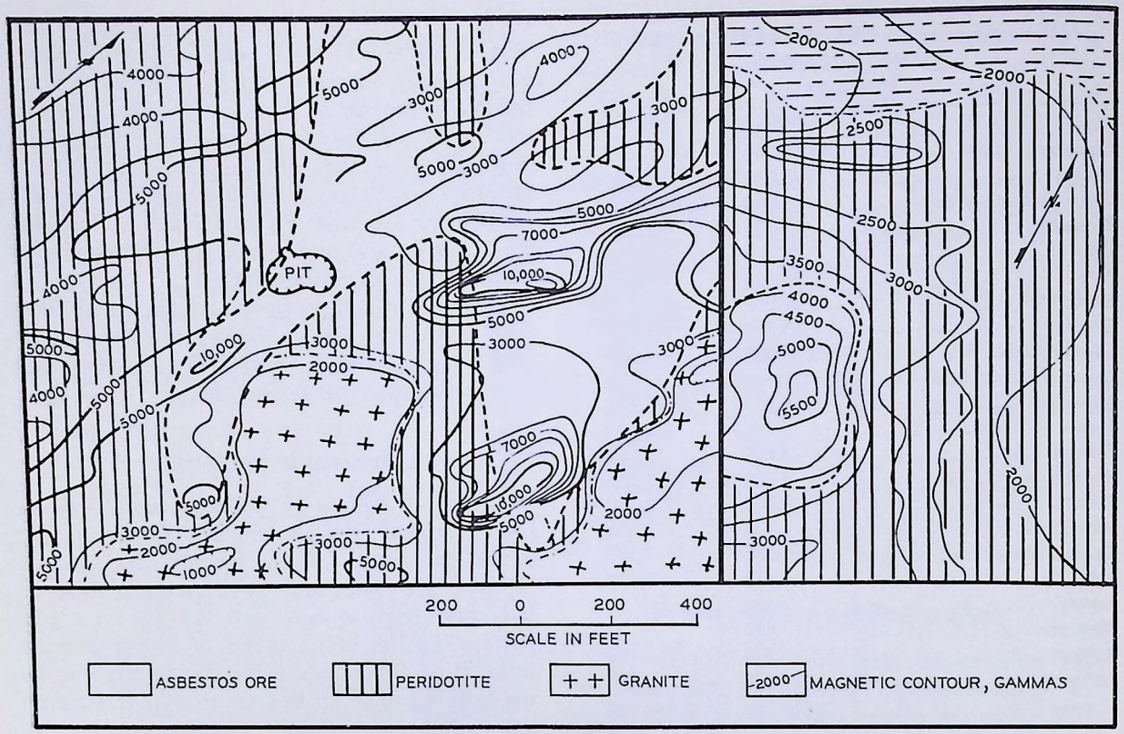
Diamond drilling is normally employed to probe beneath the overburden to assess and define the limits of an asbestos deposit. As asbestos orebodies are usually large in volume it is customary to drill vertical holes on a grid pattern. In the initial stages of exploration an interval of 400 ft and sometimes 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 there appears to be a zone with a marked elongation in one direction, holes are generally spaced at closer intervals across the strike.

When diamond drilling cross fiber deposits, good cores and satisfactory results are obtained with "E" (⅞-in. core) equipment up to a maximum depth of 300 ft. Should it be necessary to drill through sheared serpentine to reach the chrysotile deposit, or pass through shear zones within the deposit itself "A" (1 13/16-in. core) equipment is generally used. In fissile rock as found in slip fiber deposits, holes have often to be started with "B" (1⅝-in. core) and sometimes "N" (2⅛-in. core) equipment especially when holes with a depth of 1000 ft or more are to be drilled.

Steps are taken to recover the sludge only where core recovery is poor, which is generally the case with a slip fiber occurrence. 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.

OTHER METHODS

Normal trenching is sometimes resorted to in the initial stages of exploration. In regions



FIGS 7 and 8—*Results of ground magnetometer surveys of two known orebodies.*

where permafrost conditions are encountered, diamond drilling may not be practical because of the resultant brecciated character of the serpentine. In such cases exposure of the surface rock by trenching and exploration beneath the surface by adit or shaft and lateral workings may offer the only means of assessing a deposit.

Evaluation

DRILL CORE

Because the value of asbestos fiber is based principally on length it is essential that this be taken into consideration in logging diamond drill cores. Cross fiber veins are generally recorded as multiples of a sixteenth of an inch. Veins are often of irregular width and the average width of each individual vein should be estimated. Some veins are of a composite nature carrying partings or the fiber may have kinks which cause it to break readily 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 degrees and a factor of 1.414 (inverse of the sine of 45 degrees) is used. However, this can be quite misleading if the average angle is rather flat so the choice of a factor must be approached with some caution and should be checked against laboratory recovery and bulk sampling wherever possible.

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. Also, there is a certain amount of pulverized host rock which adheres to the fiber, further reducing the grade and increasing the yield. 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 employed, 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 quite close.

Slip fiber is often associated as a minor constitutent 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



FIG 9—*Graph for evaluating ungraded fiber.*

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 9). 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 pct higher. Weighting factors for the fractions of 100 for plus ½ in., 40 for minus ½ plus 4-M, 10 for minus 4-M plus 10-M, and 1 for minus 10-M have no real significance and have been chosen only to control the shape of the curve.

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

5.7 × 100	570
7.5 × 40	300
2.3 × 10	23
0.5 × 1	—
	893 points

and from the curve the fiber value would be about $520 per ton.

In applying this same procedure to the visual method it is necessary to attempt to correlate the observed lengths with the corresponding Quebec Standard Test. In order to do this, 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 3/16 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 assume that in a core length of 85 ft there are 4 veins of ½ in. length, 2 of 9/16 in., 1 of 5/8 in., 2 of 7/8 in. and 1 of 1 in.; 16 of ¼ in., 3 of 5/16 in., 2 of 3/8 in. and 2 of 7/16 in.; 23 of ⅛ in. and 10 of 3/16 in.; 74 of 1/16 in.

Reducing everything to a common denominator of 1/16th, there would be 104 such sixteenths of ½ in. and over, 105 of ¼ in. to 7/16 in., 76 of ⅛ in. and 3/16 in. and 74 of 1/16 in. totalling 359 in all.

In 85 ft there are 85 × 12 × 16 sixteenths, therefore, the uncorrected yield is

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

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

$$\text{Corrected yield} = \frac{2.2}{\sin 45 \text{ degrees}} = 3.1 \text{ pct}$$

Next to arrive at the synthetic Standard Test:

½ in.	4 M	10 M	Pan	Total
104	105	76	74	359 sixteenths
104 359 × 100	105 359 × 100	76 359 × 100	74 359 × 100	100 pct.
4.6	4.7	3.4	3.3	16.0 ozs.

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Then to find the fiber value from the graph:

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

From the graph the fiber value is found to be $432 a ton, and from this the indicated ore value is calculated to be 3.1 pct of $432 or $13.39 per ton.

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 five feet on the back and both walls to ensure that veins running parallel to the drive are not excluded.

An alternative method, currently employed at one mine in Thetford, 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 is difficult to obtain representative results.

BULK SAMPLING

The various methods of logging and sampling outlined above 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, and 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 2 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.

	Fiber value per ton	Per-cent	Ore value per ton	Yield cor-rection 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 indicates a factor of 2 but shows that the fiber value determined visually is 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	Per-cent	Ore value per ton	Yield cor-rection 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.

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, 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 in respect to both fiber content and grades.

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 can still be employed. Underground methods which have been used in the past include gloryholes, shrinkage and sublevel stoping. At present all underground mining for asbestos in the Quebec field is by 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 Jeffrey mine of the Canadian Johns-Manville Corporation is currently extracting up to 20,000 tons per day by means of block caving from one operating level.

At present in Canada there is more asbestos produced from mines using block caving than by open pit. On the other hand there is more ore mined and much more total material handled from the open workings since there is often a ratio of two or more tons of barren rock to one of ore, coupled with a lower asbestos content.

Russian production is derived mainly from open pit mines.

In Africa a large part of all the chrysotile mined is presently by underground methods. The orebodies 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 orebodies, notably in the Shabani district of Southern Rhodesia, are quite extensive in length, in one case development has been carried for three miles along the strike, and is being opened 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 cross-cuts, starting first on the hanging wall side and retreating over a considerable width toward the foot wall, 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 have been largely corrected 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 orebody. 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 degrees. A sloping face is advanced along the strike by drilling rounds of about 6 ft with jackhammers. The broken material is shovelled back from the face into temporary pillars so as to leave room for uninterrupted work at the face. The temporary pillars are later torn down from behind by hand, the barren rock sorted out and built into permanent 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 pct asbestos, so that the proportion of waste to barren works out well for the system used. The method is locally re-

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ferred to as shrinkage stoping but should not be confused because of this nomenclature, with the latter system as commonly practiced in other areas.

Milling

The flow sheet shown on page 44 (Fig 10) is a generalization of the essential steps and equipment used in Canada for the preparation of raw asbestos fiber for marketing. It is based on the dry process which has been used almost exclusively since the inception of asbestos milling in Canada some sixty eight years ago.

In the previous volume of this series published in 1949, a short description was given of some of the more commonly used equipment peculiar to the industry. There have been few major changes in the general practice since that time. A larger proportion of mill feed is now being derived from underground, so that primary crushing may be done in underground stations although in some cases surface plants serve this purpose. Large jaw crushers (the size 48 by 60 in. 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. A certain amount of hand sorting continues to be done before or after (or both) primary crushing for the purpose of removing barren rock, other refuse, and also to recover pieces of the larger asbestos veins to be used in the production of No. 1, No. 2 or run-of-mine crude. Reduction in primary crushers of the size mentioned is normally to about 7 in. and is followed quite commonly by 5½-ft or smaller cone crushers with settings ranging from ¾ to 2½ in. The next principal step is to dry the ore and it is considered good practice, where such provision can be made, to provide a storage of sufficient capacity to hold about one shift's production to assist in regulating the rate flow of ore to the driers under what may be determined as optimum temperature and air volume conditions for material of known moisture content.

Various types of rotary driers continue to be widely used in addition to the vertical tower drier which was developed for the asbestos industry and has recently been somewhat modified and improved. Both kinds of driers are shown on the flow sheet but the majority of installations use one or the other only. As with all stages of asbestos beneficiation, it is important to treat the ore in such a way as to minimize abrasion and cutting of the fiber, particularly in the earlier stages before the longer and more easily released fibrous fractions are separated from the gangue material. Where conditions permit, oversize (say, plus 1½ to 3 in.) material may be separated before drying, and bypassed to lessen the pebble-milling action of rotary driers. Where vertical driers are used the feed should not be much coarser than a 1½ grizzly opening size in order to avoid blockages in the grid-work of arresting bars with which the driers are fitted.

The chief advantage of the vertical tower over the rotary kiln type drier is a lesser degree of mechanical damage to the fiber. On the other hand, drying efficiency is better with the rotary drier and it is further very useful when open pit ores contain snow and pieces of ice. There is a limit to the air velocity which may be used in the vertical type 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 under damaging temperature conditions. 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 pulled downward with the falling material. Driers using the practical application of this principle have the discharge gas take-off at a point midway up the height of the drier, 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 emptying onto conveyor belts. The air from this operation may be used as preheated make-up air in the driers.

The air and products-of-combustion as discharged from the driers (either type) carry a considerable volume of dust. It is desirable, therefore, to provide filtering equipment in the general interest of keeping the plant area clean. Bag filters using nylon fabric 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, plus 1 in. size. Some moisture is precipitated from the gases and dust adheres to the surfaces of the crushed stone or pebbles.

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 pct moisture loss) takes place during the storage. The size of storage facilities may vary of course with mill capacity. It is fairly common to find this sufficient for a five day's supply to the mill, although some plants are operated with much less dried rock storage, or none at all.

As will be apparent from the flow sheet (Fig 10) the release and separation of fiber from gangue is accomplished by successive stages of crushing or comminution by impact. The enclosing rock is generally much more friable than the fiber so that the coincidental breakage in the fiber itself is not great if the latter is tough and flexible as is the case with a good quality chrysotile. 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 rock as a reject to go to the next stage of comminution and eventually to tailings. Finer fractions are generally screened out prior to air separation since it is obvious that much fine unwanted material would otherwise be lifted with the fiber. 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. They are again screened, and screens with suctions play an important part. Trommels, and modified forms of these such as graders and dusters, further clean the fiber and screen it into standard grade lengths.

Where the Aerofall mill is used it replaces the first stages of reduction in the mill in one operation. In practice it is adjusted to reduce the ore to about the same extent as would be done in another asbestos mill by two stages of cone crushers followed by two mild fiberizing stages or possibly one more severe fiberizing stage. The ore which is carried from the mill in the air stream when it reaches the necessary degree of comminution, is then classified by air followed by screening, and the fiber concentrates are lifted by suction similar to the common practice.

In the grading mill the fiber is further separated into the approximate length 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 and disc grinders. 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.

In recent years equipment has been developed to package the finished grades in a more compact and convenient form. The rounded packed jute bags are being supplanted by pressure-packed rectangular blocks of fiber, still usually weighing 100 lb and encased in paper or jute bags, but because of reduced size and rectangular shape, much more easily handled by palletizing and requiring less space for shipping and storage.

A large volume of air is used in an asbestos 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, for, though chrysotile asbestos dust is not as harmful as silica, it is nevertheless necessary to keep the dust content of air in the building to a minimum. It is estimated that mills having a capacity of, say, 5000 tons of ore per day use from 500,000 to over 800,000 cfm of free air. The average consumption in Canadian mills is something in the order of seven* tons of air per ton of ore treated. 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 Rhodesia 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. Reduction equipment consisting mainly of cone crushers, hammer mills and fiberizers are similar. The ore is dried in rotary or, sometimes, vertical driers. Separation is by air suction and exhaust air is treated in extensive bag filter installations. There is a much greater use made of the conventional trommel and sufficient of these are used so that each may receive only an optimum rate of feed as meted out by a suitable type of feeder. Each trommel discharge is in turn fed to what is known as a rotary air lift (a suction placed so as to lift the fiber from the outside surface of a small rotating drum made of wire mesh). Each stage of comminution is followed by a battery of up to 16 to 20

* H. Rozovsky, "Air in Asbestos Milling."[43]

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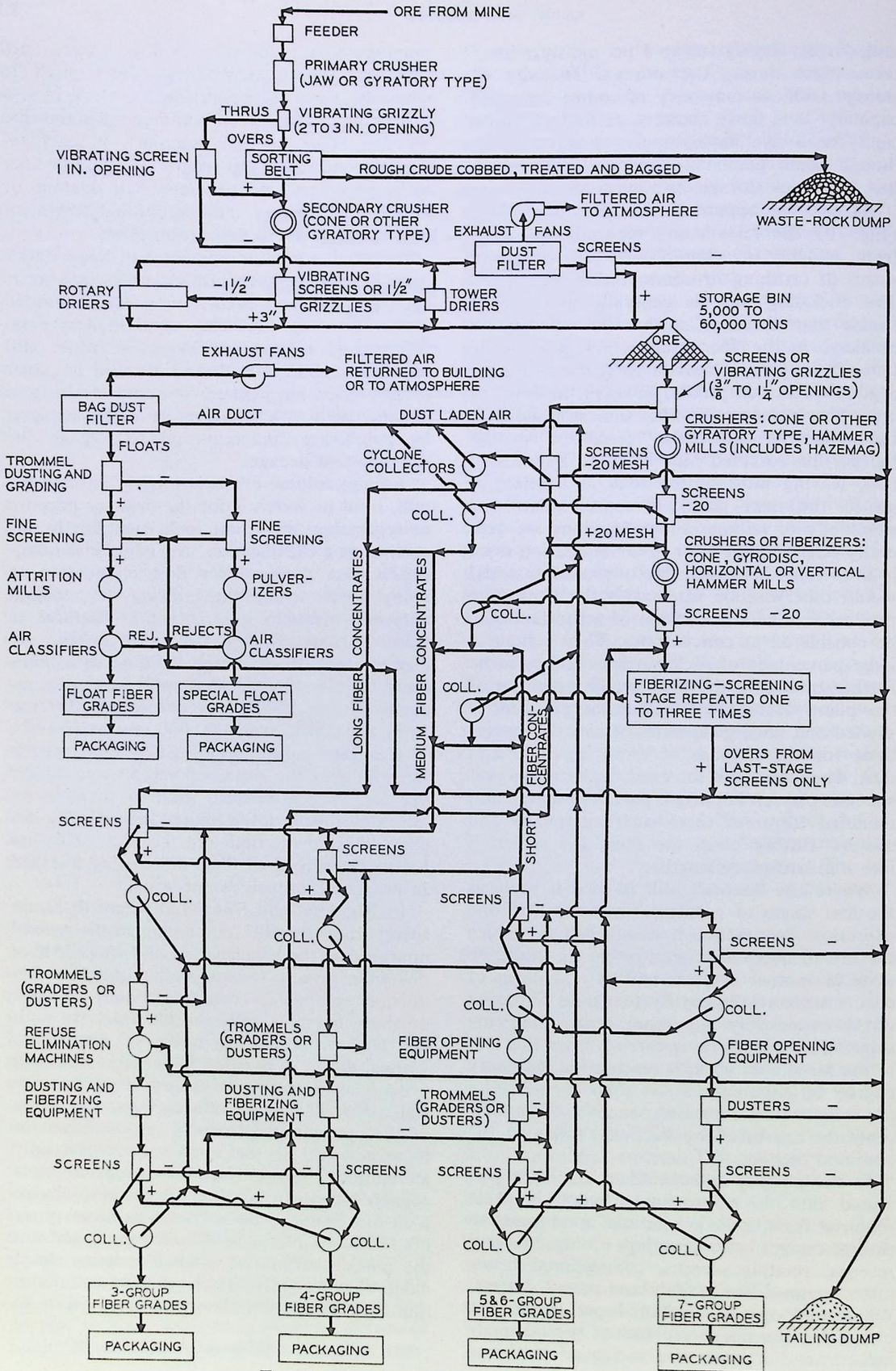


FIG 10—*Flowsheet of Canadian asbestos mill.*

trommels complete with their feeders, rotary air lifts and ancillary equipment, resulting in a series of carefully prepared concentrates. The concentrates in turn are treated in a grading plant, where further use is made of trommels and rotary air lifts. Heavy crudy* bundles (referred to as spelks or prills) are differentially opened so that too much preparation treatment is not required in the plant where it is finally to be used. Another feature of African milling is a careful control of moisture content as this may actually fall too low, particularly during the dry season, since fiber may be more easily broken or damaged under extremely dry conditions.

Formerly extensive use was made in Rhodesia of the small pan-crusher or Chilean mill. 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 in. by 14 in. Grizzly
|
Reduction to 1½ in. in small jaw crusher
|
Crushing rolls (24 in. by 48 in.) to ¾ in.
|
Trommel—1½ in.—undersize to next shorter grade circuit
|
Crushing rolls (12 in. by 36 in.) to ½ in.
|
Trommel—¾ in. (as above)
|
Degritting trommels (2 in parallel)—¼ in.
|
Bagging

* Crudy refers to asbestos which has been only partially milled, so that the fiber has not been "fluffed" but only separated from the rock. Most of the asbestos is still in the form of bundles of fibers like spicules. Further milling will cause all of the asbestos to fluff like a cotton boll. Many buyers prefer to buy asbestos in the crudy form, and do their own fluffing.

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 the 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, etc., 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 Screen Test.* This test is supervised by the Quebec Asbestos Mining Association which has set specifications for the various grades of fiber, showing the maximum and 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.

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 Screen 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

* 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 Association.

Industrial Minerals and Rocks: Nonmetallics other than Fuels (1960)
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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, surface area and others being made.

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

Following are the classifications for various grades from the more important producing areas:

QUEBEC GRADING AS SET FORTH BY THE QUEBEC ASBESTOS MINING ASSOCIATION SPECIFICATION

Group No. 1

No. 1 Crude—cross-fiber veins having ¾-in. staple and longer.

Group No. 2

No. 2 Crude—cross-fiber veins having ⅜-in. staple up to ¾-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 spinning fibers)	Guaranteed Minimum Shipping Test ½ in. Oz	4M Oz	10M Oz	Pan Oz
3D	10.5	3.9	1.3	0.3
3F	7	7	1.5	0.5
3K	4	7	4	1
3R	2	8	4	2
3T	1	9	4	2
3Z	0	8	6	2
Group No. 4 (Commonly referred to as shingle or asbestos cement fibers)				
4D	0	7.0	6.0	3.0
4H	0	5	8	3
4J	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 but also considered as short shingle fibers)				
5D	0	0.5	10.5	5
5K	0	0	12.0	4
5M	0	0	11	5
5R	0	0	10	6
Group No. 6				
6D	0	0	7	9
Group No. 7				
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

There are also groups 8 and 9 which consist of sands and gravels.

CASSIAR ASBESTOS GRADES, NORTHERN BRITISH COLUMBIA

Crude No. 1—Basically of crude ¾-in. staple and longer
AAA—Extra long textile fiber
AA—Long textile fiber
A—Textile fiber
AC—Long shingle fiber
AK—Medium long shingle fiber
AS—Shingle fiber
AX—Short shingle fiber

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 Southern Rhodesia
VRA-2 Textile fiber VRA-3 Long shingle fiber VRA-4 Shingle fiber	From the Mashaba district of Southern Rhodesia
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, Msauli—Grade 5 (Shingle fibers)	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

CLASSIFICATION OF RUSSIAN CHRYSOTILE

Grade	Type	Texture	Mark According to U.S.S.R. Standard Jan. 1, 1952
1	Textile	Hard (crudy)	J-1
2	Long shingle	Hard	J-2
		Semihard	P-2
3	Shingle	Hard	J-3
		Semihard	PJ-3
			P-3
		Soft	M-3
4	Short shingle and paper stock	Hard	J-4
		Semihard	P-4
		Soft	M-4
5	Paper stock	Hard	J-5
		Semihard	P-5
		Soft	M-5
6		Hard	J-6
		Semihard	P-6
		Soft	M-6
		Unguaranteed	K-6
7		Unguaranteed	K-7
			7-370
			7-450
			7-520
8		Unguaranteed	8-750

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CLASSIFICATION OF AUSTRALIAN CHRYSOTILE

Grade 4—2-in. fibers and longer
Grade 3—1 to 2 in. fibers
Grade 2—½ to 1 in. fibers
Grade 1—¼ to ½-in. fibers

CLASSIFICATION OF AFRICAN AMOSITE

Group 1—Produced from hand-selected long fiber at Penge Mine only.
D3 Long—over 3 in. in length
Group 2—Produced at Penge from run-of-mine fiber after longest has been hand-selected.
D11 Minus 3 in. plus ¾ in.
DX As above but graded by color
Group 3—Generally minus 2½ in. plus ⅝ in.
MD From Penge Mine
M From Penge Mine—somewhat shorter
W3 From Weltevreden Mine
K3 From Kromellenboog Mine
Group 4—Generally minus ¾ in.
S2 From Penge Mine
SK From Kromellenboog Mine
SW From Weltevreden Mine
Group 5—Generally minus ½ in.
GW From Weltevreden Mine
GK From Kromellenboog Mine

In addition to the above grades there are several from the Pietersburg field, of which WEG from the Malipsdrift area is probably the most uniformly prepared. The latter is similar in length to Group 3.

The other grades listed in the foregoing grouping are produced in the Penge area, of which the Amosa mine is the largest producer. The screen sizes 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:

CAPE BLUE (CROCIDOLITE)

E—+2¼ in.
D—+1¾–2¼ in.
C—+1¼–1¾ in.
No. 1 or B—+¾–1¼ in.
No. 2 or A and R_2—+½–¾ in.
No. 3 or S, MS and R_3—+¼–½ in.
X, SBG, H and SS—Various shorter grades.

Of the foregoing, the longer grades down to No. 2 or A are mostly hand-cobbed.

TRANSVAAL BLUE (CROCIDOLITE)

TX—+1½ in.
T_1—+⅞–1½ in.
T_2—+½–⅞ in.
T_3—+¼–½ in.
"Long"—MLS and NC300 about ¼ to ⅜ in.
T_4— and "shorts" mostly —¼ in.

Most of the above numbers have fallen into disuse. The present practice is to refer largely to "long" and "short" for the bulk of the Transvaal production. There is no recognition among the major producers that greater standardization is desirable.

AUSTRALIAN BLUE GRADES

No. 1 Long fiber, 1 in. and over
No. 2 +⅝ to 1 in.
No. 3 —⅝ in.

Uses of Asbestos*

The uses of asbestos fibers of all varieties are numerous and only some of the major ones are listed, along with a brief discussion of the products involved.

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

* For further detail see M. S. Badollet: Encyclopedia of Chemical Technology. Interscience Publishers, New York (1948) **2,** 134–142.

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 above, 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 shingles, pipe, jackets, beards, sheets and a variety of hand-moulded articles. Other uses are papers, pipe coverings, packings, gaskets, millboards, cements, roof coatings, putties 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, electricalpanels, papers, millboards, pipe coverings, gaskets, packings, brake linings, cements, roof coatings, putties and plastics.

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

Amosites, similar to Group 5 chrysotile although short in length, are finding use in insulating block of light density, such as Thermobestos or similar products, also in light weight construction materials such as marinite board.

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

Crocidolite of this grading would be considered as too short in length for use in asbestos-cement products, and therefore it 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 are quite short; however, they find usage in certain papers, cements, asphalt roof coatings, putties, paints, welding rods, floor tile and plastics.

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[26,27] are used extensively in plastics, putties, paints, welding rods, and cements.

Special Uses—Chrysotile has been used for many years for filtering wines, fruit juices, beers, pharmaceuticals, blood plasma, and other liquids. For these uses, the asbestos is usually recleaned and purified to eliminate any soluble materials that might be associated with the fiber. In some cases, the asbestos is used in conjunction with diatomaceous earth.

Tremolite and anthophyllite are well suited for filtering certain chemicals and fruit juices, for which purpose, again, the fiber should be purified before using. Some special crucibles are also made from tremolite.

Recent articles have appeared on heart surgery,[28] stating that asbestos shorts have been successfully used as an irritant to the heart muscle to increase the blood supply to the heart. Apparently, the fiber used is tremolite, ground to a definite size and highly purified.

Small amounts of pure chrysotile asbestos with platinum precipitated upon it have been used as catalysts in a sulfuric acid process.

Other known uses of asbestos have been reported in cigarette filters, and cigarette tobacco to aid in the retention of the ash.

MISCELLANEOUS USES

Sprayed Fiber—Asbestos fiber including chrysotile, amosite, or anthophyllite, may be fed into a fan or blower which, in turn, comes into contact with an atomized adhesive or bonding liquid so that the mass is sprayed by a nozzle onto a wall or ceiling. Coloring material may be added prior to spraying, if desired. This type of coating is useful in giving fire protection, acoustical properties, and insulation. This use has become quite popular during the past few years.

Asbestos in 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

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paper or cloth to form laminates with resins such as polyesters, phenolics, thermosetting silicones, melamines, furanes, etc.

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.

Asbestos in 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 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.

Gaskets—Crocidolite, as well as chrysotile fibers, is used in gaskets, along with binders such as natural rubbers, synthetic rubbers, plasticizers, and other agents to produce special products where acid resistance may be required.

Pipe Insulation—The well-known 85 pct magnesia, either in block or pipe form, is quite often made with chrysotile, amosite, or even crocidolite.

Other types of insulations of light weight, capable of withstanding temperature in the vicinity of 1200° to 1500°F are made with amosite, a silica material such as diatomaceous earth, and lime.

Prices

Canadian chrysotile fiber prices in Canadian dollars, f.o.b. mines, in 1959 ranged from $41 per short ton for 7T, which is the shortest of the regular fiber grades generally produced, to about $610 for the longest of the milled fibers. No. 1 crude sells for $1400 or more per ton. Price ranges by Quebec standard group were:

Group 3—$353 for 3Z to $610 for 3D
Group 4—$181 for 4T to $218 for 4D
Group 5—$120 for 5R to $142 for 5D
Group 6—$86 for 6D
Group 7—$41 for 7T to $75 for 7D

Cassiar fibers from northern British Columbia are sold in Canadian dollars f.o.b. Vancouver at the following prices:

No. 1 Crude—$1,522
Spinning fibers—AAA-$787, AA-$682, A-$494
Shingle fibers—AC-$325, AK-$220, AS-$181
Short shingle fiber—AX-$142

Vermont chrysotile is produced in grades similar to those of Canada and prices are about the same. Arizona fibers which are mostly graded into No. 1, 2 and 3 crudes may sell somewhat higher than Canadian, particularly for the best quality soft fiber.

Much of the African chrysotile is sold c.i.f. European ports, the remainder of this and the bulk of the crocidolite and amosite is sold f.o.b. port of embarkation; chiefly Beira and Laurenco Marques.

The following are approximate prices in 1959, for Southern Rhodesian fibers per short ton in pounds sterling and also in Canadian dollars (exchange calculated at $2.70), including the cost of bags:

C&G1 £302.10.0 ($820) c.i.f. U.S. Atlantic coast ports.
C&G2 £248.10.0 (674) c.i.f. U.S. Atlantic coast ports.
C&G3 £117.10.0 ($320.50) f.o.b. Laurenco Marques. To calculate Atlantic Port cost add $24.50 per ton in U.S. currency for freight.
C&G4 £79.0.0 ($215) f.o.b. Laurenco Marques plus freight at $22.10 U.S.
C&G5 £45.05.0 ($112) f.o.b. Laurenco Marques plus freight at $22.10 U.S.

Amosite and crocidolite prices at about the beginning of the third quarter of 1957 were quoted in the following ranges for short tons, f.o.b. U.S. Main East Coast or Gulf Ports, and include bag costs, marine insurance, ocean freight, and customs clearance:

Amosite—$245 for longest grades down to $145 for shortest.
Crocidolite (blue)—$530 for longest grades down to $235 for shortest.

Russian prices are generally lower at present than for equivalent fibers from other sources, although the opposite was the case a few years ago during a period of acute shortage. Following are prices being quoted at the beginning of 1959, c.i.f. European ports in U.S. dollars, per metric ton:

J1—$580
J2—$467
P2—$428
P3—$310
P4—$198
P5—$111
P6—$ 65

ANNUAL EXPORTS* OF ASBESTOS FROM CANADA BY AREAS IN SHORT TONS AND VALUE

		1956	1957	1958
United States	Tons	626,656	644,557	582,366
	Value	$52,017,565	$51,022,756	$48,426,000
Europe Including United Kingdom	Tons	220,820	266,274	188,401
	Value	$31,607,375	$37,912,757	$27,536,218
South and Central America	Tons	41,249	38,686	35,955
	Value	$ 6,081,185	$ 6,109,610	$ 5,814,036
Africa and Asia	Tons	60,766	59,956	36,049
	Value	$ 7,961,743	$ 8,448,452	$ 5,074,129
Australasia	Tons	14,430	21,087	23,759
	Value	$ 2,227,080	$ 3,564,834	$ 3,904,630

* Figures from Dominion Bureau of Statistics.

RUSSIAN DELIVERIES* OF ASBESTOS FIBERS 1955–1957

Country	1955		1956		1957	
	1000 Metric Tons	1000 Rubles	1000 Metric Tons	1000 Rubles	1000 Metric Tons	1000 Rubles
Bulgaria	1.4	2,354	2.6	4,872	3.2	3,491
East Germany	3.0	4,930	3.7	7,431	5.7	5,592
Poland	4.8	5,981	3.7	4,062	7.4	6,658
Rumania	0.8	856	1.0	970	1.2	861
Czechoslovakia	9.3	9,135	10.8	10,941	19.5	15,319
Hungary	4.9	5,188	4.3	4,242	4.4	2,882
Yugoslavia	1.9	2,052	1.0	1,051	3.1	3,240
Total Satellite Countries	26.1	30,496	27.1	33,569	44.5	38,043
Belgium	8.2	2,510	13.8	3,926	4.3	2,057
West Germany	5.5	3,911	8.3	7,167	12.4	8,436
Denmark	2.0	1,314	2.2	1,494	3.6	2,665
Finland	1.2	751	1.7	1,103	1.8	1,219
France	10.1	6,256	12.2	8,186	20.5	12,198
United Kingdom	2.8	730	5.6	3,791	0.3	342
Israel	—	—	1.8	1,290	—	—
Italy	—	—	1.1	510	5.0	2,042
Netherlands	3.4	1,300	3.9	1,525	2.4	586
Norway	1.2	505	0.8	339	1.1	506
Austria	0.0	47	2.3	1,342	1.0	852
Sweden	3.5	2,243	4.5	2,959	3.5	2,502
Switzerland	1.0	593	1.8	855	—	—
Turkey	—	—	0.5	320	1.0	600
Total Western Countries	38.9	20,160	60.5	34,816	56.9	34,005
All Others	2.1	1,309	1.9	1,379	2.0	1,745
Grand Total	67.1	51,965	89.5	69,764	103.4	73,793

* Figures from "Kautschuk und Gummi," West German trade magazine.

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Markets

In the period from World War II until 1953 most grades of good quality asbestos fiber were in short supply. The progressive increases in world production since 1954 have now at least temporarily reversed this condition with the result that fairly substantial inventories are available at the mines and in manufacturers' warehouses. However, it is expected that the general consumption of asbestos will continue to increase. In the United States the apparent consumption for three recent years has held at a figure of approximately 780,000 tons annually. This quantity is some 27 pct higher than the rate of consumption in 1947 and studies indicate that this or a greater rate of increase in consumption may be projected into future years.

Some of the markets outside of the United States have expanded at a much greater rate in recent years. Complete figures are not available, but an indication of the trend is given by Canadian export statistics from which it will be seen that 33 pct of the Canadian sales of raw asbestos in 1958 were to countries other than the United States. A breakdown of Canadian asbestos shipments by major geographic areas for the three recent years is shown in the table top page 51.

Statistics relative to the consumption of Russian asbestos are also of interest, as shown in the table bottom page 51.

It is apparent that a large part of the Russian production is consumed at home and by its satellite countries, and, in fact, appears to be rapidly approaching an annual rate of consumption equal to that of the United States.

The world outlook for asbestos consumption, particularly in the manufacture of asbestos-cement products, is one of steadily increasing volume in the foreseeable future.

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