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ASBESTOS: THE PHOENIX OF OCCUPATIONAL MEDICINE*

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The Phoenix was a large sized, male, fabulous mythical bird with a sweet voice and gorgeous plumage. It was sacred to the Sun, was the only one of its kind and lived for a long time.

At the end of its life it made a nest of the twigs of spice trees on which it died by setting the nest on fire and burning itself alive. From its body or its ashes or the nest which it had fertilized came forth another phoenix, perfect, but first in the shape of a white grub. The young bird, as soon as it was strong enough, took up the charred body of its father, covered itself in spices, took ashes, nest and all and flew to Heliopolis in Egypt where it deposited them on the altar of the Sun. It then died, but not before spontaneously producing an offspring.

This significant symbol of immortality, albeit totally legendary, has a distinct relationship to the magic mineral asbestos which has been said to have a half-life of infinity.

Asbestos has been called the 20th Century mineral for its production and utility has increased 20 times more than petroleum in the past 60 years. This is startling when we recognize that the mineral is practically indestructible and is capable of producing disease after a period of 20 or more years after exposure. Is the prediction of increasing incidence of asbestosis in the future exaggerated?[16]

Asbestos was known to the Ancient World. Plutarch refers to the "perpetual" lamp wicks used by the Vestal Virgins. Pliny writes of a shroud for cremation of nobility and calls asbestos "the funeral dress of kings".

Asbestos use for modern industry was begun in 1868 when 200 tons were produced in Italy. The mineral is of two varieties. Pyroxene is a serpentine fiber, an example of which is chrysotile, and is the bulk of commerical asbestos used. Amphiboles represents the second variety of asbestos and is represented by crocidolite, amosite, anthophylite, tremolite and actinolite.

* Presented at the European Medical Directors Meeting, Brussels, Belgium, 1976.

2-15
(16)

The world production is increasing annually. The largest commercial producer is Canada, which has approximately two-thirds of the total world production. Crocidolite, or "blue asbestos", is mined in South Africa and Australia. Amosite is found mostly in South Africa. The largest United States production is in Maryland and California. This variety is anthophylite, $(MgFe)_7Si_8O_{22}(OH)_2$, which has long coarse fibers of low tensile strength and thus of little commercial importance. Most varieties of asbestos have these elements present in their chemical compostion.

Physical Characteristics of Asbestos Fibers

Asbestos has an almost infinite ability to subdivide itself into smaller and more fibers. Asbestos fibers may be 2 inches or more in length but their attrition is unavoidable when separating fibers from non-fibrous rock. This results in fibers so short that the length is hardly greater than the diameter. Similarly, the diameter of bunches of fibers may be 1/32" or more in fairly crudely processed specimens but break down to 100-1000 particles — many too small to be counted with the optical microscope. In an air stream a fiber is generally unpredictable since, rather than conforming to the direction of motion like an arrow, it may spin round and round, collecting other fibers to it forming balls of fluff. In addition, asbestos fibers may divide incompletely at the ends, forming "parachutes" that stay suspended in the air. The size of the fiber is critical. Recent studies have shown that fiber penetration of the lung depends on "diameter and curliness". Harshness thus may be important as it may affect the ability of the fiber to curl.[1]

There are many classifications of diseases of the respiratory system. Asbestos fits into the causative scheme of clinical lung disease as a producer of a type of pneumoconiosis and is also a cause of malignant disease of the lungs and pleura.

Clinical Asbestosis

The characteristic feature of asbestosis is diffuse pulmonary fibrosis (alveolar-capillary block), which contrasts strongly with the nodular fibrosis of silicosis. As a rule, the lesions of asbestosis are most pronounced in the lower and middle lung zones, whereas emphysema often predominates in the upper zones. In addition to these parenchymatous changes, asbestos often causes a proliferation of the connective tissues in the visceral pleura, particularly in the basal and medial regions. There is no correlation between the severity of pulmonary fibrosis and the pleural changes. Severe pulmonary fibrosis may be present without pleural lesions and severe pleural changes with only mild pulmonary fibrosis. In progressive asbestosis there may be gross pleural thickening with horn-like plaques giving the roentgenogram a highly characteristic appearance. Calcified plaque formation, when bilateral, is said to be pathognomonic of asbestosis, but it does not necessarily develop into the malignant changes of mesothelioma.

Theories of Pathogenesis

1. *The Original Theory of Physical Irritation*
   The presence of the asbestos fibers in the terminal spaces causes irritation and damage to the walls of the alveoli, leading to fibrosis.

2. *The Solubility Theory*
   The fibrosis is due to the effects of the silicic acid and metal ions leaching out from the asbestos fibers. Asbestos is relatively more soluble than quartz and coal.

3. *The Autoimmune Theory*
   Two concepts are entertained:
   a. The presence of the asbestos in the lungs and its reaction within the alveolar phagocytes or fibroblasts either produces or localizes abnormal globulin, the presence of which can be discerned by the presence of "rheumatoid factor" in the circulating blood and in the tissues by immunofluorescent techniques.
   b. The effect of the fiber on the pulmonary phagocytes combined with their being entrapped in the respiratory bronchioles may be a factor in the initiation of fibrosis. The lysis, then, of the phagocyte at this site releases a "substance" that is not accepted as "self".

4. *Stagnation of Phagocytes Theory*
   This is similar to (3.) but involves no immunologic mechanism in the tissue destruction and fibrosis. The trapped phagocytes disintegrate and release sclerosing agents, lipids and lipoproteins.

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Pathology

Asbestosis occurs in two main anatomical forms:

1. Diffuse Fibrosis — honeycomb (cystic) lung
2. Solid Fibrosis

In either case there appears to be first an aggregation of macrophages in the alveolar spaces, followed by a desquamation of the lining epithelium. Asbestos fibers coated with hemosiderin (asbestos bodies) may be seen in a period as short as 16 days after exposure.

The characteristic lesion in asbestosis is the asbestos body, more appropriately called the ferruginous body.[3, 4, 10]

Asbestos fibers, unlike shorter particles called asbestos dust, are converted into asbestos bodies (ferruginous bodies) by deposition of yellow globules of protein and iron, producing an easily recognized and quite characteristic structure. But, before this happens, many of the thin and sharp asbestos fibers move downwards to the lung bases owing to lung movements and to gravity. This downward movement is likely to be more efficient and more rapid in the healthy lungs of the active young. Once a fiber has become a ferruginous body it is unlikely to move further, as it is usually too large to be phagocytosed or transported by lymphatics and its sharp points are now blunted by the protein globules.

In recent years the term asbestos body has been altered by some to "asbestosis body". This is an unfortunate and unwarranted change, because the great majority of lungs which show asbestos bodies have no pulmonary asbestosis at all, as the findings of many studies clearly demonstrate. This supplies a good reason to call the unique pathological lesion a ferruginous body. Recently Dr. I. J. Selikoff has stated that virtually 100% of New York City adults have ferruginous bodies. Others[5] have also made this assertion. Fortunately there is far less incidence of asbestosis.[6]

There is today an increasing amount of evidence suggesting that less intense grades of pulmonary asbestosis and even minor or trivial amounts are more likely to be associated with pleural rather than with pulmonary changes. Pleural thickening associated with asbestosis is usually calcified and has a significant frequency of malignant mesothelioma of the pleura or the peritoneum.

There is a prediction of an increase of limited basal asbestosis, malignant mesothelioma of the pleura, and mesothelioma of the peritoneum.

Signs and Symptoms

The predominant symptom is dyspnea. This is not surprising in view of the earlier statement that the basic pathophysiology is an alveolar-capillary block. Asbestosis may also present with signs and symptoms of pleural effusion.[6, 7, 8]

Lung function tests[9] are highly characteristic and constant, including:

1. Small inspiratory capacity.
2. Decreased MBC but well maintained relative to lung volume.
3. High FEV_1 relative to vital capacity.
4. Reduced vital capacity. This is the most sensitive index of the progression of the disease.
5. Reduced diffusing capacity.
6. Loss of compliance.
7. No significant changes in blood gas studies.

Radiological Findings[9]

1. Interstitial fibrosis.
2. Pleural thickening—plaques.*
3. Basal findings > Apical findings.
4. Obliteration of the costophrenic angles.
5. Shaggy cardiac shadow.
6. Thickening of interlobar septa.
7. "Ground glass" appearance, composed of linear markings and small discrete opacities in the lower lobes.
8. Honeycomb appearance just above the diaphragm.

* In one study of asbestosis with 1117 cases, there were 150 cases of pleural plaques. They were found to be more prevalent on the left side. When calcification was extensive it was usually bilateral. Calcification usually involved the parietal pleura primarily. Calcification of plaques correlated to an exposure of many years before, often 20 or more.

Differential Diagnosis[15]

1. Distinction between asbestosis and other forms of diffuse fibrosis.
   - Scleroderma
   - Idiopathic diffuse interstitial fibrosis
   - Cystic lung — *pneumoconiosis*
   - Eosinophilic granuloma
   - Sarcoidosis
   - Solid fibrosis — M.P.F.
2. Distinction between other forms of silicatosis (nodular whorled fibrosis)
3. Distinction between ferruginous bodies and hemosiderosis of elastic tissues which may mimic asbestosis. Rheumatoid asbestosis.

In summary, there are a number of short "clinical pearls" which were gleaned from a course on Environmental Lung Disease, given in New York City, 10-12 June 1976.

1. The latent period in asbestosis is long — >20 years.
2. A single exposure may be causative. This gives some credence to the concept of "Bystander's Disease". Laws of dose-response are not necessarily followed.
3. Lung cancer is seldom seen in asbestos workers who do not smoke. It is 92 times more frequent in smokers.
4. Smoking is not related to mesothelioma.[11]
5. Air pollution is not a significant factor in cancer of lung.
6. Compared to non-smokers with the same disease
   a. Fifteen times as many cases of emphysema are smokers
   b. Ten times as many cases of cancer of lung are smokers
   c. Two times as many cases of coronary artery disease are smokers
7. Eighty-five percent of mesotheliomas have a history of asbestos exposure.
8. Sputum cytology is positive prior to any x-ray evidence of carcinoma of lung.

While the first cases of pulmonary fibrosis caused by asbestos inhalation were reported in 1929,[12] and the first case of lung cancer associated with asbestos was reported in 1935,[13] it was not until 1968[14] that epidemiologic studies established the role of asbestos in the development of lung cancer in cigarette smoking asbestos workers.

We should remember a point which Professor Ted Hatch has emphasized on several occasions, "When the dust levels are very high, almost any measurement is good enough to show a change for the better. But when the dust levels are getting low but not low enough, much more attention must be given to using those measurements which are biologically most appropriate." This is almost certainly the position we are likely to have to face in controlling the asbestos dust hazard in the future.

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EXXON ASBESTOS CONTROL RECOMMENDATIONS*

EXXON CORPORATION

Although the importance of eliminating asbestos from new construction and of minimizing exposure to "old asbestos" has been emphasized in both formal and informal communications between the corporate and regional/affiliate medical departments, no formal policy statement has been issued at the corporate level. In spite of the existence of different local regulations and a recognition of the influence of local customs and economic factors, the need for a corporate position seems evident. Exposure to asbestos must be eliminated or reduced to minimal levels by eliminating its use in new construction where possible and establishing procedures for the handling of asbestos-containing material already in use so there is no health risk to employees or others.

The following recommendations are issued for the guidance of all regional affiliate management and medical personnel:

- Non-asbestos containing materials should be used in all new construction unless their use would create a greater health and safety hazard by failure to meet insulating requirements.
- The Research & Environmental Health Division, Exxon Medical Department, has and will maintain and distribute an updated list of non-asbestos containing products available on a world wide basis or in specific operating areas.
- Existing units should be surveyed by maintenance personnel to identify where asbestos was used in prior construction. This will enable exposure controls to be instituted when these units are to be worked on and there is the possibility of a release of asbestos fibers.
- Protective clothing and respiratory protective equipment must be available to employees who have to work on units when and where exposure to asbestos is a risk.

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- Adequate signs must be posted in areas where asbestos is being used or disturbed. These notices should clearly state that a potential health hazard exists and that personnel should avoid the area unless they are wearing necessary protective equipment.
- Acceptable housekeeping procedures must be instituted to minimize the spread of contamination where asbestos-containing materials are being handled. Such procedures include such steps as adequate wetting of the materials before sawing or otherwise disturbing old insulation, the use of vacuum equipment to collect finely divided material, the use of plastic drop cloths, the collection of debris in plastic bags and the burial of old material in adequately marked disposal areas.
- A monitoring program should be established to assess exposures to asbestos at regular intervals.
- Employees who are or have been potentially exposed to asbestos should be identified and included in a medical program including a yearly chest x-ray to determine if adverse health effects are occurring.
- A hazard information sheet should be developed to instruct employees who have to work with asbestos-containing materials about the potential health effects of the material and preventive measures in effect.
- Contractors and their employees who have to work with asbestos-containing materials should be provided with the same information given to Exxon employees and should be required to adhere to the same protective work practices. Their compliance should be assured by adequate monitoring.

ASBESTOS HANDLING PROCEDURE*

Asbestos fibers have been deemed a serious respiratory hazard and control of worker exposure is considered necessary to prevent asbestosis and asbestos-induced neoplasms. Various Exxon affiliates have taken positive action limiting the use of and requiring substitutes for asbestos-containing materials including talc, asbestos insulation materials (all high temperature insulation can be assumed to be asbestos or contain 5% or more asbestos as a binder), asbestos fire blankets, etc. However, asbestos has been used for many years and its presence will be noticed each time insulation must be removed, during turnaround work and sometimes in new construction when asbestos insulation is the only suitable material. At scheduled turnaround, the breaking of insulation and reinstalling same after piping completions, etc. will entail some exposure to asbestos fibers.

Despite the existence of widespread knowledge concerning the potential health hazards of this material, there is significant variation in control measures in effect at the operating affiliates. As a result, Exxon Corporation Medical Department has issued a Policy on the control of asbestos as a guide to the elimination or reduction to minimal levels in the use of asbestos in new construction where possible and to establish procedures for the handling of asbestos-containing material already in use. The following work practices are recommended:

(1) Asbestos-containing cements, mortars, coatings, grout and plaster should be mixed in closed bags or other containers. Manufacturers have high temperature mortars packed in plastic bags so that water can be added directly to the bags through a spout and moistened before opening. Moistened mortar is removed as required and mixing is completed in the shipping container. All waste is replaced in this container and sent to disposal at the end of the shift.

(2) Removal of asbestos insulation or ripping-off procedures must be done in a manner which will minimize scatter, dusting or dispersion of asbestos. After removing the wire clips and bands holding the jacket, and the jacket from the insulation, the surface insulation should be wetted. A plastic sheet placed below the piping or structure will serve subsequent clean-up. As many large pieces should be removed as feasible to minimize the number of cuts required.

(3) All waste insulation should be placed in dust-proof bags and all clean-up of asbestos dust shall be performed by vacuum cleaners or by wet cleaning methods. No dry sweeping should be allowed.

(4) There should be no spraying of asbestos material without precautions to limit the spread of overspray.

(5) Where possible, restrict movement into areas where asbestos dust is being generated by roping and signs which read "Keep Out—Authorized Entry Only."

(6) Special protective clothing should be provided to employees working in areas where asbestos dust is being generated. Care should be exercised in laundering and other handling of contaminated clothing.

Effective July 1, 1976 the OSHA time weighted average (8-hour) standard for asbestos is 2 fibers ($>5\mu m$ in length) per ml of air. A 15-minute ceiling limit of 10 fibers ($>5\mu m$/ml) also applies. Since air monitoring may not always be possible the approximate guide in Table II has been prepared as an aid to respirator selection. However, whenever there is any doubt whether these recommendations are adequate or where air monitoring data is available, respirators should be selected to insure that exposure does not exceed recommended standards.

Air monitoring techniques to determine concentrations recommended in the standard require some sophisticated equipment and skill. Accordingly to minimize exposures, a series of procedures are recommended in lieu of air monitoring. These are as follows:

All persons within the work area shall wear personal respiratory protective equipment selected on the basis of potential airborne concentrations of asbestos dust exceeding a TWA limit of 2 fibers/ml as time weighted average with a ceiling limit of 10 fibers/ml.

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Respirators supplied for the specific application should be cleaned or disposed, maintained and serviced regularly. When not in use they should be stored in dust proof containers, e.g., a sealed plastic bag.

The following classification has been adopted for the purpose of recommending appropriate respirators for the type of asbestos material involved in each operation (See Table 1).

Table 1. Classification of Asbestos Containing Materials

Group I	(Applied dry) Molded asbestos Molded calcium silicate/asbestos Molded magnesia (85%) Molded high temperature insulating block
Group II	(Applied wet) Calcium silicate (plastic) 85% magnesia (plastic) Hard-setting asbestos cement Sprayed asbestos
Group III	Cement asbestos (hard) Roofing sheets Drain pipes Building boards
Group IV	Asbestos rope, yarn tape and sealing materials (not impregnated) Asbestos blankets and clothing Asbestos millboard and paper Filter mats and gauzes
Group V	Resin-bonded and asbestos reinforced material (e.g., friction linings and electrical insulating materials) Asbestos gland packing (impregnated) Compressed fiber jointing Gaskets and preformed packings

Table 2. Respiratory Protection Equipment Selection Guide

Operation	Type of Asbestos Material Used	Respiratory Protection Required: Dry Operation		Wet Operation[3]	
		With Vent.[2]	No. Vent.	With Vent.	No. Vent.
Spraying/Demolition (Confined space)	I,II	D	D	C	D
Tearing Out Insulation	I,II				
(Confined space)		C	D	C	C
(Outdoor[1])		C	C	Fullface B	C

Table 2. (Continued)

Operation	Type of Asbestos Material Used	Respiratory Protection Required: Dry Operation — With Vent.[2]	Dry Operation — No. Vent.	Wet Operation[3] — With Vent.	Wet Operation[3] — No. Vent.
Housekeeping					
(Confined space)	All groups				
Sweeping	All groups	C	D	Fullface B	C
Vacuuming	All groups	Fullface B	C	A or B	A or B
(outdoor)					
Sweeping	All groups	Fullface B	Fullface B	B	B
Vacuuming	All groups	A or B	Fullface B	A or B	A or B
Application					
(Confined space)	I,II	Fullface B	C	Fullface B	Fullface B
(Outdoor)	I,II	A or B	Fullface B	A or B	A or B
Material Handling					
(Confined space)					
Mixing	I,II	Fullface B	C or D	A or B	A or B
Waste disposal	I,II	A or B	Fullface B or C	A or B	A or B
Charging	I,II	Fullface B	C or D	A or B	A or B
(Outdoor)					
Mixing	I,II	A or B	C	A or B	A or B
Waste disposal	All groups	A or B	Fullface B	A or B	A or B
Charging	I,II	B	Fullface B	A or B	A or B
Grinding & Sanding	III,V				
(Confined space)		A or B	C	None	A or B
(Outdoor)		A or B	A or B	None	—
Cutting & Drilling	III,V				
(Confined space)		None	A or B	None	A or B
(Outdoor)					
Cutting & Drilling	IV				
(Confined space)		None	A or B	None	None
(Outdoor)		None	A	None	None
Banding & Rivetting	III,V				
(Confined space)		None	A or B	None	None
(Outdoor)		None	A or B	None	None
Application	III,IV,V				
(Confined space)		None	None	None	None
(Outdoor)		None	None	None	None

A — Single use ½ face respirator with or without exhalation valve
B — Air purifying ½ face respirator with replaceable particulate filter
C — Powered air purifying respirator, with high efficiency filter
D — Supplied air respirator with full faceplece, continuous flow or pressure demand

Notes:

1 — Refers to any operation performed outside any confined space where natural ventilation is available

2 — Ventilation refers to any mechanical exhaust or dilution unit. When applied to "outdoor" it refers to mechanical ventilation *in addition to already present* natural ventilation.

3 — This implies a thorough soaking of the material before any operation is begun. Superficial wetting will not provide adequate control.

The following respirators or their equivalent are recommended for use when working with asbestos containing materials.

A. Single Use Respirators (Disposable)

Manufacturer*	Model Number
3M	8710
Willson	1400
A.O.	R1050
Safeline	5350
3M	8800

B. Air Purifying Respirators with Replacement Filter (Reusable)

Manufacturer*	Model Number	Replacement Filter
MSA	459440	459595(10)
MSA	459438	459321
Willson	560	R60
Willson	1210	R10
Willson	1211	R11
A.O.	R5030	R30
A.O.	R6030	R30
Safeline	5265	5905
Welsh	7506	7500-6
Welsh	7406L	7400-6
Cover	1482-F100	F100
CESCO	94R20	R20
Glendale	GR2000	F10

C. Supplied Air Respirators With Full Faceplece

Manufacturer*	Model Number	Operating Mode
SurvivAir	9011-13	Pressure demand
	9811-13	Pressure demand
3M	W840	Continuous flow
Scott	4616-11	Continuous flow
	801548	Pressure demand
MSA	460862	Continuous flow
Pulmosan	A480#10168	Continuous flow
Willson	1810	Continuous flow
Bullard	46	Continuous flow
A.O.	R6099	Continuous flow
Lear Siegler	0501-A	Pressure demand

*Addresses of manufacturers are found in the following section.

NAMES AND ADDRESSES OF MANUFACTURERS AND DISTRIBUTORS

American Optical Corp., Safety Products Div., 100 Canal St., Putnam, Connecticut 06260.

Bullard, E.D., Co., 2680 Bridgeway, Sausalito, California 94965.

Cesco Safety Products, Parmalee Industries, Inc., P.O. Box 1237, Kansas City, Missouri 64141.

Cover, H.S. Co., 107 East Alexander St., Buchanan, Mississippi 49107.

Glendale Optical Co., 130 Crossways Park Drive, Woodbury, N.Y. 11797.

Lear Siegler, Inc., 714 North Brookhurst St., Anaheim, California 92803.

Mine Safety Appliances Co., 400 Penn Center Blvd., Pittsburgh, Penna. 19535.

Pulmosan Safety Equipment Corp., 30–48 Linden Place, Flushing, N.Y. 11354.

Safeline Products, P.O. Box 550, Putnam, Connecticut 06260.

Scott Aviation Division of ATO, Inc., Lancaster, N.Y. 14086.

SurvivAir, Division of U.S. Divers Co., 3323 W. Warner Ave., Santa Ana, California 92702.

3M Company, 3M Center, St. Paul, Minnesota 55101.

Welsh Manufacturing Co., 9 Magnolia Street, Providence, Rhode Island 02909.

Willson Products Div., ESB Inc., P.O. Box 622, Reading, Pennsylvania 19603.

In the U.K. the following respirators have been approved for use in atmospheres containing asbestos fibers. The list is reproduced from the Asbestos Research Council *Control and Safety Guide—No. 1*. Please note that the protection factors recommended in this list are much higher than those recommended by U.S. standards for similar respiratory devices. The U.S. has adopted a more conservative posture on protective factors as a result of a study by Edwin C. Hyatt entitled *Respiratory Protection Factors*, Report No. LA-6084-MS. In this study the protection factors were calculated on the basis of average penetration of DOP obtained from test subjects during five basic exercises designed to simulate a wearer's head and facial movements during actual working conditions.

PART I

Respirators approved for use in asbestos concentrations up to 40 fibers per milliliter (4 fibers/ml for crocidolite). These respirators may substitute A or B in Table II.

1. Duralair dust respirator, fitted with Type R 1100 dust filter

   Safety International
   British American Optical Co. Ltd.
   Radlett Road
   Watford, Herts, WD2 4LJ
   England

2. Filtasafe single cartridge dust respirator, fitted with FC_1 fine dust filter

   Siebe Gorman & Co. Ltd.
   Davis Road
   Chessington
   Surrey KT9 1TW
   England

3. Filtasafe twin cartridge dust respirator, fitted with type FC or FC_2 fine dust filter

   Siebe Gorman & Co. Ltd.
   Davis Road
   Chessington
   Surrey KT9 1TW
   England

4. Baxter Filtrex dust respirator, fitted with an encapsulate filter

   The Leyland & Birmingham Rubber Co. Ltd.
   Leyland, Nr. Preston
   Lancashire, PR5 1UB
   England

5. Baxter Pneuseal dust respirator, fitted with an encapsulate filter

   The Leyland & Birmingham Rubber Co. Ltd.
   Leyland, Nr. Preston
   Lancashire, PR5 1UB
   England

6. Martindale Type T dust respirator*

   Martindale Protection Ltd.
   Neasden Lane
   London NW10 1RN
   England

7. Martindale Type U dust respirator*

   Martindale Protection Ltd.
   Neasden Lane
   London NW10 1RN
   England

8. Martindale Type W dust respirator*
   fitted with an encapsulated "Ultron" Type B dust filter*

   Martindale Protection Ltd.
   Neasden Lane
   London NW10 1RN
   England

9. Martindale Type X dust respirator, fitted with an encapsulated Type B fine dust filter

   Martindale Protection Ltd.
   Neasden Lane
   London NW10 1RN
   England

10. Martindale Type Y dust respirator, fitted with encapsulated Type B filters, part No. 18006

    Martindale Protection Ltd.
    Neasden Lane
    London NW10 1RN
    England

11. Safirmatic dust respirator, fitted with a yellow encapsulated dust (Type B) filter

    Chapman and Smith Ltd.
    Safir Works
    East Hoathley, Nr. Lewes
    Sussex, BN8 6EW
    England

12. Purair dust respirator, fitted with a yellow encapsulated dust (Type B) filter

    Chapman and Smith Ltd.
    Safir Works
    East Hoathley, Nr. Lewes
    Sussex, BN8 6EW
    England

13. Protective RQ 1000 dust respirator fitted with Safeair No. 54 filter cartridge*

    Protector Safety Products (UK) Ltd.
    Protector House
    719 Banbury Avenue
    Slough
    Berkshire, SL1 4LL
    England

14. Protector RQ 2000 dust respirator fitted with Safeair No. 74 filter cartridge*

    Protector Safety Products (UK) Ltd.
    Protector House
    719 Banbury Avenue
    Slough,
    Berkshire, SL1 4LL
    England

15. Protector RQ 200 dust respirator fitted with either RC 54 or RC 74 filter cartridge*

    Protector Safety Products (UK) Ltd.
    Protector House
    719 Banbury Avenue
    Slough
    Berkshire, SL1 4LL
    England

16. Protector RQ 100 dust respirator fitted with RC 54 filter cartridge*
    with exhalation valve identified by the part No. X210/D*
    Nos. 13–16 are also marketed under the name "Protectair"

    Protector Safety Products (UK) Ltd.
    Protector House
    719 Banbury Avenue
    Slough
    Berkshire, SL1 4LL
    England

17. Dustfoe 66 dust respirator fitted with fine dust filter, the respirator identified by gold coloring of body and marking thereon of part No. 260846

    Mine Safety Appliances Co. Ltd.
    Queenslie Industrial Estate
    Glasgow G33 4BT
    Scotland

18. Angus DM 662 dust respirator fitted with Angus filter cartridges type "B"

    Angus Fire Armour
    George Angus & Co. Ltd.
    Bentham
    Lancaster, LA2 7NA
    England

19. RP 1620 dust respirator fitted with RP 4 or RP 14 fine dust filters

    James North & Sons Ltd.
    P.O. Box 3, Hyde,
    Cheshire, SK14 1RL
    England

20. RP 1610 dust respirator fitted with single RP 4 filter and twin exhalation valves carrying the mark SP 1022

    James North & Sons Ltd.
    P.O. Box 3, Hyde,
    Cheshire, SK14 1RL
    England

21. RP 1660 dust respirator fitted with single RP 4 filter and single exhalation valve carrying the mark SP 1022

    James North & Sons Ltd.
    P.O. Box 3, Hyde,
    Cheshire, SK14 1RL
    England

22. Draeger Normalair dust respirator, 74/815, fitted with a fine dust filter Type DN 815

    Draeger Normalair Ltd.
    Kitty Brewster, Blyth
    Northumberland, NE24 4RH
    England

23. Phoenix dust respirator, fitted with a yellow encapsulated dust (Type B) filter

    Phoenix Accessories (Milnsbridge) Ltd.
    77 Waterloo Road, Pudsey,
    Yorkshire, LS28 8DQ
    England

24. Staysafe dust respirator with yellow encapsulated dust (Type B) filter

    Staysafe & Co., Ltd.
    909 Wolverhampton Road
    Warley
    Worcestershire, B69 9RR
    England

PART II

High efficiency respirators for use in asbestos concentrations up to 800 fibers per milliliter (80 fibers/ml for crocidolite)—(see note below). This respirator may substitute Fullface B in Table II.

1. MSA Type 3S High Efficiency Respirator, fitted with an Oval Ultra filter cartridge Part. No. 140-0013

    Mine Safety Appliances Co. Ltd.
    Queenslie Industrial Estate
    Glasgow, G33 4BT
    Scotland

PART III

Positive pressure powered respirators approved for use in asbestos concentrations up to 200 fibers per milliliter (20 fibers/ml for crocidolite)—(see note below). This respirator may also substitute Fullface B in Table II.

1. Martindale Mark II positive pressure powered respirator (fitted with a fine dust filter) Previously listed as the Martindale positive pressure powered respirator

    Martindale Protection Ltd.
    Neasden Lane
    London NW10 1RN
    England

PART IV

High efficiency positive pressure powered respirators upon which no limits of dust concentration have been placed—(see note below). This respirator may substitute C in Table II.

1. Powermask positive pressure powered respirator

    Siebe Gorman & Co. Ltd.
    Davis Road, Chessington
    Surrey, KT9 1TW
    England

NOTE: When selecting the respiratory protective equipment in parts II, III and IV above, due regard should be given to the circumstances in which it will be used which may affect visibility and maneuverability, e.g., work in confined spaces and on scaffolding.

APPENDIX II

ASBESTOS

DUST HAZARD

ASBESTOS DUST MAY BE HARMFUL TO YOUR HEALTH

AVOID BREATHING DUST

WEAR ASSIGNED PROTECTIVE EQUIPMENT

DO NOT REMAIN IN AREA UNLESS YOUR WORK REQUIRES IT

This study develops a decision method for evaluating the social acceptability of industrial controls on hazardous materials. Decisions are based on a "multiple criteria approach" that jointly considers measures such as risk-benefit tradeoff, minimum reducible health risk, maximum acceptable cost and implicit value of human life. Health risks are calculated by combining separate estimates of production and usage patterns, emissions to air and water, effectiveness of controls, pollutant dispersion and human susceptibility. Economic benefits consider employment, trade and consumer impacts, as well as direct costs of controls. The analysis focuses on asbestos as an example hazard. Relative values of hazard reduction alternatives are examined for asbestos manufacturing exhaust filters and for asbestos substitutes in brake linings. Preliminary calculations indicate risk reductions of these alternatives cannot justify their social costs.

Risk-benefit analysis for industrial and social needs

KENDALL D. MOLL* and DENNIS P. TIHANSKY:
Stanford Research Institute; George Washington University

The term risk-benefit analysis has become a commonplace expression as both the public and governmental agencies become increasingly concerned with environmental protection and the quality of life. Attendent with this concept is the notion that there is some sort of sheet used in the decision-making process for regulating environmental quality.

Informal comparisons of risks and benefits do indeed occur in setting most regulations. The underlying decision structure, however, does not always incorporate three crucial considerations: the necessity of making tradeoffs; the likelihood that tradeoff impacts are noncommensurate (that is not expressed in the same units, as dollar benefits vs. loss of life); and uncertainty about impacts of alternative decisions. Formal risk-benefit analysis is useful here because it systematically applies economic theory and decision analysis to help the policymaker understand the tradeoffs.

Risk-benefit analysis has different comparisons for different persons. Some ecologists, for example, value preservation of nature over costs of control; they might think it meaningless to compare ecological parameters with any economic concept. On the other hand, many industrialists place greater weight on the costs of preserving nature. Uncertainties or perhaps even ignorance of environmental consequences, can significantly affect an individual's value system. Fear of unknown risks often instills greater conservatism in action than is warranted by the objective situation. For instance, a minute but well publicized probability of death from exposure to a hazardous material might make an unknowing person think that he will be affected. Aggregated over all individuals, this risk could thus be exaggerated over its actual level.

Publicity about risks and benefits could also be a poor indicator of individual values. Surveys are thus important in assessing variations of public opinion, patterns of risk-taking among members of the general population and perceptions of risks and benefits.

A large spread of personal evaluations should be expected given data deficiencies on risks and benefits. Information about ambient concentra-

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tions of hazardous materials and the degree of human exposure is not generally available. More fundamental is the lack of information on inherent biological effects of these chemicals on human health. Epidemiological studies have been outstripped by the technology to produce and distribute an ever growing number of hazardous materials. For some new chemicals, the regulatory agency relies on the manufacturer and developer of derived products to furnish health information. But without a character or checklist of needs for conducting risk assessments, the manufacturer cannot really be expected to assume this additional responsibility.

Insights on benefits of product use are typically as deficient as judgements on hazard levels. Conditions for optimality in regulation depend on the "welfare function" to be maximized. One criterion frequently employed is maximum value of total output, which in principle should include such non-monetary aspects as safety, aesthetic qualities and reductions in physic tension or anxiety. Economists generally contend that these benefits of controlling hazards can be assessed collectively as the sum of the "willingness-to-pay" of all individuals affected by the action. Analytically, this requires the formulation of a consumer demand curve for feasible controls. Benefit assessment then involves integration of the area under this curve.

Determination of the overall curve relating benefits to emission control policies requires a multi-step analysis, in which the economics input occurs only after exposures and health effects have been determined. Consequently, the lack of benefit estimates for regulations can be only partly blamed on economists. The lack of meaningful exposure and dose-response relationships falls in the domain of the life and physical sciences. Without accurate knowledge of these relationships, attachment of economic values is a misleading and perhaps futile exercise.

Most regulatory agencies as well as researchers lack an appreciation of the complexities underlying benefit estimation. As a result, they tend to establish controls which minimize risks without explicitly considering product benefits. "Zero-tolerance laws," which

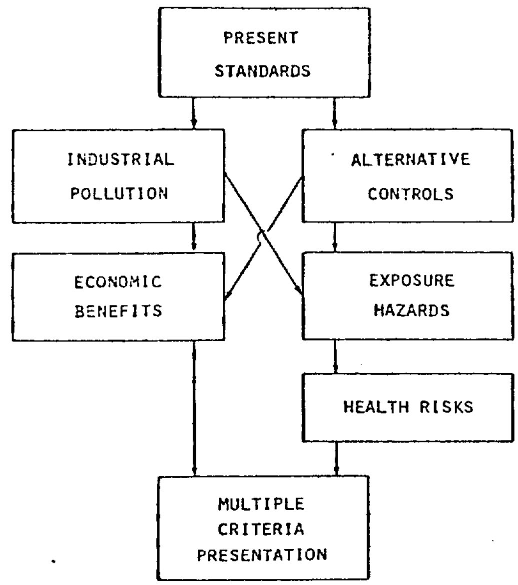

Figure 1 – Risk/benefit methodology: Analytical Steps.

prohibit any detectable amount of a hazardous material, are inflexible and can quickly become too costly. They may obligate large budgets; they may remain in effect over an extended time span; and they may adversely affect the lives of many individuals.

Although risk-benefit analysis should make decision-making more comprehensive, there are a number of limitations to its current usefulness. First, it represents an abstraction of reality and is usually simplistic. It may not be translatable into practice if it does not adequately account for all impacts. Second, the magnitude of uncertainity about both risks and benefits is typically much greater than the magnitude of their most likely values. This difficulty emerges as the most severe constraint of any formal analysis. Proxy measures are often used to measure impacts, and these proxies may be quite crude. Some authors, for example, represent risk in terms of death rates.[1] While vital, this measure fails to incorporate non-fatal results that are likely to be far more prevalent and in some cases more damaging in total than the number of deaths.

Another limitation is that risks and benefits of various actions do not usually come in single pairs. Rather, each control level implies a diversity of beneficial and costly impacts. The analyst, with limited resources and time, must

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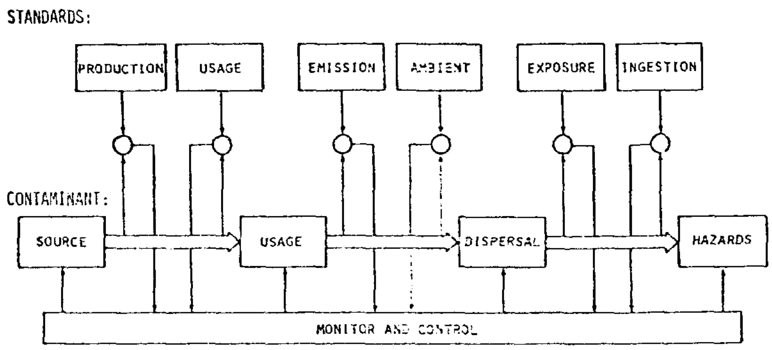

Figure 2 – Hazardous waste system.

select the most important impacts and exclude those of hopefully less importance. As he learns more, he may change the list of impacts. Still another limitation concerns weights assigned to risks. Individuals seem to waver in their evaluation of generally low-probability events as needs and perspectives fluctuate.

There have been few attempts to consider such limitations in formal risk-benefit analyses. Because highway data are readily available, risk-benefit studies are most numerous for vehicular accidents and choices of safety features for automobiles, (e.g.).[2,3] One extensive investigation of risk-benefit ratios for a number of hazardous events, such as driving and being struck by lightning selected "fatalities per person-hour of exposure" as the measure of risk and a benefit index defined as "value to the individual" in the denominator of a risk-benefit ratio.[1] The benefit in most cases was quantified as the monetary investment that consumers are willing to support for a risky venture.

Another more formal, theoretical model represents benefits of an item as the price a consumer is willing to pay for it.[4] As hazards or risks increase with item use, its value declines correspondingly. However, there is an additional "non-pecuniary" part of risk, he claims, beyond which the consumer or general public refuses to buy or use the item. This implies the existence of a threshold level of risk acceptance. Whether such a level actually exists was not demonstrated.

In the remainder of this paper, we present a new approach toward risk-benefit analysis. It incorporates risk and benefit comparisons, as in the above referenced studies. But it goes beyond their scope by including uncertainty factors and by showing how various decision-making approaches can result in different priorities. The conceptual model to be presented was applied to a selection of feasible controls on hazardous materials, namely, cadmium and asbestos usage in the United States.[5]

The methodology follows very closely that recommended in the recent National Academy of Sciences report on Decision Making for Regulating Chemicals in the Environment.[6] The most significant aspect of this methodology is its reliance on a "multiple criteria" approach. A multiple criteria approach involves the consideration of many factors bearing on the decision in addition to those of "risk" and "benefit," such as "minimum reducible risk," "maximum socially acceptable risk," "maximum acceptable cost," and "value of human life."

As shown in Figure 1, the analysis starts with a review of present standards and proceeds to parallel examinations of the existing pollution system and alternative controls that might be applied to it. The parallel approach continues with second stage investigations of economic benefits on one branch and of population exposures and resultant health hazards on the other. Finally, the economic benefits and the health risks are combined with other relevant parameters in a graphical presentation of the multiple criteria affecting the decision. This presentation is applied under a variety of possible decision rules to derive acceptable standards and develop priority research needs for future improvement of the decisions.

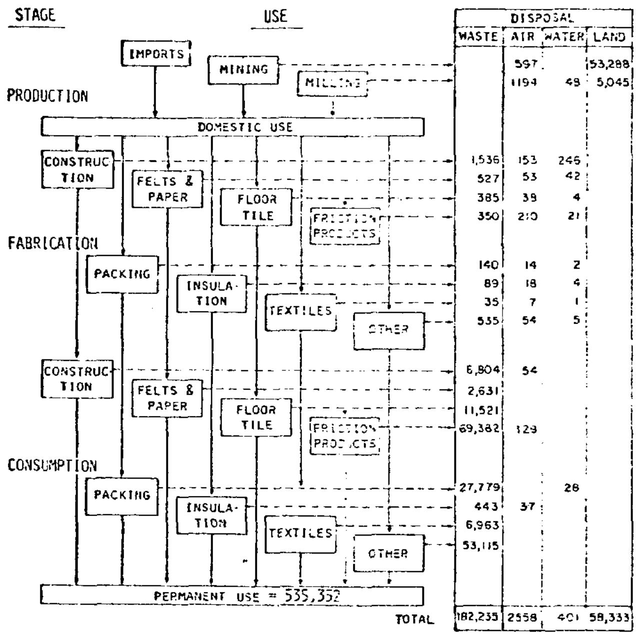

Figure 3 - U. S. Asbestos flow (metric tons per year).

When we examine the top box, Present Standards, in more detail, we discover the kind of control system illustrated in Figure 2. This figure shows how various types of standards impinge on the hazardous waste system and on the monitoring and control mechanisms that accompany it. Standards must be compared with the actual amount of hazardous waste present at a given point in the hazardous waste flow system. For example, production standards must be compared with some measure of the actual production. The difference between the standard and actual production is used as a signal for the monitor and its control system to implement corrective measures if necessary. The same kind of feedback control must operate for usage standards, emission standards, ambient air or water standards, exposure standards and ingestion standards. Note from the figure however, that controls do not have to be applied at the same point that the monitoring signal is observed. Excessive exposures, for example, could be corrected by more restrictive controls over emissions concentrations. These multiple feedback possibilities allow for very complex control systems.

The multiple feedback loops do impose two requirements on the monitoring and control systems. Whatever standards are developed must be measureable and they must be consistent with other standards that they may be applied at other points in the control process. For example, the OSHA asbestos standard was reduced from 5 visible fibers to 2 fibers per milliliter on July 1, 1976. However, the visual methods currently used to count asbestos concentrations account for less than 5% of total fibers and no one knows whether the visual identifiable fibers affect health more than the smaller fibers.[7] Standards cannot be made very precise until this conversion problem is solved.

When we decide that some measure of pollution, say weight, is most meaningful, then the second step is to analyze the industrial pollution of various media (air, water, and land) that occurs at different stages of the system, from extraction to final disposal. These amounts are shown in Figure 3. We have used a materials balance approach to estimate the amounts of asbestos going to each use and each disposal media and reconcile their totals with our best estimates of overall use and disposal. The quantities (not all of which are shown in the figure) therefore are additive both vertically and horizonatally along the different flow paths. This requires some very difficult data search and

EMISSION SOURCE:	MANUFACTURING FACILITIES	AUTOMOBILE BRAKES
CONTROL METHOD:	FABRIC FILTERS	SUBSTITUTE MATERIAL
ORIGINAL EMISSIONS:	547 METRIC TONS	129 METRIC TONS
CONTROL EFFECTIVENESS:	96%	100%
NATIONAL COST:		
LOW	$2.5 MILLION	$52 MILLION
MEAN	$3	$65
HIGH	$3.6	$81

Figure 4–Asbestos control costs and effectiveness.

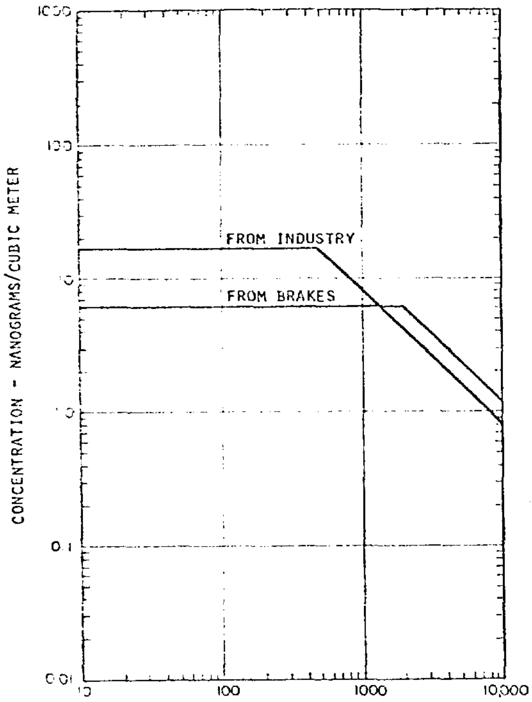

Figure 5–Asbestos air concentrations.

reconciliation work, almost to the point of being creative when the data is particularly sparse. However, we feel it is necessary in order not to miss large parts of the problem simply because the data is difficult to obtain. It gives us a plausible base from which to make an overall systems analysis and, at the same time, highlights areas where existing data may need to be refined. It also provides a first-order priority base for examining alternative controls.

In our analysis, we observe that although land disposal accounts for the great bulk of asbestos pollution, the largest source of air contamination is the 547 metric tons emitted from fabrication operations. We therefore have examined controls for asbestos fabricators. We also have examined the possibility of eliminating the second most significant airborne source: emissions from users of friction products (i.e., brake linings). Economic costs and operational effectiveness of control alternatives for these two pollution sources were examined in the next two steps, as shown in Figure 4. For asbestos manufacturing processes, we ascertained that fabric filters are the most effective method to control emissions.[8] They can eliminate about 96% of stack emissions. We estimated the total national cost for such a program would run about $2 million per year, plus another $1 million for monitoring and enforcement.

Substitution of other materials for asbestos brake linings is speculative since no satisfactory material has yet been found. But if one assumes that a material can be found for a 50% cost increase, the total extra cost would run to about $65 million per year.

These economic costs have to be balanced against the control program's reduction in public exposure and consequent hazard, which we also examined. Figure 5 shows the total areas now exposed in the U.S. to various concentration levels from industrial sources and from brake lining emissions, according to our simplified model of emission sources and air dispersion. Note that industrial sources are more concentrated over a smaller area than are brake-shoe sources. Total exposure to the population is about 80 mg/m^3 from each source.

The big hurdle in our analysis, as in most such analyses, came in trying to develop a dose-response function to evaluate the effects of these exposures. To do this, we looked at death rate estimates for the three most important causes of death from asbestos: mesothelioma, other cancers and non-cancer respiratory diseases.

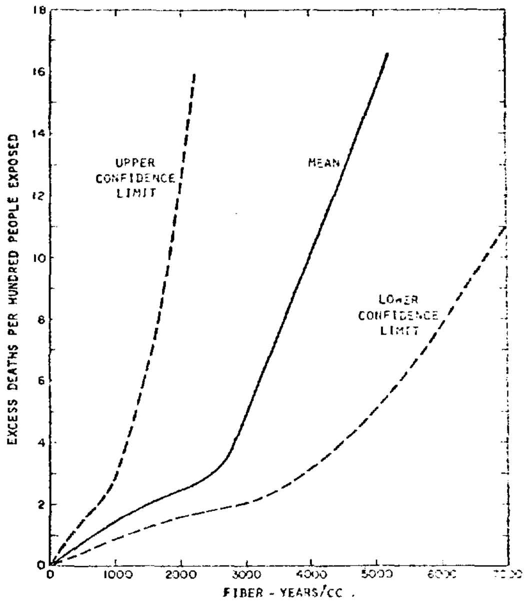

Figure 6–Asbestos dose-response: respiratory system disease.

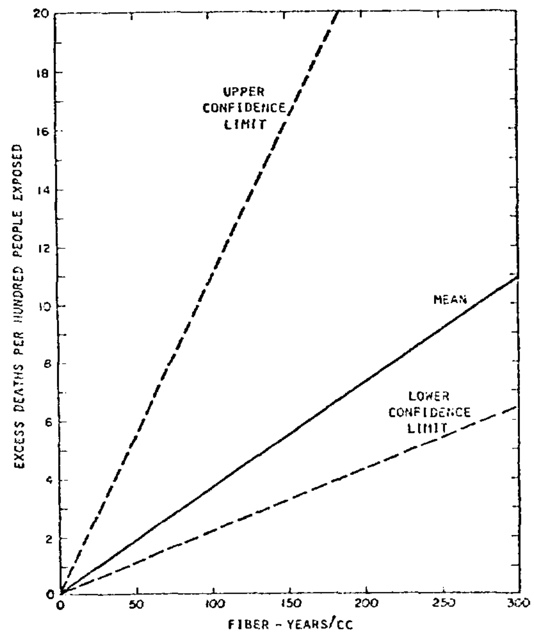

Figure 8–Asbestos dose response: mesothelioma.

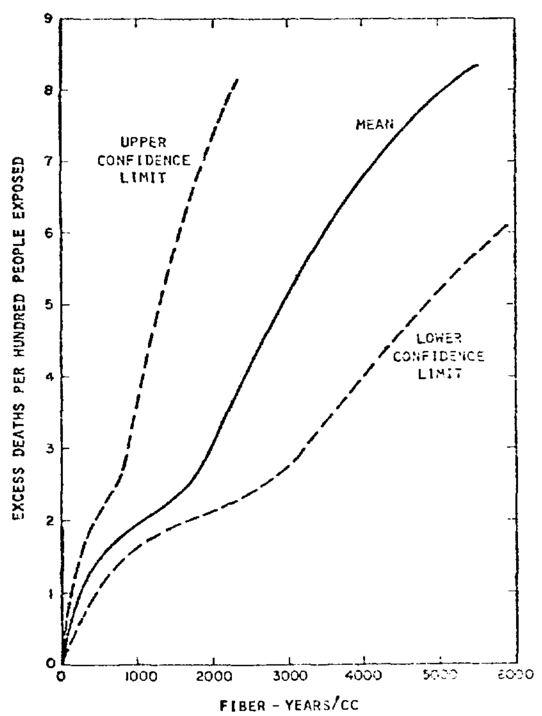

Figure 7–Asbestos dose-response: cancer (except mesothelioma).

Figure 6 shows excess deaths versus accumulated asbestos dosage for non-cancer respiratory diseases.[9] As with most of our data, we had some problems here in converting from one set of measures and dosage assumptions to another. For Figure 6, uncertainties in these conversion factors were the major uncertainties in determining the confidence limits that are shown.

Figure 7 illustrates excess death rates of people exposed to asbestos from all cancers except mesothelioma.[9] The Mae West shape is simply a matter of curve fitting and has no known physiological basis.

Excess deaths from mesothelioma only are shown in Figure 8. This diagram presents the widest uncertainty of all because its two references[10,11] both attributed their original data to a common source but differed by a factor of five in their resultant calculations.

By summing these three causes of excess death and combining their uncertainties as independent random variables, we arrived at the overall dose-response curves of Figure 9. We show these for analytical purposes as straight lines emanating from the zero intercept, although in fact we have no strong basis for assuming that the mean value is a straight line or that the uncertainties are fixed fractions of the dosage.

Mesothelioma appears to be the most significant contributor to the total excess death rate. Asbestosis produces a significant number of illnesses in addition to the excess deaths, but morbidity effects were not included in our analysis.

Hazards from ingestion of food and water were likewise not considered, since most studies of relative hazards indicate that the principal mode of entry of retained asbestos is via the lungs.[12-14]

Finally, we did not consider the effect of population mobility on the hazard, even though people with high exposures are statistically very unlikely to live next to an asbestos factory for their entire lives.

But these neglected effects are all relatively insignificant compared to the order-of-magnitude uncertainties and the other difficulties of reaching a tradeoff between risks and benefits. An overall method of evaluating and presenting risk/benefit tradeoffs is illustrated in Figure 10. Here, the two main parameters are measured in the separate dimension of the chart. The vertical scale shows risk in terms of lives saved by a control alternative relative to the existing "status quo" situation and the horizontal shows negative economic benefit (or cost) involved. Each alternative, surrounded by an ellipse representing the confidence limits, can be shown in terms of this tradeoff of lives versus non-health economic benefits. The dollar tradeoff between health and economic effects is not charted, but any particular valuation of human life can be represented by a diagonal line originating at the status quo position. Alternatives lying above this tradeoff line would be cost-effective in terms of that particular life valuation, whereas alternatives below the line would presumably not be.

Other constraints can also be shown on the chart; these act to restrict the feasible domain with which alternative solutions may be sought. At the top a "minimum reducible risk" line represents a limit in the number of lives that might be saved by any feasible alternative. The minimum reducible risk might be considered as a background level of contamination below which further reductions are extremely difficult. At the opposite side of the feasible domain, the "maximum acceptable social risk" represents a

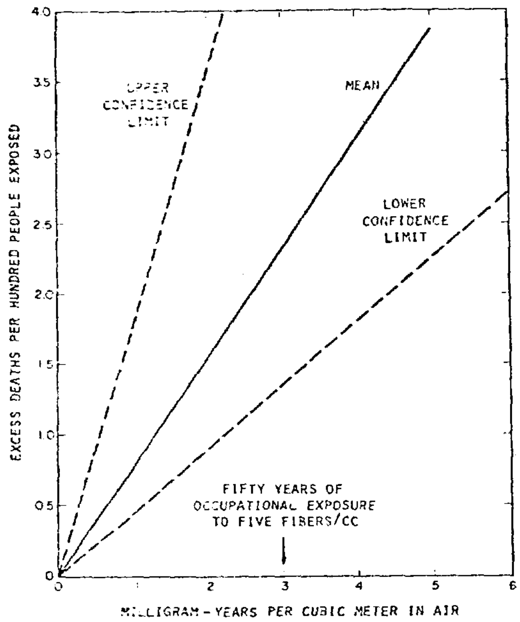

Figure 9 - Asbestos dose-response: total.

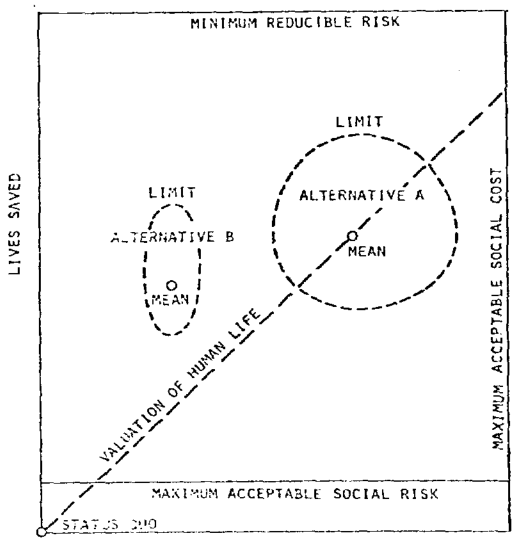

Figure 10 - Multiple criteria comparison method.

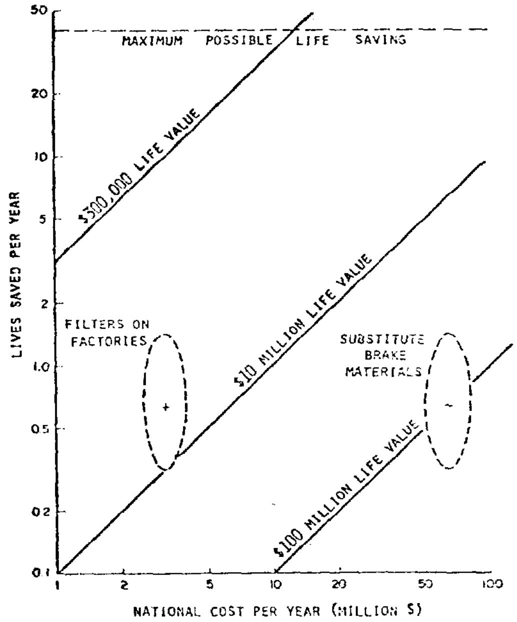

Figure 11 – Asbestos pollution control alternatives.

number of lives lost that will not be readily accepted by society. The maximum risk might be some vague social limit such as the prevailing rate of disease, or it may represent a "here and now" risk limit as defined by existing standards and regulations. Another constraint, not usually mentioned together with risk limits but nevertheless logically comparable, is that of "maximum acceptable social cost." This represents the maximum expenditure that society is willing to obligate at a particular time to solve a particular pollution problem. Equity considerations among the population are also now generally accepted as valid constraints. Equity considerations can be considered by making comparable charts for the analysis of each ethnic, income, geographic, generational, or other identifiable interest group. Together, the risk, benefit, and other constraints make up the "multiple criteria" problem.

When we apply this methodology to the asbestos control alternatives we obtain Figure 11, which has been derived specially for this paper. The first feature one notices in this logarithmic scaled chart is that lives saved by the two alternatives are about the same: namely, 0.6 person per year each, give or take confidence limits of about a factor of two in each direction. But implementation costs of the two alternatives differ by more than 20:1.

If one wishes to assign a value to saving lives, the chart shows that the factory filter alternative costs less than $10 million per life saved whereas brake substitution costs about $100 million per life. Neither alternative comes close to the $300,000 valuation that workers in hazardous occupations implicity give to their own lives[15,16] (see the upper diagonal line).

For this reason, both alternatives appear inefficient as measures for protecting the general public, if economic tradeoffs are considered. As always in such studies, however, we must qualify our conclusions. First, we have not considered potential effects of these measures on the health of industrial workers, which very likely would be more significant than those to the general public. Inhalation hazards to brake shoe installers, for example, would be completely eliminated by substitution of some other material for asbestos in brakes. Second, we have only examined two alternatives. Calculations based on our exposure model indicate that about 37 people per year could potentially be saved by eliminating asbestos from our ambient air (see top horizontal line in Figure 11). This potential life saving is 50 times as great as we get from either of the two alternatives considered, so additional protection possibilities certainly are worth investigating.

These and other factors that go beyond the assumptions of a particular analysis almost need to be considered by decision-makers in real life. Therefore, no single chart can give a complete answer. In addition to the formal trade-off charts of the type shown in Figures 10 and 11, a full presentation should include the listing of many supplementary criteria by which decision makers or other interested parties can derive their own values. Such a list is shown in Figure 12.[6]

Choices among the criteria presented can be made on the basis of many decision procedures, including those of expected value and ordinary old fashioned biases such as optimism, pessimism and probability. So many selection methods are available, in fact, that decision makers in some ways will have greater freedom

	COMMENTS	ALTERNATIVES			
		NO REGULATION	BAN NOW	OPTION CONTROL A	OPTION CONTROL B
I. HAZARDS AVOIDED					
A. HEALTH					
B. ENVIRONMENTAL					
II. COSTS OF CONTROL					
A. DIRECT					
B. INDIRECT					
C. MARKET STRUCTURE					
III. BENEFITS LOST					
IV. DISTRIBUTION OF BENEFITS & COST					

Figure 12--Display of benefits and costs.

of action than they ever had before. The choice among alternatives may remain ambiguous. But at least decision makers will have explicit, quantitative means for weighing the practical tradeoffs that in the long run are going to have to be considered.

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Accepted August 29, 1976

A method is described for calculating confidence intervals for particle or fiber concentration, and for dust collector penetration. The span of the interval depends upon the value of fiber concentration or collector penetration reported and upon the number of particles or fibres counted.

Uncertainty in particle counting and sizing procedures

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Introduction

The concentration of particles in a gas can be determined by passing a known gas volume through a filter and counting particles on representative filter portions. Particle concentrations are valuable to determine compliance with legal standards, as for asbestos fibers in workroom air, or to determine the particle size collection efficiency of a dust collection device by making counts of simultaneous upstream and downstream samples. For both applications, it is important to estimate the count reliability. Although enough particles must be counted to establish the validity of the result within acceptable limits, it is wasteful to insist upon excessive counting to obtain needlessly high reliability.

Particles for microscopic counting are conveniently collected on membrane filters[1,2] or electron miscroscope grids[1,3,4]. The "stratification" particle counting method[5-7] illustrated in Table I is often used to reduce counting time. An initial traverse is made by examining a representative number of fields under the microscope. All particles seen are segregated into convenient, continuous size categories. Subsequent traverses note entries for only those size ranges in which particles are present in relatively small numbers. The average number of particles in each size range per traverse, $\bar{x}$, is then calculated as shown in Table I. Stratified counting is a way to emphasize those particles whose concentrations are most difficult to assess with statistical reliability because of their relative rarity.

Nomenclature

A — inverse of the fraction of total filter area examined per traverse
G — inverse of the total volume of gas passed through a filter
m — number of an equal area, counting outward from filter center
M — total number of equal areas into which a filter is divided

David Leith, Assistant Professor at the Harvard University School of Public Health, holds Bachelors and Masters degrees in chemical engineering from the University of Cincinnati, and a Doctorate in Environmental Health Sciences from Harvard. His interests lie in industrial hygiene and air pollution control.

Melvin W. First, Professor of Environmental Health Engineering at the Harvard University School of Public Health, is a diplomate of the American Academy of Environmental Engineers and a Director of the American Board of Industrial Hygiene. Dr. First was a Director of AIHA from 1964-1967.

TABLE I
Data Tabulation for Particle Sizing by Stratified Counting[5]

TRAVERSE	PARTICLE SIZE RANGE, MICROMETERS < 0.44	0.45-0.62	0.63-0.88	0.89-1.29	1.30-1.79	1.80-2.49	2.50-3.49	3.50-4.99	5.00-7.09	7.10-10.00	TOTAL PER TRAVERSE
1	57	87	54	36	21	24	6	12	0	3	300
2							12	6	3	0	21
3									3	0	3
4									2	1	3
5									2	1	3
6									1	2	3
Total, N	57	87	54	36	21	24	18	18	11	7	333
Mean Count per Traverse, $\bar{x}$	57	87	54	36	21	24	9	9	1.8	1.2	300
Std. Deviation of Mean, $\sigma_{\bar{x}}$	7.55	9.33	7.35	6.00	4.58	4.90	2.12	2.12	0.55	0.45	
95% Confidence Interval	72 to 42	105 to 69	68 to 40	48 to 24	30 to 12	34 to 15	13 to 4.8	13 to 4.8	2.9 to 0.7	2.1 to 0.3	

n — number of traverses performed in a stratified counting procedure

N — total number of particles of a certain size counted through all traverses

N_{down} — N for filter downstream of a particle collector

N_{up} — N for filter upstream of a particle collector

P — number of particles per volume of gas

P_{down} — P for gas downstream of a particle collector

P_{up} — P for gas upstream of a particle collector

Pt — dust collector penetration (1 − efficiency), P_{down}/P_{up}

r_m — distance from center of filter to point where microscope is to be focused for equal area m

r_f — radius of filter

x — number of particles in a certain size range present in one traverse

$\bar{x}$ — mean number of particles in a certain size range found per traverse

σ — standard deviation of x

$\sigma_{\bar{x}}$ — standard deviation of $\bar{x}$

σ_{Pt} — standard deviation of Pt

Microscopic field selection

When a filter holder has a small diameter inlet relative to the filter diameter, the largest particles may concentrate on that part of the filter directly downstream of the gas inlet. Dennis and co-workers[8] found that such radial concentration gradients did not occur for particles smaller than 20 micrometers diameter when filter holders were used which had a ten degree included angle between gas inlet and filter surface. However, filter holders of this design are not always practical because of their large size.

To avoid bias when using a conventional holder with small inlet, fields are usually selected at random from a pie shaped piece of the circular filter paper. About twenty fields must be examined[2] to complete one unbiased estimate of the particle size distribution. Totally random field selection gives an unbiased estimate of particle concentration when a sufficiently large number of fields is examined. However, the same result can be obtained with fewer fields by an ordered approach. Because the pressure drop across a membrane filter is sufficient to assure uniform gas velocity normal to the filter surface, the volume of gas flowing through each equal, concentric area on the filter will be the same, unless the central areas become plugged because of excessive particle deposition there. The overall dust concentration for the gas sampled will be the average of the concentrations found in the gas passing through each of the equal areas. To utilize an ordered approach, the microscope should be focused at the center of each equal area ring present in the sector, and a single field examined. After one field in each equal area has been inspected, all data can be combined to make an entry for one traverse, as shown in Table I.

Additional traverses are made along different radii of the filter sector.

This equal area traverse method for locating counting fields is analogous to the method used for positioning a pilot-static tube when determining the average gas velocity in a round duct. Average gas velocity could be determined by measuring the velocity at many random points within the duct cross section and averaging the results found. However, the number of measurements needed to reach the same statistical reliability using this approach is greater than for the equal area method, and the random approach is not used. By analogy, it is as logical to use an ordered approach for locating counting fields on a membrane filter as it is to use it for locating pitot-static measuring points in a duct.

The distance, r_m, from the center of a filter of radius r_f to the midpoint of each of M equal areas can be found from

$$\frac{r_m}{r_f} = \sqrt{\frac{2m-1}{2M}} \quad (1)$$

Here, m is the number assigned to an equal area, starting from the filter center and counting outwards. Alternatively, values can be found in a reference giving the relative distance from the wall at which a pitot probe should be placed in order to have an unbiased estimate of average gas velocity in a circular duct.[9,10]

95% confidence intervals

After stratified counting procedures have been employed and mean concentrations for particles in each size range calculated, it is important to determine confidence intervals for these values. Systematic sources of error such as anisokinetic sampling, inaccuracies of flow measuring devices, improper microscope calibration and the like can be minimized through careful experimental technique.[11] Assignment of particles to improper size categories is not a significant problem when trained observers use a standard Porton graticule for determining particle diameter.[12]

A source of non-systematic sampling error that cannot be eliminated by control of experimental procedures is associated with random variations in the number, x, of particles in a certain size range which are present in each traverse of a stratified counting procedure comprising in traverses. A Poisson distribution describes the variation in these x values [12-14]. The standard deviation of these values, σ, therefore equals the square root of the mean number of particles in that size range per traverse, $\bar{x}$, i.e.

$$\sigma = \sqrt{\bar{x}} \quad (2)$$

The standard deviation of the mean, $\sigma_{\bar{x}}$, is the standard deviation, σ, divided by the square root of n, the number of traverses.

$$\sigma_{\bar{x}} = \sqrt{\frac{\sigma^2}{n}} = \sqrt{\frac{\bar{x}}{n}} \quad (3)$$

From Equations 2 and 3,

$$\frac{\sigma_{\bar{x}}}{\bar{x}} = \sqrt{\frac{1}{n\bar{x}}} = \sqrt{\frac{1}{N}} \quad (4)$$

where N is the total sum of all particles in a certain size range counted through all traverses. Equation 4 is an application to stratified counting of the expression given by Chapman and Ruhf for the relative error associated with repeated counts of particles in liquid suspension.[15] Appropriate values for the standard deviation of the mean, $\sigma_{\bar{x}}$, are given for the data shown in Table I. The number concentration of particles in a certain size range, P, is proportional to x, the mean number of particles of this size per traverse, to the inverse, A, of the fraction of total filter area examined per traverse, and to the inverse, G, of the total gas volume passed through the filter.

$$P = \bar{x}\, A\, G \quad (5)$$

The standard deviation of a product can be found from[16]

$$\left(\frac{\sigma_{\bar{x}AG}}{\bar{x}AG}\right)^2 = \left(\frac{\sigma_P}{P}\right)^2 = \left(\frac{\sigma_{\bar{x}}}{\bar{x}}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_G}{G}\right)^2 \quad (6)$$

With careful technique, the standard error associated with A and G can be made small compared to that for x. The substitution of Equation 4 into Equation 6 gives the relative standard error associated with a measurement of concentration, P.

$$\frac{\sigma_P}{P} = \sqrt{\frac{1}{N}} \quad (7)$$

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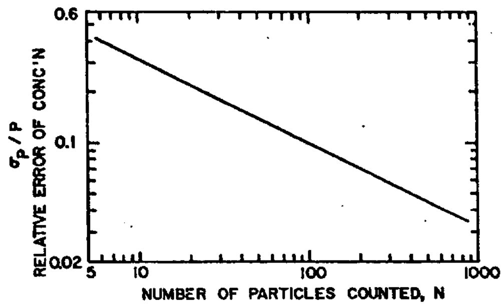

Figure 1 – Number of particles counted versus relative error of particle concentration.

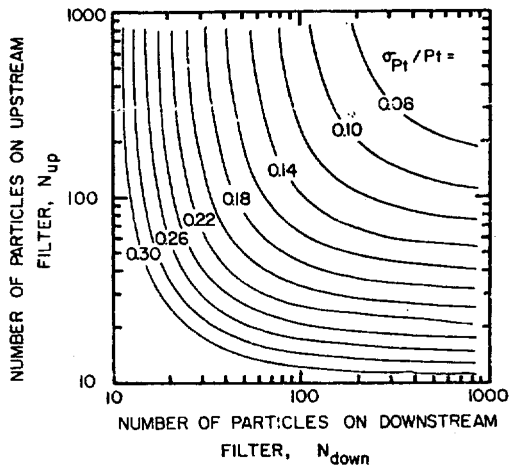

Figure 2 – Number of particles of one size counted on downstream filter versus number of particles of that size counted on upstream filter, with relative error of penetration as parameter.

A 95% confidence interval about P will extend plus and minus 1.96 times the standard deviation for P.

$$P \pm 1.96\, P \sqrt{1/N} \tag{8}$$

Figure 1 is a plot of the relative standard error of particle concentration, σ_P/P, against the number of particles counted, N.

Applications

When asbestos fibers are counted to determine compliance with an applicable standard, it is prudent to determine periodically the mean fiber concentration and associated confidence interval. The count should be continued only until the standard is no longer contained within the confidence interval, as one can then state with 95% certainty whether or not the standard has been met. When the fiber concentration is close to the standard, it will be necessary to count a larger number of particles to establish with 95% confidence whether or not the standard is met, than when the concentration is clearly well above or below the standard.

For example, after counting 50 asbestos fibers on a membrane filter, one might find that the mean concentration in the air passed through the filter was 1.5 fibers/cc. Equation 8 and Figure 1 show that one can state with 95% confidence that the true fiber concentration was $1.5 \pm 1.96 \times 1.5 \times (1/50)^{1/2}$, or from 1.08 to 1.92 fibers/cc. The upper bound of the confidence interval for this example is below the 1976 OSHA standard of 2.0 fibers/cc. Counting additional fibers would make the 95% confidence interval smaller, but would be unnecessary if 95% confidence that the standard is met is sufficient.

Equation 4 can also be used to determine confidence intervals about an experimentally determined value for dust collector penetration or efficiency. Penetration for particles of a certain size is the ratio of particle concentration in the downstream gas to the analogous concentration in the upstream gas.

$$Pt = \frac{P_{down}}{P_{up}} \tag{9}$$

The standard deviation of this quotient is[16]

$$\left(\frac{\sigma P_{down}/P_{up}}{P_{down}/P_{up}}\right)^2 = \left(\frac{\sigma_{Pt}}{Pt}\right)^2 = \left(\frac{\sigma P_{up}}{P_{up}}\right)^2 + \left(\frac{\sigma P_{down}}{P_{down}}\right)^2 \tag{10}$$

The substitution of Equation 7 into Equation 10 yields

$$\frac{\sigma_{Pt}}{Pt} = \sqrt{\frac{1}{N_{up}} + \frac{1}{N_{down}}} \tag{11}$$

Therefore, a 95% confidence interval about Pt will extend plus and minus 1.96 times the standard deviation of Pt, as shown in Equation 12.

$$Pt \pm 1.96\, Pt \sqrt{1/N_{up} + 1/N_{down}} \tag{12}$$

Equation 11 indicates that the relative error in penetration for particles of a certain size is only a function of the total number of particles of that size counted upstream, N_{up}, and downstream, N_{down}, of the collector. This relationship is plotted in Figure 2.

Equation 11 and Figure 2 show, for example, that to be 95% confident that pentration of particles in a certain size range is between 40 and 60% ($1.96\ \sigma_{Pt} = 10\%$ with mean penetration of 50%) it will be necessary to count 200 particles in this size range on the upstream filter and 200 particles in the same size range on the downstream filter. Alternatively, 500 particles counted upstream and 125 downstream would give the same result. However, the fewest total particles that must be counted to achieve a given relative error in penetration will always be found when the number of particles counted on the upstream and downstream filters is equal. This can be proven by differentiating Equation 11 with respect to N_{up}, setting the derivative equal to zero, and proceeding in the usual manner. When the particle deposit is less dense on the downstream filter, it becomes necessary to make more traverses for that filter in order to count about the same number of particles as are counted on the upstream. Or, a larger field size could be used for the less dense filter. When the particles observed on a filter are separated into many size categories to determine collector particle size efficiency, it is necessary to observe a large total number of particles to generate adequate confidence in the penetration or efficiency results for each size range considered.

When it is desirable to maintain a 95% confidence interval of constant size, i.e. a constant value of σ_{Pt} for all size ranges, Equation 12 shows that fewer particles need be counted in each size range as penetration decreases. The stratified counting technique can be used with good effect to concentrate the microscopist's efforts on the size ranges where penetration is high. Therefore, it is worthwhile to identify these size ranges as soon as possible by making a preliminary estimate of penetration based on an initial traverse of the upstream and downstream filters.

This method of calculating confidence intervals applies whenever concentrations are determined by counting. The techniques outlined above can be used for data from automatic counting devices such as optical instruments working on light scattering principles, as well as for data from other automatic counting devices.

Summary

An equal area traverse method is described for selecting microscopic fields when counting particles or fibers on a membrane filter. This method is analogous to that used to position a pitot-static tube in a duct when determining average gas velocity. The equal area traverse approach is an aid in avoiding inadvertent counting bias due to nonrandom field selection.

Although confidence intervals are important to establish the significance of particle concentration or collector efficiency data, they are seldom calculated or reported. When particle size data are generated by a stratified counting procedure, the method described can be used to establish with 95% confidence whether or not mean concentrations are below or above a fixed value.

Confidence intervals about values of penetration or efficiency can be calculated in a similar manner. The stratified counting approach allows the microscopist's efforts to be concentrated onto those particle size ranges where small confidence intervals for penetration are the most difficult to achieve. Charts have been prepared that make it possible to determine easily the number of particles or fibers which must be counted to assure desired confidence intervals.

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Counting Asbestos Fibers by the Most Probable Number Method

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A procedure for evaluating asbestos fiber counts is described which uses the most probable number method of bacteria counting. This technique is faster than conventional counting methods, with approximately comparable accuracies, although it suffers from a lack of rigor and requires the observer to estimate fiber concentrations to within an order of magnitude before counting. For the routine assessment of a large number of asbestos samples this procedure would seem to be more desirable than conventional counting because of the economy of time as well as being easier on the observer.

Introduction

RECENT FINDINGS ON THE TOXICITY of asbestos have led to increased interest in sampling and analytical procedures for determining the concentration of asbestos fibers in air. The Occupational Safety and Health Administration has established an interim eight-hour time weighed average airborne allowable concentration of five asbestos fibers greater than 5 microns length per cubic centimeter of air, and this standard will be lowered to 2 fibers/cm^3 on July 1, 1976.

Evaluation of asbestos fiber concentrations in air is carried out using samples collected on membrane filters and viewed with phase contrast illumination at 400X-450X.[1,2] This method is the standard field sampling method adopted by the Public Health Service.

Fibers are assumed to be distributed randomly over the filter surface and at least 20 but no more than 100 fields are to be viewed. At least 100 fibers are counted which gives a 95% confidence limit of ± 20%. Because of the relatively small amount of sample collected, more than 100 fields would have to be viewed if one were to find 100 fibers on a 10 minute sample collected at a rate of 2 liters per minute from air containing 5 fibers (5 microns length) per milliliter, and if the concentration were only 2 fibers per milliter, 435 fields would have to be assessed.[3] Of course, the number of fields necessary could be decreased by increasing the sampling time—in the latter case a 90 minute sample would yield 100 fibers in 50 fields—but the flexibility of short-term samples is then lost.

Counting fibers is a tedious and time-consuming business fraught with a number of subjective decisions for the microscopist to make. For example, in the case of two fibers lying side by side he must decide when a fiber is a fiber or when it is only a large particle. (It is considered that any particle having an aspect ratio of three or greater is a fiber).

If the sample is relatively light, a great deal of information is lost which actually can be used to determine fiber density. Besides actually counting the number of fibers, there is another quite distinct statistical method which could be used for estimating the number of fibers randomly distributed over a surface, the so-called most probable number method. In this paper the method will be applied to asbestos fiber counting and the advantages and limitations of its use will be discussed.

Theory

The concept of the most probable number method for esitmating randomly distributed number densities was first described by McCrady[4] and more recently by Cochran[5] and principally was applied to the problem of estimating bacterial densities. Chapman[6] applied the method to dust counting but it was not received with much enthusiasm for reasons which will be discussed later. Most recently the technique has fallen into disfavor even for estimating bacterial concentrations in milk and water samples, mainly because of the advent of more direct membrane filter techniques. For fiber counting however, the method appears promising because it eliminates the need to resolve individual fibers and with the low densities normally found, gives the same counting accuracy in a much shorter period of time and with much less eyestrain.

Consider a filter of area A which is broken up into a fields. If there are m fibers distributed randomly over the filter surface, then the average number of fibers per field, f, is

$$f = \frac{m}{a} \qquad (1)$$

The probability, P, than n fibers lie in a certain field can be expressed using the Poisson relationship

$$P(n) = \frac{f^n}{n!}e^{-f} \qquad (2)$$

provided that a is a large number. The probability of a field being void of fibers is, from above

$$P(o) = e^{-f} \qquad (3)$$

If the void fields are distributed randomly across the filter and L fields are sampled, the probability that exactly l of these fields will be void is

$$P_l(o) = \frac{L!}{l!\ (L-l)!}[P(o)]^l\ [1 - P(o)]^{(L-l)} \qquad (4)$$

Equation 4 gives a distribution of probabilities which is very small for small l and rises

TABLE I
95% Confidence Interval for a Given Average Number of Particles Per Field

Particles/Field True Average	L = 25	L = 50	L = 100	L = 200
	95% Confidence Interval Expressed as a Percentage of the True Average (left column, minus; right column, plus)			
0.1	100 — 229.1	75.8 — 138	56.7 — 84.9	43.3 — 51.1
0.2	76.6 — 156	58 — 79.7	41.3 — 51.7	29.8 — 35
0.3	69.6 — 111.3	49.9 — 58.8	34.1 — 43.1	25.9 — 28.1
0.4	54.8 — 90.3	42.1 — 59.8	31.5 — 36	23.1 — 25.5
0.5	56.3 — 79.4	41.1 — 52	27.8 — 36.2	21.8 — 22.6
0.6	52.7 — 76.2	37.4 — 40.8	27.9 — 33.6	18.7 — 22.8
0.7	47.5 — 55.2	35.6 — 47.4	23.9 — 32.2	18.8 — 21.7
0.8	45.6 — 73.8	33.6 — 38.8	25.1 — 31.5	18.1 — 21.2
0.9	44.3 — 75.6	32.8 — 38.9	22.3 — 31.4	17.6 — 19.4
1	43.2 — 57.5	32.2 — 39.7	21.9 — 31.7	17.4 — 19.5
1.1			23.9 — 28.7	17.4 — 18.1
1.2			21.8 — 29.6	16.3 — 18.5
1.3			22 — 26.8	16.5 — 19.2
1.4			23.3 — 28.4	15.6 — 18.1
1.5			22.6 — 29.9	15.9 — 19
1.6			20.9 — 26.8	16.3 — 17.9
1.7			21.4 — 28.7	16.8 — 19
1.8			22.1 — 25.6	16 — 20
1.9			20.2 — 33.1	15.2 — 21.4
2			23.5 — 30.3	15.7 — 20.2

to some maximum value before becoming small again. The most likely probability, that having the largest value, occurs at

$$l = Le^{-f} \qquad (5)$$

Turning this around, the most probable fiber concentration is thus

$$f = ln\ (\frac{L}{l}) \qquad (6)$$

The above development results in a simple procedure for assessing fiber concentration. A number of fields are scanned to determine only whether fibers are or are not present in any given field. Then by taking the natural log of the ratio of the number of fields scanned divided by the number of fields containing no fibers (Equation 6) the most probable number of fibers per field can be estimated.

As the number of fields scanned is increased, the accuracy of the estimate increases. Table I shows the 95% probability range for scans of 20, 50, 100 and 200 fields at various fiber densities, as calculated from Equation 6. Thus, for example, assaying 100 fields will yield results within about ± 30% of the true value 95% of the time, regardless of the total number of fibers seen, provided, of course, that the average fiber density is somewhere around two fibers per field or less. Assaying 200 fields will increase the accuracy of the 95% confidence interval to something less than 20% of the true count.

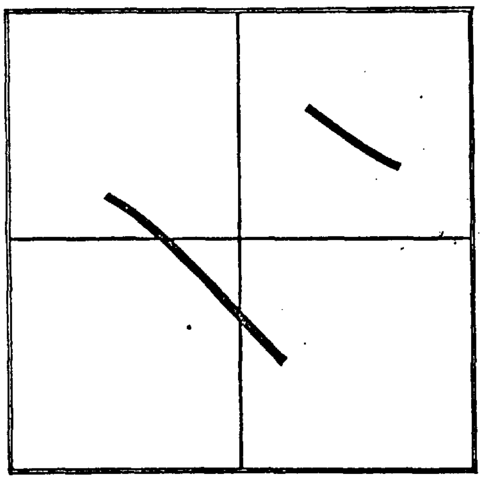

Figure 1. Various orientations of fibers in the microscope field.

For the case of $L = 200$, the accuracy appears to increase with an increasing average number of particles per field. This will continue until the point is reached where there is a good chance that every field contains at least one fiber. This occurs when the average number of fibers per field is slightly in excess of three. Thus for this method it is necessary to estimate ahead of time the fiber concentration to within one order of magnitude so that there will be about 0.2 to 2 fibers per field, or, if there appear to be plenty of fibers in evidence, to then use the direct count method. Of course, the number of fibers per field can be easily varied by changing the field size.

Definition of a Field Containing a Fiber

Thus far, for the purpose of development of the theory, fibers have been considered as if they were particles. But they are not. A fiber has length and as such may start in one field, extend through another or several others and finally terminate in yet another field. Figure 1 illustrates such a situation. The fiber originates in the upper left hand corner, continues through the lower left hand corner and then ends in the lower right hand corner. The fiber in the upper right corner represents no problem.

There are several ways in which the fiber that passes through several fields can be treated. First, only the lower (or upper) end of the fiber can be considered, and the field that it lies in then is a field not devoid of fibers. In the rare case where the fiber is perfectly horizontal, some convention, such as choosing the left hand side of the fiber would be appropriate. A field would be considered blank if the lower end of a fiber were not in it. Thus, in Figure 1, only the fields on the upper right hand side and lower right hand side would be considered to contain fibers. Since each fiber is associated with one "lower" end, the estimated number ends would equal the estimated number of fibers.

A second approach would be to call a field void only if it contained no fiber ends at all. In Figure 1 only the lower left hand field would be considered to be void. The most probable number of ends would then be estimated and since each fiber has two ends, the most probable number of fibers would be the estimated number of ends divided by two. An obvious disadvantage of this approach is that the upper limit of density which could be used is half of what otherwise would be used.

The most reasonable approach is to assess only one end of the fiber. If the fiber is a bundle with a rough end lying on the edge of a field so that there is some question as to whether it is in or outside of the field, then the same rules as those used in particle counting could be applied to determine whether the fiber is in the field or not.

Experimental

In order to determine the efficacy of the proposed counting procedure a number of asbestos samples were counted using a direct counting method and a record was kept of the number of void fields observed. Most probable number data as determined from

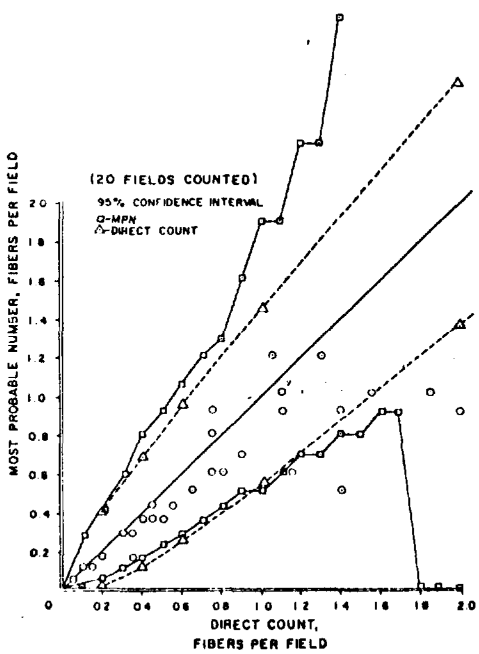

Figure 2. Most probable number data as determined from Equation 6 versus direct count.

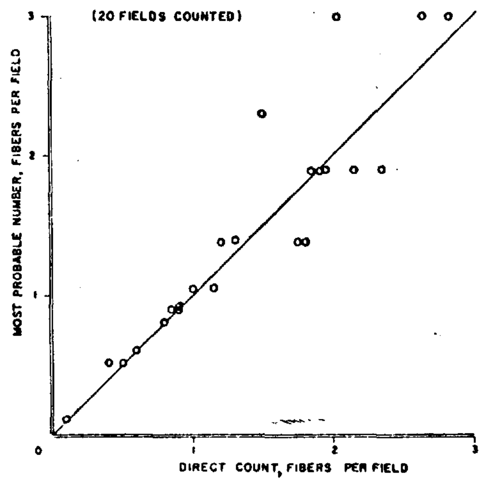

Figure 3. Plot of most probable number versus direct count for data from computer simulation for 20 fields.

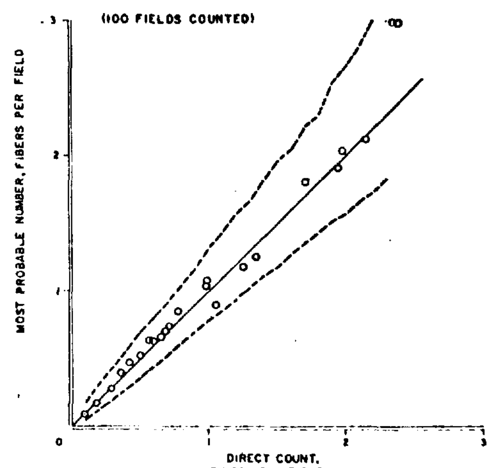

Figure 4. Plot of most probable number versus direct count for data from computer simulation for 100 fields.

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Equation 6 are plotted as a function of the direct count which was observed for the samples and the results are shown on Figure 2. Also shown on this figure are the 95% confidence limits for both the MPN method and direct counting. Although there is some spread in the data, the general reproducibility is apparent. However, it appears that the most probable number method consistently gives results which are lower than those determined by direct count. This observation is consistent with a similar one of Chapman's who surmised that the difference could be due to failure to see a single particle in an otherwise void field.

For more extensive work a computer simulation was developed in which fields of 10,000 bits were assigned particles randomly corresponding to some preset particle density. Then fields of various sizes were randomly chosen and the average number of particles per field determined using the two methods. In addition, the absolute number of particles per field was determined. From this simulation it was possible to carry out non-biased counts using both conventional counting and the most probable number method for samples of 20, 100 and 200

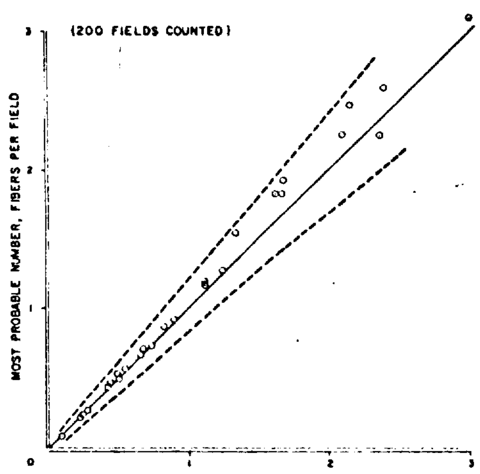

Figure 5. Plot of most probable number versus direct count for data from computer simulation for 200 fields.

fields. These data are shown in Figures 3, 4 and 5. Unlike the actual experimental data, however, there appears to be no bias toward the direct count information, indicating that the higher count averages noted on the actual direct counts results from a bias introduced by the observer rather than by the technique. Similar to Figure 2, error limits for the 95% confidence interval are shown as dotted lines.

Advantages and Disadvantages

The advantages of the most probable number method are threefold. Sampling times are shorter, lighter samples with less chance of overlap can be used, and counting times are shorter. Using fairly light samples for asbestos concentration assessment means that shorter sampling times are needed in the field, often an advantage to the industrial hygienist. For a given number of fibers observed, the MPN method implies greater accuracy if this total number is relatively small. There is less eyestrain for the microscopist since he only has to determine whether there is or is not something there, and not resolve a specific number of fibers. If problems of fiber clumping have occurred they will be more evident because of the lighter sample density. Finally, since fields are being counted instead of particles, the counting should proceed at a faster pace. For example, in discussing particle counting by the most probable number method, Chapman pointed out that one observer could determine particle concentrations about twice as fast using the most probable number method compared to standard counting methods while another observer was three times as fast using the MPN method. We have not studied counting times objectively, but subjectively the people in this laboratory who have compared the two methods for counting asbestos fibers also feel that the most probable number method is much faster.

The principal disadvantage of the most probable number method is that it is not rigorous. An observer could, in theory, accurately count the total number of fibers deposited on a filter whereas using the most probable number method, even if the whole filter were assessed, the observer would in the end still only have an estimate of the number of fibers present. In addition, for a given number of particles per field, the 95% confidence intervals for the direct counting method are slightly narrower than for the most probable number method, the effect becoming increasingly pronounced when the average number of fibers per field exceeds two. The accuracy is sufficient, however, for routine asbestos counting.

Summary

A procedure for evaluating asbestos fiber counts is described which uses the most probable number method of bacteria counting. This technique is faster than conventional counting methods, with approximately comparible accuracies, although it suffers from a lack of rigor and requires the observer to estimate fibers to within an order of magnitude before counting. However, for the routine assessment of a large number of asbestos samples this procedure would seem to be more desirable because of the economy of time as well as being easier on the observer.

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Handling Asbestos

Chrysotile Asbestos in Plastics

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Asbestos has received a great deal of attention and publicity in recent years, especially after it was designated a "target health hazard" by OSHA and a "hazardous air pollutant" by the EPA. Many of the articles on asbestos by the press have been emotionally oriented or distorted and, in some cases, stories have been sensationalized, based on obvious misinterpretation of facts. The use of half-truths or unsubstantiated statements has led to general confusion and the unfair castigation of asbestos and products containing asbestos. The purpose of this paper is to put the matter of asbestos use and asbestos hazards into a logical and practical perspective. In this paper, the different types of asbestos and their many uses are discussed, along with government regulations controlling the use of asbestos. The health hazards associated with asbestos, both occupational and environmental, and some industrial experience with air sampling and dust control measures are also covered.

KEY WORDS: Asbestos; Plastics; Air pollution; Toxicology.

What is Asbestos?

Asbestos is a commercial or generic term used to describe six naturally occurring "asbestiform" minerals that are fibrous, hydrated metal silicates. The six varieties are divided into two classes—serpentine and amphibole—based on their crystal structure. Chrysotile is the only member of the serpentine class, while the amphiboles include crocidolite, amosite, anthophyllite, tremolite, and actinolite. Chrysotile is by far the most-used variety and accounts for over 95% of U.S. consumption, as noted in *Table* 1.

Crocidolite, also known as blue asbestos, is imported from South Africa. Because of its high mechanical strength and good resistance to acids and alkalis, it is used to reinforce a limited variety of plastics where its pronounced color is not objectionable. Amosite, also imported from South Africa, is used primarily in thermal insulation. Although there are some deposits of anthophyllite in the U.S., most of it is imported from Finland. It is used primarily as a filler for polypropylene and in insulating materials. A comparison of the four varieties of asbestos which are of commercial importance is presented in *Table* 2. It should be noted that there are significant differences between chrysotile and amphiboles with regard to chemical composition and certain physical properties.

Where is Asbestos Used and Why?

Asbestos has served mankind for more than 100 years in a broad variety of applications. The general areas in which asbestos is used in the U.S. are shown in *Table* 3. Based on information from asbestos producers and consumption surveys, it is estimated that the plastics industry uses about 33% of the 800,000 tons consumed annually, which makes it the largest single user of asbestos fiber.

The largest uses of asbestos by the plastics industry are in vinyl-asbestos floor tile and in phenolic molding compounds. It is also used in other plastics such as polypropylene, polyester, nylon, melamine, epoxy, silicone, and vinyl. Asbestos provides a valuable function in such products as brake linings, clutch facings, electrical components, automotive parts, furniture, boats, sealants, coatings, adhesives and mastics. The most important functions of asbestos in plastics are reinforcement, dimensional stability, heat resistance, flow control, and general-purpose filling. Most of the functions are supplied by short-fiber chrysotile asbestos fiber, although longer chrysotile fibers and other asbestos varieties are sometimes required for particular properties.

Why Use Chrysotile?

Among the several advantages of chrysotile, which set it apart from the amphibole minerals and account for its widespread and increasing usage, are world-wide availability, mechanical strength, flexibility, positive surface charge, low iron content, softness, and low refractive index. It is conservatively estimated that chrysotile asbestos is used in over 3,000 applications and, in most of these applications, it is an essential ingredient for which no replacement is readily available.

The information in *Table* 1 shows that the use of chrysotile asbestos and its share of the total market are steadily increasing. This is due partly to technical advances permitting the broader use of chrysotile in plastics and the general decline in the use of asbestos in certain fireproofing and insulating materials. In addition, there is increasing evidence that crocidolite and amosite are more hazardous to

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Table 1—Apparent U.S. Consumption of Asbestos, Tons[a]

Year	Total	Chrysotile	Amosite	Crocidolite
1967	720,583	686,044 (95)[b]	12,558 (1.7)	14,917 (2.1)
1968	817,363	775,711 (95)	20,467 (2.5)	13,965 (1.7)
1969	784,321	749,708 (96)	14,618 (1.9)	10,558 (1.3)
1970	728,131	695,770 (96)	14,261 (2.0)	8,936 (1.2)
1971	758,571	729,272 (96)	14,580 (1.9)	6,953 (0.9)
1972	808,554	791,020 (98)	7,125 (0.9)	5,374 (0.7)

(a) Information based on import and production data from U. S. Bureau of Mines' Minerals Yearbooks.
(b) Percent of total shown in parentheses.

Table 3—Apparent U.S. Consumption of Asbestos By General Use Areas

Area of Use	Percent of Consumption
Construction	40
Floor tile	15
Felt paper	15
Friction and packing	14
Insulation	3
Textiles	2
Other	11

human health than chrysotile.[1] Since 1970, the use of crocidolite in Britain has been restricted after a panel of experts "concluded there was sufficient evidence to suggest other types of fibre should be substituted for crocidolite wherever possible."[2]

What is the Asbestos Hazard?

It is readily accepted that asbestos, like many other foreign bodies, can cause disabling lung damage (pulmonary fibrosis), commonly referred to as asbestosis. This disease and bronchogenic carcinoma (lung cancer) are the two most common asbestos-related diseases. It is important to note that, based on epidemiological data, these diseases have occurred primarily in workers with high, long-term exposures to asbestos dust. It is of further interest that one noted researcher has reported that neither of these diseases is peculiarly related to or caused solely by the inhalation of asbestos fiber.[3] Another important consideration is the relation between cigarette smoking and lung cancer, as reported by Dr. E. C. Hammond and Dr. I. J. Selikoff.[4] In this study, they reported that: "It seems clear, then, that lung cancer is uncommon among asbestos insulation workers who have no history of cigarette smoking and that if the risk is increased, such increase is not great."

A third disease, mesothelioma, has more recently been associated with persons exposed to asbestos. Mesothelioma is an extremely rare cancer of the lining of the chest (pleura) or the abdominal cavity (peritoneum). In contrast to the lung diseases, there is some evidence that mesothelioma can occur after brief exposures to relatively high fiber levels.

According to the 33-member Advisory Committee on Asbestos Cancers of the International Agency for Research on Cancer (a division of the World Health Organization): "There is evidence of an association of mesothelial tumors with air pollution in the neighborhood of crocidolite mines and of factories using mixtures of asbestos fiber types. The evidence relates to conditions of many years ago. There is evidence of no excess risk of mesotheliomas from asbestos air pollution which has existed in the neighborhood of chrysotile and amosite mines. There are reported differences on incidence of mesothelioma between urban and rural areas, the causes of which have not been established. There is no evidence of a risk to the general public at present."[5]

The same body quoted above has also concluded that there is, at present, no evidence of lung damage by asbestos to the general public; and such evidence as there is does not indicate any risk of cancer resulting from asbestos fibers present in water, beverages, food, or in the fluids used for the administration of drugs.

While there seems to be general agreement that the public is not in any present danger from asbestos, it is also recognized that excessive, long-term occupational exposure can cause serious health problems. Also, if man-made emissions are not controlled, then environmental contamination could could approach harmful levels. During the past two years, significant legislation has been enacted by the Federal government to reduce and control occupational exposure to asbestos fibers and to minimize fiber emissions to the environment. Additional standards or regulations have been proposed or enacted by many states and local governments.

Table 2—Comparative Data for Asbestos Minerals[a]

Formula	Chrysotile $3MgO2SiO_2 \cdot 2H_2O$	Crocidolite $Na_2O \cdot Fe_2O_3 \cdot 8SiO_2 \cdot H_2O$	Amosite $1.5MgO \cdot 5.5FeO \cdot 8SiO_2 \cdot H_2O$	Anthophyllite $7MgO \cdot 8SiO_2 \cdot H_2O$
Composition, %				
SiO_2	37—44	49—53	49—53	56—58
MgO	39—44	0—3	1—7	28—34
FeO	0—6	13—20	34—44	3—12
Fe_2O_3	0—5	17—20	—	—
Al_2O_3	0—2	—	2—9	0—2
H_2O	12—15	2—5	2—5	1—6
CaO	0—5	—	—	—
Na_2O	—	4—8	—	—
$CaO+Na_2O$	—	—	0—3	—
Crystals	Fine fibers	Brittle fibers	Prismatic	Prismatic
Color	Gray green	Blue	Gray/brown	Gray
Texture	Soft silky	Harsh	Harsh	Harsh
Flexibility	Very good	Good	Good	Poor
Hardness, mohs	2.5-4	4	5.5-6	5.5-6
Fiber diameter, A	180-300	600-900	600-900	600-900
Tensile, mpsi	800	600	200	<4
Surface charge	Positive	Negative	Negative	Negative
Resistance to acid	Poor	Good	Good	Very good
Resistance to alkali	Good	Good	Fair	Good

(a) Sources: Modern Plastics Encyclopedia (1973), and Encyclopedia of Chem. Tech., Vol. 2.

Summary of OSHA Regulations

The William-Steiger Occupational Safety and Health Act of 1970 became effective on April 28, 1971, with prudent to permit additional contamination of the public environment with asbestos. Continued use at minimal risk to the public requires that the major sources of man-made asbestos emission into the atmosphere be defined and controlled.' "[7]

What is Industry Doing?

The Asbestos Information Association/North America reports that, during the past 30 years, the asbestos industry has spent millions of dollars to improve mining, milling, and manufacturing methods.[8] The establishment of safer working conditions has been a prime target and this work continues unabated and in close association with government agencies and independent medical researchers.[9]

The ultimate goals of the asbestos industry are: Reduction of work-area dust to minimum levels; Protection of workers from asbestos-related diseases; Maintenance of environmental emissions at levels low enough to preclude public endangerment.

Air Sampling

In order to comply with OSHA standards and to determine the need for dust control measures, air monitoring should be conducted in areas where asbestos is regularly handled or used. OSHA standards require that "all determinations of airborne concentrations of asbestos fibers shall be made by the membrane filter method at 400-450X (magnification) (4 millimeter objective) with phase contrast illumination."[10] The equipment for collecting air samples costs less than $400 and is readily available. A phase contrast microscope can be obtained for as little as $600, or an existing microscope can be modified for "counting" the asbestos fibers in compliance with NIOSH criteria.[11]

Air samples have been collected and analyzed on a regular basis by the asbestos industry for years. Except for a few applications where dust control is an engineering problem, industry is finding that dust levels are already within acceptable standards or that minimum changes are necessary to achieve compliance. Although data on many asbestos/plastic applications are not available, the summary in *Table* 4 is typical of our measurements of dust levels during asbestos handling in various types of plants and operations. The dust levels reported are ceiling concentrations, and it should be noted that the allowable OSHA level is 10 fibers/cc. In most cases, the TWA exposure level would be well below OSHA standards. Most of the data were collected before the installation of any special dust-control measures. Monitoring often shows that obviously dusty conditions are caused by materials other than asbestos. This does not preclude the need for controls, but it could change their scope and facilitate compliance with government regulations. Because of "bad press," asbestos is frequently ordered out of use without regard to whether or not a hazard actually exists due to air contamination. If acceptable dust levels are feasible, there is no need to replace asbestos at the expense of product quality or economic penalty. Gordon Everett of EPA points out that information on the biological effects of asbestos is very limited and that the effects of many substitutes have not been investigated at all. Before asbestos is replaced, it should be certain that a safer alternative is available.[12]

Table 4—Typical Air Sampling Results[a]

Type Plant Or Operation	Ceiling Concentration, Asbestos Fibers/cc
Floor tile	1-3
Polyester	1-3
Phenolic compounding	2-5
Handling phenolic	3-14
Caulks and sealants	0-8
Gypsum compounds	2-9

(a) Source: Union Carbide Corp., from air monitoring reports.

Obviously there are more people exposed to products containing asbestos than there are to raw asbestos fibers. As noted previously, more than 90% of the asbestos used in this country is in products in which the asbestos is "locked in" or bound with cement, plastics, or other binders, so that there is no release, or at least no significant release, of fibers in work areas or to the environment. Materials or products with locked-in fibers would include: floor tile, polyester resins, phenolics, sealants, coatings, brake linings, friction materials, rubber, roofing compounds, and reinforced plastics. Since an abrading action on some of these products could release asbestos fibers, appropriate monitoring and/or control measures should be instituted if it is thought that such action would release fibers.

Dust-Control Measures

Asbestos producers and users are spending a considerable amount of time and money on various dust-control measures. Conventional means to achieve minimum dust levels include: filtered ventilation systems on process equipment, local ventilation for saws and similar tools, conversion to a "wetted" operation, leak-proof packaging, vacuum clean-up, more care in bag disposal and other asbestos waste handling, and automatic bag openers. Unusual innovations include: pelletized asbestos, special packaging, and treated products.

Only short-fiber chrysotile is available as pellets, but this product serves a fair portion of the asbestos market. Pellets not only reduce dust during conventional handling but they are also available in bulk hopper cars and can be transferred and used in totally enclosed systems. Barring leaks in the system, dust in work areas is virtually eliminated. Used in bulk, asbestos pellets also reduce shipping costs, eliminate warehouse storage and handling, facilitate automation, reduce clean-up, and eliminate bag handling and disposal. The pellets contain no binder and are friable enough to be dispersed in dry form or in aqueous or resinous systems with conventional high-shear grinding equipment.[13]

Several types of special packaging are currently available, and suppliers consider customer requests for unusual requirements. The floor tile industry can obtain asbestos in plastic bags which can be added directly to the compounding operation. Asbestos in bleached paper bags assembled with water-soluble glue and printed with water-dispersible ink can be added directly to paper-making finishes or acoustical tile formulations.

Although "wetted" asbestos is not generally available, most suppliers are working with customers to provide "dustless" products. When justified by market demand, asbestos can be treated with water, mineral spirits, glycol, or other materials compatible with the application or system.

Conclusion

Asbestos is one of industry's many raw materials which involves a potential hazard when not used with reasonable respect and care. Although all forms of asbestos are recognized as hazardous to health when inhaled excessively, there is growing evidence that crocidolite and amosite are more hazardous than chrysotile. Fortunatethe following Congressional purpose: "To assure so far as possible every working man and woman in the nation safe and healthful working conditions and to preserve our human resources." The Act established the Occupational Safety and Health Administration (OSHA) within the Department of Labor, which has responsibility for administration and enforcement. Research and related functions are handled by the Department of Health, Education and Welfare (HEW) through the National Institute of Occupational Safety and Health (NIOSH). Five million employers and 60 million of the nation's 80 million workers are covered by OSHA. Specifically excluded from coverage are government employees and operations which are protected under other federal health and safety laws. In a news release issued January 4, 1972, OSHA announced a Target Health Hazards Program aimed at improving health factors associated with working conditions. The following five substances were designated to be the focus of initial and concerted efforts by OSHA and NIOSH: asbestos, cotton dust, silica, lead, and carbon monoxide.

At the present time, new standards have been established only for asbestos, although, of the 8,000 toxic substances on the NIOSH list, only 500 are covered by standards and many of those need updating. The new Standard for Exposure to Asbestos Dust was published in the *Federal Register*, Vol. 37, No. 110, on June 7, 1972. The basic exposure standard is an 8-hr time weighted average (TWA) of five fibers, longer than 5 micrometers, per cubic centimeter of air. The TWA limit is to be reduced to two fibers per cubic centimeter on July 1, 1976. A peak concentration of 10 fibers per cubic centimeter is not to be exceeded at any time. All of the fiber concentrations are those to which an employee may be exposed without protective clothing and equipment. The first basic requirement of the new standard is monitoring to determine whether or not fiber concentrations are in excess of the exposure limits. Some asbestos suppliers provide a monitoring service to customers, and a similar service may be obtained from state health department officials, insurance carriers, or private consultants. The law requires that monitoring be repeated as necessary to ensure that employees are not exposed to levels in excess of the exposure limits.

Improper interpretation of the regulations has created many misconceptions about equipment and procedures needed to properly use asbestos. If exposure limits are not exceeded, there are no further compliance requirements except for medical examinations. Medical examinations are required for all employees in any occupation exposed to airborne concentrations of asbestos fibers. The examinations are relatively simple and should cost no more than $50 per year, per employee.

Respirators and special clothing are required in the construction trade for the spray application of insulation and fireproofing materials, and for the removal of such materials. This special protection is not required for any other use of asbestos unless exposure limits are exceeded. This is also true for other items such as specially equipped tools, change rooms, clothes laundering, and waste disposal. Respirators are not a substitute for engineering controls, but the law allows their use while controls are being implemented, in special situations where controls are not feasible or adequate, in emergencies, and for infrequent short-term job assignments. Caution labels are required on products containing asbestos except where the fibers have been modified by a bonding agent or other material to prevent dusting during any normal subsequent use or handling. Besides raw asbestos fiber, products which require package labeling could include: dry acoustical spray products and joint cements, unsaturated roofing felt and textiles, and some insulating products made without adequate binders. The labeling of a product does not prohibit its use. It should be noted here that in at least 90% of the products containing asbestos, the fibers are solidly locked into the product thereby presenting little danger of dust generation during normal use and handling of the product.[6]

EPA Standards

Whereas OSHA is responsible for the protection of the worker, the Environmental Protection Agency (EPA) is charged with improving the environment to which the general public is exposed. On March 31, 1971, asbestos, along with beryllium and mercury, was identified as a "hazardous air pollutant" by the Administrator of the EPA. National Emission Standards for asbestos were then published by EPA in the *Federal Register*, Vol. 38, No. 66, April 6, 1973. Although no numerical emission standards were established, operating criteria are prescribed to prevent or limit asbestos emissions to the outside air from asbestos mills, roadways, certain manufacturing operations, building demolition, and the spray-on application of materials used to insulate or fireproof equipment and machinery. The law further requires that spray-on materials used to insulate or fireproof buildings, structures, pipes, and conduits shall contain less than 1% asbestos on a dry-weight basis. This should significantly reduce emissions to which the general public may be exposed, especially in large urban areas.

". . . the Administrator (of EPA) has determined that, in order to provide an ample margin of safety to protect the public health from asbestos, it is necessary to control emissions from major man-made sources of asbestos emissions into the atmosphere, but that it is not necessary to prohibit all emissions.

"In this determination, the Administrator has relied on the National Academy of Sciences' report on asbestos, which concludes: "Asbestos is too important in our technology and economy for its essential use to be stopped. But, because of the known serious effects of uncontrolled inhalation of asbestos minerals in industry, and uncertainty as to the shape and character of the d.se-response curve in man, it would be highly im-

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ly, the plastics industry uses primarily chrysotile asbestos and, in most products, the fibers are locked-in to prevent airborne contamination. Although asbestos dust levels are generally lower than expected, industry continues to expend large amounts of time and money to further improve the quality of the workplace. Although the general public is not currently in danger, occupational controls are required to prevent future environmental contamination.

Chrysotile asbestos is an important and necessary raw material, vital to the nation's safety and economy; and, with proper control, it can be used safely and in compliance with government regulations. Medical, scientific, government, and industrial personnel must continue to work closely together to establish reasonable exposure limits, provide safe work areas, and eliminate any possibility of public endangerment. ☐

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