STUDIES ON THE EFFICACY OF DUST RESPIRATORS FOR ASBESTOS DUST

by

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Master of Engineering Thesis.

Abstract

A manikin and an automatic resuscitator were used in this research to simulate the human respiratory function in order to investigate the performance characteristics of various commercially available dust respirators currently in use for protection against fibrous dusts. Some of these respirators which have been approved by the U.S. Bureau of Mines and other non-approved types are extensively used for protection against pneumoconiosis-producing and nuisance dusts. Eleven respirators, seven of the approved type and four non-approved, were tested in this study.

The performance characteristics of these respirators were evaluated for three different fiber dust concentration levels. Each level was maintained for a six-hour period of test for each respirator.

The efficiencies of all but one of the respirators were in excess of 95 per cent for the conditions maintained in the tests. Furthermore, these efficiencies increased with a rise in dust concentration and with the length of time under test.

However, sufficient data was not available for a comparison of performance of the dust respirators for fibrous dust as opposed to an equidimensional dust.

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INTRODUCTION

Health hazards associated with inhalation of fibrous dusts, especially asbestiform varieties, have become a matter of increasing concern.

Although the best procedure to prevent the inhalation of harmful fibrous dust by personnel is the removal of the dusts at their source of generation or the reduction of the dust concentration to levels sufficiently low so as not to cause bodily harm, there are situations where, for one reason or another, these procedures are inapplicable, impractical, impossible or not adequately effective. In such situations, an efficient personal protective respirator is utilized to protect personnel.

The use of respirators of many designs has long been promoted by industrial hygienists associated with the mining industries and the factories which manufacture asbestos products. In general, most respirators are selected from the list approved for protection against pneumoconiosis-producing dusts by the U.S. Bureau of Mines. It is recognized, however, that there is very little published data concerning the efficacy of these respirators for protection against fibrous dusts in particular.

In view of this fact, Prof. F.T.M. White, Chairman of the Department of Mining Engineering and Applied Geophysics, McGill University, has therefore, accepted a health research grant from the industry for performing this research.

The criteria of this research are based on the normal human respiration rate in order to facilitate the investigation of the characteristics of each respirator's performance. It is necessary to point out that each respirator had been subject to a six-hour experiment for each dust concentration level rather than a common test period of 90 minutes only. Furthermore, the tests were made at three different dust concentration levels. As there were eleven different types of respirators included in this research, the time for recording experimental data was in excess of six months.

This information should be useful to industrial hygienists and safety engineers in aiding them to select the proper dust respirator for protection against fiber dusts.

Chapter I

GENERAL DESCRIPTION

1. The Mineral - Asbestos

1.1 Names of Asbestos

Asbestos is a name which contradicts the essential characteristic of the mineral, and it does not burn. The word asbestos is derived from the Greek verb "shennumi" which means "to quench", "die down" or "extinguish". The contradiction probably arose through confusion with a fabulous stone which was reputed to burn with an inextinguishable flame.

The word "asbestos" is used in North America and in North European languages; but in the southern Latin languages, it is called "amiantos"; in Dutch and Russian - "asbests"; in French - "asbeste" or "amiante"; in Italian and Spanish - "amianto" and "asbesto"; in Czech - "asbest" or "Dobsina"; in Polish, Slovakian and Servian - "azbest"; in Hungarian - "azbeszt". It has also been known in Germany as stone flax "steinflachs", and French-Canadian miners refer to it as cotton stone "pierre-à-cotton". Crocidolite and chrysotile are Greek words meaning "woolly stone" and "fine fair of gold" respectively.

1.2 Humans and Asbestos

The use of asbestos can be traced back to ancient times. It was almost certainly woven into the wicks of the "perpetual lamps of the Vestal Virgins". It was also said that cremation cloth was made of asbestos, and in which dead bodies were enwrapped to be consumed by fire, and, it was referred to by the people as a rare and costly cloth - "linum vivum" - "the funeral dress of Kings". They believed it to be of vegetable origin, the highly silky appearance and unctuous feel giving them the impression that it was an organic substance.

In 28 B.C., a Greek doctor Anaxilous discovered that asbestos could be used as a material for acoustic purposes after he had found that if surrounded by asbestos linen, a tree could be felled noiselessly. Charlèmagne's tablecloth, which he recovered harmlessly from a fire in a successful attempt to impress an enemy, was undoubtedly of woven asbestos, and our ancestors are recorded as having used the material for napkins which could simply be cleansed by throwing them into a fire. Later on, a Venetian magazine published that a substance, which was incombustible, was found in Italian mines.[24]

Before the 17th century asbestos was merely an object of superstition and curiosity, and until sometime in the 19th century, when serpentine asbestos (or chrysotile) was discovered in Canada, the emphasis was placed on conservation of heat by lagging rather than resistance to fire.

Following the great progression of science within these recent several decades, when man realized that asbestos is most abundant and useful to industry, its output has increased over a 1,000 - fold in 60 years, compared with a mere 50 - fold for oil - an industry often regarded as the symbol of industrial growth.

1.3 The Uses and World Production

There are more than 3,000 recorded uses of asbestos. Since asbestos is a major constituent in such a wide variety of products, a fact that we tend to take for granted, the terms for asbestos as:

"the mineral of a thousand uses", "the magic mineral" and "the mineral of unparalleled properties", are most suitable. The absence of asbestos from a specific product could in many cases radically change its form and thereby render it useless for the requirement involved.

There are many uses of asbestos, 95% of which can be considered to be chrysotile. Longer fibers are used in spinning and weaving, e.g. cloth and ropes. The shorter fibers are stronger and interlace more readily, and are used in rigid compositions, liquids and semi-solids.

The general uses to which asbestos is put, are listed as below:-

Acetylene cylinder packings;	Acid-resistant compounds;
Acoustic plaster;	Adhesives;
Asbestos cement;	Asbestos millboard, rollboard, wall board;
Asbestos cloth, yarn, woven, spinning, tapes and ropes;	Asbestos paper and felt;
Asphalt compounds;	Boiler coverings;
Bulkhead lining;	Caulking and sealters;
Cements;	Ceramics;
Chlorine cell diaphrangms;	Curbing;
Dry mix;	Extruded;
Fibrated greasers;	Fillers;
Filters;	Fire resisting materials;
Floor Tiles;	Friction material;
Insulation material;	Magnesite flooring;
Oil-well muds;	Paints;
Pipe fiber;	Plastics;

Profile calender;

Roof coating;

Shingle;

Wick packing.

Raw material;

Sheet packing;

Welding rods;

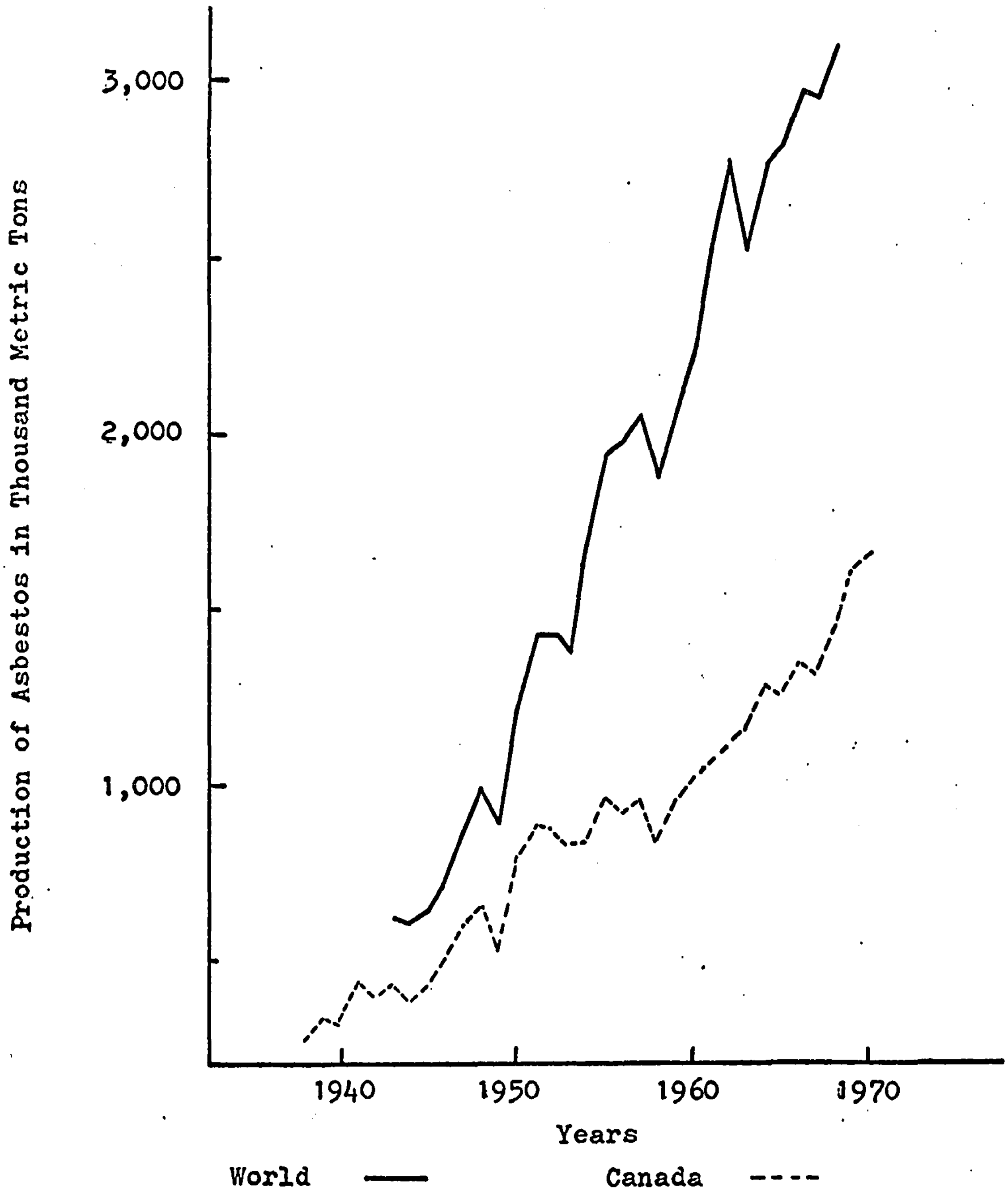
Asbestos probably occurs and is produced in nearly every country in the world. The major producer in the world was Canada; but in recent years, there has been a great increase in Russian production which now outranks Canada as the major producer. Due to the recent development of the Coalinga fiber deposits in California, the production of asbestos has been increased in the United States over the past few years. Since the Australian crocidolite mines were closed in 1966, this source was eleminated from the market. South Africa remains as the significant area producing crocidolite and amosite.

The world production of asbestos has increased from 500 tons in 1880, to 330,000 tons in 1925, to 446,000 tons in 1938, to 2,055,000 tons in 1958, to over 3,000,000 in 1968, and that it is still rising as shown in Fig. 1.

2. Asbestos in Modern Technology

2.1 The Geology and Its Occurrences

Asbestos did not originate as a primary constituent of the earth's crust because it is a metamorphic or transformation product of other minerals or rocks. The genesis of asbestos was extended over millions of years - it is necessary to distinguish between transformation processes (metamorphoses) and asbestos-producing actions. The different phases of



WORLD PRODUCTION OF ASBESTOS

Fig. 1

asbestos formation did not proceed uniformly because they were affected by the prevailing local tectonic movements and geological conditions. These involved repetitions, changes in temperature, disturbances, overlappings, pressure, tension and torsion, as well as the other factors such as intrusions, dislocations, fissurings, intense crushing (mylonitization), etc.

Studies by Riordon(94), Mevenkov(77), Gabrielse(45), Berger(15), indicated that it is essential to distinguish between two kinds of metamorphic process: the formation of serpentines or serpentinites, and the production of amphibolitic substances. Both metamorphoses were associated with an enrichment of the starting materials with SiO_2. The formation of serpentine occurred with auxiliary uptake of water. Both types of transformations (processes and products), are of prime importance in explaining that asbestos shows many phenomena and characteristics.

Apparently, asbestos is made up of SiO_2, metal oxides, and water. Their theoretical composition can be viewed as a surface in the triangular co-ordinate system (Fig. 2).

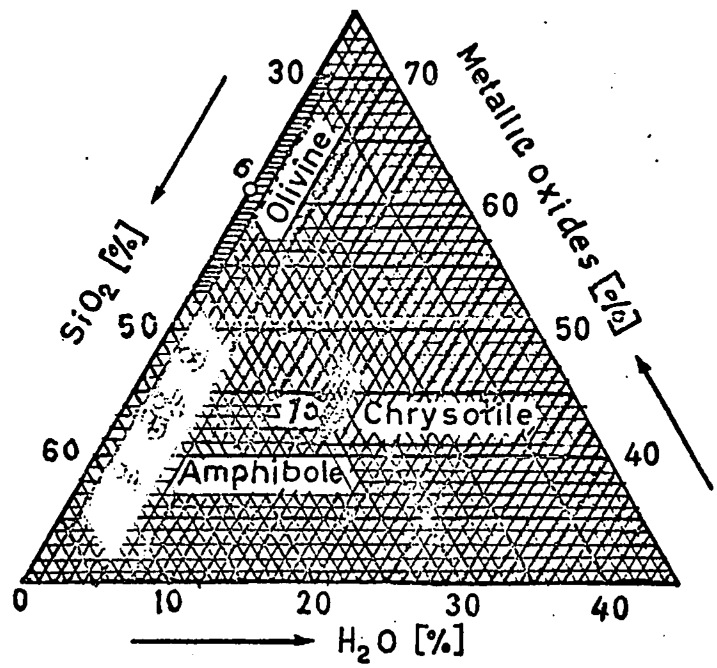
The transformation processes may be based on the following formulas:-

a) $$3(MgFe)_2SiO_4 + \underline{SiO_2 + 4H_2O} \longrightarrow 2(MgFe)_3 \left[(OH)_4Si_2O_5\right]$$

(peridotite or dunite) — (hydrothermal solution of Silicic acid) — (serpentine)

b) $$3(MgFe)_2SiO_4 + (MgFe)SiO_4 + 4H_2O \longrightarrow 2(MgFe)_3 \left[(OH)_4Si_2O_5\right] + (MgFe)O$$

$\underbrace{\text{(peridotite)} \quad \text{(a pyroxene)}}_{\text{(Polymineralic Peridotite)}} \qquad \underbrace{\text{(serpentine)} \quad \text{(oxides)}}_{\text{(serpentinite)}}$



1) Chrysotile, Serpentine, Antigorite 3) Crocidolite 5) Anthophyllite
2) Tremolite 4) Amosite 6) Olivine

FIG. 2: THEORETICAL AND ACTUAL COMPOSITION OF ASBESTOS
(Olivines are shown to illustrate absorption of water in formation of serpentine)

(Berger, Reference 15)

c) $2(MgFe)_3 \left[(OH)_4Si_2O_5\right] + 4(CaMgFe)\ SiO_3$ ———

(serpentine) (a pyroxene)

$\longrightarrow (CaMgFe)_7 \left[(OH)Si_4O_{11}\right]_2 + 3(CaMgFe)\ O + 3H_2O$

$\underbrace{\text{(an amphibole)} \qquad\qquad \text{(oxides)}}_{\text{(amphibolite)}}$

d) $3Ca\ Mg\ (CO_3)_2 + \underline{2SiO_2 + 2H_2O} \longrightarrow Mg_3 \left[(OH)_4Si_2O_5\right] + 3\ CaCO_3 + 3\ CO_2$

(dolomite) (hydrothermal solution of silicic acid) (iron-free serpentine) (calcite)

e) $2Mg_3 \left[(OH)_4Si_2O_5\right] + 5\ FeCO_3 + 4\ SiO_2$ ———

(serpentine) (siderite)

$\longrightarrow Mg_2Fe_5 \left[(OH)Si_4O_{11}\right]_2 + 4MgCO_3 + CO_2 + H_2O$

(riebeckite) (magnesite)

f) $5Ca\ Mg(CO_3)_2 + \underline{8SiO_2 + H_2O} \longrightarrow Ca_2Mg_5 \left[(OH)Si_4O_{11}\right]_2 + 3\ CaCO_3 + 7\ CO_2$

(dolomite) (hydrothermal solution of silicic acid) (actinolite) (calcite)

The varieties of asbestiform minerals can be divided into two main groups on the basis of their crystal structure: serpentine and amphiboles.

(1) Serpentine - chrysotile asbestos.

(2) Amphiboles includes five recognized asbestiform varieties: crocidolite, amosite, tremolite, actinolite and anthophyllite.

The geology of asbestos deposits are such that their formation needs the common geological principle of the right host rock, basic structural features, and ideal conditions of temperature and pressure.

"Chrysotile": The most valuable deposits occur in serpentine, contoured by hydrothermal alteration of ultrabasic rocks such as dunite, peridotite, and pyroxenite. Emplacement and subsequent alteration of an ultrabasic rock mass below the then-existing earth's surface took place; the alteration of form followed, including folding, faulting, and shearing processes. The serpentine shattered in specific regions affording fractures for entry of hot water. Subsequently these waters dissolved the serpentine (hydrous magnesium silicate) over a certain period of time, pursued by a decreased pressure and temperature until the solution became supersaturated. Fibrous crystals of magnesium silicate began to grow within the solution filled channelways, maintained in their open state by tremendous hydrostatic pressure. These crystals, which we call chrysotile asbestos, started to grow on both walls of the fracture and sprouted inward toward the centre. The width of the fracture defined the maximum length of the fiber.

This is the most common type of chrysotile asbestos deposit whose variations are: (a) slip fiber; (b) mass fiber; and, (c) cross fiber.

Slip fiber deposits are transformed from serpentine. Hot waters saturated in the highly shattered rock which was subjected to continual shearing action during crystallization, and fiber growth presented parallel to the fracture faces.

Mass fiber deposits, for instance: the Coalinga, California type, display extreme intergranular and faulting processes in the serpentine host rock, through which hot waters diffused. Fibers occur within the sheared rock as small white leathery platelets or clumps. Apparently, its crystal growth occurred throughout the rock.

Cross fiber in dolomitic limestone, its process of formation is the same as that in the normal cross-fiber deposit. The host rock is of sedimentary origin, but hot water dissolved the magnesium in the dolomite, forming supersaturated solutions in contract features.

"Crocidolite and Amosite": Both have a common origin and occur in similar rocks. The host rocks usually are banded ironstones, which are transformed from sedimentary formations. The zones within the seams containing the crocidolite veins are soda rich in contrast to the amosite zones; but crystallization occurred in situ under conditions of moderate pressure and temperature in the presence of moisture from the surrounding rocks.

"Tremolite, Actinolite and Anthophyllite": They generally occur in lenticular forms of mass fiber, and are widely found among schistose igneous and metamorphic rocks rich in hornblende or pyroxene. Also tremolite and actinolite are often found in impure limestone and dolomite that has undergone recrystallization.

2.2 The Chemical and Physical Properties

Asbestos differs from other minerals and its chemical and physical properties are of an entirely different origin. In this aspect much work has been published in recent years by Speil & Leineweber(102), Hendry(52), Gaze(46), Hodgson(54), and Deer, Howie & Zussman(34). The above-mentioned characteristics will be discussed briefly as follows:-

2.21 Chemical Composition:

The chemical composition of the asbestos is dependent on the asbestos group and its occurrences.

The range of chemical analyses for asbestiform materials are listed in Tables 1, 2 & 3.

Table 1

PERCENTAGE COMPOSITION OF ASBESTOS

Variety	*SiO_2*	*MgO*	*Iron oxides Al_2O_3*	*CaO Na_2O*	*H_2O* [1]
Chrysotiles [2]	35—44	36—44	0—9 [3]	0—2	12—15
Crocidolites	49—57	3—15 [4]	20—40 [5]	2—8	2—4
Amosites Montasites	45—56	4—7	31—46 [5]	1—2	1—3
Anthophyllite asbestoses	52—64	25—35	1—10	0—1	1—5
Tremolite- and Actinolite asbestoses	50—63	18—33	2—17	1—10	1—4

[1] The water content should not be equated with the loss on ignition.
[2] Cross- and longitudinal fibers.
[3] The content of magnetite (Fe_3O_4) may be as high as 4%, the content of FeO and Fe_2O_3 may reach 6% each, the ratio FeO/Fe_2O_3 varies between 0.5 and 2.0.
[4] The bright blue crocidolites from Bolivia and China with higher MgO- and lower iron content cannot be regarded as anomalies and hence they were included here.
[5] The proportion of iron (II) is around 60% in crocidolite; about 90% in amosite.

(Reference 15)

Table 2 Chemical Composition of Chrysotiles

	Chrysotiles				
	Jeffrey Mine Asbestos, Quebec	New Idria, California (Coalinga)	Arizona	Africa Transvaal	Russian
SiO_2	44.1	38.4	41.07	41.83	42.09
MgO	41.6	39.9	42.35	41.39	41.68
Fe_2O_3	0.92	1.1	0.42	1.29	4.01
FeO	0.86	2.4	0.14	0.08	—
Al_2O_3	0.34	0.44	0.55	0.30	0.79
Cr_2O_3	0.019	0.31	0.03	—	—
NiO	0.010	0.18	tr	—	—
Mn_3O_4	0.03	0.10	0.07	0.04	—
CaO	0.04	0.96	1.02	tr	—
TiO_2	0.01	0.05	0.01	0.02	—
Na_2O	0.06	0.04	tr	—	—
K_2O	0.04	0.04	0.03	—	—
H_2O	13.2	14.0	13.97	13.66	12.9

Theoretical chrysotile composition: 43.4% SiO_2, 43.5% MgO, 13.1% H_2O.

(Speil & Leineweber, Reference 102)

Table 3

CHEMICAL COMPOSITION OF ASBESTIFORM AMPHIBOLES

	Asbestiform amphibole (range %)				
	Crocidolite	Amosite	Anthophyllite	Actinolite	Tremolite
SiO_2	49-53	49-53	56-58	51-56	55-60
MgO	0-3	1-7	28-34	15-20	21-26
FeO	13-20	31-44	3-12	5-15	0-4
Fe_2O_3	17-20	—	—	0-3	0-0.5
Al_2O_3	0-0.2	—	0.5-1.5	1.5-3	0-2.5
CaO	0.3-2.7	—	—	10-12	11-13
K_2O	0-0.4	0-0.4	—	0-0.5	0-0.6
Na_2O	4.0-8.5	tr	—	0.5-1.5	0-1.5
H_2O	2.5-4.5	2.5-4.5	1.0-6.0	1.5-2.5	0.5-2.5

(Reference 102)

The ideal formulas of the six kinds of asbestos as deduced from these considerations are contrasted in the following compiliation:-

Chrysotile	$Mg_3 [(OH)_4Si_2O_5]$
Crocidolite	$Na_2MgFe [(OH)Si_4O_{11}]_2$
Amosite	$MgFe_6 [(OH)Si_4O_{11}]_2$
Anthophyllite	$(Mg\ Fe)_7 [(OH)Si_4O_{11}]_2$
Tremolite	$Ca_2Mg_5 [(OH)Si_4O_{11}]_2$
Actinolite	$Ca_2(Mg\ Fe)_5 [(OH)Si_4O_{11}]_2$

2:22 Physical Properties:

The physical properties of asbestos, which have been known for many years, include its resistance to heat, noiselessness, high tensile strength, flexibility, texture, spinnability and acid resistance. Chrysotile is blackish green, yellowish green or white in colour. In most cases the fiber, when drawn out in threads, is white, with silky luster. The crocidolite's luster is very silky, and of a dull, lavender blue colour due to the presence of ferrous ions in the molecule. Amosite usually is a brownish yellow to almost white in colour. Tremolite and Actinolite are generally white, grey greenish or yellowish in colour.

Their physical properties are shown in Tables 4, 5 & 6.

Table 4

TYPICAL PHYSICAL PROPERTIES OF CHRYSOTILE, CROCIDOLITE, AND AMOSITE

		Chrysotile white asbestos	Crocidolite blue asbestos	Amosite
Approximate diameter of smallest fibers	micron	0.01	0.08	0.1
Specific gravity		2.55	3.37	3.45
Average tensile strength	lb./inch^2	350,000	500,000	175,000
Modulus of elasticity	lb./inch^2	23.5×10^6	27.0×10^6	23.5×10^6

(Gaze, Reference 46)

Table 5

PHYSICAL PROPERTIES USED FOR CHARACTERIZATION OF ASBESTIFORM MINERALS

		Chrysotile	Crocidolite	Amosite	Anthophyllite	Actinolite, Tremolite
Density g/cm³		2.56	3.02–3.42	3.10–3.60	2.85–3.57	3.02–3.44
Hardness (Moh's)		2½	5	5–6	5½–6	5–6
Crystal system		Monoclinic	Monoclinic	Monoclinic	Orthorhombic	Monoclinic
Unit cell dimensions—	a	5.30 ± 0.002 Å	9.75 Å	9.6 Å	18.5 Å	9.85 Å
	b	9.10 ± 0.05	18.0	18.3	18.0	18.1
	c	7.32 ± 0.02	5.3	5.3	5.3	5.3
	γ	93°	103°	105° 50	—	104° 50
Refractive index	α	1.532–1.549	1.654–1.701	1.665–1.696	1.596–1.694	1.599–1.688
	β		1.662–1.711	1.675–1.709	1.605–1.710	1.612–1.697
	γ	1.545–1.556	1.668–1.717	1.698–1.729	1.615–1.722	1.622–1.705

(Reference 102)

Table 6

PROPERTIES OF ASBESTOS FIBER

	Chrysotile	Crocidolite	Amosite	Tremolite	Actinolite	Anthophyllite
Flexibility	Very flexible	fair to good	good	brittle	brittle	brittle to flexible
Length	short to 3"	short to 3"	1/4" to 6"	short to long	short to long	short
Texture	harsh to silky	harsh or soft	coarse but pliable	harsh to soft	harsh	harsh to soft
Tensile strength	very high	very high	fair	weak	very weak	weak
Acid resistance	fairly soluble	very good	good	fairly resistant	highly resistant	fair to good
Spinnability	very good	fair	fair	poor	poor	poor
Resistance to heat	good	poor	good	fair to good		very good

(Hendry, Reference 52)

2.23 Thermal Behaviour:

The resistance to the action of heat is one of the most important properties of asbestos. The thermal behaviour of the various varieties is not the same. In general, the chrysotile is more heat-resistant than the amphibole asbestoses, and the anthophyllite asbestos has the best stability at elevated temperatures, so its thermal utilization limits are the highest. "The transformation products resulting from the changes in the crystal structure (chrysotile — olivine or enstatite) may themselves be determined roentgenographically"[79,105]. The melting points and the specific heats of a number of varieties are shown in the following table[15].

Asbestos	Melting point (°C)	Specific heat (keal/kg °C)
Chrysotile	circa 1500	0.251 to 0.266
Anthophyllite asbestos	circa 1480	0.210
Amosite	circa 1400	0.193
Tremolite asbestos	1320 to 1380	0.212 to 0.217
Crocidolite	$<$ 1180	0.201

The influence of temperature after exposure to heat is listed in Table 7 and Figures 3 & 4

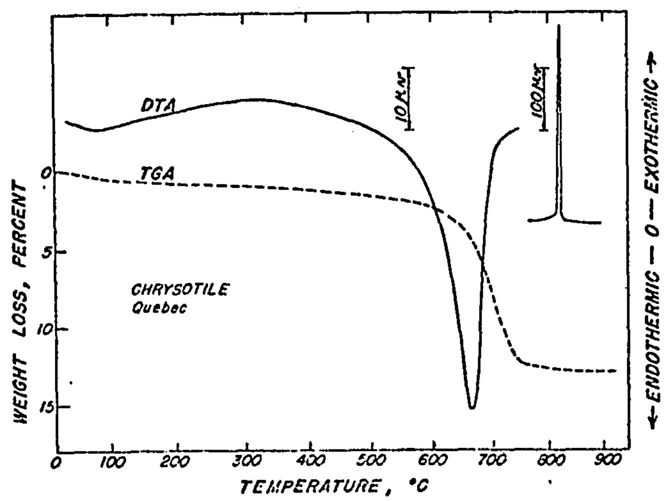
Table 7

INFLUENCE OF TEMPERATURE ON PERCENTAGE WEIGHT LOSS OF AMPHIBOLE ASBESTOSES AFTER EXPOSURE TO HEAT FOR 120 MINUTES

Temp.(°C)	*Crocidolite*	*Amosite*	*Anthophyllite asbestos*	*Tremolite asbestos*
204	<0.1	0.2	<0.1	<0.1
315	0.3	0.6	0.2	<0.1
427	0.7	1.0	0.4	0.2
538	0.9	1.2	0.4	0.3
650	1.04 *	1.4	0.5	0.4
760	1.03	1.4	0.5	0.5
870	0.9	1.5 *	1.1	0.7
980	0.8	—	2.4 *	2.2 *

* Temperature required to reach the maximal loss of weight.

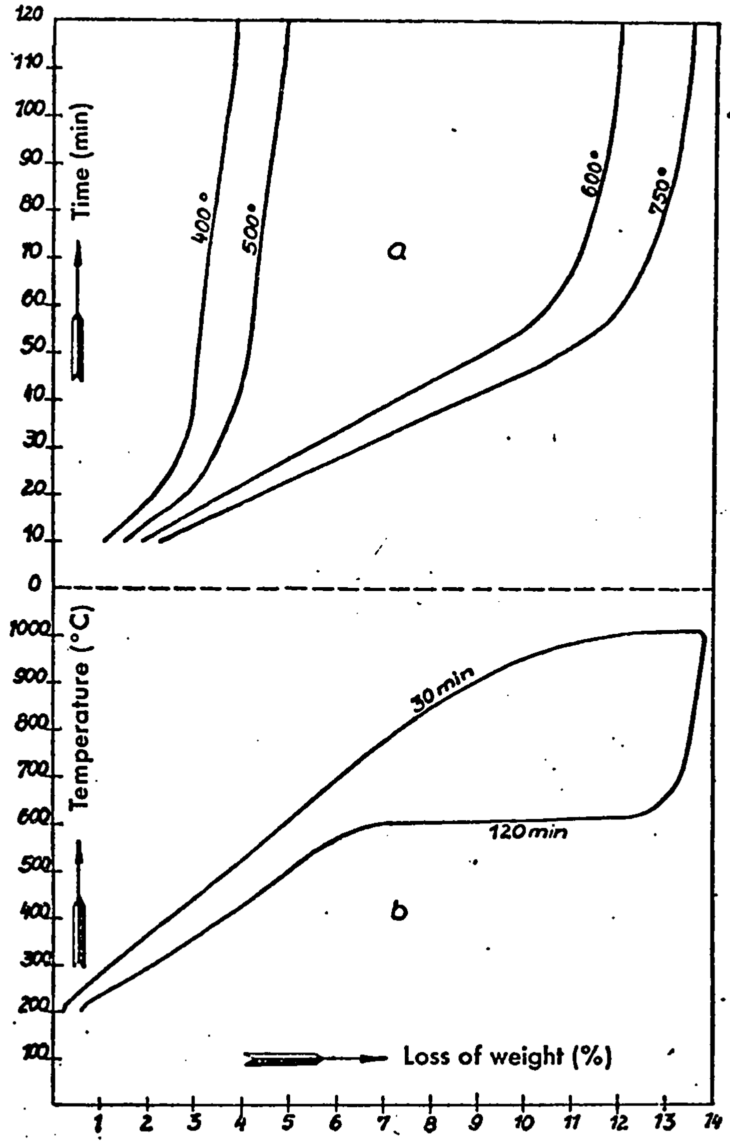
(Reference 15)



Differential thermal analysis (DTA) and thermal gravimetric analysis (TGA) of chrysotile. Sensitivity was decreased above 750°C in the DTA. The weight loss due to dehydroxylation is approximately 13 per cent.

Fig. 3

(Reference 72)



Losses in Weight of Ural Chrysotile

a) Effect of time at various temperatures
b) Effect of temperature at different times

Fig. 4

(Reference 15)

2.24 Acid Resistance:

Since 1885, the reactivity of chrysotile with acids had been recognized[111], and, in 1890, chrysotile was found to be the most susceptible to acid attack of all the serpentine minerals by Clark and Schneider[23]. Later on, an electron microscopic and X'ray diffraction study on acid-treated chrysotile and antigorite was made by Nagy and Bates,[84] and their experimental results agreed with the above conclusion. Badollet[10] also summarized the available information on the stability of asbestiform minerals. Strong acids can decompose chrysotile rapidly with the removal of all MgO and a total weight loss of about 60%. The time required to reach this maximum loss depends on the length of exposure, the kind and concentration of the acid, temperature, and the degree to which the asbestos had been opened. In contrast to the amphibole asbestos, the chrysotiles, because their ratio $SiO_2/MgO = 1$, have lost practically all of their strength at the maximum loss of weight and consequently they should be designated as acid-non-resistant. The data of solubility of asbestos minerals in 25% of variety of acids or caustic solution is shown in Table 8.

Hodgson[54] studied the rate of decomposition of asbestiform fibers in boiling 4N hydrochloric acid. He found the following relative order of stability as shown in Fig. 5.

2.25 Reaction with Water and Humidity:

Asbestos fibers are subject to attack by water[56]. An experiment had been made to prove that the concentration of magnesium in the extract was quite high during the first 3-4 hours of soxhlet extraction and afterwards began to decrease. The decrease in magnesium concentration

Table 8

SOLUBILITY OF ASBESTOS MINERALS IN 25% ACID OR CAUSTIC[a]

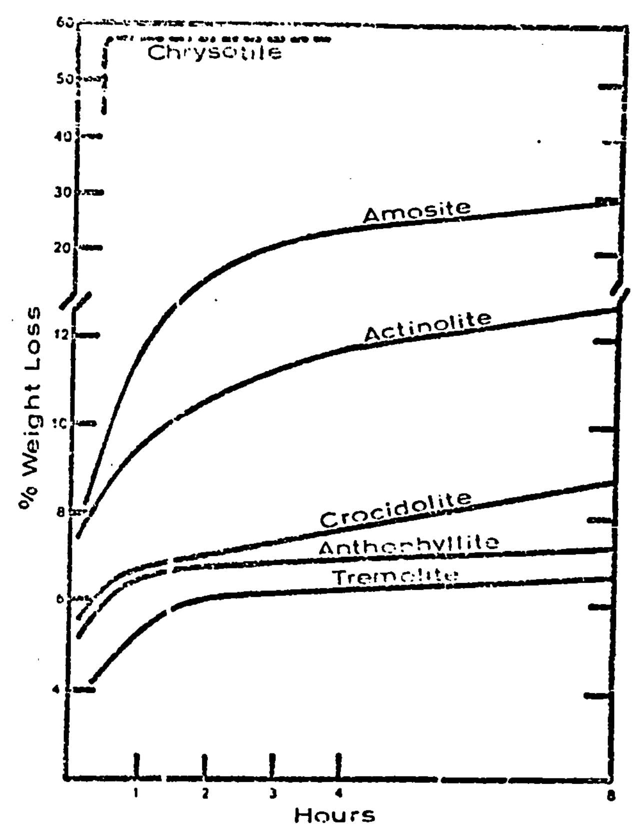
	Per cent loss in weight, refluxing 2 hours				
	HCl	CH_3COOH	H_3PO_4	H_2SO_4	NaOH
Chrysotile	55.69	23.42	57.18	55.75	0.99
Crocidolite	4.28	0.91	4.37	3.69	1.35
Amosite	12.84	2.63	11.67	11.35	6.97
Anthophyllite	2.66	0.60	3.16	2.73	1.22
Actinolite	20.31	12.28	20.19	20.38	9.25
Tremolite	4.77	1.99	4.99	4.55	1.80

[a] Reproduced with permission from Canadian Mining and Metallurgical Bulletin, April, 1951.

(Reference 102)

Fig. 5

Acid resistance of asbestos (4N HCl boiling)



(Hodgson, Reference 54)

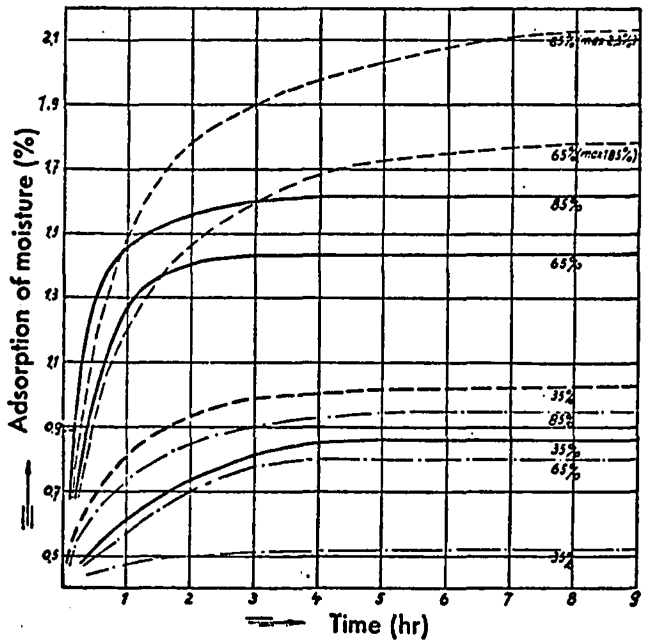
was accomplished by the formation of a precipitate of amorphous magnesium silicate. After the initial rapid reaction, the quantities of magnesium and silica removed are proportional to the chrysotile composition. The removal of silica may be preceded by the formation of colloidal silica or by way of solution. Doubtlessly, chrysotile is slowly "soluble" in water under conditions of continuous extraction.

For crocidolite, Thompson[112] had made an experiment and noted that 4% of the silica and 6% of the sodium are removed by soxhlet extraction with water. Under this condition, the action was equivalent to that of alkalies at corresponding temperatures.

Asbestos fibers take up moisture from the air by potency of their adsorption capability. The difference in the rate at which moisture is taken up and the degree of this adsorption[72, 87], in relative humidity of the air, are shown in Figures 6 & 7. A finding that compressibility under constant pressure increases with rising humidity or moisture content, is important with respect to the use of asbestos blankets for thermal insulation. The following results were obtained with Canadian chrysotile (30 grams).

Relative Humidity (%)	BEFORE COMPRESSION Volume (cm^3)	Density (g/cm^3)	AFTER COMPRESSION Vol. Change (cm^3)	Density (g/cm^3)
0	82	0.37	27	0.50
60	68	0.44	24	0.57

(Reference 15)

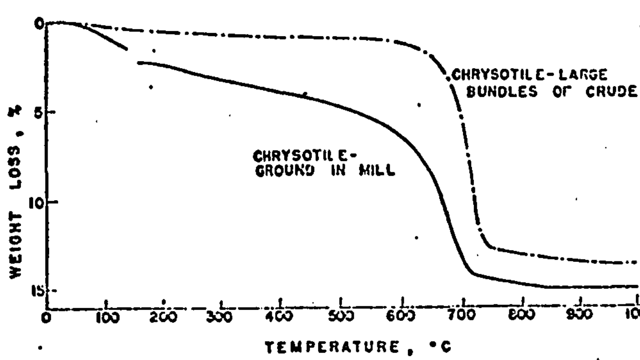


RELATION OF RATE OF ADSORPTION OF MOISTURE FROM ATMOSPHERIC HUMIDITY AND TIME AT 20 C

Chrysotile — — — ; Amosite ———— ; Crocidolite —·—·—

Fig. 6

(Reference 15)



.—Thermal gravimetric analyses of chrysotile crudes from Black Lake, Quebec. The sample in the lower curve was ground in a Mixer Mill; the loss in weight from room temperature to 150°C is due to surface moisture. Heating rate was 5°C/min.

Fig. 7

(Martinez, Reference 72)

2:26 Tensile Strength:

The tensile strength of the bundles of fibers is dependant upon the variety and grade of asbestos and is the determining factor with regard to their extraction from the rock and, this strength in combination with the length and flexibility of the fiber, controls other characteristics such as their spinning qualities. On the other hand, the strength of the fibers is reflected in the strength of the finished asbestos products. Zukowski and Gaze[138] revealed a strong dependence of strength on fiber length with maximum values of 61,000 kg/cm^2 for crocidolite, and 58,000 kg/cm^2 for chrysotile, with a fiber length of approximately 2mm. The data on tensile strength of asbestos is shown in Tables 9 & 10. The decrease in strength of asbestos after exposure to heat for constant periods at variable and constant temperatures is also shown in Table 11.

Table 9

Tensile Strength of Asbestos

Ore samples	Tensile strength ($\times 10^3$, kg/cm^2)	Youngs modulus ($\times 10^6$ kg/cm^2)	Average cross-sectional area of fibers tested ($\times 10^{-6}$ cm^2)
Chrysotile, Arizona, U.S.A.	38.5	1.48	2.07
Chrysotile, Thetford, Canada	37.1	1.49	2.13
Crocidolite, Koegas, Cape Province	29.0	1.50	1.65
Crocidolite, Koegas, Cape Province	31.5	1.54	1.33
Crocidolite, Pomfret, Cape Province	47.5	1.72	1.64
Crocidolite, Pomfret, Cape Province	36.2	1.78	1.34
Crocidolite, Cochabambo, Bolivia	14.7	1.73	2.43
Amosite, Penge, Transvaal	26.3	1.46	2.71
Amosite, Penge, Transvaal	20.2	1.46	1.83
Anthophyllite, Paakilla, Finland	25.0	1.59	0.95

(Reference 102)

Table 10

TENSILE STRENGTH OF ASBESTOS

Asbestos	Tensile strength (kp/mm²)	Elongation (%)	Remarks (V = variation coefficient)
Chrysotiles	30 to 125	—	General statements
Quebec	30 to 67	—	V = 31 to 62%
Ural	75 to 230	1.8	Extremely different test conditions
S. Rhodesia	16 to 110	0.5–1.6	Span 16–39 mm; fineness, 0.09–0.3 mm²
Transvaal	34 to 79	3.7	V = 39–41%; different test conditions
China	46 to 58	1.2	V = 47.4% Nm = 1680 10 mm between clamps
Crocidolites	70 to 225	—	General statements
S. Afr. Rep. without closer designation	60 to 135	1.5	V = 39 to 90%; different test conditions
Kuruman, Prieska	58 to 140	—	Std. dev. 9–25
Pietersburg	51 to 60	—	Std. dev. 4–5
Malips River	100	—	Standard deviation, 10
Amosite	11 to 63	—	Different test conditions
Anthophyllite	<3	—	
Tremolite	<6	—	

In comparison: Steel wire = 50–150; cotton = 30–70; glass fibers = 80–200 kp/mm²

(Reference 15)

Table 11

DECREASE IN STRENGTH OF ASBESTOSES AFTER EXPOSURE TO HEAT FOR CONSTANT PERIODS (3 MIN, 60 MIN) AT VARIABLE AND CONSTANT TEMPERATURE

Type	Temperature (°C)	Strength (kp/mm²)	Decrease in strength (%)
Chrysotile (strength of fiber bundles 20 to 30μ diameter after 3 min at °C)	20	92.0	0
	315	84.4 (70.3) *	8.4
	427	67.5	26.7
	538	54.8	40.5
	650	29.5 (1.4) *	68.0
Chrysotile: Quebec 3-F	Strengths	42 to 52.0	24.0 to 35.8
Chrysotile: Quebec 3-K	at 20°C,	33.3 to 67.3	12.0 to 15.0
Chrysotile: Quebec Crude 1	Decreases	127.5	18.5
Chrysotile: S. Rhodesia mill fiber	after 60 min at 375±	88.3	21.5
Crocidolite: So. Afr. Rep.	10°C	99.0	64.2

* Values in parenthesis after 60 minutes exposure to heat.

(Reference 15)

2.3 The Molecular and Crystal Structure of Asbestos

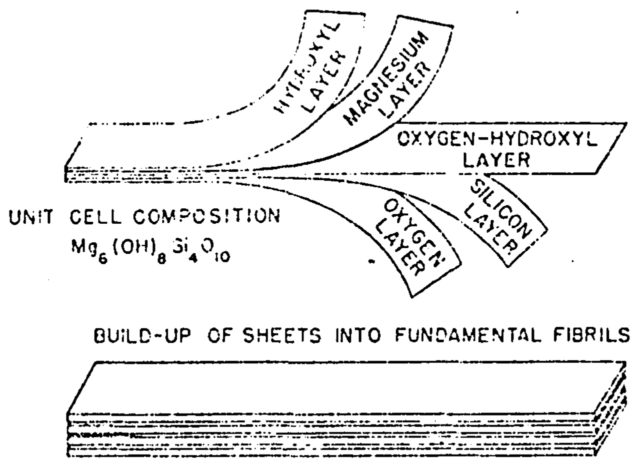
Asbestos' subdivision into chrysotile (serpentine) and amphibole asbestoses was discussed in the preceeding pages. As in the case of all natural silicates, the basis of the structural unit of both kinds of asbestos is composed of silicon-oxygen tetrahedra; the structural difference in the constitution of the two kinds of asbestos is due to the different arrangement of the SiO_2- tetrahedra. In chrysotile, their structure is of Si_2O_5 - double layers (laminar structure) in amphibole asbestoses they join to reproduce Si_4O_{11} - double chains (banded structure). The chains are held together by primary linkages (principal valences) of interrelated cations, but the Si_2O_5 - layers are interlocked with layers of brucite $\{Mg(OH)_2\}$.

2.31 Chrysotile:

The crystal structure of chrysotile asbestos was recognized by Warren, Bragg & Herring[124, 125]. These investigators realized that the mineral has a layered type structure similar to the Kaolinite group. This structure is based on an infinite silica sheet $(Si_2O_5)_n$ in which all the silica tetrahedra are pointing in the same direction. Attached to one side of this sheet is a brucite $Mg(OH)_2$ layer in which two-thirds of hydroxyls are replaced by the apical oxygens of the silica tetrahedra. The result shows a double sheet (see Figure 8). The mismatch in the dimensions of the silica and brucite sheets brings a strain in the structure. Better matching of the layers and relief of the strain can be accomplished in three ways[102].

(1) Substitution of larger ions in the silica sheet or smaller

Fig. 8

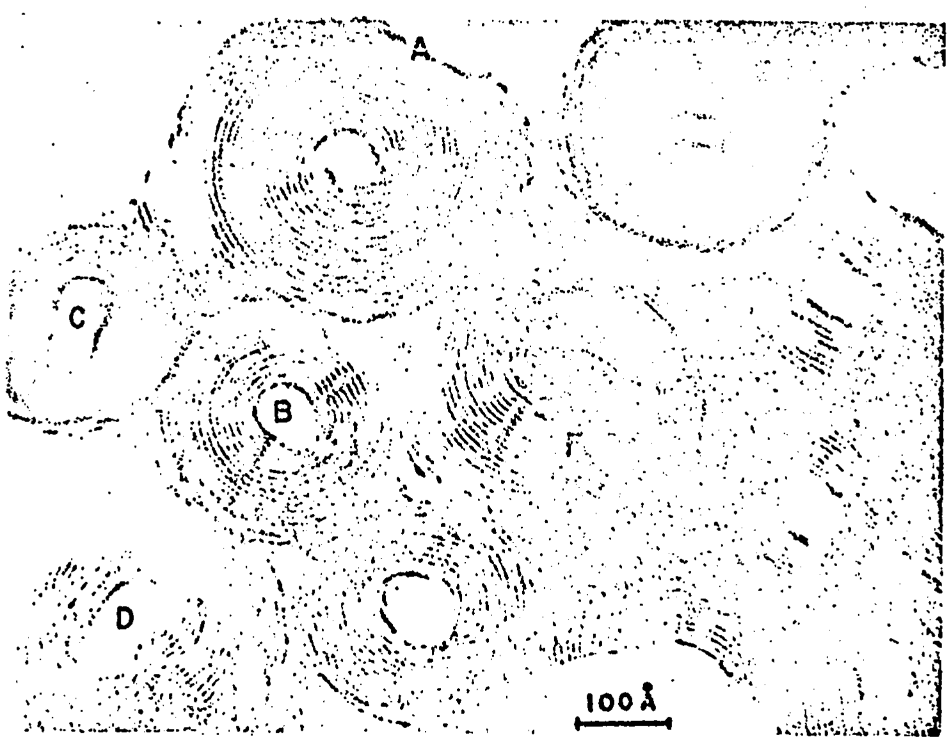


Fundamental sheet of chrysotile.

(Reference 102)

Fig. 9

High resolution electron micrographs of chrysotile



(Reference 102)

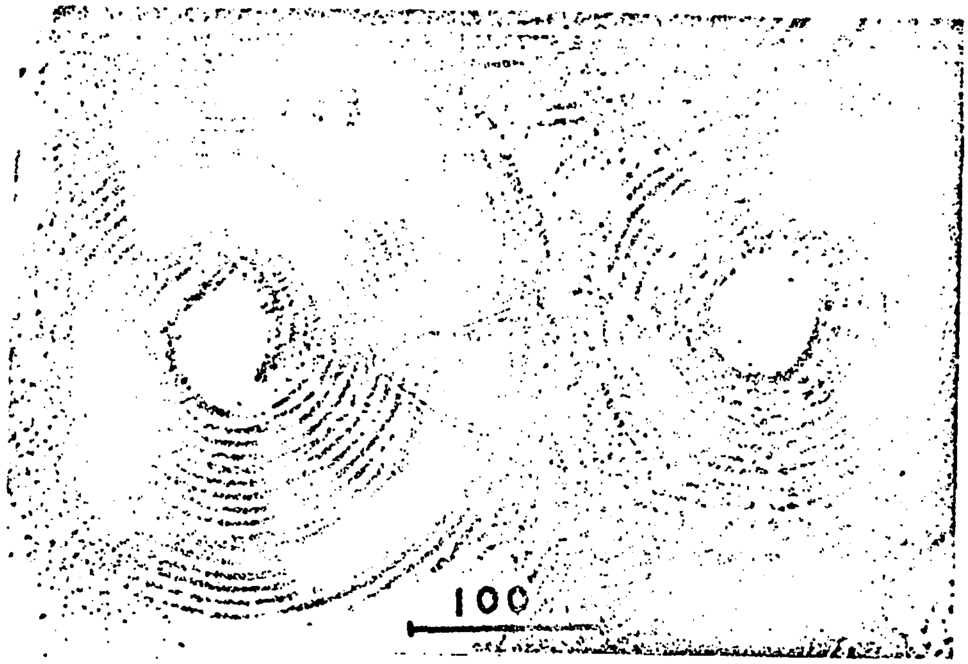
ions in the brucite sheet.

(2) Distortion of the octahedra brucite network or of the tetrahedra silica network.

(3) Curvature of the sheet with the brucite layer on the outer surface.

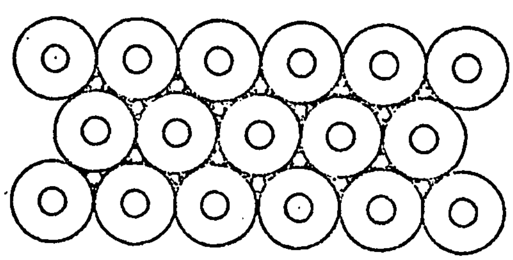
After a detailed study from the electron micrographs, Maser, Rice & Klug[73], and, Yada[134] discovered that the fibers are not solid but hollow tubes formed from rolled-up sheets. Chrysotile asbestos, therefore, consists of bunches of these tubes tightly packed together, and it seems that the tubes themselves, and spaces between them, are filled with crystal fragments or amorphous material of the same composition. The tubes do not stick together very strongly, and a good quality chrysotile may thus be fiberized. From an analysis of the electron micrograph, it appears that the single ultimate tubes are present while most of the fibers normally encountered consist of bunches of tubes. By means of high resolution electron microscopy, it is noted that the actual crystal lattice planes are both parallel and perpendicular to the fiber axis (Figures 9 & 10). The tubular structure is also observed by examining bunches of fiber "end-on" (Figure 11) in the electron microscope. The mean internal diameter of the elementary crystal (fibril) of the hollow chrysotile fiber is about 0.018μ, the external diameter averages 0.034μ. No elementary fibers actually are found; however, in practice, the diameter averages between 0.75μ to 1.5μ. Anon[6] claimed that the cylindrical crystal lattice (even if filled with amorphous or partially oriented matter) induces a contrasting effect under the electron beam, giving the appearance of hollowness in the fiber structure (Figure 12).

Fig. 10



High resolution electron micrographs of chrysotile
(Reference 102)

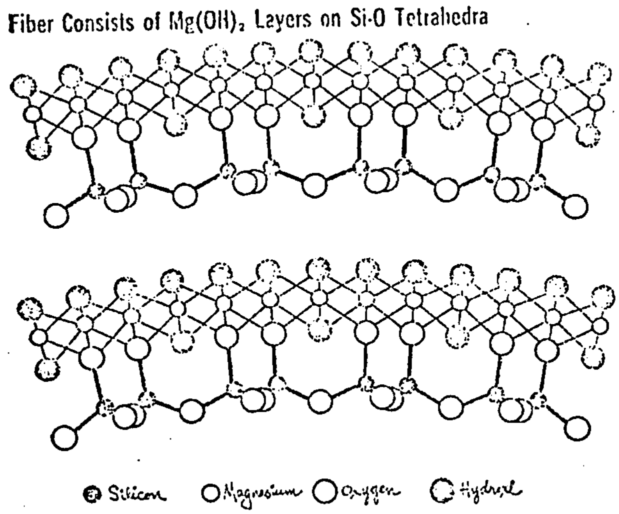
Fig. 11



"End-on" view of cylindrical fibers showing fine material in interstices.

(Pundsack, Reference 88)

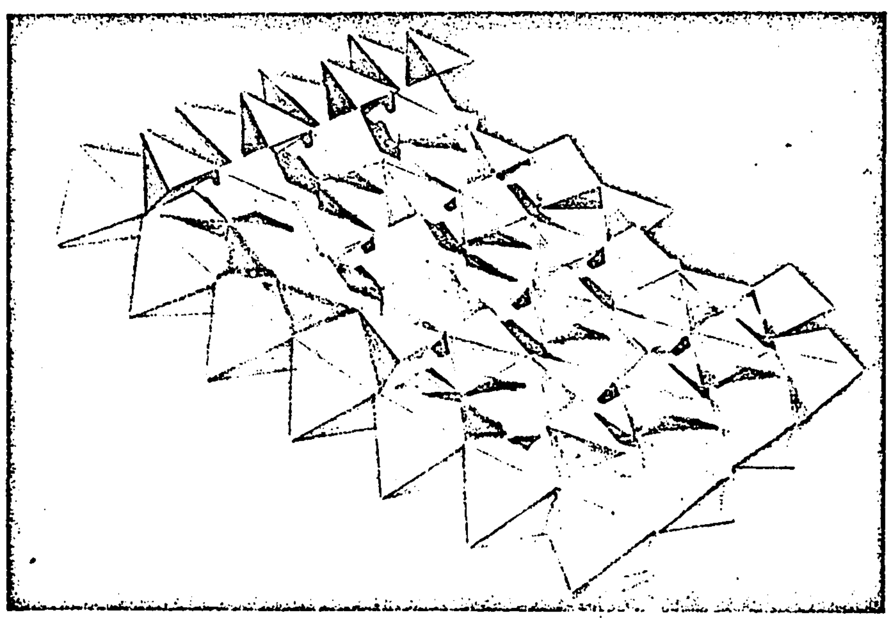
Fig. 12



—Schematic drawing representing a portion of the curved wall layer of chrysotile. The fiber consists of layers of octahedral sheets of magnesium hydroxide and tetrahedral sheets of silicon-oxygen. The fiber walls are believed to be made up of twelve to twenty such layers, with each one being about 7.3 Å thick

(Anon, Reference 6)

Fig. 13



Schematic representation of the structure of chrysotile asbestos. Note the curvature, resulting from the "tight fit" of the tetrahedral silica layer.

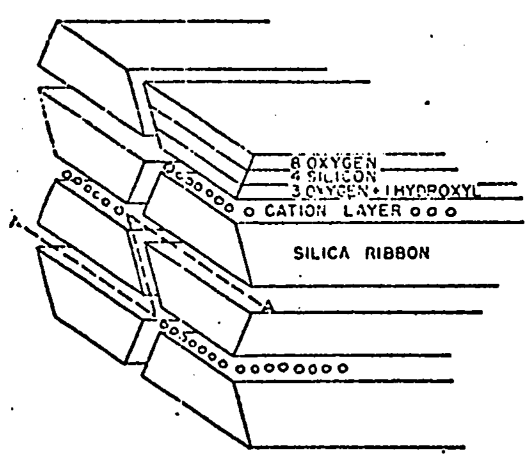
(Gaze, Reference 46)

The sheet structure of the tubes or scrolls is made up of two layers: the first layer is composed of a continuous network of tetrahedral silica which is interlocked with the second layer, a brucite-like sheet of octagonal magnesium hydroxide. The spacing of the hexagonal silica sheet is somewhat tighter than a perfect fit with the brucite layer and the sheets are thus contorted into scrolls or tubes with the magnesium hydroxide layer on the outside (Figure 13).

2.32 Amphibole:

The basic crystal form of the amphibole minerals is not so complicated as the serpentines. A double silica chain (Si_4O_{11}) is its basic structure. These chains are twined "back-to-back", with a layer of hydrated cations in between to meet the negative changes of the silica chains. The final structure is composed by the stacking of these sandwich ribbons in an ordered array. An illustration of this structure is shown in Figure 14.

Fig. 14



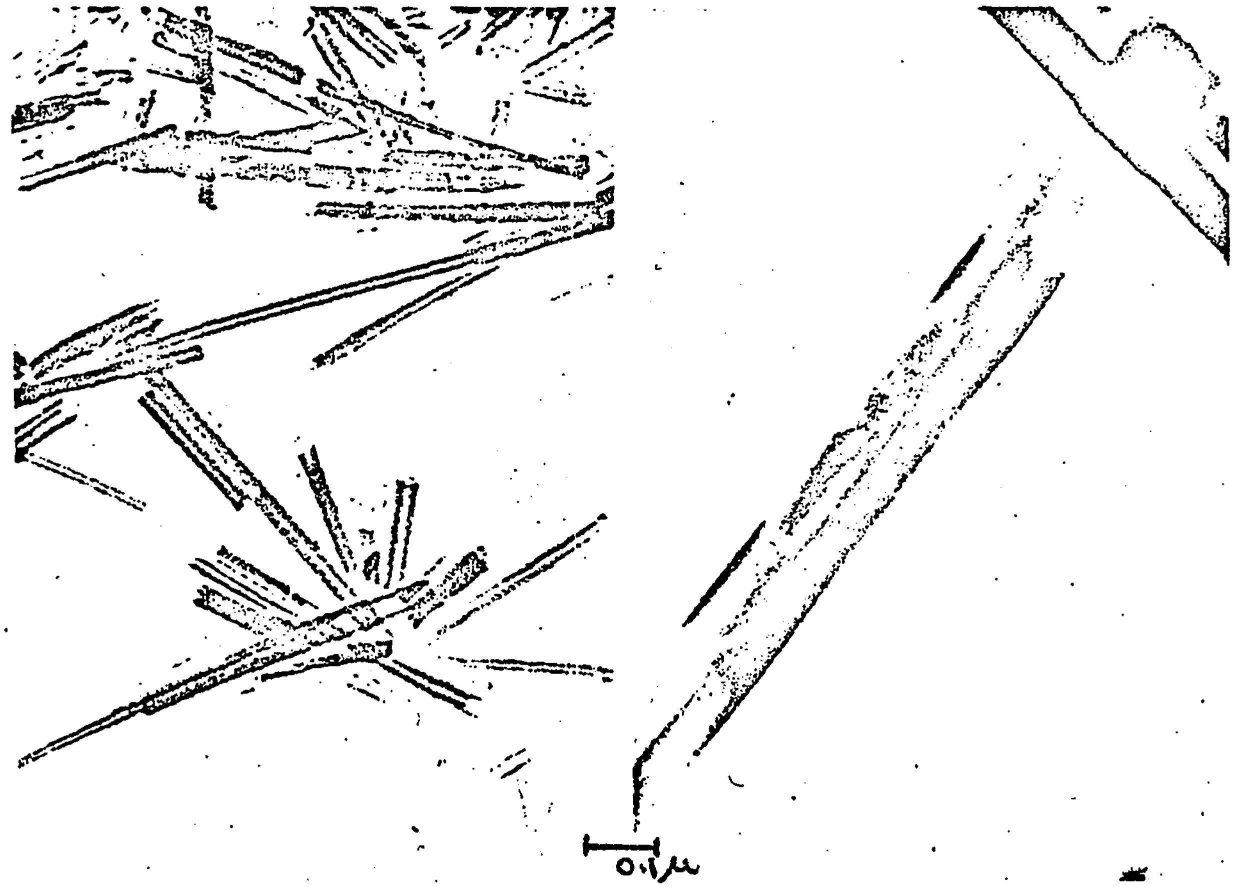
Amphibole structure.

(Reference 102)

The various minerals in the amphibole groups are characterized by the cations which occur in the structure. The main cations are sodium, iron calcium, and magnesium. As the bonding between these ribbons is quite weak, the crystals can easily be cleaved parallel to the ribbons along A-A.

For each variety of asbestiform amphibole, a different mineral name is given to correspond with every massive form. Generally, the varieties of asbestiform material are not found along with the massive counterparts. Undoubtedly, the local geochemical conditions existent at the time of formation contributed to the relative ease of cleavage of any specific deposit and, therefore, to its commercial utility. Both the massive and asbestiform varieties are of the same chemical compositions and crystal structure. In spite of their similarity, a petrographic examination and physical properties still can distinguish the difference.

As shown on an electron micrograph (Figure 15), the structure of amphibole asbestos is apparently quite different from that of chrysotile. It is sufficient to use an electron micrograph of crocidolite as an illustration of amphibole fibers as a whole, and it is generally impossible to differentiate with certainty between the various amphibole fibers by electron-optical methods. The mean diameter of amphibole ranges from 0.1μ to 0.2μ. No elementary fibers actually are found, but in commercial samples, the diameter averages between 1.5μ to 4.0μ. The smallest fibers of the amphibole varieties are solid and they are coarser than the finest fibers of chrysotile. Amphiboles have a very good construction consisting essentially of octahedral cation-oxide units arranged in narrow strips and sandwiched between corresponding strips made up of hexagonally arranged.silica tetrahedra. The



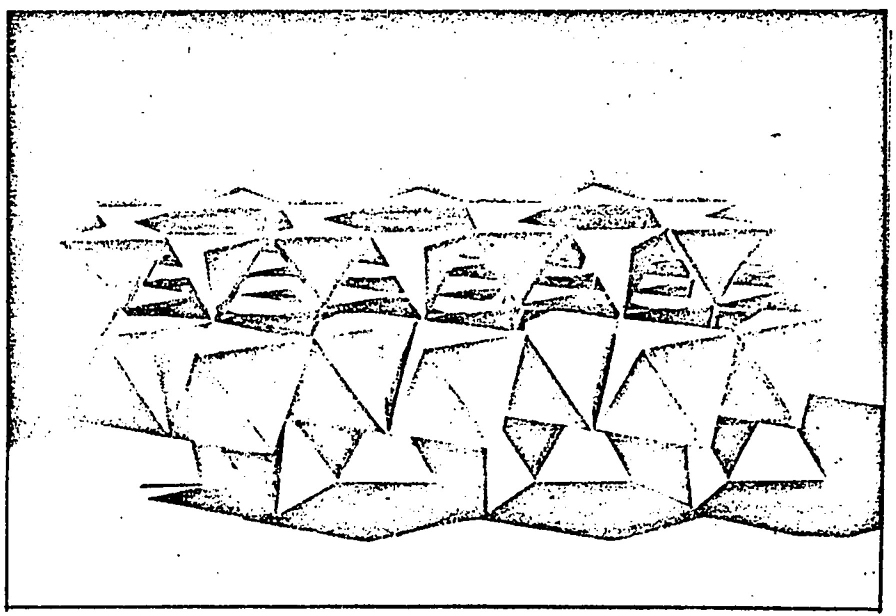
Electron micrographs of chrysotile (left) and crocidolite fibers at the same magnification.

Fig. 15

(Reference 46)

strips are only loosely bonded to each other along the edges and faces, and fibrous cleavage readily occurs (Fig. 16).

Fig. 16



Schematic representation of the structure of amphibole asbestos.

(Reference 46)

3. Hazards of Asbestos to Human Health

3.1 Pulmonary Deposition and Penetration of Inhaled Asbestos Dust.

The respiratory system serves as the portal of entry into the body for a great variety of air-borne substances, both gaseous and particulate. Many of these atmospheric contaminants are capable of producing injury and disease when they are deposited and accumulate in sufficient amounts in the lungs, or, after transfer from the lungs, in sensitive sites deeper within the body. Timbrell[113] stated that particles are deposited in the respiratory system by the action of four different mechanisms:

(1) Particles are removed from the inhaled air by settlement under gravity, the magnitude of deposition being proportional to particle free falling speed and the time available for sedimentation.

(2) When a change in the direction air flow occurs, particles owing to their inertia tend to continue on their original paths. Some may be deposited in this way on the nasal hairs and on the walls of airways. The efficiency of inertial deposition depends on the relative magnitudes of the drag and inertial forces. The magnitude of inertial deposition is thus proportional to the particles' free-falling speed.

(3) Particles suspended in the air are under ceaseless bombardment by gas molecules which constantly displace them and may cause their deposition on surfaces in the respiratory system. Particle removal by this mechanism is significant only in the small pulmonary air spaces.

(4) There is a fourth mechanism. For a compact particle to

remain suspended in the air, its centre must be separated from all surfaces by distances greater than the particle radius. Deposition occurs when the distance from a surface reduces to equality with the particle radius. The magnitude of deposition by this interception effect in airways increases with increase in the ratio of particle size to tube diameter. For compact particles 10 microns and smaller in size the effect is of no real significance even in the finest airways which are several hundred microns in diameter.

According to Timbrell's experimental result,

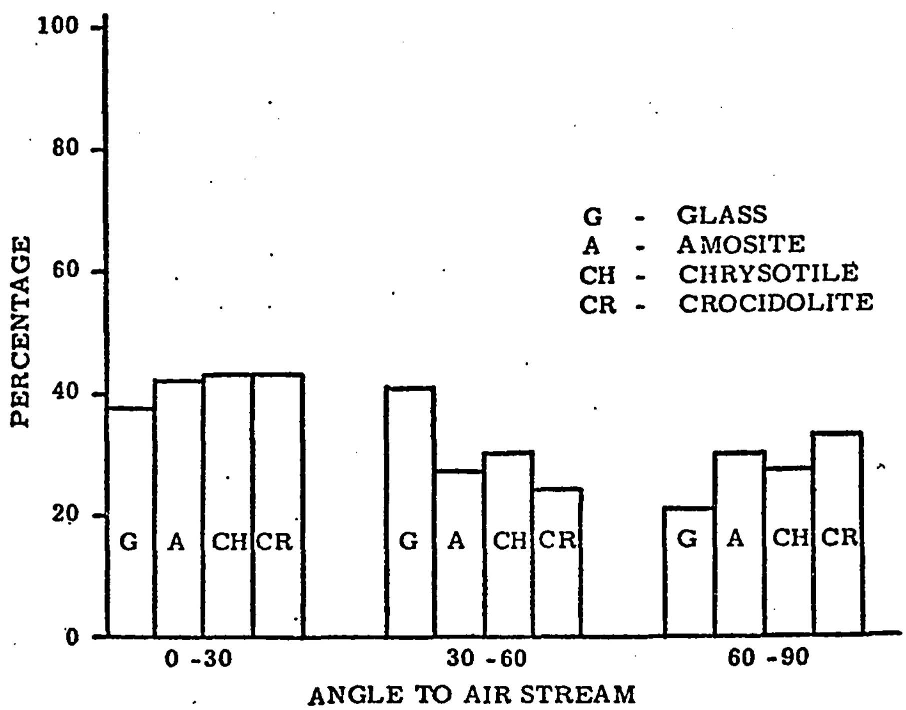
" The falling speed of a fiber is predominantly determined by the diameter and shows little sensitivity to the length, especially when the aspect ratio is high. If a fiber has a sufficiently small diameter, the falling speed can be low enough for the fiber to escape deposition by the settlement, and inertial precipitation mechanisms in the upper part of the respiratory tract, and deep penetration to the pulmonary air spaces is possible. "

The more symmetrical a fiber, the greater its chance of penetrating . The limitation of the lengths of the fibers which reach the pulmonary air spaces is imposed by the nasal hairs and by the small diameters of the respiratory bronchioles. Timbrell also stated that taking 10 microns as the upper limit to the diameters of spherical particles of unit density that can reach the pulmonary air spaces, the expected upper limit to the diameters of long regular asbestos fibers that can reach these spaces is about 3.5 microns.

The compact particles found in significant numbers in alveoli are 10 microns and smaller in size. It is true even when men are known to have been exposed to aerosols containing larger compact particles in sensible concentrations. On the contrary, asbestos fibers 50 microns and even 200 microns and longer have been found in alveoli.

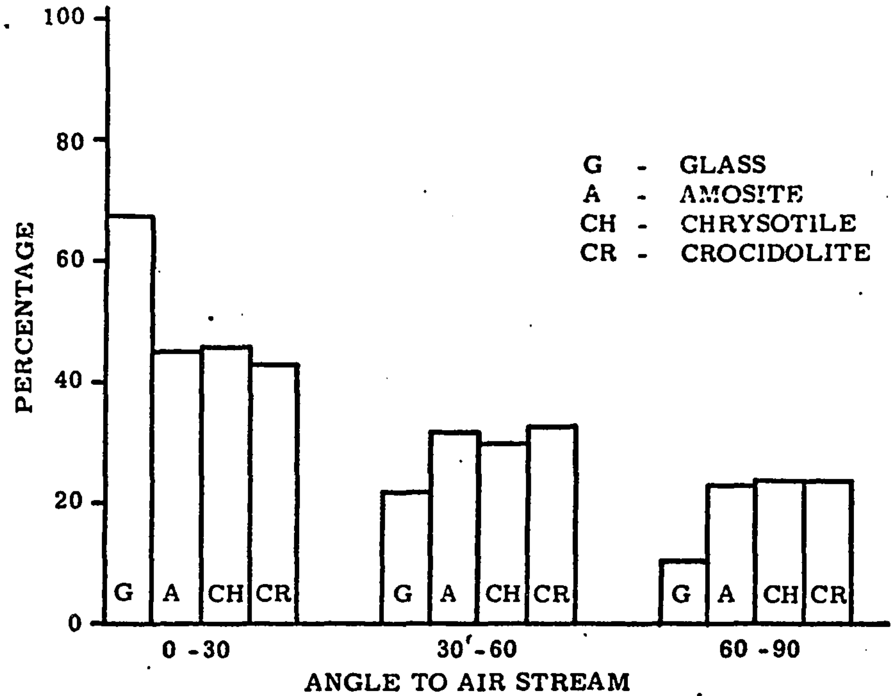
Timbrell[113] also illustrated the states of penetration of asbestos dust through the respiratory system by Figures 17, 18, 19, 20A & 20B).

Fig. 17



Frequency histograms in which percentage of fibers is plotted against angle to the airstream (axis of duct) in the aerosol spectrometer, for glass, amosite, chrysotile and crocidolite fibers with aspect ratios <5.

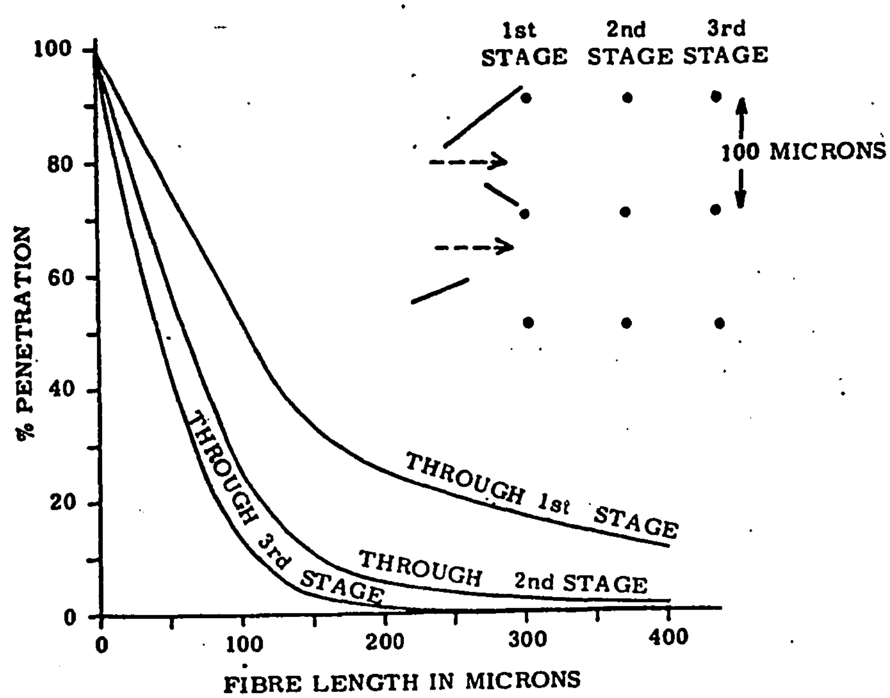
(Timbrell, Reference 113)



Frequency histograms in which percentage of fibers is plotted against angle to the airstream (axis of duct) in the aerosol spectrometer, for glass, amosite, chrysotile and crocidolite fibers with aspect ratios > 5.

Fig. 18

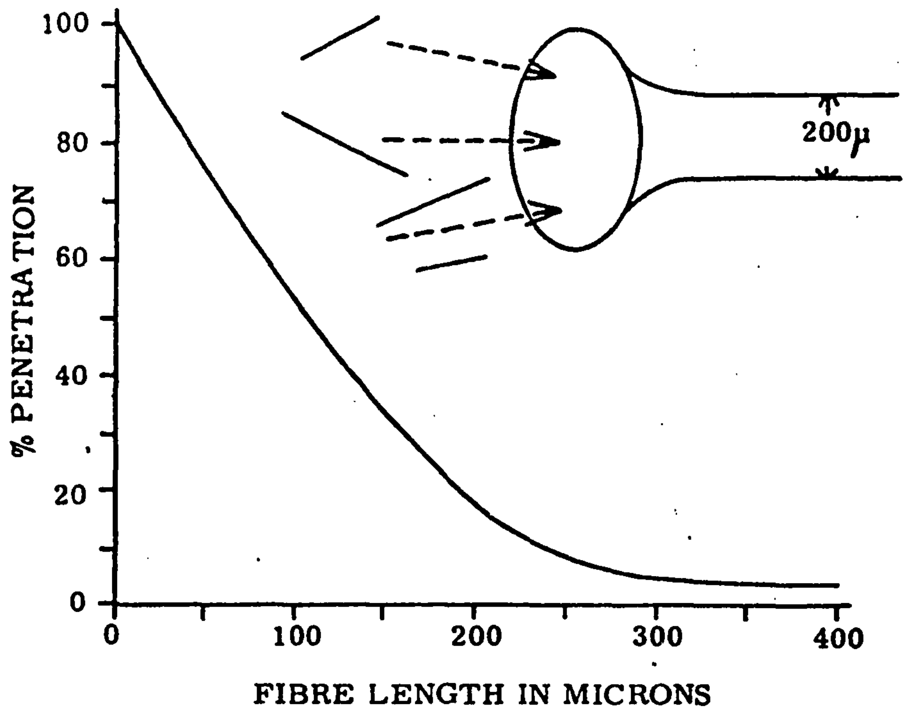
(Reference 113)



Calculated penetration curves for fibers through one, two or three stages of nasal hairs.

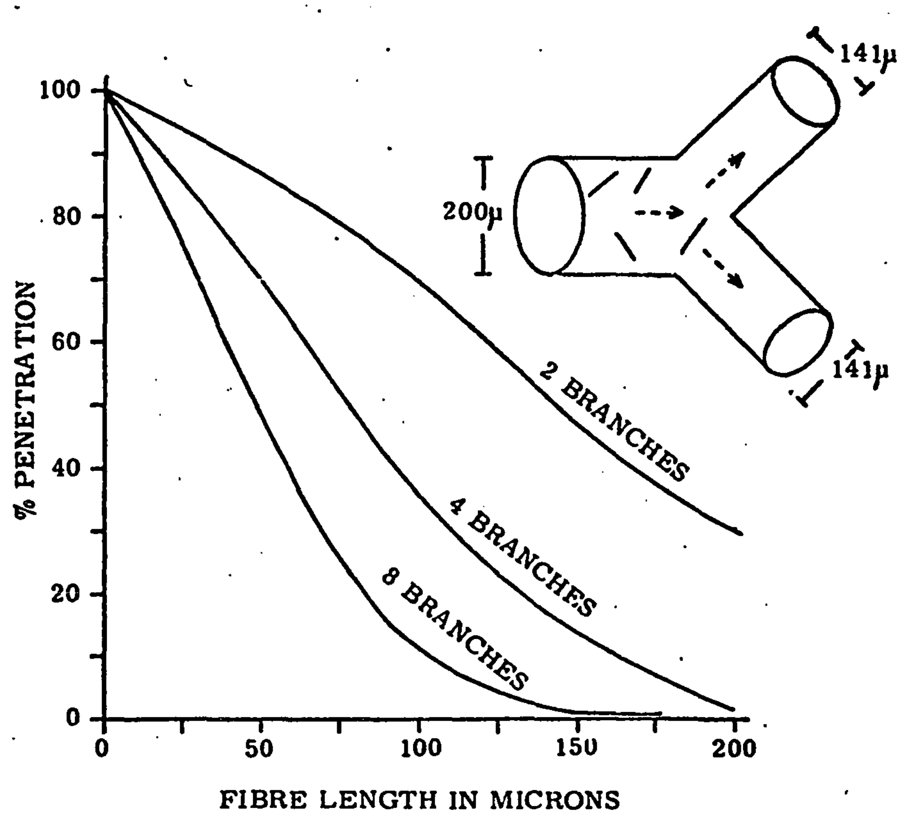
Fig. 19

(Reference 113)



Calculated penetration curve for fibers into a respiratory bronchiole.

Fig. 20
(Reference 113)



Calculated penetration curves for fibers through branching of a respiratory bronchiole, for cases of two, four or eight branches.

Fig. 20 A
(Reference 113)

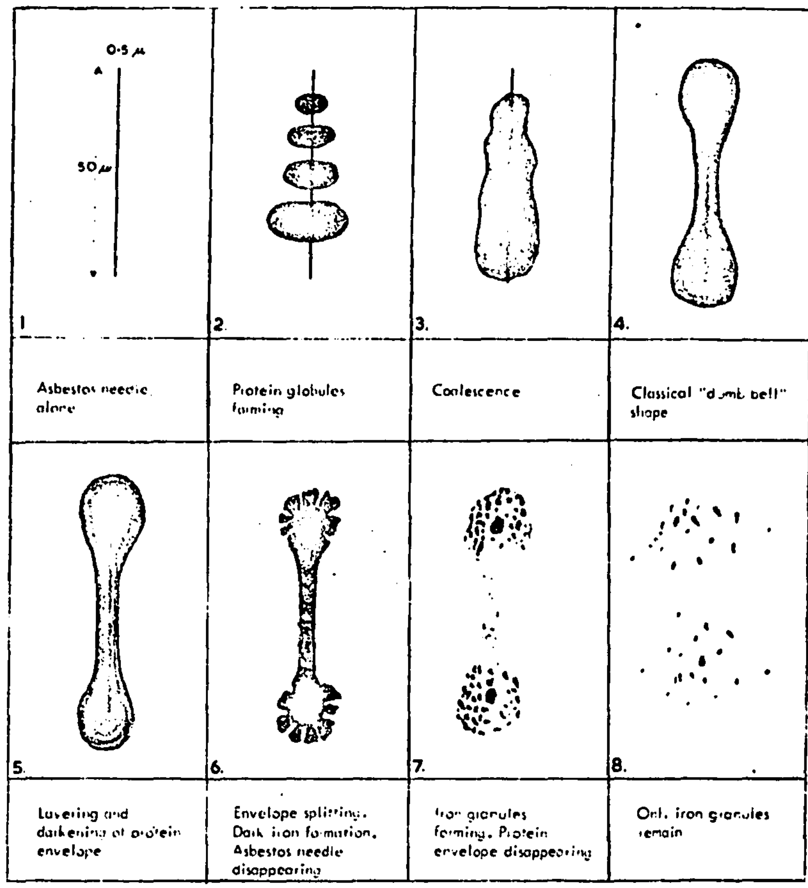
3.2 The Pulmonary Pathology of Asbestosis

The pathological view of the chemical life history of the asbestos body, suggests that, if an asbestos needle is thrust across, magnesium hydroxide, which gives an alkaline reaction when it is dipped in an indicator, is formed at the free end. A series of chemical reactions occur along the sides of the needle, and such reaction induces illness which is generally unique in industrial pulmonary disease. These asbestos bodies are about 3 microns thick and 70 microns long compared with the dimensions of the naked needles of asbestos lying free in the lung which averages 50 microns in length and 0.5 micron in diameter. Although in shape, they look like "a chain of beads" as well as "a match with heads at both ends", they are usually described as "dumb bell". Whilst the naked needles in the lung induce a physico-chemical change to the asbestos, these asbestos bodies become less fragile and less rigid than the naked needles. As it lies in the tissues, the needle gradually become encapsulated with a clear substance which slowly becomes manifest after about two months in the lung.

An illustration of the chemical life history of asbestos body was made by Browne[18] (Figure 21), and his detailed description is reproduced as follows:

" This coating first appears as globules along the centre of the needle which gives a chain-of beads appearance. Then the ends become surrounded with a thicker curved covering which forms what the German workers picturesquely call a 'hull'. The material from which this 'hull' is made is amphoteric, reacting with either acid or alkali; it gives a positive biuret reaction and it is dissolved by the proteolytic enzyme, trypsin.

Fig. 21



The chemical life history of the asbestos body.

(Browne, Reference 18)

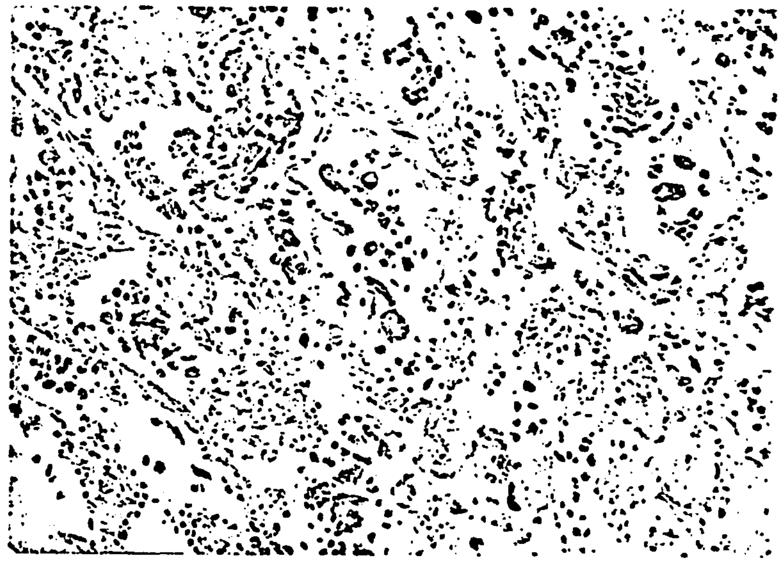
The evidence, therefore, strongly suggests that the substance which surrounds the asbestos needle to form the body is a protein. Indeed, a kind of asbestos body has, in fact, been synthesized by coating a needle with egg albumen. As the asbestos body becomes older, the needle in its centre becomes less noticeable, and finally disappears. No needles can be seen which are shorter than 10 microns which suggests that they eventually go completely into solution. An asbestos needle count in the lung also suggests gradual solution, as the longer the patients survive after last inhaling asbestos, the smaller the intrapulmonary fibers appear to be. The whole asbestos body eventually becomes segmented and radial cracks appear in the bulbous rounded ends, and at last, nothing is left but a string of dark granules which appear to be iron oxide which has gradually accumulated in the protein envelope as it has become older. What, therefore, started as a clear symmetrical asbestos needle ends as an opaque collection of amorphous iron granules. "

3.3 Hazards of Asbestos Exposure and Associated Diseases

The clinical symptoms of asbestosis are similar to those of silicosis, nevertheless there are some marked differences. Silicosis renders a patient particularly susceptible to tuberculosis, while asbestosis seems to lead to enlargement of the heart and often to death by heart failure. Microscopical examination[13] showed varying degrees of fibrosis, from dense, relatively acelluar fibrous tissue obliterating lung structure to mild interstitial fibrosis (Figure 22), in which the general architecture of the lung is preserved. A small portion of the lung showed normal alveolar walls; in these areas fibrosis was concentrated around respiratory

Fig. 22

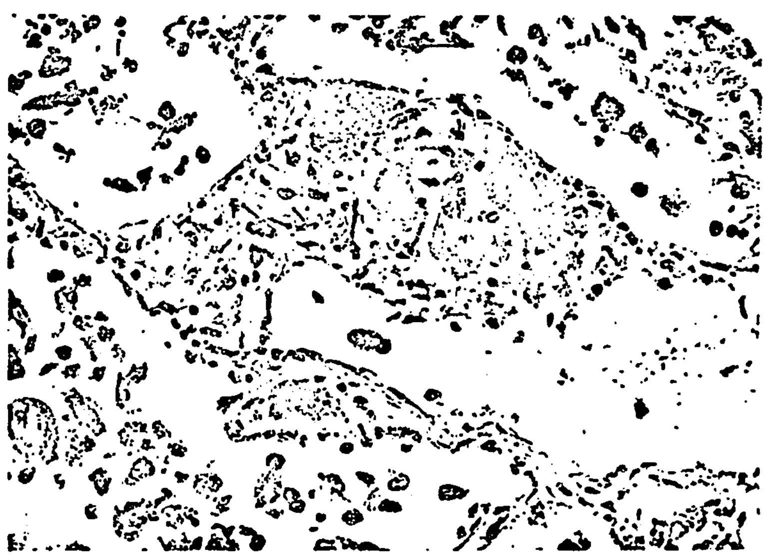
A Photograph of Mild Interstitial Fibrosis



(Bates & Christie, Reference 13)

Fig. 23

Asbestosis Body in the Interstitium



(Reference 13)

bronchioles. Many histiocytic cells existed in the alveolar spaces in the fibrotic areas and the alveolar lining cells were often swollen and cuboidal. Large numbers of asbestosis bodies were seen both in alveolar spaces and in the interstitium (Fig. 23). Scattered large cells were seen throwing over and enclosing the bodies. Elsewhere, large cells were seen containing asteriod bodies. Moderate thickening of the pulmonary arteries existed. The pleural plaques were composed of dense acellular hyaline tissues.

In 1906, asbestos bodies were discovered by Montagne Murray[81], in the lungs of a man who died in 1900 after having worked in an asbestos textile plant. Subsequently, King, Clegg and Rae[64] undertook a series of experiments with asbestos dust in the lungs of rabbits. They found the animals exposed to long asbestos fibers developed nodules similar to the experimental silicotic nodule. The animals exposed to short fibers developed a "diffuse interstitial reticulinosis". Then, Cooke[26] McDonald[74], Merewether[76], Berkley[16], Wagner[122], Holt[57], and Davis[33] also experimented with asbestos dust to study deposition and retention in animals. It was found that when tiny asbestos fibers reside in the body, they are eventually coated with an iron-protein substance which frequently forms clubbed ends, giving rise to the typical drumstick appearance. Eisenstadt[40] considered that fiber bodies are formed in a period of 10 or more years. Over the course of that latent period, the collagen cover of asbestos bodies "ripens" by forming transverse cracks, enabling them to breakdown and liberate a toxin which causes a reactive fibrosis in the lungs. This substance was thought to be carcinogenic. However, it seems unlikely that any human physiological process is capable of achieving complete destruction of these fibers.

In Collins'[24] view: " The protein coating of the fibers is probably simply a defensive mechanism rather than an aggressive one, preventing further migration of minute needles capable of direct penetration of tissues. " Keal[61] in 1953 quoted a report, by Wyss, of fibers in the urine of patients with asbestosis and they have also been found in the thyroid and spleen. Keal brings this as evidence of haematogenous spread of fibers, and suggests that a combination of mechanical and chemical factors may determine the peritoneum as the location of neoplastic change. These findings may also be considered as evidence that fibers can and do penetrate tissue directly.

From a peritoneal or ovarian cancer case's clinical report, they revealed that there is a high incidence in women exposed to asbestos[61], and the portal of entry might probably be the genital tract. Thus, lymphogenous spread of the tumours occurs, but haematogenous spread is rarely encountered[86]. As fiber penetration of skin may occur, ingestion of fibers and skin contacts to fibers may, therefore, effect a similar result.

In a study of the hemolytic activity of asbestos fibers undertaken by MacNab and Harington[71], only chrysotile was found to have a marked hemolytic activity, similar to that elicited by quartz. Other asbestos forms were either completely inactive or only weakly lytic. They attributed the high lytic property of chrysotile to the adsorptive capacity of this type of fiber: chrysotile, in fact, adsorbs five times more proteins from serum than silica.

As a result of the study in vitro on the hemolytic activity of different asbestos types (chrysotile, crocidolite, amosite, anthophyllite), Secchi & Rezzonico[99] observed that chrysotile proved to have potent hemolytic activity whereas crocidolite, amosite and anthophyllite were either completely inactive or only weakly lytic.

Wagner[121] stated that a number of hypotheses to explain the pathogenesis of asbestos disease have been proposed, but none is widely accepted:-

" (a) The original theory of physical irritation — that the presence of the asbestos fibers in the terminal airspaces caused irritation and damage to the walls of the alveoli leading to fibrosis.

(b) The solubility theory — that the fibrosis is due to the effects of silicic acid and metal ions leaching out from the asbestos fibers.

(c) The autoimmune theory, in which there are two concepts: (1) 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 tissue by immunofluorescent techniques. (2) That 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 the fibrosis. The suggested mode of action being that lysis of the phagocyte at this site releases a substance that is not accepted by the tissue as 'self'.

(d) The stagnation of phagocytes theory — this is similar to the second concept in the autoimmune hypothesis, but involves no immunological mechanism in the tissue-destruction and fibrosis. "

From the histological viewpoint, symptons of asbestosis may have the following occurrence with respect to exposure of humans:-

Pulmonary fibrosis (asbestosis),

Bronchogenic Cancer,

Mesothelioma,

Ferruginous (asbestos) bodies,

Pleural plaques.

The following data, presented by Buchanan(19), shows the incidence of asbestosis and lung cancer, and, the average of 'asbestosis' cases at death according to type, recorded from 1924 to 1963 in Great Britain (Tables 12 & 13):-

Table 12

INCIDENCE OF ASBESTOSIS AND LUNG CANCER 1924–1963

Period	Males			Females		
	All asbestosis	Asbestosis and cancer of the lung	Per cent with cancer of the lung	All asbestosis	Asbestosis and cancer of the lung	Percent with cancer of the lung
1924-1930	13	—	Nil	7	—	Nil
1931-1940	66	13*	19.7	82	5	16.1
1941-1950	92	21†	22.8	45	5*	11.1
1951-1960	144	45	31.3	40	11	27.5
1961-1963	77	42‡	54.5	18	4	22.2
1924-1963	392	121	30.9	192	25	13.0

*Includes one case recorded as "cancer of pleura."

†Includes one case recorded as "sarcoma of pleura."

‡Includes four cases recorded as "mesothelioma of pleura."

(Buchanan, Reference 19)

AVERAGE AGE OF 'ASBESTOSIS' CASES AT DEATH ACCORDING TO TYPE

Period	Males						Females					
	Asbestosis only		Asbestosis + tuberculosis		Asbestosis + intrathoracic cancer		Asbestosis only		Asbestosis + tuberculosis		Asbestosis + intrathoracic cancer	
	Cases	Av. age	Cases	Av. age	Cases	Av. age	Cases	Av. age	Cases	Av. age	Cases	Av. age
1924-1940	43	49.3	23	44.3	13	55.6	52	39.6*	32	33.7	5	49.0
1941-1950	54	55.9	17	42.1	21	54.3	31	45.2	9	37.6	5	41.2
1951-1960	86	58.1	13	55.3	45	56.4	28	56.7	1	51.0	11	51.0
1961-1963	34	60.4	1	53	42†	57.6	13	57.8	1	54	4	62.5

*Average age at death based on 50 cases only.

†One case also had pulmonary tuberculosis.

Table 13
(Reference 19)

Chapter II

THE ASBESTOS HYGIENIC STANDARD AND ITS CONTROLS

1. Hygienic Standards for Asbestos Dust

1.1 Motes & Fibers in the Air

In the mining and processing plants of the asbestos industries, the sources of air-borne particulates may be classified as follows:-

(1) Fibrous asbestos

(2) Asbestos type minerals (serpentine, antigorite, etc.)

(3) Non-asbestos type minerals occurring with asbestos (magnetite, peridotite, chromite, quartz, nickel.)

(4) Non-process materials (air pollution)

An air sample from an asbestos plant taken by any efficient device and examined microscopically reveals that there are motes and fibers. The grains or motes can be represented as spheres in shape, and the fibers may be represented as greatly lengthened cylinders. The hygienic significance of the two types of particles is different. Therefore, motes and fibers can be discussed separately.

Motes: Because there is an inherent size classification in airborne dust, many investigators[51, 32, 49, 106] discovered that one seldom sees particles larger than 10 microns diameter in an air sample from any mineral dust producing operation. Ayer and Lynch[7] took air samples, from an asbestos textile plant, which appear to be from the process, and the size-distribution of these other mineral particles was as follows: Median diameter: 0.45μ to 0.8μ; 30 to 55 per cent less than 0.5μ; 87 to 98 per cent less than 2μ; 1 to 4 per cent above 5μ, the major proportion of the dust by weight of either the total sample or a respirable fraction is contributed by particles larger than 1 micron.

Fibers: Dreesen[38] and Fulton[44] reported that the normal diameter of airborne asbestos fibers was less than 0.5 micron. Electron micrography confirms this; in fact, the diameter of most of the airborne asbestos fibers is less than 0.1 micron. When the aspect ratio of a particle is greater than three to one, it is defined as a fiber, most of which, by number, are short; median lengths from electron micrographs are between 1 and 2 microns.

Typical geometric standard deviations of air borne samples' fiber length are 2 to 4. The median length of fibers: 2.5 microns to 3.5 microns; 8 to 15 per cent less than 1 micron; 65 to 75 per cent less than 5 microns; 87 to 90 per cent less than 10 microns. Median diameter (thickness) of fibers: about 0.55 micron; 43 per cent less than 0.5 micron; 82 per cent less than 1 micron; 98 per cent less than 2 microns[49]. The larger diameter (up to 1 micron) fibers contribute the major portion by weight of respirable fiber, and among which, there are many small diameter fibers, most of them are well under 5 microns in length but with virtually no upper limit to the microscopic length. Fibers up to 50 microns in length may be visible in the respirable fraction of air samples; however fibers 500 microns and longer, some with diameter 3 microns and less, have been found in clouds of asbestos particles.

The most applicable respirable airborne particle diameters for asbestos sampling appear to be those suggested to the Office of Health and Safety of the United States Atomic Energy Commission by a group of consultants in 1961, and adopted in AEC regulations. They are:-

% Respirable	Particle diameter μ (unit density sphere)
100	$\leqslant 2$
75	2.5
50	3.5
25	5
0	10

1.2 The Theory of Fibrous Dust Toxicity

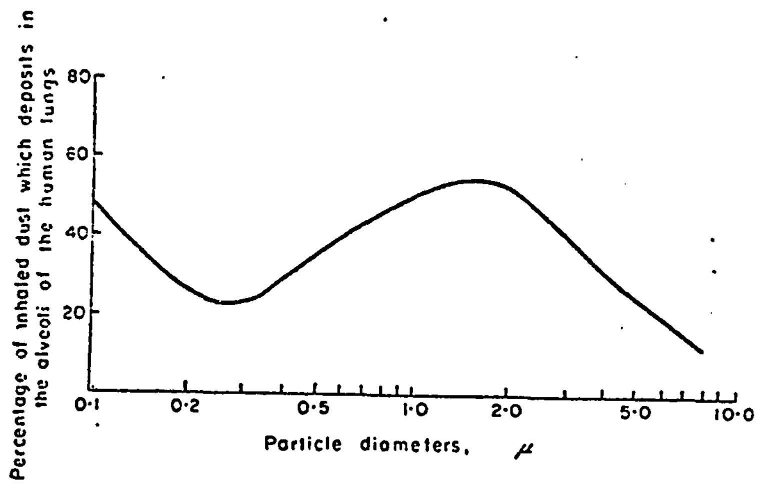
Due to a considerable difference in respiratory tracts and the number of exposed fibers between humans and animals, it is difficult to apply any conclusion to human asbestosis from the results of experimental asbestosis performed on animals. However, the experimental asbestosis has given rise to two causation theories which throw some light on the relationship of particle size to pathogenicity in asbestosis. They are the theory of mechanical damage and the theory of chemical damage and chemical action, respectively.

The theory of mechanical damage was tested by Vorwald, Durkan and Pratt[120]. They found that asbestos dust particles which were smaller than 3 microns in length had little or no reaction on pulmonary tissues. This was greatly different from silicosis, which is caused by silica dust of the same size. Thus if asbestos particles no longer than 5 microns are inhaled, very little disease would develop and the process would advance more slowly than when the airborne particles contained a predominance of fibers of 10 to 50μ[20]. In the meantime, Green[48] states that samples of asbestos, the cause of asbestosis, indicate that the majority of fibers are less than 10 microns in length and 2 microns in diameter.

On the other hand, with the chemical theory, it discloses that fibrosis is the result of the chemical action of an unknown fibrogenic agent (could be silica) released by disintegration of asbestos bodies (silicates)[137]. Nagelschmidt[83] discovered that in over half the asbestosis lungs from Great Britain and South Africa, practically no asbestos fiber was found, irrespective of grade of fibrosis, and that asbestos dust might possibly be dissolved in the lungs, or become as minute particles.

According to Findeisen[41], there is an optimum size of between 1 micron and 2 microns in diameter, at which maximum alveolar deposition occurs, decreasing to a minimum at about a quarter of a micron and increasing as particles become even smaller. Figure 24 shows the retention versus size by Davies[30]. Evidently, the smaller particles of silica, down to perhaps a half-micron, act more quickly than larger ones in producing a fibrotic condition and, weight for weight, are more dangerous. Whilst there is no available evidence concerning the effects of silica particles around the 0.1 micron size, they are considered as of less danger than those in the 1 micron region. Davies states that, although the fibrogenic activity of quartz increases as particle size decreases from 5 microns to 0.5 micron, at some smaller size a reverse tendency must take place as colloidal particles produce less effect.

Fig. 24



Particle size and percentage deposition in the human alveoli.

(Davies, Reference 30)

1.3 Hygiene Criteria for Air-borne Asbestos

In April 1964, The American Conference of Government Industrial Hygienists (A.C.G.I.H.) presented a threshold limit value (TLV) for asbestos dust, as determined by impinger samples, of 5 million particles per cubic foot (177 particles/ml) of air for a daily eight-hour exposure, 40 hours per week. This figure was recommended by Dreesen, Dalla Valle, Edwards, Miller and Sayers[38] after a study of 541 employees in three asbestos textile plants using chrysotile. Only three uncertain cases of pneumoconiosis were found in those exposed to dust concentrations under five mppcf, whereas numerous well-marked cases were found above five mppcf. Both fibrous and non-fibrous particles were counted. But in 1967, Cooper[27] observed that the TLV of 5 mppcf for asbestos rests on shakier evidence than most TLVs. He principally argued that the impinger counts include all dusts and that a large proportion of asbestos fibers have diameters below the resolving power of the light microscope and are not counted at all. He pointed out that asbestosis appeared in insulating workers who were exposed to concentrations much below the time weighed average of 5 mppcf. Leathart and Sanderson[67] in some observations on asbestos considered a TLV of 5 mppcf tobe too high. It has been suggested by various investigators that as there can be no certainty of a concentration which is harmless to man, the TLVs for known or suspected carcinogens should be established as zero. Ayer & Lynch[7] suggested that on a weight basis, the present TLV for asbestos may be greater than 1 mg/m^3 of respirable dust. Crocidolite, however, has been shown to produce, in addition to the asbestotic inflammation, also mesothelioma. In a statement issued in early 1968 by the A.C.G.I.H., it states:

" Since no safe limit can be established for this form of asbestos at this time, until more definitive data are obtained, it is recommended that workers exposed to crocidolite be equipped with air supplied helmets. "

In May of the same year, a new proposal was made by the A.C.G.I.H., on a TLV of 12 fibers per ml for asbestos fibers larger than 5 microns in length, as determined by the membrane filter technique[4]. However, they did not allow sufficient time for various investigators to critically analyse the TLV of 12 fibers/ml.

Further to the above, they have in 1970, proposed to lower the

TLV to 5 fibers/ml for all types of asbestos fibers which are over 5 microns in length[5].

The United States Atomic Energy Commission proposed that the concentration of the respirable fraction can be compared to a modified maximum permissible concentration (MPCa) on a simple basis. The following equation as established by the International Commission on Radiological Protection can be used to calculate MPCa :

$$MPCa = \frac{10^{-7}\ qf_2}{Tf_a\ (1-e^{-0.693}\ t/T)} \mu c/cm^3$$

where

qf_2 = burden of radionuclide in the critical body organ (μc)

f_2 = fraction of radionuclide in critical organ of that in total body

T = effective half life (days)

t = period of exposure (days)

f_a = fraction of the body burden in the organ of reference

The published MPC_a standards for insoluble particles were calculated from this equation using the factor f_a to represent the fraction of the material, taken into the body by inhalation, that arrives in the critical organ, Assuming $f_a = 0.125$ in all cases where the lung is the critical organ, i.e. that 25% of the airborne dust is "respirable", and "one-half of the respirable" dust is retained. Thus, the MPC_a for insoluble "respirable" dust should be 25% of the MPC for total airborne dust. The International Commission on Radiological Protection stated the following in connection with the value of f_a :

" Retention of particulate matter in the lungs depends on many factors, such as size, shape, and density of the particles, the chemical form, and whether or not the person is a mouth breather; however, when specific data are lacking, it is assumed the distribution is as shown below.

Distribution	Readily Soluble Compounds	Other Compounds (%)
Exhaled	25	25
Deposited in upper respiratory passages and subsequently swallowed	50	50
Deposited in the lungs (lower respiratory passages)	25 This is taken up into the body.	25*

* Of this, half is eliminated from the lungs and swallowed in the first 24 hours, making a total of 62-1/2 per cent swallowed. The remaining 12-1/2 per cent is retained in the lungs with a half life of 120 days, it being assumed that this portion is taken up into the body fluids. "

In Canada, Canadian Johns-Manville Co. Ltd. has been using 6 fibers longer than 5 microns per cubic centimeter as a Threshold Limit Value at their mining and milling operations.

An informal limit of 4 fibers longer than 5 microns per cubic centimeter has long been utilized by the asbestos industry in England. The Committee on Hygiene Standards of the British Occupational Hygiene Society(66) have recommended that exposures which lie in certain ranges of dustiness be designated by categories according to the following scheme:-

DUST CATEGORY	CONCENTRATION AVERAGED OVER 3 MONTHS ($fibers/cm^3$)
Negligible	0 - 0.4
Low	0.5 - 1.9
Medium	2.0 - 10.0
High	Over 10.0

and they have proposed a variety of acceptable instruments with alternative specific indices of concentration for sample collection of chrysotile asbestos dust. These indices are:-

METHOD	CONCENTRATION
Membrane filter	2 $fibers/cm^3$
"Respirable" mass	0.03 mg $magnesium/m^3$
	0.04 mg SiO_2/m^3
	0.10 mg ash/m^3
	0.12 mg $asbestos/m^3$
Thermal precipitator	25 $particles/cm^3$ greater than 1μ after incineration
Impinger	10 $particles/cm^3$
Royco particle count	2 $particles/cm^3$ greater than 4 microns

Good industrial hygiene practice tends towards controlling exposures below the hygiene maximum rather than maintenance at the maximum.

As the most relevant parameter of respirable fiber concentration (i.e. surface area, weight length, count) cannot be determined from present biological evidence, some Germanic investigators[62,123] elected to use "dust factors" instead of TLVs to evaluate working conditions. The formula of determining the "dust factor" is:

$$F \doteq \frac{K_G \times K_A}{100}$$

where

F = dust factor

K_G = total concentration of all dust particles in ppcc of air (ppcc - particles per cubic centimeter)

K_A = asbestos fiber concentration in ppcc of air

Kesting[63] suggested the following categories for describing safe limits:

F_1 = 0-20 .... no hazard

F_2 = 20-40 .... low hazard

F_3 = 40-60 .... medium hazard

F_4 = above 60 .... high hazard

He indicated that an asbestos disease should not be expected with the range of $F \doteq 0 - 20$. This suggested "dust factor" seems to be reasonable as it depends upon both the total dust and the fiber, and it is particularly more applicable in the mining industry, since there might be a percentage of up to 80 per cent of dust from the parent rock which could be biologically relatively inert.

As it probably applies in most dusty industries, there are no reliable quantitative hazards of fibers and other dust particles standards.

Rajhans[91] suggested: " The TLVs, or the safe limits established in various countries, are only meant to be used as a guide and should not be given a legal connotation. It should further be understood that the values of TLVs have been, in some cases, decreased in the past and there is every possibility that they may be further reduced as fresh information becomes available, especially in the case of known or suspected carcinogens like asbestos. "

2. Dust Control in the Mining Industries

2.1 Sources of Dust

The many possible asbestos dust sources in mining and milling are from open pit, drilling, blasting, loading, handling, grinding, screening, drying, and so forth. In the mine, the most significant source of pollution lies in the uniqueness of the milling procedure, which is a dry process requiring large air flows.

The separation of asbestos fiber from its ore, the opening up and cleaning of the fiber, and finally its blending and grading are done by mechanical means. Whereas, most of other mineral dressing processing usually adopt wet methods which are entirely different from asbestos dressing processing. And, asbestos milling is, indeed, a dry process with considerable handling, which tends to produce large quantities of air-borne particles and fiber.

Fiber is released by impact methods from the rock and is separated on vibrating screens. With such methods, there is less damage in separating fiber from rock. In practically all phases of the operation, air is utilized to separate and to transport the fibrous material. Air is considered as the life-blood of asbestos milling. Large quantities of dust are produced during dry asbestos milling. However, pneumatic transport is an inherent process component so that only a fraction of the total air moving capacity in a mill is provided exclusively for dust control. Every ton of asbestos fiber utilizes about 75 tons of process air, and 25 tons of air out of the process air, are utilized to remove dust at belt conveyors, non-aspirated screens, bucket elevators, pressure-packing machine, graders, hoppers, rock and fiber bins, etc.[107] As a rule of thumb, Horn[58] mentioned that it requires ten tons of air to produce one ton of fiber.

2.2 Dust control of the Environment

White[128], in "The Total Environment of Mining", suggested that, one of the aspects in the establishment of a comprehensively attractive working environment, is a composite one of physical, chemical, biological, psychological and sociological elements; together, they constitute the working conditions within the industry — each giving rise to problems of control. Therefore, dust control of the environment should be designed to correlate the above suggestion.

A critical design of dust control methods, is recommended as follows:-

(a) substitution of enclosed mechanical methods to replace manual handling for dusty work.

(b) effective enclosure of dust-producing machines and plant (with automatic operation, if possible),

(c) application of exhaust draught at dust-producing points,

(d) general ventilation,

(e) local exhaust ventilation,

(f) substitution of wet methods for dry,

(g) the use of dust respirators (and other personal protective devices),

(h) decreasing the daily exposure through a short work period.

(i) isolation of the hazardous process from the remainder of the plant with special protection for workers necessarily included in the area isolated.

(j) medical supervision.

Chapter III

THE USE OF DUST RESPIRATORS

1. A History of Respirators

Dust respirators have been in use since Roman times and earlier. There was concern about the effects of dusts in lead mines and refineries, and through the ages there has been apprehension about dusts from gypsum, limestone, and so forth (116).

In 1931, an investigation was carried out by the British Medical Research Council at Porton, concerning the dusts which cause pulmonary disease in industry. From the study of a wide range of industries, it was revealed that finer particles of dust, down to about half a micron in diameter, were to be found in the lungs of persons affected by occupational pulmonary disease. After several years' investigation, a general performance specification for dust respirators was drawn up which included filtering efficiency, resistance to breathing, comfort and wearability. This specification was adopted by the Factory Department of the British Government, who had become activity interested in dust respirators largely as a result of regulations published in 1931 which made dust respirators compulsory for some branches of the asbestos industry.

Various designs of respirators were produced in World War I, ending with the almost historic Small Box Respirator, which was the first Government canister respirator design. Possibly one of the most notable material benefits of World War I respirator research was that it gave the world activated charcoal, which is usually an absorbent for gases and vapours in industry. Under the influence of war, the research on respirators evolved the concept of mechanized respirator assembly methods, standard methods of test and inspection, and it gave a background of knowledge on the physiology of the respirator and some information on the variability of the contours of the human face.

Subsequent to World War II, a result of respirator industrial developments have been encouraged and helped by the Government to design the filter materials and other components for war respirators. There are a number of commercially designed dust respirators, which meet the required standards and approved for use in specific atmospheres.

In general, the dust respirator position is now better than it have ever been, but finality and perfection have by no means been reached, especially in view of the very much more toxic materials which are now being manufactured and used.

2. The Principle of Dust Respirators

By definition, a respirator is a breathing apparatus which incorporates a filter and/or absorbent which removes poisonous or unpleasant materials from the air inhaled by man. Respirators, as defined, are classified into two groups: (A) - Atmosphere supplying, and (B) - Air purifying.

The first group (A) consists of the self-contained breathing apparatus, air-line respirators, hose masks, and air supplied hoods and helmets. Wearers of these devices are supplied with uncontaminated air from a source other than the surrounding atmosphere.

The second group (B) includes the mechanical-filter respirators, chemical-cartridge respirators, and gas masks. The wearer of these devices breathes the air from the surrounding area, but a mechanical or a chemical filter removes most of the contaminants before the air is inhaled.

The main purpose of this research is to study the dust respirators which are the mechanical-filter types. These are included in the second group. Dust respirators usually consist of a half mask, covering the nose and mouth, with a filter attached. A filter is made of fibrous material which permits the passage of air, but removes the harmful particles by physical trapping in the filter as air is inhaled. The characteristics of these protective devices create some discomfort for the wearer. As the respirator is used, the accumulation of contaminants in the filter medium increases the resistance to air flow.

2.1 The Filter Material

The filters are made of various typesof material. Commonly used materials are mixtures of asbestos with cotton or wool (the filtering action being overwhelmingly due to the fine asbestos fibers), papers of asbestos and cellulose felt, and, recently, of fine glass fibers and wool-resin medium.

The Canadian and British particulate filters used in the army canister are composed of a mixture of merino wool and asbestos in definite proportions. The civilian canisters contain pads of wool impregnated with resin, as well as the merino wool asbestos pads. The Americans use paper filters made of alpha cellulose impregnated with asbestos. The French particulate filters are composed of alpha cellulose plus activated charcoal. The Germans used pleated cotton or wool pulp fiber, impregnated with asbestos.

2.2 The Physics of Fibrous Filters

The respiratory filter media is composed of fibers of different diameters, lengths and orientations in such a manner as pads, felts or papers, and, notwithstanding the apparent tight packing, the interstitial distances are usually many times greater than the diameters of particles which it is expected to remove from the air. Apparently, this word "filter" is normally sensed as a sieve, but actually its action is mainly through the inertial effect of the larger particles and the Brownian motion of the smaller ones. Whilst the streamlines of the air bend around the fibers the massive particles take a more direct path and in doing so, due to van der Waals forces, may touch a fiber and adhere. The smaller particles are accompanied with air molecules to strike across the flowlines, and to follow a tortuous path so that there are more chances of striking a fiber. Furthermore, small electrostatic charges on particles and fibers may help in increasing filter efficiency and it is also easy to observe that for particles which deviate by the equivalent amount from an air flowline those of large radii are more likely to touch a fiber; that is known as the interception effect. Brownian motion is more effective at the lower velocities while inertial effects are greater at higher velocities.

2.21 Basic Law of Filtration:

Filters remove particles under two methods: the Rodebush[96] method and the Taylor[110] method.

Rodebush proposed the following equations for sheet or layer type filters:

$$\frac{N}{N_o} = e^{-K\Delta X} = e^{-S}$$

Darcy's Law

$$P = r \cdot v \cdot \Delta X$$

$$\frac{S}{P} = \frac{K \cdot \Delta X}{r \cdot v \cdot \Delta X} = \frac{K}{r \cdot v}$$

where

N and N_o	are number of particles in the smoke stream before and after filtration respectively.
X	= thickness of the sheet
K	= the stopping coefficient
ΔX	= actual thickness of filter
r	= resistance per unit thickness
P	= pressure drop across the filter
v	= the linear flow in cms. per minute
S	= $K\Delta X$

Taylor developed a method for the comparison of filtering materials on a standard basis. If the filtering material and the cloud of particles are homogeneous, the filtration obeys the usual exponential law i.e. the fraction which penetrates the sheet decreases exponentially with the thickness, therefore

$$-\log_{10} P = K \cdot T$$

Darcy's Law,

$$r = R \cdot T \cdot \frac{U}{A}$$

$$A = \frac{U \cdot (-\log P) \cdot R}{K \cdot r}$$

$$A = C_1 \cdot \frac{R}{K}$$

$$C_1 = \frac{U \quad (-\log P)}{r}$$

$$V = A \cdot T$$

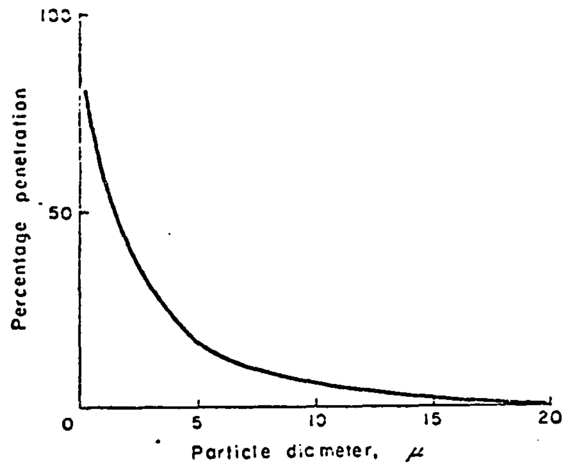
$$V = C_2 \cdot \frac{R}{K^2}$$

$$C_2 = \frac{U \cdot (-\log P)^2}{r}$$

where

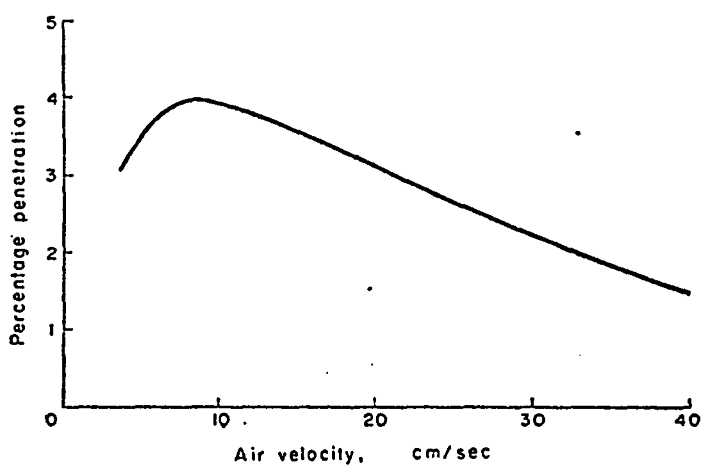
U	=	Flow rate of air cc/min.
A	=	Area of filtering material in sq. cms.
T	=	Thickness of filtering material in cms.
R	=	The resistance constant.
V	=	Volume of filtering material in ccs.
K	=	Penetration constant.
r	=	Resistance in cm of H_2O of a particular filter.
P	=	The penetration of a filter as a fraction of unity.
C_1 and C_2	=	Constant.

The results of some respirator-filter experiments of percentage penetration related to the humidity, particle diameter, flow rate, and mass concentration, respectively, are illustrated by Dorman[37] in Figures 25 & 26, and by Yaffe[135] in Figures 27, 28 & 29.



Penetration vs. size for a poor quality paper filter.

Fig. 25
(Dorman, Reference 37)



Variation in penetration of 1μ particles with velocity through a glass fibre filter.

Fig. 26
(Reference 37)

Experiments with Carbon Smoke (Particle Size 0.2 - 12.0 Micron)

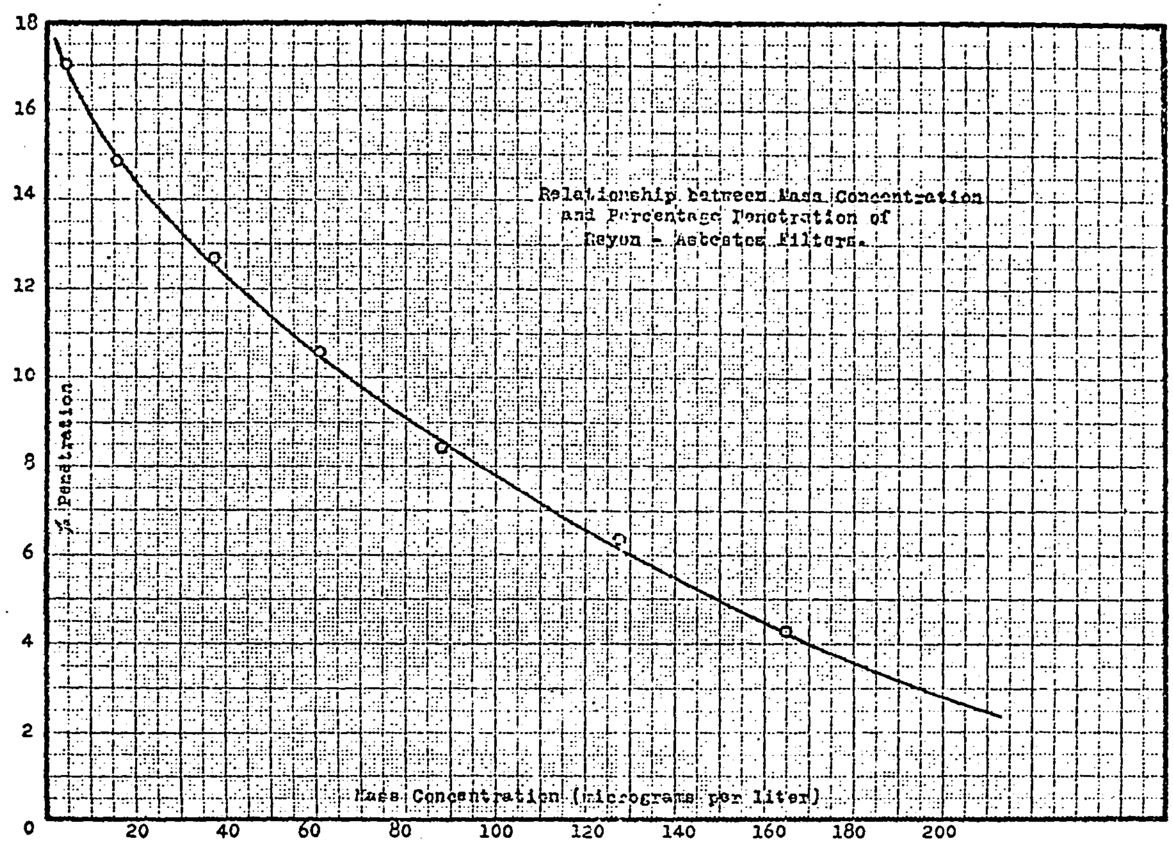


Fig 27 **Relationship between Mass Concentration and Percentage Penetration of Rayon-Asbestos Filters.**
(Yaffe, Reference 135)

Experiments with Carbon Smoke (Particle Size 0.2 - 12.0 Micron)

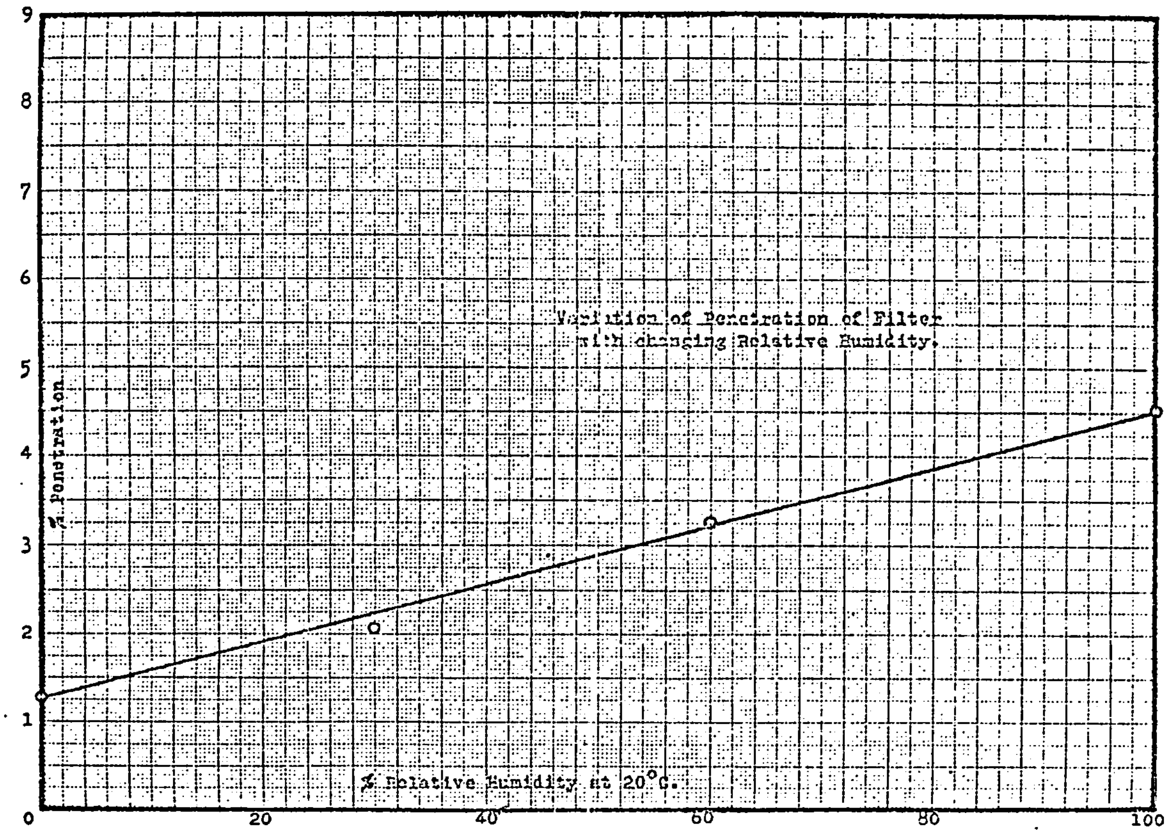
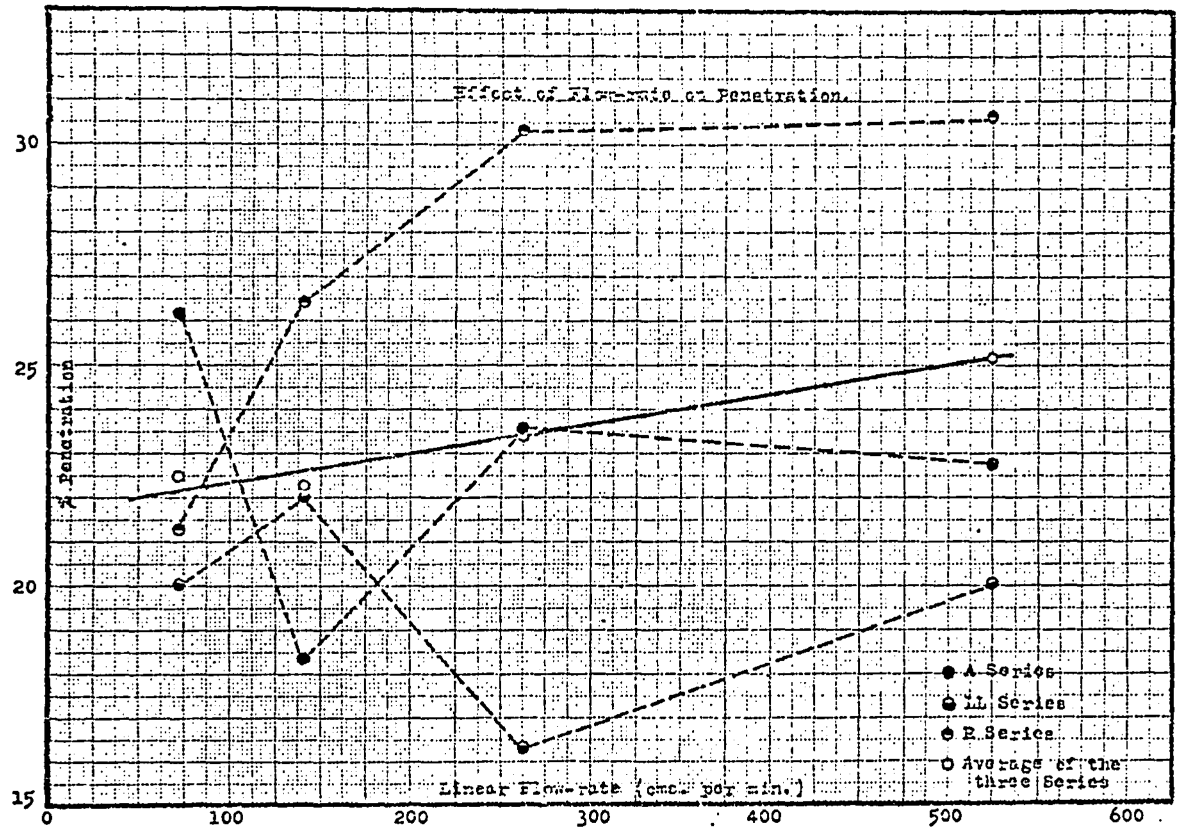


Fig 28 Variation of Penetration of Filter with changing Relative Humidity

(Reference 135)

Fig 29   Effect of Flow-rate on Penetration



Experiments with Oleic Acid Smoke
(Particle Size 0.14-0.17 Micron)

A - Filter medium made from the beginning of the batch
R - Filter medium made from the middle of the batch
LL - Filter medium made from the end of the batch

(Reference 135)

2.22 Mechanical Theory of Filtration:

Filtration is neither a screening nor a sieving effect. That this is so can be readily seen by comparing the diameters of the smoke particles caught and the pore diameters of the filters. Kaufmann[60] developed the mathematical theory of the fibrous type of filter. He considered each single fiber of the filter equivalent to a separation body as in Sell's[101] theory. The filter would then be composed of an irregular spaced lattice of such bodies. Kaufmann then considered the streamline flow around these fibers. Four types of deposition may occur:

(1) A fundamental separation may occur resulting from the relative location of the particles with respect to the cylinder if the distance of their path from the fiber surface at right angles to the current is less than the particle radius. Kaufmann considered this effect experimentally and found that it did not depend on the flowrate, but only on the geometrical configurations of the filter. It was found that the filtering efficiency increased rapidly with the increased ratio of particle size/fiber size. Thus for this type of filtration, the smaller fibers will be the more efficient.

(2) Kaufmann then considered the centrifugal forces involved. Using Sell's relation, he obtained an effect which was a function of the velocity, the particle radius square, and the reciprocal of the fiber diameter. Thus, here again, fibers of finer diameter will increase filtration efficiency.

(3) Filtration will also occur due to Brownian motion, the so-called diffusion filtration. This deposition is assumed to take place

mainly on the sides of the fiber due to the passage of the air. With some approximations, Kaufmann obtained the mathematical analysis of this effect. It was found to be a function of the reciprocals of the velocity, particle size, and fiber size.

(4) Kaufmann also considered the filtration due to electrostatic attraction between particles and fibers. This was found to be a function of the reciprocals of the velocity, particle size and fiber size.

According to the Kaufmann theory, the fiber radius plays a very important role in filtration problems.

2.3 Physiological Aspects of Respirators

An ideal respirator should be designed to meet the scientific requirements and the wearer's desire. In particular, there must be proper allowance for the physical and biological attributes of the wearer and his environment. As a respirator is inevitably a hindrance, so an aim of designing it should tend to keep those who are wearing them as near as possible within normal physiological limits. Cotes[28] stated that a respirator should conform to the anatomical and physiological criteria, as listed below:-

Relation to human anatomy and physiology and individual variability, including:

(i) Age and Sex

(ii) Mask Fit

(iii) Air Flow Characteristics

(iv) Oxygen or Air

(v) Mask Deadspace

(vi) Gas Humidity

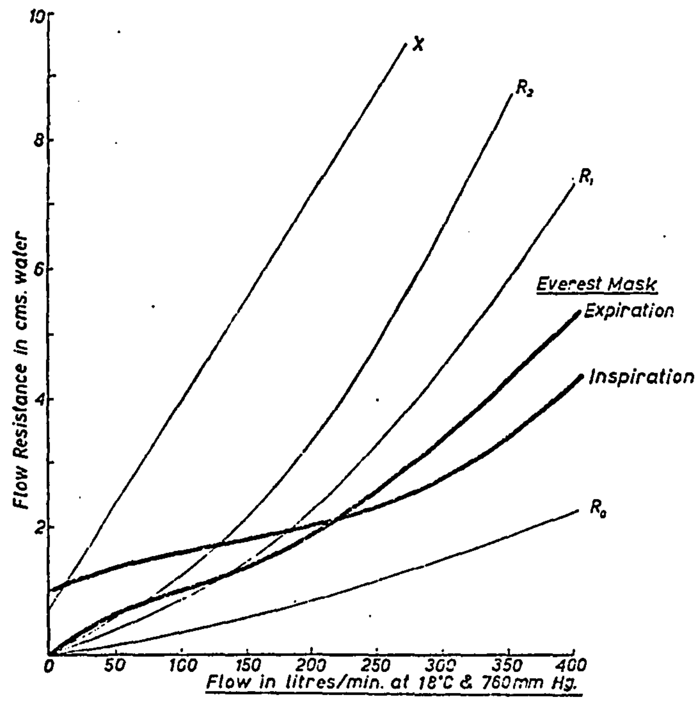
(Vii) Temperature Effects

2.31 Mask Fit:

Generally, a half face mask is usually adopted as a dust respirator against asbestos dust, and since human faces differ from each other in size, it is difficult to cope with fitness. The United States Bureau of Mines(117) require a facepiece test in which the complete respirator shall be fitted to the faces of 15 to 20 persons having a wide variety of facial shapes and sizes. In order to test the suitability of the fit of the respirator on these subjects, the exhalation valve and the inhalation port(s) shall be held closed, and each subject shall exhale gently into the facepiece until a slight but definite positive pressure is built up in the facepiece. The absence of outward leakage of air between the facepiece and the subject's face shall be evidence of acceptable fit of the facepiece.

2.32 Airflow Characteristics

It is very important for a designer to design a respirator with careful consideration in controlling the resistance to breathing. If it is too high, the filter may probably become clogged with use, respiration will be impeded and the wearer may adopt an attitude in which a leak occurs. Whereas, if resistance is very low the forces tending to suck the mask on to the face during inspiration are also low and the risk of leaks again increases. The relationship between the effect of age and the maximum allowable resistance is varied and this has not been fully explored. As breathing ability decreases with age, therefore, a resistance which is acceptable to a young man may not be tolerated by an older one.



R_0 = characteristics of low resistance M.B.C. machine.
R_1 = characteristics of apparatus producing no significant reduction in M.B.C. when compared with performance using low resistance apparatus.
R_2 = characteristics of apparatus producing significant reduction in M.B.C. in 7 normal subjects.
X = approximate dividing line between respiratory resistances which are subjectively noticeable and those which are not. (HART, 1943)

Flow resistance characteristics of Everest mask compared with resistance needed (McKerrow, 1955) to reduce maximum breathing capacity of normal subjects. (Cotes, 1954: by courtesy of Royal Society.).

Fig. 30

(Cotes, Reference 28)

McKerrow[75] has studied the effect upon maximum breathing capacity in normal subjects of a series of orifice resistances (Figure 30).

Figure 30 shows the acceptable resistance is likely to vary with the subject's ventilation minute volume since it is more vulnerable to the effects of resistance at high rates of air flow. Thus, in the specification, it is necessary to include the anticipated work level which determines ventilation.

3. Standard Test Methods for Dust Respirators

A specific standard test for asbestos dust respirators has not yet been announced by United States and Canadian Governments. As a rule, asbestos dust is considered as a kind of pneumoconiosis-producing dust. For protection against this kind of dust, the United States Bureau of Mines[117] has defined a standard test for its respirator, as follows:-

" Dust tests of respirators designed for respiratory protection against dusts having a TLV not less than 2.4 million particles per cubic foot, dusts, fumes, and mists having a TLV less than 0.1 milligram per cubic meter. Three respirators will be tested with a mechanical-testing apparatus under the following controlled conditions:

(i) Relative humidity - 20 to 80 per cent.

(ii) Room temperature - approximately 25°C.

(iii) Rate of continuous air flow - 32 liters per minute.

(iv) Test suspension — not less than 50 nor more than 60 milligrams of flint (99+per cent free silica) per cubic meter of air. The flint shall be ground to pass 99+per cent through a 325 mesh sieve. The particle-size distribution of the test suspension shall have a geometric mean of 0.4 to 0.6 micron, and the standard geometric deviation shall not exceed 1.96.

(v) Duration of sampling period -- 90 minutes for each respirator. Tested under these conditions, the total amount of unretained test suspension shall not exceed a total of 4.5 milligrams for the three respirators nor more than 2 milligrams for any single respirator. "

" The resistance to airflow of a complete respirator on inhalation and on exhalation will be determined on a mechanical apparatus before and after the tests are conducted. The continuous rate of airflow will be 85 liters per minute. And, the resistance to inhalation of respirators approved for respiratory protection against radon daughters and asbestos dust and mist, and which shall not exceed 18 millimeters of water-column height before and 25 millimeters height immediately after each test, and the resistance to exhalation shall not exceed 15 millimeters of water-column height at any time.[118] "

In England, penetration tests usually adopt heterogeneous clouds of methylene blue or sodium chloride at flow rate of 30 liters/minute; the size distribution is nearly all below 1 micron with a mass median diameter of 0.6 micron. The particulate is sprayed from a 1 per cent aqueous solution under controlled conditions and the solid test cloud is formed by evaporation of the water. The methylene blue test relies on the matching of the blue stains produced on esparto paper by different volumes of the filtered and unfiltered clouds. For instance, if a 2 minute exposure of the filtered cloud (60 liters) matches 24 cm^3 of the neat cloud the penetration is 24 x 100/60,000 or 0.04 per cent. The British Standard states that the penetration as measured on the methylene blue apparatus should not exceed 10 per cent.

The sodium chloride test relies on the yellow coloration of a flame by sodium. A photo-multiplier views the flame through appropriate light filters and the increase in intensity, indicated by the deflection of a galvanometer, gives a measure of the penetration, the relationship being linear. As the result of the measured penetration in this test is much higher than would be obtained by using natural dusts, (in which large particles are normally present) therefore, this result should be treated merely as an indicator which enables comparisons to be made between different filters.

The resistance to breathing is measured at 85 l/min. or 3 ft^3/min. This flow rate is considered to be about the peak rate of inspiration of a man breathing at a minute volume of 30 l/min. As for inhalation resistance, there are two figures mentioned in B.S. 2091 and 1954 for testing dust respirators: Type (A) - 3/4 in. water gauge; Type (B) - 1 3/4 in. water gauge when the whole respirator is mounted on a hollow model in an airtight manner. The figure for Type (B) is to allow for higher efficiency fibers. In both types exhalation resistance should not be greater than 1/2 in. water gauge.

Chapter IV

STUDIES ON THE EFFICACY OF DUST RESPIRATORS

1. A New Experiment for Testing Dust Respirators

Since the U.S. Bureau of Mines had on August 20, 1934 issued a test and approval schedule pertaining to particulate filtering type respiratory protective devices, including dust respirators, many experimenters(69, 93, 100, 127) have studied the efficacy of dust respirators; but most of them basically used a method similar to the U.S. Bureau of Mines.

A new idea for testing the efficacy of dust respirators relates more to the human respiratory function than the above method, and is discussed in this chapter. This new experiment attempts to test the respirators under conditions similar to those of the normal human breathing cycle. Such test will provide:

(i) Efficiency of dust respirator filtration; and,

(ii) Resistance of the dust respirator filtering medium.

A block diagram of the sequence of performing the particular elements of the process and their relationship, as a whole, is illustrated in Fig. 31. Fig. 32 demonstrates the experimental plant design.

There are two major steps in the pursuit of the above work: collection of the dust samples, and assessment of these dust samples.

1.1 Collection of Dust Samples

In regard to the sampling process, it is necessary to consider the relationship between dust, air, respiration, and respirators. Firstly,

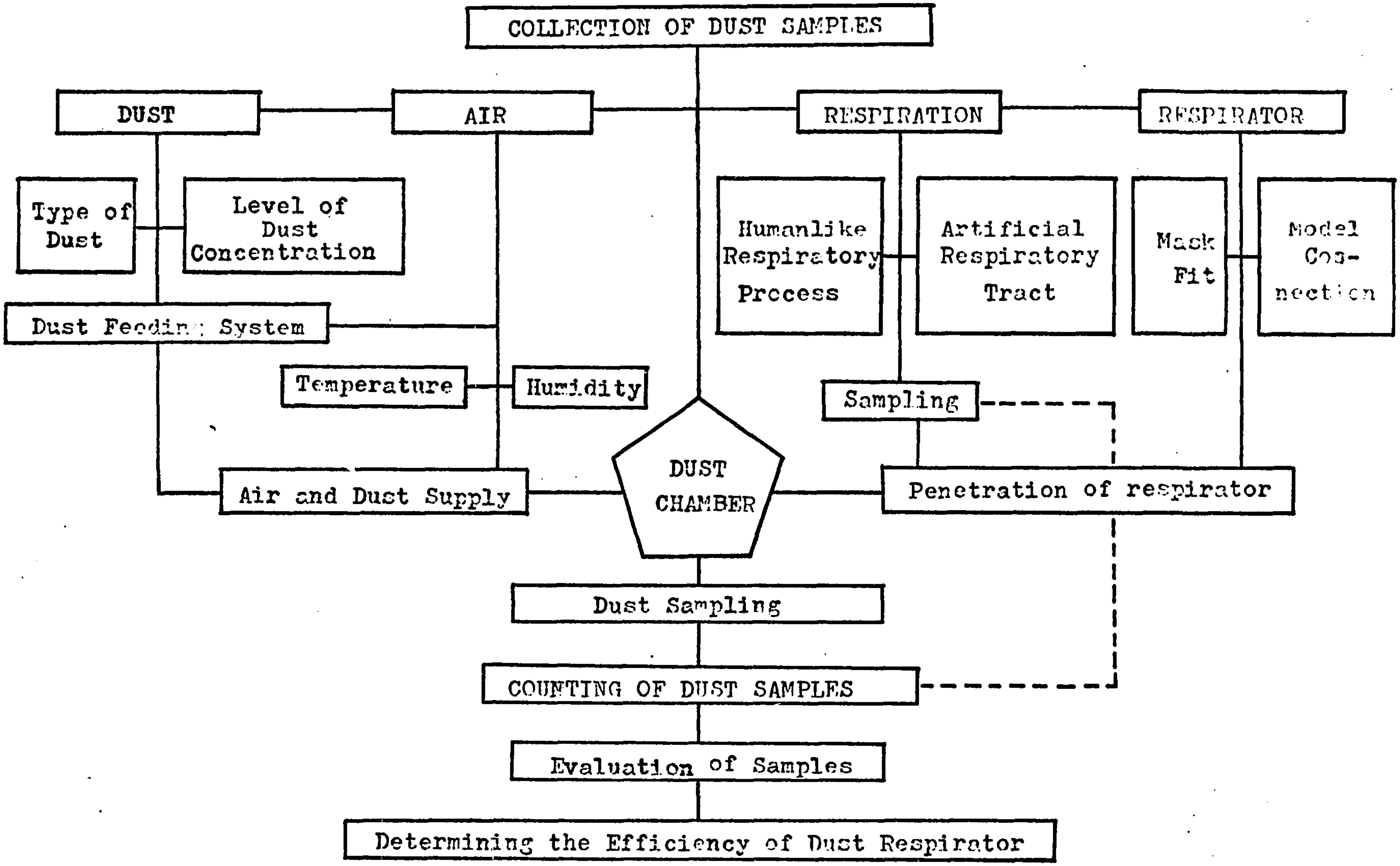


Fig. 31 PROCESS FLOW SHEET

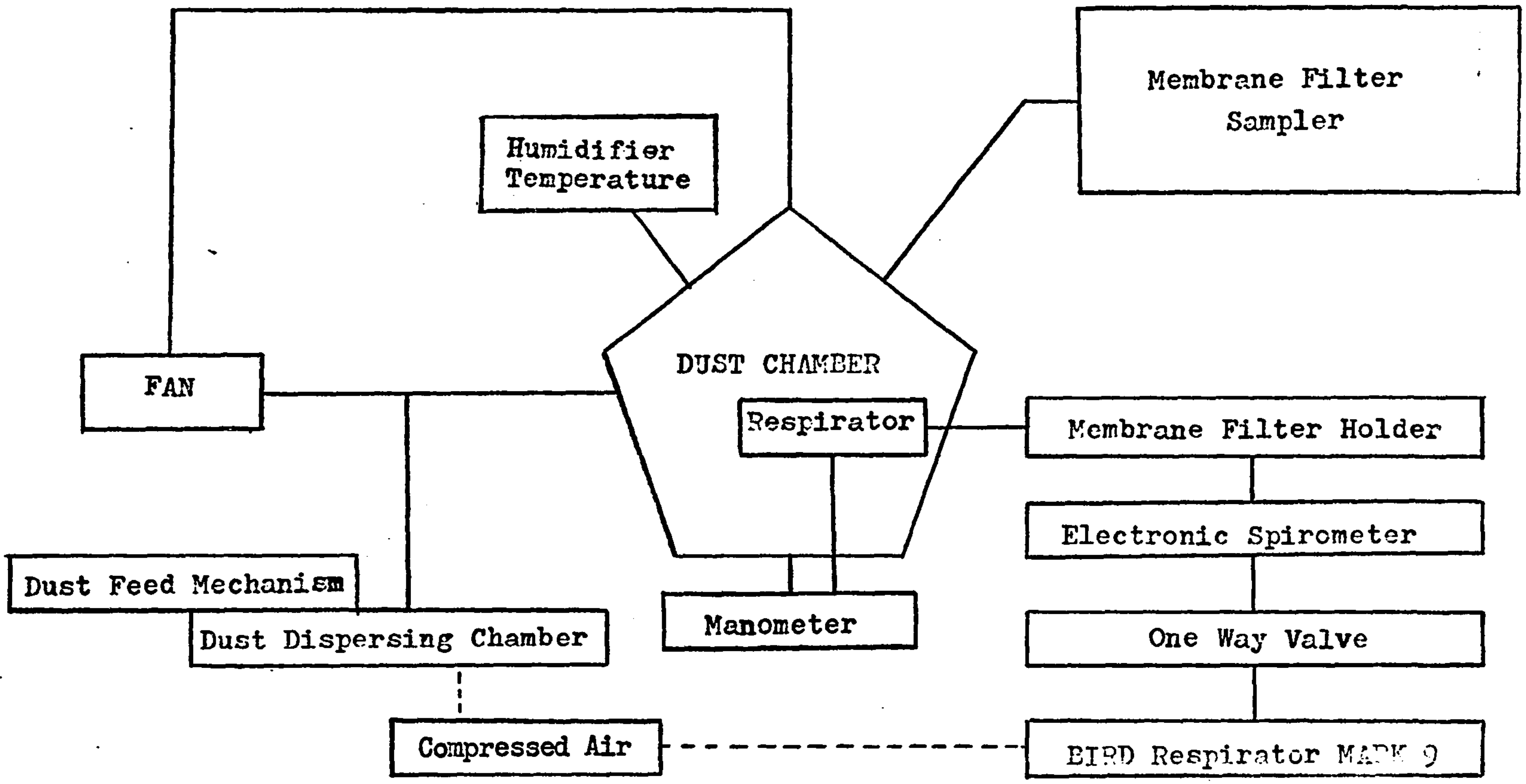


Fig. 32 EXPERIMENTAL PLAN DESIGN

it is necessary to establish a defined level of dust concentration in a chamber where the temperature and humidity are adjusted to simulate a normal working environment. Secondly, a humanlike breathing machine must be connected, together with the desired respirator, for testing, to a manikin in the dust chamber. Thirdly, it would be necessary to adopt various dust sampling instruments to obtain dust samples from within the dust chamber, and in the air which had passed through the respirator. Simultaneously, it is important to investigate and record the influence of different filter materials on the resistance of the respirators.

1.2 Assessment of Dust Samples

As a sequence to the above procedure, the collected samples must be studied, classified, and evaluated, in order to determine the efficiency of the respirators.

2. Air & Dust

When asbestos dusts are inhaled in relatively dry air, they will increase in size within the respiratory system by water absorption, in consequence of the high relative humidity which is maintained in the respiratory system. For this reason, hygroscopic particles are deposited to a higher degree than non-hygroscopic materials of the same (dry) size. This is strikingly demonstrated by the comparative results obtained by Dautrebande and Walkenhorst.[29] In view of these facts, the desirable working environment in the chamber has to be maintained by utilizing a humidifier in conjunction with a hygrometer (Fig. 33) to control the humidity.

A Canadian chrysotile asbestos dust (Fig. 34) supplied by the

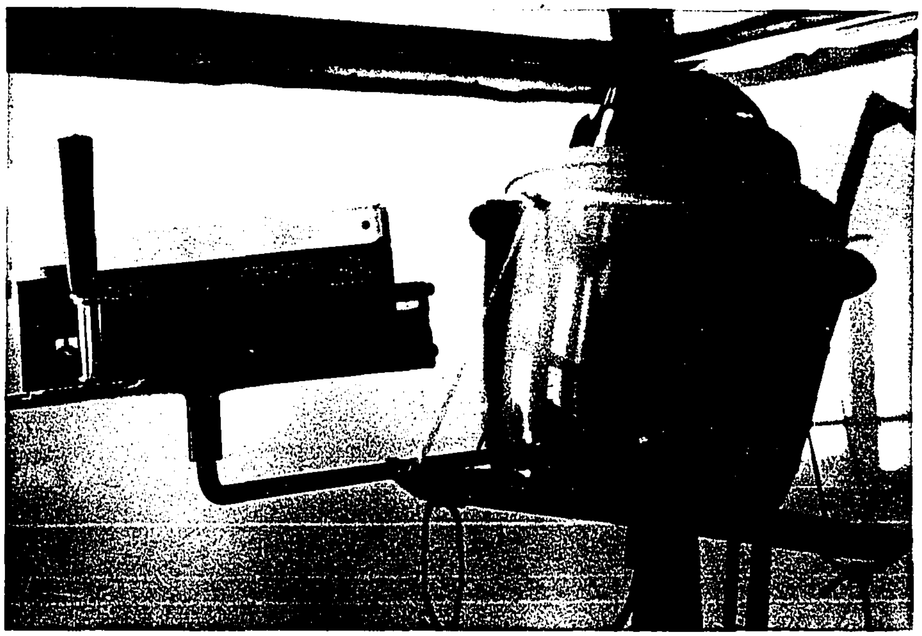


Fig. 33 Humidifier & Hygrometer

Fig. 34 Micrograph of the fibrous test dust taken with phase contrast illumination.

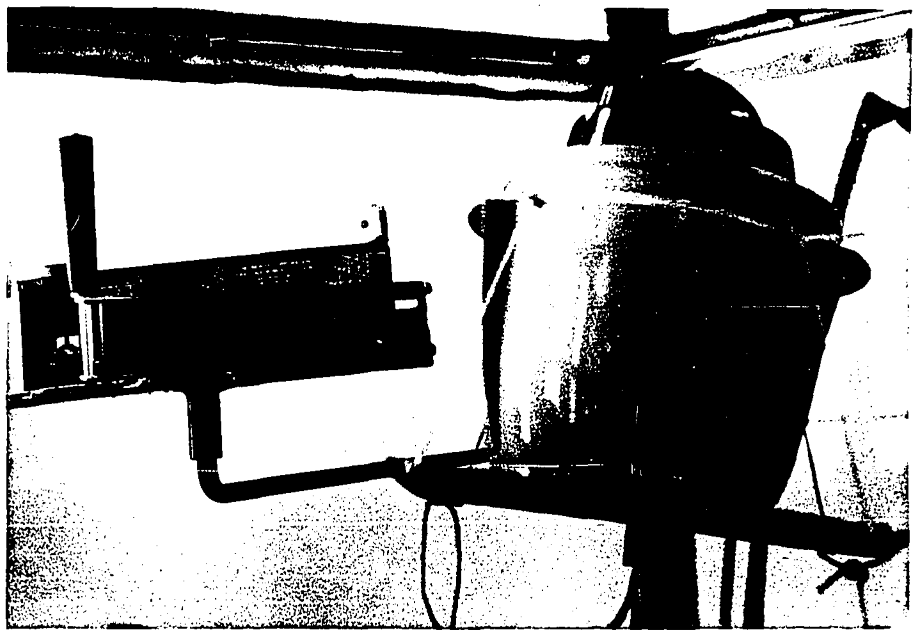


Fig. 33 Humidifier & Hygrometer

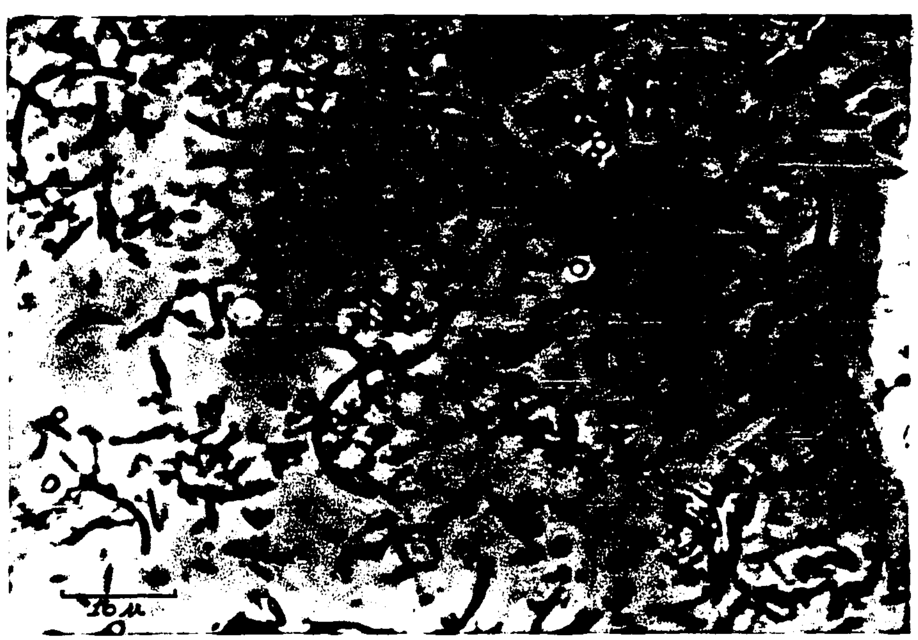


Fig. 34 Micrograph of the fibrous test dust taken with phase contrast illumination.

Johns-Manville Research & Engineering Centre, Manville, New Jersey, U.S.A., was chosen as the fibrous dust for preparing the test apparatus. This fiber is Plastibest 20, a specialty-grade fiber which contains less than 25% dust which will pass through a 200-mesh sieve. The fibrous dust was twice micro-pulverized and twice air-jet milled. The resultant fiber is predominantly of respirable size. It is a specially cleaned source of chrysotile asbestos fiber for research and development purposes.

3. Respiration

3.1 The Respiratory Function

The major function of the respiratory system (Figure 35) is to provide an adequate amount of air into the lung, then to provide arterialized blood at each moment to all of the tissue of the body. From a mechanical point of view, the lung consists of a large conglomerate of minute, expansile air spaces that ventilate to the atmosphere through a complex arborized airway. The air spaces and air passages contain fluid surfaces and tissue that possess quasi-elastic properties[43].

The function of the lung is, as already stated, to arterialize the mixed venous blood. This involves the addition of proper quantities of CO_2. This is achieved by pulmonary gas exchange which involves a number of processes (Figure 36). The first of these is ventilation: this includes both volume and distribution of the air ventilating the alveoli. A large enough volume of inspired air must reach the alveoli each minute, and this air must be distributed evenly to approximately 500 millions of alveoli with a mean diameter of 0.2 mm in the lungs[35], i.e. the volume of air going to each alveolus should be in proportion to

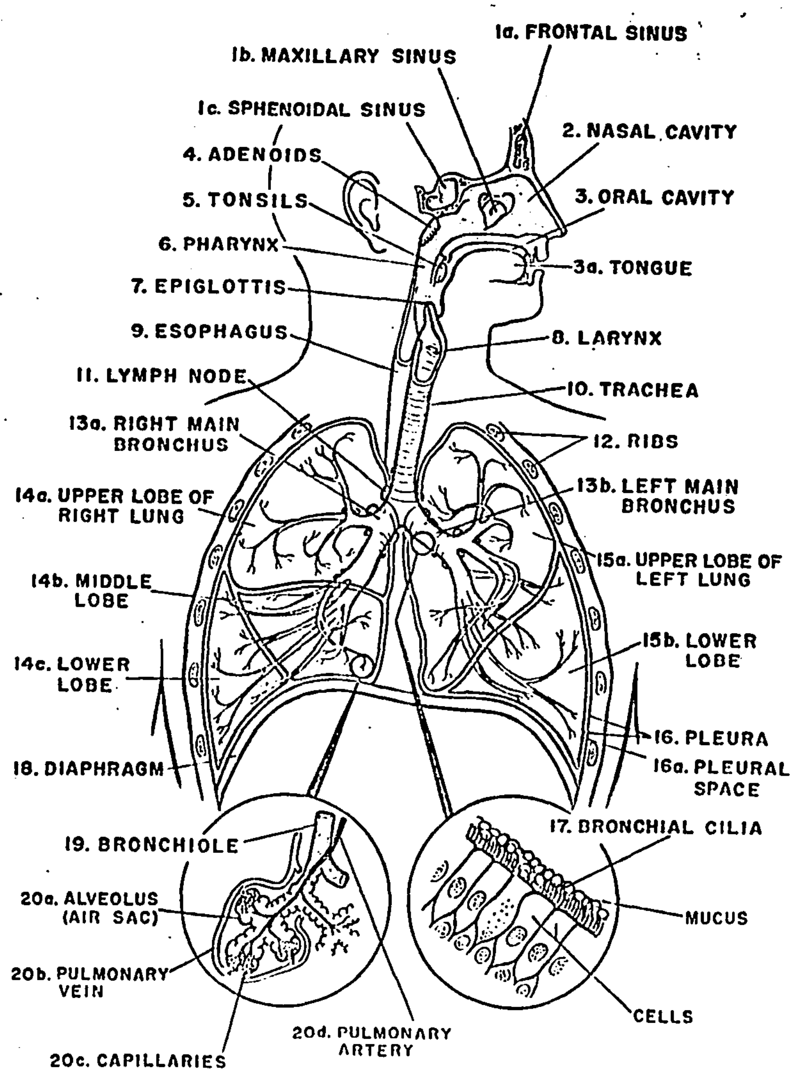


Fig. 35 The Respiratory System

(courtesy of National Tuberculosis Association.)

This chart of the RESPIRATORY SYSTEM shows the apparatus for breathing. Breathing is the process by which oxygen in the air is brought into the lungs and into close contact with the blood, which absorbs it and carries it to all parts of the body. At the same time the blood gives up waste matter (carbon dioxide), which is carried out of the lungs with the air breathed out.

1. The SINUSES (Frontal, Maxillary, and Sphenoidal) are hollow spaces in the bones of the head. Small openings connect them to the nasal cavity. The functions they serve are not clearly understood, but include helping to regulate the temperature and humidity of air breathed in, as well as to lighten the bone structure of the head and to give resonance to the voice.

2. The NASAL CAVITY (nose) is the preferred entrance for outside air into the Respiratory System. The hairs that line the inside wall are part of the air-cleansing system.

3. Air also enters through the ORAL CAVITY (mouth), especially in people who have a mouth-breathing habit or whose nasal passages may be temporarily obstructed, as by a cold.

4. The ADENOIDS are overgrown lymph tissue at the top of the throat. When they interfere with breathing, they are generally removed. The lymph system, consisting of nodes (knots of cells) and connecting vessels, carries fluid throughout the body. This system helps to resist body infection by filtering out foreign matter, including germs, and producing cells (lymphocytes) to fight them.

5. The TONSILS are lymph nodes in the wall of the pharynx that often become infected. They are an unimportant part of the germ-fighting system of the body. When infected, they are generally removed.

6. The PHARYNX (throat) collects incoming air from the nose and mouth and passes it downward to the trachea (windpipe).

7. The EPIGLOTTIS is a flap of tissue that guards the entrance to the trachea, closing when anything is swallowed that should go into the esophagus and stomach.

8. The LARYNX (voice box) contains the vocal cords. It is the place where moving air being breathed in and out creates voice sounds.

9. The ESOPHAGUS is the passage leading from mouth and throat to the stomach.

10. The TRACHEA (windpipe) is the passage leading from the pharynx to the lungs.

11. The LYMPH NODES of the lungs are found against the walls of the bronchial tubes and trachea

12. The RIBS are bones supporting and protecting the chest cavity. They move to a limited degree, helping the lungs to expand and contract.

13. The trachea divides into the two main BRONCHI (tubes), one for each lung, which subdivide into the lobar bronchi—three on the right and two on the left. These, in turn, subdivide further.

14. The right lung is divided into three LOBES, or sections. Each lobe is like a balloon filled with sponge-like lung tissue. Air moves in and out through one opening—a branch of the bronchus.

15. The left lung is divided into two LOBES.

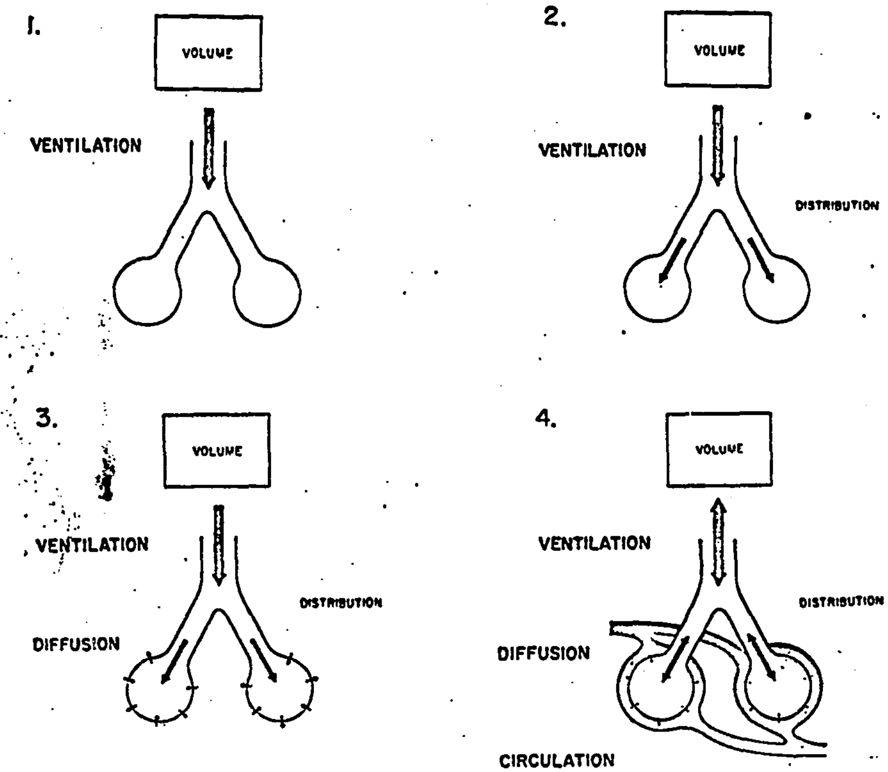
16. The PLEURA are the two membranes, actually one continuous one folded on itself, that surround each lobe of the lungs and separate the lungs from the chest wall.

17. The bronchial tubes are lined with CILIA (like very small hairs) that have a wave-like motion. This motion carries MUCUS (sticky phlegm or liquid) upward and out into the throat, where it is either coughed up or swallowed. The mucus catches and holds much of the dust, germs, and other unwanted matter that has invaded the lungs and thus gets rid of it.

18. The DIAPHRAGM is the strong wall of muscle that separates the chest cavity from the abdominal cavity. By moving downward, it creates suction to draw in air and expand the lungs

19. The smallest subdivisions of the bronchi are called BRONCHIOLES, at the end of which are the alveoli (plural of alveolus).

20. The ALVEOLI are the very small air sacs that are the destination of air breathed in. The CAPILLARIES are blood vessels that are imbedded in the walls of the alveoli. Blood passes through the capillaries, brought to them by the PULMONARY ARTERY and taken away by the PULMONARY VEIN. While in the capillaries the blood discharges carbon dioxide into the alveoli and takes up oxygen from the air in the alveoli.



PROCESSES INVOLVED IN PULMONARY GAS EXCHANGE

The alveoli, where rapid gas exchange occurs, are represented by rounded areas; leading into these are tubes depicting the conducting airways or anatomic dead space (light gray in *4*) in which no effective gas exchange occurs. Rectangular blocks indicate the minute volume of breathing. The two arrows entering the alveoli show distribution of total inspired gas (large arrow) to various alveoli. In *3* and *4*, small arrows crossing alveolar walls designate the process of diffusion of O_2 out of the alveoli into the blood and of CO_2 from the blood into the alveoli. The shaded channel surrounding the alveoli in *4* represents pulmonary blood flow; it enters the capillary bed as mixed venous blood (dark) and emerges as arterialized blood (light). In *5*, the left side is a summary of the processes of ventilation, diffusion and circulation. The right side represents the pulmonary "tissues" responsible for the mechanical properties of the lung: parallel lines in the conducting airways represent the fine airways responsible for airway resistance; the springlike coil surrounding the alveoli represents the elastic tissues of the lung, and stippled areas in the coil are the non-elastic tissues

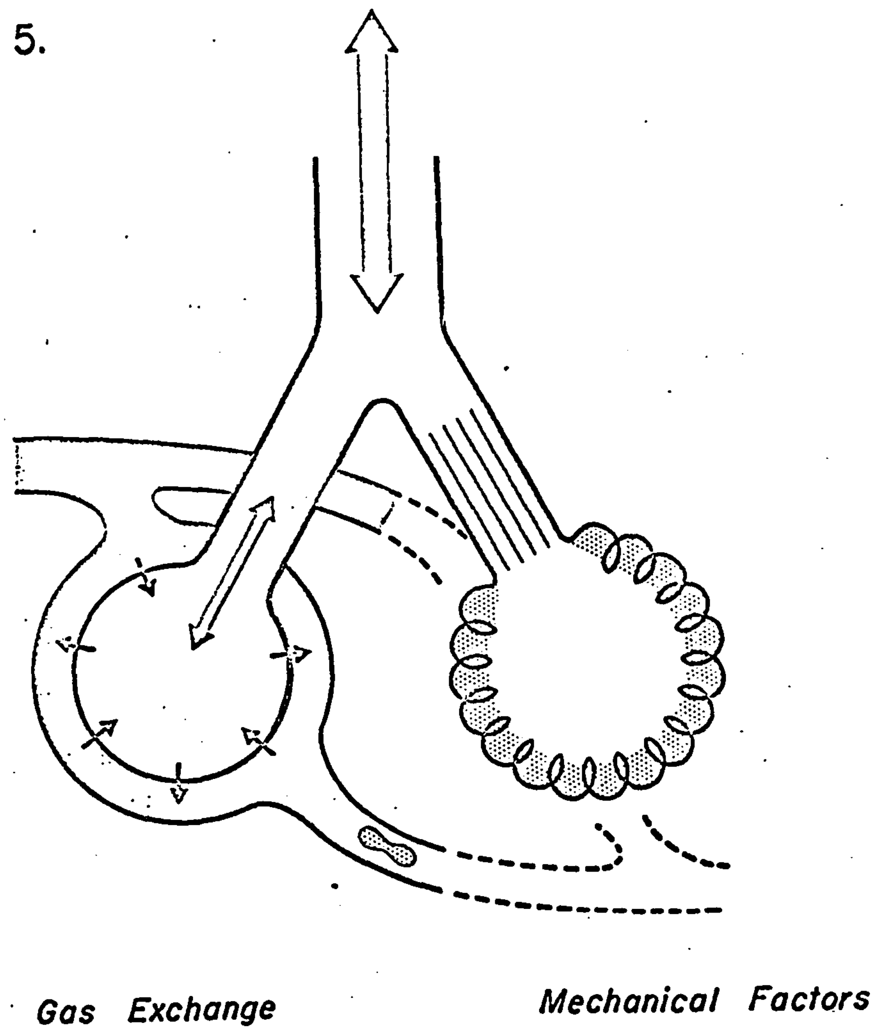


Fig. 36

(Reference 25)

the volume of that alveolus. The second of these is the process of diffusion, by which O_2 and CO_2 pass across the alveolocapillary membranes. And, the third is pulmonary capillary blood flow; this must be adequate in volume and all of the mixed venous blood must be distributed evenly to all the ventilated alveoli[25].

3.11 The Lung Volumes:

For many years, the only tests of pulmonary function were the measurements of the lung volumes (Figures 37 & 38). Actually, these do not evaluate function since they are essentially anatomic measurements. Changes in the lung volumes, however, are often caused by alterations in physiological process, and for this reason it is important to know normal values.

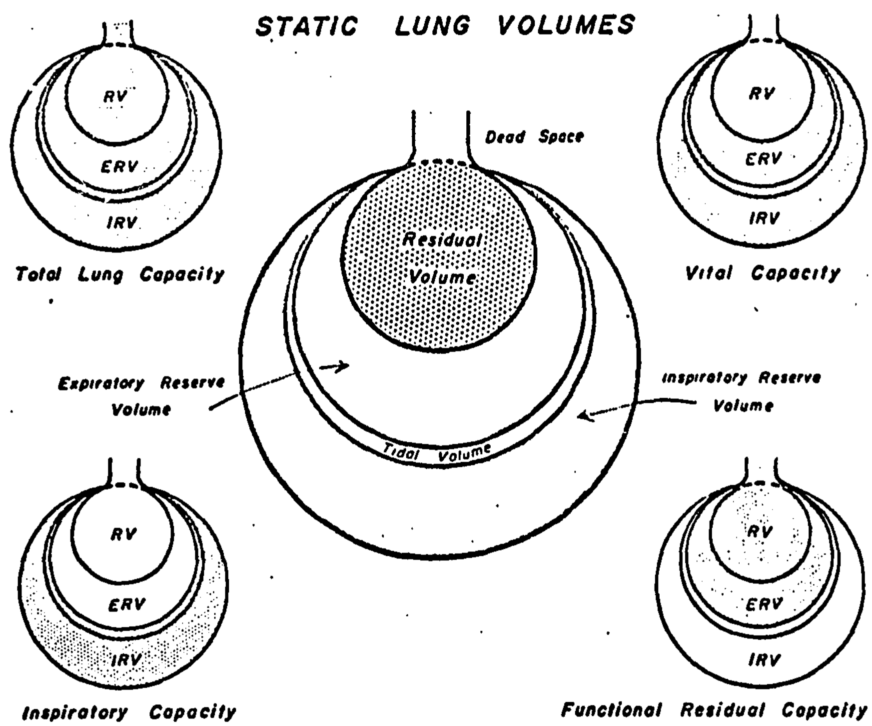
Pulmonary Function Tests: The most commonly used tests and the normal values are as follows[25, 108]:

(1) Total Lung Capacity: The sum of the vital capacity and the residual volume. This, in other words, is the total volume of air in the lungs at maximal inspiration. Its normal value is about 5500 to 6000 cc.

(2) Vital Capacity: The maximal amount of air one can expire after a maximal inspiration. Its normal average value is about 4000 to 5000 cc.

(3) Inspiratory capacity, (formerly complemental or complementary air) is the maximal volume of gas that can be inspired from the resting expiratory level. Its normal volume is 3600 cc.

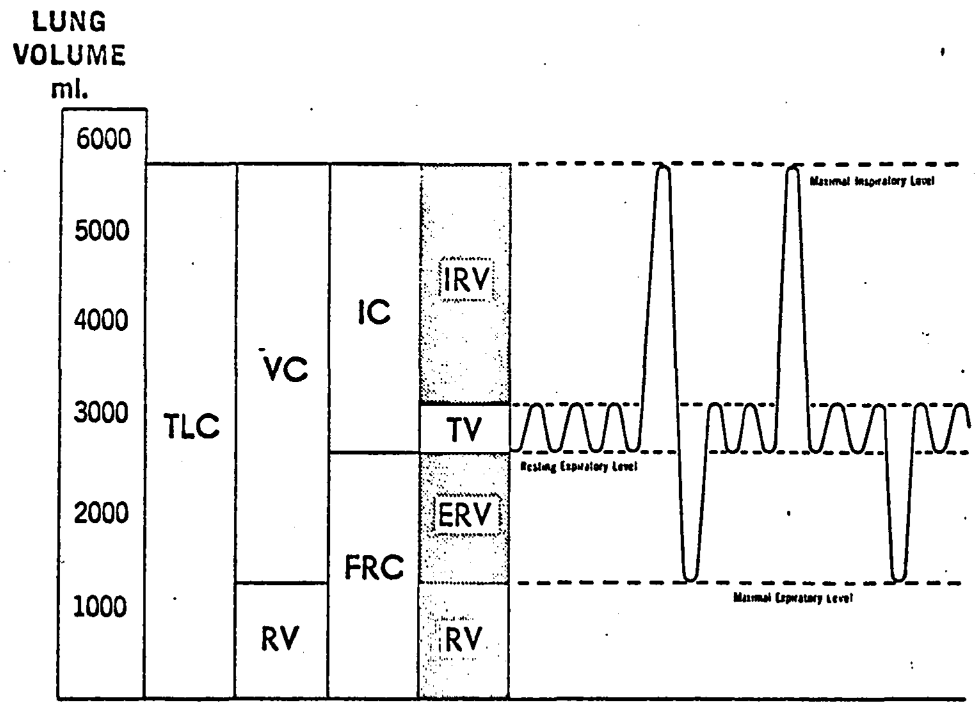
(4) Functional residual capacity is the sum of the expiratory reserve



The large central diagram illustrates the four primary lung volumes and approximate magnitude. The outermost line indicates the greatest size to which the lung can expand; the innermost circle (residual volume), the volume that remains after all air has been voluntarily squeezed out of the lungs. Surrounding the central diagram are smaller ones; shaded areas in these represent the four lung capacities. The volume of dead space gas is included in residual volume, functional residual capacity and total lung capacity when these are measured by routine techniques.

Fig. 37 Static Lung Volumes

(Reference 25)



TLC — Total lung capacity — volume of air in the lungs after a maximum inspiration.

VC — Vital Capacity — volume of air which can be expelled from the lungs with maximum effort after a maximal inspection.

IC — Inspiratory Capacity — maximum volume of air which can be inspired after a normal expiration.

FRC — Functional Residual Capacity—volume of air present in the lungs after a normal expiration.

TV — Tidal Volume — volume of air moving in or out of the lungs during each cycle.

IRV — Inspiratory Reserve Volume — maximum volume of air which can be inspired following a normal inspiration.

ERV — Expiratory Reserve Volume — maximum volume of air which can be expired following a normal expiration.

RV — Residual Volume — volume of air remaining in the lungs after a maximal expiration.

MV — Minute Volume — volume of air passing in or out of the lungs in one minute. (Rate x TV).

Fig. 38 Lung Capacities and Volumes

(Reference 25)

and the residual volume.

(5) Tidal volume is the amouht of air one normally inspires or expires during each respiratory cycle. The normal value is about 500 cc.

(6) Inspiratory reserve volume (formerly complemental or complementary air minus tidal volume) is the maximal amount of gas that can be inspired from the end-inspiratory position.

(7) Expiratory Reserve Volume: The amount of air one can expire from the end point of passive expiration. The normal value is about 1,000 cc.

(8) Residual Volume: The volume of air remaining in the lungs after one has expired all the air he possibly can. The normal value is about 1,500 cc.

(9) Rate of Breathing: This is the total circulation of air movement per minute. The average rate of breathing is about 11-14/minute in healthy individuals. The normal rate is 12/minute.

(10) Minute Value: This is the total amount of air breathed per minute. The normal is 6 liters per minute.

(11) Physiological Dead Space: This is the anatomic dead space and the gas ventilating alveoli in excess of that required to arterialize blood. The normal is about 150 cc.

(12) Maximal Expiratory Flow Rate: This represents the maximal rate of flow obtained while performing a vital capacity exercise. The normal is usually 4 to 6 liters per second.

(13) Maximal Breathing Capacity: The maximal volume of air that can be ventilated during a 1-minute period with maximal effort. The normal

value for the male is 125 to 150 liters per minute, for the female is 100 liters per minute.

(14) Alveolar Ventilation: The actual amounts of inspired air which enter the alveoli each minute. The normal value is 2.3 liters per minute.

(15) Oxygen Consumption: The amount of oxygen taken in by the body per minute. The normal values range from 110 to 150 cc per minute.

(16) Carbon Dioxide Excretion: The amounts of carbon dioxide given off by the body. Normal values range from 88 to 120 cc per minute.

(17) Respiratory Quotient: The carbon dioxide excretion divided by the oxygen consumption. The normal value is 0.8.

Furthermore, Fowler[42] found that in a normal young man's lung, about 40% of the inspired air provides ventilation to only one-sixth of the lung volume, leaving the remaining 60% to ventilate the other five-sixths of the lung volume.

3.12 Mechanics of Ventilation:

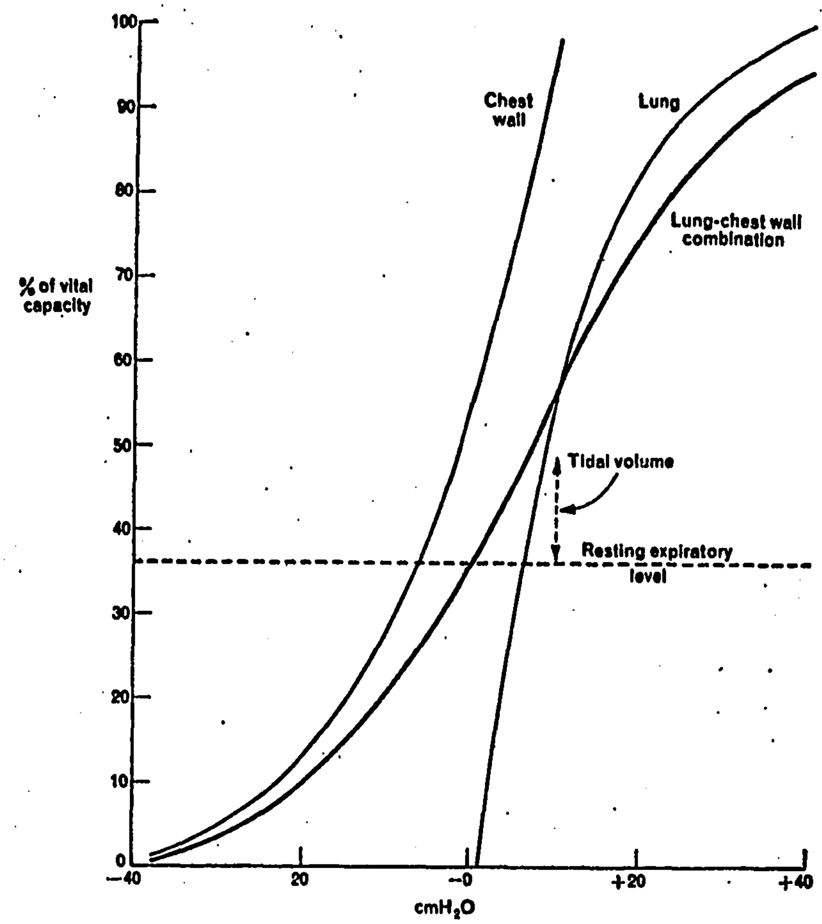
Pulmonary ventilation is produced by the rhythmic contraction of the inspiratory muscles which cause expansion of the thorax and lungs. The respiratory muscles must overcome both the elastic recoil of the tissues and the resistance of the airways to the flow of air through them. The elastic recoil is a static force determined by the size and mechanical properties of the chest whilst airway resistance is a dynamic measurement which depends on the size and properties of the airways[109].

The elastic recoil of the lung is produced by two components of approximately equal magnitude. These are the surface tension of the fluid lining the alveoli and the elasticity of the lung tissue itself. As with the chest wall, the elastic recoil of the lung is proportional to the volume change throughout the normal range of lung inflation (Figure 39), and the compliance is given by the ratio.

Volume Change (Change in Transpulmonary Pressure): Since this measurement is made during a period of breathholding, it is known as the static compliance. Lung compliance is similar in magnitude to chest-wall compliance and may be taken as 200 ml/cm H_2O in a normal adult.

Rahn[89] used three types of measurement for the pressure-volume diagram of the lung: (1) maximum expiratory and inspiratory pressure at different lung volumes, (2) relaxation pressures at different lung volumes, (3) vital capacities, tidal air, and inspiratory and expiratory reserves at different lung pressures. Then, he exerted for a few seconds a maximal inspiratory or expiratory effort through a mouthpiece connected to a mercury manometer. Since this was a closed system, no actual inspiration or expiration occurred. In consequence of the muscular effort, the pressure in the lung was increased or decreased in relation to atmospheric pressure. The result of his experiment is that, during relaxation, an increase of 1 mm Hg in the pulmonary pressure increases the lung volume by 94 ± 35 cc. The pressure-volume, related to the thorax and lung, of breathing is shown in Figures 40 & 41.

A laboratory experiment had been done by Mushin[82] for the difference existing between "pressure at the mouth" and "pressure in the alveoli" (Figure 42). The pressure as recorded at the "mouth" rises to 20 cm H_2O.



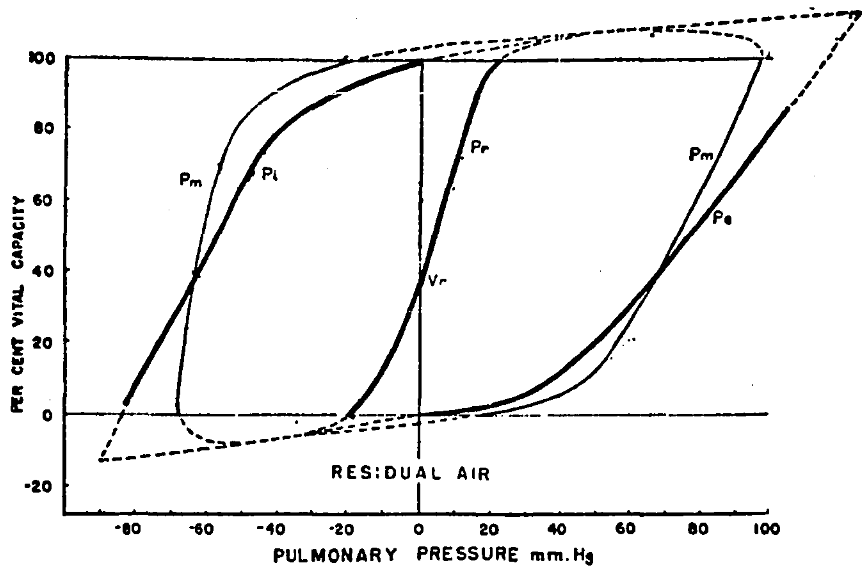
Pressure-volume diagram of lung, chest wall and lung-chest wall combination. A transpulmonary pressure gradient of 5 cmH_2O is required to inflate the lung to the resting expiratory level. The ratio

$$\frac{\Delta V}{\Delta P} \text{ (= compliance)}$$

is constant over the normal range of lung inflation. At higher or lower lung volumes the relationship is alinear, the alinearity at the height of inspiration being determined mainly by the lung whilst the alinearity in maximum expiration is determined mainly by the chest wall.

Fig. 39

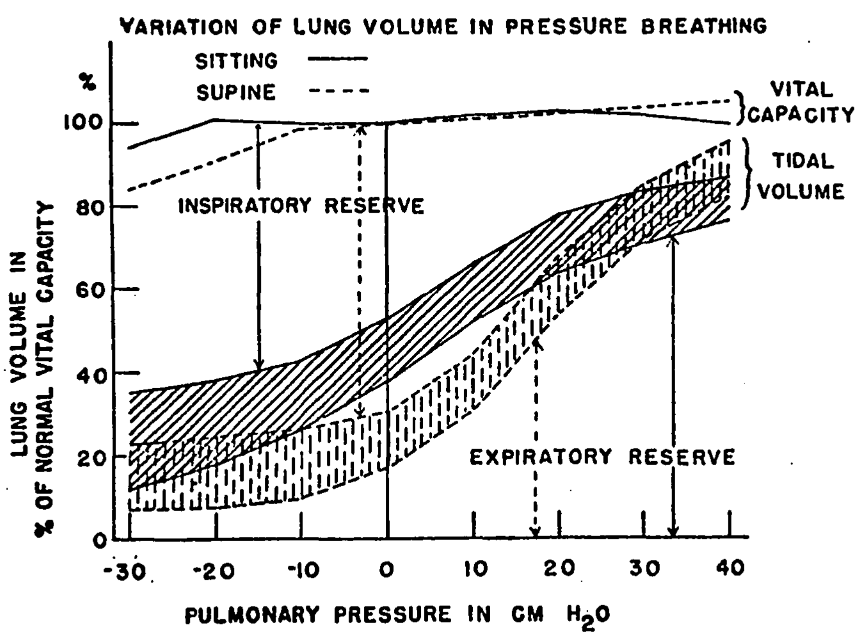
(Reference 109)



. Pressure-volume diagram of breathing. *Pi* and *Pe*, maximal inspiratory and expiratory pressures respectively; *Pm*, maximal pressure exerted by muscles; *Pr*, relaxation pressure; and *Vr*, relaxation volume.

Fig. 40

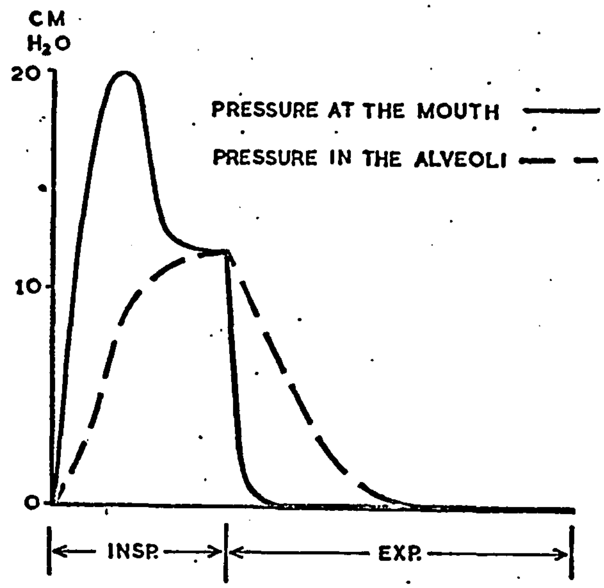
(Reference 89)



. Variation of lung volume in pressure breathing. The effects of intrapulmonary pressure on vital capacity, tidal volumes and expiratory and inspiratory reserves.

Fig. 41

(Reference 89)



-Graph showing the difference that can exist between 'pressure at the mouth' and 'pressure in the alveoli'. Reproduced from recordings made during a laboratory experiment with an 'artificial lung' having a compliance = 0·05 l./cm H_2O and an airway resistance = 2 cm H_2O/(l./sec). Controlled respiration was by squeezing a bag, the pattern being a quick and forceful inspiratory phase followed by a longer expiratory phase.

Fig. 42

(Reference 82)

3.2 Artificial Pulmonary Respiration

3.21 Artificial Respiratory Tract

The artificial respiratory tract used in these experiments, is coupled to a mechanical breathing machine (Bird Mark 9 respirator). Only the inhalation action of the latter is used in the tests. A 3/4" plastic hose connects the Bird Mark 9 respirator to a humanlike head model (Figures 43A & 43B) which is fixed inside the dust cloud chamber.

A funnel-shaped plastic section is installed in the throat of the manikin in order to prevent the dust from settling between the mouth and throat. Static Pressure Tubes are installed into the throat and at the outside of the head model in the chamber, respectively. These two tubes are connected to a micromanometer (Figure 44) whose readings cover a range of 300 mm and can be taken quickly and readily to 0.02 mm by subdividing the graduations of 0.2 mm by eye. The main purpose of this installation is to survey the resistance of the respirator.

A standard membrane filter holder is installed behind the manikin for collecting fibers which penetrate the respirator. Downstream from the filter holder, there is a probe from an electronic spirometer (Figure 45) whose work is to measure the air flowrate. This unit is specially designed for measuring the air flowrate during respiration. Its measurement ranges are: Tidal Volume, 0 to 2 liters; and Minute Volume, 0 to 30 liters per minute.

A one-way-valve, fitted between the spirometer and the Bird Mark 9, prevents any reversal flow caused by the differential pressure existing between the Bird Mark 9 and the chamber during the respiratory

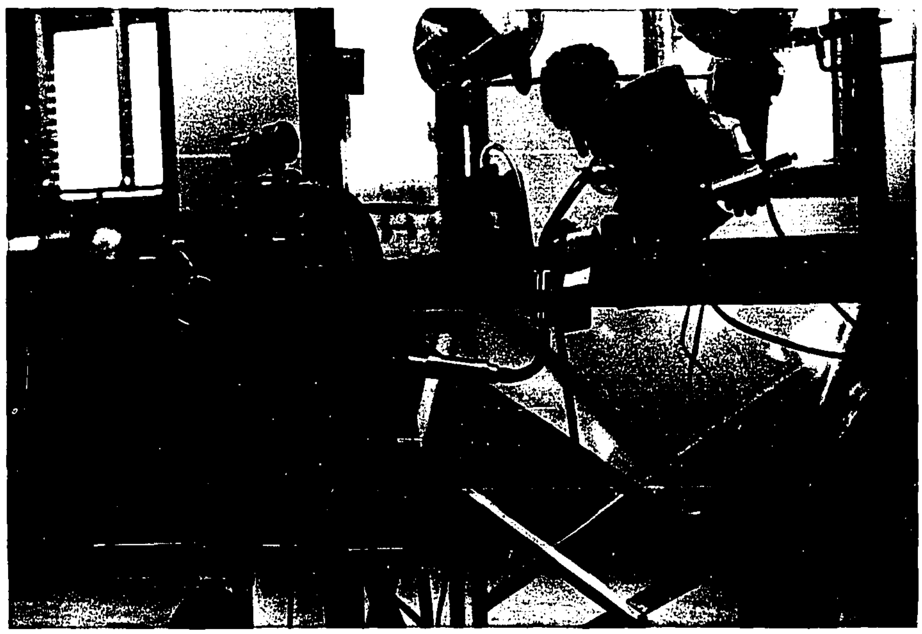


Fig. 43A Artificial Respiratory Tract

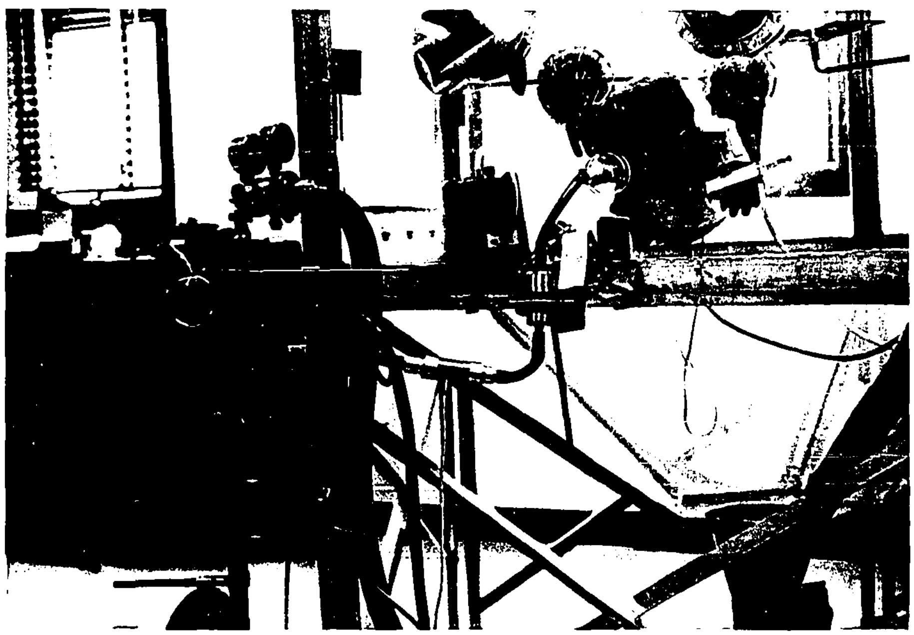


Fig. 43A Artificial Respiratory Tract

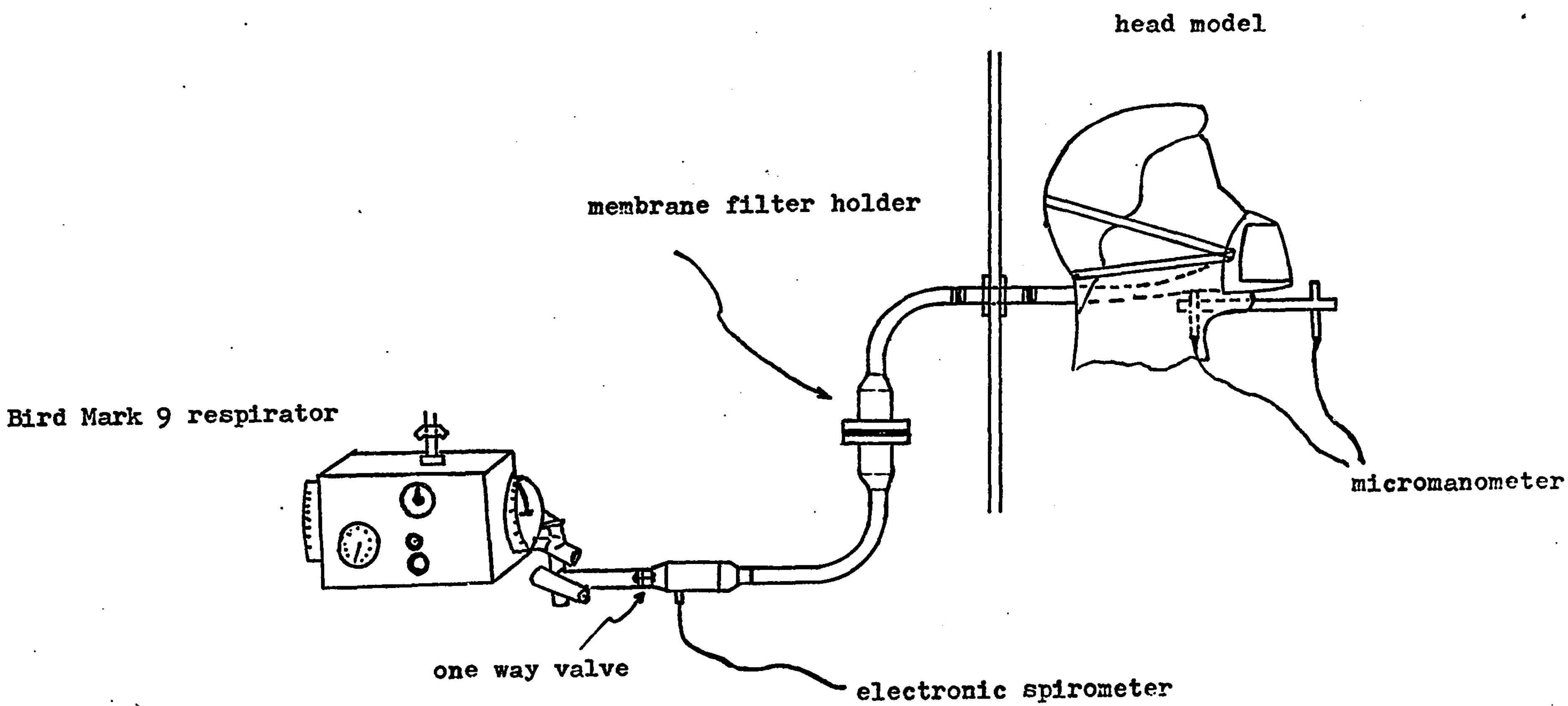


Fig. 43B Artifical Respiratory Tract

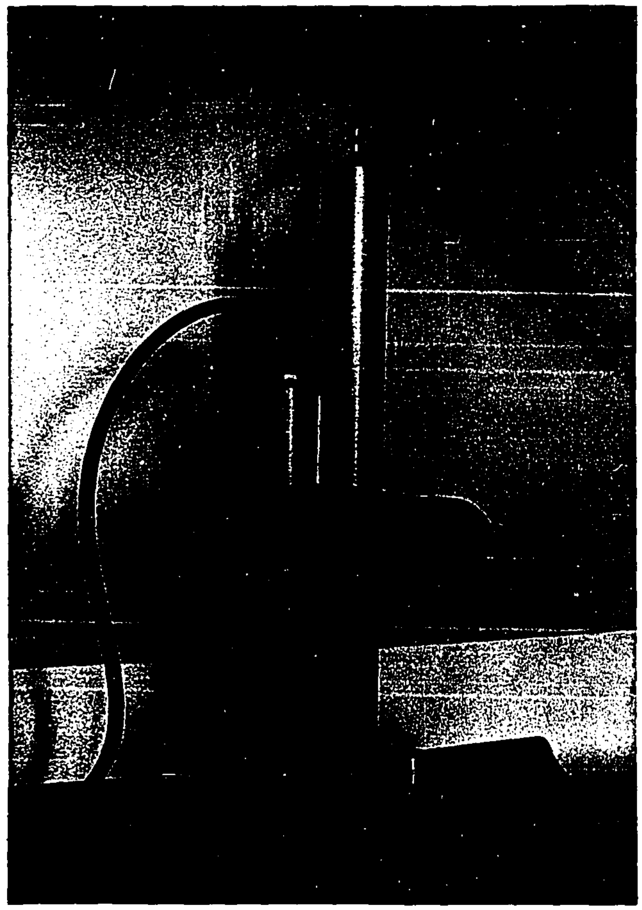


Fig. 44 Micromanometer

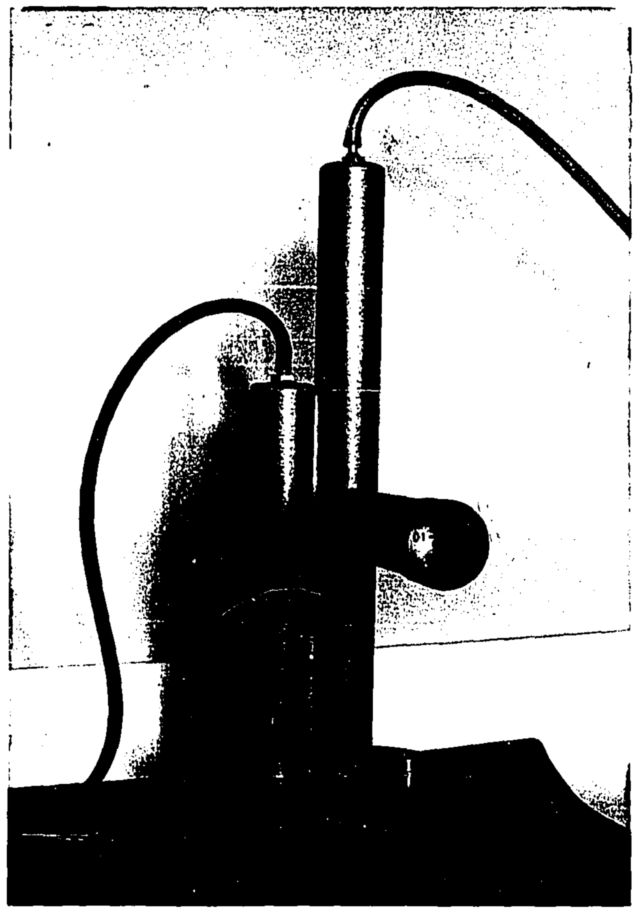


Fig. 44 Micromanometer

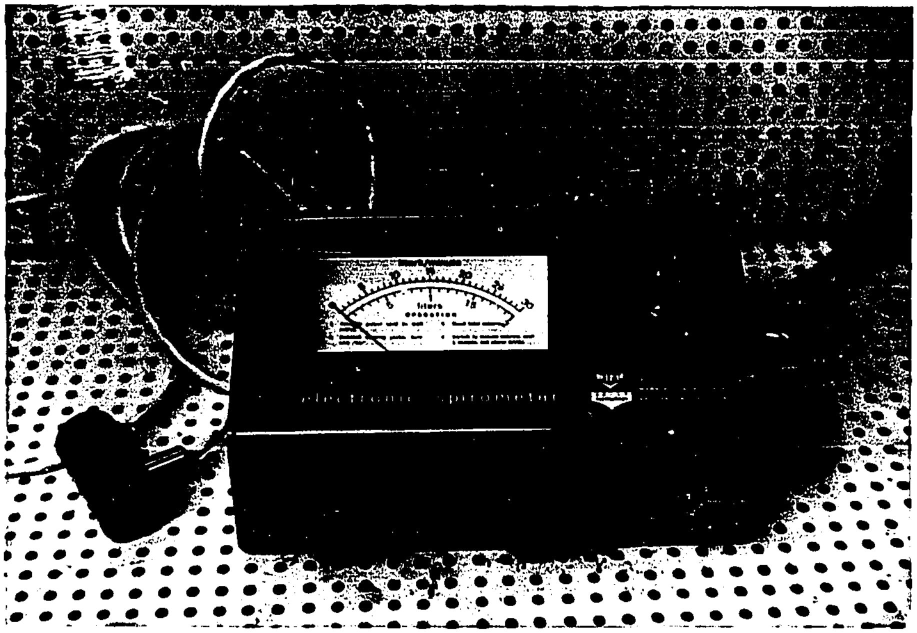


Fig. 45 Electronic Spirometer

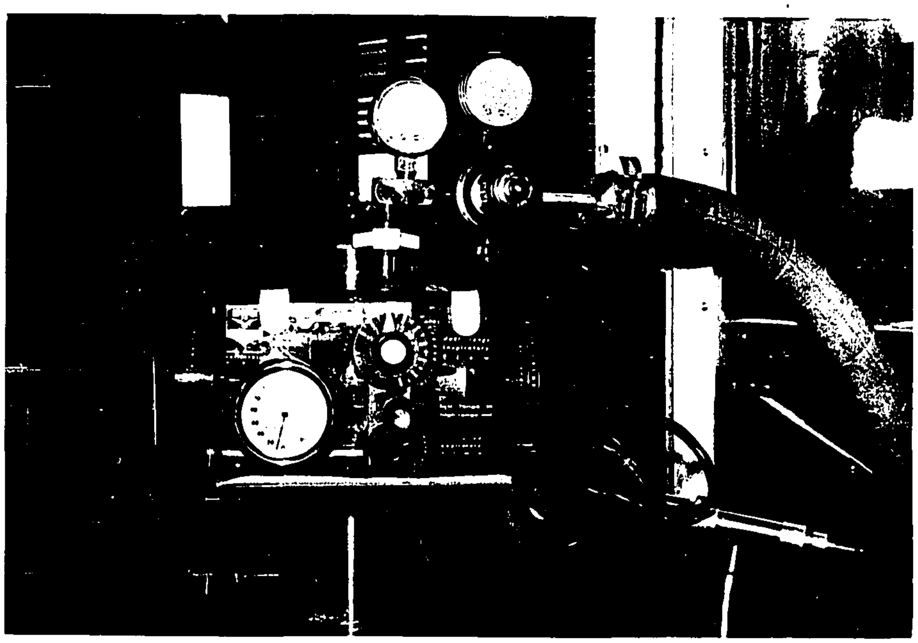


Fig. 46 Bird Mark 9 Respirator

Fig. 45 Electronic Spirometer

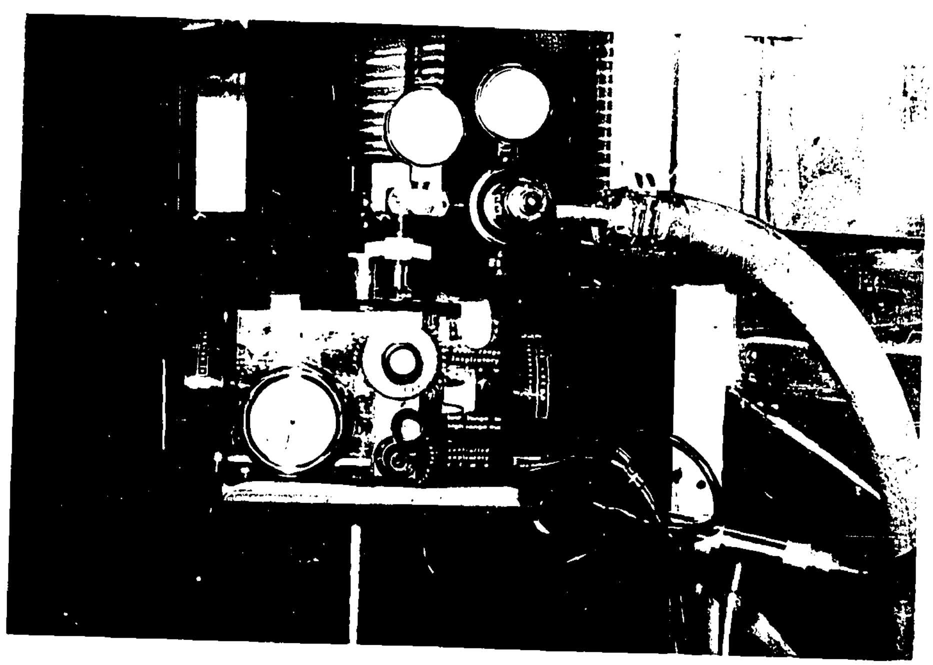


Fig. 46 Bird Mark 9 Respirator

cycle. This enables the membrane filter to obtain accurate samples during the test periods.

3.22 Mechanical Ventilator - BIRD Mark 9:

The Bird Mark 9 (see Figure 46) positive-negative phase respirator was developed by Bird engineers to provide qualified physicians with a universal function in a positive-negative respirator. It is a highly professional type of respirator capable of ventilating the smallest laboratory animals or the largest zoological species. In clinical and research applications, it will ventilate the smallest neonate or the largest man. Almost any conceivable flow/pressure combination during inspiration or expiration can be easily created to meet existing physiopathology(17). A breathing condition similar to that in humans can be obtained through an artificial respiratory tract from this machine.

This mechanism is driven by compressed gas delivered at 50 to 85 lbs./sq. inch. The gas source is connected to the machine through a needle valve which controls inspiratory flow rate. It then passes through a sliding valve to two ports. Gas flow through one of these closes the expiratory portion of the non-breathing valve. Gas from the other port passes to the airmix control and thence to the main chamber; this is connected to the manikin through the non-rebreathing valve. As pressure builds up in the chamber, a diaphragm is forced to the left against the pull of the right magnet (Figure 47); the position of which controls the inspiratory pressure. Inspiration ends when the force applied to the diaphragm overcomes that exerted by the magnet and the diaphragm moves to the left, carrying with it the sliding valve. This cuts off the supply of fresh gas. The valve is

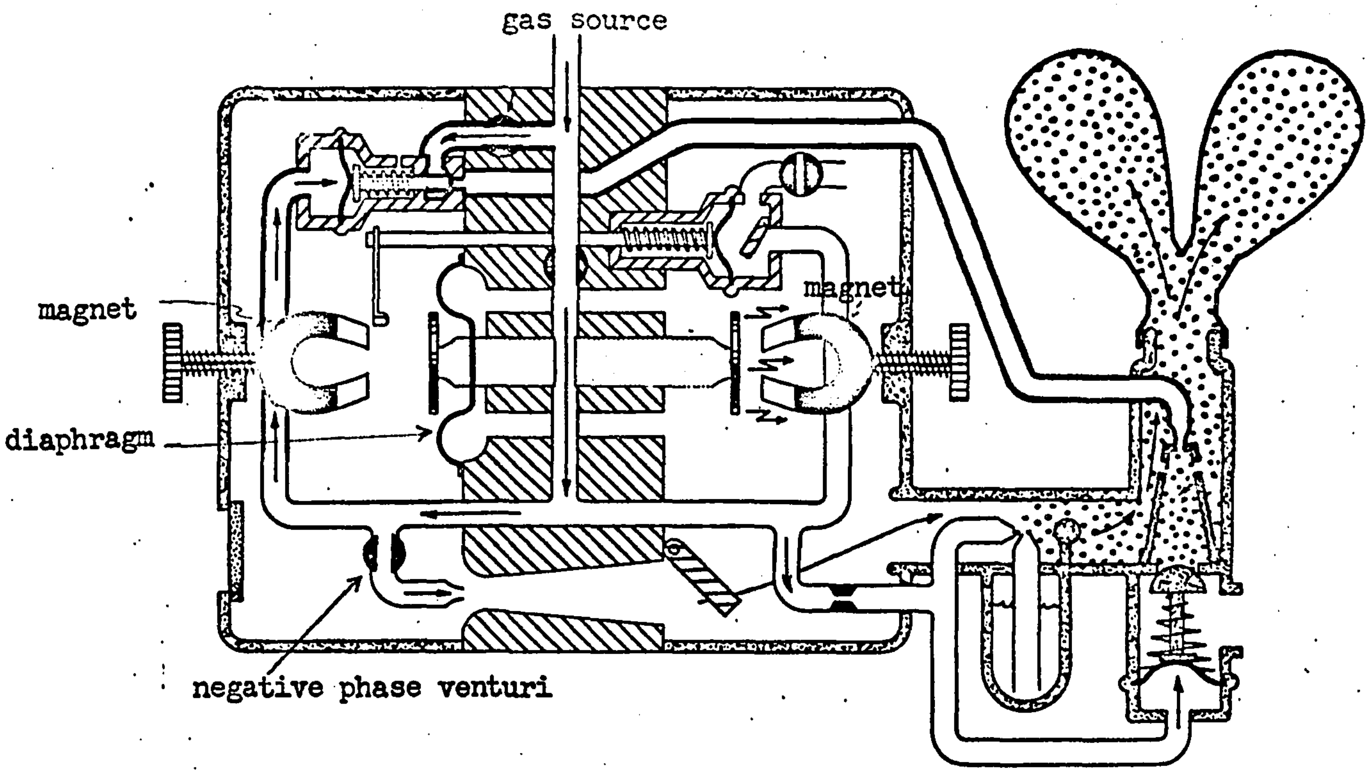


Fig. 47 Inhalation

(Bird Space Technology Inc.)

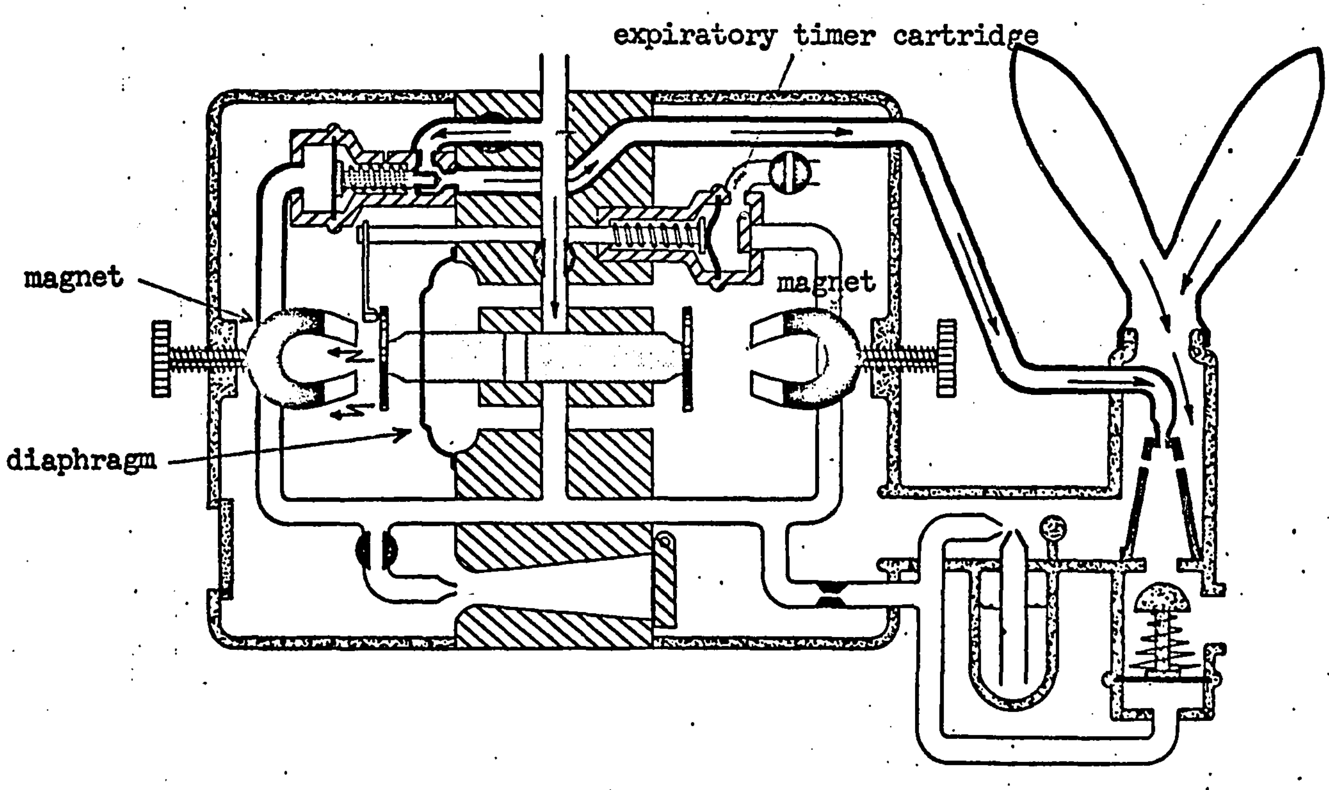


Fig. 48 Exhalation

(Bird Space Technology Inc.)

held in this position by the left magnet (Figure 48). The pressure closing the expiratory port of the non-rebreathing valve leaks away through an adjustable bleed valve and through the nebulizer jet and expiration commences.

As the pressure in the main chamber drops, the pull of the right magnet snaps the diaphragm back and inspiration starts gain. The position of the left magnet, balanced against the pull of the right magnet, controls the duration of expiration, and by increasing the pull of the left magnet, the machine can be made patient-triggered. When this is done, an additional small chamber is included (diaphragm valve). This is filled with compressed gas during inspiration, and it leaks away during expiration by a controlled leak. When the pressure falls sufficiently, the diaphragm at the end of chamber (diaphragm valve) pulls on a lever, which in turn pulls the valve rod back to the inspiratory position.

The capacity of this machine is as follows:

Positive inspiratory pressure range .... 0 to 200 mm Hg

Negative expiratory pressure range ....0 to -20 mm Hg

Inspiratory flowrate, low range 0 to 200 liters per minute at 25 mm Hg resistance to flow.

Inspiratory flowrate, high range 0 to 272 liters per minute at 40 mm Hg resistance to flow.

4. Dust Cloud Chamber

In order to simulate actual working conditions in a plant, the dust concentration in a test chamber must be accurately controlled if comparative results are to be obtained.

The design of a suitable dust cloud chamber should be guided by the following requirements;

(1) Uniform air flow and distribution in the whole dust cloud chamber.

(2) Include an apparatus which introduces the dust particles into the dust chamber uniformly.

(3) Be air-tight with the dust cloud flowing through the chamber.

(4) An even dust distribution throughout the chamber.

(5) A controllable dust concentration level which can be maintained for a long period of time.

(6) Means to decrease the electrostatic forces within the chamber.

(7) Incorporate a means of introducing the dust to the chamber and removing it from the chamber.

4.1 Chamber Shape and Construction

The optimum design of dust chamber would be a circular or at least a regular polygon horizontal cross-section, with uniform inlet and outlet connections. Since it is quite difficult to construct a circular chamber, the most practicable one is a polygon type. According to the empirical experimentation, the easiest controllable dust concentration is achieved in a chamber having a volume ranging between 64 and 216 cubic feet. The shape of the chamber chosen was a pentagonal pyramid (see Figures 49A & 49B). The sides of the pentagon are 3.5 feet in length and the height of the cylindrical part is 2.9 feet. These dimensions give a cross-sectional area of about 2.1 square feet. The volume is about 60 cubic feet, and both ends of pyramid are equal sided: each at a length of 3.5 feet and 1.7 feet height. Each volume of pyramid is 15 cubic feet

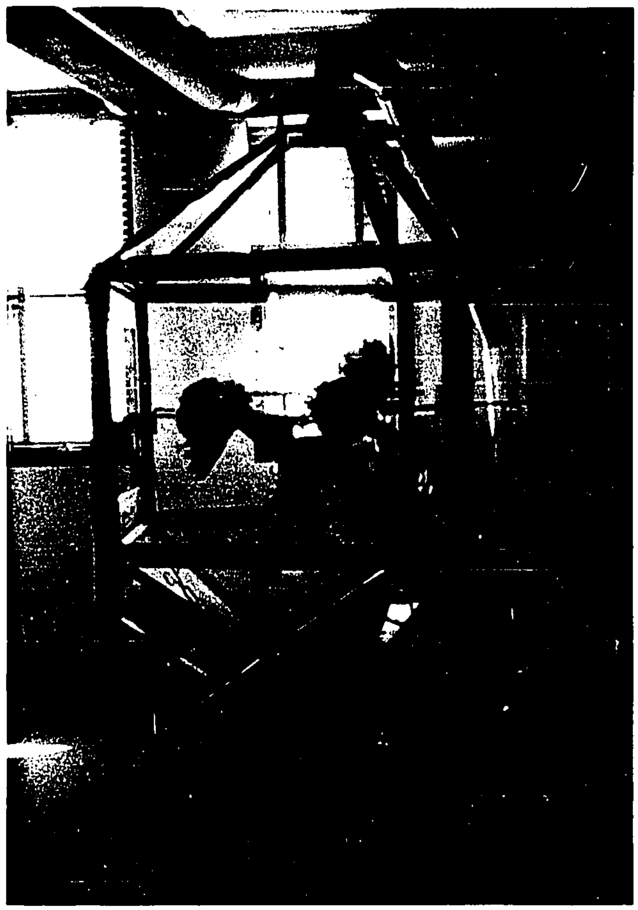


Fig. 49A Dust Cloud Chamber

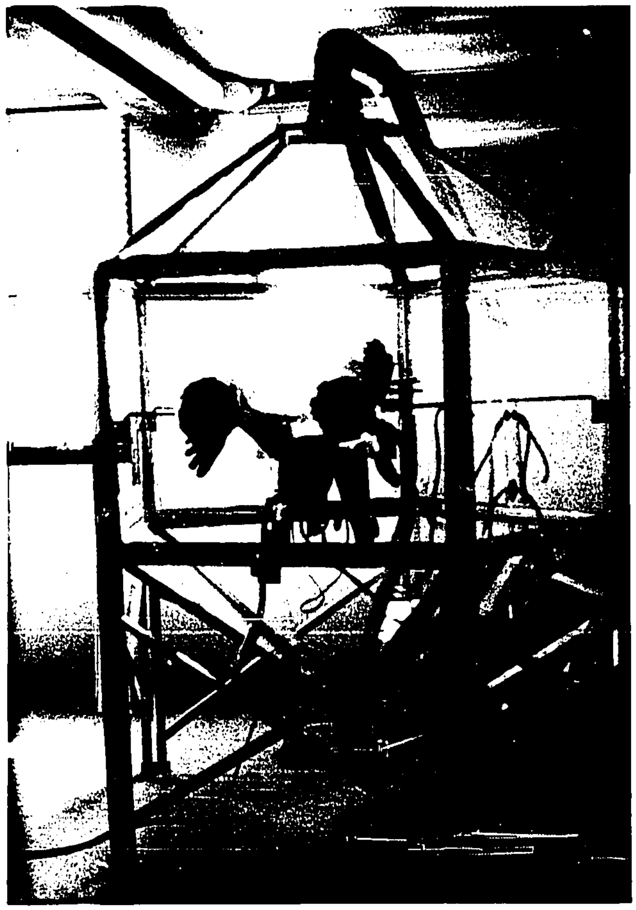


Fig. 49A Dust Cloud Chamber

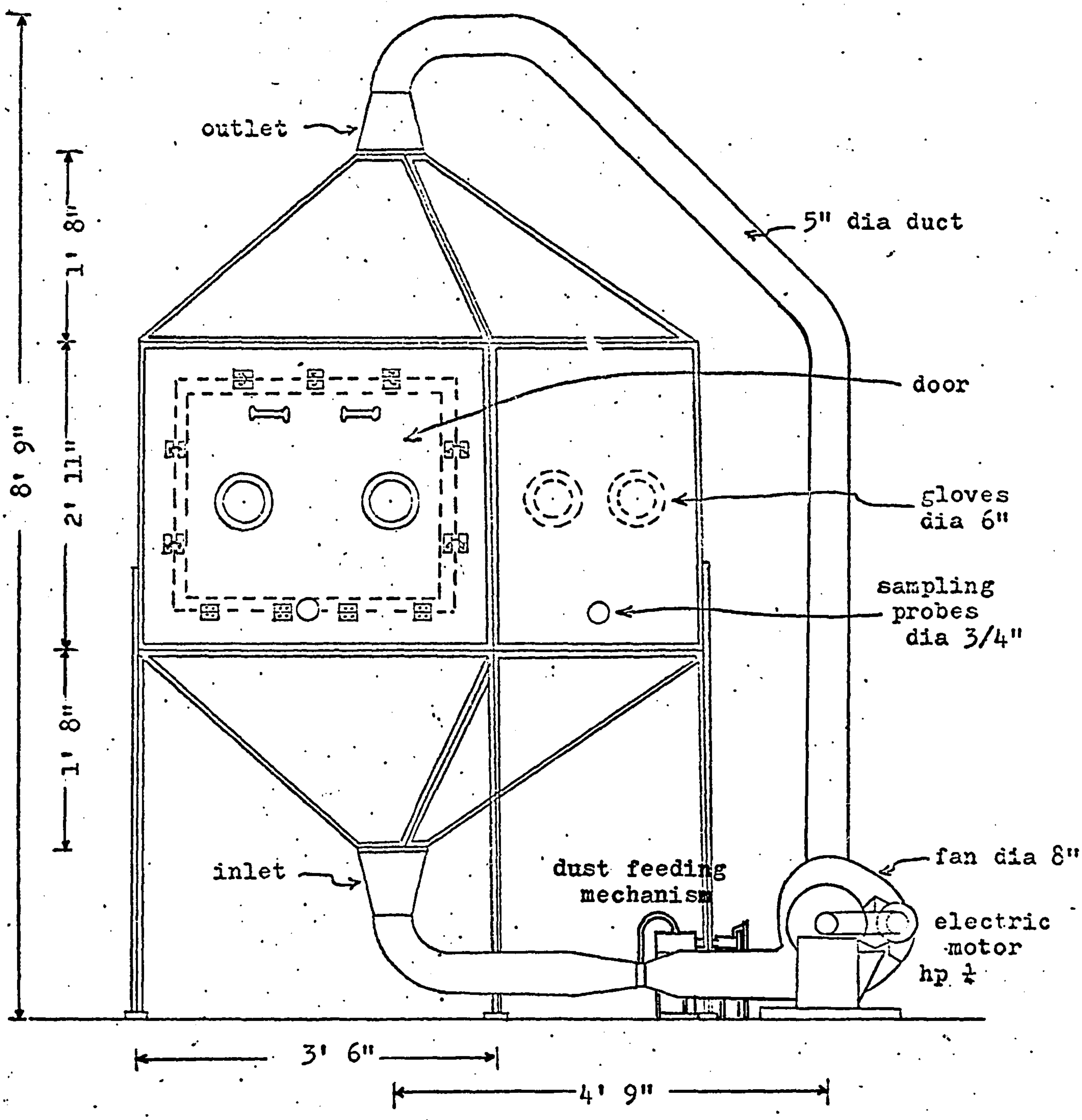


Fig. 49B Dust Cloud Chamber

so that the whole chamber has a total volume of 90 cubic feet.

In order to overcome the static electricity problem, the construction of the chamber is mainly of plexiglass, and on which the internal surfaces will be coated with detergent which contains sodium sodensol sulfide. The framework is constructed of aluminum alloy and the joints were made airtight by aluminum pastes. At both sides, there is also one pair of 31" long rubber gloves for handling and operating dust sampling instruments inside the chamber. The size of galvanized iron connective duct is 5" in diameter and a radial bladed type exhaust fan is used. The fan delivers 332 c.f.m. at a S.P. of 1/8" H_2O, and is driven by a 1/4 horsepower motor. A venturi tube is used to introduce the dust from the dust dispenser (see Figure 50) into the connective duct. The inlet of the dust pipe at the venturi in the connective duct is simply a 3/16" diameter tube welded onto the galvanized iron duct.

4.2 Generating Dust Cloud Apparatus

A simple dispenser for generating dust clouds from standard reference samples of asbestos has been developed by Timbrell, Hyett and Skidmore[115].

A satisfactory dust dispenser must have two essential characteristics:

(1) Be capable of maintaining relatively loose packing of the asbestos;
(2) Have the ability to apply an efficient yet gentle action to separate the fibers before they are made airborne.

The dispenser designed for these tests has two principal parts: firstly, a feed mechanism, and secondly, a dispersing chamber in which the asbestos

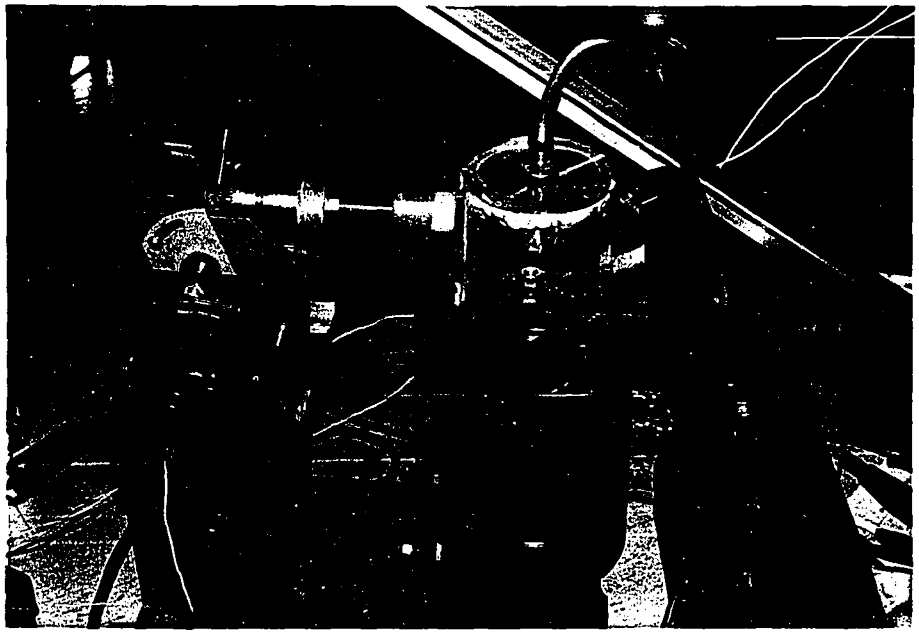


Fig. 50 Dust Cloud Apparatus

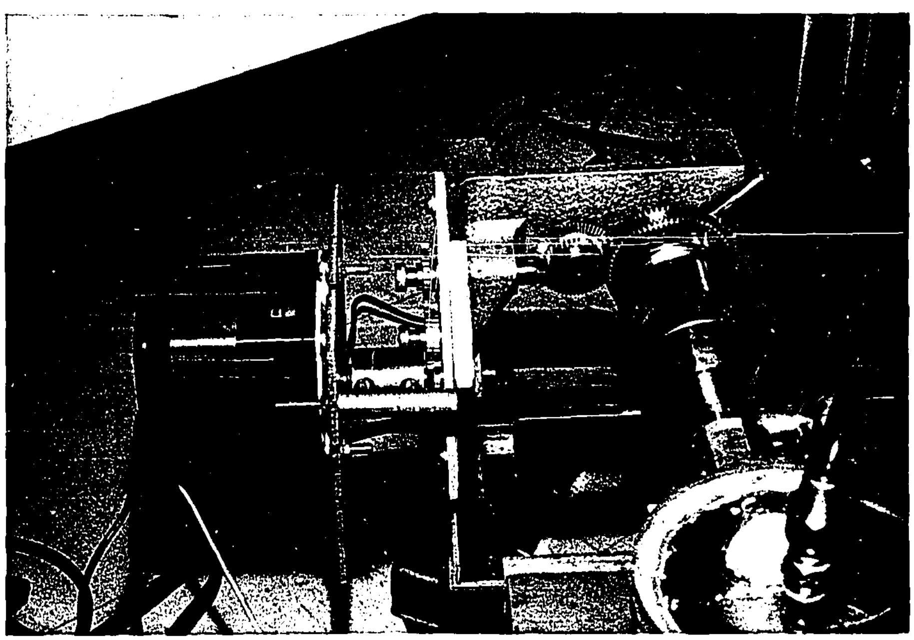


Fig. 51 Dust Feed Mechanism

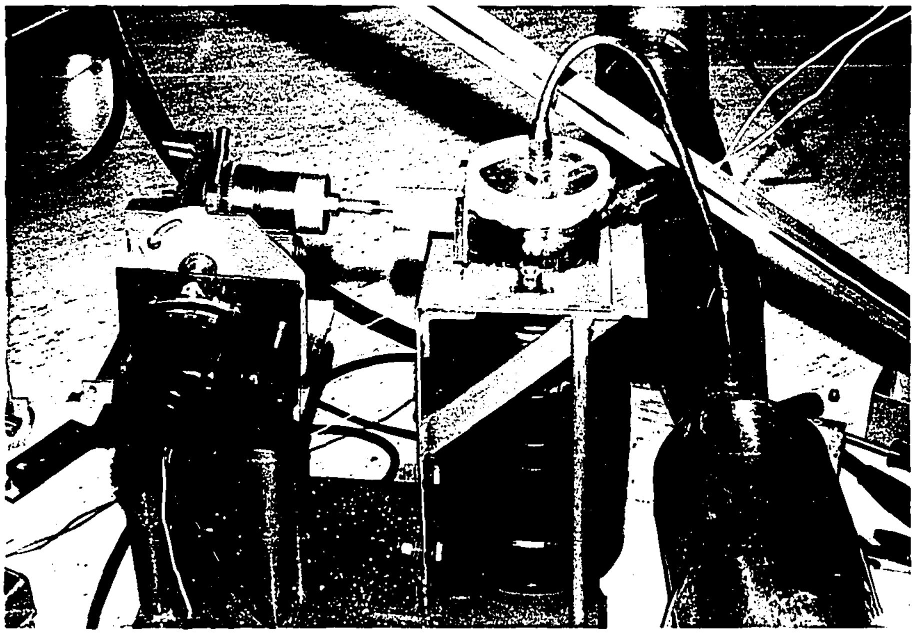


Fig. 50 Dust Cloud Apparatus

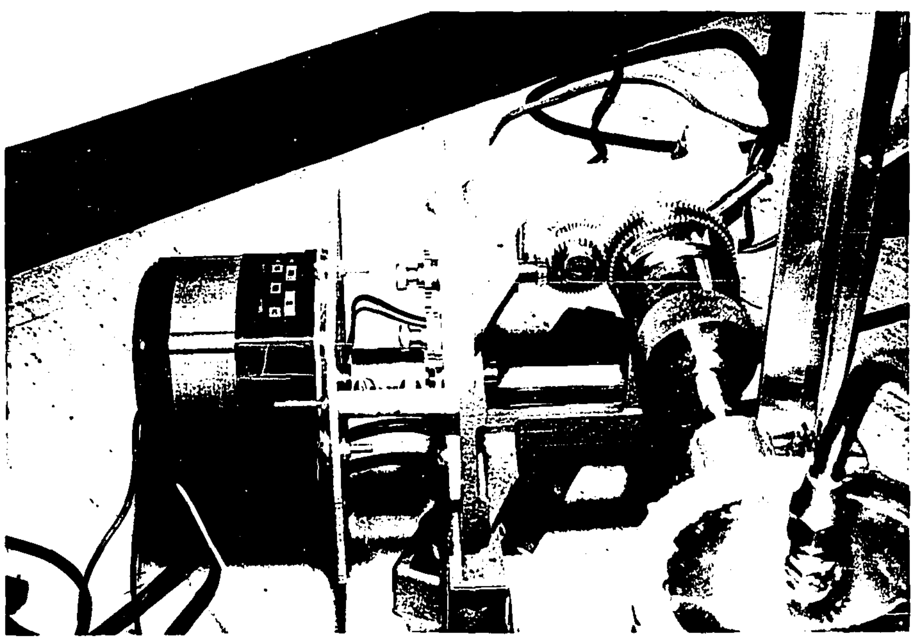


Fig. 51 Dust Feed Mechanism

flocks are disintegrated until the fibers separated off are of sufficiently small aerodynamic size for them to pass to the exhaust through an aerodynamic sieve. It should be noted that the aerodynamic size of a fiber is mainly determined by its diameter and is almost independent of the length.

Air is supplied to the dispersing chamber through a side tube from a compressed air supply. This airflow has two functions. The first purpose is to prevent the circular motion of the asbestos from becoming too regular. The second function of the airflow is to expel particles from the dispersing chamber and to provide, in conjunction with the circular motion, aerodynamic particle classification. As the flocks are dispersed, the aerodynamic drag exerted on released particles by the general motion of the air towards the exhaust tube may overcome the tendency of the rotation to keep them at the outer wall of the chamber.

4.21 Dust Feed Mechanism:

The feed mechanism (see Figure 51), which delivers the asbestos into the dust dispersing chamber, is a piston-cylinder arrangement. This mechanism is available commercially[132]. It is driven by an electric synchronous motor through a train of interchangeable gears, so that a large range of speeds can be obtained at will.

The synchronous motor runs at a constant speed of 2 r.p.m. A large range of variable speeds between the motor shafts and cross shaft may be obtained by using four of the set of 11 gears supplied with the apparatus.

The gearing between the cross shaft and the piston feed to the dust dispersing chamber is fixed at a ratio of 30-1, i.e. 30 turns of the cross shaft = .038" (1 mm).

4.22 Dust Dispersing Chamber:

The construction of the dispersing unit is based on a steel bowl with rotating vanes (see Figures 52 and 53). This dispersing chamber is in two separable parts. The lower part is an electric motor whose shaft carries on the upper end the driving half of a dog clutch. This motor provides a speed of 1,725 rev./minute. The upper part consists of a steel bowl. A spindle through a centered bearing in the base of the bowl carries on the lower end the driving half of the dog clutch and on the upper end is secured an iron core with a special-shaped rotor. This rotor is cut from 3/64" thick steel plate. The profile shape is as shown in Figure 54. A screw keeps the rotor in the core. The clearance between the edge of the rotor and surface of the bowl is small enough to prevent asbestos accumulating in any recesses while operating the dispenser, but not small enough to cause the asbestos to be rolled into balls as it tends to do if caught between two closely spaced surfaces moving relative to one another.

The removable cover of the dispersing chamber is made from a plexiglass which is a press fit on the steel bowl. The exhaust tube has a 1/4" internal diameter and is grounded to avoid electrostatic charging of the particles. It is a press fit in the center of the cover.

A dust feeding hole of 1" diameter is cut in the wall of the bowl by means of a trepanning cutter, at the position shown in Figure 55.

A shaped steel flange, to which a tube has been soldered, is secured to the steel bowl over the hole. The other end of the tube is attached to the piston-cylinder of the dust feed mechanism.

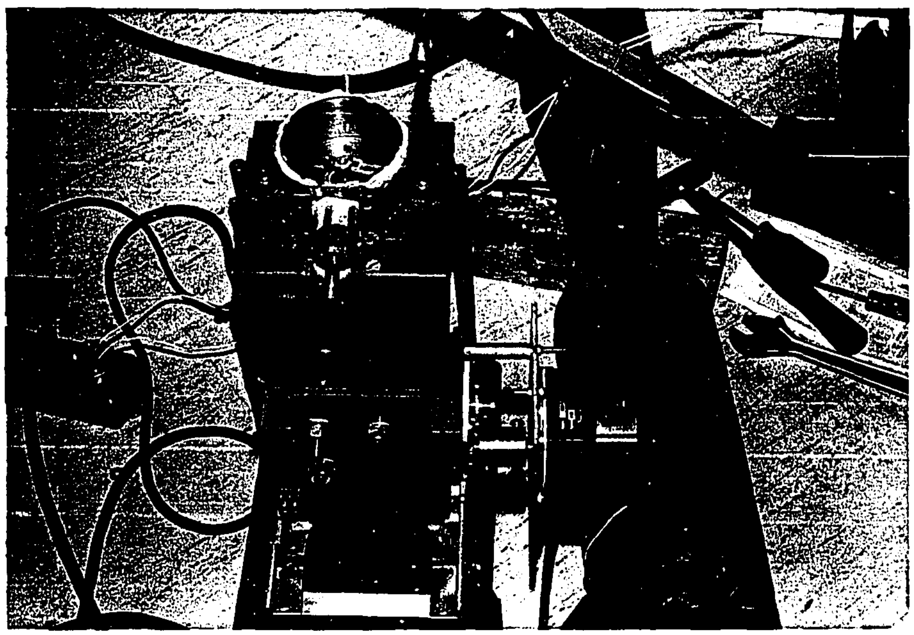


Fig. 52 Dust Dispersing Chamber

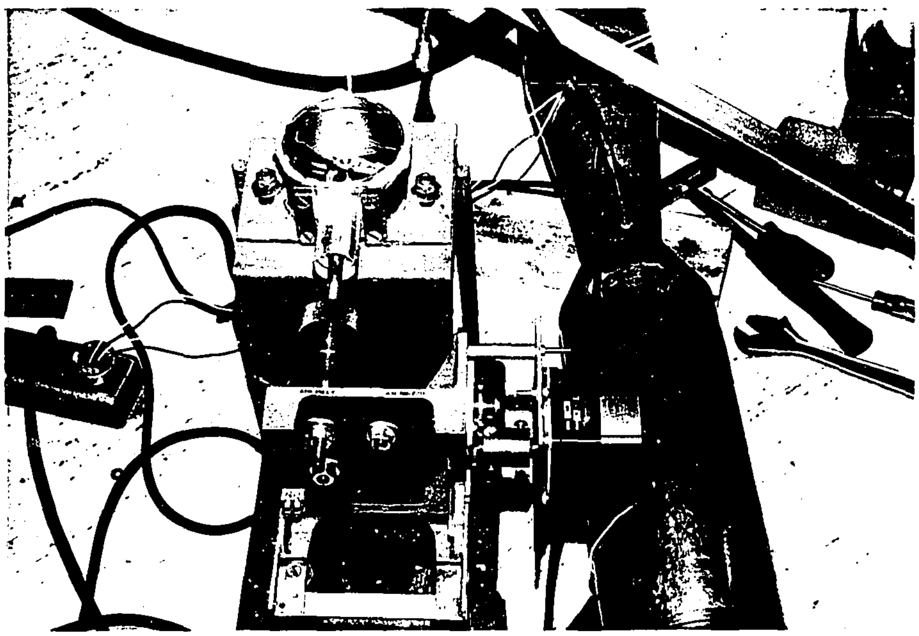


Fig. 52 Dust Dispersing Chamber

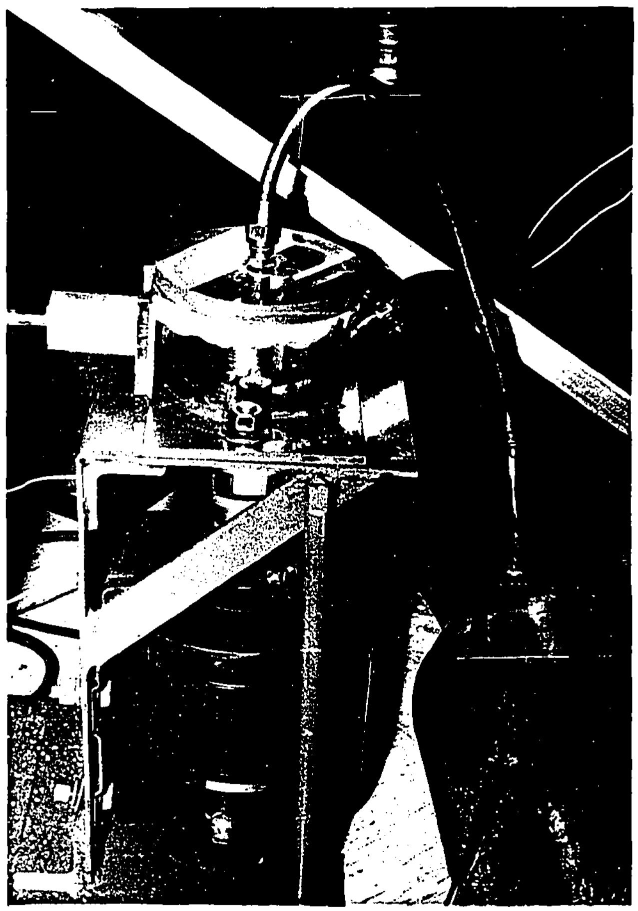


Fig. 53 Dust Dispersing Chamber

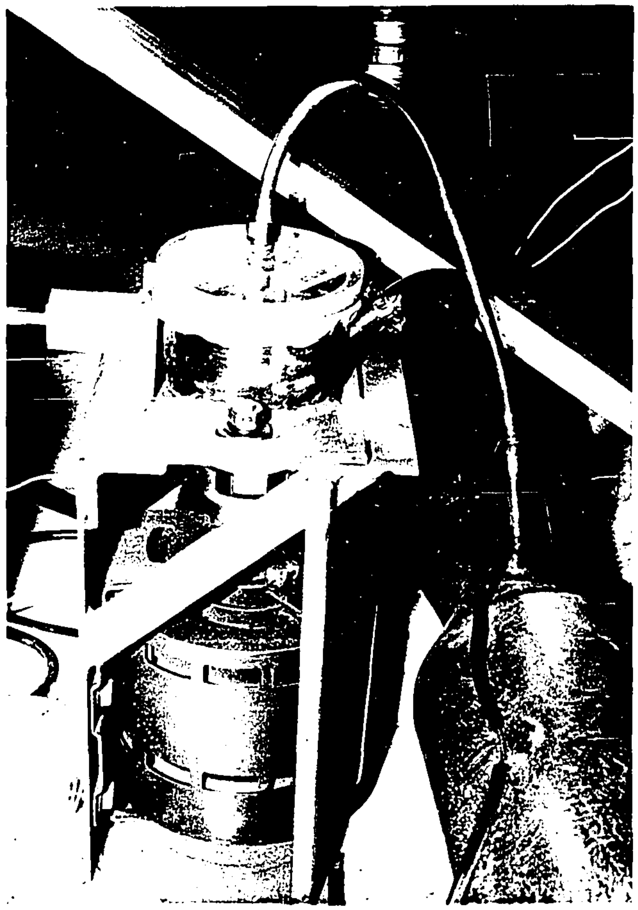


Fig. 53 Dust Dispersing Chamber

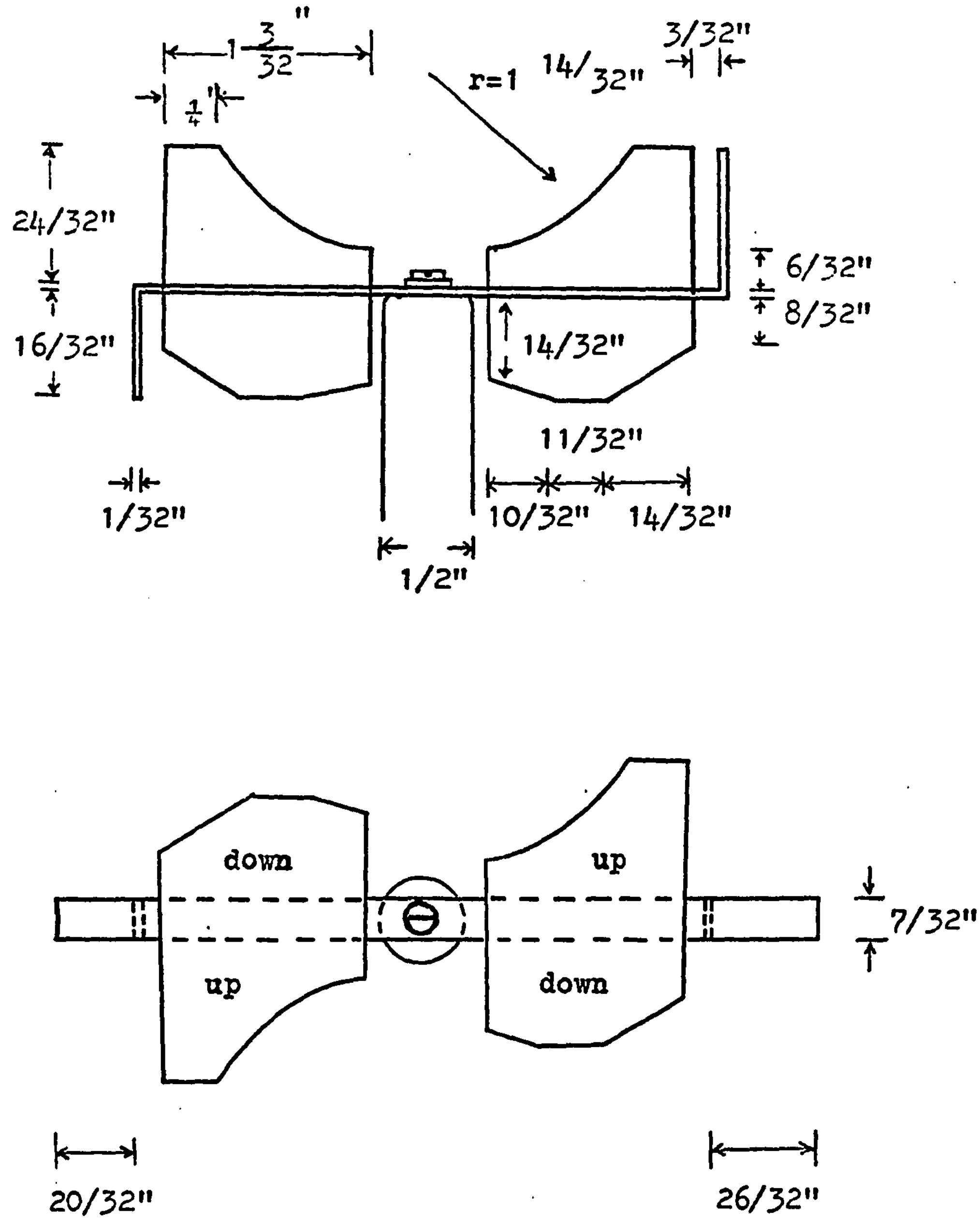


Fig. 54 Metal Plate to Form the Rotor (for Dispersing Chamber)

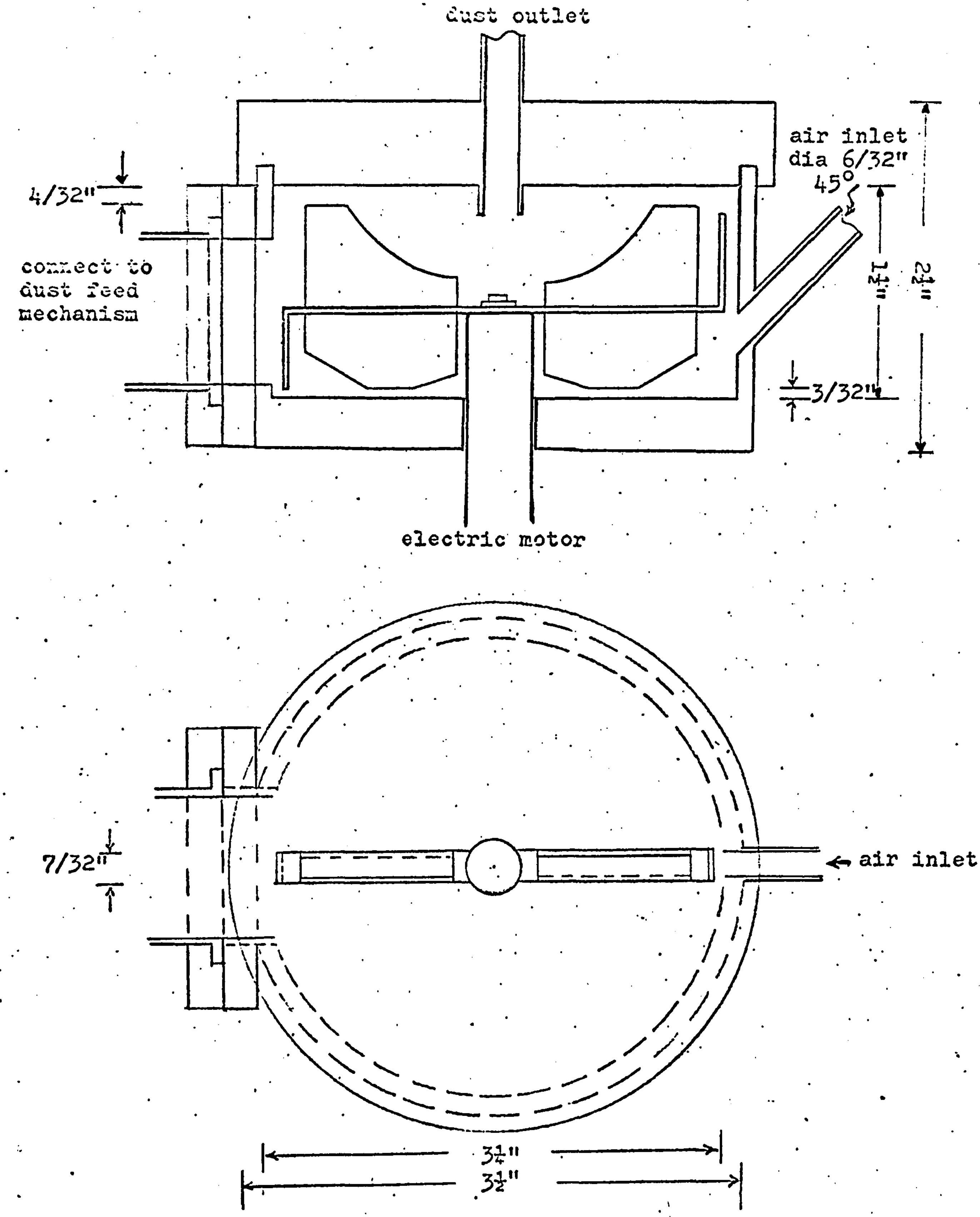


Fig. 55 Fiber Dust Dispersing Chamber

(Reference 115)

The air supply tube is in the opposite side of the hole, and the internal diameter is 3/16". The air supply through the adjustable orifice to the dispenser is at the rate of 20 liters per minute.

5. Dust Respirators

Eleven different types of half-face dust respirators employed in the study are supplied by Canadian Johns-Manville Co. Ltd. Seven of them were approved by the U.S. Bureau of Mines for use against dusts; and the other four were non-approved nuisance dust type respirators. These include different style, filtering material, and filtering area. Their names are as follows:-

"Dustfoe 77" Respirator (Figure 56):

This respirator, which is made by Mine Safety Appliance Co., is approved for protection against dust, pneumoconiosis-producing mists, and chromic acid mist, by the U.S. Bureau of Mines. This respirator can be separated into two main parts: body and rubber face cushion, which is flexible so as to conform to the facial features of the wearer. This unit also contains both inhalation and exhalation valve systems. Its filter is replaceable. The weight of this respirator is approximately 4 ounces.

"R 9100 SURE-GUARD" Respirator (Figure 57), and

"R 9100T SURE-GUARD" Respirator (Figure 58):

Both are made by American Optical Corporation, and have been approved by the U.S. Bureau of Mines. R 9100 is approved for protection against the inhalation of pneumoconiosis-producing and nuisance dusts; R 9100T is approved for protection against toxic dusts not significantly

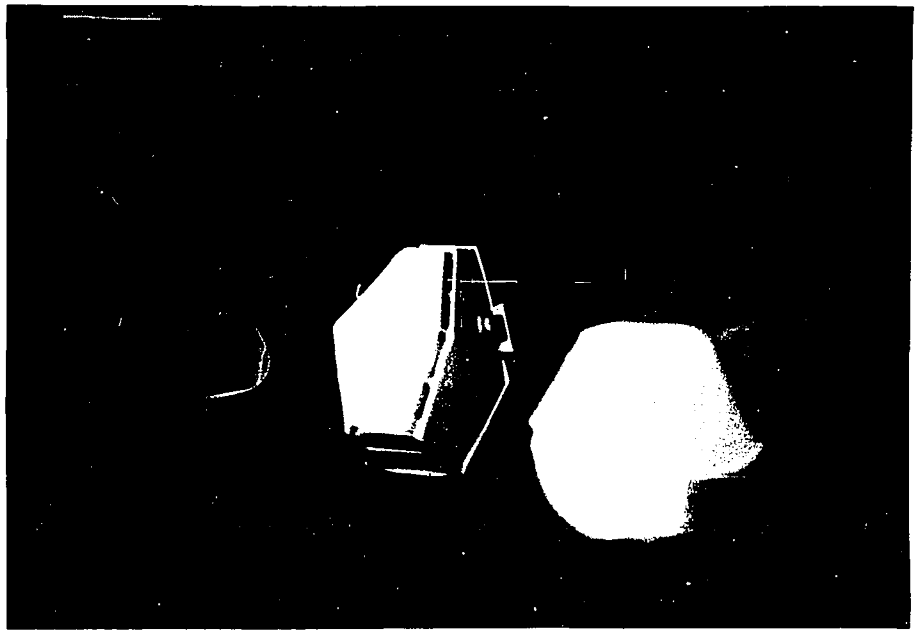


Fig. 56 "Dustfoe 77" Respirator

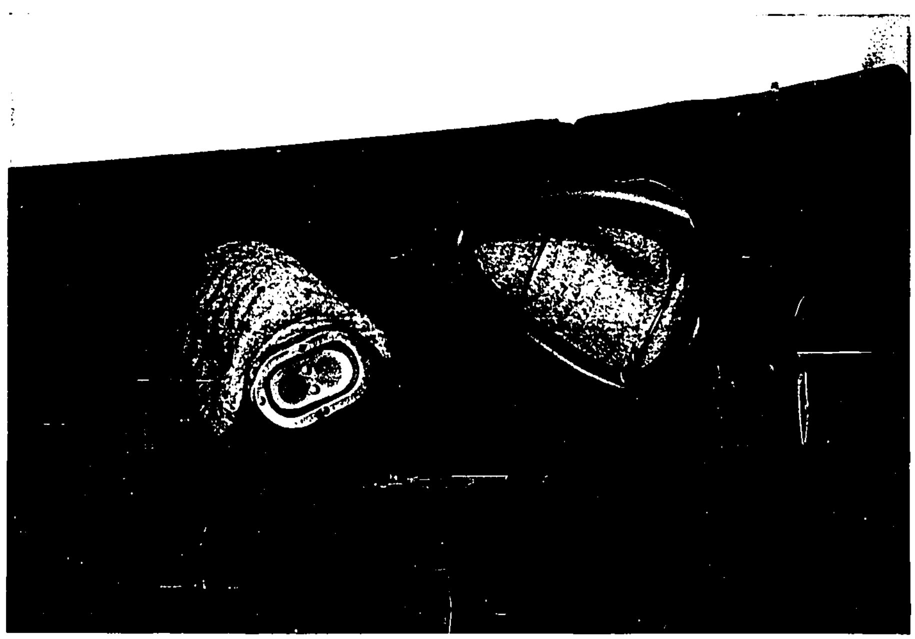


Fig. 57 "R 9100 SURE-GUARD" Respirator

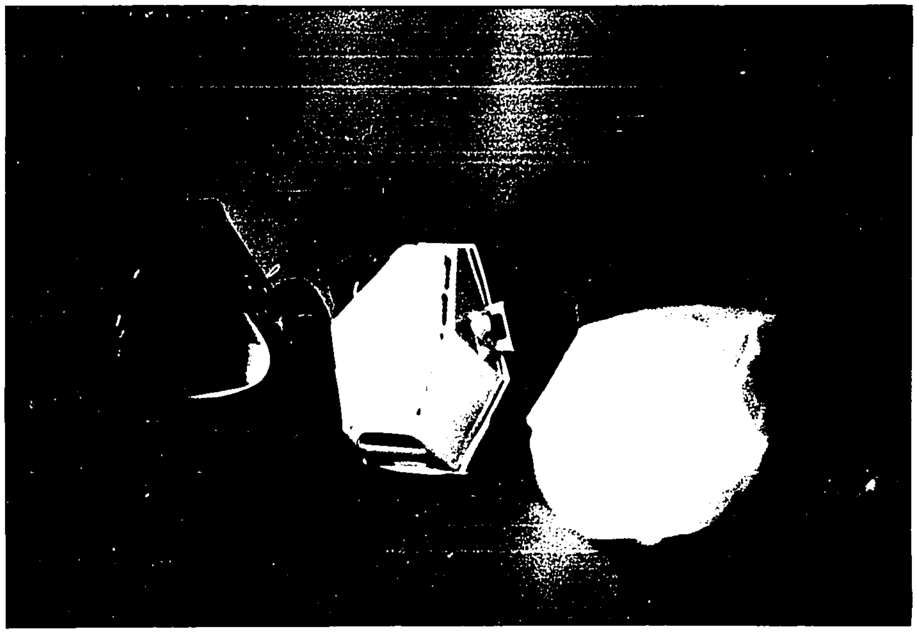


Fig. 56 "Dustfoe 77" Respirator

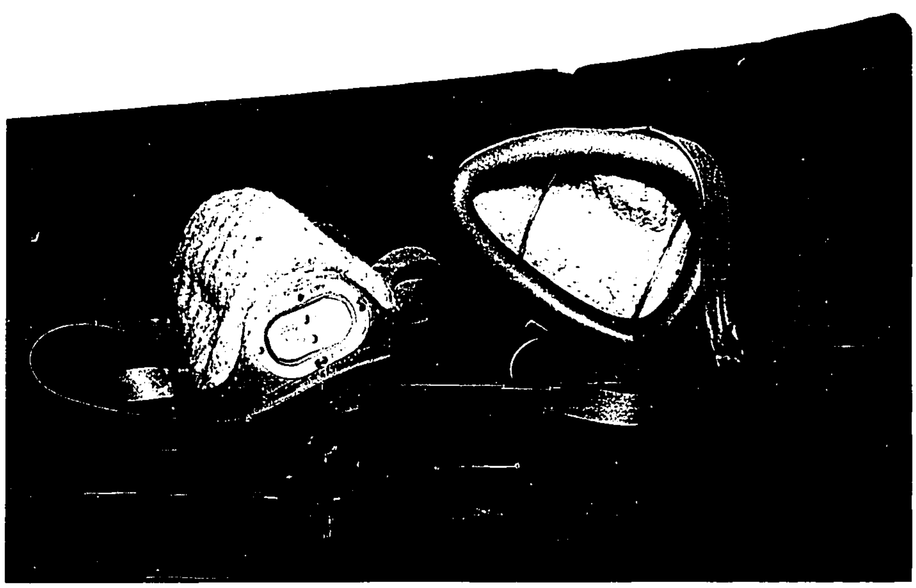


Fig. 57 "R 9100 SURE-GUARD" Respirator

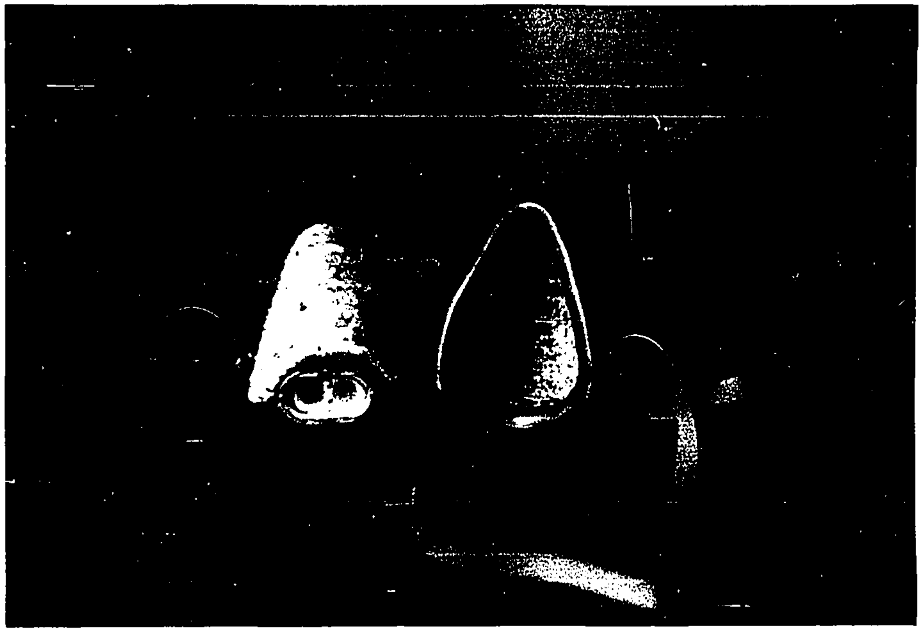


Fig. 58 "R 9100T SURE-GUARD" Respirator

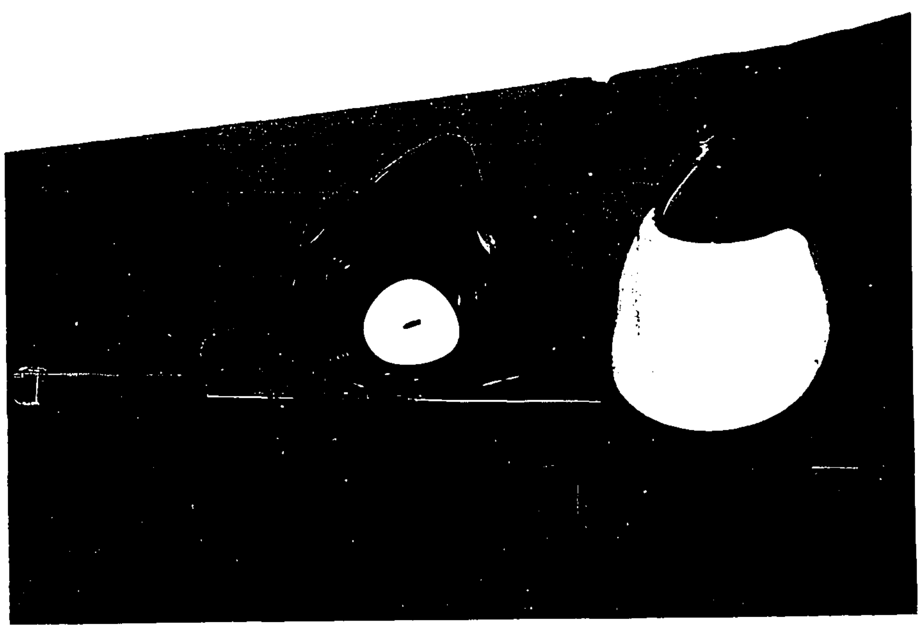


Fig. 59 "Welsh 7050 Black" Respirator

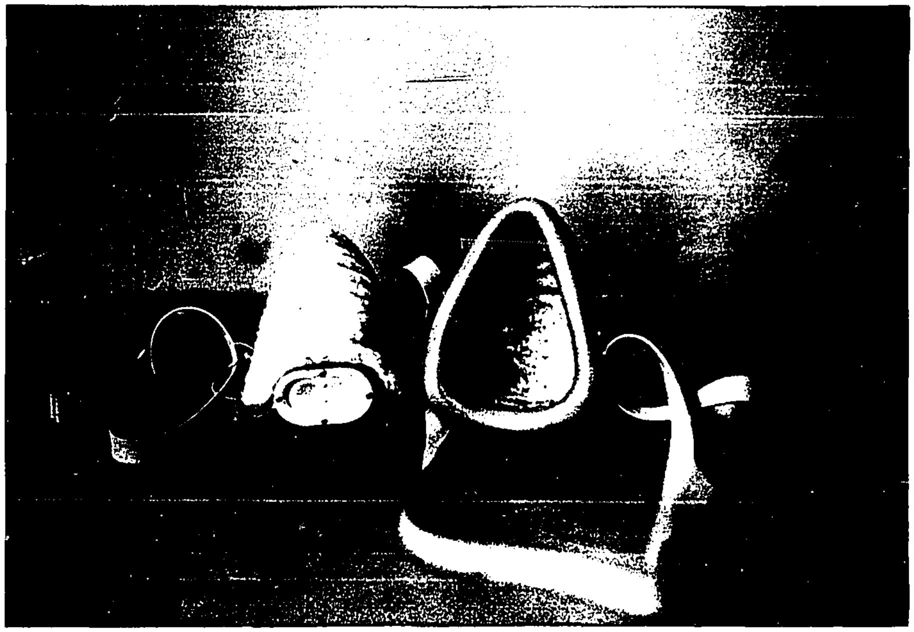


Fig. 58 "R 9100T SURE-GUARD" Respirator

Fig. 59 "Welsh 7050 Black" Respirator

more toxic than lead. Both styles are the same, but not of the same filtering material. They have exhalation valves and the sealing edges of the facepieces are made of soft rubber. Each weighs approximately 2 ounces. Their filters can be cleaned by an air jet, and reused.

"Welsh 7050 Black" Respirator (Figure 59),
"Welsh 7160" Respirator (Figure 60), and
"Welsh 7161" Respirator (Figure 61):

These three respirators are made by Welsh Manufacturing Co., and have been approved by the U.S. Bureau of Mines for protection against dusts, pneumoconiosis-producing mists, and chromic acid mist. Each facepiece is composed of soft plastic. All contain both inhalation and exhalation valve systems. They weigh approximately 2 ounces each.

AO Disposable Dust/Mist Respirator (Figure 62):

This respirator has been awarded U.S. Bureau of Mines Approval for protection against pneumoconiosis-producing and nuisance dusts, toxic dusts not significantly more toxic than lead, and chromic acid mist in concentrations that are not immediately hazardous to life or health. Its characteristic is that it has a large filtering area of 29½ square inches. This respirator contains an exhalation valve and a soft, plastic, foam pad that effectively seals the respirator to the face. It is designed to be discarded after a single wearing. It weighs only 1¾ ounces.

3M Brand # 8500 Respirator (Figure 63),
3M Brand # 8705 Respirator (Figure 64),and,
3M Brand # 8710 Respirator (Figure 65):

These are manufactured by Minnesota Mining & Manufacturing Co.,

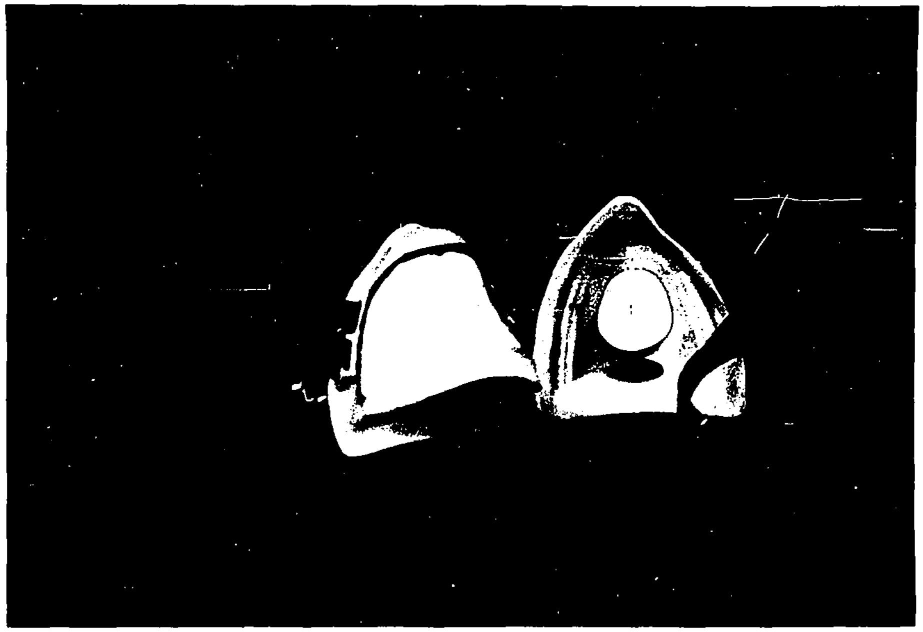


Fig. 60 "Welsh 7160" Respirator

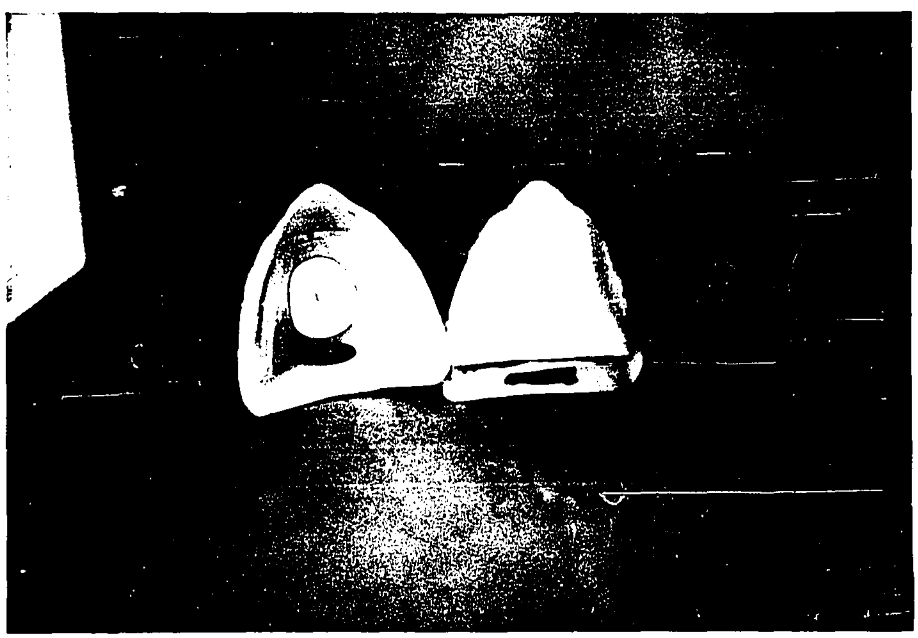


Fig. 61 "Welsh 7161" Respirator

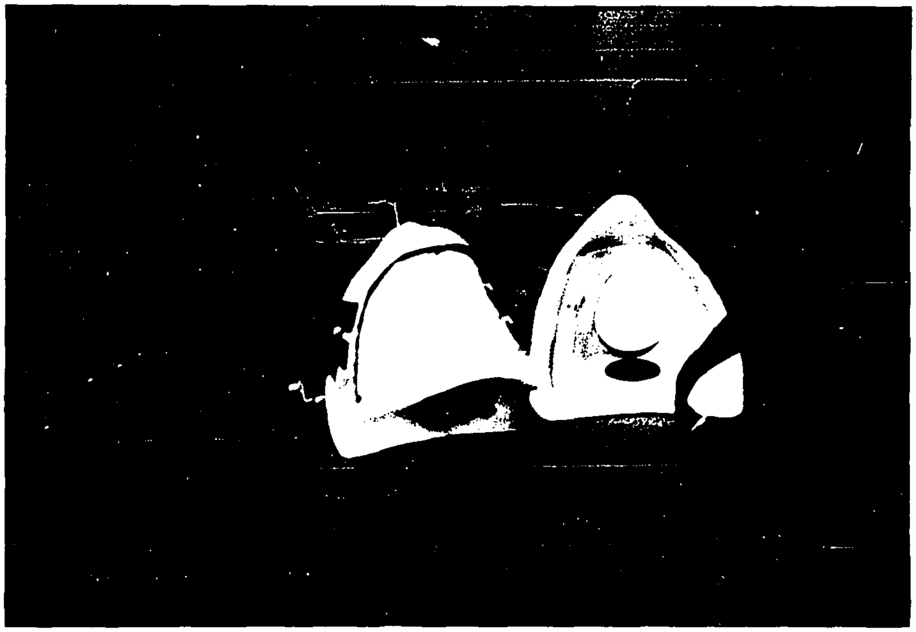


Fig. 60 "Welsh 7160" Respirator

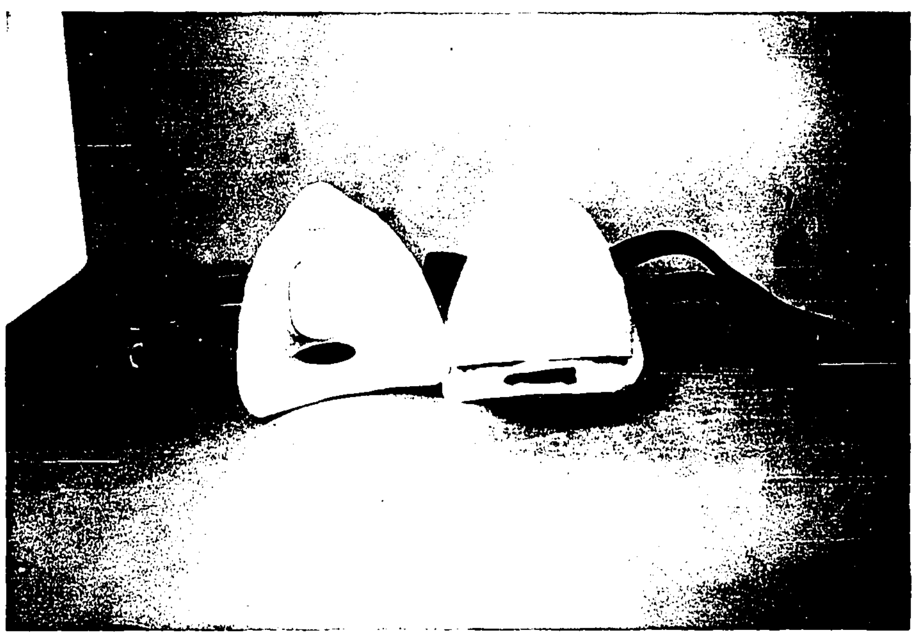


Fig. 61 "Welsh 7161" Respirator

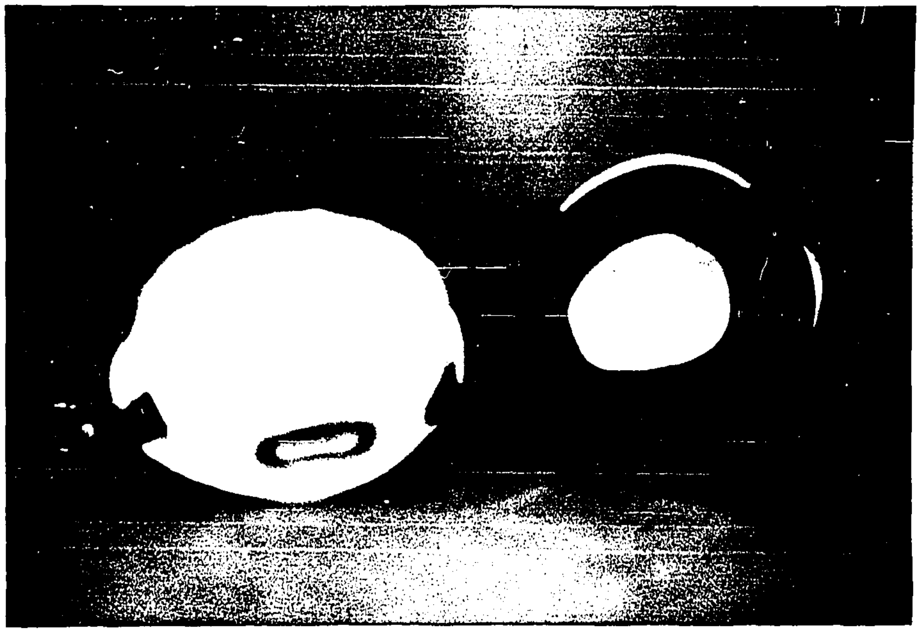


Fig. 62 AO Disposable Dust/Mist Respirator

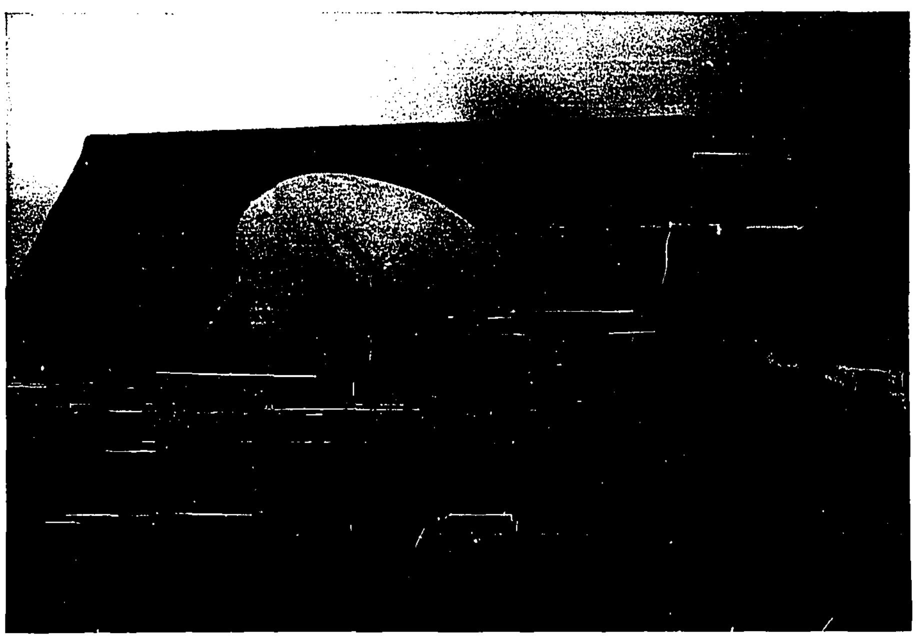


Fig. 63 3M Brand # 8500 Respirator

Fig. 62 AO Disposable Dust/Mist Respirator

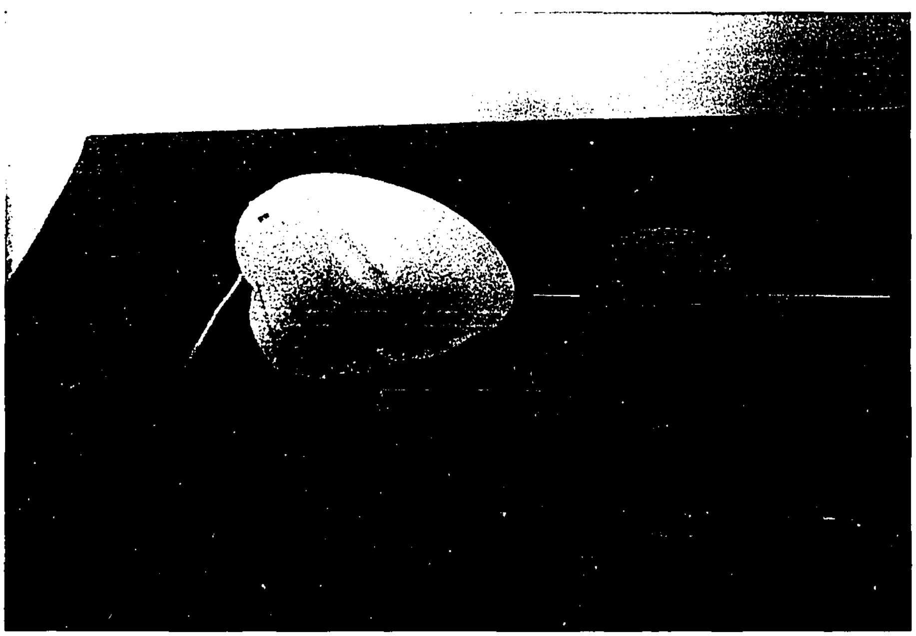


Fig. 63 3M Brand # 8500 Respirator

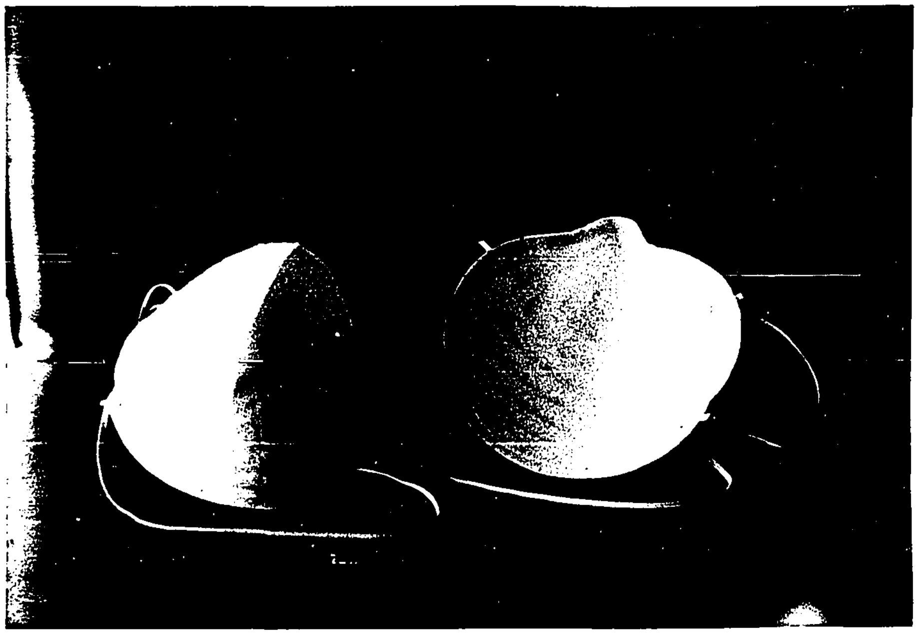


Fig. 64 3M Brand # 8705 Respirator

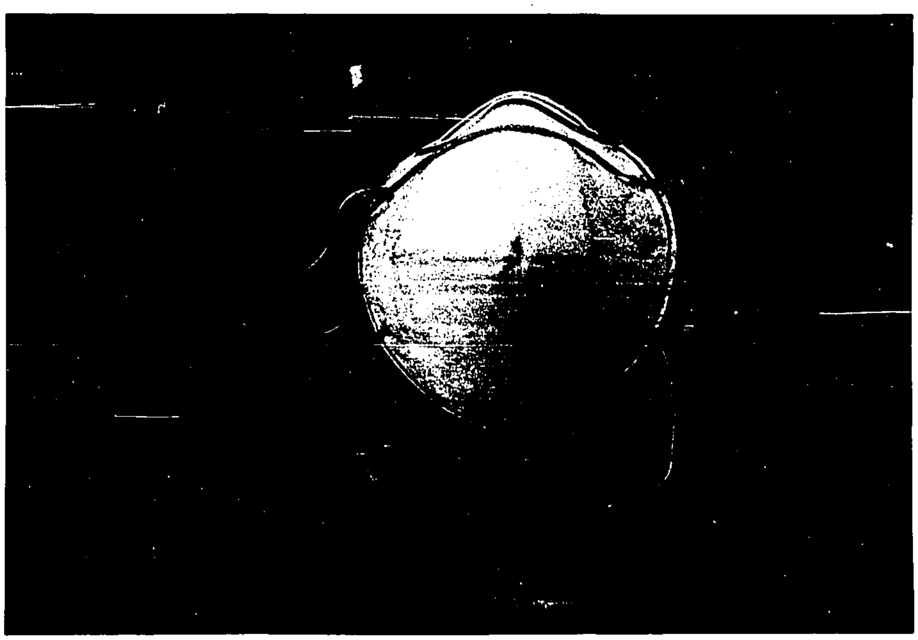


Fig. 65 3M Brand # 8710 Respirator

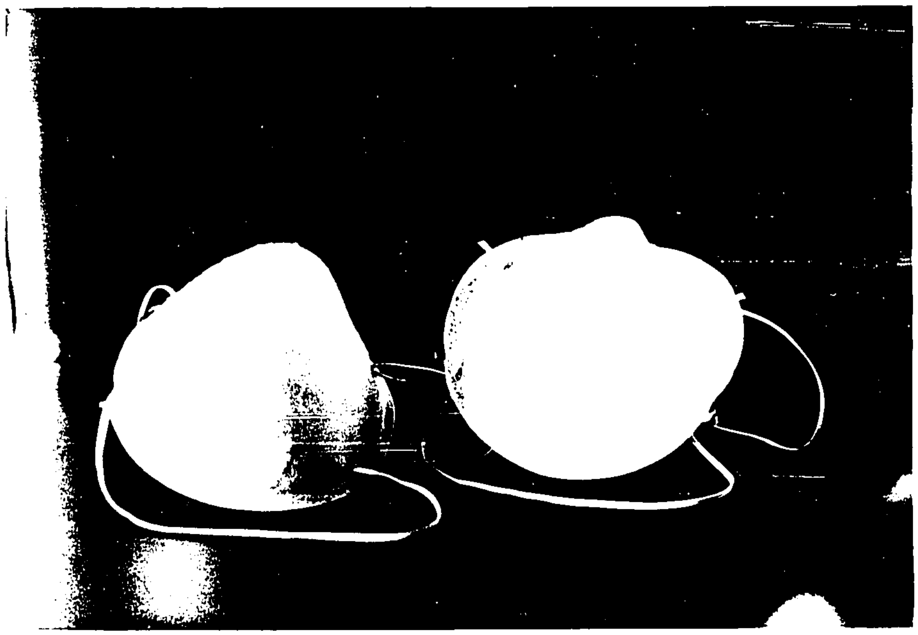


Fig. 64 3M Brand # 8705 Respirator

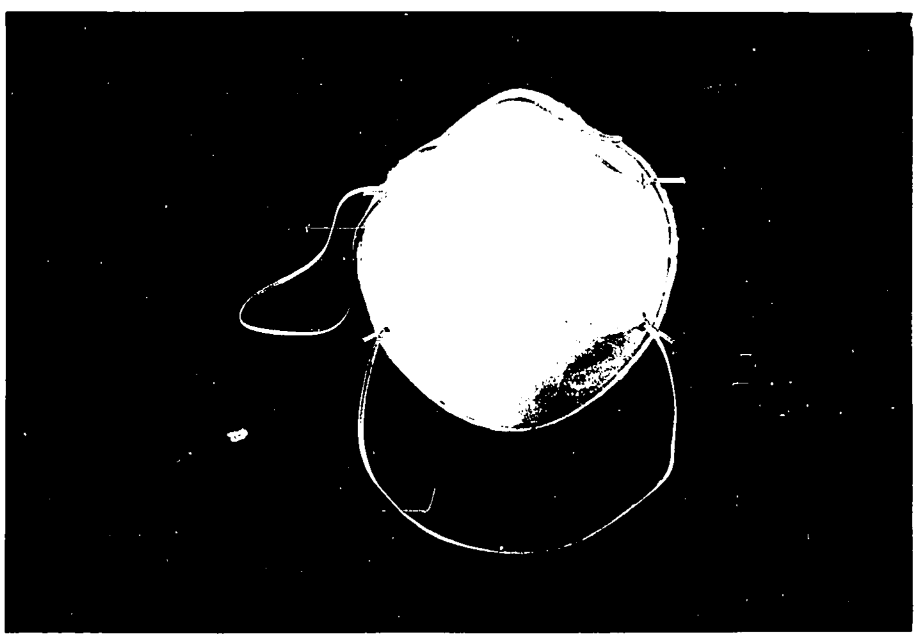


Fig. 65 3M Brand # 8710 Respirator

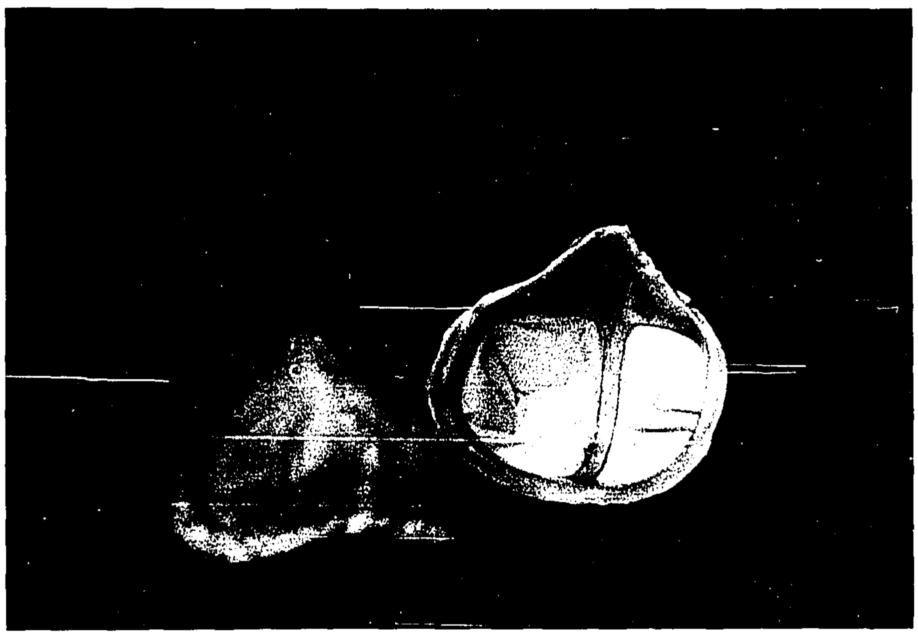


Fig. 66 "Prototype A" Respirator

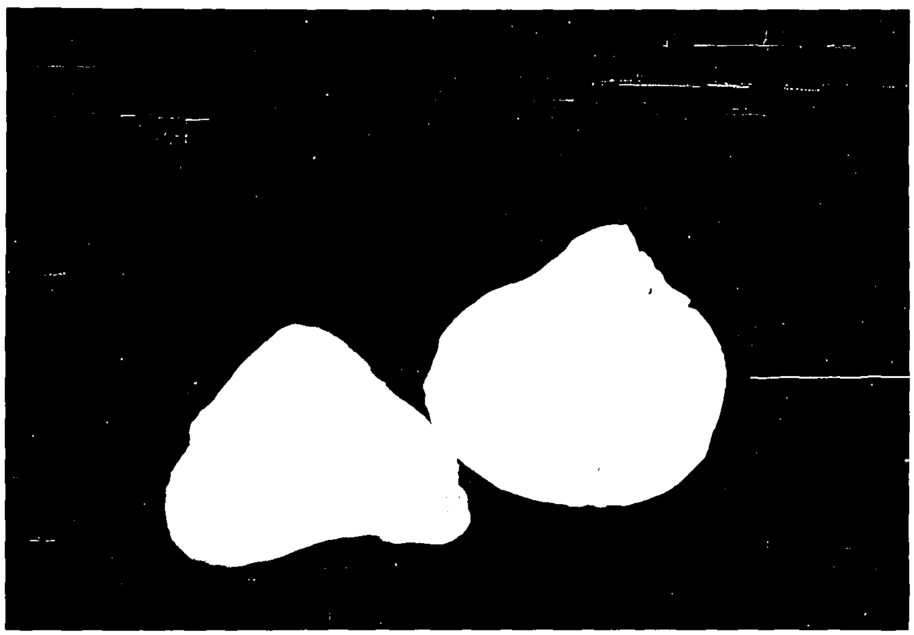


Fig. 66 "Prototype A" Respirator

but have not yet been approved by the U.S. Bureau of Mines. These are designed for single use purpose and as respiratory protection against pneumoconiosis-and-fibrosis-producing dusts. These are all light weight: # 8500 and # 8710 approxmiately weigh 1/8 ounce each, and # 8705 approximately weighs only $\frac{1}{4}$ ounce. The main desirable feature of these models is that they are inexpensive.

"Prototye A" Respirator (Figure 66):

This respirator has not yet been approved by the U.S. Bureau of Mines. It has a plastic frame to hold the filter body. The outer surface of this respirator is made of a cotton-wool-like material. This model is designed for single use. Its weight is approximately $\frac{1}{2}$ ounce.

6. Dust Sampling & Evaluation

A wide variety of instrument is available for sampling airborne asbestos dust, such as[1, 8, 90, 95]:-

Membrane Filter Method,

Gravimetric Method,

Impinger,

Konimeter,

Thermal Precipitator,

Royco Particle Counter.

The optimum of sampling methods must be judged by biological, physical and chemical properties, and the method chosen should be able to give three kinds of information: the aerosol's concentration, composition, and particle size distribution[59, 78].

In recent years, Timbrell and Holmes[114] investigated the asbestos industries and have suggested that a criteria for sampling for asbestos dust requires both gravimetric and fiber counting methods. A comprehensive historical account and a description of stages in the development of the membrane filter method had also been given by Holmes[55]. Although it is highly suitable for mass determination and chemical analysis, it leaves much to be desired for the estimation of size-frequency distribution[12].

In view of the aforesaid reasons, the membrane filter was selected for gravimetric and fiber counting methods for this research work.

6.1 Sampling Equipment

Sampling equipment was installed in two locations: components within the chamber, and those in-line with the respirator.

In the chamber, sampling is employed by the pumping technique for first level of fiber concentration (20 fibers per cc, approximate dust concentration based on fibers larger than 5 microns in length.). The air suction is operated by a monitaire permissible air sampling pump (Fig.67) which is manufactured by Union Industrial Equipment Corporation. An aerosol open-type filter holder (Figure 68) is adopted instead of a sampling head, so as to obtain the best dust distribution at the membrane filter. Its sampling rate is adjusted to 2 liters per minute.

For the second and third levels of dust concentration (approximate concentration based on larger than 5 microns in length, is at 50 fibers per cc and 100 fibers per cc respectively), the air suction is supplied by a vacuum pump (Figure 69) which is manufactured by the Welch Scientific Company. A small plastic tube connects both the vacuum pump, and the open-type filter

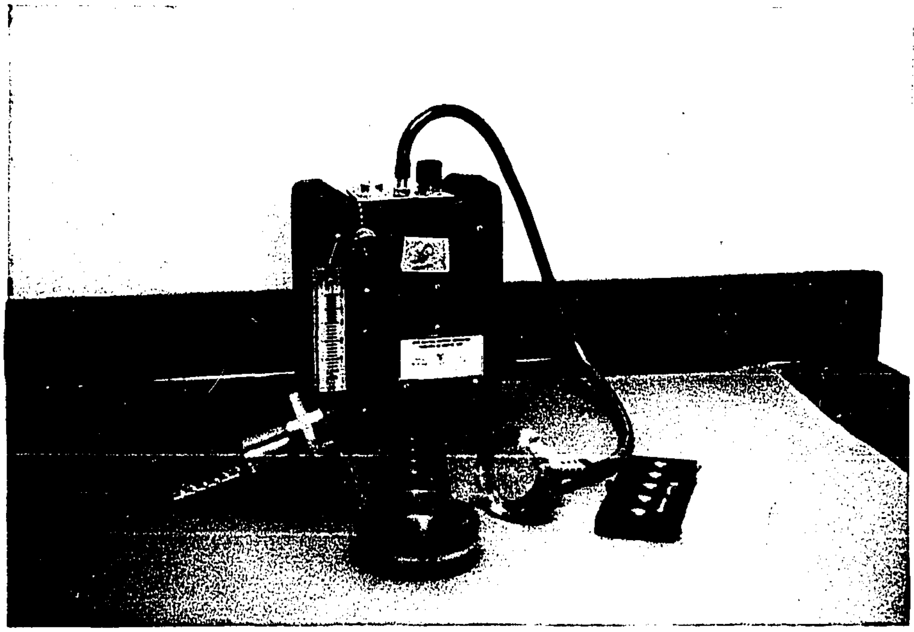


Fig. 67 "Monitaire" Pump

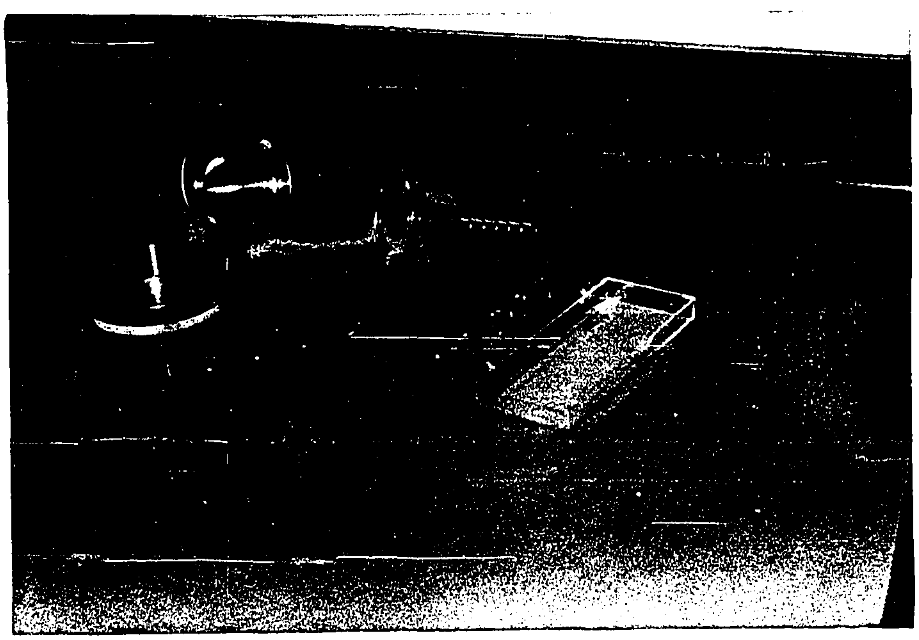


Fig. 68 Aerosol Standard & Open-type Filter Holder
with Orifice

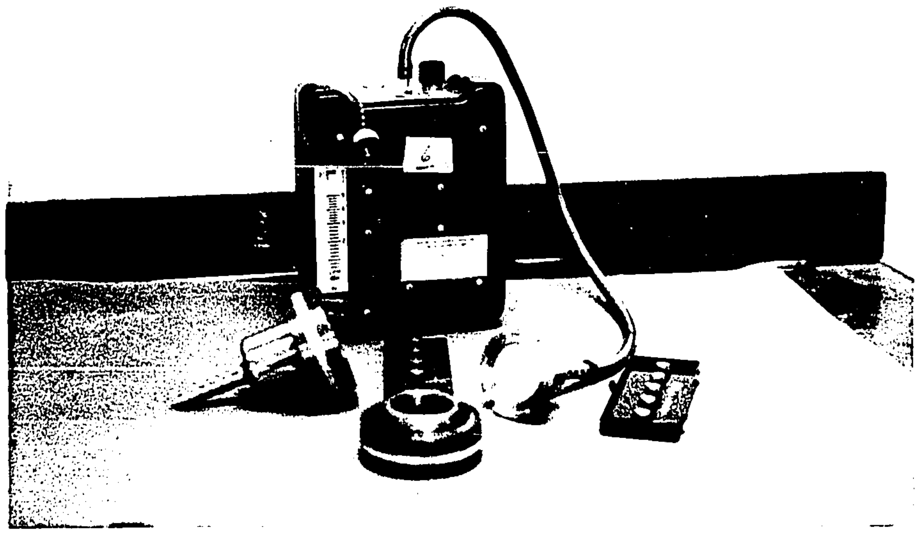


Fig. 67 "Monitaire" Pump

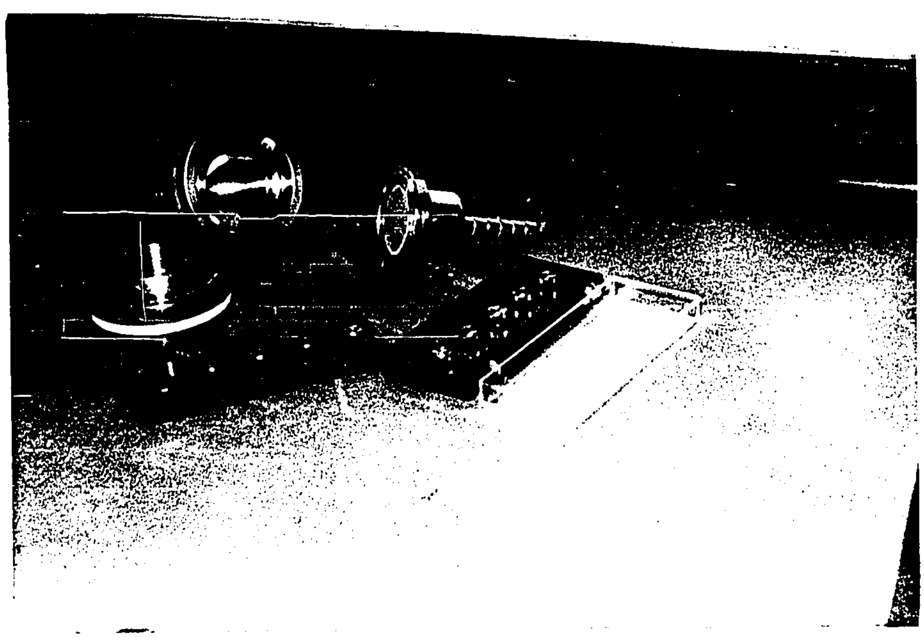


Fig. 68 Aerosol Standard & Open-type Filter Holder with Orifice

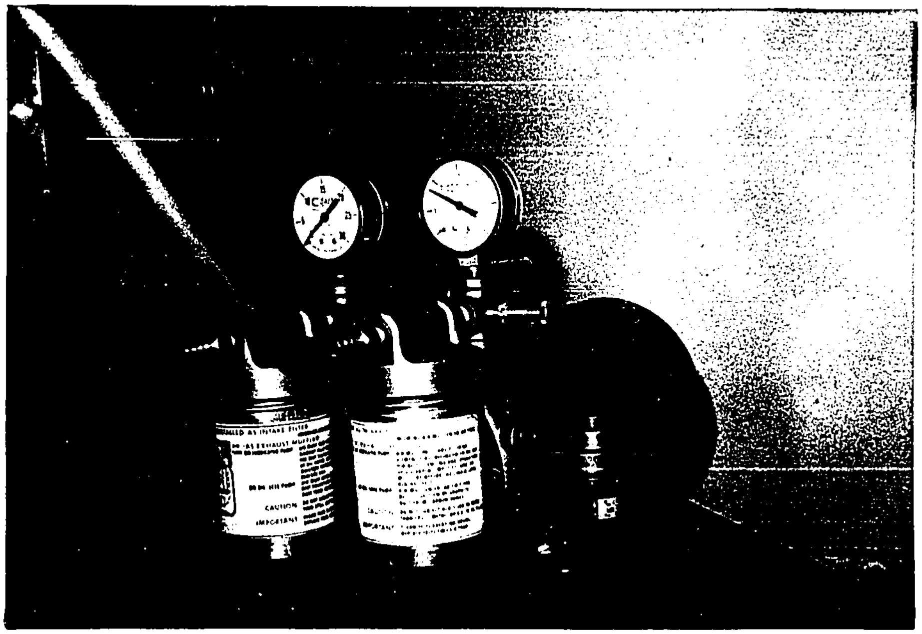


Fig. 69 Vacuum Pump

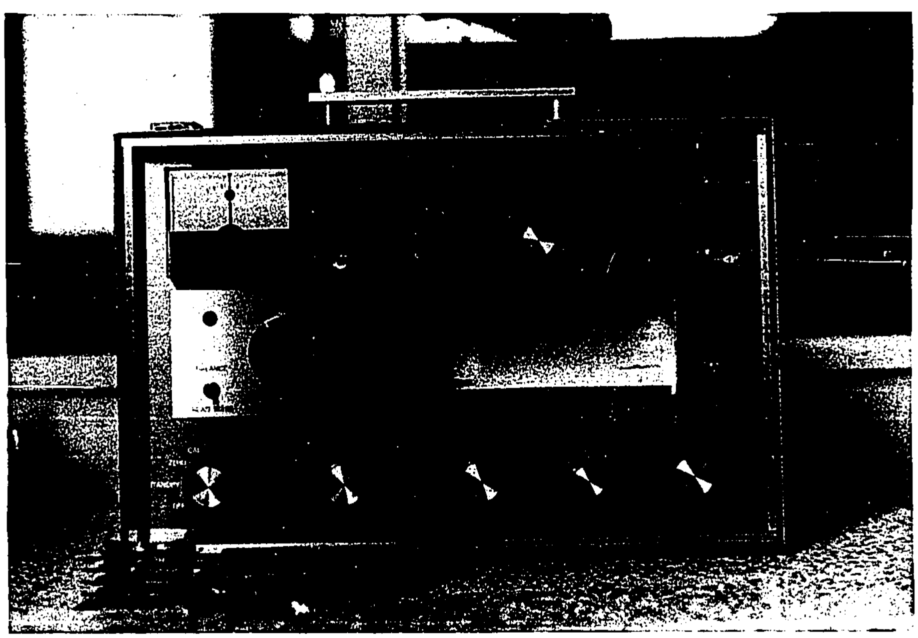


Fig. 70 G-2 Electrobalance

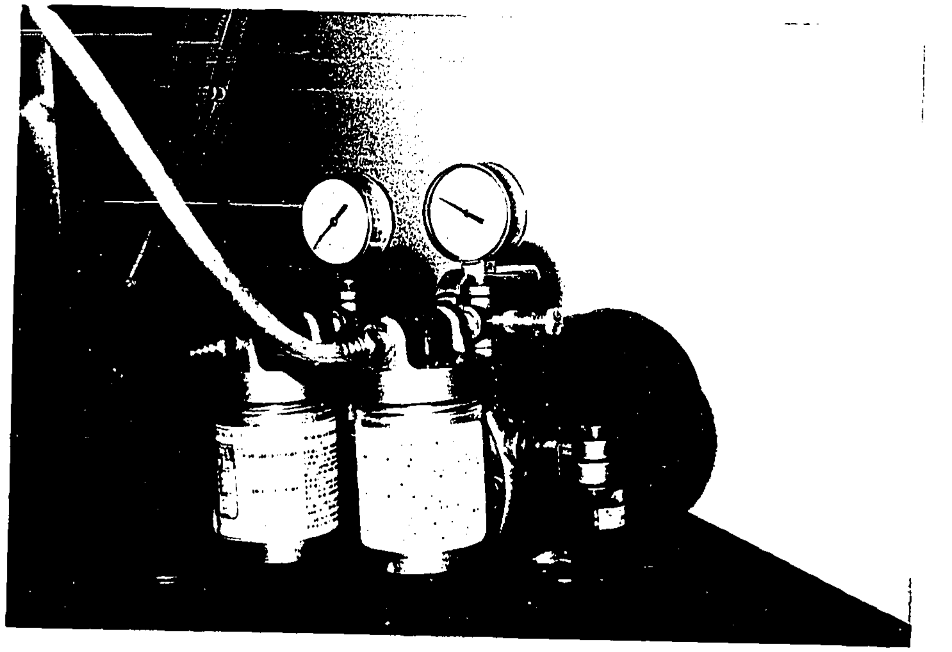


Fig. 69 Vacuum Pump

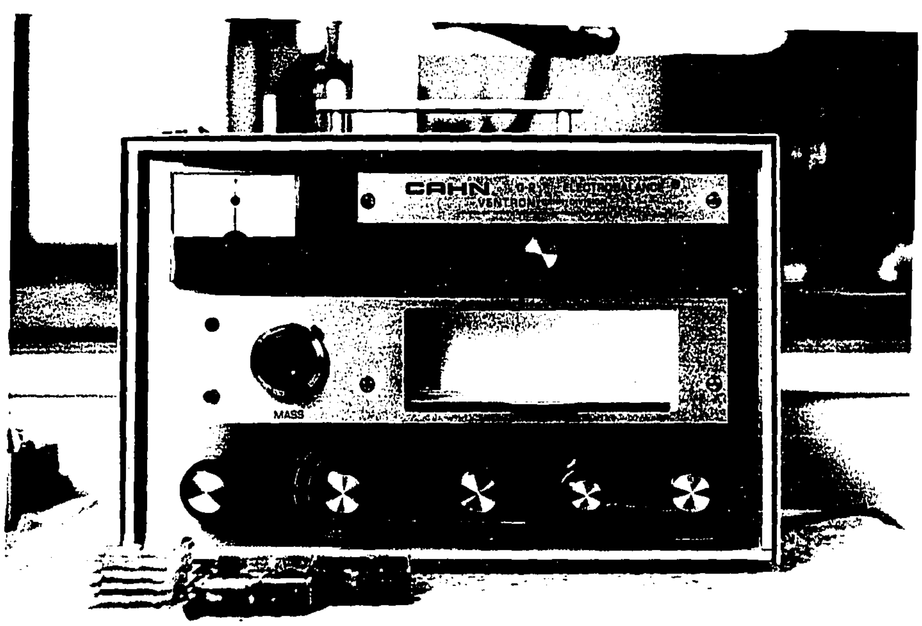


Fig. 70 G-2 Electrobalance

holder in the chamber. The sampling rate is controlled by fixing a specific limiting orifice of 500 cc per minute onto the holder.

Dust which penetrates the respirator is collected on an aerosol standard filter and holder which is installed between the respirator and the Bird Mark 9 (see Figure 50). The sampling rate is selected at 6 liters per minute to simulate the normal respiration rate for a man at rest.

The membrane filter medium employed for all sampling is a "millipore Type AA White, grid, 47 mm diameter filter, pore size 0.8μ". The open filter area of all the sampling holders is 9.6 sq. cm.

6.2 Gravimetric Method

From experience, Roach[95] made observations on a number of methods and reports favourably on a gravimetric method. He concluded that the measurement of mass concentration was far simpler than the measurement of number concentration. It is quicker and more accurate to weigh a sample than to count it by eye. But the gravimetric method has an undesirable limitations in that it gives no indication of particle or fiber size distribution.

The sample weighing instrument used is a "G-2 Electrobalance" (Figure 70) which is manufactured by Ventron Instruments Corpn. Its capacity is 2.5 grams and the sensitivity is 50 nanograms. Full scale ranges are from 0 - 0.5 milligram to 0 - 1 gram, readable to 0.01%.

Each and every membrane filter media was weighed before and after the experiment. The sampling concentration is evaluated on mg/m^3 unit basis. The formula of evaluation is as follows:

$$\text{Dust Concentration } (mg/m^3) = \frac{W - w}{t \times v}$$

Where

W = weight after experiment (mg)

w = weight before experiment (mg)

t = sampling time (minute)

v = sampling rate (m^3/min.)

6.3 Fiber Counting:

In recent years, the development of the membrane filter technique employing the phase contrast microscope has been revealed as the most suitable method for fiber dust counting. It has been recommended by many researchers[2, 8, 39, 55, 66, 91], and is widely used in asbestos industries.

The fibers are counted under a "Photomicroscope" (Figure 71) fitted with a Ph_2 Neofluar 25/0.60 objective, optovar 1.6, and 12.5 X eyepiece. It is manufactured by Carl Zeiss.

The prepared samples are observed at a magnification of 500 X by phase contrast illumination. Phase contrast provides more accuracy in counting as it increases the visibility of the particles so that more smaller particles will be seen[14].

The sizing is carried out by incorporating an eyepiece graticule in one of the eyepieces, which consists of a rectangle sub-divided into nine equal oblongs and having, above and below, a series of graded circles and black spots, respectively. Two modes of counting are used: (a) counting all fibers with length to width ratio of 3 or greater (b) counting only those fibers longer than 5 microns.

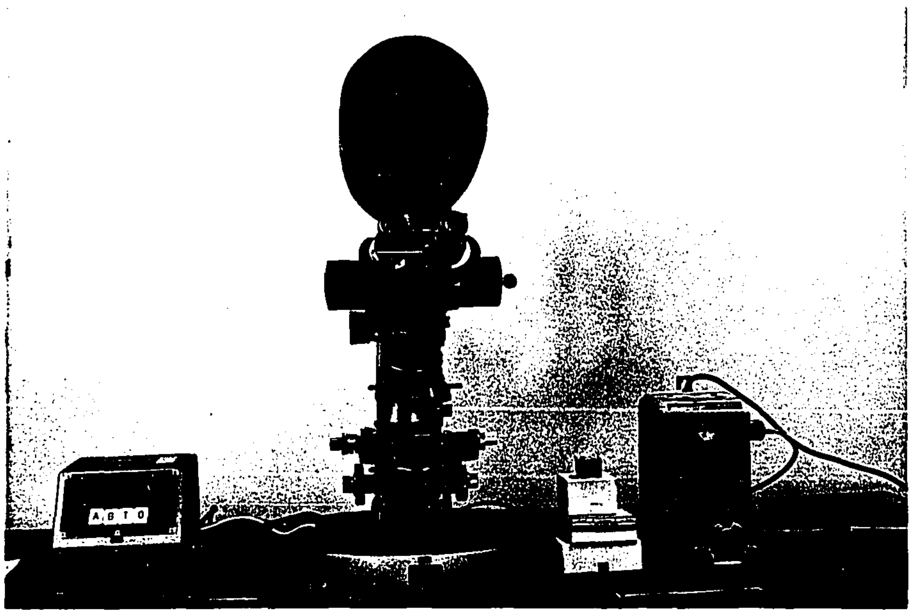


Fig. 71 Photomicroscope

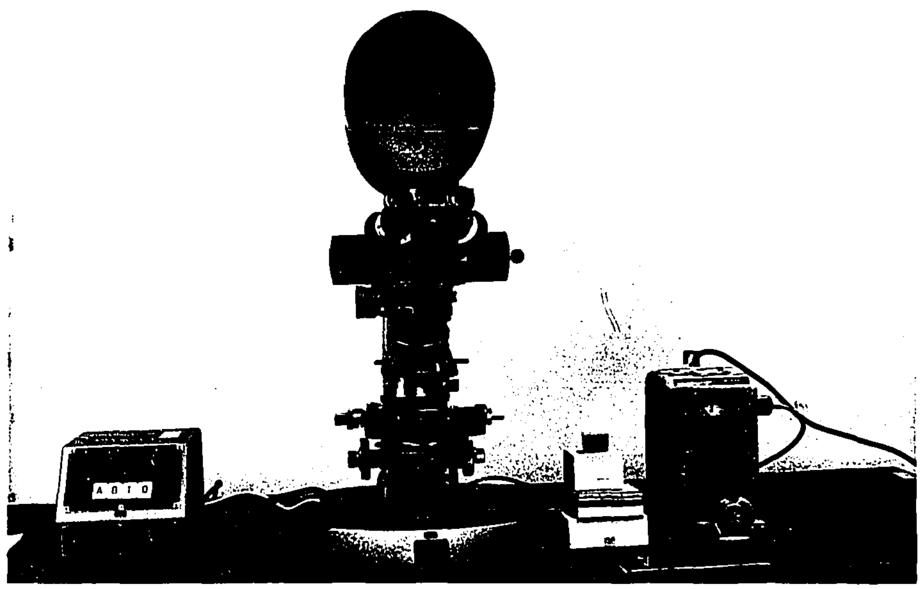


Fig. 71 Photomicroscope

The evaluation of dust fiber samples is defined by the following formula:

$$\text{Dust Concentration (fib./cc)} = F \times \frac{A}{a} \times \frac{1}{v}$$

Where

F = Average graticule fiber count.

a = Eyepiece graticule counting area. mm^2

A = Total membrane filter sample area. mm^2

v = Volume of sample. cc

Chapter V

IMPLEMENTATION OF EXPERIMENTS AND THE RESULTS

1. Implementation of Experiments

The experiments discussed in this chapter were conducted with the equipment described earlier herein, and basically, in accordance with the aforementioned theory.

The period of testing one respirator was for four intervals totalling six hours in order to facilitate sample counting at the dust concentration on the membrane filter (viz. at every 90 minutes, a new membrane filter was replaced). Each respirator is tested for three different dust concentration levels as follows:

LEVEL	Dust Concentration (Larger than 5 microns in length)
1st	Approx. 20 fibers/cc
2nd	Approx. 50 fibers/cc
3rd	Approx. 100 fibers/cc

The experimental dust is taken from the standard dust which is screened by Tyler's Standard Screens (48 mesh to 200 mesh) (Figure 72), and every 4 grams of dust is pressed to 2 cm in the plastic syringe (unit density of plug 2 g/cm). The syringe is then placed in the dust feed mechanism where the feeding rate is generally uniform. In order to achieve a constant dust concentration in the dust cloud chamber, the 2:1 gear ratio is adopted for 1st level; 1:1 gear ratio for 2nd level; and, 1:3 gear ratio for 3rd level.

In the dust cloud chamber, a whirling hygrometer is employed to

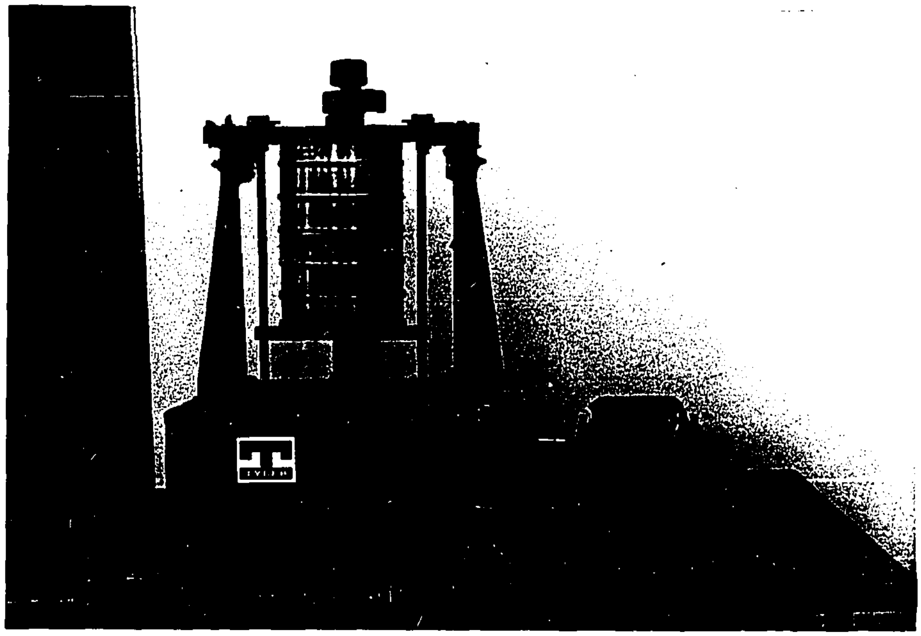


Fig. 72 Tyler's Standard Screen

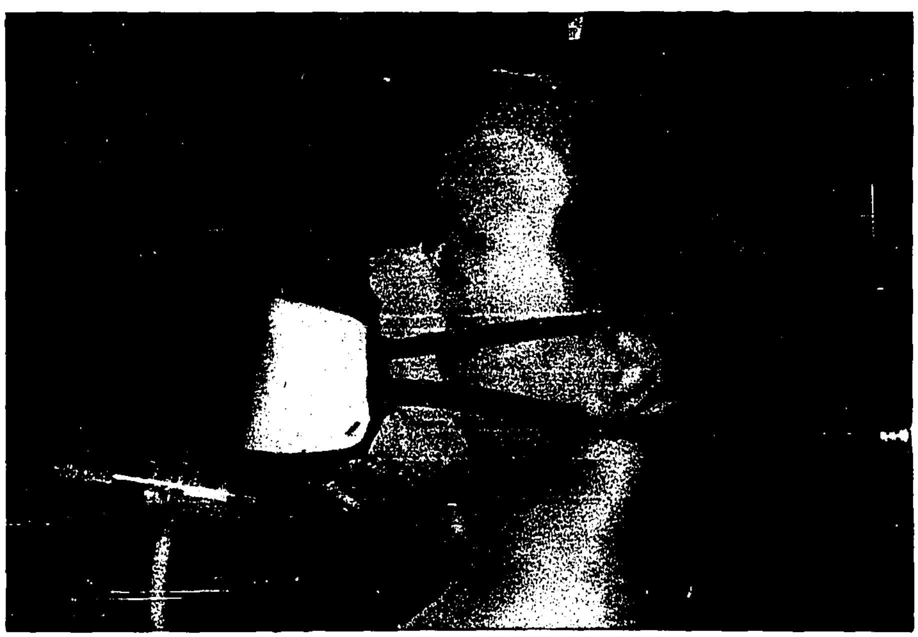


Fig. 73 Humanlike Head Model

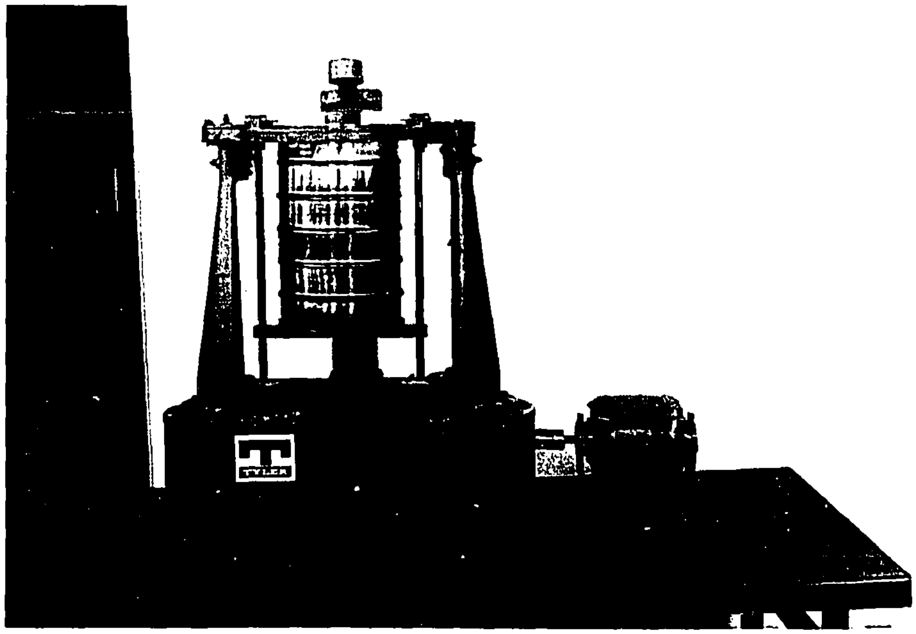


Fig. 72 Tyler's Standard Screen

Fig. 73 Humanlike Head Model

survey both the temperature and the humidity, so whilst the experiment is being executed, the desired constant psychrometric condition is always maintained.

During the test, each respirator is sealed with a common vinyl-foam tape onto the humanlike head model (Figure 73) in order to prevent leakage of air. The inhalated air pressure at the mouth of the model is adjusted to rise rapidly to 20 cm H_2O (the reason of selecting this rate has already been discussed in Chapter IV Figure 49). The inhalation volume is adjusted to 6 liters per minute which is a normal human breathing rate. The dust fibers penetrating the respirator are collected on a pre-weighed membrane filter in a holder which is located between the manikin and Bird Mark 9.

An aerosol open-type filter holder with a preweighed membrane filter media for collecting samples, is located in the chamber beside the respirator. The sampling time for this unit is the same as the one behind the manikin, but the sampling rate for 1st level is 2 liters per minute (operated by a Monitaire) and, the 2nd and the 3rd levels are 500 cc per minute respectively (operated by a vacuum pump).

A micromanometer, which is connected between two static pressure tubes, indicates the resistance of the respirator during the experimental period. The initial and final resistances across the filter are recorded.

The following procedure is used to prepare a sample for microscopic examination:

The filter containing the fibers is placed on a piece of a clean glass, and 1/8 of the total area is cut out with a razor blade.

The cut out portion looks like a sector shaped piece. A few drops of immersion oil are dropped on a clean 3 x 1 inch microscope slide, then, using tweezers, the sector shaped piece is carefully placed onto the slide. The sample is then covered with a clean cover slip, making sure that no air bubbles are trapped underneath its surface.

When the above preparation is implemented, the slide containing the fiber sample is placed in the photomicroscope under phase contrast illumination and a magnification of 500 X. All fibers larger than 5 microns and total fibers in the eyepiece graticule (5300μ^2 area) are counted. The sector shaped piece is visually separated into about 30 central fields from the sharp point of the sector through to the circular edge for sample counting, the results of which are then averaged.

2. Results

The experimental data resulting from the numerous tests carried out in the pursuit of this project are presented in tabular, graphical and pictorial form on pages 136 to 177 inclusive.

TABLE 14

R 1 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

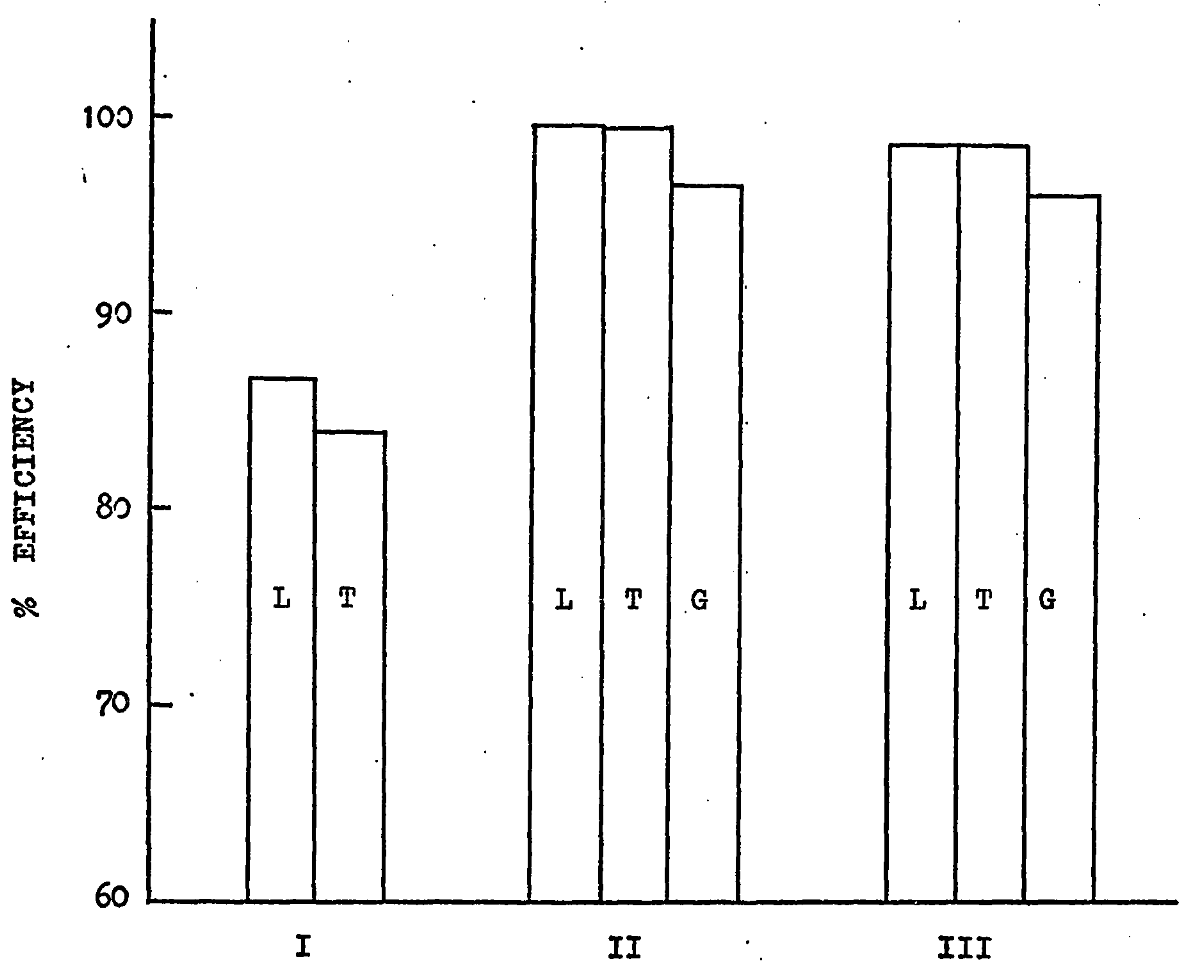
LEVEL	TIME	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE at 6 Lpm (mm H_2O)	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-metric		
	in min.	>5 µ	Total		>5 µ	Total		>5 µ	Total		Initial	Final
I	90	20.6	30.2		3.5	6.3		83.1	79.2		0.060	0.080
	180	24.6	36.3		3.0	5.3		87.8	85.4		0.080	0.180
	270	21.0	33.2		2.9	4.9		86.3	85.3		0.180	0.260
	360	22.0	31.5		2.5	4.6		88.7	85.4		0.260	0.500
Average		22.1	32.8		3.0	5.3		86.6	83.8		0.060	0.500
II	90	43.6	79.2	23.750	0.3	0.7	1.140	99.3	99.1	95.2	0.440	0.420
	180	60.8	99.2	29.770	0.1	0.3	1.072	99.8	99.7	96.4	0.420	0.460
	270	41.6	92.0	27.595	0.1	0.1	0.939	99.9	99.8	96.6	0.460	0.500
	360	54.0	89.2	26.758	0.1	0.2	0.482	99.9	99.9	98.2	0.500	0.520
Average		50.0	89.9	26.968	0.2	0.3	0.908	99.7	99.6	96.6	0.440	0.520
III	90	74.8	113.6	42.001	1.4	2.5	2.100	98.2	97.8	95.0	0.360	0.320
	180	81.6	122.4	45.265	1.3	1.4	1.901	98.5	98.9	95.8	0.320	0.420
	270	79.2	130.8	48.358	0.7	1.4	1.789	99.1	98.9	96.3	0.420	0.420
	360	104.0	158.4	58.630	0.7	1.1	1.642	99.3	99.3	97.2	0.420	0.480
Average		84.9	131.3	48.564	1.0	1.6	1.858	98.8	98.8	96.2	0.360	0.480

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 74

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 1 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION			AVERAGE EFFICIENCY OF RESPIRATOR, %		
		Fibers/cc		mg/m^3	Counting		Gravimetric
		$>5\mu$	Total		$>5\mu$	Total	
I	6	22.1	32.8		86.6	83.8	
II	6	50.0	89.9	26.968	99.7	99.6	96.6
III	6	84.9	131.3	48.564	98.8	98.8	96.2



AVERAGE DUST CONCENTRATION LEVEL

L - $>5\mu$ T - Total G - Gravimetric

FIG. 75

R 1 RESPIRATOR -- TIME VERSUS RESISTANCE ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3		
	> 5 μ	Total		Initial	Final
I	22.1	32.8		0.060	0.500
II	50.0	89.9	26.968	0.440	0.520
III	84.9	131.3	48.564	0.360	0.480

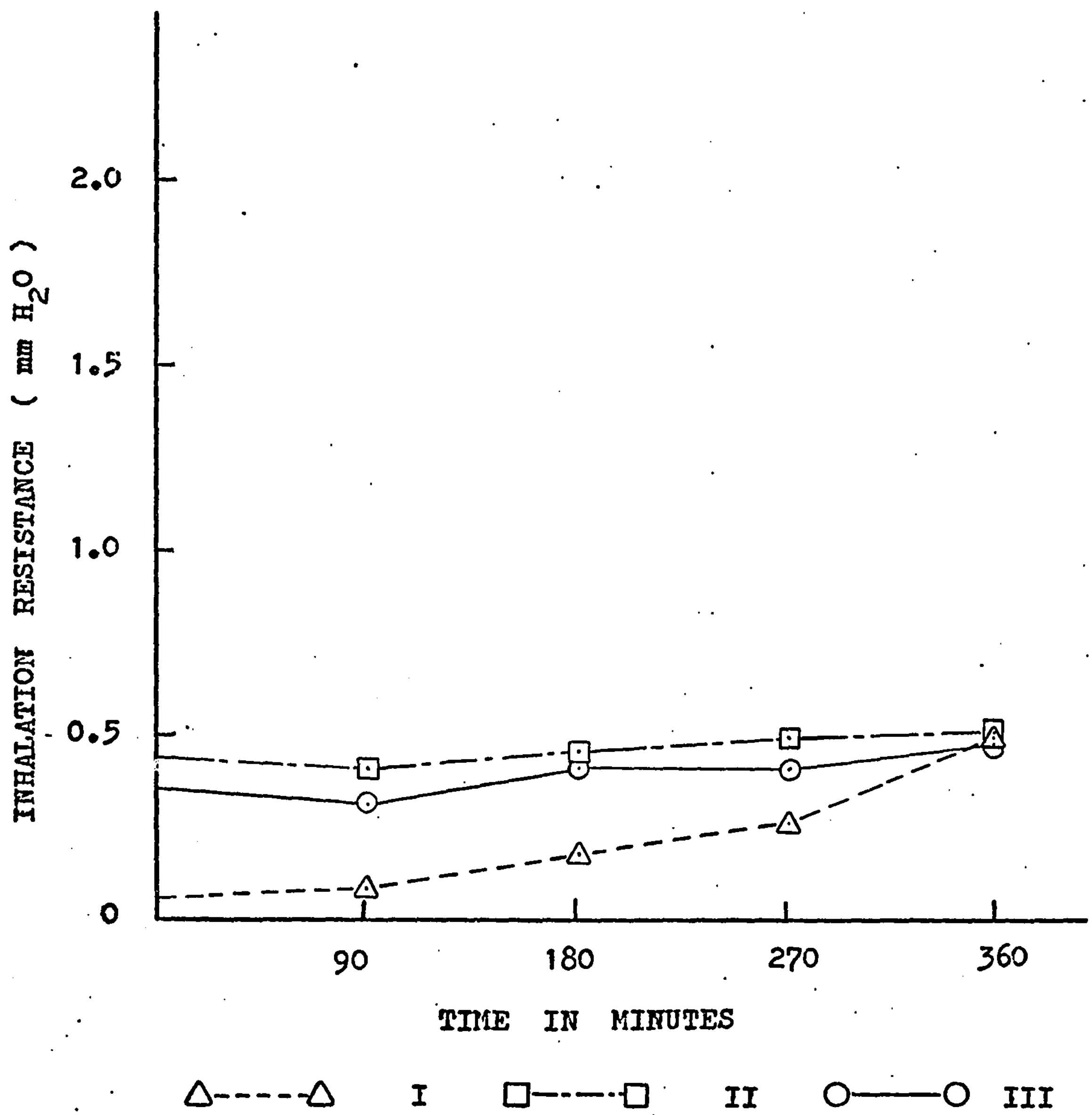
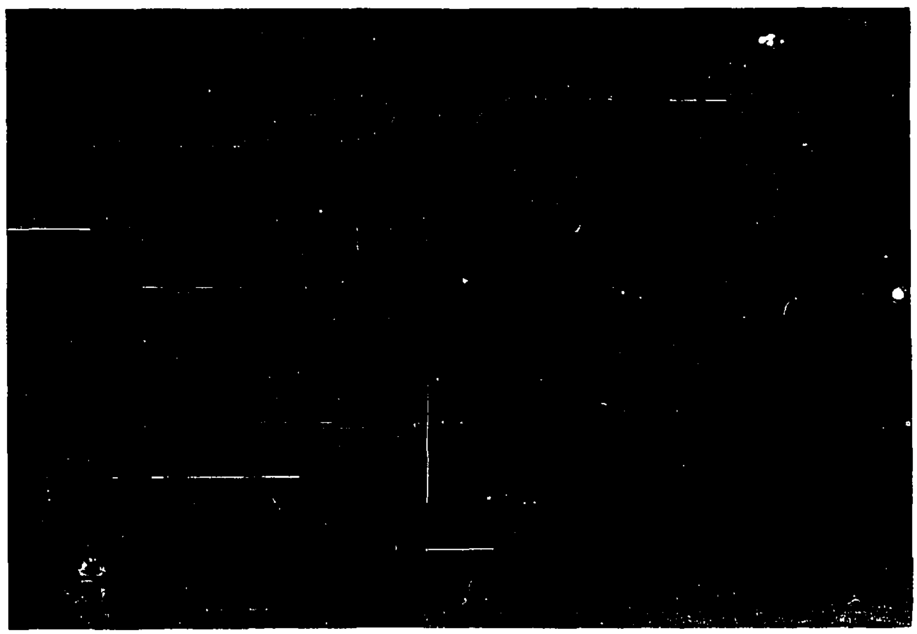
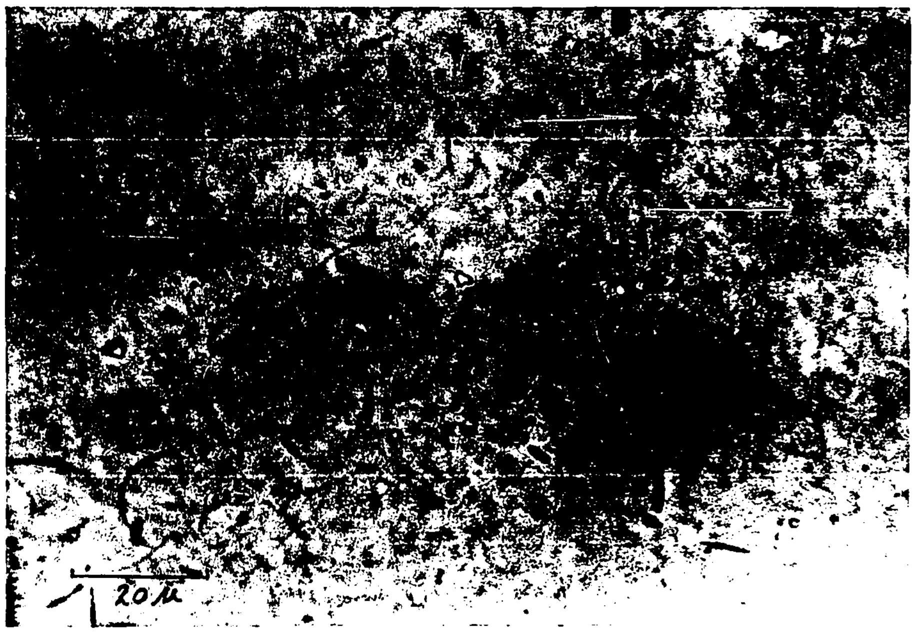


Fig. 76



A micrograph of fiber dust breakthrough filter media of R 1 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

Fig. 76



A micrograph of fiber dust breakthrough filter media of R 1 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

TABLE 15

R 2 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

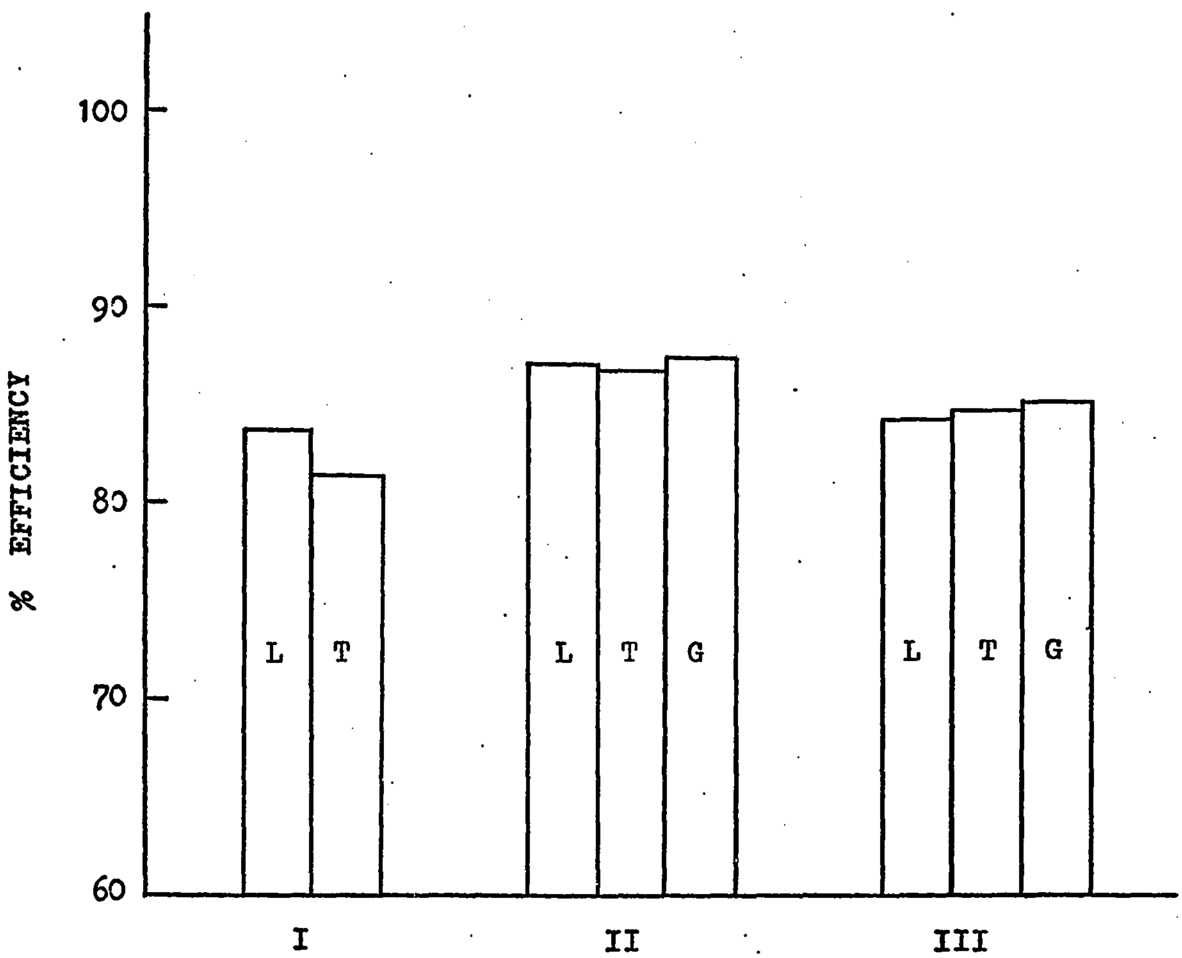
LEVEL	TIME	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE at 6 Lpm (mm H_2O)	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-metric		
	in min.	>5 µ	Total		>5 µ	Total		>5 µ	Total		Initial	Final
I	90	16.4	19.2		2.9	4.0		82.3	79.0		0.220	0.300
	180	16.5	29.0		3.7	6.2		77.6	78.6		0.300	0.340
	270	20.9	26.4		3.9	5.0		81.4	80.9		0.340	0.380
	360	28.9	31.5		3.1	4.6		89.1	85.3		0.380	0.400
Average		20.7	26.5		3.4	4.9		83.6	81.5		0.220	0.400
II	90	54.6	77.0	23.101	6.8	9.2	4.320	87.6	88.0	81.3	0.340	0.300
	180	50.8	80.4	24.123	6.4	9.7	2.581	89.5	87.9	89.3	0.300	0.340
	270	61.5	92.1	27.630	9.0	13.8	3.923	85.4	85.0	85.8	0.340	0.460
	360	60.0	86.0	25.805	8.3	11.4	1.729	86.2	86.8	93.3	0.460	0.560
Average		59.2	83.9	25.164	7.6	11.0	3.138	87.2	86.9	87.5	0.340	0.560
III	90	99.5	136.4	50.500	16.3	21.0	8.332	83.6	84.6	83.5	0.260	0.240
	180	110.0	151.3	55.961	21.9	27.5	8.226	80.1	81.8	85.3	0.240	0.480
	270	115.2	173.5	64.125	17.3	29.3	10.196	85.0	83.1	84.1	0.480	0.260
	360	100.9	160.2	59.281	10.1	17.1	6.995	89.6	89.3	88.2	0.260	0.440
Average		106.4	155.4	57.466	16.4	23.7	8.437	84.4	84.7	85.3	0.260	0.440

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 77

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 2 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION Fibers/cc > 5 µ	Total	mg/m^3	AVERAGE EFFICIENCY OF RESPIRATOR % Counting > 5 µ	Total	Gravimetric
I	6	20.7	26.5		83.6	81.5	
II	6	59.2	83.9	25.164	87.2	86.9	87.5
III	6	106.4	155.4	57.466	84.4	84.7	85.3



AVERAGE DUST CONCENTRATION LEVEL

L - > 5 µ   T - Total   G - Gravimetric

FIG. 78

R 2 RESPIRATOR -- TIME VERSUS RESISTANCE
ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3		
	> 5 µ	Total		Initial	Final
I	20.7	26.5		0.220	0.400
II	59.2	83.9	25.164	0.340	0.560
III	106.4	155.4	57.466	0.260	0.440

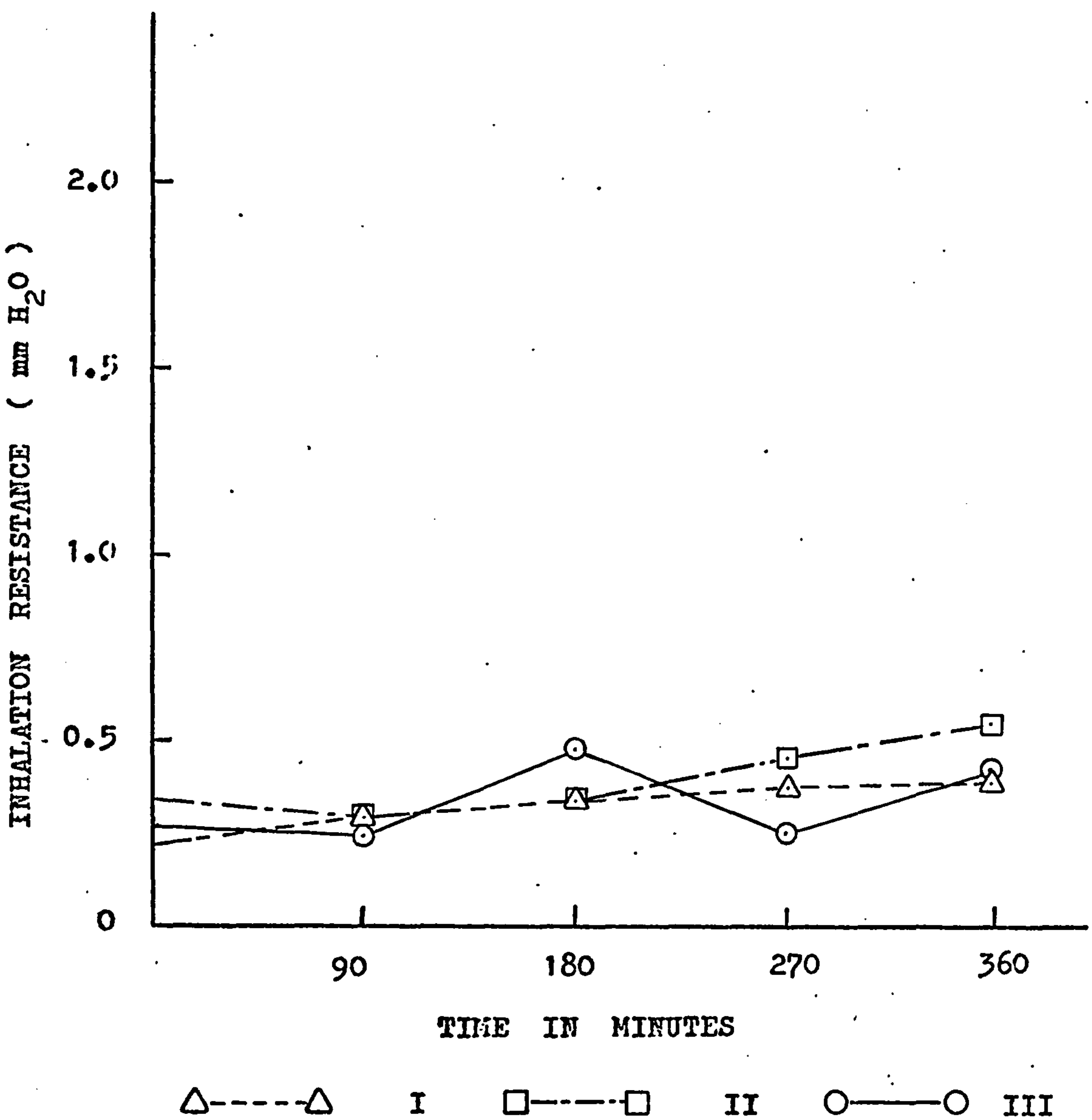
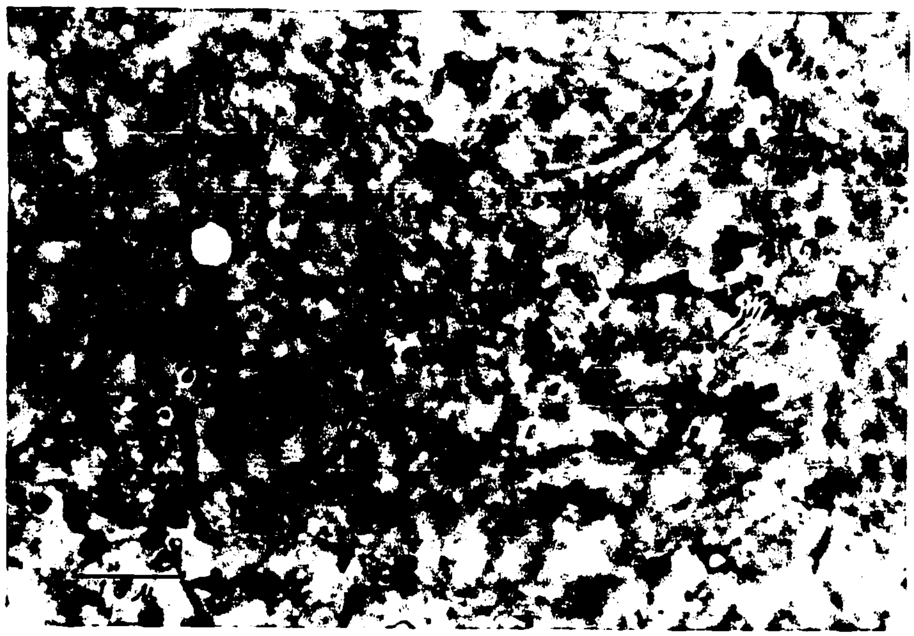


Fig. 79

A micrograph of fiber dust breakthrough filter media of R 2 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

Fig. 79



A micrograph of fiber dust breakthrough filter media of R 2 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

TABLE 16

R 3 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

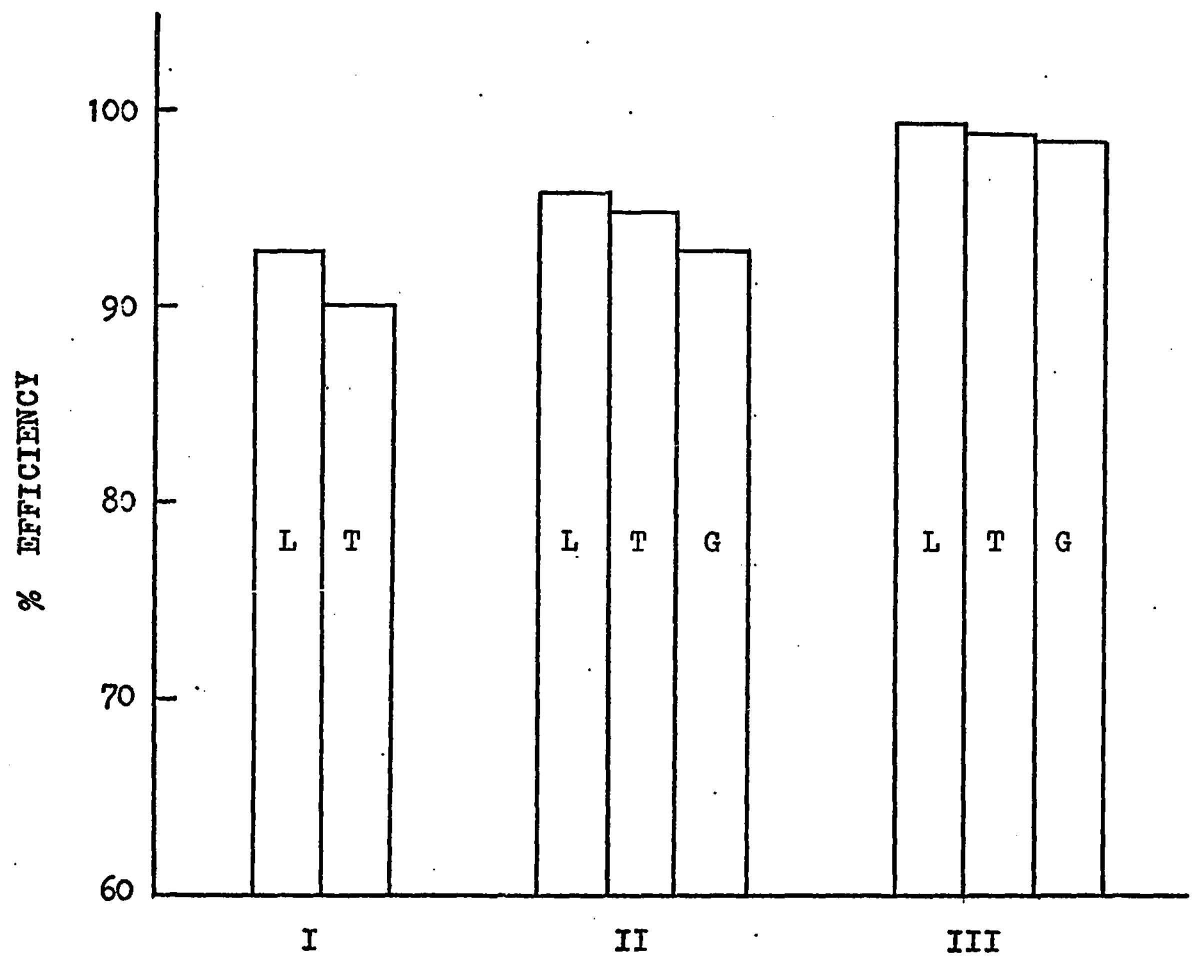
LEVEL	TIME	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE at 6 Lpm (mm H_2O)	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-metric		
	in min.	>5 µ	Total		>5 µ	Total		>5 µ	Total		Initial	Final
	90	18.8	36.1		1.6	4.7		91.5	87.0		0.060	0.080
I	180	18.2	40.1		1.9	4.1		89.6	89.8		0.080	0.180
	270	15.4	34.3		0.7	2.9		95.4	91.5		0.180	0.260
	360	18.7	27.0		1.0	1.9		94.7	92.8		0.260	0.500
Average		17.8	34.4		1.3	3.4		92.7	90.0		0.060	0.500
	90	39.0	70.6	21.185	2.9	5.0	2.246	92.5	92.9	89.4	0.060	0.160
II	180	37.2	61.4	18.427	1.6	3.7	1.456	95.7	93.9	92.1	0.160	0.300
	270	40.5	70.1	21.033	1.7	3.7	1.325	95.7	94.7	93.7	0.300	0.400
	360	43.0	75.6	22.684	0.6	2.0	1.021	98.7	97.4	95.5	0.400	0.640
Average		39.9	69.4	20.832	1.7	3.6	1.512	95.7	94.8	92.7	0.060	0.640
	90	122.0	178.0	65.873	2.2	4.3	1.976	98.2	97.6	97.0	0.040	0.400
III	180	117.6	157.2	58.185	0.5	1.4	1.109	99.6	99.1	98.1	0.400	0.900
	270	99.7	131.3	48.592	0.3	0.9	0.486	99.7	99.3	99.0	0.900	0.820
	360	100.2	140.0	51.837	0.3	1.0	0.207	99.7	99.3	99.6	0.820	1.360
Average		109.8	157.6	56.121	0.8	1.9	0.945	99.3	98.8	98.4	0.040	1.360

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 80

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 3 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION			AVERAGE EFFICIENCY OF RESPIRATOR %		
		Fibers/cc		mg/m^3	Counting		Gravi-metric
		$>5\mu$	Total		$>5\mu$	Total	
I	6	17.8	34.4		92.7	90.0	
II	6	39.9	69.4	20.832	95.7	94.8	92.7
III	6	109.8	157.6	56.121	99.3	98.8	98.4



AVERAGE DUST CONCENTRATION LEVEL

L - $>5\mu$ T - Total G - Gravimetric

FIG. 81

R 3 RESPIRATOR -- TIME VERSUS RESISTANCE ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3		
	> 5 μ	Total		Initial	Final
I	17.8	34.4		0.060	0.500
II	39.9	69.4	20.832	0.060	0.640
III	109.8	157.6	56.121	0.040	1.360

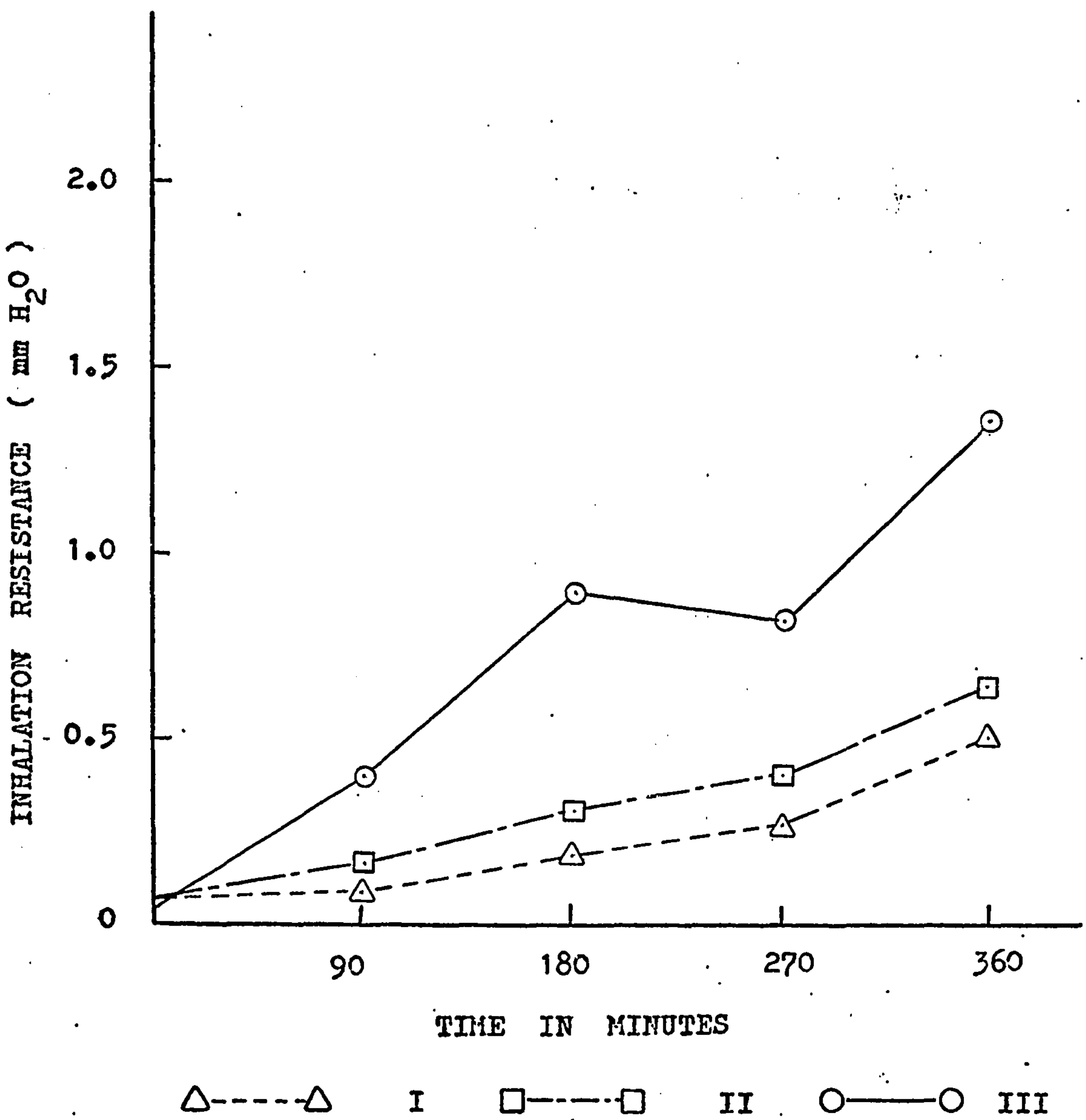
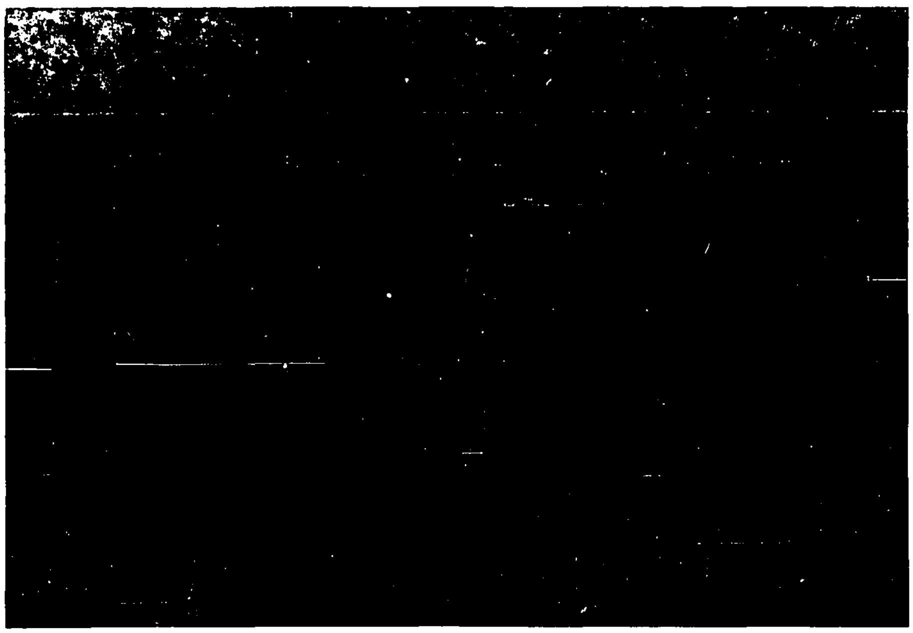
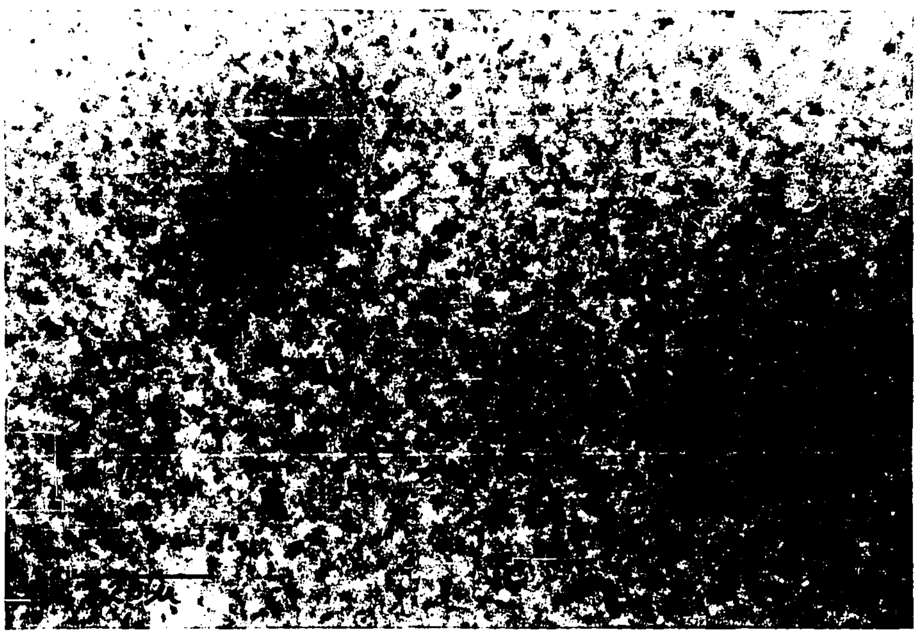


Fig. 82



A micrograph of fiber dust breakthrough filter media of R 3 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

Fig. 82



A micrograph of fiber dust breakthrough filter media of R 3 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

TABLE 17

R 4 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

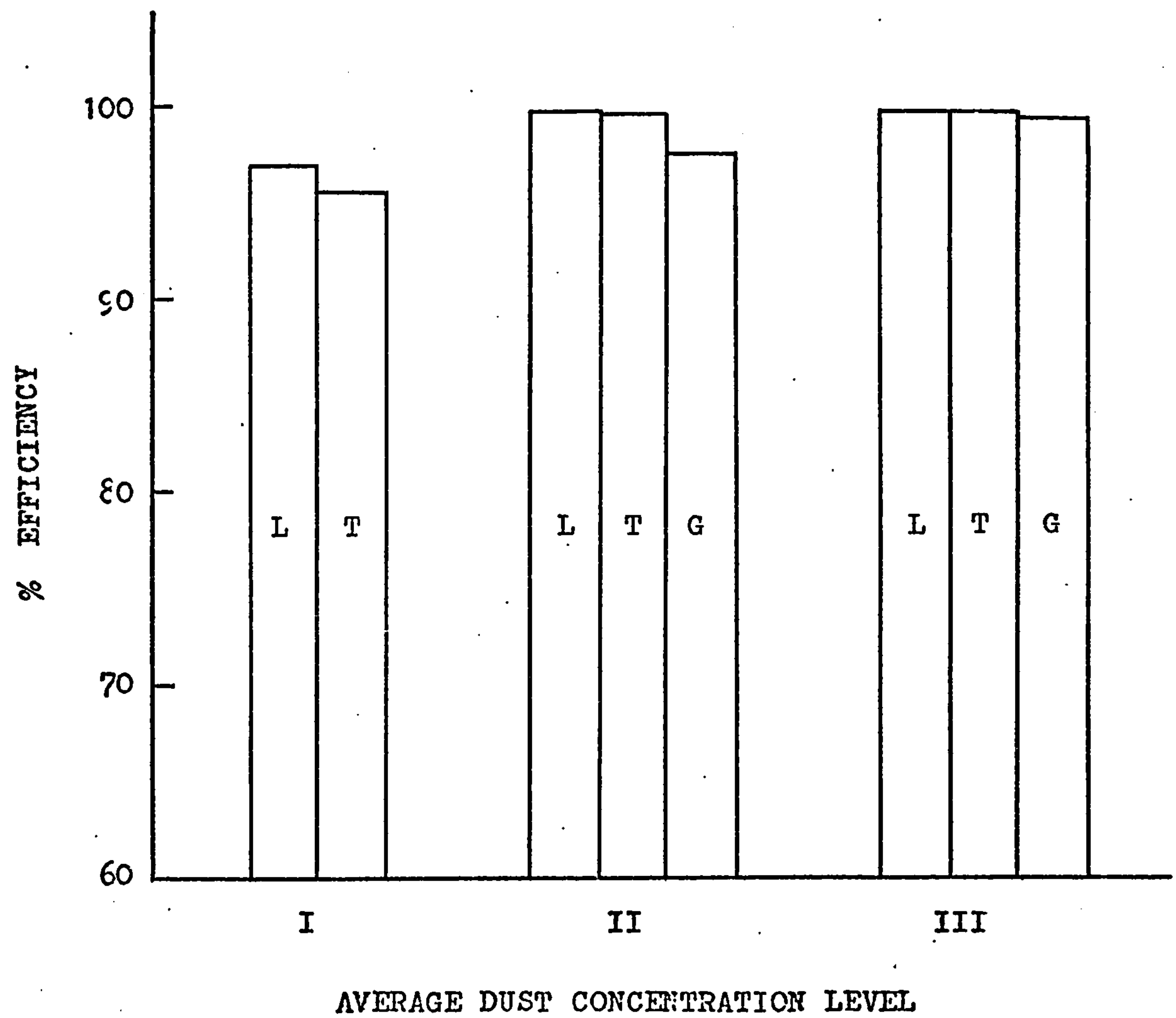
LEVEL	TIME in min.	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE at 6 Lpm (mm H_2O)	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-metric		
		>5 µ	Total		>5 µ	Total		>5 µ	Total		Initial	Final
I	90	27.6	35.0		1.7	3.0		93.9	91.4		0.340	0.360
	180	27.7	37.6		0.9	1.8		96.8	95.1		0.360	0.380
	270	20.5	35.3		0.4	0.9		98.1	97.5		0.380	0.400
	360	22.1	38.5		0.2	0.5		99.1	98.8		0.400	0.400
Average		24.5	36.6		0.7	1.6		97.0	95.6		0.340	0.400
II	90	50.0	93.6	28.101	0.06	0.3	0.984	99.9	99.7	96.5	0.400	0.600
	180	53.1	95.4	28.620	0.05	0.2	0.887	99.9	99.8	96.9	0.600	0.260
	270	50.8	94.0	28.197	0.05	0.2	0.508	99.9	99.8	98.2	0.260	0.440
	360	54.8	96.6	28.975	0.04	0.1	0.348	99.9	99.9	98.8	0.440	0.400
Average		52.2	94.9	28.473	0.05	0.2	0.682	99.9	99.8	97.6	0.400	0.400
III	90	104.0	144.8	53.576	0.1	0.3	0.321	99.9	99.8	99.4	0.440	0.440
	180	82.8	129.2	47.798	0.1	0.3	0.191	99.9	99.8	99.6	0.440	0.460
	270	112.8	152.8	46.697	0.1	0.2	0.187	99.9	99.9	99.6	0.460	0.560
	360	90.7	131.5	48.849	0.1	0.1	0.147	99.9	99.9	99.7	0.560	0.580
Average		97.6	139.6	49.230	0.1	0.2	0.212	99.9	99.9	99.6	0.440	0.580

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 83

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 4 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION			AVERAGE EFFICIENCY OF RESPIRATOR %		
		Fibers/cc		mg/m^3	Counting		Gravimetric
		>5 μ	Total		>5 μ	Total	
I	6	24.5	36.6		97.0	95.6	
II	6	52.2	94.9	28.473	99.9	99.8	97.6
III	6	97.6	139.6	49.230	99.9	99.9	99.6



L - >5 μ T - Total G - Gravimetric

FIG. 84

R 4 RESPIRATOR -- TIME VERSUS RESISTANCE ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3		
	> 5 µ	Total		Initial	Final
I	24.5	36.6		0.340	0.400
II	52.2	94.9	28.473	0.400	0.400
III	97.6	139.6	49.230	0.440	0.580

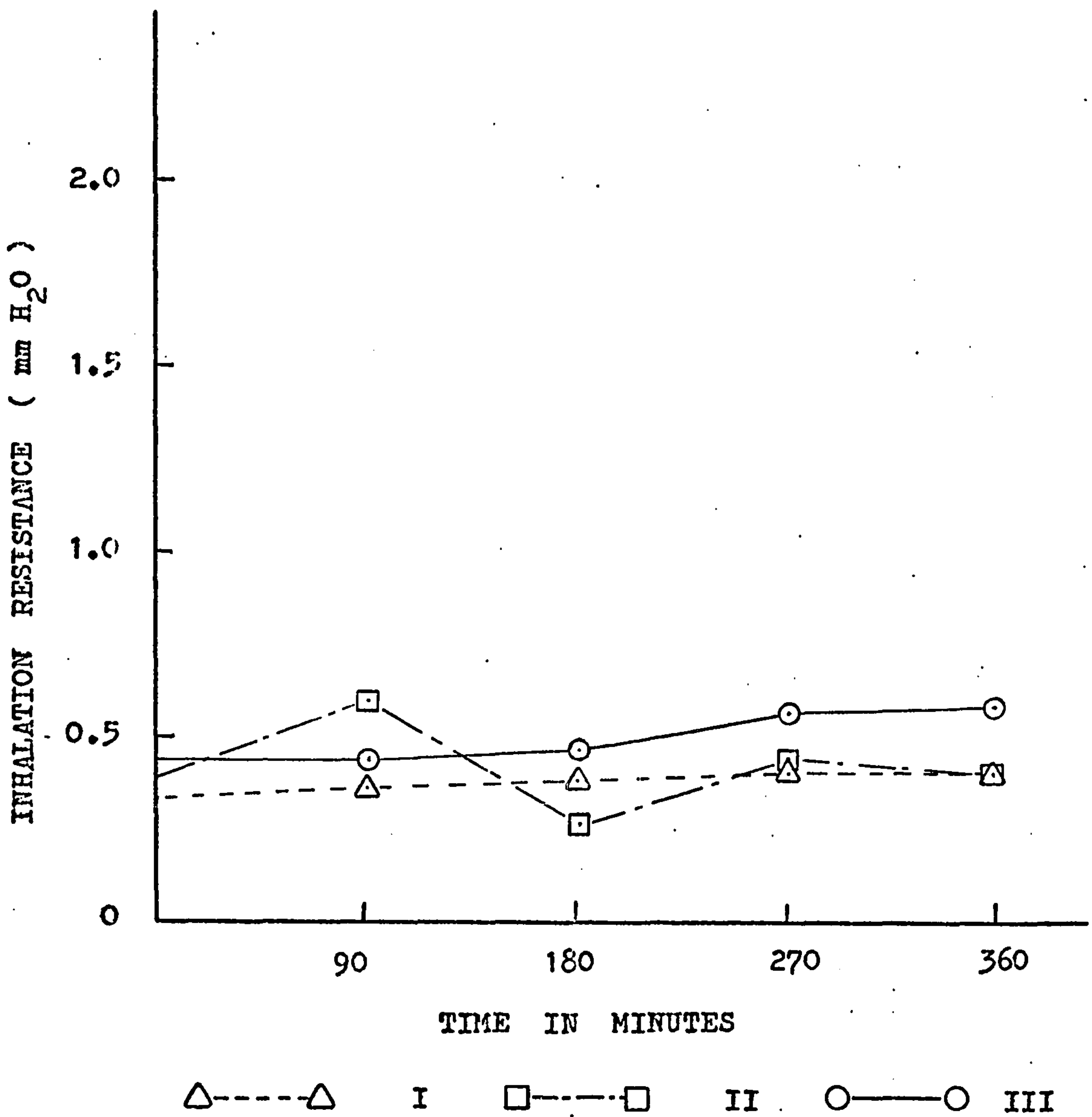
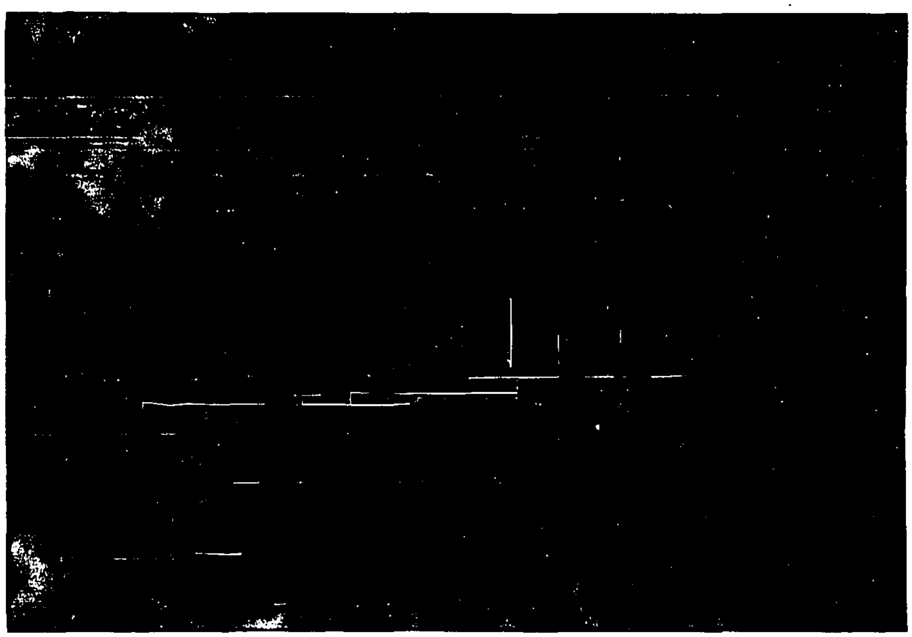
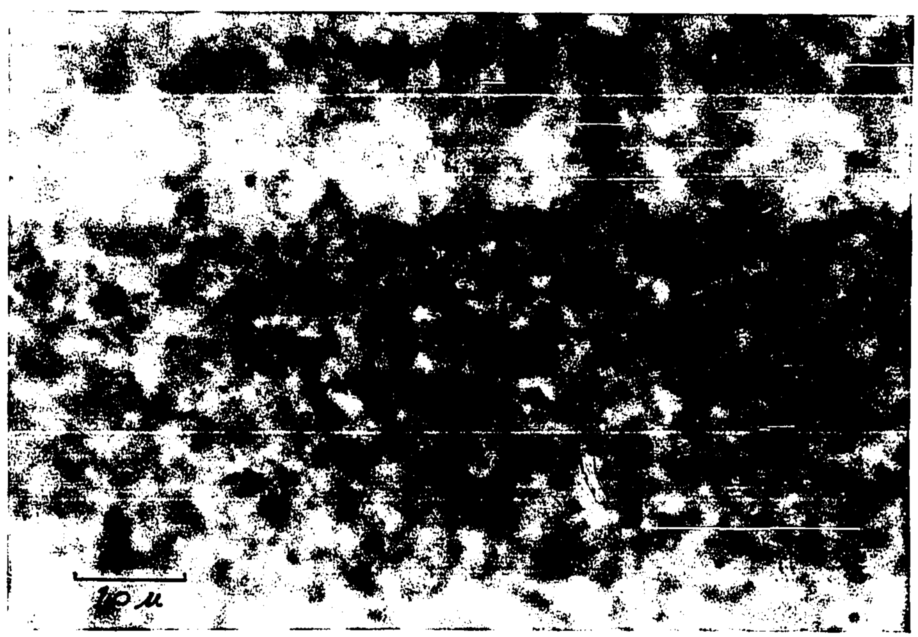


Fig. 85



A micrograph of fiber dust breakthrough filter media of R 4 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

Fig. 85



A micrograph of fiber dust breakthrough filter media of R 4 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

TABLE 18

R 5 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

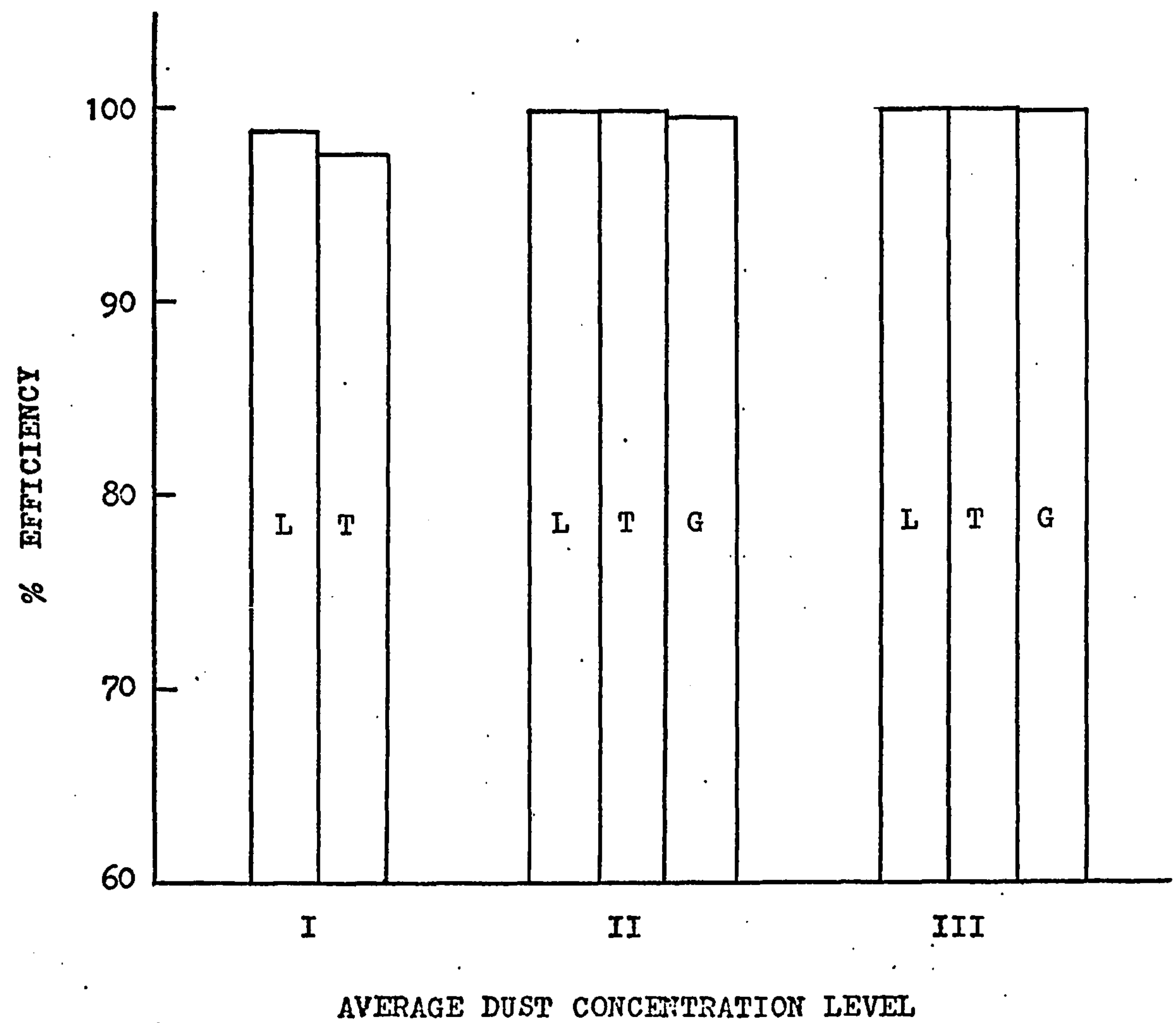
LEVEL	TIME	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-metric	at 6 Lpm (mm H_2O)	
	in min.	>5 µ	Total		>5 µ	Total		>5 µ	Total		Initial	Final
I	90	21.5	35.1		0.47	0.98		97.8	97.2		0.280	0.360
	180	25.0	38.3		0.38	1.03		98.5	97.3		0.360	0.360
	270	23.7	36.4		0.24	0.69		99.0	98.1		0.360	0.380
	360	20.0	33.1		0.10	0.33		99.5	99.0		0.380	0.420
Average		22.6	35.7		0.30	0.76		98.7	97.9		0.280	0.420
II	90	47.2	88.0	26.395	0.04	0.2	0.370	99.9	99.8	98.6	0.280	0.380
	180	50.5	90.2	26.989	0.04	0.2	0.189	99.9	99.8	99.3	0.380	0.300
	270	47.2	62.4	18.715	0.03	0.1	0.075	99.9	99.9	99.6	0.300	0.400
	360	50.9	78.5	23.545	0.02	0.1	0.047	99.9	99.9	99.8	0.400	0.460
Average		48.9	79.8	23.911	0.03	0.15	0.170	99.9	99.9	99.3	0.280	0.460
III	90	122.0	165.1	61.124	0.12	0.33	0.183	99.9	99.8	99.7	0.200	0.400
	180	115.8	158.4	59.608	0.11	0.16	0.119	99.9	99.9	99.8	0.400	0.420
	270	109.5	147.3	54.489	0.11	0.15	0.109	99.9	99.9	99.8	0.420	0.380
	360	127.3	180.0	66.615	0.13	0.18	0.067	99.9	99.9	99.8	0.380	0.440
Average		118.7	162.7	60.459	0.12	0.21	0.119	99.9	99.9	99.8	0.200	0.440

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 86

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 5 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION			AVERAGE EFFICIENCY OF RESPIRATOR %		
		Fibers/cc		mg/m^3	Counting		Gravimetric
		$>5\mu$	Total		$>5\mu$	Total	
I	6	22.6	35.7		98.7	97.9	
II	6	48.9	79.8	23.911	99.9	99.9	99.3
III	6	118.7	162.7	60.459	99.9	99.9	99.8



L - $>5\mu$ T - Total G - Gravimetric

FIG. 87

R 5 RESPIRATOR -- TIME VERSUS RESISTANCE

ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3		
	> 5 μ	Total		Initial	Final
I	22.6	35.7		0.280	0.420
II	48.9	79.8	23.911	0.280	0.460
III	118.7	162.7	60.459	0.200	0.440

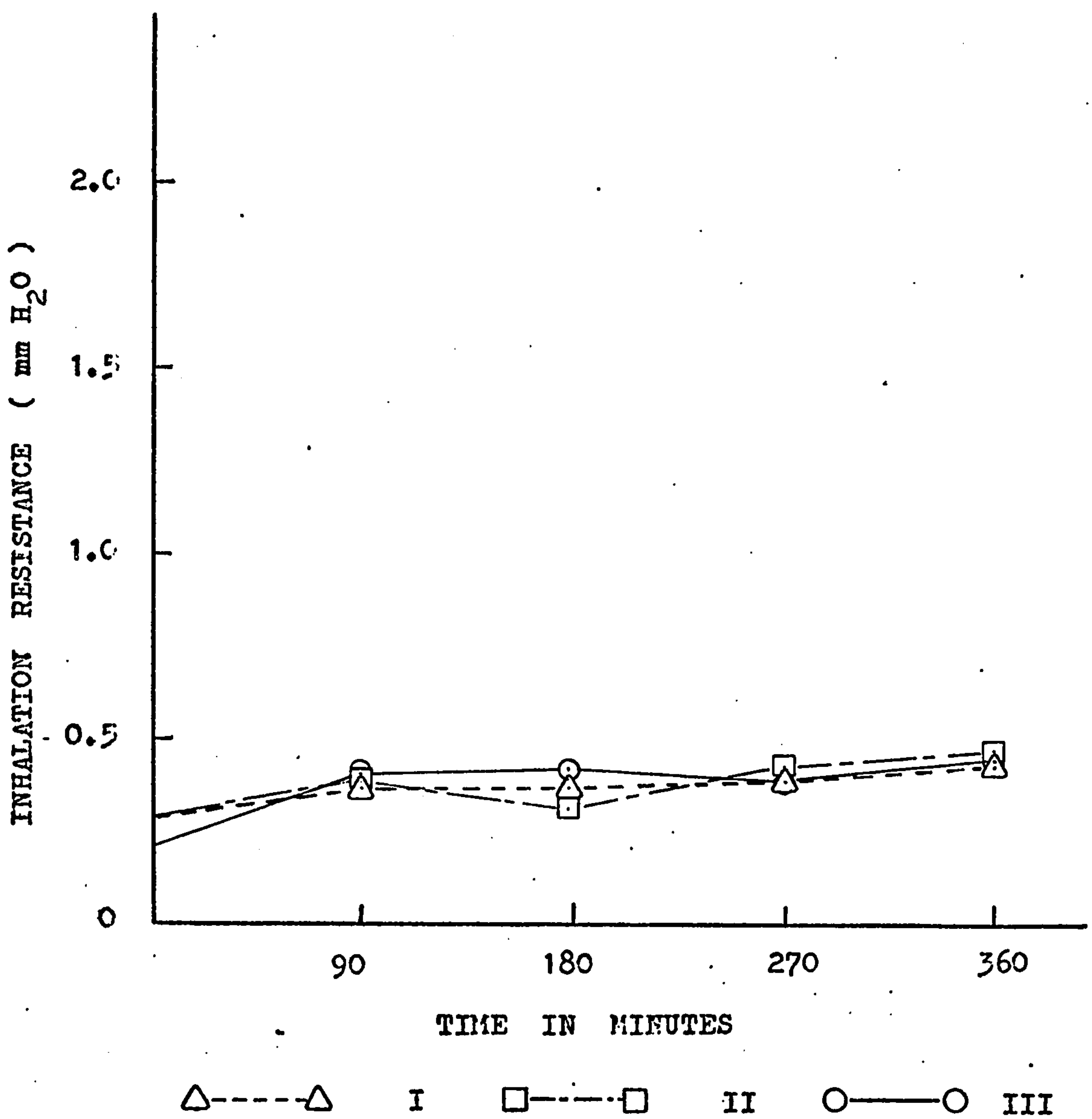


TABLE 19

R 6 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

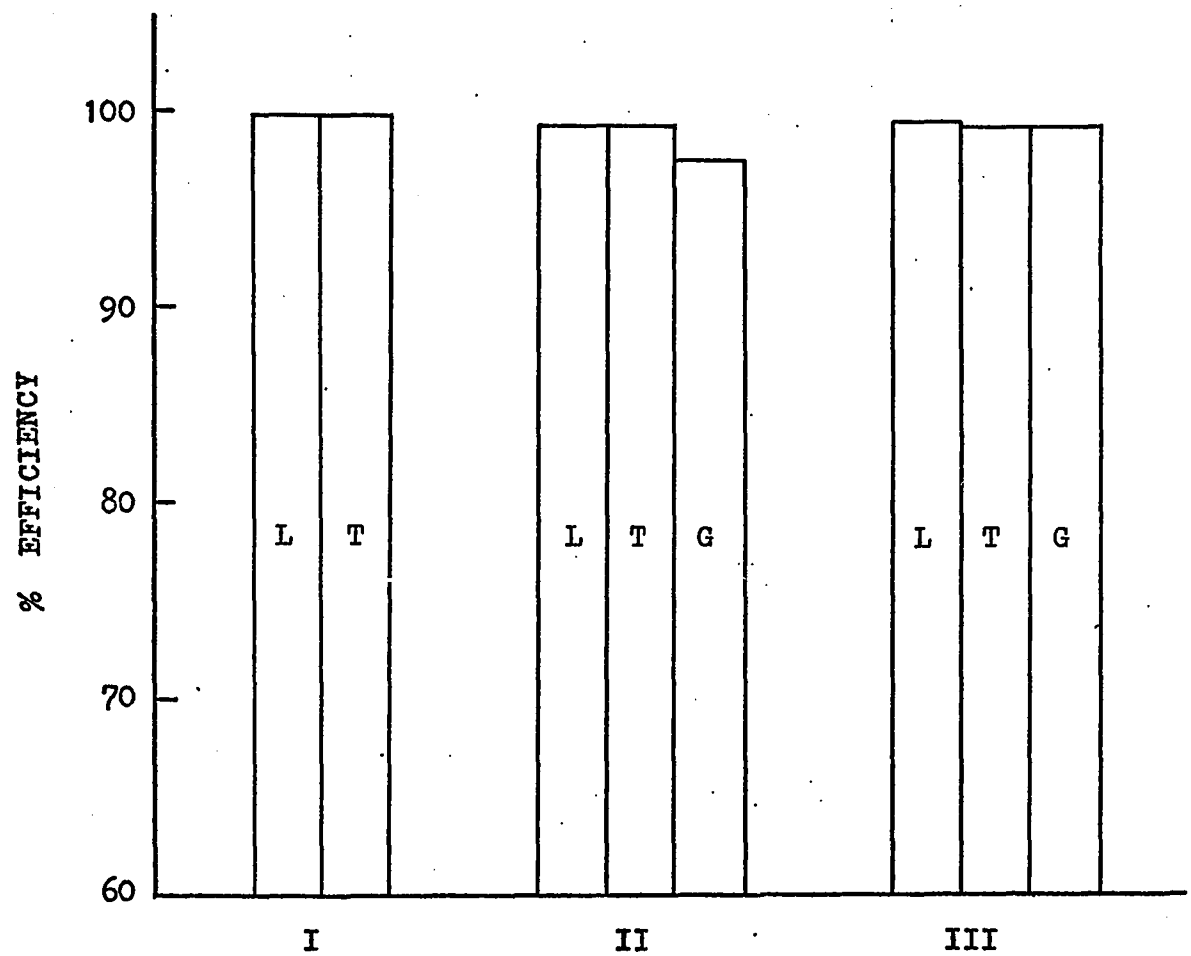
LEVEL	TIME	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE at 6 Lpm (mm H_2O)	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-metric		
	in min.	>5 μ	Total		>5 μ	Total		>5 μ	Total		Initial	Final
I	90	20.6	34.5		0.04	0.03		99.8	99.9		0.160	0.160
	180	19.5	36.0		0.04	0.04		99.8	99.9		0.160	0.180
	270	20.0	35.8		0.02	0.04		99.9	99.9		0.180	0.180
	360	19.1	38.0		0.02	0.04		99.9	99.9		0.180	0.180
Average		19.8	36.6		0.03	0.04		99.9	99.9		0.160	0.180
II	90	61.6	83.2	24.962	0.2	0.4	0.584	99.7	99.5	97.7	0.180	0.180
	180	49.3	80.5	24.150	0.2	0.3	0.894	99.6	99.8	96.3	0.180	0.180
	270	45.6	71.2	21.365	0.1	0.2	0.406	99.8	99.7	98.1	0.180	0.160
	360	50.7	83.6	25.080	0.1	0.1	0.276	99.8	99.9	98.1	0.160	0.180
Average		51.8	79.6	23.889	0.2	0.3	0.540	99.6	99.6	97.7	0.180	0.180
III	90	76.4	128.0	47.355	0.5	1.2	0.473	99.4	99.1	99.0	0.260	0.380
	180	119.6	187.2	69.192	0.6	1.9	0.263	99.5	99.0	99.1	0.380	0.400
	270	75.6	140.8	52.112	0.3	1.0	0.261	99.6	99.3	99.5	0.400	0.400
	360	72.0	134.8	49.793	0.1	0.4	0.199	99.8	99.7	99.6	0.400	0.380
Average		85.9	148.5	54.613	0.4	1.1	0.389	99.7	99.3	99.3	0.260	0.380

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 88

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 6 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION Fibers/cc $>5\mu$	Total	mg/m^3	AVERAGE EFFICIENCY OF RESPIRATOR % Counting $>5\mu$	Total	Gravimetric
I	6	19.8	36.6		99.9	99.9	
II	6	51.8	79.6	23.889	99.6	99.6	97.7
III	6	85.9	148.5	54.613	99.7	99.3	99.3



AVERAGE DUST CONCENTRATION LEVEL

L - $>5\mu$ T - Total G - Gravimetric

FIG. 89

R 6 RESPIRATOR -- TIME VERSUS RESITANCE ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3	Initial	Final
	> 5 μ	Total			
I	19.8	36.6		0.160	0.180
II	51.8	79.6	23.889	0.180	0.180
III	85.9	148.5	54.613	0.260	0.380

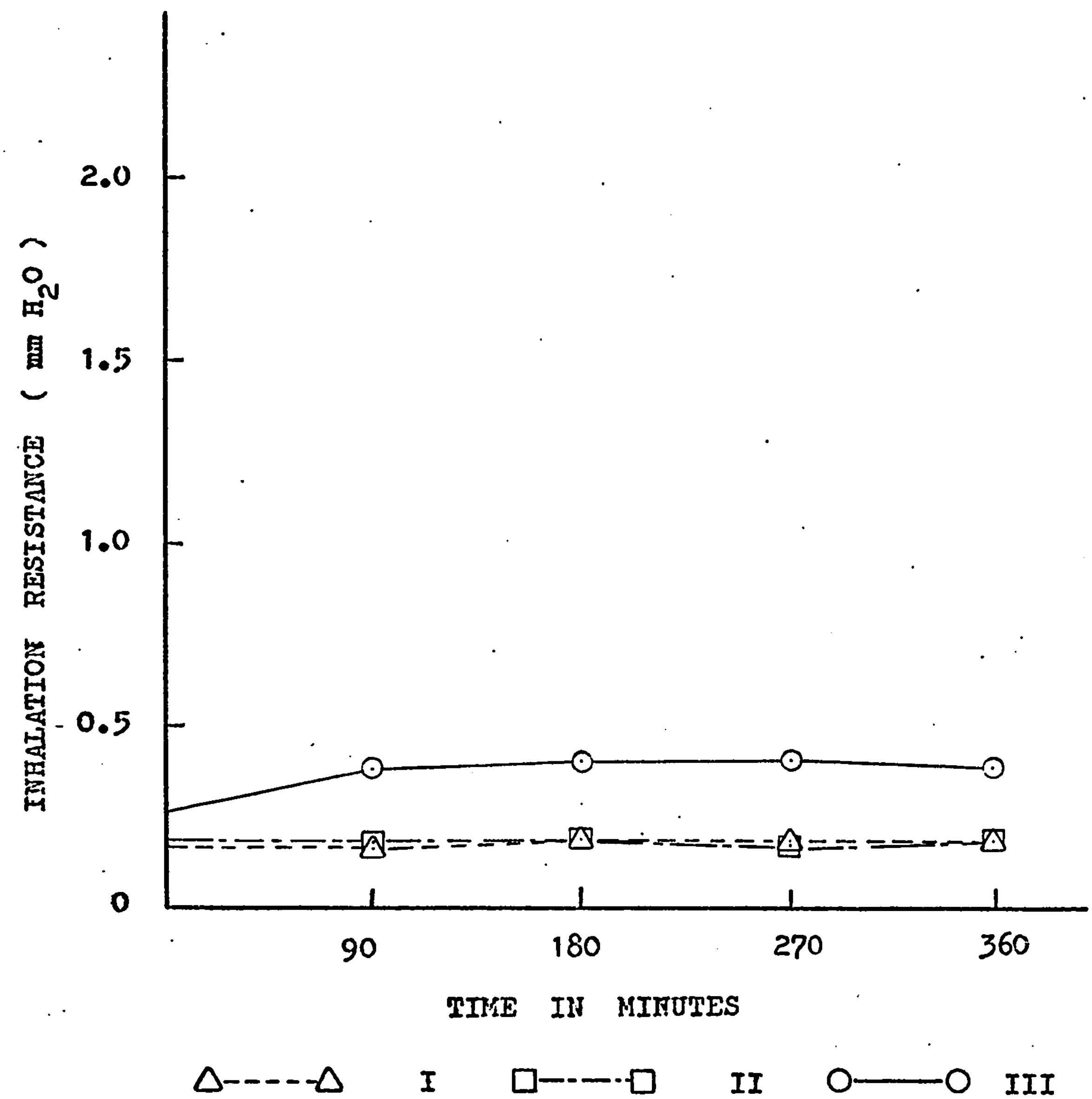


TABLE 20

R 7 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

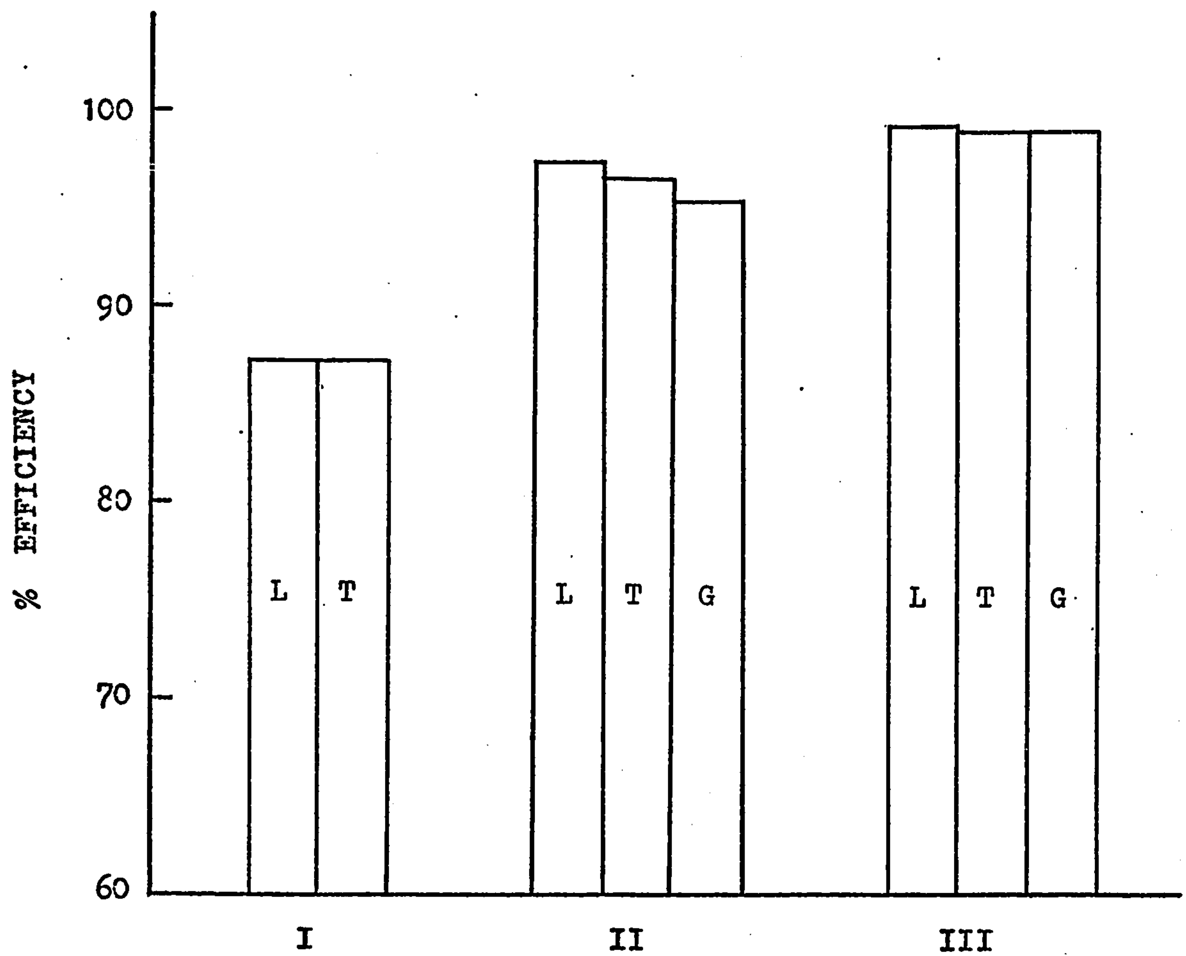
LEVEL	TIME in min.	DUST CONCENTRATION IN CHAMBER: Fibers/cc >5 µ	DUST CONCENTRATION IN CHAMBER: Fibers/cc Total	DUST CONCENTRATION IN CHAMBER: mg/m^3	FILTER MEDIA PENETRATION: Fibers/cc >5 µ	FILTER MEDIA PENETRATION: Fibers/cc Total	FILTER MEDIA PENETRATION: mg/m^3	EFFICIENCY OF DUST RESPIRATOR %: Counting >5 µ	EFFICIENCY OF DUST RESPIRATOR %: Counting Total	EFFICIENCY OF DUST RESPIRATOR %: Gravimetric	INHALATION RESISTANCE at 6 Lpm (mm H_2O): Initial	INHALATION RESISTANCE at 6 Lpm (mm H_2O): Final
I	90	30.9	39.7		4.5	5.5		85.5	86.2		0.340	0.360
	180	25.1	36.0		3.4	4.3		86.3	88.0		0.360	0.400
	270	26.0	40.0		3.2	5.8		87.7	85.6		0.400	0.380
	360	20.9	30.6		2.2	3.1		89.2	89.9		0.380	0.380
Average		25.7	36.6		3.3	4.7		87.2	87.2		0.340	0.380
II	90	47.8	70.4	21.120	2.5	3.8	1.309	94.6	94.6	93.8	0.540	0.540
	180	52.8	66.8	20.041	1.8	3.6	1.162	96.6	94.7	94.2	0.540	0.560
	270	49.4	67.2	20.163	0.4	1.1	0.726	99.2	98.3	96.4	0.560	0.560
	360	50.6	69.5	20.850	0.3	0.6	0.563	99.4	99.2	97.3	0.560	0.580
Average		50.2	68.5	20.543	1.3	2.3	0.940	97.5	96.6	95.4	0.540	0.580
III	90	99.2	119.2	47.671	0.9	1.3	0.763	99.1	98.9	98.4	0.620	0.700
	180	84.4	111.2	44.490	0.7	1.0	0.623	99.2	99.1	98.6	0.700	0.720
	270	96.0	121.2	48.365	0.5	1.3	0.484	99.5	98.9	99.0	0.720	0.980
	360	76.4	105.6	42.237	0.3	1.4	0.169	99.6	98.7	99.6	0.980	0.980
Average		89.0	114.3	45.691	0.6	1.3	0.510	99.3	98.9	98.9	0.620	0.980

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 90

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 7 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION Fibers/cc $>5\mu$	Total	mg/m^3	AVERAGE EFFICIENCY OF RESPIRATOR % Counting $>5\mu$	Total	Gravimetric
I	6	25.7	36.6		87.2	87.2	
II	6	50.2	68.5	20.543	97.5	96.6	95.4
III	6	89.0	114.3	45.691	99.3	98.9	98.9



AVERAGE DUST CONCENTRATION LEVEL

L - $>5\mu$ T - Total G - Gravimetric

FIG. 91

R 7 RESPIRATOR -- TIME VERSUS RESISTANCE
ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3	Initial	Final
	> 5 μ	Total			
I	25.7	36.6		0.340	0.380
II	50.2	68.5	20.543	0.540	0.580
III	89.0	114.3	45.691	0.620	0.980

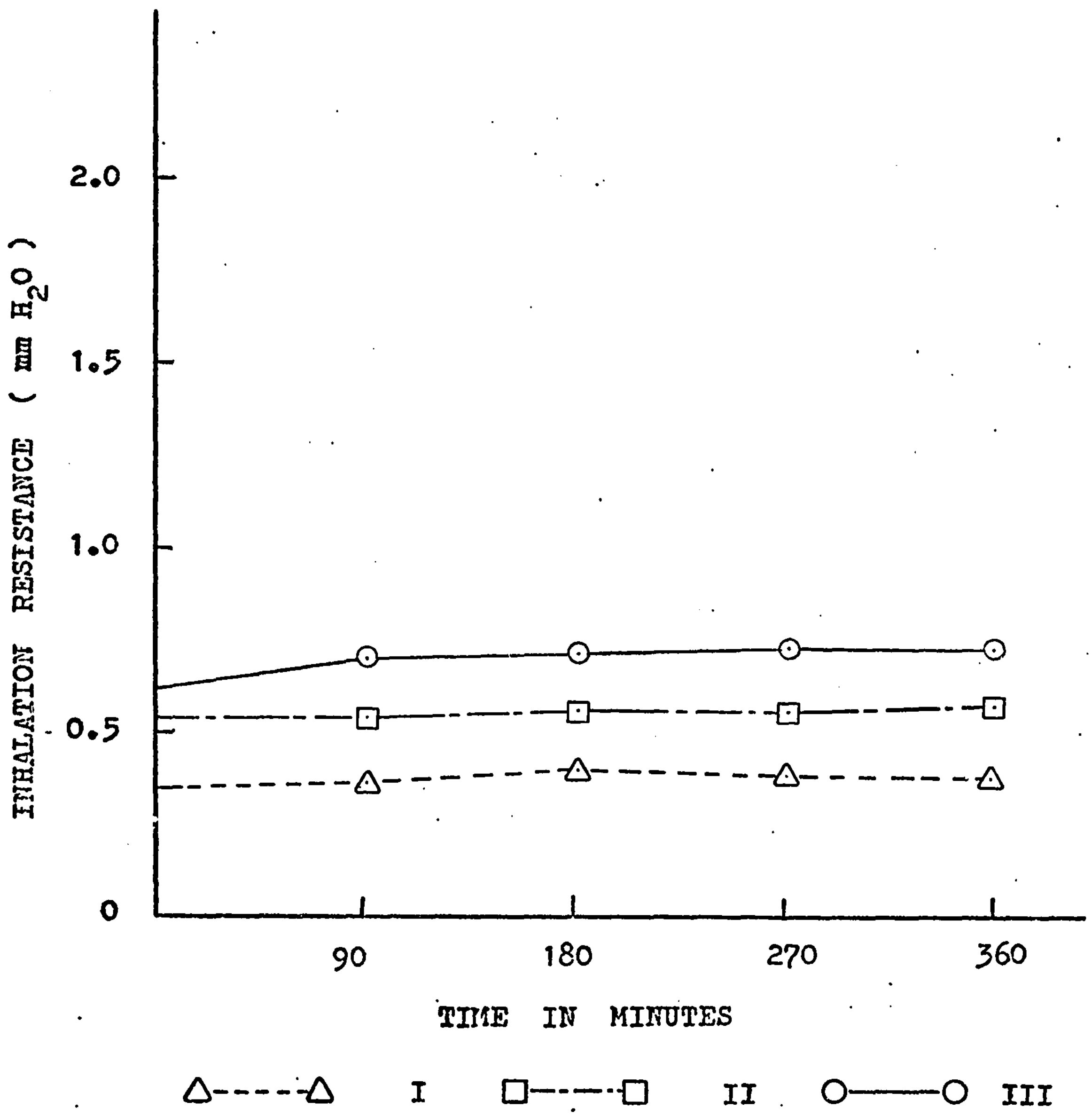
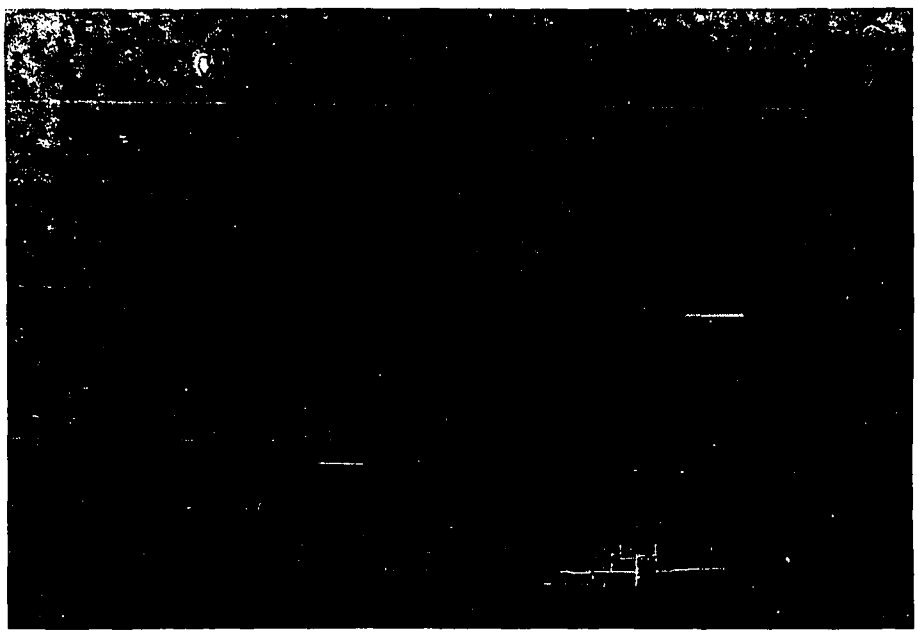
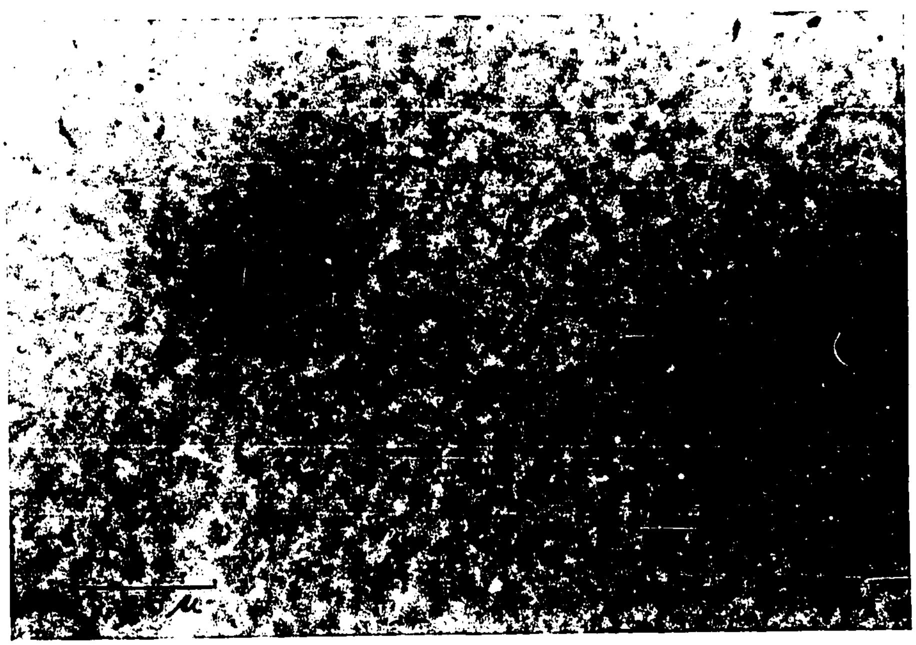


Fig. 92



A micrograph of fiber dust breakthrough filter media of R 7 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

Fig. 92



A micrograph of fiber dust breakthrough filter media of R 7 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

TABLE 21

R 8 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

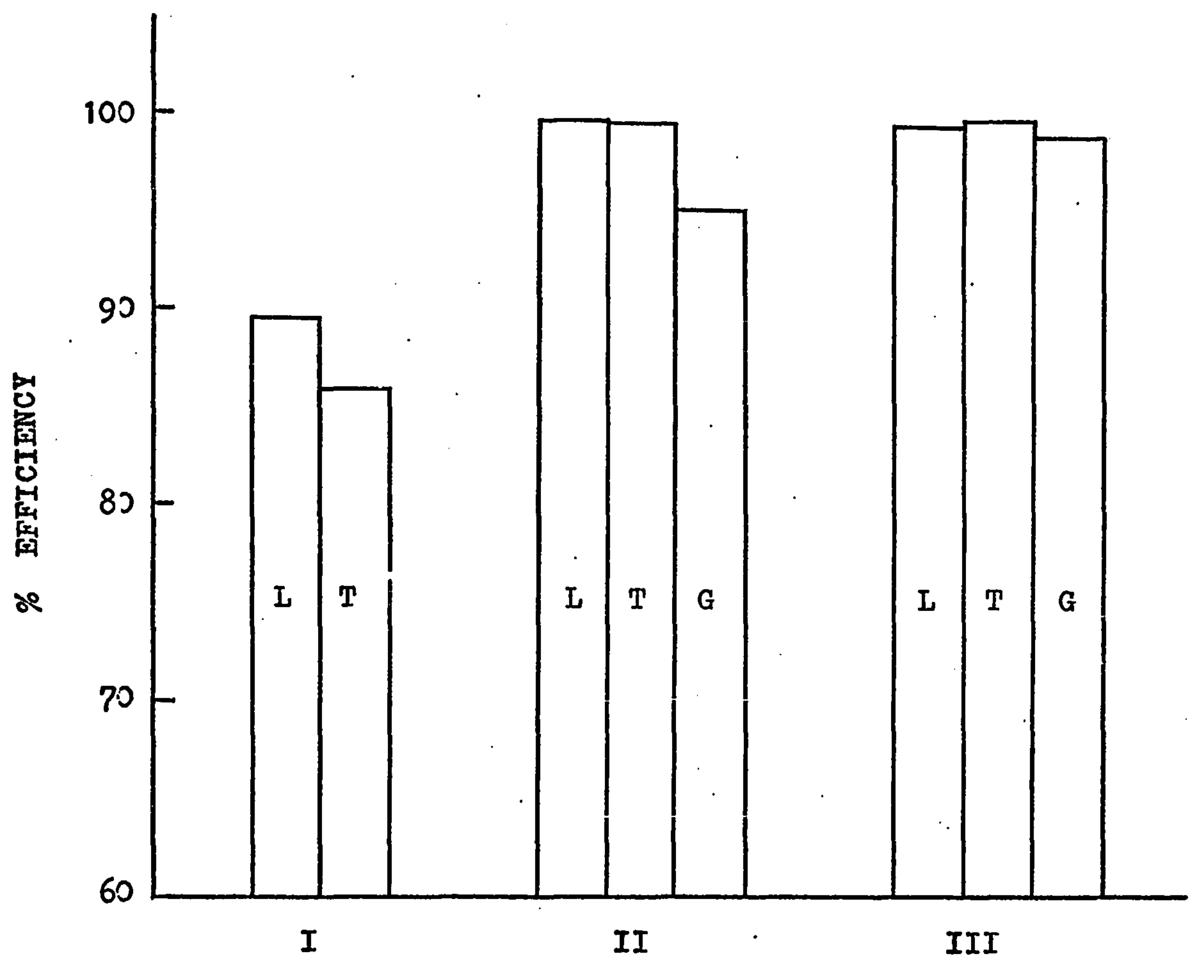
LEVEL	TIME	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE at 6 Lpm (mm H_2O)	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-		
	in min.	$>5\mu$	Total		$>5\mu$	Total		$>5\mu$	Total	metric	Initial	Final
I	90	24.6	32.0		3.2	5.3		87.4	83.5		1.240	1.320
	180	18.9	24.4		1.6	3.4		91.5	86.1		1.320	1.332
	270	19.7	25.3		2.2	3.7		88.4	85.4		1.332	1.338
	360	20.2	24.8		1.6	2.8		91.1	88.8		1.338	1.336
Average		20.9	26.6		2.2	3.8		89.5	85.8		1.240	1.336
II	90	85.6	118.0	35.402	0.3	0.8	1.912	99.6	99.3	94.6	1.210	1.210
	180	65.6	94.8	28.443	0.2	0.3	1.479	99.7	99.7	94.8	1.210	1.340
	270	62.8	91.2	27.360	0.2	0.3	1.323	99.7	99.7	95.2	1.340	1.280
	360	55.6	80.4	24.125	0.1	0.2	0.941	99.8	99.8	96.1	1.280	1.360
Average		67.4	96.3	28.830	0.2	0.4	1.414	99.7	99.6	95.1	1.210	1.360
III	90	95.0	100.4	31.123	0.9	0.2	0.407	99.1	99.8	98.7	1.420	1.380
	180	115.2	139.6	45.064	0.9	0.3	0.542	99.2	99.8	98.8	1.380	1.580
	270	99.6	131.2	40.125	0.5	0.3	0.361	99.5	99.8	99.1	1.580	1.800
	360	98.5	125.4	38.537	0.1	0.3	0.193	99.9	99.8	99.5	1.800	1.800
Average		102.1	124.2	38.712	0.6	0.3	0.376	99.4	99.8	99.0	1.420	1.800

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 93

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 8 RESPIRATOR

LEVEL	TIME	AVERAGE DUST CONCENTRATION			AVERAGE EFFICIENCY OF RESPIRATOR %		
		Fibers/cc		mg/m^3	Counting		Gravi-metric
	in hr.	$>5\mu$	Total		$>5\mu$	Total	
I	6	20.9	26.6		89.5	85.8	
II	6	67.4	96.3	28.830	99.7	99.6	95.1
III	6	102.1	124.2	38.712	99.4	99.8	99.0



AVERAGE DUST CONCENTRATION LEVEL

L - $>5\mu$ T - Total   G - Gravimetric

FIG. 94

R 8 RESPIRATOR -- TIME VERSUS RESISTANCE

ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3		
	> 5 µ	Total		Initial	Final
I	20.9	26.6		1.240	1.336
II	67.4	96.3	28.830	1.210	1.360
III	102.1	124.2	38.712	1.420	1.800

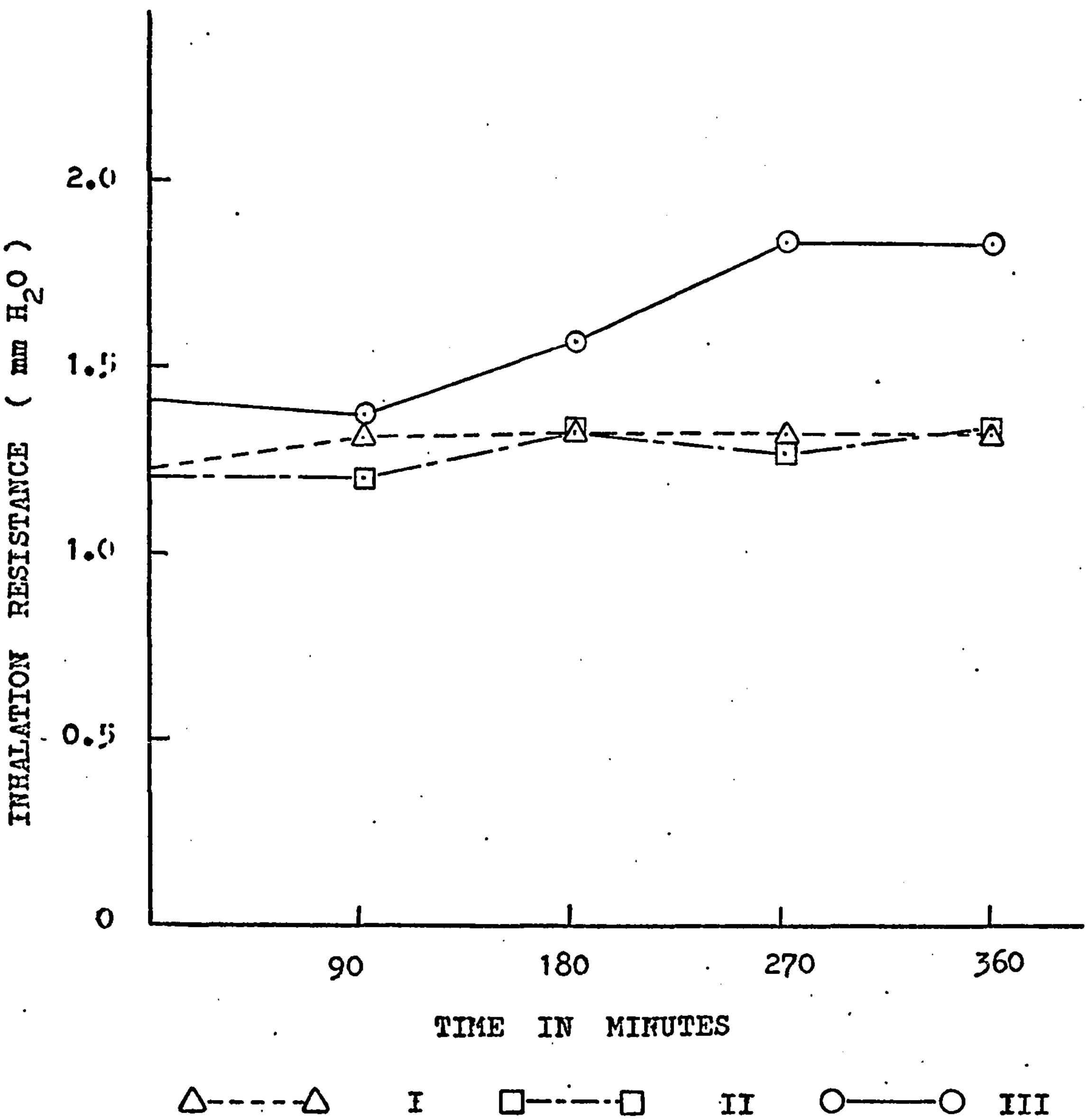
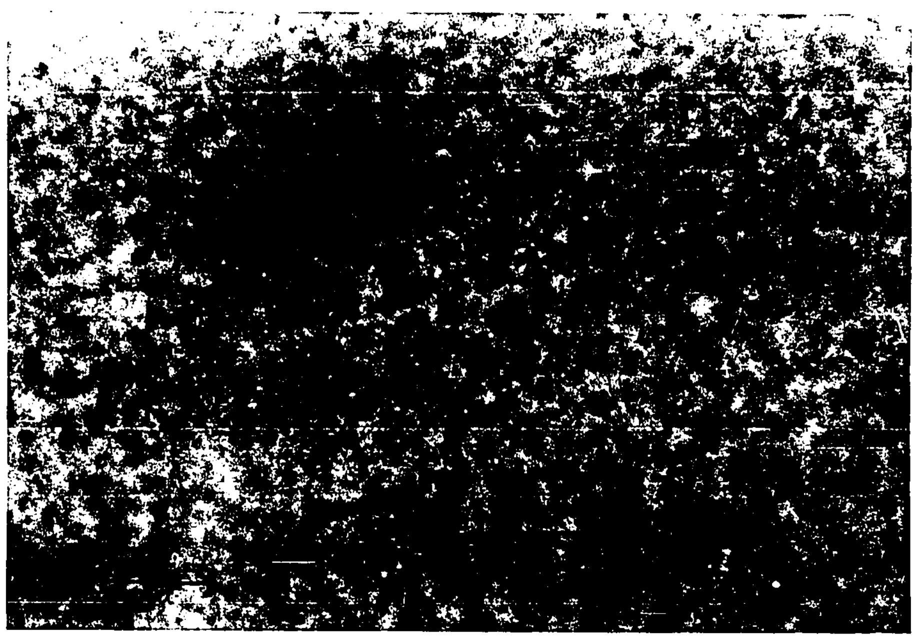


Fig. 95

A micrograph of fiber dust breakthrough filter media of R 8 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

Fig. 95



A micrograph of fiber dust breakthrough filter media of R 8 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

TABLE 22

R 9 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

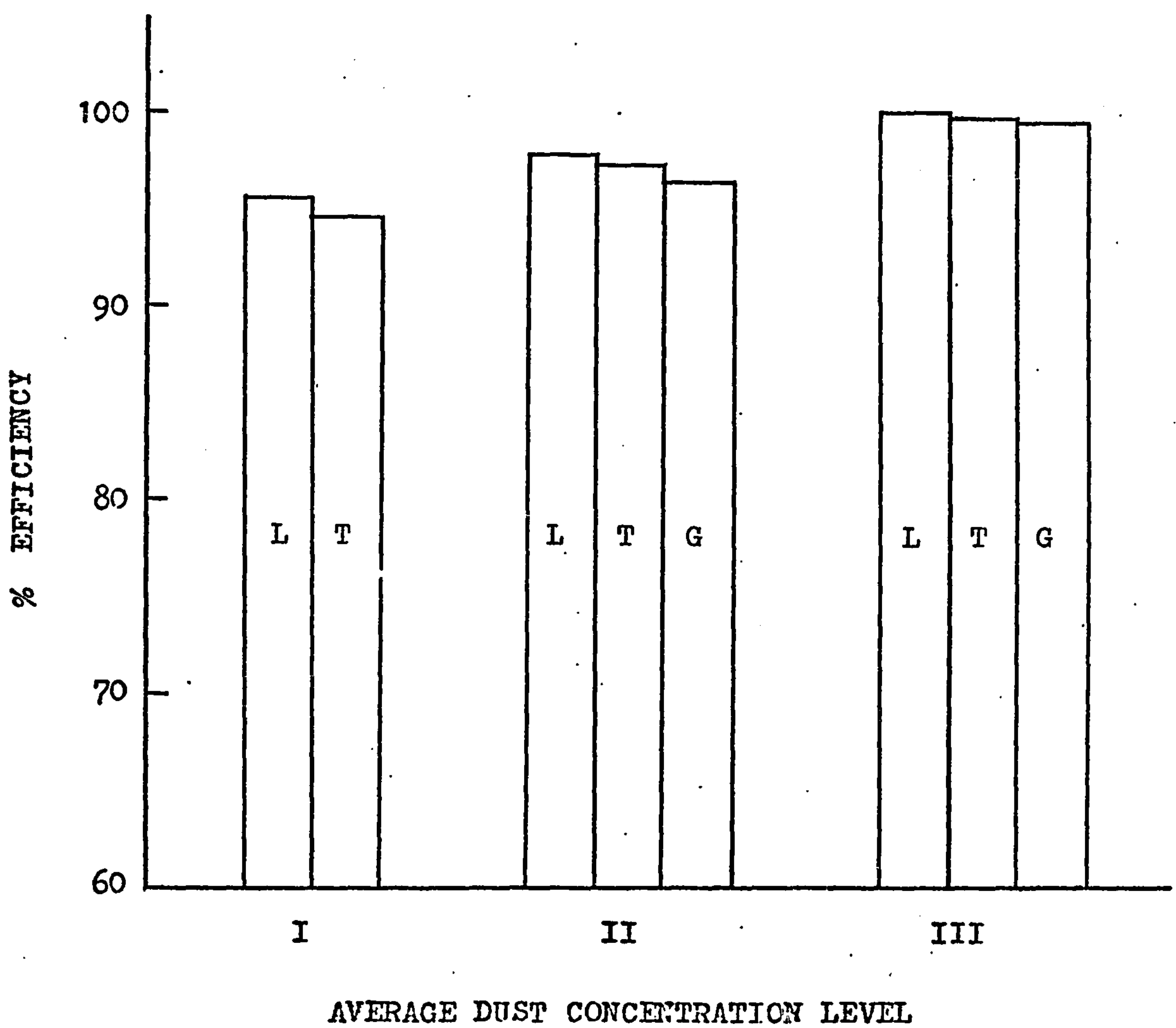
LEVEL	TIME	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE at 6 Lpm (mm H_2O)	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-metric		
	in min.	>5 µ	Total		>5 µ	Total		>5 µ	Total		Initial	Final
I	90	20.8	38.2		1.1	2.2		94.7	94.5		0.200	0.220
	180	25.3	43.5		1.2	2.3		95.2	94.6		0.220	0.240
	270	27.5	45.8		1.1	2.7		96.0	94.7		0.240	0.260
	360	38.0	57.3		1.3	2.9		96.6	94.9		0.260	0.320
Average		27.9	46.2		1.2	2.5		95.6	94.6		0.200	0.320
II	90	45.8	70.4	21.120	1.7	2.8	1.056	96.2	96.0	95.0	0.200	0.220
	180	51.5	57.1	22.535	1.3	2.6	0.924	97.5	96.6	95.9	0.220	0.240
	270	55.2	80.2	24.061	0.9	1.7	0.842	98.3	97.9	96.5	0.240	0.180
	360	57.0	82.0	24.600	0.5	1.2	0.713	99.1	98.5	97.1	0.180	0.320
Average		52.4	76.9	23.074	1.1	2.1	0.884	97.8	97.3	96.2	0.200	0.320
III	90	101.6	134.4	49.725	0.4	0.8	0.597	99.6	99.4	98.8	0.260	0.280
	180	109.4	141.1	52.211	0.4	0.7	0.470	99.6	99.5	99.1	0.280	0.320
	270	104.0	135.6	49.859	0.3	0.7	0.199	99.7	99.5	99.6	0.320	0.380
	360	112.0	140.9	52.200	0.2	0.6	0.156	99.8	99.6	99.7	0.380	0.460
Average		106.8	138.0	50.999	0.3	0.7	0.356	99.7	99.5	99.3	0.260	0.460

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 96

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 9 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION Fibers/cc > 5 μ	Fibers/cc Total	mg/m³	AVERAGE EFFICIENCY OF RESPIRATOR % Counting > 5 μ	Counting Total	Gravimetric
I	6	27.9	46.2		95.6	94.6	
II	6	52.4	76.9	23.074	97.8	97.3	96.2
III	6	106.8	138.0	50.999	99.7	99.5	99.3



L - > 5 μ T - Total G - Gravimetric

FIG. 97

R 9 RESPIRATOR -- TIME VERSUS RESISTANCE ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3		
	> 5 µ	Total		Initial	Final
I	27.9	46.2		0.200	0.320
II	52.4	76.9	23.074	0.200	0.320
III	106.8	138.0	50.999	0.260	0.460

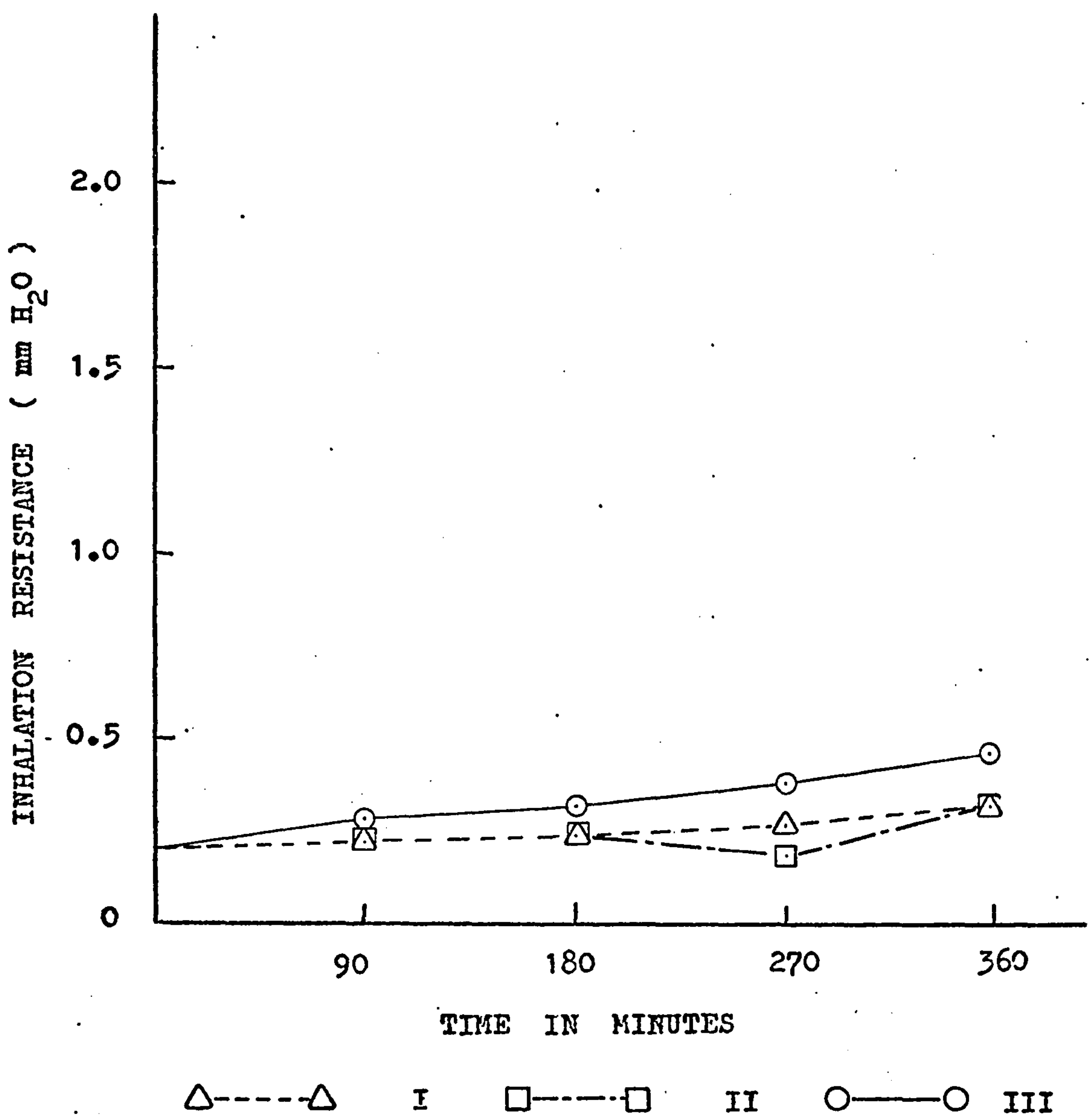
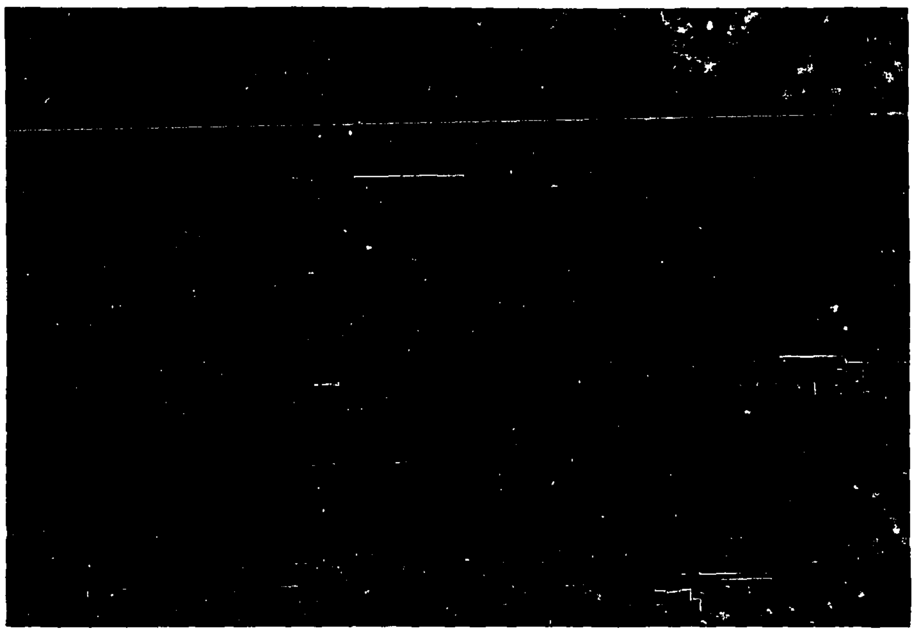
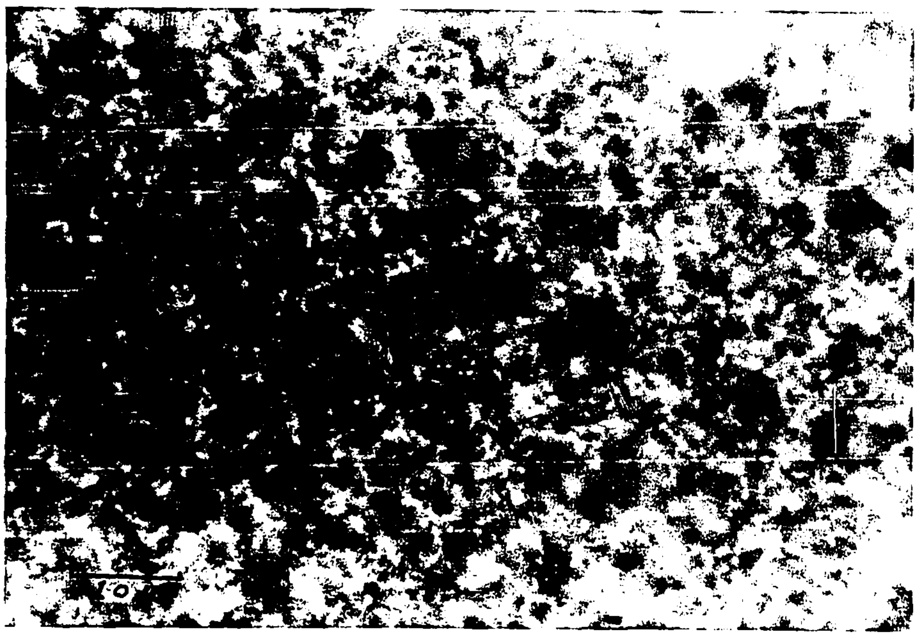


Fig. 98



A micrograph of fiber dust breakthrough filter media of R 9 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illnmination.

Fig. 98



A micrograph of fiber dust breakthrough filter media of R 9 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

TABLE 23

R 10 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

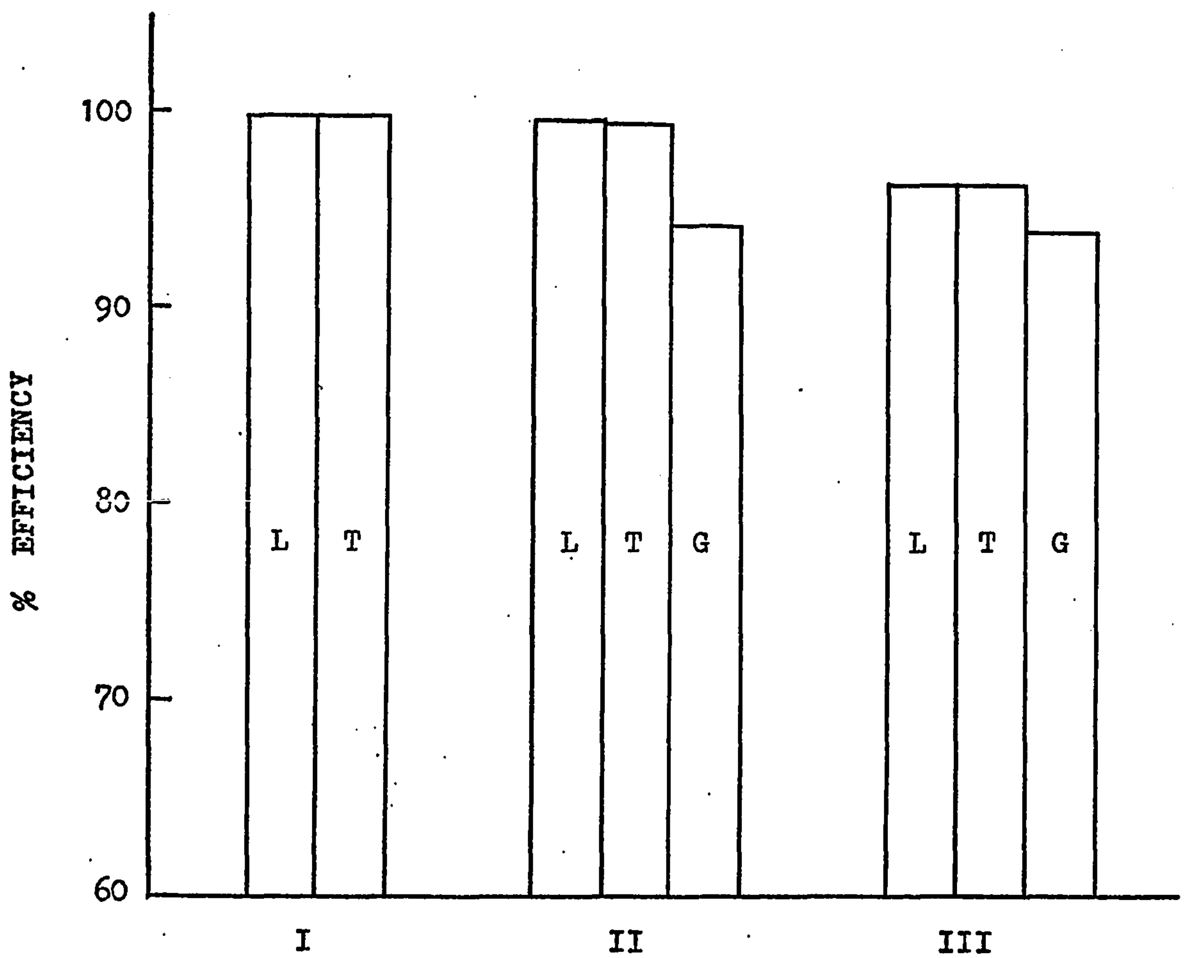
LEVEL	TIME in min.	DUST CONCENTRATION IN CHAMBER Fibers/cc >5 µ	Total	mg/m³	FILTER MEDIA PENETRATION Fibers/cc >5 µ	Total	mg/m³	EFFICIENCY OF DUST RESPIRATOR % Counting >5 µ	Total	Gravimetric	INHALATION RESISTANCE at 6 Lpm (mm H_2O) Initial	Final
I	90	20.4	30.8		0.04	0.06		99.8	99.8		0.240	0.300
	180	22.6	32.7		0.05	0.07		99.8	99.8		0.300	0.400
	270	21.5	33.4		0.02	0.03		99.9	99.9		0.400	0.540
	360	20.7	30.0		0.02	0.03		99.9	99.9		0.540	0.560
Average		20.6	31.7		0.03	0.05		99.8	99.8		0.240	0.560
II	90	50.8	67.2	20.162	0.3	0.5	1.735	99.4	99.2	91.4	0.280	0.420
	180	47.6	70.1	21.045	0.3	0.4	1.747	99.4	99.4	91.7	0.420	0.500
	270	53.2	72.0	21.630	0.1	0.4	0.952	99.8	99.4	95.6	0.500	0.380
	360	58.0	71.5	21.450	0.1	0.4	0.493	99.8	99.5	97.7	0.380	0.680
Average		52.4	70.2	21.071	0.2	0.4	1.232	99.6	99.4	94.1	0.280	0.680
III	90	98.8	162.0	59.937	4.8	6.8	4.315	95.2	95.8	92.8	0.360	0.600
	180	116.8	180.0	66.595	5.4	7.2	4.662	95.4	96.0	93.0	0.600	0.800
	270	90.4	152.8	56.497	3.2	5.6	3.559	96.5	96.3	93.7	0.800	1.120
	360	117.2	146.0	54.979	3.5	5.0	2.581	97.1	96.6	95.3	1.120	1.300
Average		105.8	160.2	59.502	4.2	6.2	3.779	96.1	96.1	93.7	0.360	1.300

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 99

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 10 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION Fibers/cc $>5\mu$	Total	mg/m^3	AVERAGE EFFICIENCY OF RESPIRATOR % Counting $>5\mu$	Total	Gravimetric
I	6	20.6	31.7		99.8	99.8	
II	6	52.4	70.2	21.071	99.6	99.4	94.1
III	6	105.8	160.2	59.502	96.1	96.1	93.7



AVERAGE DUST CONCENTRATION LEVEL

L - $>5\mu$ T - Total G - Gravimetric

FIG. 100

R 10 RESPIRATOR -- TIME VERSUS RESISTANCE ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3	Initial	Final
	> 5 μ	Total			
I	20.6	31.7		0.240	0.560
II	52.4	70.2	21.071	0.280	0.680
III	105.8	160.2	59.502	0.360	1.300

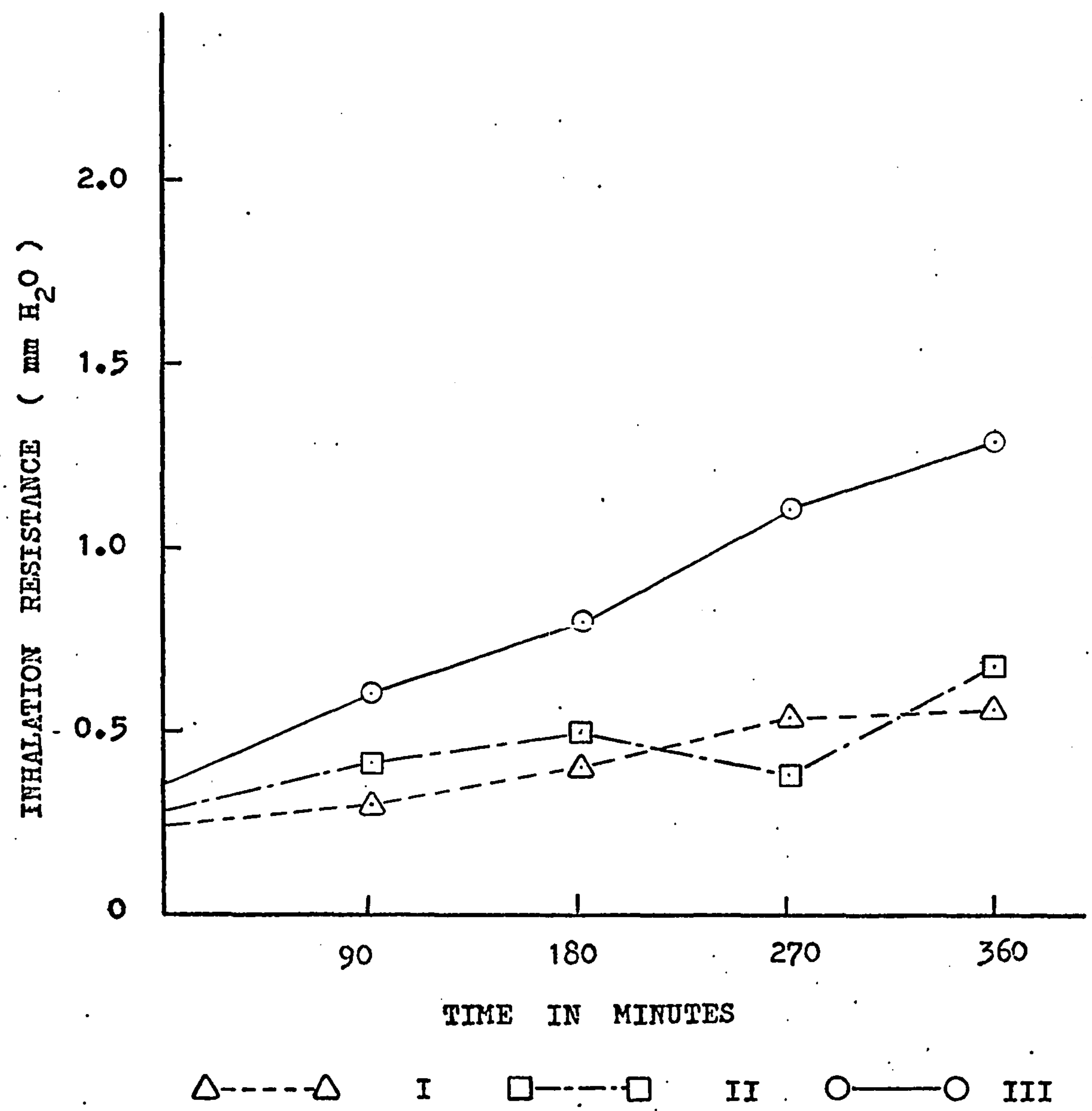
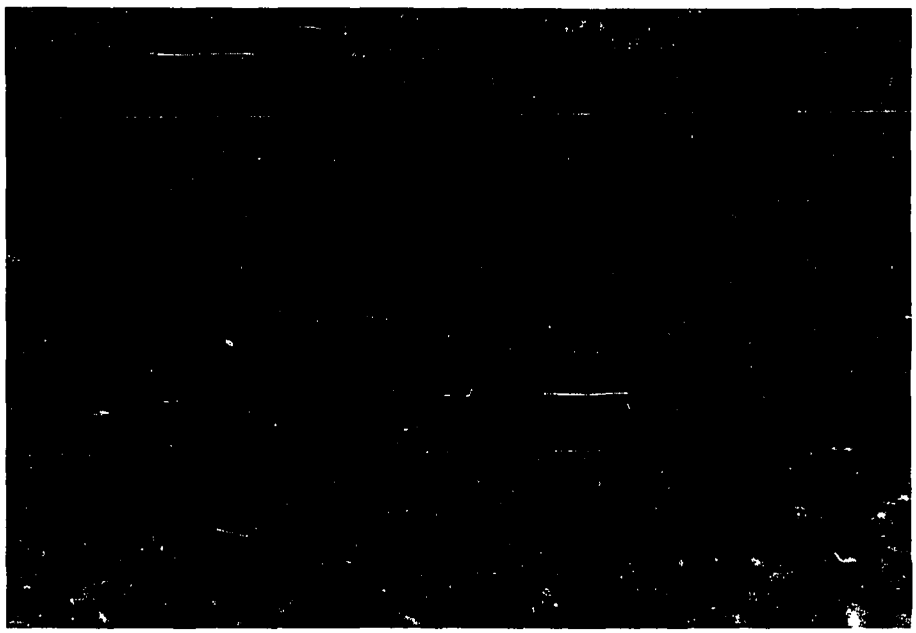
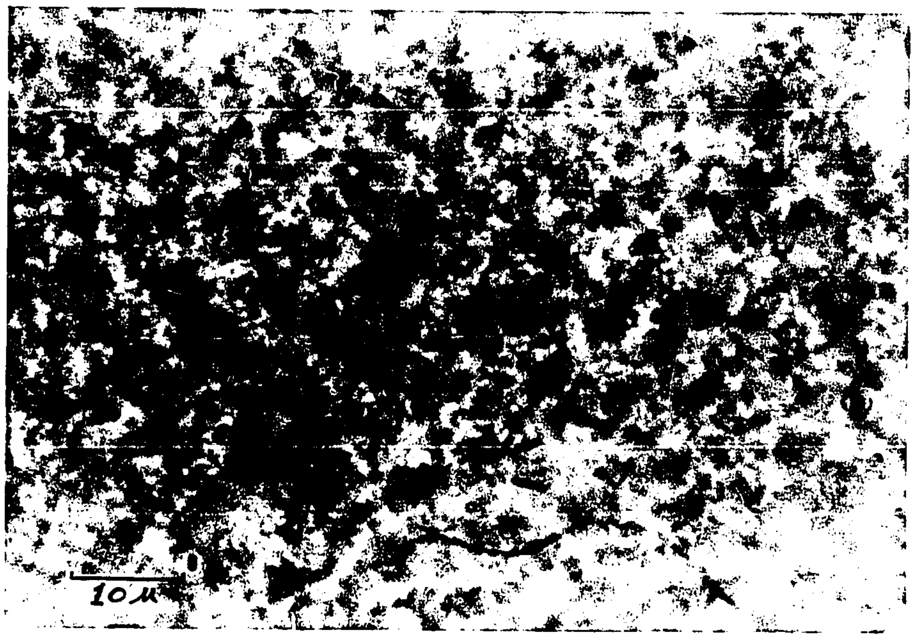


Fig. 101



A micrograph of fiber dust breakthrough filter media of R 10 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

Fig. 101



A micrograph of fiber dust breakthrough filter media of R 10 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

TABLE 24

R 11 RESPIRATOR PERFORMANCE AGAINST A FIBROUS TEST DUST

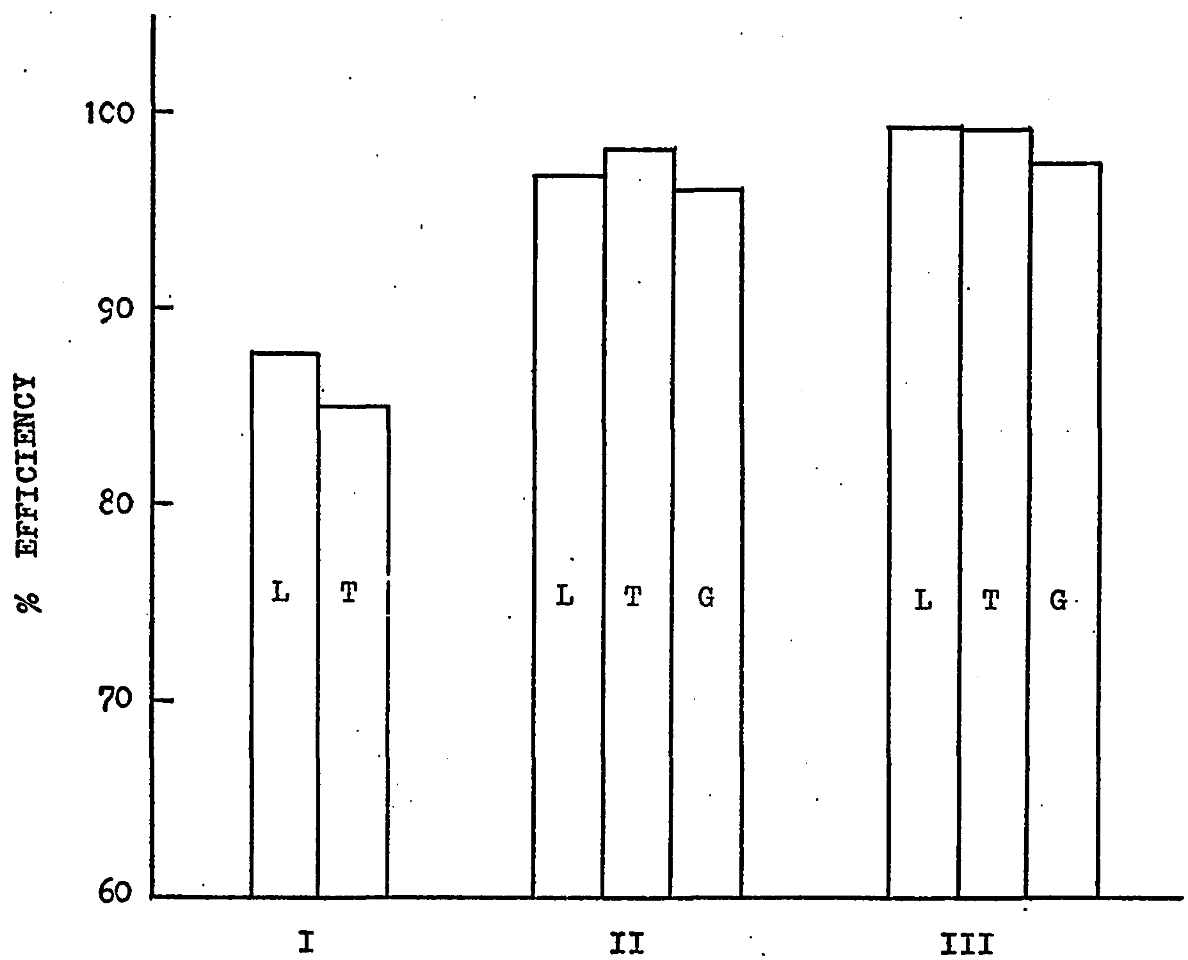
LEVEL	TIME	DUST CONCENTRATION IN CHAMBER			FILTER MEDIA PENETRATION			EFFICIENCY OF DUST RESPIRATOR %			INHALATION RESISTANCE at 6 Lpm (mm H_2O)	
		Fibers/cc		mg/m^3	Fibers/cc		mg/m^3	Counting		Gravi-metric		
	in min.	>5 μ	Total		>5 μ	Total		>5 μ	Total		Initial	Final
I	90	25.5	45.4		4.1	9.2		83.8	79.7		0.280	0.380
	180	18.2	40.0		2.5	6.1		86.3	84.8		0.380	0.280
	270	19.0	37.3		2.0	5.8		89.5	84.5		0.280	0.340
	360	22.0	42.5		1.6	3.6		92.7	91.6		0.340	0.340
Average		21.2	41.3		2.6	6.2		87.7	85.0		0.280	0.340
II	90	50.1	96.0	28.803	2.5	2.0	1.469	95.1	97.9	94.9	0.220	0.300
	180	46.7	101.2	30.360	1.6	2.3	1.366	96.6	97.8	95.5	0.300	0.260
	270	59.6	115.0	34.495	1.8	2.6	1.242	97.0	97.8	96.4	0.260	0.460
	360	51.6	116.4	34.901	1.0	2.0	0.768	98.0	99.9	97.8	0.460	0.400
Average		52.0	107.2	32.132	1.7	2.2	1.211	96.7	98.1	96.2	0.200	0.400
III	90	89.8	132.8	49.154	0.9	1.9	1.966	99.0	98.6	96.0	0.280	0.420
	180	104.4	158.2	58.571	0.6	1.2	1.874	99.4	99.5	96.8	0.420	0.540
	270	113.6	189.2	70.042	0.5	0.9	0.630	99.6	99.6	99.1	0.540	0.480
	360	90.4	151.2	56.930	0.6	1.2	1.252	99.3	99.2	97.8	0.480	0.440
Average		99.6	157.9	58.672	0.7	1.3	1.431	99.3	99.2	97.5	0.280	0.440

All the experiments were conducted at a temperature of 70-80° F and relative humidity of 45-65 %.

FIG. 102

EFFICIENCY VERSUS DUST CONCENTRATION FOR THE R 11 RESPIRATOR

LEVEL	TIME in hr.	AVERAGE DUST CONCENTRATION			AVERAGE EFFICIENCY OF RESPIRATOR %		
		Fibers/cc		mg/m^3	Counting		Gravi-metric
		> 5 μ	Total		> 5 μ	Total	
I	6	21.2	41.3		87.7	85.0	
II	6	52.0	107.2	32.132	96.7	98.1	96.2
III	6	99.6	157.9	58.672	99.3	99.2	97.5



AVERAGE DUST CONCENTRATION LEVEL

L - > 5 μ   T - Total   G - Gravimetric

FIG. 103

R 11 RESPIRATOR -- TIME VERSUS RESISTANCE
ON THE DIFFERENT DUST CONCENTRATION LEVEL

LEVEL	AVERAGE DUST CONCENTRATION			INHALATION RESISTANCE AT 6 Lpm (mm H_2O)	
	Fibers/cc		mg/m^3	Initial	Final
	$>5\mu$	Total			
I	21.2	41.3		0.280	0.340
II	52.0	107.2	32.132	0.200	0.400
III	99.6	157.9	58.672	0.280	0.440

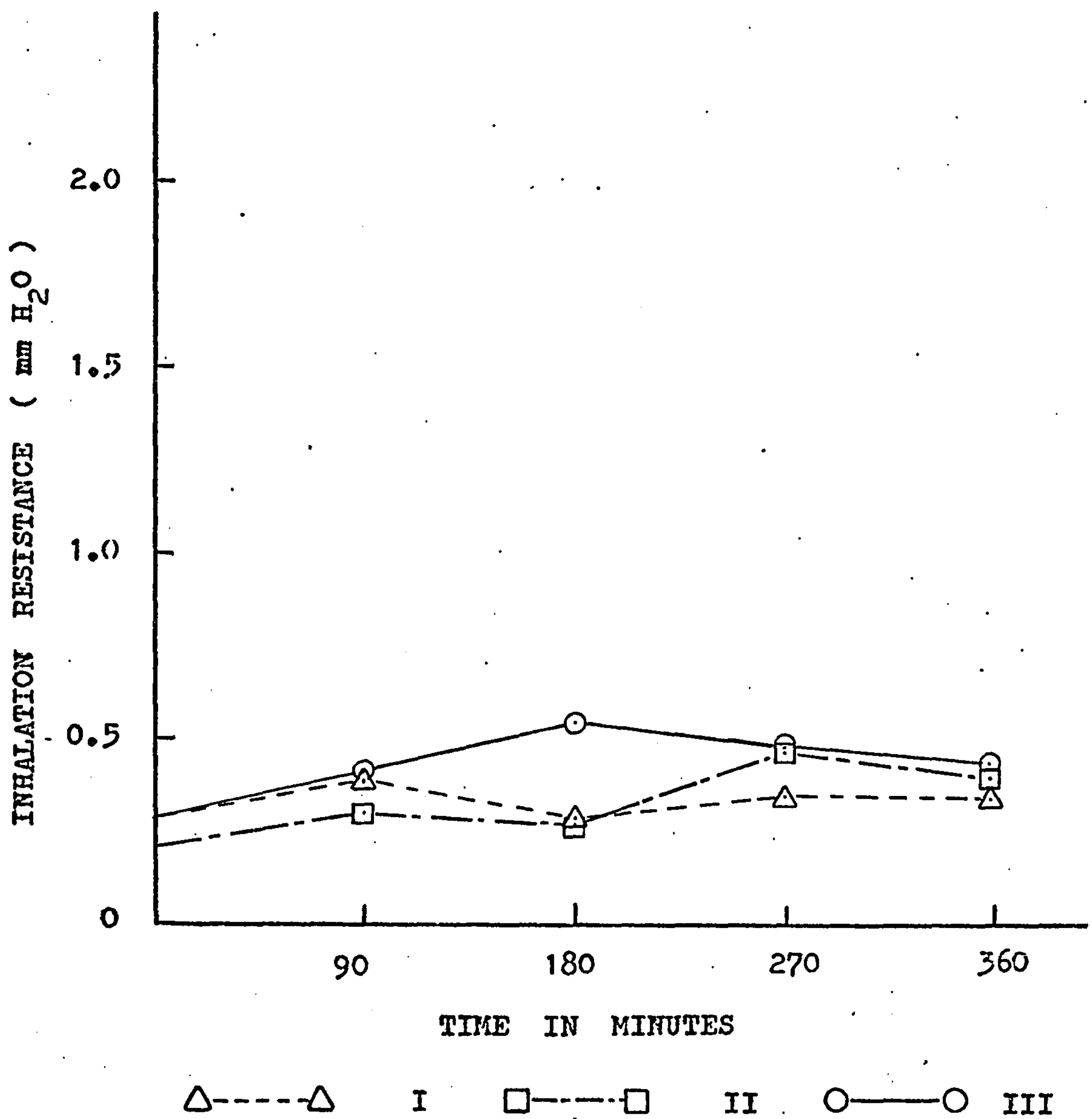
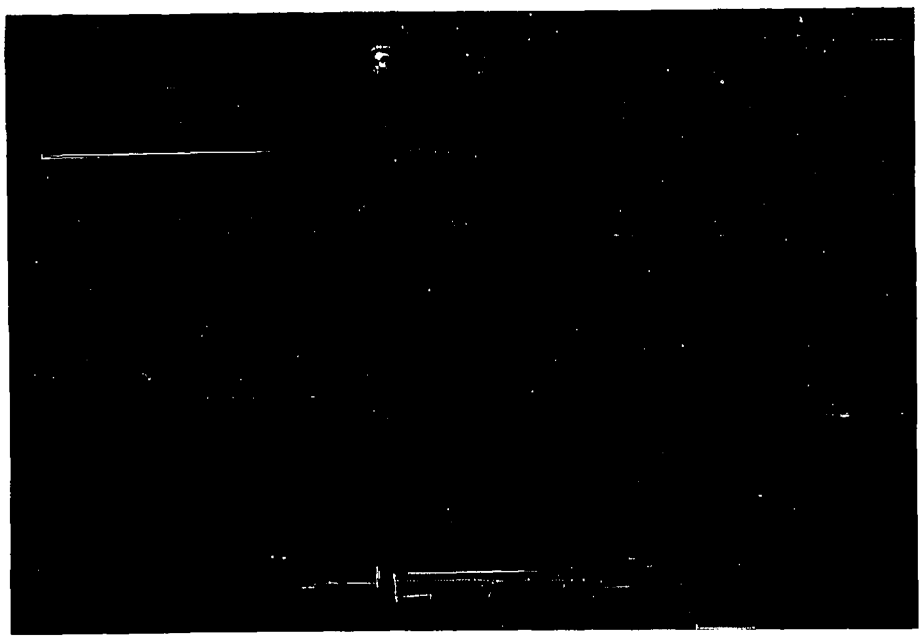
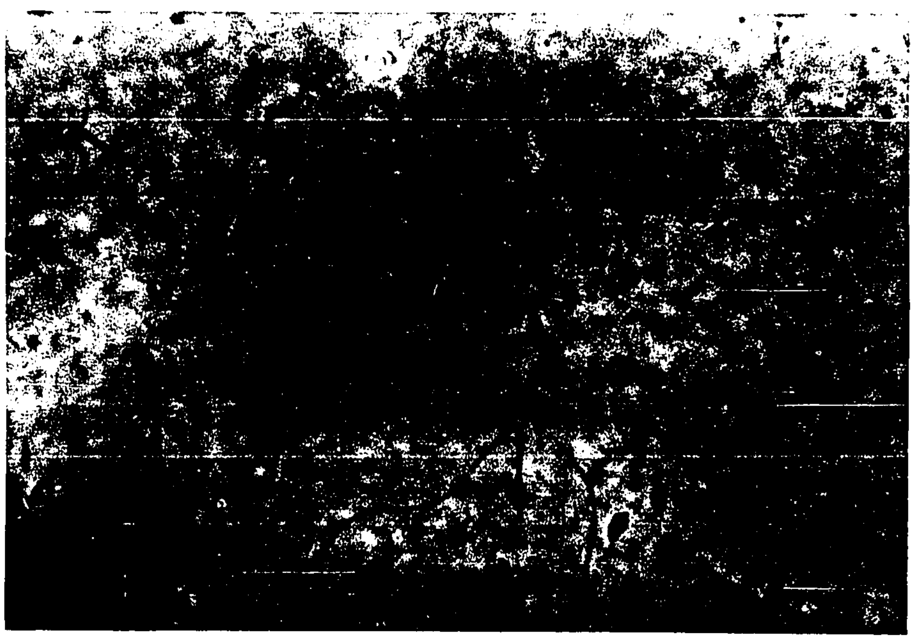


Fig. 104



A micrograph of fiber dust breakthrough filter media of R 11 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

Fig. 104



A micrograph of fiber dust breakthrough filter media of R 11 respirator collected on a 0.8-micron membrane filter, taken with phase contrast illumination.

3. Additional Test for the Relationship Between Various Inhalation Flow Rates and Inhalation Resistances

In order to distinguish clearly the relationship between various inhalation flow rates and inhalation resistances, an additional test was rendered on the R 7 respirator by adopting the same equipment and method with the exception of changing the inhalation flow rate. Consequently, it appears that, when the air flow rate is increased, the respirator's inhalation resistance is simultaneously increased: the detailed indication of which is shown in Table No. 25 and Figure No. 105. According to this test result, if 6 liters per minute flow rate is changed to the commonly used standard test flow rate of 85 liters per minute, the inhalation resistance will then be increased to 12.896 mm H_2O from 0.520 mm H_2O.

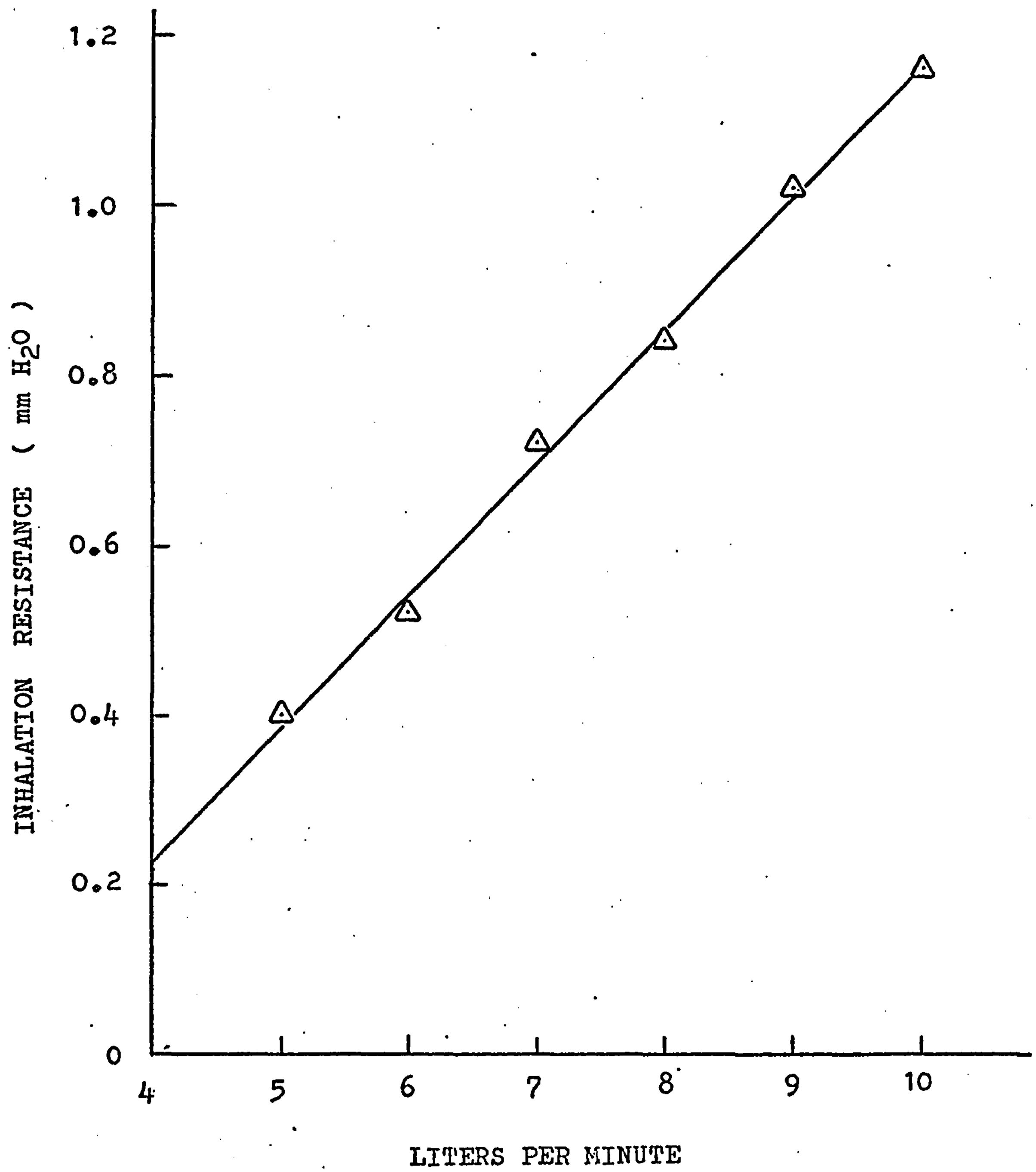
Table 25

VARIOUS INHALATION FLOW RATES VERSUS INHALATION RESISTANCES IN R 7 RESPIRATOR

Inhalation Flow Rate L/Min.	Inhalation Resistance mm H_2O
4	0.220
5	0.400
6	0.520
7	0.720
8	0.840
9	1.020
10	1.160

Fig. 105

INHALATION FLOW RATES VERSUS INHALATION RESISTANCES
IN R 7 RESPIRATOR



4. Discussion of Results

It is worthy to mention that the dust respirators were selected at random for this experiment so the quality of the filter medium may sometimes differ. This would account for the variation in the initial resistance while the efficiency of filtration is not affected to a significant degree.

R 1 Respirator:

According to the results gained from the experimental data, the efficiency varied for the I, II and III dust concentration levels. Of these dust concentration levels, the first is the lowest, and the resistance appears to increase as the test period is lengthened. In reviewing the data, it would appear that this respirator would be most suitable for use at the second level.

R 2 Respirator:

In practice, this one is generally preferred and it is considered to be a good respirator. In addition to other good features, it also has both inhalation and exhalation valves. This unit has been approved by the U.S. Bureau of Mines. It had been tested also by Weeks and Burns(127), with the same fiber dust used in these tests but not by the same method nor at the same air flow rate as adopted for this research. The result of their experiments was that the fiber breakthrough was 0 %. On the other hand, the experimental results of the present tests indicate that this unit has the lowest efficiency of all the respirators tested. Because of this difference it was decided to repeat the tests with the exhalation valve effectively sealed. However, even under these test conditions, the efficiency did not reach 90 per cent. In reviewing the experimental data for each 6-hours test for each dust concentration level, it appeared that the efficiency was at a minimum for a certain period while its resistance remained normal. This phenomenon is difficult to explain and should be thoroughly investigated in future studies.

Another feature of this respirator which bears mention is that after the termination of each 6-hours' experiment, the respirator was untied, and, a large number of fibers were observed on the inner bottom of the respirator. It was apparent that these fibers had penetrated the filter medium of the respirator and settled out before reaching the membrane filter thereby erroneously increasing the calculated efficiency of the respirator.

In order to investigate further this respirator, an additional test was performed with granite dust which had been screened through a 400-mesh sieve. The results by gravimetric means only was an efficiency of 93.7 per cent. These tests appear to suggest that this respirator may provide good protection against other kind of dusts while it may not be suitable for chrysotile fiber dust.

R 3 Respirator:

This is not yet approved by the U.S. Bureau of Mines. It is a discard type of respirator and has no exhalation valve. In the experiments, it was noted that its efficiency was increased. The resistance was rapidly increased with length of time under test and the increments in dust concentration level. The final resistance for the III dust concentration level was three times that of the initial resistance.

Under these conditions, it may create difficulties to breathing due to the increase in resistance. Furthermore, the dust samples collected through the respirator, when viewed under the microscope, showed much more small particles than in tests on other respirators. These results indicate that this respirator provides better protection against fiber dust than other types of dust.

R 4 Respirator:

This unit is also designed for single-wear use, and has no exhalation valve. Although this has not yet been approved by the U.S. Bureau of Mines; the experimental results indicate that it appears to be a good respirator. Besides its efficiency, the resistance between initial and final period is very regular and does not increase at a significant rate.

R 5 Respirator:

This respirator is not approved by the U.S. Bureau of Mines. It is a single-wear unit without exhalation valve. The filter material is similar to the R 4 respirator. It appears to have a very high efficiency for the three different dust concentration levels used in these experiments, and its resistance from the initial to the final period appears to be very normal.

R 6 Respirator:

This unit is a single-wear type, with no exhalation valve. Though it is not approved by the U.S. Bureau of Mines, the experimental data indicate that it is a good respirator because of its high efficiency and low resistance.

R 7 Respirator:

This respirator has gained approval from the U.S. Bureau of Mines. It has a simple exhalation valve. The efficiency of this respirator varied at each dust concentration level, and its resistance increased uniformly with time and the rise in dust concentration level.

R 8 Respirator:

This respirator has already gained the U.S. Bureau of Mines' approval. It can be reused by cleaning with compressed air, and it has a simple exhalation valve. Its efficiency appeared to be high on both II and III dust concentration levels as compared with the first dust concentration level.

Attention is drawn to the deficiency that there was a high resistance at the initial moment of inhalation and this will result in difficult breathing.

R 9 Respirator:

This unit is approved by the U.S. Bureau of Mines. It has both inhalation and exhalation valves, and it is designed for single-wear use. The experimental data obtained, show that its efficiency at the first dust concentration level to the third dust concentration level rose from 95% to 99.7%. Its inhalation resistance appears to be very low from the initial through the final periods.

R 10 Respirator:

This unit has also been approved by the U.S. Bureau of Mines. It is similar to the R 9 respirator and it also has both inhalation and exhalation valves. According to the data recorded, there is an interesting feature to note. This respirator appears to have a high efficiency.

However, as the dust concentration level was raised, the efficiency of the respirator decreased and the resistance increased. In view of these contradictory results it was decided to repeat these tests only to find that the results were the same. This is indeed a strange phenomenon and one that should be investigated further.

R 11 Respirator:

This unit is approved by the U.S. Bureau of Mines, and has both an inhalation and an exhalation valve. It is designed for single-wear use. It shows to be of normal efficiency. From the beginning of the tests, its efficiency increased with the time and with increase in dust concentration level. Its resistance also rose with the length of time under test.

Chapter VI

CONCLUSIONS

The determination of the efficacy of a respirator is a complicated and difficult problem, as it involves a number of variable factors. These can generally be classed as: (a) the filter medium of the respirator, (b) air flow characteristics (resistance), (c) mask fit, and (d) the general acceptance by the worker. All of the abovementioned factors will influence the efficacy of a respirator.

The U.S. National Survey[100] had once made a survey on the use of masks among 12,051 workers. Upon an inquiry of: "Do you wear a mask working at a dusty job?", only 4 per cent reported they always wore a mask while working at a dusty job, and almost 30% never used such protection. The next inquiry was: "What difficulties have you had with masks?". Consequently, it appeared that the most common problem was discomfort -- this was noted by 37 per cent of the workers answering, while interference with breathing was noted by 21 per cent.

In view of the results of the above survey, the determination of the practical efficacy of a respirator should include a factor relating to the acceptability by the wearer.

In this research, the main investigations were concentrated on the filter medium efficiency and the air flow characteristics (inhalation resistance). A review of the results of these experiments provides the following summary and analysis:

Filter Medium:

(a) Excluding the R 2 respirator, the other ten respirators' efficiencies at the 2nd dust concentration level and above, are above 95 per cent.

(b) In comparing the results by the counting technique with the gravimetric method, the efficiency by the former method appears to be higher than by the latter.

(c) With the exception of R 6 and R 10 respirators, the efficiency of the respirators increases with the higher dust concentration levels.

(d) At the same dust concentration level, it generally appears that the longer the test period, the higher the efficiency will be.

(e) Normally, under the fiber counting technique, counting the larger than 5 micron fibers results in higher efficiency than by counting the total.

Air Flow Characteristics (Inhalation Resistance):

(a) The inhalation resistance normally increases as the dust concentration level is increased.

(b) The inhalation resistance normally increases as the time under test increases.

(c) For the same respirator, the inhalation resistance sometimes differs between the initial and the terminal periods, whereas the efficiency remains almost unchanged.

(d) From the tests on the R 3 respirator and the R 10 unit, the inhalation resistance for the 3rd dust concentration level in the 6 hour experiment, appears to be three times higher than that for the first dust concentration level.

Finally, the results of these tests had the following conclusions:

(1) If a dust respirator is used for protection against different types

of dusts, the efficiency will vary with the type of dust.

(2) In order to test a dust respirator for protection against fiber dusts, the most suitable method is to adopt both the fiber counting technique and the gravimetric method.

(3) The tests on dust respirators will be facilitated by the use of a humanlike breathing apparatus and a manikin similar to the one used in these tests.

Chapter VII

RECOMMENDATIONS FOR FURTHER STUDY

In view of the results of these experiments, it is apparent that different test methods will have a variable effect on the efficiency of the respirator's filtration medium. In order to further the progress in this field, the best experimental methods should be selected, and these should include consideration of the appropriateness of human physiology and the medical hygienic standard as well as the practical environment. Hence for further studies the following suggestions are presented:

(1) For the experiments, the fiber dust should simulate the actual suspension found in a working environment. In practice, the dust in the mining industries might contain up to 80 per cent dust from the parent rock and this dust could be biologically inert.

(2) In regard to the equipment for the experiments, one should endeavour to adopt a humanlike breathing system which includes the processes of inhalation and exhalation. The inhalation flow rate should be higher in order to simulate real working conditions. During the period of exhalation, the air volume and relative humidty should be the same as that which exists for the human breathing condition. It is believed that the high humidity of the air expelled on exhalation by humans will have a significant effect on the efficiency of the filter in the dust respirator.

(3) An experiment to test for mask fitting should also be developed, because in recent years, it has become evident that the limiting factor in the performance of conventional dust respirators is the

leakage between the respirator facepiece and the wearer's face[69, 126]. Such leakage greatly affects the efficiency of the respirator, so a further study on this point should merit consideration.

(4) Finally, it is recommended that more detailed studies be made on the dust respirators which showed contradictory results in the present investigations. The reasons for the non-conformity between the efficiency and resistance for increases in dust concentrations should be determined.

LIST OF ILLUSTRATIONS

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