HANDBOOK OF FABRIC FILTER TECHNOLOGY. VOLUME I. FABRIC FILTER SYSTEMS STUDY

Charles E. Billings, et al

GCA Corporation
Bedford, Massachusetts

December 1970

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HANDBOOK OF FABRIC FILTER TECHNOLOGY

VOLUME I

FABRIC FILTER SYSTEMS STUDY

by

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GCA CORPORATION

GCA TECHNOLOGY DIVISION

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A report is presented on fabric filter technology in which the following areas are discussed extensively: 1. Current developments in fiber fabric treatments and applications; 2. The pressure drop, efficiency and performance characteristics observed in operating fabric filters and their relationship to the underlying physical and chemical phenomena of the collection process; 3. The description of models of currently available fabric collectors; 4. Fabric and filter properties of importance in application for industrial gas filtration; 5. Engineering factors involved in the design of the overall system; 6. Data on pressure drop performance and its variation; 7. Practical guidelines for estimating the cost of various fabric filteration approaches; 8. Operation and maintenance of fabric filters.

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FOREWORD

This document is submitted to the Department of Health, Education and Welfare, National Air Pollution Control Administration, in partial fulfillment of the requirements under Contract CPA 22-69-38. The principal technical objectives under the contract were: (1) to evaluate the status of engineering technology currently available to the researcher, manufacturer and user of fabric filter systems; (2) investigate the current practices in the application of fabric filtration; (3) investigate major air pollution control areas which could be amenable to control by fabric filtration; (4) make a critical review and engineering evaluation of the major types of fabric filter devices currently available in order to assess the strength and weakness of each type of device; (5) prepare a comprehensive report containing the information collected in the task areas cited above; and (6) develop five-year research and development programs specifying the research and development efforts required to fill the stated technical gaps. The results of the contract efforts are presented in the following four volumes:

Volume I - Handbook of Fabric Filter Technology

Volume II - Appendices to Handbook of Fabric Filter Technology

Volume III - Bibliography Fabric Filter Systems Study

Volume IV - Final Report Fabric Filter Systems Study

The following professional staff members of the GCA Technology Division contributed to the study and preparation of this report: Dr. Charles E. Billings, Mr. Richard Dennis, Dr. Leonard M. Seale, and Dr. John Wilder. The results of the contract efforts, partially presented in this document, covered the period from January 1969 to January 1971.

Mr. Dale Harmon of the Process Control Engineering Division, National Air Pollution Control Administration, served as the Contract Project Officer.

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INTRODUCTION

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CHAPTER 1

INTRODUCTION

1.1 GENERAL DESCRIPTION

A fabric filter consists of a porous flexible layer of textile material through which a dusty gas is passed to separate particles from the gas stream. As particles accumulate, resistance to gas flow increases. Deposits are removed periodically by vigorous cleaning of the cloth to maintain the pressure drop across the filter within practical operating limits. Provision of methods for cleaning the fabric in place is a distinguishing characteristic of this class of gas filter.

Fabric filters are commonly used for control of dust concentrations in the range of 10^2 $\mu g/m^3$ (urban atmospheric dust) to 10^3 g/m^3* (pneumatic conveying). They provide effective removal of particles whose sizes range from submicron fumes to >200 micron (μm) powders. Fabrics are available to permit operation at gas temperatures up to about 550°F and to provide chemical resistance against specific constituents of the gas or particulate. Fabric filters can provide a substrate for support of granular reactants or adsorbents, to recover gaseous components.

The quantity of ventilation air or process gas, and the dust concentration, in conjunction with specific flow-resistance properties of the particulate deposit, determine the amount of cloth area required for any selected value of operating pressure differential. An operating pressure drop is generally selected in the range of 3 to 4 inches of water, for economic reasons, but some designs operate substantially in excess of 10 inches of water. Superficial filtration velocities (total air volume filtered/total cloth area), commonly called the air-to-cloth ratio, are generally in the range of 1 to 15 cfm/ft^2, i.e., 1 to 15 ft/min.** However, values in excess of 50 ft/min can be achieved at moderate flow resistance with certain cleaning devices on coarse dusts.

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* One gram per cubic meter = 0.435 grains per cubic foot.

** Average for shaker type, reverse air and pulse jet are approximately 2.5/1, 2/1 and 6/1, respectively.

Collectors are readily available in sizes from a few square feet of cloth up to several hundred thousand square feet. Total gas flows handled by individual units range from < 100 cfm to $>10^6$ cfm. Units up to a few hundred square feet of cloth are fabricated and assembled by semi-automatic production line techniques, produced in relatively large quantities, and shipped assembled. Larger units, which are carefully designed to meet the requirements of specific applications, are frequently fabricated for assembly at the installation site.

Costs vary in proportion to size and with respect to kind and arrangement of fabric and cleaning apparatus; initial collector costs are typically in the range of 0.35 to 1.25 dollars per cfm. Actual installed costs, including necessary auxiliary equipment, may be 2 to 3 times the base cost of the filter, a figure of 2.25 times being suggested as a reasonable average estimating approximation.[1] Total annual operating costs relative to weight removal efficiency for fabric filters and other gas cleaning equipment are shown in Figure 1.1 adapted from Stairmand.[2] Fabric filters are seen to yield lower penetrations (higher efficiency) at costs lower than those predicted from the guideline shown. This favors fabric filters in those situations where their use is not precluded by other factors, and where very high collection efficiency is required for fine particles.[2] Generally, high efficiency at reasonable cost is an inherent characteristic of the separation process utilized in fabric filters. If they are properly designed, installed, operated and most important, properly maintained, fabric filters will collect more than 99.9% of the incoming dust on most applications.

In many industrial applications, the discharge from the fabric filter can be returned to the interior of the plant, as it will be respirably acceptable if the conveying gas is respirable. This effects a saving on the heating or cooling of make-up air. The collector discharge dust concentration will frequently be found to be less than 100 $\mu g/m^3$ which is as low or lower than ambient atmospheric dust concentrations found in many major U.S. cities. In general, increased outlet concentrations are associated with higher inlet concentrations, more cleaning energy, and higher filtering velocities. Performance and cost relationships are explored and considered in more detail in subsequent chapters.

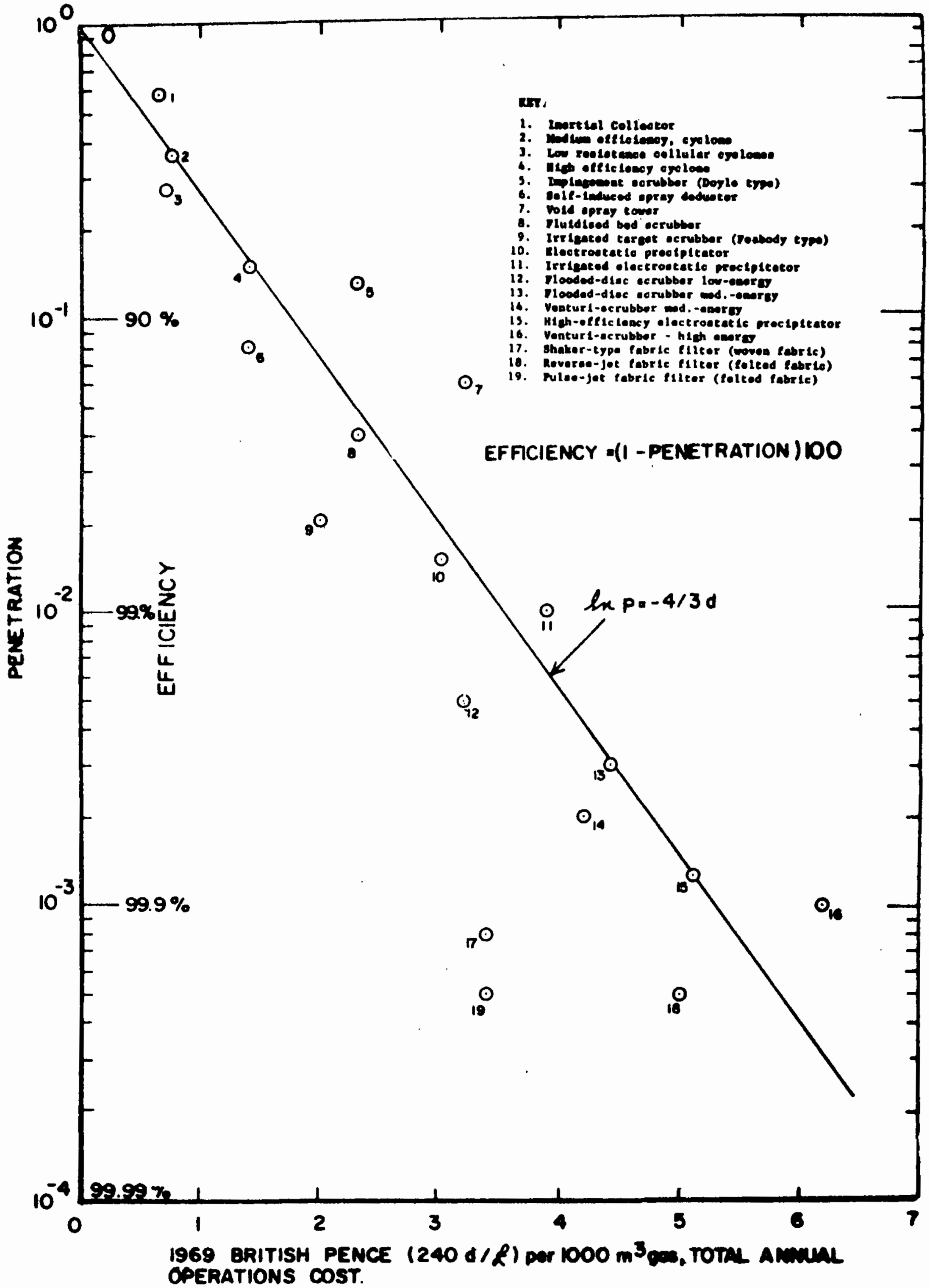


Figure 1.1. Cost of Gas Cleaning Equipment Treating Fine Industrial Dust (From Stairmand, Ref. 2) (Basis, 8000 hours per year).

1.2 HISTORICAL ASPECTS OF FABRIC FILTRATION

1.2.1 Early Filtration Equipment

The use of textile fabrics as filters for the separation of airborne dust and fume includes much of the recorded history of man, probably encompassing the textile and metallurgical technologies developed in the Egyptian Old Kingdom (ca. 5000 B.C.). Earliest recorded applications of fabrics as filters appear in the use of a cloth drawn over the mouth and nose to prevent inhalation of dusts by millers and bakers, miners and stone cutters, and in lead refining and non-ferrous metallurgy. Surviving records from Biblical times mention the use of woven sacks (bags) placed over the head and tied round the neck for protection from dusts in mining and refining of lead oxide. This primitive practice persists essentially unchanged to the present under certain dusty conditions.[3]

Davies[4] has reviewed the early history of the use of fabrics and fibrous materials for respiratory protective devices, (see summary in Appendix 1.1), together with some early contributions to the present day understanding of aerosol filtration. The major stimuli to the development of an understanding of the filtration process, especially of the initial step of particle deposition in a cleanable fabric filter, were associated with the protection of workers from dust. This includes medical respirators for reduction of airborne infectious agents; fire-fighters smoke protection; and respiratory protection from chemical, biological and radiological aerosols in industrial and military environments. Development of industrial fabric filters has proceeded independently for the processing of large volumes of gas for product recovery, protection of machinery or other equipment, as well as for worker health or nuisance control. The recovery of valuable products from dusts and fumes in non-ferrous smelting and refining operations was probably one of the earliest applications of industrial fabric filters. The escaping fume represented an economic loss. In addition, in the case of lead and arsenical ores, the fume was the source of injury to the surrounding populace and livestock and damage to the surrounding property, resulting in damage suits and further economic penalties.

Table 1.1 summarizes some of the developments of fabric filters for industrial dust and fumes.

1.2.1.1 Early Designs.- Figure 1.2 illustrates a single bag design patented in 1852 by Jones (see Appendix 1.2) for the recovery of zinc oxide fume, probably used in New Jersey zinc works of that time. A bag at least 8 feet in diameter by 70 feet long was suggested for sixty small retorts. The filtering velocity is estimated to have been about 0.4 ft/min. Fabrics suggested were closely woven cloths of cotton, wool, flax, or other fibrous textiles. Cleaning was accomplished by striking the bag on the outside during operation or by stopping the blower, allowing the bag to collapse and then striking it. The use of reverse air flow cleaning was suggested by turning the bag inside out and applying the pressure to the opposite side. The branch tubes from the main bag were emptied during operation by tying the top and opening the bottom. Jones cites the prior use of a series of canvas bags open at one end for natural draft, in the collection of lamp-black (carbon black) from incomplete combustion of oils. (Lamp black was produced for ink and paint pigment in ancient Chinese civilizations, more than 5,000 years ago.) The Jones patent contains discussions of the basic design requirements of all fabric filters: a closely woven fabric, means for retaining or supporting the fabric, consideration of the amount of fabric area necessary, a blower or exhauster, means for cleaning the fabric of accumulated dust and fume, and provision for discharge of the collected product. Subsequent fabric filter patents relate to new and useful improvements or modifications involving these same basic requirements.

Other early uses of fabric filters include the configuration shown in Figure 1.3a employing natural draft,[12] and "long filter sleeves hung in rows, tied together at the bottom, while the dirty gases were ducted into the top..... At intervals the sleeves were shaken manually and emptied."[7] Figure 1.3b illustrates an early filter related to the fabric filter but using instead granules and screens. More will be said about this type of filtration later in this report.

Initial mining and smelting of zinc in the Missouri, Kansas and Oklahoma areas in the late 19th century resulted in further developments of

Table 1.1

EARLY HISTORY OF FABRIC FILTER APPLICATIONS AND RELATED TECHNOLOGY

Date	Event	Reference
1852	Collection of ZnO fume in 8 ft. x 40 ft. bag of woven cotton, wool, or flax, forced (or drawn) through by fan-blower, approximate filtering velocity 0.5 ft/min.	Ebaugh (5)
1867	Screens in the side of a house substituted for the bags previously employed as filters for ZnO, Wetherill and Hall, U.S. Patent 72,032.	Ebaugh (5)
1870	Fabric collection suggested for lead fume, Percy, "Metallurgy", p. 449. Initial mining of Zinc in the Joplin, Missouri area.	Ebaugh (5)
1876	Lone Elms Works (A.S. & R.), Joplin, Mo. installed two-section bag house for recovery of fume from Scotch Hearth lead smelting furnace; concrete tube sheet containing (18 in. diam.) thimbles, bags fastened at top on downstream side of fan, cleaned by airing or allowing the bags to tremble in the current of air created by opening the thimble floor doors and the stack dampers after shutting off gas flow into the chamber; later hand shaken.	Labbe & Donoso (6)
1881	Beth patent, German, mechanical vertical motion to top of bags, cement mill dust, downstream of fan, wooden casing, 2 bag compartmented unit (est. 1 ft. diam. x 6 ft high).	Strauss (7) Ihlefeldt (8)
1885	Cyclone apparently first patented by Jackson.	Lapple (9)
1888	Solvay, Eng. Patent 18,573, Sand filter (probably to treat lime kiln dust for purification of CO_2 to ammoniated brine for sodium bicarbonate and soda ash).	Gibbs (10)
1892	Large metallurgical bag house developed by Iles and associates, (U.S. Patents	Ebaugh (5)

Table 1.1 (Continued)

Date	Event	Reference
1892 (cont.)	475,774; 480,834; 484,016;-017) for lead and zinc furnaces (not for copper furnaces or roasters) consisting of lower dust chambers 14 feet high compartmented, and with provision for closure of inlet, and upper bag chamber 30 to 45 feet high, one room, walls and partitions of brick, 18 compartments showing in lower chamber, bag-house 140 ft. long x 55 ft. wide; tube sheet, iron or steel plate with 18 in. diameter nipples for wool (earlier cotton) bags, outlet initially direct through ventilators and later through 200 ft. stack; capacity 150 to 250,000 cfm, 3000 to 4500 bags 18 in. x 30-33 ft (130 ft^2/bag, filtering velocity 0.3 ft/min), note suggested fiber blends in warp and fill (U.S. Patent 485,797) and lower section of bag to be of wool reinforcement nearest thimble. Temperatures of 70 to 270°F used, but 160° most satisfactory, cleaned by hand, then by external hand-operated lever beaters.	
1893	Reverse air flow in use for cleaning.	Ihlefeldt (8)
1894	Rings around centers of bags attached to wire led outside of building, hand-shaken by end of rope, Rourke, (U.S. Patent 530,553).	Ebaugh (5)
1907-8	Early tests of Rhodes and Sprague on neutralization of copper furnace and roaster gases passed to bag house by addition of zinc oxide to protect bags.	Ebaugh (5)
1909	Bags attached to short levers extended from a central shaft, whose outer end projects beyond the bag house wall, there provided with a larger lever to shake the bags by hand.	Ebaugh (5)
1948	Development of venturi scrubber.	Ekman and Johnstone (11)

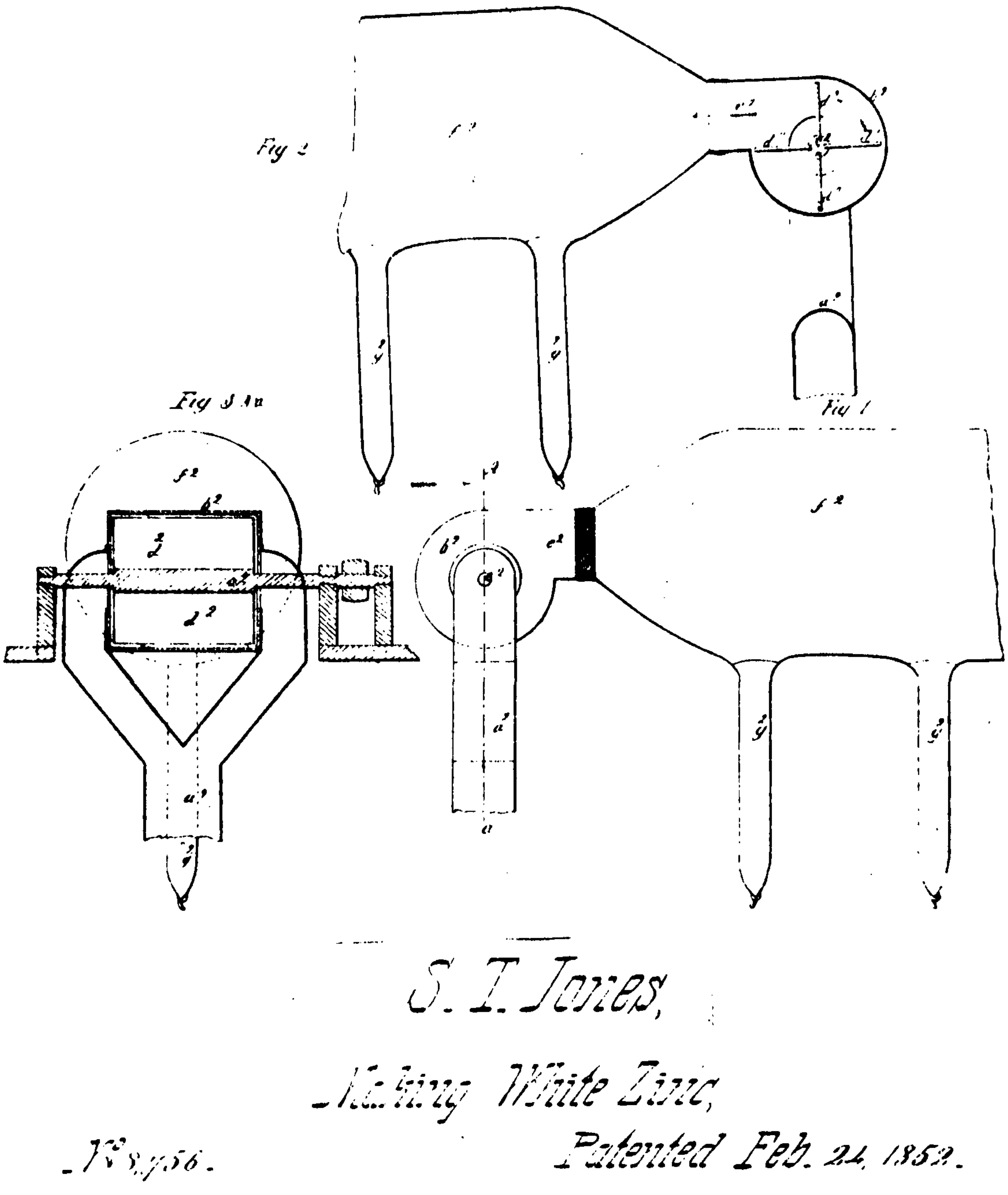
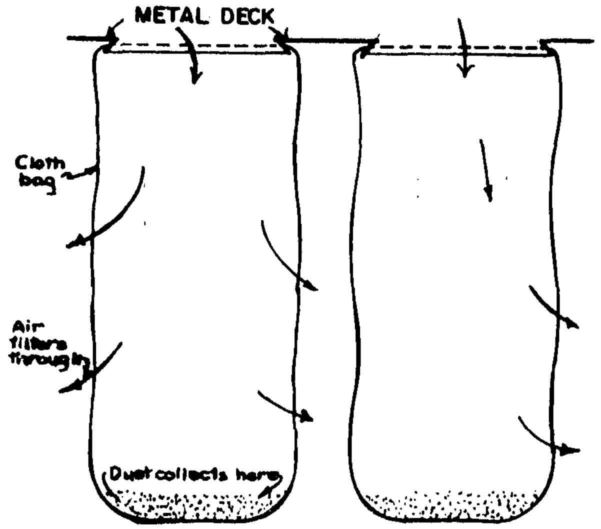
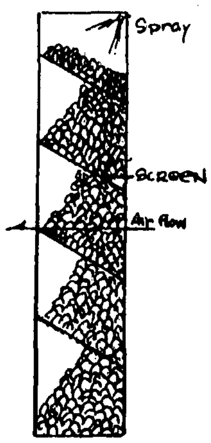


Figure 1.2 -Early Fabric Filter for Zinc Oxide Control
(See also Appendix 1.2.)



(a) A filter bag, an early type of dust removing apparatus.



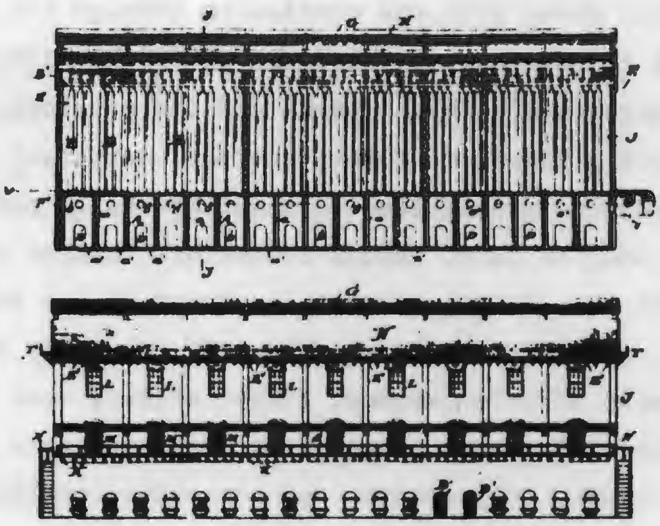
(b) Section through an old time coke air filter.

Figure 1.3 -Early Filters for Dusts. (From Lewis, Ref. 12.)

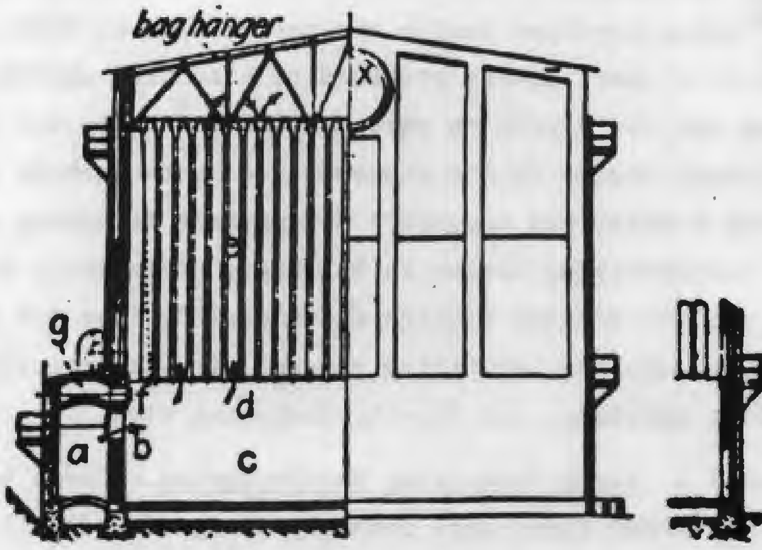
fabric filters. Labbe and Donoso[6] cite a two-section bag house for recovery of fume from Scotch Hearth lead smelting furnaces constructed in 1876 at the Lone Elms Works of Joplin, Missouri. Lead fume was removed from the bags initially by shutting the damper between the bag house and the fan discharge, and then airing the bags, causing them to tremble. Lead fume dropped into the lower chamber (smoke cellar) and was sintered in place.

During the period of rapid economic development, that followed the completion of the trans-continental railway in about 1869, large metallurgical production facilities were built in the western and inter-mountain states (e.g., Montana, Utah). Later during the period 1880 to 1890 large metallurgical bag houses containing several thousand bags were constructed for use in zinc and lead smelting[5],such as shown in Figure 1.4. Thirty foot bags of cotton or wool were hung from supports near the top of the building and the lower open ends were tied to nipples or thimbles projecting from the floor of the bag compartment. The lower dust chamber was partitioned into as many compartments as there were flues leading to the bag house, enabling a part of the system to be shut down as required for cleaning. Cleaning probably involved some reverse flow of gas through the fabric. The dimensions of the housing shown in Figure 1.4 are approximately 140 ft. long by 60 ft. high, with a depth of the order of 90 ft. (est). Filters of this type were suitable for flue gas volumes of about 50,000 to 150,000 cfm depending upon the application (e.g. Scotch Hearth or lead blast fume).

Copper furnace and roaster gases containing high concentrations of sulfur dioxide and sulfur trioxide could not be filtered because of acid deterioration of the fabric. However, the feasibility of fabric treatment by neutralization of the smelter smoke with zinc oxide or lime dusts was demonstrated in the 1907-1908 period and suggested for effluents from copper blast furnaces, reverberatories, and converters in 1909. Claims for damage to vegetation and cattle from smelter smoke became an important factor during this period and required the simultaneous removal of fine metallic oxide fume particles (lead, arsenic) and the reduction of sulfur dioxide emissions.[13]



(a) Iles' Bag House (from Ref. 5)



(b) Typical Bag House Filtering System
(from Ref. 15)

Figure 1.4 - Bag Houses for Lead and Zinc Smelting.

The vigorous application of Cottrell's electrostatic precipitation process, beginning about 1910 and continuing through the 1920's, resulted in the virtual cessation of development of fabric filter equipment.[14] The simultaneous construction of high stacks and the development of sulfur dioxide flue gas recovery plants (chamber, contact, sorption) during the period 1910 to 1920 reduced ground level concentrations of noxious fumes and sulphurous gases and, in turn, tended to inhibit further development on fabric filtration systems. Fabric filters continued in use for lead and zinc furnace applications, however, but it wasn't until the early 1950's that significant new development efforts resumed. These efforts were directed primarily toward new methods of fabric cleaning and new synthetic fabrics capable of withstanding both higher temperatures and corrosive conditions.

1.2.1.2 Early Cleaning Methods.- In the early equipment, the removal of accumulated dust and fume from the interior surfaces of bags was accomplished by shaking or beating by hand or with a simple lever-bar. For lead and arsenical fumes, however, this was a particularly unhealthy and unsatisfactory method. Hand or foot operated shaker bars are still used in small unit dust collectors (< 300 ft^2). Automatic shakers, as shown in Figure 1.5,[7,8] were developed during the period 1880 to 1910. By 1909, bags were suspended from short levers attached to a central shafting which could be pivoted back and forth with an external lever.[6] This was soon automated by tying all shaker shafts in one chamber to a central shaft outside the housing and with a motor and eccentric arrangement imparting either a vertical or horizontal reciprocating motion to the bags. Subsequent modern compartmented fabric filters contain electro-mechanical devices for automatically stopping the flow, shaking, admitting reverse air when required, dwelling for a period to allow settling, and finally restoring flow.

1.2.1.3 Early Commercial Manufacturing.- Large bag houses for lead and zinc dusts and fumes were commonly designed and built by the works engineers of the individual smelter companies.[15,16] In addition, continuing engineering development work by the individual companies was directed toward defining the relationships between pressure drop, volume ($\Delta p \sim Q^2$), dust concentration and collection efficiency (Seitz, A.S. & R., 1929).[6] Much attention

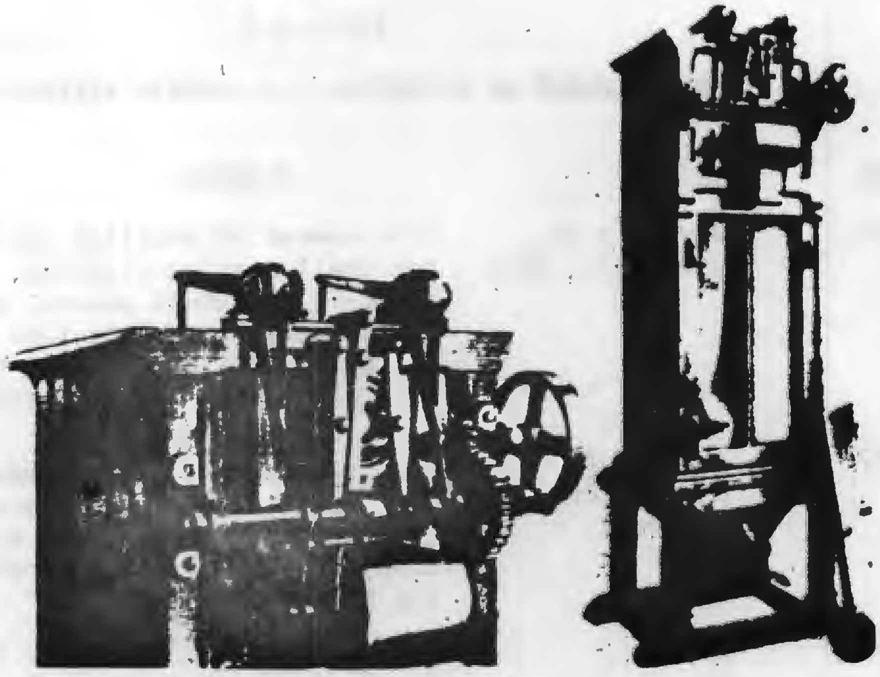


Figure 1.5 -Early Automatic Shaker Mechanism and Filter (From Ref. 7.)

was also given to fabric life, acid resistance, and strength.[6] Fabric substitutes were considered for higher temperature operation as alternatives to cooling by water sprays or added air. The construction of automatic fabric filters by works engineers is still a common practice, particularly in the non-ferrous metallurgical industry.

The commercial production of fabric filters for control of many types of dusts and fumes developed within several industrial firms who initiated manufacture of these devices for their own specific applications. Estimates of the founding date and principal product lines of some of the present U.S. suppliers of fabric filters are shown in Table 1.2. Sly, Pangborn, and Wheelabrator were originators of foundry casting cleaning equipment such as tumbling mills (Sly) and compressed air sand blast and airless abrasive shot blast chambers (Pangborn, Wheelabrator). Large quantities of metallic and sand dusts generated during casting cleaning required

Table 1.2

DEVELOPMENT OF PRINCIPAL U.S. FABRIC FILTER MANUFACTURERS

Date	Firm	Remarks	Reference
1874	W.W. Sly Co., Cleveland, Ohio	Development of tumbling mills for small casting cleaning (1880-7), original patents on fabric collectors, envelope screen design (1920), travelling reverse flow air cleaning device since 1951.	C.L.*, 22
1877	Buffalo Forge Co., Buffalo, New York	Blowers, fans, machine tools, inertials and scrubbers; acquired Aeroturn reverse-jet from Koppers 1965, publishers of fan engineering handbook since 1925.	C.L., 22
1881	Day Co., Minneapolis, Minn.	Sheet metal shop, probably cyclones, for sawdust and shavings from Mississippi River lumbering operations, Hersey reverse-jet collector since 1948.	C.L.
1905	Pangborn Corp., Hagerstown, Md.	Sand and shot blast cleaning equipment, continuous multi-bag and envelope screen designs, 1920, reverse flow cleaning since 1952, pulse-jet design 1959, acquired by Carborundum Co., Buffalo, N.Y. 1965.	C.L.
1907	Western Precipitation Corp., Los Angeles, Cal.	Electrical precipitators, Hersey reverse-jet collectors built since 1952, glass fabric bag with collapse cleaning since 1957, acquired by Joy Mfg. Co., 1959.	14
1907	Research-Cottrell, Bound Brook, N.J.	Electrical precipitators, glass bag filters since 1965e, Flex-kleen, (1959) acquired with pulse-jet type, 1968.	14
1908	Wheelabrator Corp., Mishawaka, Ind.	Shot blast casting cleaning cabinets; airless abrasive shot blast systems, 1920; dust collecting equipment built since 1924.	C.L.

*Company Literature

Table 1.2 (Continued)

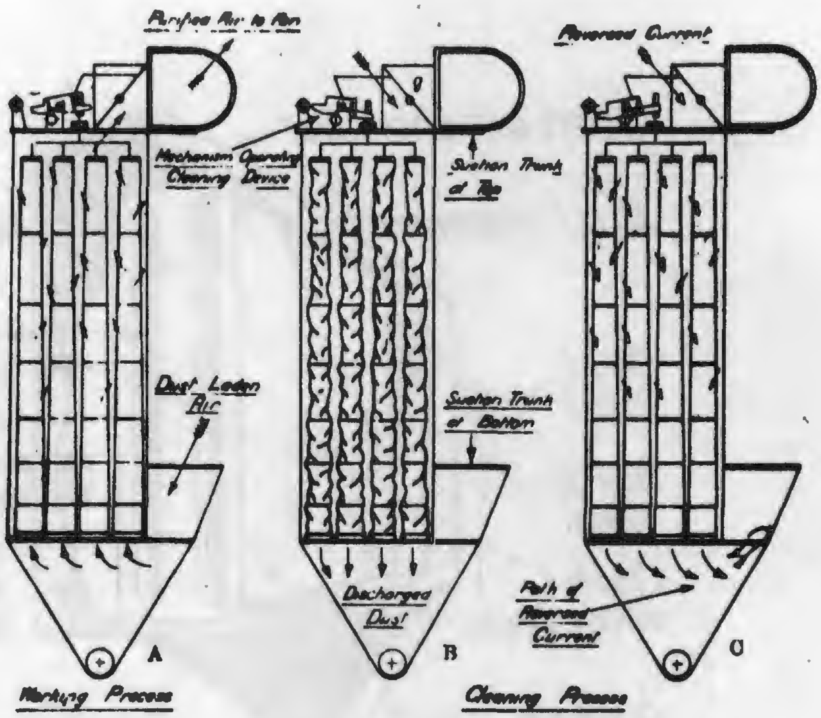
Date	Firm	Remarks	Reference
1910	Northern Blower Co., Cleveland, Ohio	Fans, blowers, cement mill process equipment, merged with Buell Engineering Co., Inc., 1960.	C.L.
1917	Dracco Corp., Cleveland, Ohio	Fans, blowers, pneumatic conveying systems, cement, metallurgical process equipment, merged with Fuller Co., 1957; first glass fabric bag collectors, 1957, with sonic cleaning 1960, plenum pulse 1968.	C.L.
1923	Pulverizing Machinery Co., Summit, N.J.	Pulverizing mills, powder classifiers, pneumatic conveying systems, reverse-jet collectors built since 1945, original pulse-jet design introduced 1957, acquired Airetron Co., scrubber, inertials, electricals 1958, plenum pulse-jet designs 1969, acquired Menardi & Co. (1954) in 1969.	C.L.
1925	American Air Filter Co., Inc., Louisville, Ky.	Filtration devices for space heating and air-conditioning, fixed fabric, paper types, inertials, scrubbers for most dusts; for fibrous dusts (1947), reverse-jet filter built 1953, glass fabric collector since 1959, pulse-jet introduced 1969.	C.L.

ventilation and dust control for protection of machinery as well as for recovery of abrasive. As a result, envelope shaped fabric geometries supported on a screen or frame were developed by Sly and Pangborn in the 1920's. Wheelabrator began manufacture of cylindrical bag filters about 1916 for use with blast cleaning equipment. Northern Blower (Buell) and Dracco (Fuller) began manufacture of fabric filters for cement mill dust recovery during the period 1910 to 1920.

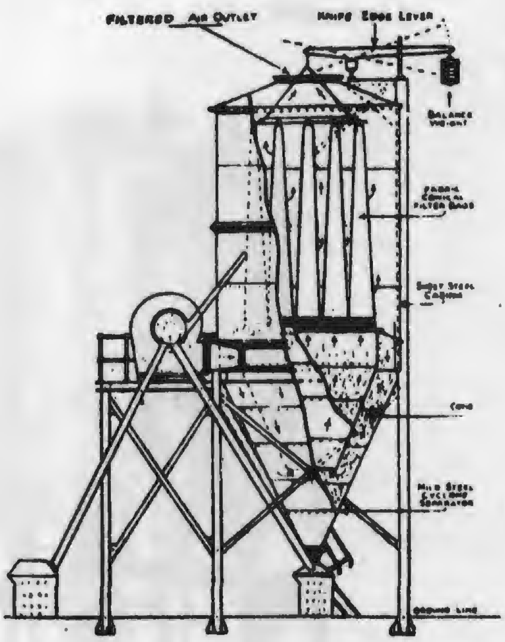
The fabric configurations, fabric supports, and automatic cleaning mechanisms, developed during the 1920's and 30's, have in general withstood the test of time and are still commercially available today. Some of these early production designs developed prior to about 1940 are shown in Figure 1.6.[10,15,19,20] The British units (Figure 1.6a, 1.6b) illustrate the use of conical bags with a larger inlet at the bottom tapering toward the top hanger.

The Hersey reverse jet filter using dense woolen felt bags was developed during the 1940's:

> "It grew out of an effort to provide a means of collecting silicious ore crushing plant dust in the Coeur d'Alene mining district of Idaho (ca. 1939) which would produce a constantly permissible silica dust count, not possible with shaken woven cloth bags operating on a time switch. The first attempt was with various means of pressure controlled shaking of large wool felt bags. Although the wool felt was dense enough to prevent leakage after shaking, it finally blinded. This was followed by variations of reverse jet applications, some of which broke down the filter medium, and some of which failed to achieve a level porosity balance.
>
> Finally in 1941 a reverse jet filter consisting of one 36" diameter by 16 ft. bag, lengthened later to 32 feet, was started in a large grain elevator on an experimental basis. After three years of service it was considered proven that wool felt would stand the service and that constant air flow and pressure drop could be maintained with the right combination of reverse jet action and filter medium base. By 1950, several hundred reverse jet filters were applied to various problems in widely diversified industries including chemical, metallurgical, pigments, abrasives, textiles, grain, flour, cereals, sugar, ceramics, cosmetics, confections and drugs.

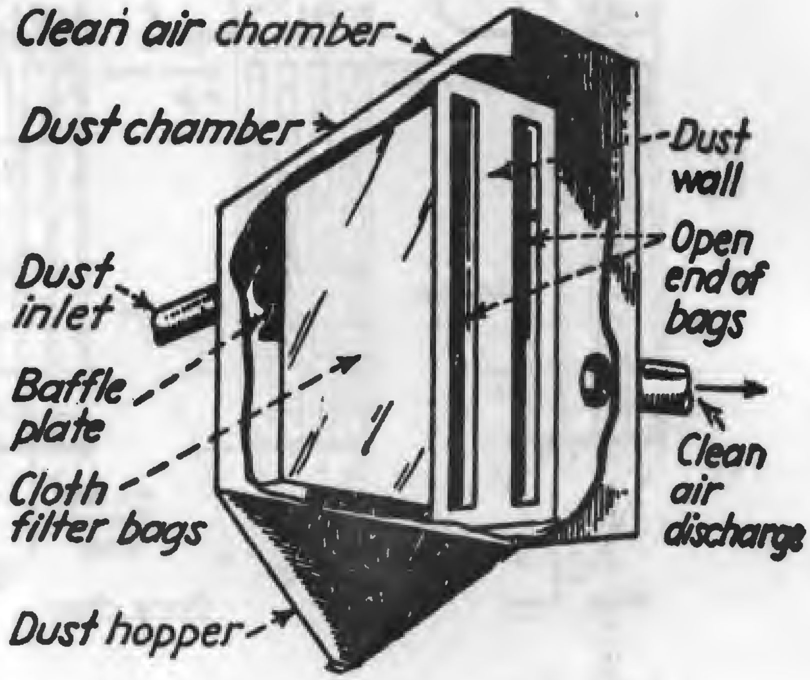


1.6a -Mechanically Cleaned Bag Filter, ca 1924, British Design (from Ref. 10).



1.6b -Waring Dust Collector (suspended conical bag unit), with cyclone separator, ca 1940, British Design (from Ref. 19).

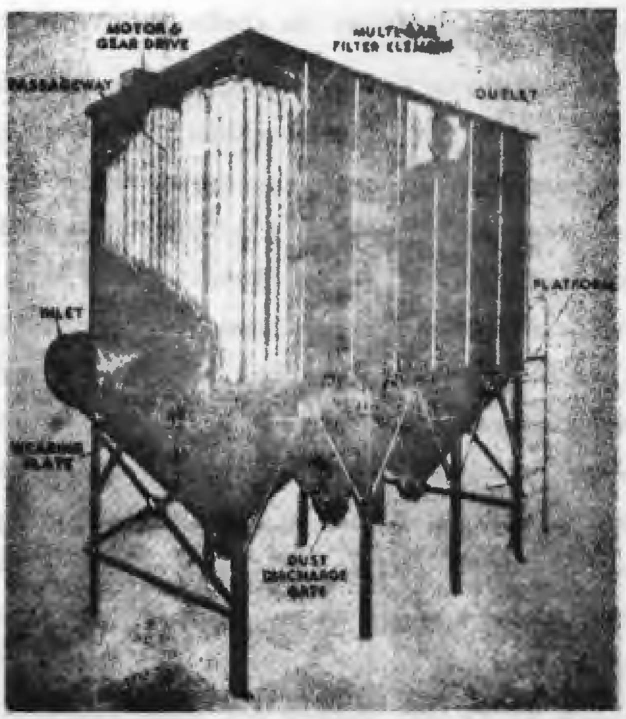
Figure 1.6 -Pre-1940 Equipment Similar to Present Designs.



1.6c -Sly Dust Filter. (W.W. Sly Manufacturing Co.) (from Ref. 15).

1.6d -Dracco "Perfecto" Filter. (Courtesy of Fuller Company).

1.6e -Cloth Screen Dust Collector. (Pangborn Corporation). (From Ref. 20.)



1.6f -Bag Filter (Dracco Corporation). (From Ref. 20.)

Although the patent literature has disclosed numerous conceptions of reverse flow filters of both the blow thru jet and the vacuum sweeper type, none of them reached commercial success or significant practical use so far as is known. They lacked the combinations of features ..... which provided high-capacity one-step separation without leakage."[21]

Typical fabric dust and fume collectors of principal U.S. manufacturers during the period 1945 to 1950 were summarized by Silverman[19] (Appendix 1.3a) and by Lapple.[9] The reverse-jet filter was manufactured by several U.S. firms (as indicated in Appendices 1.3b and 1.3c), during the 1950's. Appendix 3.1 presents a 1969 survey of U.S. manufacturers and Chapter 3 includes a description of the major products available in that year.

The pulse-jet filter shown in Figure 1.7 was developed in the mid 50's and introduced in 1957 by T.V. Reinauer of Pulverizing Machinery.[24] This device, which employs a short pulse of compressed air to cause fabric motion (with reverse flow) to remove dust from the outside of felt filter bags, requires no moving parts inside the collector. At this time (1970) most major U.S. manufacturers of fabric filters have introduced some form of air-jet or pulse cleaning configuration in their fabric filter product lines.

For many years fabric filter developments have been directed at increasing the filtering velocity while maintaining a reasonable pressure drop of a few inches of water. A continuing approach to accomplishing this end has been on-stream cleaning. The early manufacturers of envelope geometries introduced continuous back-flow air cleaning carriage configurations in the early 1950's. Operating gas velocities have increased from about 0.2 ft/min, on early infrequently hand shaken units, to nearly 3 ft/min on modern automatic compartmented fabric filters. The relatively recent reverse-jet and reverse-pulse units, which are continuously cleanable on-stream, permit operation at velocities up to 10 to 20 ft/min, depending on conditions. Figure 1.8 shows these developments in filtering velocity increases and suggests near-future increases of one or even two orders of magnitude. Development studies were reported in 1962 on cleanable industrial filter configurations with gas velocities up to 300 ft/min for high temperature metallurgical furnace fume (1000^{o}F) utilizing low energy shock wave cleaning of fibrous

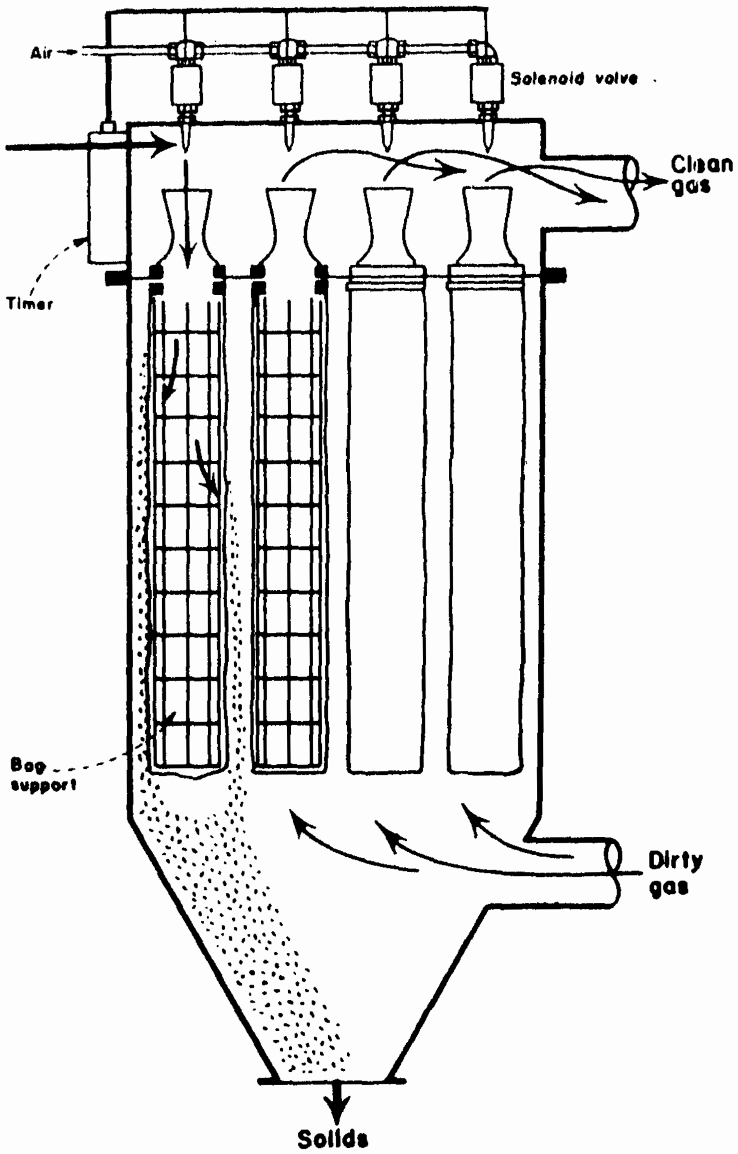


Figure 1.7 -Pulse-jet Configuration (ca 1957). (Mikro-Pulsaire[R] design; from Ref. 23).

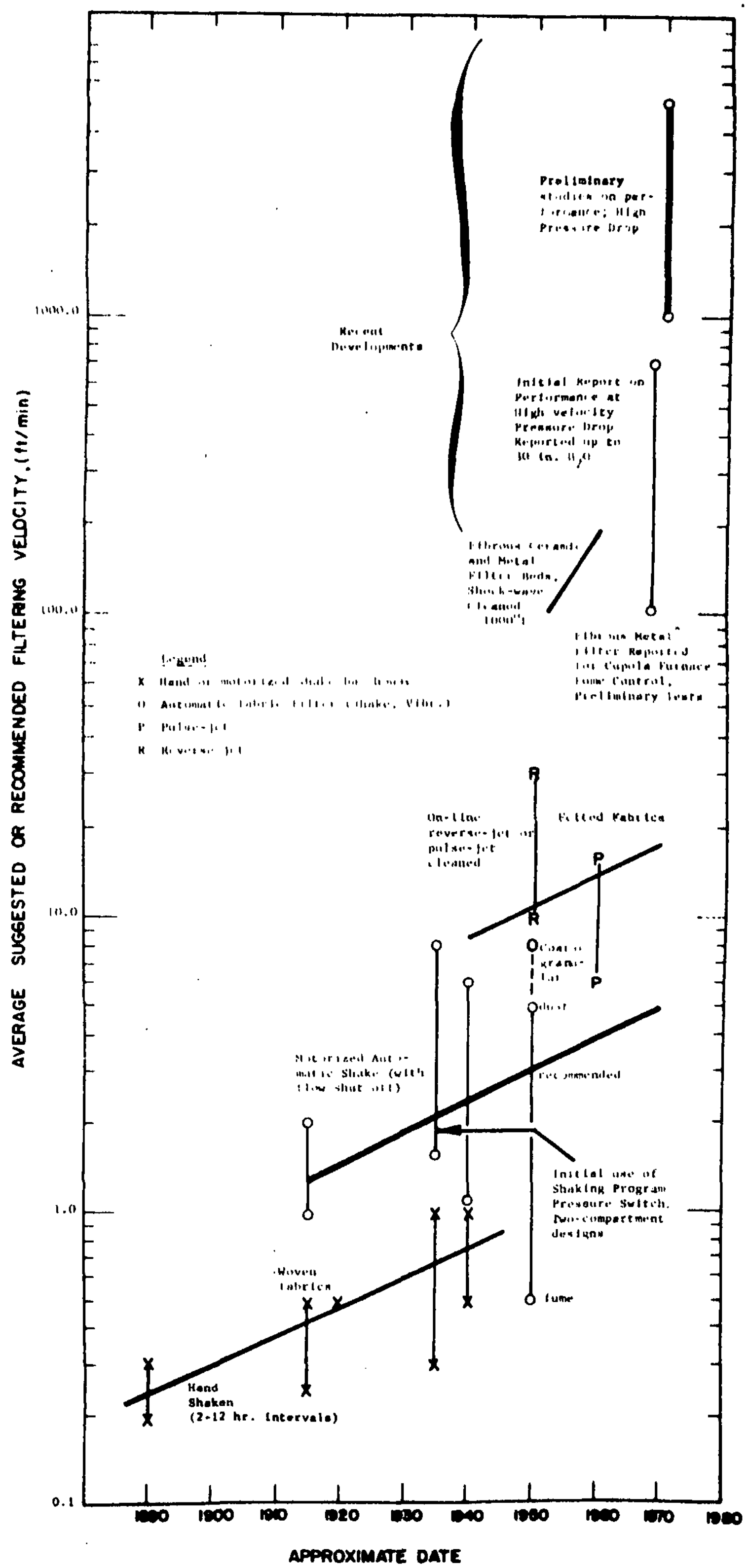


Figure 1.8. Historical Development and Present Status of Filtering Velocity.

mats.[24] Studies continue on cleanable refractory granular filter media[25,26] and devices for utilization of granular media with pulse-jet cleaning[27] to meet the requirements of demanding physical and chemical environments. These unusual filter configurations are not subject to the same limitations in filtration velocity as are fabric filters. This point will be discussed further in Chapter 2.

1.2.2 Fabric Developments

As noted above, fabric filter designs have been modified to take advantage of the rapid growth over the past 25 years of fabric technology. This technology has included completely new developments in fibers, yarn, and textile processes; most notably the synthetic fibers and glass fabrics enabling filtration both at higher temperatures and under more corrosive conditions. Figure 1.9 shows the development of filtration temperature capability, for example. Because of the outlook for still more chemically and thermally stable fibers is improving, the simultaneous evolution of fabric technology and collector and cleaning designs seems likely to continue.

Woven cotton and woolen flannel fabrics used in the early non-ferrous metallurgical bag houses[5] were suitable for temperatures below 200°F. Attempts to use woven asbestos fabrics for higher temperature applications were unsuccessful because the materials were not mechanically strong enough to resist the vigorous shaking required to dislodge dust.[19] Fine steel wool mats[28] or stitched blanket mats[18], used for metallurgical furnace fumes in the 1920's, were not sufficiently cleanable by rapping or shaking[19], and since they also oxidized rapidly at temperatures in the vicinity of 300°F they have not found wide application.

Man-made polymer textile fibers having improved temperature and chemical resistance have been developed and marketed commercially since the latter part of the 1940's. Orlon[R*] acrylic multi-filament fabrics were tested prior to 1950 in fabric filters,[9,29,30] for acidic atmospheres up to 300°F. Fabric weaves were developed for optimum permeability and dust retention properties, and techniques were perfected for heat setting the fabric prior

*Registered trademark

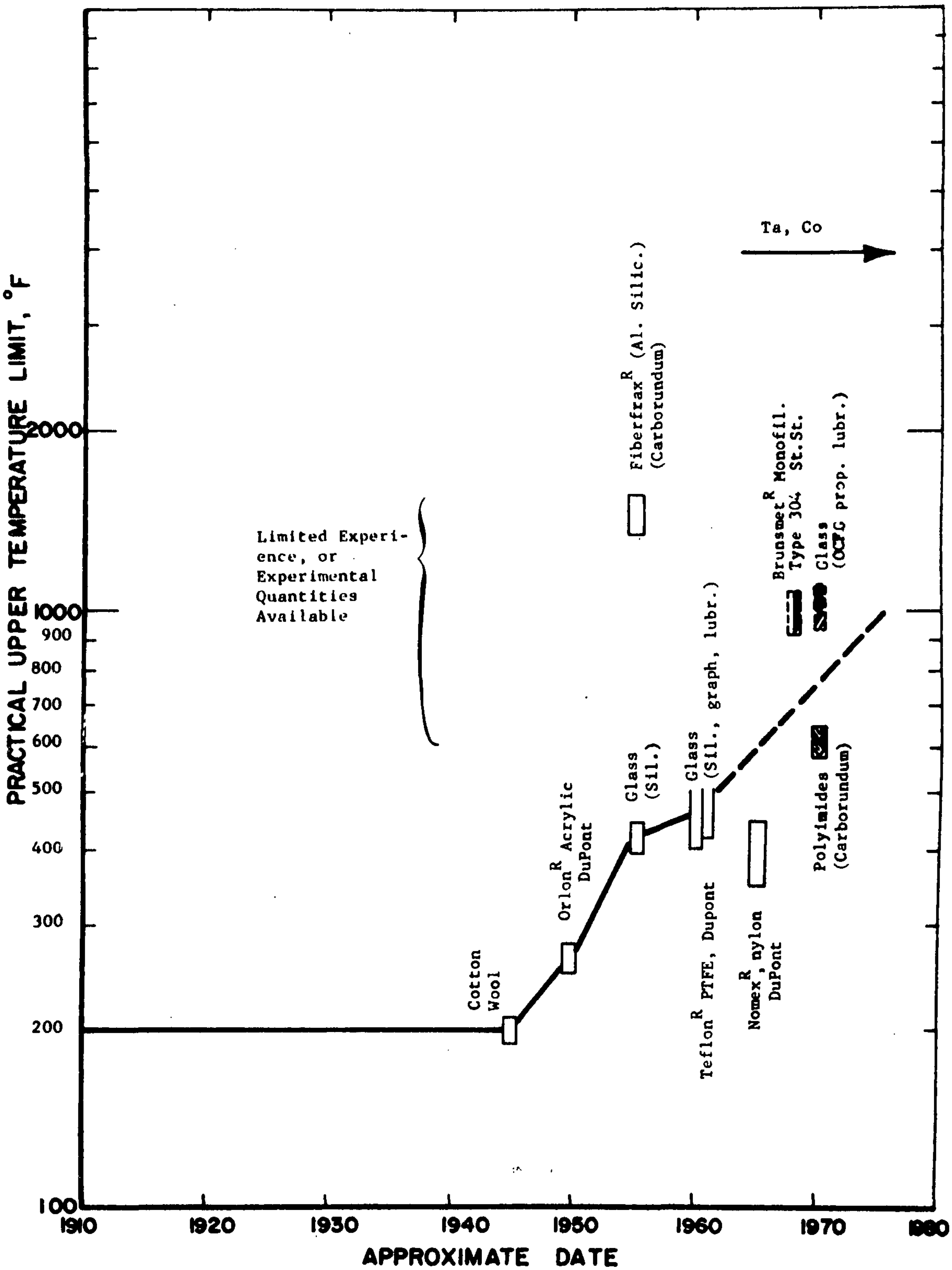


Figure 1.9. Development of Cleanable Filtration.

to sewing it into bags in order to eliminate shrinkage under operating conditions.[30] Orlon^R fabrics were being used successfully at 275°F by Wheelabrator and others by 1951[31,32,33] for numerous applications. These included carbon black, foundry cupolas, electric furnaces, rock dryers, dry grinding mills, spray driers, sinter machines, and brass refining furnaces, with auxiliary cooling as required.

By 1954, several other man-made fiber textiles had been evaluated for their usefulness in filtration at higher temperatures,[30] including nylon, vinyon, Dynel^R (~60% vinyl chloride, acrylonytride) and Dacron^R (polyester):

> "In no case were these fabrics found to be capable of withstanding continuous operation in the temperature ranges for which Orlon^R and fiberglass fabrics are suitable. However, some of these fabrics possess resistance to certain chemicals which has justified their use in special cases. For example, nylon possesses superior resistance to alkaline materials and is often used in gas filtration at a maximum temperature of 225°F. Vinyon possesses satisfactory resistance to certain chlorides and, to a lesser extent, fluorides; however, its maximum operating temperature is 200°F, and this limit has sharply reduced its general applicability."[30]

Glass fibers in mat form have been widely used in the filtration of low concentrations of atmospheric dusts in building ventilation air cleaning, from the 1930's onward.[34] Early attempts were made to produce durable filtration fabrics from glass fiber, but experience soon showed that these filter media were entirely unsuccessful from the standpoint of resistance to mechanical damage during handling and shaking. Despite this drawback, the use of fiberglass had an obvious advantage in that it could withstand operating temperatures in the neighborhood of 400° to 450°F.[30] USPHS-sponsored research efforts were directed to high temperature bag filter developments through use of colloidal graphite lubricants for fiberglass filter fabrics to improve flexure life (A.D. Little, Inc., 1957-1959).[35] In 1950 Dracco installed the first full scale commercial fiberglass installation at Hudson Bay Mining and Refining. This large, shaker and reverse air cleaned, installation marks a significant milestone in the employment of graphite and siliconized glass filter fabrics.

Subsequent PHS evaluation (1963) of the effects of added colloidal graphite treatment to commercial silicone-treated glass fabrics indicated substantial improvements in flexure life below 550°F.[36] As a consequence, the majority of fiberglass textiles used for gas filtration today (1970) are generally treated with silicones and graphite for high temperature operation. Fabric lives comparable to those of other fabrics are now achieved. Newer proprietary glass fabric treatments are now undergoing evaluation and pilot scale testing for operation at temperatures up to approximately 1000°F.

DuPont's Nomex®, a high temperature (450°F) nylon was tested in filter bags on a small scale during 1962 and 1963, and was made commercially available in 1964.[37] It has been used in a number of filtration applications including carbon black, calcining effluents, and non-ferrous metal fumes in both woven and felted designs. Teflon® (fluorocarbon) filter fabric is available, with chemical properties and heat resistance of considerable merit, but its applications have been limited by cost. Other high temperature media, including ceramics (e.g. Fiberfrax® by the Carborundum Co.) and fine monofilament metal fiber (e.g. Brunsmet® by Brunswick Corp.) have been woven and tested on bench and pilot scale for high temperature applications.

Other equally important advances have occurred in textile technology during the period 1945 through 1970. It has been necessary to develop spinning, weaving and finishing techniques for each of the man-made fibers consistent with the required fabric permeability and dust retention properties. Methods for heat setting, finishing, and sewing have been developed to provide long life under a wide range of environmental exposures. Felts suitable for use in pulse-jet and reverse-jet fabric filters have been developed (Smith, MIT, ca. 1957) by mechanical needle punching of staple filaments through woven fabric substrate.[38] Processes for the texturizing or bulking of filament yarns have been developed to provide numerous tiny filaments within the woven interstices necessary for good dust retention. Chapter 4 discusses in greater detail the available fibers, yarns, and fabrics and their production and properties with respect to filtration performance.

1.2.3 Manufacturers and Market Developments

The history of the present U.S. fabric filter industry is the sum of the growths of individual firms that have developed specific devices, configurations, and products to meet the needs of temporal markets. As indicated above, major steps in applications growth have been associated with improved cleaning methods and devices for higher air-to-cloth ratio (compartmented automatic and reverse air on-stream devices) and with recent developments in fiber and fabric technology. Apart from relatively small amounts of independent research efforts, the growth of the fabric filter industry has been achieved through applications-oriented developments by individual users and fabric filter manufacturers.

Although not a widespread practice today, early filters (prior to about 1910) were largely constructed by individual users for applications such as metallurgical fume recovery. The demonstration (1916) that fine respirable ($\leq$ 10 μm) mineral dusts were dangerous (by many investigators, including Higgins, Lanza, Laney, and Rice of the Public Health Service and the Bureau of Mines) led to increased requirements for silicious dust control in foundry, granite, pottery and similar industries. Toxic metallic compounds (e.g. Pb, As) had long been recognized as hazardous, but the importance of particle size in occupational health had not heretofore been established. The use of toxic particulate smokes as military tactical agents during the first World War (1916-1918) also provided substantial impetus to research and development in basic aerosol science, respiratory deposition and fate, and in methods for generation, sampling, analysis, and most importantly collection of fine particulates. These efforts have been further augmented by the advent of production of nuclear materials after 1945-1950.

Simultaneous developments in foundry sand blast and casting cleaning operations also resulted in filter development by firms such as Pangborn, Wheelabrator and Sly. Other developments of fabric filters have been associated with powdered materials technology, such as pneumatic transport and fine grindings, as in cement production by Fuller Company and Norblo (Buell). Since about 1945-1950, control of particulate air pollutants has been largely responsible for the steady growth in the fabric filter market. This growth has been made possible by advances in fabric resistance to temperature and to other physical and chemical environmental factors.

1.2.3.1 Manufacturers.- A census or enumeration of U.S. fabric filter manufacturers has been estimated periodically since 1950 for the Atomic Energy Commission, as shown in Figure 1.10. Manufacturers for the years 1950, 1954, and 1961 are listed in Appendix 1.3, along with characteristics of their equipment. Manufacturers and equipment for the year 1969 are given in detail in an Appendix to Chapter 3. Together these summaries indicate the growth of the industry through the continual addition of new products, and also through increasing numbers of manufacturers.* For the purpose of these tabulations, manufacturers have been included who have product capability for a fixed installation greater than about 10 square feet of fabric (i.e., greater than portable commercial industrial vacuum cleaners which would contribute an estimated additional 30 manufacturers). Included is the range from bin-vent and unit dust collectors (one to a few bags, < 100 cfm) through major installations of the order of 10^6 sq. ft. As Figure 1.10 shows, the fabric filter industry has in the vicinity of 50 producers at present.**

It should be emphasized that the individual producers represent a wide spectrum of capability for product and application, design engineering, service, industrial application, and market specialization and penetration. They also vary in ability to respond to new or novel application requirements and specifications. For example, only a limited number of the four dozen manufacturers are large enough or qualified to respond to a major high temperature air pollution control application such a kiln or furnace effluent, and able to provide the engineering design, fabrication, construction, installation and operational shake down required for turn-key responsibility. On the other hand, these same firms might not be in a position

* See also Appendices 1.4 and 1.5.

** It is important to note, however, that the IGCI members in 1969 accounted for 83 percent of the total fabric filter system sales.

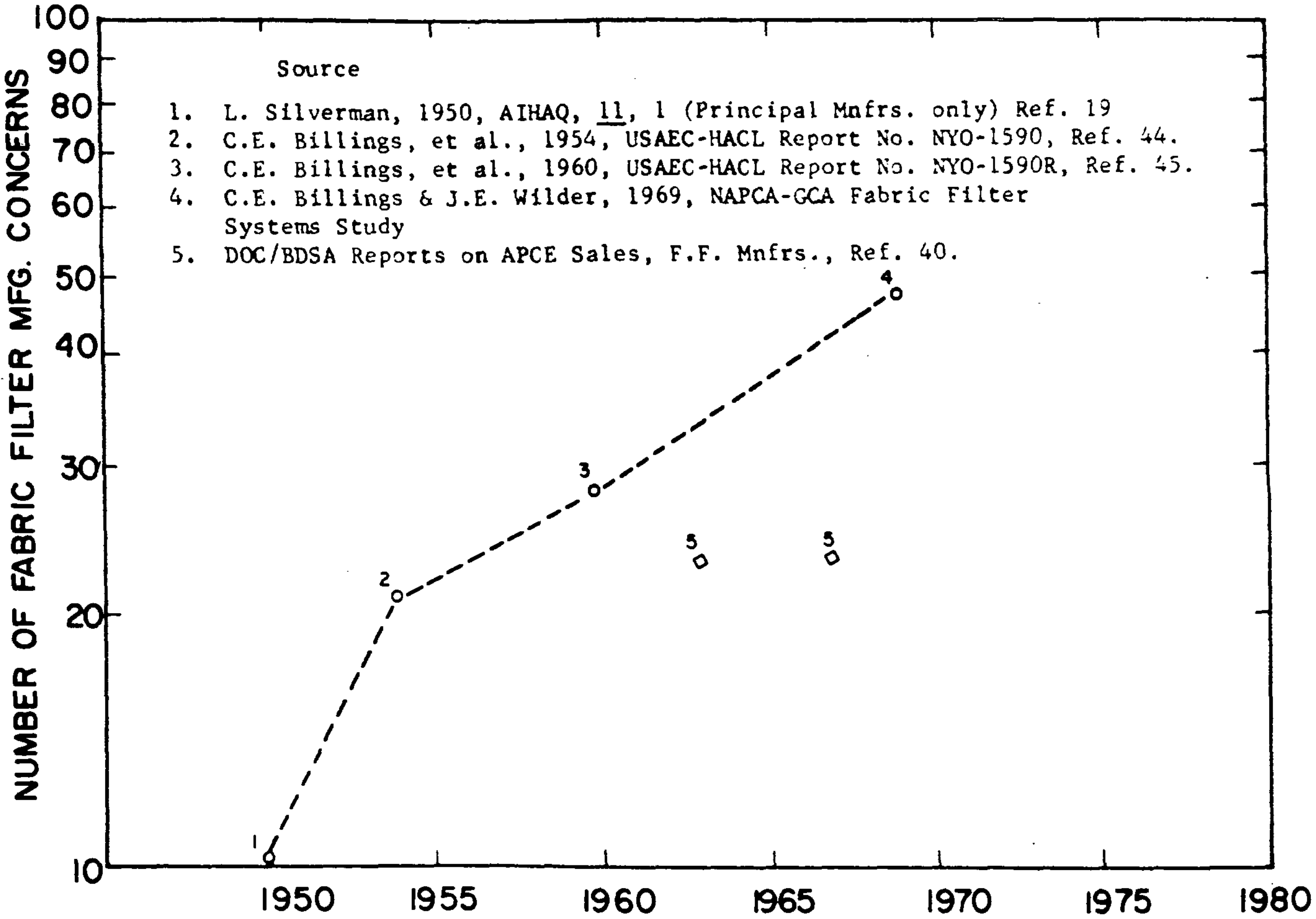


Figure 1.10. Estimates of Number of Fabric Filter Manufacturers (1950-1969).

to respond or compete profitably in small- to medium-sized units, where other producers are especially qualified. Although producers have traditionally tended to concentrate in specific related markets, these distinctions are gradually disappearing with the increase of filter applications and the tendencies toward acquisition and merger characteristic of the 1960's. Furthermore, major suppliers of fabric sewn into ready-to-use filter elements have traditionally been independent of the fabric filter manufacturers, but this characteristic of the industry is also disappearing.

Appendix 1.4 estimates the fabric filter equipment sales and also the total air pollution control equipment sales of each identified manufacturer. These estimates illustrate two major factors associated with the manufacture of fabric filters. First, no single producer has a majority of the market; rather the total sales are divided among some 45 to 50 large and small firms. Second, nearly all manufacturers have other products, and fabric filters are estimated to provide a relatively small fraction of their total annual sales. These two factors have important consequences relative to research funding. No single producer is large enough to be able to fund more than a modest program in fabric filter research, typically 1 to 2 percent of FF sales. When funded, these programs tend to be concerned with specific markets, applications problems, or product development. Most open literature technical publications presented by industry representatives emphasize engineering applications, e.g., "How XYZ Co. solves its Fume Problem," rather than the fundamental aspects of filtration. The orientation of these companies to applications rather than to research has undoubtedly been a significant factor in the growth pattern of the fabric filter industry.

The larger fabric filter producers, for the most part, manufacture a full range of air pollution control equipment including inertial collectors, scrubbers, and electrostatic precipitators. Thus, their interests have not been confined only to the development of fabric filter equipment.

1.2.3.2 Fabric Filter Industry.- An estimate of the average growth rate of the fabric filter industry during the past 20 years is shown in Figure 1.11. Reported total annual sales for two major producers who

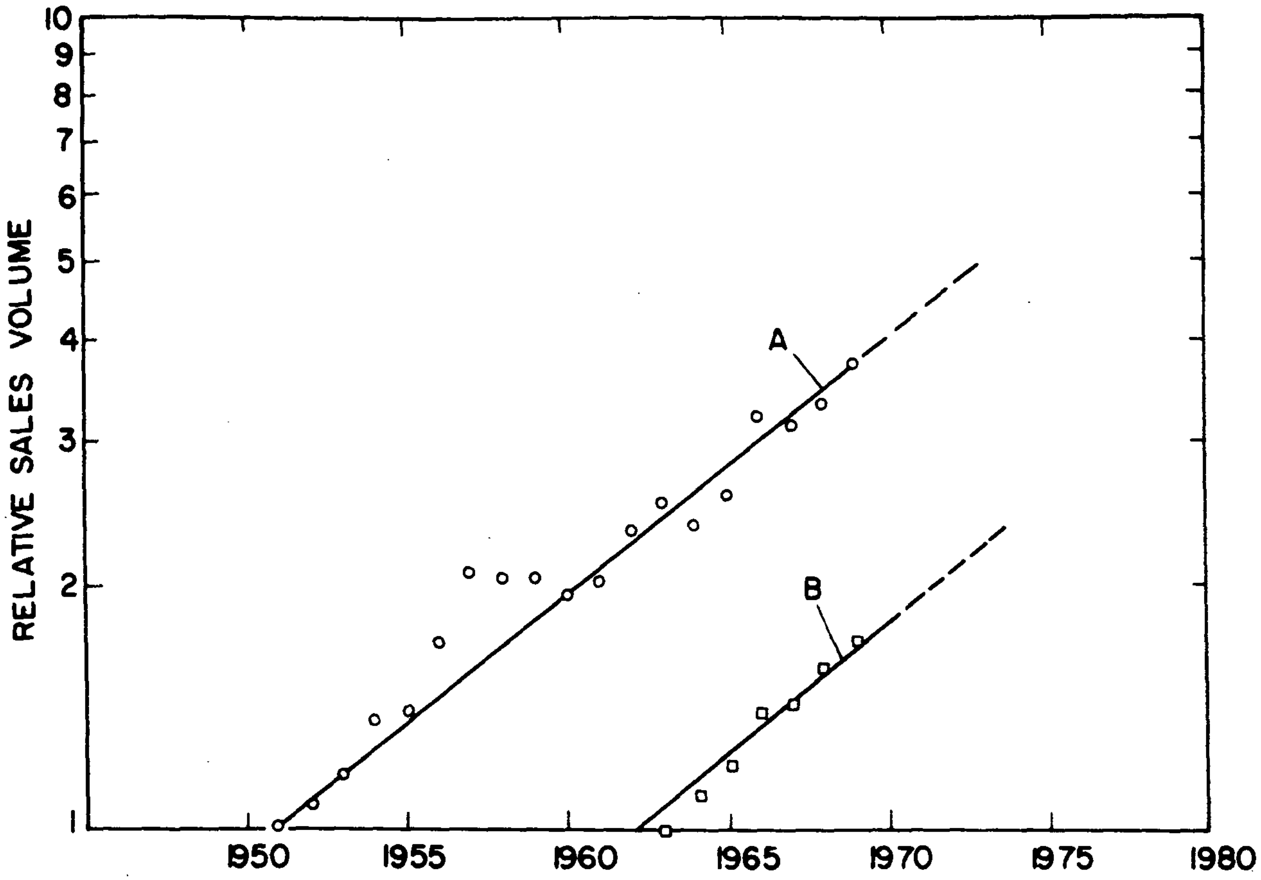


Figure 1.11. Average Air Pollution Control Equipment Industry Growth Rate As Estimated from Reported Sales of Two Mature Manufacturers of Gas Cleaning Products (Relative to 1951 (A) and 1963 (B) Sales Volume.)

supplied sales data were normalized to the initial year indicated. Both producers are prominent in the fabric filter industry having well developed product lines, world-wide marketing organizations, access to necessary operational and expansion capital, responsible service, and experienced engineering staffs. It appears that the average sales of well established firms, in the air pollution control equipment business, have tended to double in about 10 years (7.2 percent annual growth rate). In neither instance does there seem to be any major perturbation associated with accelerated air pollution control sales at least through 1969. Both seem to be increasing at approximately the same rate. This growth rate is considered as typical for modern U.S. industry; for example, the average sales of the ten largest industrial companies in the U.S. were $3.3 billion in 1954 and $6.5 billion in 1964.

Figure 1.12 estimates the growth of the particulate air pollution control equipment market, and also that part of it associated with fabric filters. Curve A represents an estimate of the growth rate of the mature air pollution control equipment industry derived from Figure 1.11. Curve B represents total particulate control equipment sales estimated from various reporting sources as indicated. Sales prior to 1963 seemed to follow the growth rate estimation given in Curve A. However, from 1963 through 1967 (last available data), sales have tended to increase more rapidly as a consequence of legislative and social pressures for greater air pollution controls. From this data base Curve B has been extrapolated at the same rate to 1970 as shown, indicating estimated 1969 sales of $140 millions. From the standpoint of future estimates or projections it seems unlikely that this rate of increase can continue, so Curve B has been conservatively estimated to return, after 1970, to the mature industry growth rate defined in Curve A.

Sales of fabric filters for air pollution control purposes are shown associated with Curve C as reported by Business and Defense Services Administration, (1963, 1967) and the Industrial Gas Cleaning Institute in

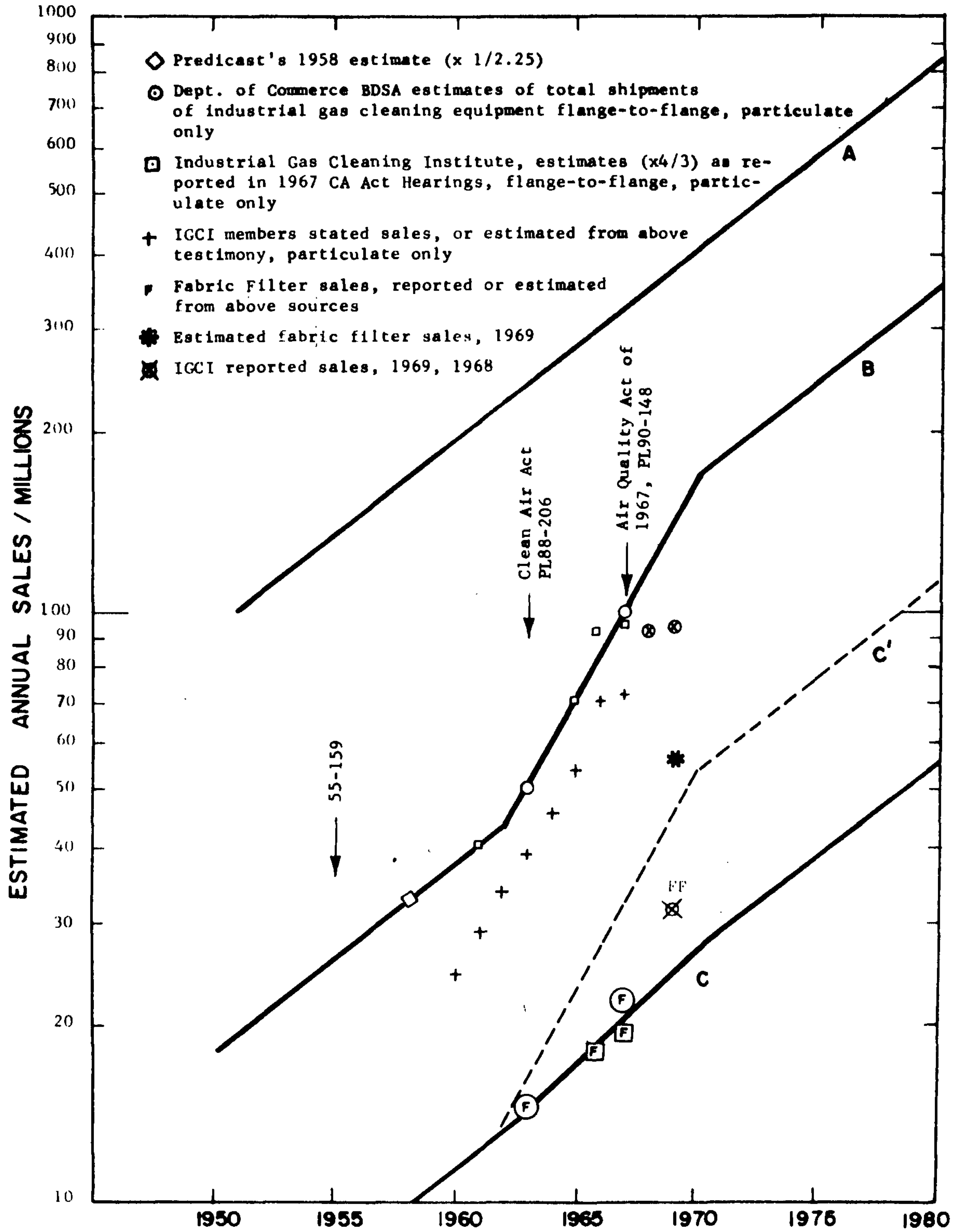


Figure 1.12. Particulate Air Pollution Control and Fabric Filter Sales.

conjunction with the Department of Commerce and NAPCA (1966, 1967).* Filter sales have reportedly increased from $14 million (1963) to approximately $20 million (1967). The slope of the growth estimate Curve C is not greater than about 10% above what would be predicted from the Curve A mature industry growth rate estimate. In view of the relatively rapid growth in sales shown in Curve B for all particulate control equipment, this seems to indicate a decreasing relative share of the control equipment market for fabric filters. This is rather surprising considering the expansion of application markets through fabric and filter device technological developments. Curve C indicates an estimated pollution control fabric filter sales of $25 million in 1969. Curve C′ has been included to demonstrate the growth rate of pollution control fabric filter sales, had they grown from 1962 at a rate parallel to Curve B or total control equipment sales (est. 1969 FF sales $45 million). The asterisk at $55.5 million for estimated 1969 aggregate sales of all fabric filters results from a consideration of individual fabric filter manufacturers in Appendix 1.4.

This estimate of $55.5 million for the annual fabric filter sales is of the order of twice the Figure 1.12 estimate provided by extrapolation of Department of Commerce BDSA and IGCI sales. The reasons for the difference in the two independent estimates are not evident, except for a possible qualification to the data provided in the earlier surveys. There, process equipment applications have been excluded by definition as not related to air pollution control. For the purposes of estimating total numbers of fabric filters in use, the lower figures have been used, recognizing that the estimates so provided may be low by a factor of order 2.

Further statistics of the fabric filter industry and its development are presented in Appendix 1.5. An analysis of these data yields the following estimates:

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*These surveys were directed toward fabric filter air pollution control applications and simultaneous product recovery. The distinction is frequently unclear, however, and the surveys may include some non-air pollution control sales.

	Fabric Filters In use, ca. 1910	Sold in 1969	In Use, as of 1969
Number of Fabric Filters:	750	7500	100,000
Average filter size (ft^2):	400	3000	---
Total filter area (ft^2):	$0.3x10^6$	$22x10^6$	$243x10^6$
Fabric sold (ft^2):	---	$100x10^6$	---
Gas volume filtered (cfm):	$0.15x10^6$	---	$750x10^6$
Filter sales:	---	$\$22x10^6$	---
Fabric sales:	---	$\$33x10^6$	---

It is emphasized that these estimates are tentative, and are not as precise as could be generated by a national census or register of fabric filter devices. Sizes and costs of fabric filter equipment will be the subject of later sections of this handbook.

1.3 OPERATING PRINCIPLES

A fabric filter is made up of a woven or felted textile material in the shape of a cylindrical bag or flat supported envelope. The textile material is contained in a metal housing having inlet and outlet gas connections, a dust storage hopper, and means for cleaning the fabric periodically.

Woven fabrics consist of parallel rows of yarns in a square array. Open spaces between adjacent yarns are occupied by projecting fibers. Felted fabrics consist of close, randomly intertwined fibers compacted to provide fabric strength. In operation, dusty gas passes through the filter normal to the fabric and dust particles, at the start of filtration, deposit on individual fibers and yarn surfaces. Additional particles then deposit and accumulate on already deposited particles forming filamentous aggregate structures which project into the gas stream. As deposition and accumulation continue, openings between yarns and individual fibers become occupied by aggregates and reduced in size. Eventually a more or less continuous deposit forms, analogous to the filter cake common in liquid filtration. Particle collection then occurs by mechanisms associated with porous granular media. Thus, the fabric filtration process may be considered to consist of at least three distinct phases: (1) initial or early deposition, when depositing particles land on individual fibers, fibrils or filaments of the yarn; (2) intermediate deposition when particles accumulate on previously deposited particles, long filamentous particle aggregates form, and bridging of interweave and interstitial spaces occurs leading to the formation of a more or less continuous deposit; and (3) the continued deposition of particles on a matrix similar to a granular layer, leading to the formation and consolidation of a filter cake.

Accumulation of dust causes an increase in gas flow resistance, as a consequence of the particle drag forces and interparticle pore (capillary) resistance. The properties of the particle bed (porosity, permeability) also change during the formation of the deposit. Aggregates deform, bend, collapse, or reorient under the action of the gas flow and the increasing compressional pressure in the bed as its depth increases. Fundamental mechanisms of deposit formation and cake mechanisms are considered in greater detail in Chapter 2.

The filter bag (sleeve, tube, or envelope) is supported by external and sometimes internal structures to permit the dusty gas to flow through the housing from an inlet section to a clean gas outlet section. This is shown in Figure 1.13 in one of several typical arrangements. In the particular arrangement the bag is fastened at the bottom to a tube sheet or cell plate and held up vertically by a top hook on an overhead rack. The bag may be pulled to the desired tightness by means of a tension adjustment. Gas flows into the inside of the bag from the bottom and passes up the interior and through the bag to the outlet ducting. The gas may then go to the suction inlet of a blower and hence out of the system, either returning to the ventilated space or to the outdoor atmosphere. Alternatively, the blower can be located on the inlet side of the fabric filter so that it draws air or gas from the ventilated system or process and discharges it to the bag collector under pressure. In this latter case, as before, the gas

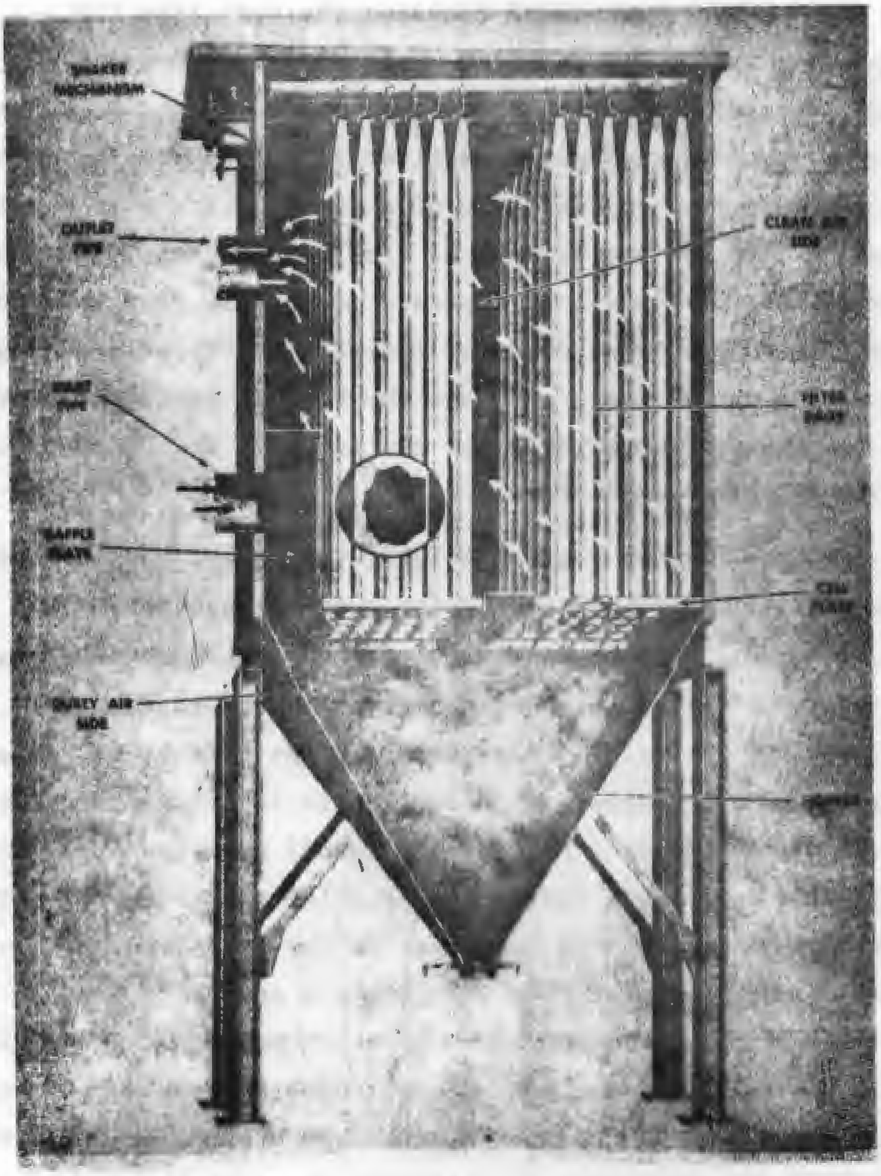

Figure 1.13 -Typical Fabric Filter Arrangement
(Courtesy of Wheelabrator Corp.)

passes through the fabric leaving the dust on the inner surface, and the gas is then discharged.

There are several methods of removing the dust from the inside of the filter bags. In the design shown the dust may be removed by stopping the flow and allowing the dust to fall off by its own weight. More typically the dust is removed by vigorously oscillating the suspension rack back and forth (~ 5 cps) through an amplitude of a few inches. This shaking motion, imparted to the bags in the absence of flow, causes sufficient forces to be transmitted to the deposit to separate most of it from the fabric substrate. The dust then drops down the interior of the bag, through the mouth of the bag at the tube sheet, and into the hopper. Collected dust is removed from the hopper periodically or continuously for disposal or return back into the production process.

Cohesion and adhesion forces, holding individual particles together or to the underlying fibers or yarns, exist over a range of values. The application of a cleaning force by shaking initially removes a large amount of the deposit on the first few shake cycles but then progressively less and less on succeeding cycles. A substantial amount of residual deposited particulate material remains within the fabric interstitial spaces. The remaining deposit produces a residual (cleaned) pressure drop across the fabric. It also provides a fairly high initial particle collection efficiency upon resumption of flow of the dusty gas on the next filtration cycle as the individual residual particles and particle aggregates act as objects for collection of the incoming dust. Upon resumption of filtration the dust deposit more rapidly acquires a continuous character because of the residual material. These deposition processes proceed at different rates within the total bag structure at different areas of the fabric in response to the amount of flow passing locally, which depends upon the amount of residual dust. Thus a local area which has a more porous or open residual structure will tend to allow more flow and, initially at least, material will deposit faster. These initial differences tend to even out so that filtration velocities and dust deposition rates tend to become uniform over the entire fabric surface.

As the gas flows outward through the bag the velocity inside the bag decreases. Since the particle-gas motion is vertical, there are flow and particle stratification effects which enter into the analysis of the macroscopic processes of deposition, accumulation, and gas flow through the media. In the configuration depicted in Figure 1.13, the upward flow within the bag and the turn of the gas in leaving the hopper and entering an individual bag tend to separate larger particles out of the flow by gravity or inertia. Larger particles carried into the tube are deposited in the lower end of the tube as the gas velocity, progressively decreases as it uses. This stratification of particle sizes has important consequences on deposit characteristics and on fabric performance and life over the entire bag length, but especially at the bottom near the entry.

The operation cycle of the fabric filter thus contains two phases. The first is a filtration phase during which material is depositing and accumulating on the fabric while pressure drop across the deposit is increasing, and as a consequence total flow is decreasing. The second is a cleaning phase with no filtration flow during dust removal. By compartmenting sections of bags and isolating these one at a time from the gas flow for cleaning, the total flow from the process ventilated can be maintained reasonably constant. This cleaning procedure can be automatic and the operation continuous. The residual dust deposited and retained within the fabric interstices gradually reaches an equilibrium value after numerous filtration and cleaning cycles, after which the residual pressure drop remains more or less constant throughout the useful life of the fabric ($\sim 10^4$ - 10^7 cleaning cycles).

Particles entering a new fabric initially contact individual fibers, fibrils, and yarn filaments and are separated from the gas by several filtration mechanisms (see Chapter 2). Deposited particles serve as additional obstacles for further capture of other particles. After cleaning, the residual dust provides a substantial number of obstacles for further particle collection. The collection efficiency of a fabric filter is defined as

$$\text{Efficiency} = 1 - \frac{\text{outlet dust concentration}}{\text{inlet dust concentration}} = 1 - \text{Penetration} \quad (1.1)$$

It may be determined for an operating filter from simultaneous measurements of inlet and outlet dust concentrations by appropriate stack sampling techniques.

The basic collection efficiency of new filter fabric is generally in the range of 50 to 75% for submicron atmospheric dust (0.5 μm count median diameter, and an inlet concentration of 75 $\mu g/m^3$) at 3 to 8 ft/min. As dust accumulates, efficiency rises. By the time the deposit amounts to 2 to 3 grams of dust per square meter (~ 3 to 5 grains per square foot) the collection efficiency usually exceeds 90%. This happens in about one minute at an inlet dust concentration of 2.3 g/m^3 (1 gr/ft^3), a common industrial dust loading. Overall efficiency then continues to increase with dust accumulation, and will generally exceed 99% when the deposit reaches 150 g/m^2 (0.03 lb/ft^2), i.e., after an hour or less at common industrial dust concentrations. After a period of cyclic filtration and cleaning ranging from a few hours to a few days the residual deposit will stabilize and thereafter efficiency will remain greater than 99%. During usual operating conditions, fabric filter overall weight collection efficiency will exceed 99.9%. The collection efficiency for the submicron fraction of the inlet dust is usually at least greater than 90%.

The high overall efficiency is related to the nature of the accumulated deposit. Overcleaning in order to reduce flow resistance will frequently cause a reduction in overall efficiency and a slight visible puff of dust may be observed upon resumption of filtration. The dust collection efficiency for the submicron fraction may then be less than 80% until cake formation. Collection efficiency and pressure drop performance relationships between dust, fabric, cleaning, and design parameters are discussed in subsequent sections. Overcleaning can also shorten the life of the fabric and thereby contribute substantially to the cost of maintaining the filter system. Fabric life averages about one year, although it can vary from a few weeks up to 20 years. The actual fabric life and indeed the entire filter performance depend on the design of the filter, the application conditions and the care given the filter system. These are all the subjects of later sections of this handbook.

1.4 FABRIC FILTER APPLICATIONS AREAS

It is the purpose of this section to cite several general application areas of fabric filters and of alternative particulate control equipment. As indicated earlier there are estimated to be at least 10^5 fabric filter particulate collectors in use (1969) treating on the order of 750×10^6 cfm. These fabric filters range over more than a hundred different applications, and in size over six orders of magnitude. The spectrum of sizes in use is also estimated, insofar as possible, within the limits of data now available. Later in Chapters 6 and 9, more specific applications will be described.

Friedrich[39] has estimated "that approximately 80 percent of all manufacturing plants produce dust loadings and particles small enough to warrant or require the use of..." fabric filters. Since there are some 311,000 manufacturing plants in the U.S. (1969 Statistical Abstracts) this provides an approximation of the potential usage of fabric filters. This estimate, of course, represents a reasonable approximation of the total market for particulate control devices including fabric filters, electrostatic precipitators, scrubbers and mechanical collectors. Since each system has unique qualifications for specific applications, the performance and economic aspects of each type of device must be evaluated in the context of the applicable particulate control requirements. Addressing our attention specifically to fabric filter systems, however, we emphasize that this approach to particulate control is highly versatile. With design modifications they may be used in the treatment of process gases, for the recovery of powdered products, and for the recovery of nuisance or toxic dusts and fumes for the protection of the environment as in air pollution control. As indicated earlier these applications include mining and minerals processing (both metallic and non-metallic), chemical and allied manufacturing, food products, rubber and plastics, metal refining, primary metallurgy, and machinery. Fabric collectors handle dusts from crushing, grinding, pulverizing, conveying, milling, drying; fumes from cement kilns, iron melting cupolas, reverberatory and electric arc furnaces; and carbonaceous smoke from incomplete combustion of chemical process streams as in carbon black manufacture and fuel combustion, to mention just a few.

The principal advantages of fabric filter systems in such installations are:

- Particle collection efficiency is very high and can be maintained at high levels.
- Efficiency and pressure drop are relatively unaffected by large changes in inlet dust loadings for continuously cleaned filters.
- Filter outlet air may be recirculated within the plant in many cases.
- The collected material is recovered dry for subsequent processing or disposal.
- There are no problems of liquid waste disposal, water pollution, or liquid freezing.
- Corrosion and rusting of components is usually not a problem.
- There is no hazard of high voltage, simplifying maintenance and repair and permitting collection of flammable dusts.
- Use of selected fibrous or granular filter aids permit the high efficiency collection of submicron smokes and gaseous contaminants.
- Filter collectors are available in a large number of configurations resulting in a range of dimensions and inlet and outlet flange locations to suit installation requirements.

Some limitations in the use of fabric filters include:

- Fabric life may be shortened in the presence of acid or alkaline particle or gas constituents, and at elevated temperatures.
- Temperatures much in excess of 500°F require special refractory mineral or metallic fabrics that are still in the development stage.
- Hygroscopic materials, condensation of moisture, or tarry, adhesive components may cause crusty caking or plugging of the fabric, or require special additives.
- Certain dusts may require fabric treatments to reduce seeping of the dust or in other cases to assist in the removal of the collected dust.
- Concentrations of some dusts in the collector (~ 50 g/m^3) may represent a fire or explosion hazard if spark or flame is admitted by accident. Fabrics can burn if readily oxidizable dust is being collected.
- Replacement of fabric may require respiratory protection for maintenance personnel.

Filter applications can be categorized to reflect similarities of industrial processes, unit operations, or filter usage patterns. Surveys of fabric filter applications by some categories are available, such as the Business and Defense Services Administration (BDSA) survey of fabric filter sales for the year 1967 summarized in Table 1.3.[40]

Table 1.4 presents a summary of sales reported by member companies of the Industrial Gas Cleaning Institute for the years 1966 and 1967.[41] Data are presented by Standard Industrial Category Number (S.I.C. No.)* for value and number of collectors sold. Fabric filters represent the largest number of devices sold in each year, and were employed in all categories except domestic, commercial, and industrial heating plants.

Data obtained from these two surveys may underestimate total fabric filter usage because: (1) questionnaires are believed to have been specifically directed only to air pollution control sales; and (2) the number of manufacturers of fabric filters surveyed (23 by BDSA, 15 by IGCI) was less than half the total number of about 50 manufacturers.

Data from the IGCI particulate air pollution control equipment summary in Table 1.4 have been combined in ten categories as shown in Table 1.5 to illustrate present usage patterns and for later estimation of potential application areas. In addition, these combined figures may be compared to similar figures developed by BDSA in Table 1.3 for some of the categories. Several conclusions may be drawn from Table 1.5:

(1) Major 1967 application areas for fabric filters included all categories except Combustion, Pulp and Paper, and Petroleum

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*For more S.I.C. detail, see "Standard Industrial Classification Manual," Bureau of the Budget, Washington, D.C.

Table 1.3

INDUSTRIAL GAS CLEANING EQUIPMENT--MANUFACTURERS' SHIPMENTS BY END USE, 1967

(Thousands of dollars)

End use	Electrostatic precipitators	Scrubbers, particulate	Mechanical collectors	Fabric filters	% Fabric Filters of all Types
Iron and steel..........	5,783	7,423	2,300	4,536	22.5
Utilities...............	15,506	([1])	2,476	([1])	---
Chemicals...............	1,207	3,709	3,130	5,344	40.5
Rock products[2]...........	2,760	1,142	1,038	3,602	42.4
Pulp and paper..........	([1])	989	802	122	---
Mining and metallurgical.	([1])	825	389	1,855	---
Refinery................	([1])	([1])	([1])	([1])	---
All other[3].............	687	3,901	8,408	4,959	27.6
Exports.................	([1])	651	([1])	1,081	---
Total shipments	36,509	19,229	22,381	21,730	21.8

[1] Not published to avoid disclosure.

[2] "Rock products" includes cement and asbestos plants.

[3] "All other" includes shipments to distributors where end use can not be identified.

(From Ref. 40)

TABLE 1.4

SUMMARY OF THE MANUFACTURERS' REPORT OF AIR POLLUTION CONTROL EQUIPMENT SALES (PARTICULATE)*

INDUSTRIAL CLASSIFICATION	Year	ELECTROSTATIC Number	ELECTROSTATIC Amount	MECHANICAL Number	MECHANICAL Amount	FABRIC FILTER Number	FABRIC FILTER Amount	WET SCRUBBER Number	WET SCRUBBER Amount
ALL EQUIPMENT, NEC **	1966	1	63,680	938	953,121	1,250	801,548	143	[illegible]
	1967	0	0	1,066	551,012	1,380	907,779	112	540,444
DOMESTIC & COMMERCIAL HEATING PLANTS	1966	0	0	7	12,849	0	0	1	6,300
	1967	0	0	16	115,783	0	0	0	0
INDUSTRIAL HEATING PLANTS	1966	3	300,533	113	907,468	0	0	9	33,000
	1967	6	736,327	106	885,153	0	0	36	241,100
MINING (S.I.C. No. : 10)	1966	5	395,000	33	194,222	35	409,676	58	490,114
	1967	6	559,000	27	185,843	24	187,622	50	406,257
MINING AND QUARRYING OF NONMETALLIC MINERALS, EXCEPT FUELS (S.I.C. No.: 14)	1966	0	0	224	388,733	55	334,594	28	288,648
	1967	0	0	178	336,136	46	378,234	20	124,950
FOOD AND KINDRED PRODUCTS (S.I.C. No. 20)	1966	0	0	119	407,330	394	1,074,862	65	199,816
	1967	0	0	85	298,277	315	949,096	82	350,268
TEXTILE MILL PRODUCTS (S.I.C. No.: 22)	1966	0	0	5	7,374	45	84,741	0	0
	1967	0	0	2	1,335	20	73,618	0	0
APPAREL & RELATED PRODUCTS (S.I.C. No.: 23)	1966	0	0	0	0	0	0	0	0
	1967	0	0	0	0	1	428	0	0

*(From Ref. 41).

**NEC = Not Elsewhere Classified.

TABLE 1.4 (Continued)

SUMMARY OF THE MANUFACTURERS REPORT OF AIR POLLUTION

CONTROL EQUIPMENT SALES (PARTICULATE) (Continued)

INDUSTRIAL CLASSIFICATION	Year	ELECTROSTATIC Number	ELECTROSTATIC Amount	MECHANICAL Number	MECHANICAL Amount	FABRIC FILTER Number	FABRIC FILTER Amount	WET SCRUBBER Number	WET SCRUBBER Amount
LUMBER AND WOOD PRODUCTS, EXCEPT FURNITURE (S.I.C. No.: 24)	1966	0	0	197	381,689	81	205,845	6	80,099
	1967	0	0	331	600,985	127	403,181	6	22,076
FURNITURE & FIXTURES (S.I.C. No.: 25)	1966	0	0	22	85,204	31	20,320	0	0
	1967	0	0	47	94,702	65	77,727	0	0
PAPER AND ALLIED PRODUCTS (S.I.C. No.: 26)	1966	19	2,696,185	53	114,325	75	160,577	42	567,036
	1967	9	1,654,280	48	65,590	55	135,927	44	483,822
PRINTING AND PUBLISHING (S.I.C. No.: 27)	1966	0	0	44	28,477	6	18,460	12	22,758
	1967	0	0	27	21,056	7	13,039	10	25,642
CHEMICAL & ALLIED PRODUCTS (S.I.C. No.: 28)	1966	11	772,085	358	880,561	791	3,857,694	147	1,490,181
	1967	5	394,605	306	936,531	776	3,787,876	132	1,417,583
PETROLEUM REFINING AND RELATED INDUSTRIES (S.I.C. No.: 29)	1966	2	72,680	50	3,455,610	44	183,697	18	121,521
	1967	5	537,965	42	2,237,788	27	259,166	26	214,726
RUBBER AND MISCELLANEOUS PLASTICS PRODUCTS (S.I.C. No.: 30)	1966	0	0	153	197,791	186	399,605	33	111,212
	1967	0	0	93	106,083	137	339,399	40	108,841
LEATHER AND LEATHER PRODUCTS (S.I.C. No.: 31)	1966	0	0	74	50,462	81	54,803	1	1,895
	1967	0	0	90	65,159	97	77,196	0	0

TABLE 1.4 (Continued)

SUMMARY OF THE MANUFACTURERS REPORT OF AIR POLLUTION

CONTROL EQUIPMENT SALES (PARTICULATE) (Continued)

INDUSTRIAL CLASSIFICATION	Year	ELECTROSTATIC Number	ELECTROSTATIC Amount	MECHANICAL Number	MECHANICAL Amount	FABRIC FILTER Number	FABRIC FILTER Amount	WET SCRUBBER Number	WET SCRUBBER Amount
STONE, CLAY, GLASS & CONCRETE PRODUCTS (S.I.C. No.: 32)	1966	11	2,351,850	99	380,909	406	2,814,952	20	132,570
	1967	13	2,054,695	91	332,825	276	3,450,635	18	210,549
PRIMARY METAL INDUSTRIES (S.I.C. No.: 33)	1966	20	3,966.483	386	927,599	819	5,738,669	261	7,395,356
	1967	16	2,366,368	356	704,457	833	6,587,496	305	5,616,656
FABRICATED METAL PRODUCTS (S.I.C. No. 34)	1966	0	0	162	109,286	226	207,725	5	22,467
	1967	0	0	0	0	264	251,527	5	34,241
MACHINERY, EXCEPT ELECTRICAL (S.I.C. No.: 35)	1966	0	0	521	329,444	855	574,546	0	0
	1967	0	0	375	270,210	704	581,670	0	0
ELECTRICAL MACHINERY (S.I.C. No.: 36)	1966	0	0	245	146,923	376	337,055	3	14,995
	1967	0	0	203	140,671	321	258,873	7	43,099
TRANSPORTATION EQUIPMENT (S.I.C. No.: 37)	1966	0	0	149	95,848	200	272,056	2	432,500
	1967	0	0	147	105,321	187	342,152	2	39,500
INSTRUMENTS (S.I.C. No.: 38)	1966	0	0	121	72,184	141	141,763	0	0
	1967	0	0	108	75,836	160	221,117	0	0
MISCELLANEOUS MFG. INDUSTRIES (S.I.C. No.: 39)	1966	0	0	89	58,204	107	111,070	0	0
	1967	0	0	77	53,927	121	91,296	4	70,770
ELECTRIC, GAS & SANITARY SERVICES (S.I.C. No.: 49)	1966	55	15,998,885	139	1,854,969	33	369,361	25	833,534
	1967	63	22,774,900	129	1,798,669	20	221,670	115	787,031
TOTAL	1966	127	26,617,381	4,281	12,040,582	6,237	18,173,618	879	13,015,318
	1967	123	31,078,140	3,950	9,985,349	5,963	19,595,543	1,014	10,738,154

PARTICULATE CONTROL TOTAL	Year	Number	Amount
	1966	11,524	69,846,899
	1967	11,050	71,397,186

Table 1.5

SUMMARY OF IGCI REPORT OF FABRIC FILTER SALES FOR AIR POLLUTION CONTROL

	1966				1967					
			% by Category				% by Category		% FF $ of all APCE	Average FF
	No.	$ x 10^3	No. %	$ %	No.	$\$x10^3$	No. %	$ %	$ in Category*	Cost, $
1. Combustion SIC 010,020,49	33	369	0.5	2.0	20	221	0.3	1.1	1	11,000
2. Food & Feed SIC 20	394	1,075	6.3	5.9	315	949	5.3	4.8	60	3,000
3. Pulp & Paper SIC 26,27	81	179	1.3	1.0	62	149	1.0	0.8	6	2,400
4. Inorganic Chem. SIC 28/	156	681	2.5	3.8	146	661	2.5	3.4	24	4,500
5. Organic Chem. SIC 28/30	821	3,576	13.2	19.7	766	3466	12.8	17.7	70	4,500
6. Petrol Ref. SIC 29	44	184	0.7	1.0	27	259	0.5	1.3	8	9.600
7. Non-metal-lic Min Ind SIC 14,32	461	3,150	7.4	17.3	322	3828	5.4	19.5	56	11,900
8. Iron & Steel, Fdy SIC 10/33/	725	5219	11.6	28.7	735	5755	12.3	29.4	42	7,800
9. Non-Ferrous Met SIC 10/33/	129	929	2.1	5.1	122	1019	2.0	5.2	35	8,400
10. Misc NEC SIC 00,22,23, 24,25,31,34, 35,36,37, 38,39	3393	2812	54.4	15.5	3447	3288	57.9	16.8	55	960
TOTALS	6237	18,174	100.0	100.0	5962	10,595	100.0	100.0		
$/FF		$2,910				$3290				
% FF $ of Total APCE $		26%				27%				

*APCE $ = Sales of all types of air pollution equipment for particulate control.

Refining, which in 1967 represented in all less than about 3% of filter sales.

(2) Fabric filters apparently represent more than 50% of particulate control device sales in Food and Feed, Chemicals, and Non-metallic Minerals, and between 35 and 45% for Metallurgical applications.

(3) The average cost of a fabric filter sold in 1967 was approximately \$3290 (as compared to \$253,000 for the average electrostatic precipitator, \$2530 for the average mechanical collector, and \$10,600 for the average scrubber). Using the previously assumed average cost of \$1 per sq. ft., the average filter size was 3290 sq. ft.

(4) Approxomately 58% of the units sold in 1967 cost less than \$1000 (category 10), while less than 6% of the units sold cost more than \$10,000 (categories 1 and 7). The dollar volume represented by these groups was approximately the same (~20% of sales), a characteristic of the size distribution of fabric filter installations. This pattern is further illustrated in the discussion which follows.

Two major U.S. manufacturers have provided information on typical 1967 and 1968 sales, including product model, application area and size of collector, for each of some 1200 units sold during this period. This sample is believed to represent 5 to 10% of the total number of fabric filters produced in the U.S. for this period, and approximately the same fraction of total dollar value. The distribution of fabric filters by application and size is presented in Table 1.6. These figures indicate that manufacturer C had major product penetration (>10% of area sold, column 2) in categories 7 and 8, and that manufacturer D had major penetration (column 4) in categories 2, 5, and 7. Manufacturer C produced a larger number of collectors with areas >3200 sq. ft., whereas manufacturer D produced more collectors with areas <320 sq. ft. Statistical analyses of number-size data indicate the following median sizes:

	Mnfr. C	Mnfr. D
Median Size by Area:	5500 sq. ft.	1100 sq. ft.
Median Size by Number:	1500 sq. ft.	250 sq. ft.

The median collector area produced for the two manufacturers combined for both years was approximately 650 sq. ft. The differences in medians for the two manufacturers cannot be directly translated to gas volume treated

Table 1.6

SALES OF TWO FABRIC FILTERS MANUFACTURERS BY INDUSTRIAL CATEGORY

(1967 - 1968 Combined Sample)

Category	Manufacturer C % Tot. Area	Manufacturer C % Tot. No.	Manufacturer D % Tot. Area	Manufacturer D % Tot. No.	Distribution of Fabric Filter Size, Sq.Ft., % Nos. <100	100-320	320-1000	1000-3200	3200-10,000	1000-32,000
1. Combustion	8.0	6.0	---	---	0	0	15	29	53	3
	---	---	2.2	1.3	0	25	25	50	0	0
2. Food & Feed	4.7	2.3	---	---	0	8	30	8	23	31
	---	---	22.6	24.3	23	34	30	9	4	0
3. Pulp & Paper	2.0	0.8	---	---	0	40	60	0	0	0
	---	---	0	0	0	0	0	0	0	0
4. Inorganic Chem.	3.0	3.8	---	---	0	0	23	50	27	0
	---	---	8.0	14.0	32	34	27	7	0	0
5. Organic Chem.	9.7	13.3	---	---	0	3	50	20	25	1
	---	---	28.9	24.2	29	29	19	18	5	0
6. Petrol Refining	0	0	---	---	0	0	0	0	0	0
	---	---	0	0	0	0	0	0	0	0
7. Non-metallic Minerals	39.3	45.1	---	---	0	7	34	29	26	4
	---	---	28.2	21.8	17	38	30	9	6	0
8. Iron & Steel Foundry	10.0	4.5	---	---	0	4	8	34	23	31
	---	---	2.2	1.0	0	33	67	0	0	0
9. Non-Ferrous Metals	4.9	1.7	---	---	0	30	20	30	10	10
	---	---	2.1	2.9	47	0	41	12	0	0
10. Not Elsewhere Classified	18.4	22.5	---	---	0	14	35	17	32	2
	---	---	3.8	10.5	33	27	38	2		0
TOTALS	100	100	100	100	14	18	31	19	13	5
				CUM % Nos.	14	32	63	82	95	100

or sales dollar volume because of differences in applications and design. For example, as will be seen in Chapter 7, a 650 sq. ft. collector could have a cost range of 2 to 10 $/sq. ft. or more.

The analyses presented above have been directed to: (a) an estimate of the total number of fabric filters in use and their cost to enable a reasonable estimate of the likely yield from research and development investment; and (b) an estimate of the distribution of the use of fabric filters (categories, sizes, and numbers) to establish the state-of-the-art and gap areas in applications to be identified with research needs. For maximum confidence it would be extremely valuable to have additional data on each application, or on a reasonably representative sample. Since the number of fabric filter installations is probably in excess of 100,000, a representative sample would require at least several hundred installations within the ten use categories to characterize adequately the range of variables in each process and each operation.

Limited surveys of this kind have been made including a number of NAPCA programs, recently completed or presently underway, and an independent survey of the Non-metallic Minerals Industry reviewed in Appendix 1.6.[42] NAPCA systems studies completed as of early 1970 include: Category 1, Incineration (Arthur D. Little, Inc.); 2, Pulp and Paper (A.A. Sirrine); 8, Iron and Steel (Battelle Memorial Institute); 9, Non-Ferrous Metallurgy (Arthur G. McKee). Others are planned, programmed or in progress. Each of the completed studies present substantial detail of the technical requirements for particulate pollution control; e.g. operations, processes, gas temperatures and flows, particulate rates, etc. However, it isn't possible from a study of these reports, to obtain technical details about more than a few variables associated with specific fabric filter installations.

Technical aspects of the utilization of fabric filters have been described for many types of applications in the "Air Pollution Engineering Manual"[43] based on typical installations in Los Angeles County. Source inventory data which might be used to estimate the whole population is not given, however. Similar presentations have been prepared by and for the iron foundry industry. It has not been possible to deduce the extent or magnitude of controls for major application categories from these manuals.

1.5 SUMMARY

Fabric Filter dust collectors are one of 4 major types of particulate control equipment. They are highly efficient, economically attractive in many applications and are widely used throughout industry. Their origin is traceable back many centuries and some of the initial design approaches developed in the late 19th century are still found in new installations. Within the last 20 years, however, innovations have been made which have been widely accepted and which have resulted in significant improvements in system performance.

There are now over 100,000 fabric dust collectors in use, in hundreds of different dust applications and over a size range of six orders of magnitude.

Approximately 50 U.S. manufacturers are now supplying in the vicinity of 7,500 fabric filters a year with sales of $25 to 50 million. The fabric for these filters has a similar sales volume. Apparently, as a direct consequence of this broad supply of manufacturers and the fact that no single manufacturer has a large percentage of the market, there is an economically based reluctance to undertake the research programs necessary to fully exploit the applications potential of fabric filter systems.

The analyses presented in this volume, and the conclusions derived therefrom, have been hampered by a lack of available and reliable information. As will be shown later, better fabric filtration equipment is needed for both present and potential applications. This need may justify a more penetrating survey of the present art from any of several standpoints - performance of fabrics, methods of cleaning the fabric, varieties of dust, similarities of application, manufacturers' R & D experience, etc. In fact any such survey must cover several of these standpoints to some degree in order to be effective, as they are so interrelated.

The principal conclusions which we have reached based on foregoing discussion and tabulations, and the information presented in the appendices, are:

1. The fabric filter market in 1969 including both hardware and fabric sales is estimated to have been about $\$50 \times 10^6$. It may very well have been twice this as a result of conservative reporting and estimating.

2. Historically the fabric filter market has approximately doubled every ten years and indications are that the recent growth rate has been about the same, although the growth rate of all air pollution control equipment has been approximately twice this.

3. There are now approximately 50 manufacturers of fabric filter equipment, and the number is increasing at the rate of 2 or 3 per year.

4. Fabric sales are a large proportion of the total fabric filtration market.

5. Because the fabric filter industry is composed of a large number of producers of equipment, each producer has a small portion of the market and apparently cannot invest more than a modest amount on research. (As will be seen in Chapter 4, a similar comment applies to the manufacturers and processors of filter fabrics and fibers.)

6. Research and development efforts tend to be concerned with specific markets, applications problems, and equipment improvement, rather than with basic engineering investigations which might result in significant advances in fabric filtration technology.

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CHAPTER 2

FABRIC FILTER TECHNOLOGY

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FABRIC FILTRATION TECHNOLOGY

2.1 INTRODUCTION

The purpose of this chapter is to relate the pressure drop, efficiency and performance characteristics observed in operating fabric filters to the underlying physical and chemical phenomena of the collection process. The latter may be examined at three analytical levels, as outlined in Table 2.1, macroscopic, microscopic and molecular.

From the macroscopic point of view, the filtration process can be considered to consist of a collection phase, in which dust is removed from the gas that penetrates the filter media, and a cleaning phase during which the gas flow through the media may or may not be interrupted depending on the cleaning system. Analysis of the process is presented below, with respect to a single bag element, by considering the macroscopic aspects such as the fabric material type, geometry, weave and treatment; and by the form and transmission characteristics of the application of cleaning energy including frequency, amplitude and duration. The performance of the complete collector and further characteristics of fabric and cleaning on single bag collectors are discussed in Chapters 4 and 6.

The underlying features of the filtration and cleaning processes have been approached at the microscopic level by consideration of fluid-particle mechanics, deposition phenomena, accumulation structures, particle removal efficiency and resulting pressure drop. The special single particle-collector case, essentially a two-body problem for which many theories have been developed, remains under continuing investigation. Analysis of collection and pressure drop in a practical multi-particle system with cake formation, however, is less well-developed.

Processes at the molecular level include effects of absorbed or adsorbed vapors, humidity, adhesion, cohesion and electrostatic charge on particles and the fabric filter elements. Analyses of these effects which are properly in the domain of colloid and interfacial phenomena,

TABLE 2.1

ELEMENTS IN THE ANALYSIS OF FABRIC FILTER TECHNOLOGY

Level of Analysis	Typical Dimension	Elements of Analysis
MACROSCOPIC	$> 10^0$ cm	Fabric design,material, yarn type, weave, finishes, bag configuration (length/diameter), design, suspension, cleaning process variables (type, frequency, amplitude, duration, repetition rate, energy input pattern and amount), flow patterns in bag, deposit relationship to pressure drop, macroscopic deposit flow property (drag).
MICROSCOPIC	$\sim 10^{-2}$ cm	Yarn characteristics, treatments, (texturizing, bulking, napping, needling, felting); deposition of particles on individual yarn elements, deposition on previously deposited particles, structure of cake; deposition in and on cake; compaction of cake, collapse, reorientation; reentrainment in flow; cleaning, adhesion of individual particles and of aggregate structures, size of deposit structures removed, mass-energy-force relationships in cleaning.
MOLECULAR	$< 10^{-5}$ cm	Fiber surfaces, particle surface, adhesion, humidity effects, electrostatic charge, adsorption, forces and phenomena of attachment arising from molecular considerations.

are summarized in this chapter, in forms suitable for engineering estimates. The approach taken in this chapter is to discuss the interrelationships between these molecular and microscopic processes and the observable (macroscopic) performance of a single filter element (bag), i.e., pressure drop and efficiency, fabric life and fabric filtration costs.

2.2 DESCRIPTIVE AEROSOL TECHNOLOGY

2.2.1 Particle Size, Concentration, and Terminology

An aerosol is defined as a stable system of solid or liquid particles suspended in a gas. If the gas is relatively of turbulence and essentially motionless, stability obtains only when particles are about 1 μm in diameter and of unit density. In the case of highly turbulent and fast flowing gas streams, however, particles in the 100 μm diameter range may remain in suspension. Thus, in the context of this discussion, use of the term "aerosol" refers to particulate dispersions which effectively undergo no change in particle concentration or size properties during transit to a dust collection device. A particle is considered to be a single continuous unit of solid or liquid matter, composed of many molecules and hence, much larger than molecular size (~ 0.001 μm)*. A particle may also consist of two or more unit structures (agglomerates) held in contact by interparticle adhesive forces, such that it behaves as a single entity while aerosolized. Typical sizes of particulate dispersions of concern are shown in Figure 2.1. Sizes range from macromolecular to about one-tenth millimeter (100 μm) in diameter with an approximate range of mass from 10^{-21} to 10^{-6} grams per particle. The maximum size that remains suspended for appreciable periods depends upon the relative magnitudes of the fluid forces acting upon the particle and the external forces tending to remove particles from the system.

The presence of a dust particle represents a local discontinuity which modifies the continuum properties of the gas, e.g., viscosity (μ), density (ρ), and thermal conductivity (κ). Alterations of the gas properties may be significant if the particle concentration is high or

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*μm = micrometer, 10^{-6} m (formerly micron, μ)

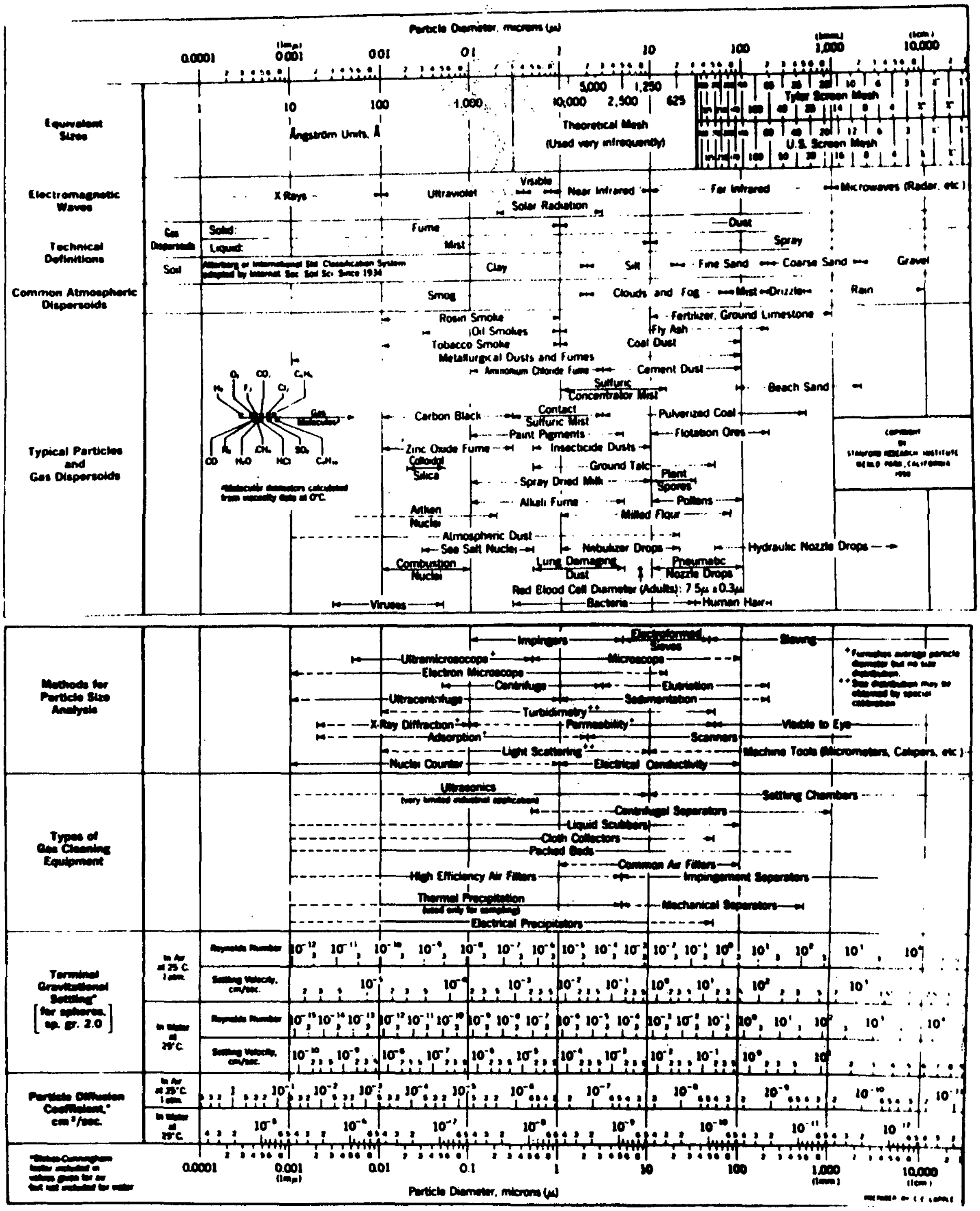

Figure 2-1. Characteristics of Particles and Particle Dispersions (Courtesy Stanford Research Institute)

if the fluid velocity gradient is large. Figure 2.2 presents the concentrations encountered in several industrial and atmospheric environments.[2]

A concentration of 100 gm/m^3 (typical of that found in pneumatic conveying systems and representing about 10 percent of the supporting air density) will decrease the air viscosity by about 10 percent. Similar behavior is observed in hydrosol systems. However, the more common concentrations encountered in filtration practice (~ 10 $grams/m^3$) will have very little measurable effect on the continuum properties of the fluid as far as macroscopic analysis of motion, matter and energy are concerned, except in systems where the rate of change of energy is high.[4,5,6,7]

Aerosol behavior can be considered as a part of the general study of disperse systems in fluids. Analysis of the physical characteristics and kinetic properties of an aerosol system will contain both the properties of the particles (e.g., size, shape, density) and the continuum properties of the fluid. For particle size approaching the average intermolecular distance in the gas (molecular mean free path, λ^*), motion of the particle with respect to the fluid is greater than estimated from its continuum behavior. Analysis of the motion will contain a slip correction factor for small particles (< 1 μm at NTP) or at reduced gas pressure, depending upon the particle Knudsen number, $K_n = 2\lambda/D_p$.

An important characteristic of particulate systems, from the physical and chemical points of view, is the greatly increased area per unit of mass available for interaction with surfaces as in adhesion and with molecular constituents of the gas as in adsorption and catalysis. Two or three phases coexisting may lead to chemical reaction at high rates, combustion and explosion, heterogeneous reactions, catalysis, condensation, health effects, etc. Interfacial characteristics of a particulate system are also of interest in the effectiveness of inter-particle contacts, molecular accommodation, adhesion and interactions with boundaries.

A particle is defined above as a discrete kinetic unit of solid or liquid matter, and an aerosol as a system of particles suspended

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$^*\lambda = 65 \times 10^{-8}$ m, NTP

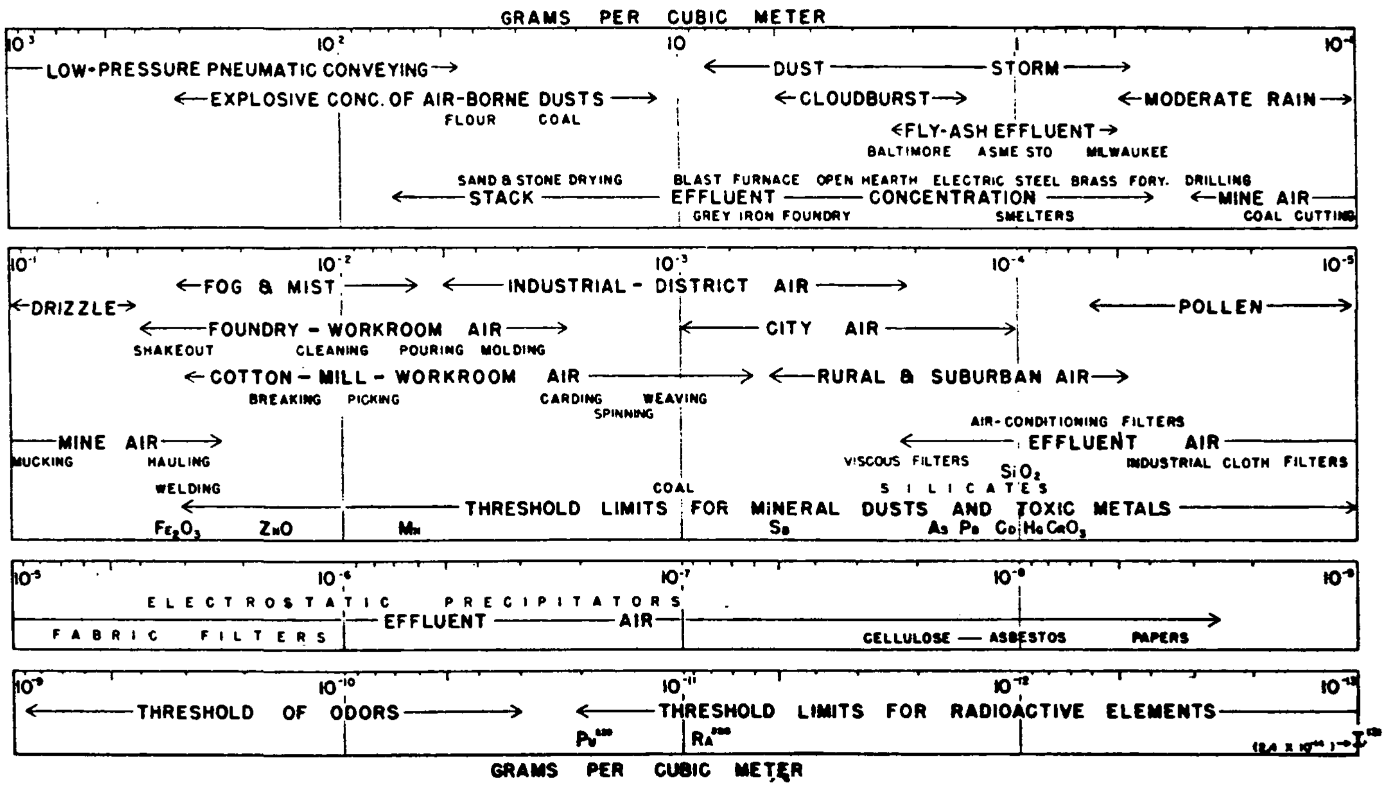


Figure 2.2. Typical Concentrations of Particulate Suspensions
(From First and Drinker, Ref. 2)

in a gas. Aerosol systems (see Figure 2.1) are usually classified by common terms relating to particle origin or occurrence, such as:

- Dusts - solid particles arising from mechanical disintegration or resuspension of solid materials in comminution processes (drilling, crushing, grinding, pulverizing), in which the individual particles usually have the same chemical composition as the parent material. Sizes range from macroscopic (visible powders) to microscopic, and shape is determined by the crystalline nature of the parent substance.

- Fogs, mists, clouds - liquid particles formed by mechanical disintegration of a liquid or by condensation of molecular constituents in gas upon suitable nuclei. Size range is generally above one micron. When they become larger than 50 to 100 μm by collision and coalescence, they tend to fall as drizzle or rain, or if the gas is saturated, the particles may persist.

- Fumes - arise from combustion, sublimation or distillation processes; particle composition is frequently different from the bulk parent material through oxidation or hydrolysis in the gas. Size is generally below one micron and typical fumes such as iron oxide or zinc oxide from metallurgical operations will coagulate rapidly to form loose aggregate particles. Sizes formed will vary with temperatures, air motion, or rate of cooling.

- Smoke - visible material arising from combustion of organic materials typically; particles may consist of fine solid inorganic ash constituents with condensed carbonaceous pyrolysis fragments such as tarry liquids of low vapor pressure. Size is generally below 1 μm. Chimney smoke from combustion of fossil fuels may also contain fly ash or soot flakes of relatively larger sizes, above 1 μm, depending on the combustion conditions, fuel use pattern, or particle deposition and reentrainment in the flue gas passages.

- Smog - deonotes an aerosol of the type associated with atmospheric pollution that consist mainly of a combination of smoke and fog. Photochemical smog implies a complex aerosol formed from condensation of gaseous hydrocarbons from combustion products of liquid fuels, through chemical reaction processes in urban atmospheres, potentiated by solar radiation, and has typical biological manifestations (eye irritation, plant damage) in addition to visibility reduction.

- Atmospheric dust or the atmospheric aerosol - is the sum of all types of particulate matter suspended in the atmosphere (e.g., haze), including many of the components above, with a wide variety of chemical constitutents depending upon source and history. Size is typically submicron to about 10 μm for well mixed, aged material. In addition, local anthropogenic sources may release relatively large particles that may not remain airborne over large distances. Injection of large quantities of material into the atmosphere at high altitudes (stratosphere, > 3 x 10^4 ft) may give rise to a large-sized component sufficient to appear throughout the global circulation. Natural sources of atmospheric particles include sea spray solid residues; smoke from forest fires; blown dust from prairie erosion; dust from volcanic eruption; and pollen, spores and plant exudates.

2.2.2 Significant Characteristics of Particles with Respect to Filtration

2.2.2.1 Particle Size.- The size of particles and their chemical composition, physical state, and concentration are major variables in industrial gas cleaning systems. Most natural aerosol particles are polydisperse* with respect to size, and frequently with respect to shape, density, and chemical composition. In some special situations, such as the preparation of sediments, glass spheres, and powdered metals or resins, one may encounter size distributions which approach the monodispersed state. Methods for characterization of the size spectra which were indicated earlier in Figure 2.1, are summarized in the following discussion.

Techniques and size analysis apparatus for area and stack measurements are described in more detail elsewhere.[8,9] The most recent instrument available for fundamental particle size, surface, and composition spectral analysis is the scanning electron microscope.[8]

For many purposes in dust collector design, size analysis is performed with the Bahco** micro-particle analyzer which employs a centrifugal winnowing configuration to separate size fractions by aerodynamic behavior in a flowing gas stream. Other techniques in current use include centrifugation, sedimentation, and electrical resistance changes

*The terms polydisperse and monodisperse are often used to describe aerosols containing a range of sizes and a single particle size, respectively.

**H.S. Dietert Co., Detroit, Michigan. See also ASME Power Test Codes, PTC-28-1965.

(Coulter) in liquids, optical microscopy, and screen analysis with conventional and micromesh sieves.[8] Most of the available instruments have an effective lower limit of about 1 μm, as shown in the following summary table:

Sizing Technique	Size Capability Range
Common Testing Sieves	20 mesh (= 840 μm) to 325 mesh (= 44 μm)
Micromesh Sieves	~5 μm - 50 μm
Sedimentation, Elutriation	> 50 μm
Cyclones, respirably size selective	> 50 μm
Centrifugation - Whiting, MSA	> 5 μm
Bahco Micro-Particle	≳ 1 μm
Aerosol spectrometers, Goetz, Stober	0.2 - 10^2 μm
Light microscope	> 0.2 μm
Electron microscope	0.001 → 10^2 μm
Scanning electron microscope	> 0.05 μm

Size analyses below 1 μm are usually performed with an electron microscope, which provides resolution down to approximately 0.001 μm.

Particle size refers to some characteristic dimension of the physical geometry, as for example a diameter measured in a consistent manner. It may, however, reflect the particle behavior in a fluid, as for example in sedimentation, from which a diameter can be inferred.

The particle size distributions of many naturally occurring aerosols tend to be somewhat similar, because of the commonly acting mechanisms of particle formation and removal. On the other hand, the size distributions of particles generated by industrial processes are highly variant, depending on the source and age of the material. Size distributions are frequently described by one or more of the following statistical parameters, among others:

- Range - the size of the largest and the smallest particle.
- Mean size - the arithmetic average sizes of all particles.

- Median size (by number) - that size for which there are an equal number of smaller and larger particles.
- Median size (by weight) - that size for which the weight of all smaller particles equals the weight of all larger particles.
- Standard deviation <u>or</u> a geometric standard deviation - a measure of the range with respect to average particle size (see any standard statistics text).

It is important that there be no misunderstanding as to which diameters (mean or median, by number, weight or surface) are used to characterize a dust since their numerical values can easily vary by a factor of ten,and up to one hundred or greater,with highly polydisperse materials.

2.2.2.2 <u>Shape and Structure</u>.- Individual particle shape depends upon the methods of particle formation. The shapes of particles formed by disintegration operations (as in comminution, attrition, pulverizing, grinding) are determined largely by the nature of the parent material. Usually, they appear as irregular crystalline granules. Particles formed by condensation processes, from vapor phase reactions, e.g. metallurgical fumes and smokes, or from high temperature combustion processes, e.g., fly ash, are frequently regular in shape (spherical, cubic). Subsequent changes take place in particle shape and structure as a function of the history of the particle in its environment, and may include crystallization, hydration, collisions and coagulation, or chemical reaction (condensation of moisture, oxidation) with gas phase constitutents. Spherical liquid particles produced by condensation may coalesce on contact to form larger droplets. Volatilization of metallurgical vapors proceeds simultaneously with oxidation, followed by condensation and solidification of primary particles ($< 10^{-2}$ μm) and further coagulation to form larger chain-like floccs of spheres or cubes (as with iron oxide, magnesium oxide). Carbon black is produced as soot from pyrolysis of liquid or gaseous hydrocarbons and involves vapor phase decomposition and condensation of molecular carbon to form small semi-graphitic spheres (10^{-2} - 0.5 μm), typical of condensation aerosols, with formation followed by rapid coagulation.

Particle size and particle structure are functions of the formation process and of concurrent and/or subsequent events. Therefore, changes in size and structure must be considered in the design or specification of fabric filters, especially if the material to be collected is freshly-formed or likely to undergo chemical or physical changes while on the fabric, making subsequent removal difficult.

Typical shapes and observed concentrations[10] of airborne materials likely to be encountered in urban atmospheres are shown in Table 2.2. A more comprehensive presentation of morphological features and other characteristics of some 500 specific dusts is presented in McCrone's Particle Atlas.[11] Light optical and electron photomicrographs of typical particulate materials are shown in Figures 2.3, 2.4 and 2.5.[12,13,14]

The following text discusses analytical solutions for particle capture mechanisms and for pressure drop, based on models for spherical particles. It is evident from the photomicrographs that particles likely to be encountered in practice are seldom uniform spherical entities, but rather are irregular granular or highly chain-like floccs. These natural forms may be compared to those cited in Table 2.2. The shape and structure of a particle will influence its collection, its interaction with the fabric, and its behavior as an element in a granular deposited layer or cake. Characterization of the size, shape, and structure for most particles of concern requires costly and sophisticated analysis and little has been done to relate properties of the particulate system to behavior in a fabric filter deposit, or to effects on filter performance. Most dry dusts from manufacturing operations involving product handling, venting, and the related processes consist of highly aggregated systems of single particles. Since they are often compacted so that their envelope shapes are approximately spherical, their aerodynamic behavior can be predicted adequately from spherical models. Most analytical treatments are based on resistance forces arising from spherical shape. Irregular shapes will experience greater resistance forces which counter the gravitational force and lead to reduced settling velocity.

2.2.2.3 Coagulation.- Formation of fine solid particles in high concentrations by vapor phase condensation is generally followed by rapid coagulation. Coagulation occurs in all aerosol systems at a rate

TABLE 2.2

MAJOR SHAPES OF AIRBORNE PARTICLES AND TYPICAL CONCENTRATION RANGES*

Shape	Appearance	Kinds	Wt % in dust Range	Wt % in dust Average	Shape factors** α_s	Shape factors** α_v
spherical		smokes, pollen, fly ash liquid droplets	0-20	10	π	$\pi/6$
cubical		salt crystals, MgO indiv. part.				
irregular-cubical		mineral dusts, cinders	10-90	40	3-8	0.2-0.5
flakes		minerals, graphite epidermis, mica	0-10	5	1.5-2	0.02-0.1
acicular, spiny		zinc oxide, ammonium sulfate				
fibrous		lint, plant fibers, asbestos, talc, fiber glass, man-made fiber	3-35	10	$\pi D_f L$	$\frac{\pi}{4} D_f^2 L$
condensation floccs		carbon smokes coagulated metal oxide fumes, e.g. iron oxide	0-40	15	0.2-2	0.01-0.1

*from Whitby and Liu, Ref. 10 with additions

** α_s = surface shape factor

α_v = volume shape factor

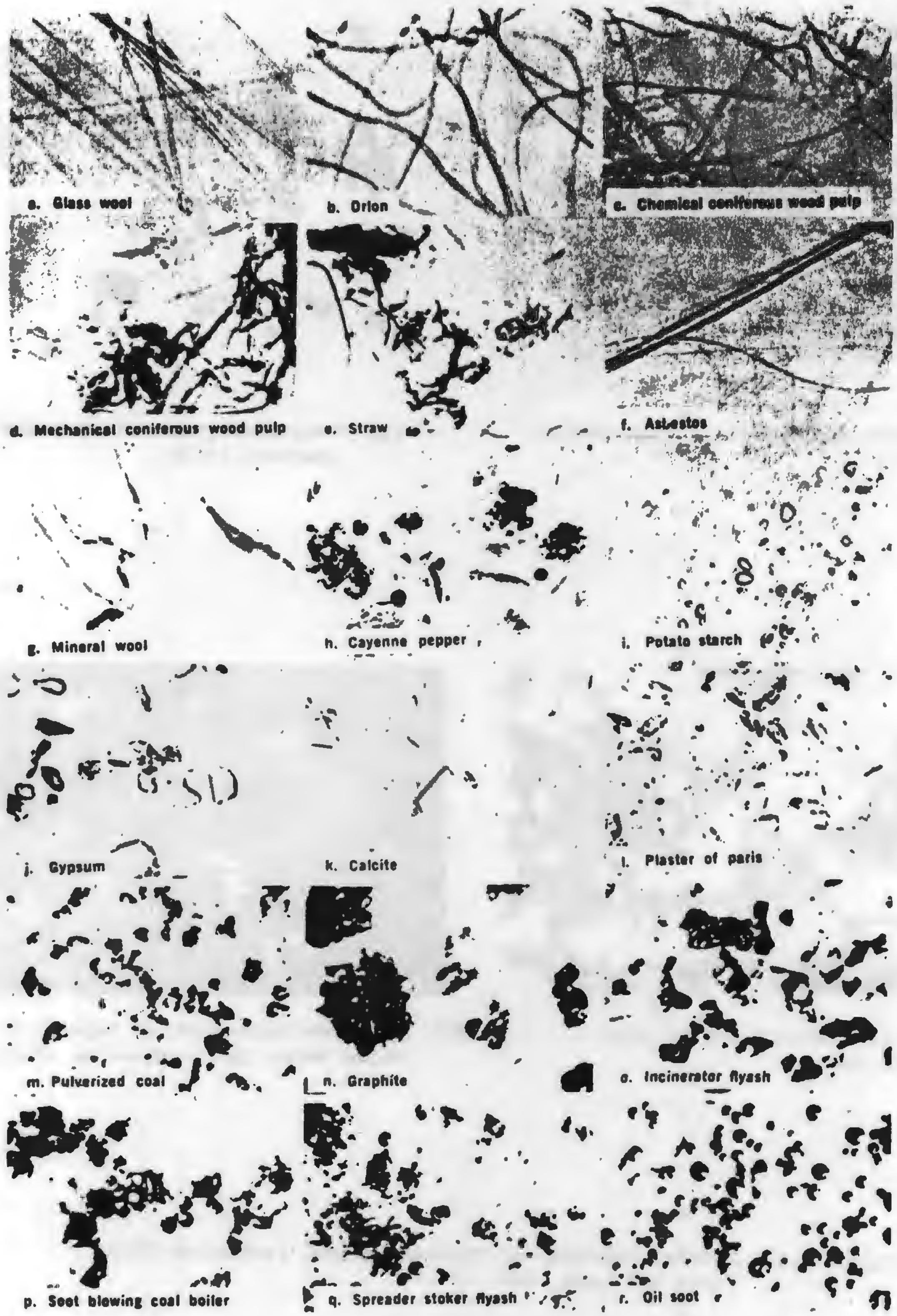
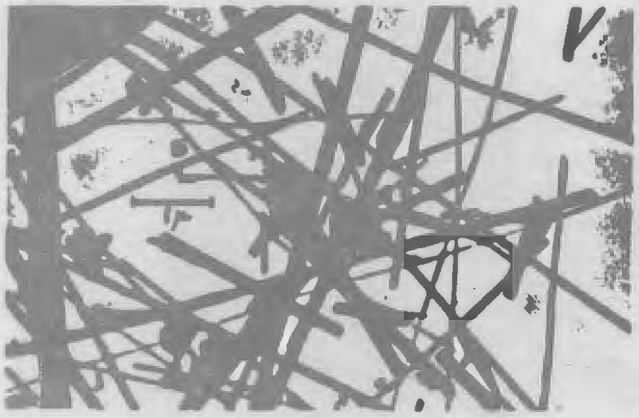
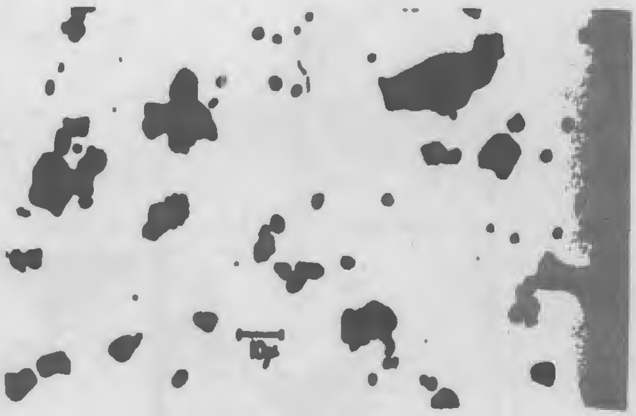


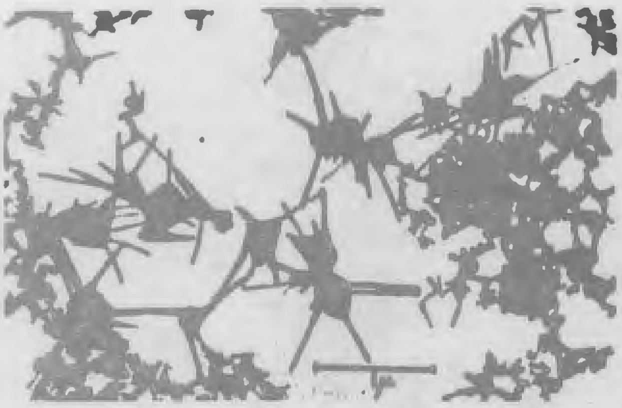
Figure 2.3. Photomicrographs of Various Atmospheric Particles (from McCrone and Saltzenstei, Ref. 12).



(a) Electron micrograph of crocidolite needles



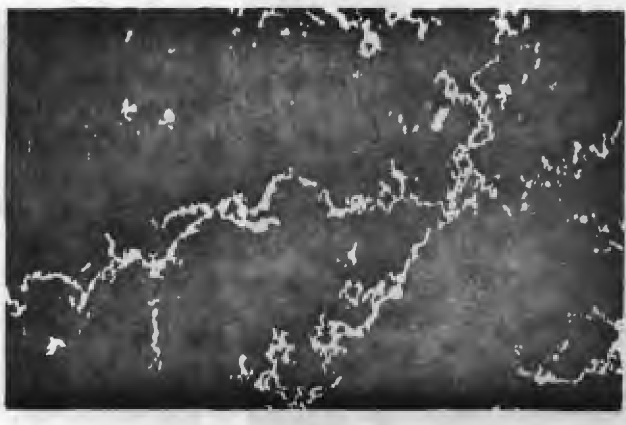
(b) Photomicrograph of coal dust (Watson, 1953)



(c) Electron micrograph of zinc oxide smoke

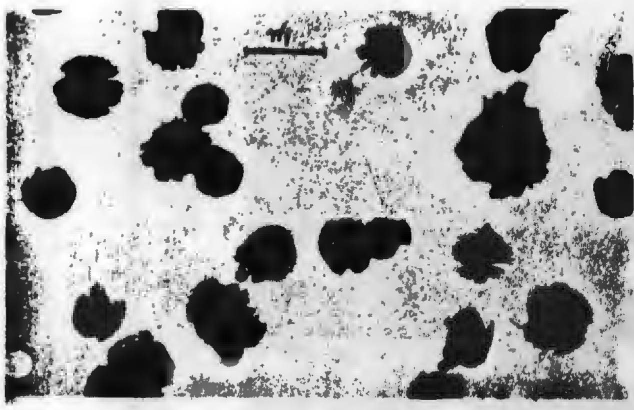
(d) Electron micrograph of magnesium oxide smoke (gold-palladium shadowed)

Figure 2.4. Photomicrographs of Typical Aerosol Particles (From Green and Lane, Ref. 13).



(e) Electron micrograph of iron oxide smoke (gold-palladium shadowed)

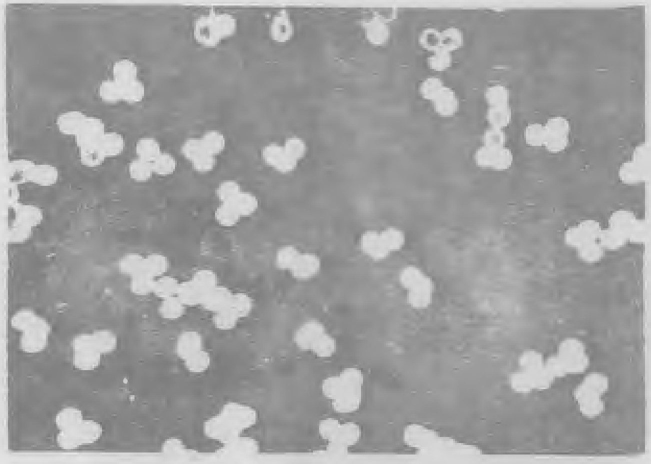
(f) Electron micrograph of gold shadowed polystyrene particles formed by spraying 1% solution in carbon tetrachloride and evaporating the droplets.



(g) Electron micrograph of methylene blue particles showing crystallization

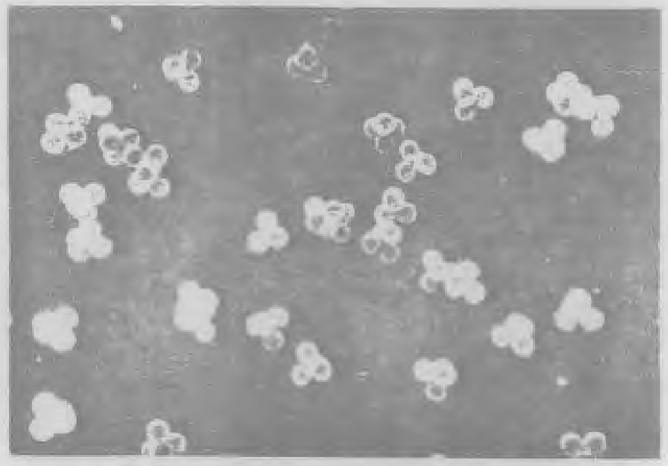
(h) Electron micrograph of sodium chloride crystals formed by spraying from solution in water and evaporating the droplets (gold palladium shadowed)

Figure 2.4. Photomicrographs of Typical Aerosol Particles (Continued).

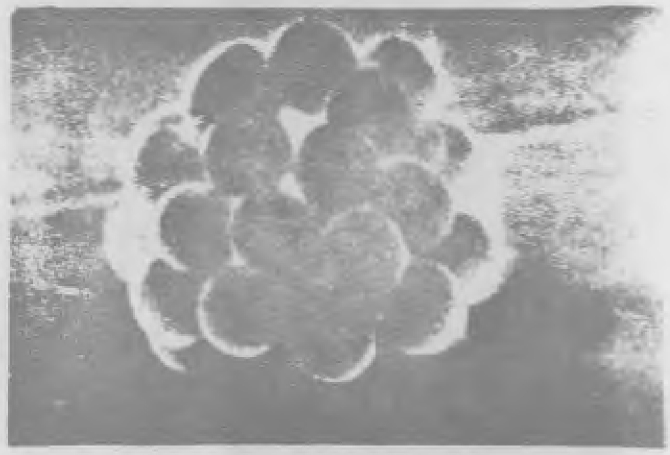


(a) Micrograph of triplet aggregates of latex spheres of 7.9 x 10^{-5}cm diameter (Stereoscan scanning electron microscope)

(b) Micrograph of octahedral aggregates of six latex spheres of 7.9 x 10^{-5}cm diameter (Stereoscan, scanning electron microscope)



(c) Micrograph of tetrahedral aggregates of four latex spheres of 7.9 x 10^{-5}cm diameter (Stereoscan scanning electron microscope)



(d) Micrograph of a giant aggregate of latex spheres of 7.9 x 10^{-5}cm diameter (Stereoscan, scanning electron microscope)

Figure 2.5. Scanning electron photomicrographs of aggregrates of monodisperse test particles used to determine density and aerodynamic diameter. (From Stöber et al., Ref. 14).

proportional to the concentration of particles and, as shown above, has a marked effect on particle mass, size, shape, and structure. Coagulation arises as a consequence of relative motion and collisions among individual particles. As will be discussed below, impact forces between small particles and surfaces are sufficiently large so that collisions usually result in the formation of an adhesive bond. For particles less than about 1 μm, the principal phenomenon promoting contact arises from Brownian (thermal) motion of the particles caused by impact with the suspending gas molecules.

For simple systems of monodisperse spherical particles, the rate of coagulation is[13]

$$- dn/dt = Kn^2 \qquad (2.1)$$

where n is the particle number concentration per cc, K is the coagulation coefficient, and t is the time.

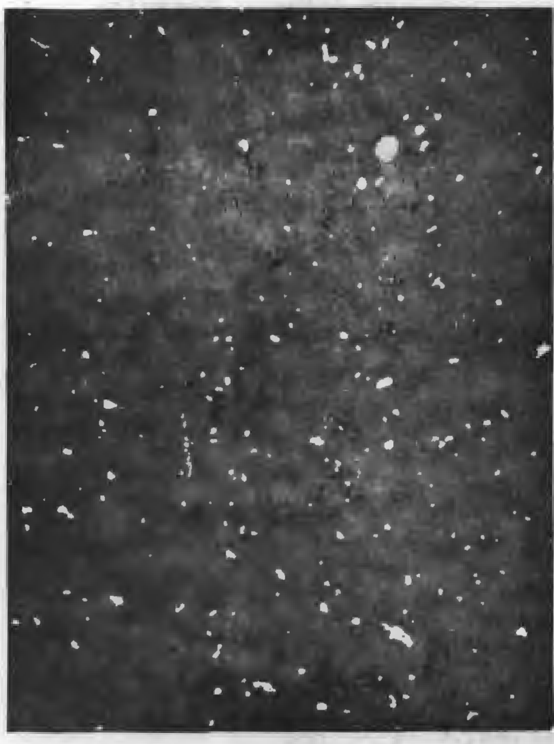
For thermal motion of the particles,

$$K = 4\ k\ T\ C_c/3\ \mu_f \qquad (2.2)$$

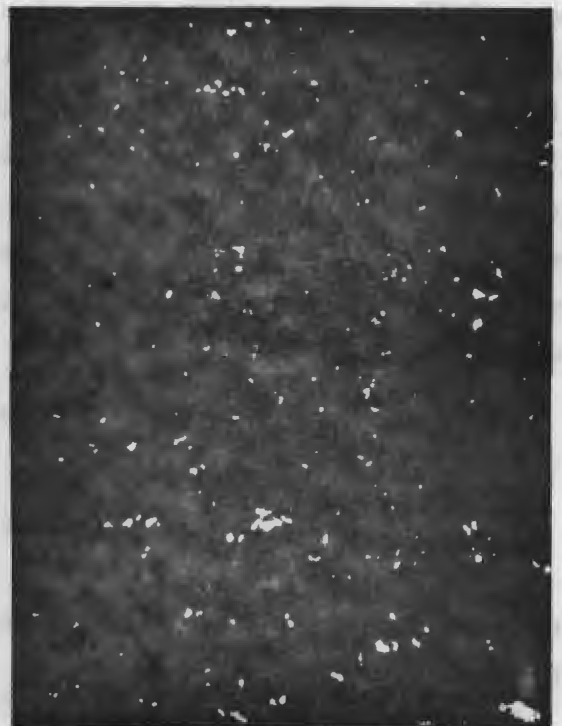
where k is the Boltzmann constant, T the absolute temperature, μ_f the fluid viscosity, and C_c the Cunningham-Millikan slip correction factor. Integration yields the expression

$$\frac{1}{n} - \frac{1}{n_o} = \frac{4kT}{3\mu_f} \cdot C_c \cdot t \qquad (2.3)$$

for the concentration particles, n, at any time, t, with the initial condition of $n = n_o$ particles at the onset of coagulation, t = 0. The theoretical value of the coefficient $(4kT/3\mu_f)$ has been found to be in general agreement with measured values, to within a factor of 2, (of the order of 5×10^{-8} per cc-min) for particles in the range $0.1 < D_p < 1$ μm. For $t \sim 10^2$, the particle concentration must be $> 10^6$/cc for substantial coagulation to occur. The experimental verification of thermal coagulation is illustrated in Figure 2.6, taken from the pioneering studies of Whytlaw-Gray and Patterson.[15] This figure shows the large, loose,



9 minutes after dispersal



29 minutes after dispersal

49 minutes after dispersal

244 minutes after dispersal

Figure 2.6. Coagulation of Metal Oxide Fume (From Whytlaw-Gray and Patterson, (Ref. 15)).

irregular masses of chain-like aggregates formed from metal oxide smokes of cadmium and zinc oxide. Less tendency to form string-like complexes was observed in oxides of lead, copper, magnanese and chromium, somewhat greater in iron, while oxides of magnesium, aluminum, and antimony appeared similar to clusters shown in Figure 2.6. Later investigations utilizing electron microscopy have established the metal oxides structures as large loose irregular stringy chains as shown in Figure 2.4.[13]

These observations are doubly significant in the study of fabric filter technology. First, the capture of these large aggregate particles by fibrils and by the previously deposited granular cake should be substantially greater than would be estimated on the basis of the individual particles forming the complex. Secondly, these aerosolized aggregate structures are very similar to the kinds of aggregates formed upon collection of particles in fabric and granular filters. Typical material removed by the cleaning of fabric filters also appear as highly complex structures.

More recent analytical treatments of coagulation for aged disperse systems are available.[16,17] These have led to a model of the particle size distribution for the coagulating aged atmospheric aerosol which has been experimentally verified.[18]

The process of coagulation and the resulting structure of aerosol aggregates is influenced by several factors including particle shape, electrical charge on the interacting particles, adsorbed vapors, and fluid shear gradients as a consequence of stirring or mixing in the aerosol, sonic fields, and also because of sedimentation of larger particles or collision of particles on walls or collection on obstacles in the flow. The production of aerosol aggregates as an aid to the build-up of particle size to make the particles easier to remove from suspension has been investigated. The use of filters as agglomerators has been shown to be practical in the filtration of both solids and liquid aerosols.

2.2.2.4 <u>Density</u>.- Suspended particulate density is related to the method of formation and subsequent events. Initially dust formed by attrition of a solid will have the density of the parent material. However, if it undergoes subsequent surface oxidation or hydration, for example, its density will change. Particles formed by condensation processes undergo substantial coagulation, as shown above for metallurgical fumes such as ZnO, MgO, Fe_2O_3, or carbon blacks. The density of these agglomerates will be less than that of the particle materials due to air inclusions, as shown in Tables 2.3[15] and 2.4.[19] Density of these aggregates is about one-tenth of the density of the parent material because of encapsulated void volume (up to 90%). Other recent studies of the aerodynamic behavior or particle aggregates include those of Stöber et al.,[14] Johnstone and Sehmel[20] (who confirmed the earlier finding for MgO given in Table 2.3) and Kunkel,[21] and Megaw and Wiffen.[22] Aerodynamic properties of fine fibrous particles are under intensive investigation in conjunction with observations of excess numbers of these particles in the lungs of urban dwellers.

Difficulties have been encountered in measuring the discrete particle densities of organic dyes used as test aerosols (uranine and methylene blue) according to Stein, Esmen and Corn,[23] Sehmel,[24] and McKnight and Tillery.[25] Inconsistencies in reported dimensions are attributed to differences in manner of generation, degree of drying, and sampling.

Fly ash particles from combustion of pulverized coal typically contain fused hollow spheres (cenospheres) having densities substantially below that predicted from material properties alone. These differences are of significance in predicting the atmospheric transport of released particulate materials from anthropogenic sources with respect to environmental effects. They are very important in predicting and interpretating fabric filter performance.

From a practical point of view, particle density can be assumed to range from 1 to 0.1 that of the true density of the parent material. Estimates of density and particle size of aerosol aggregates are required in order to relate particle mass to particle collection in inertial systems and to predict the effects of acceleration and fluid forces in the cleaning of fabric filters.

TABLE 2.3

PARTICLE DENSITIES FOR AGGLOMERATES*

Material	Floc Density g/cc	Normal Density g/cc
Silver	0.94	10.5
Mercury	1.70	13.6
Cadmium Oxide	0.51	6.5
Magnesium oxide	0.35	3.65
Mercuric chloride	1.27	5.4
Arsenic trioxide	0.91	3.7
Lead monoxide	0.62	9.36
Antimony trioxide	0.63	5.57
Aluminum oxide	0.18	3.70
Stannic oxide	0.25	6.71

*From Whytlaw-Gray and Patterson, Ref. 15.

TABLE 2.4

TYPICAL DENSITY RATIOS FOR AEROSOL PARTICLES AND PRECIPITATED SMOKES*

Material	Density Ratio**	Reference
PbO	0.089-0.049	Kohlschutter and Tuscher (1921) Precipitated smokes
Sb_2O_3	0.11	Kohlschutter and Tuscher (1921) Precipitated smokes
Al_2O_3	0.19	Kohlschutter and Tuscher (1921) Precipitated smokes
As_2O_3	0.049	Kohlschutter and Tuscher (1921) Precipitated smokes
NaCl	0.045	Moffat and McIntosh (1957) Precipitated smokes
MgO	0.064-0.145	Johnstone (1961) and Whytlaw-Gray and Patterson (1932) Aerosol Particles
$HgCl_2$	0.115-0.517	Whytlaw-Gray and Patterson (1932)
Au	0.0109-0.34	Whytlaw-Gray and Patterson (1932)
W	0.07	Johnstone (1961)

*From Beekmans, Ref. 19.

**Ratio of observed particle densities to the true density of the material, i.e., solids fraction, α. This ratio for a material composed of equal, randomly packed spheres is 0.61, i.e., 39% porosity, $\epsilon = 1-\alpha$.

A fabric filter collector reduces a gaseous dispersion of particles to a powder mass. The porosity of the powder (void fraction), $\epsilon = 1 - \alpha = 1$ - bulk density/true density) affects the collected cake pressure drop through its effect on permeability. Powder bulk density and porosity data for a variety of materials are given in Tables 2.19, 2.20, and 2.21.

In summary statements of aerosol size properties (dimensions alone) are not adequate for prediction of particle aerodynamic behavior or for estimation of filter cake porosity. Unless the particles are of reasonably regular shape, the size, shape, and structure must be considered simultaneously to explain physical measurements.

2.2.2.5 Surface Area.- The large amount of surface area per unit mass (specific surface) is a characteristic feature of dusts, powders and aerosol systems. For example, a cubic centimeter of unit density material distributed as 1 μm spheres will have a specific surface of 11.5 m^2/gram. Surface areas of some common mineral dusts are given in Figure 2.6a.[27] Fine particulate matter, which may have specific surface areas ranging from 10^{-2} m^2/gram (sands) to 10^3 m^2/gram (carbon black), provide extensive area for chemical and physical reactions with gas phase constitutents. Materials of practical interest are usually found to have greater surface areas than those predicted by geometrical considerations alone for the reason that such considerations do not ordinarily take surface roughness or interstitial surface into account.

Organic and inorganic combustible materials may burn or explode when finally subdivided. Effects of particle characteristics (shape, size, and concentration) on the intensity of explosions for a wide variety of materials of technical interest have been presented by Hartmann, Nagy and co-workers at the U.S. Bureau of Mines.[29-35] Hartmann's summary of earlier (1916-1957) Bu. Mines studies of explosive characteristics of representative dust dispersions is given in Table 2.5.[36] These studies indicate that explosibility is inversely proportional to particle size, as illustrated in Figure 2.7.[32] Minimum explosive concentrations in air are in the range of 10 to 100 grams/m^3 (10 to 100 oz/10^3 ft^3 or 4.3 to 43 grams/ft^3), c.f. Figure 2.2. For the aluminum data shown in

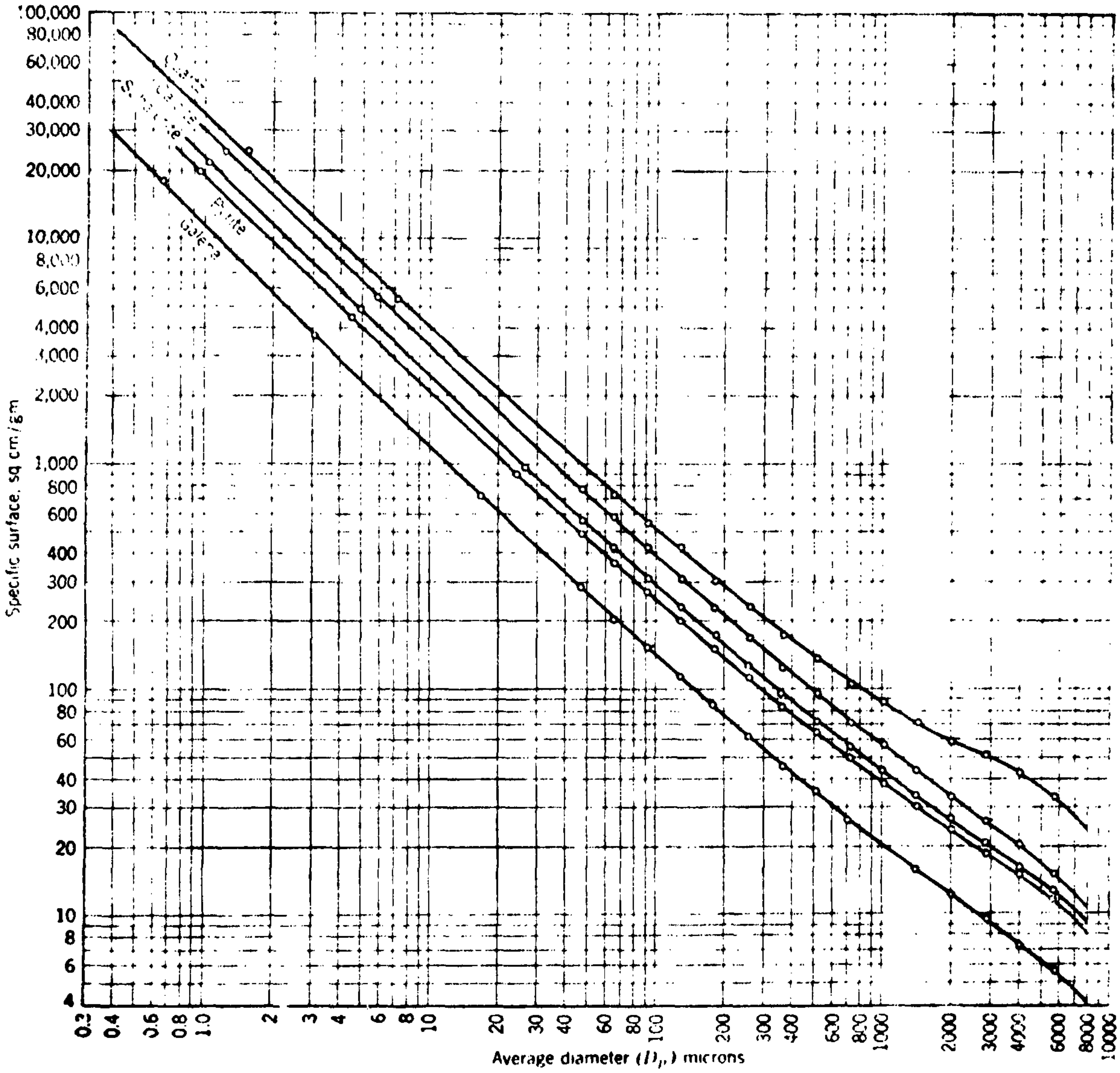


Figure 2.6. Measured specific surface of five common minerals (From G. G. Brown and Associates, Unit Operations, John Wiley and Sons, New York, 1950, by permission) (From Reference 27.)

TABLE 2.5

EXPLOSION CHARACTERISTICS OF VARIOUS DUSTS*

Type of dust	Ignition temp of dust cloud, deg C	Min spark energy required for ignition of dust cloud, millijoules	Min explosive concentration, oz per 1,000 cu ft	Max explosion pressure, psi	Rates of pressure rise, psi per sec		Limiting oxygen percentage to prevent ignition of dust cloud by electric sparks
					Avg	Max	
Metal powders							
Aluminum, atomized	640	15	40	90	3,500	10,000+	7
Aluminum, milled	550		45	70	2,000	4,250	
Aluminum, stamped	550	10	35	100	10,000	10,000+	4
Boron (86% B, 8% Mg)	470	60	135	90	900	2,500	
Iron, carbonyl	320	20	105	50	1,500	7,000	10
Iron, electrolytic	320	240	200	45	500	1,000	13
Iron, hydrogen reduced	315	80	120	45	800	1,750	13
Magnesium, atomized	600	120	10	80	2,000	5,250	3
Magnesium, milled	520	40	20	95	3,000	10,000+	†
Magnesium, stamped	520	20	20	80	3,400	10,000+	†
Manganese	450	80	125	50	1,300	2,750	15
Silicon	775	80	100	105	2,000	10,000	13
Thorium	270	5	75	50	1,400	3,250	†
Thorium hydride	260	3	80	60	2,100	6,750	6
Tin	630	160	190	35	500	1,250	16
Titanium	330	10	45	80	3,400	10,000+	†
Titanium hydride	440	60	70	95	3,800	10,000+	13
Uranium	*	45	60	55	1,600	3,500	†
Uranium hydride	*	5	60	45	2,900	6,250	0.5
Vanadium	500	60	220	35‡	200	300	13
Zinc	600	650	480	50	600	1,750	10
Zirconium	*	5	40	65	800	8,750	†
Zirconium hydride	350	60	85	60	2,400	8,750	11
Aluminum-cobalt alloy (60-40)	950	100	100	80	2,500	8,500	
Aluminum-copper alloy (50-50)	950	100	100	70	800	2,500	
Aluminum-nickel alloy (60-40)	960	80	190	80	2,600	10,000+	
Calcium-silicon alloy	540	220	600	75	400	10,000+	
Dowmetal	430	80	20	85	3,600	10,000+	†
Ferromanganese (1.4% C)	450	80	130	45	1,400	4,250	
Ferrosilicon (80% Si)	860	280	400	90	1,500	3,600	19
Ferrotitanium, low-carbon	370	80	140	55	2,200	9,500	13
Magnesium-aluminum alloy (50-50)	535	80	50	90	4,000	10,000+	†
Plastics							
Allyl alcohol resin	500	20	35	105	2,800	10,000+	
Butadiene-styrene resin	440	60	25	80	1,400	4,000	
Cellulose acetates	320	10	25	110	2,800	6,750	11
Cellulose propionate	460	45	25	105	1,600	4,750	
Coumarone-indene resin	520	10	15	85	2,800	8,500	14
Dimethyl terephthalate	570	20	30	90	3,100	10,000	
Gums (arabic, copal, etc.)	360	30	30	95	1,500	5,000	14
Lignin resin	450	20	40	80	1,700	4,750	17
Methyl cellulose	360	20	30	100	1,900	6,000	
Methyl methacrylate	440	15	20	100	500	1,750	14
Phenolic resins	460	10	25	80	1,700	6,000	14
Pine-rosin base resin	440	...	55	80	1,900	7,500	
Polyacrylonitrile	500	20	25	90	2,000	5,000	
Polyamide	500	20	30	90	1,800	7,000	
Polyester resin-glass fiber mixture (65-35)	440	50	45	85	2,200	6,000	
Polyether alcohol resin	460	160	45	65	500	1,000	
Polyethylene resin	410	30	20	80	1,500	3,500	13
Polyethylene terephthalate	500	35	40	90	1,600	7,500	13
Polystyrene	490	15	15	90	2,400	7,000	14
Polyvinyl acetate resin	520	120	35	75	1,200	3,000	
Rubber, synthetic, hard	320	30	30	95	1,100	3,000	15
Shellac	400	10	20	75	1,400	3,500	14
Styrene-maleic anhydride copolymer	470	20	30	80	2,300	9,500	
Urea resin	450	80	70	85	800	2,000	17
Vinyl butyral resin	390	10	20	60‡	500	1,000	14
Vinyl chloride-acrylonitrile polymer	530	15	35	85	1,700	4,500	
Vinyl copolymer resin	500	60	100	40	200	500	
Agricultural products							
Alfalfa	460	320	100	65‡	500	1,000	
Cellucotton	440	60	50	100	900	3,000	
Cinnamon	440	40	40	115	1,400	4,000	
Citrus peel, dehydrated	490	45	60	100	1,200	3,000	
Clover seed	470	80	60	60	400	1,000	15
Cocoa	420	100	45	62‡	550	1,200	
Coffee	410	160	85	50	150	250	13

*From Hartmann, Ref. 36.

TABLE 2.5 (Continued)

Type of dust	Ignition temp of dust cloud, deg C	Min spark energy required for ignition of dust cloud, millijoules	Min explosive concentration, oz per 1,000 cu ft	Max explosion pressure, psi	Rates of pressure rise, psi per sec		Limiting oxygen percentage to prevent ignition of dust cloud by electric sparks
					Avg	Max	
Corncob meal	400	60	30	120	1,200	3,750	
Cornstarch	380	30	40	110	2,200	6,750	10
Cotton seed	470	80	55	90	800	2,500	15
Dextrin, corn	400	40	40	105	1,800	7,000	
Furfural residue	440	40	40	105	1,400	4,000	
Grain dust	430	30	55	95	1,000	2,750	
Guar seed	500	60	40	105	1,400	4,750	
Lycopodium	480	40	25	85	2,300	7,000	13
Nut shells	420	50	30	105	1,900	4,000	
Onion, dehydrated	410	...	130	60‡	400	1,250	
Pea, dehydrated	560	40	50	100	2,100	6,000	
Pectin	420	35	75	110	1,800	8,000	
Potato starch	440	25	45	95	2,300	8,000	
Pyrethrum	480	80	100	80	600	1,500	
Rice	440	40	45	95	1,000	2,750	
Soybean	520	50	35	100	1,200	3,250	15
Sugar	350	30	35	90	1,600	5,000	
Tung	440	240	70	110	1,400	3,500	
Wheat dust	470	50	70	105	1,500	3,500	
Wheat flour	380	50	50	95	1,200	3,750	
Yeast	520	50	50	105	1,000	2,500	
Miscellaneous							
Adipic acid	550	70	35	75	1,200	2,750	
Aluminum stearate	400	15	15	95	1,200	4,750	
Aspirin	660	25	35	85	2,000	10,000+	
Bark dust (Douglas fir)	540	40	30	90	2,900	9,500	
Beryllium acetate	620	100	80	80	600	2,000	17
Calcium lignin sulphonic acid	590	100	160	80	600	2,000	
Carbon, activated	660	...	...	40‡	200	300	
Casein, rennet	520	60	45	65	400	1,000	17
Cellulose	480	80	55	100	1,100	2,750	13
Charcoal (pine wood)	620	...	...	40‡	200	250	
Coal, low volatile	635	...	...	45	300	600	
Coal, medium volatile	605	120	120	60	300	600	18
Coal, high volatile (Pgh. seam)	610	60	55	85	800	2,250	16
Coal, subbituminous	455	60	45	95	1,200	3,000	
Cork	470	45	35	100	2,000	5,500	
Diazoaminobenzene	550	20	15	90	2,900	10,000+	
Dinitro-ortho-cresol	440	80	25	55‡	1,300	2,250	15
Diphenyl	650	60	35	55	400	1,500	
Gilsonite	560	25	20	90	1,200	3,750	
Hexamethylenetetramine	410	10	15	100	2,400	10,000+	14
Lactalbumin	570	50	40	90	900	2,750	13
Lignite	440	60	45	90	800	2,750	15
Liver protein	520	45	45	80	800	2,250	
Napalm	450	40	20	85	1,000	3,000	12
Paraformaldehyde	410	20	40	100	2,500	10,000+	
Peat, sphagnum	460	50	45	85	900	2,250	
Pentaerythritol	450	10	30	90	1,700	9,500	14
Phenothiazine	540	...	15	80	1,400	4,250	16
Phthalic anhydride	650	15	15	70	1,300	4,250	14
Phytosterol	330	10	25	75	1,500	8,000	
Pitch, coal tar (58% vol matter)	710	20	35	95	1,900	6,000	15
Procaine penicillin	450	...	25	50‡	1,000	2,000	
Rubber, crude, hard	350	50	25	80	1,200	3,800	15
Secobarbital sodium	520	95	105	55	250	500	
Soap	430	60	45	85	600	1,750	
Sodium alkylarylsulphonate	540	...	130	75‡	400	1,250	
Sodium benzoate	560	80	55	85	1,800	10,000+	
Sodium carboxymethyl cellulose	350	560	150	60	300	600	
Sorbic acid	470	15	25	90	3,000	10,000+	
Sulphur	190	15	35	80	1,700	4,750	11
Vitamin B_1	500	80	105	80	1,000	2,250	
Wood flour	430	20	40	110	1,600	5,500	17

* When uranium, uranium hydride, and zirconium were dispersed into air at room temperature, the dust clouds ignited under some conditions.

† The oxygen reduction data in this table are based on tests made in air-CO_2 mixtures. Dust clouds of thorium, titanium, uranium, zirconium, Dowmetal, and certain magnesium and magnesium-alloy powders ignited in pure CO_2.

‡ Pressures and rates of pressure rise for these dusts were measured by an older testing technique.

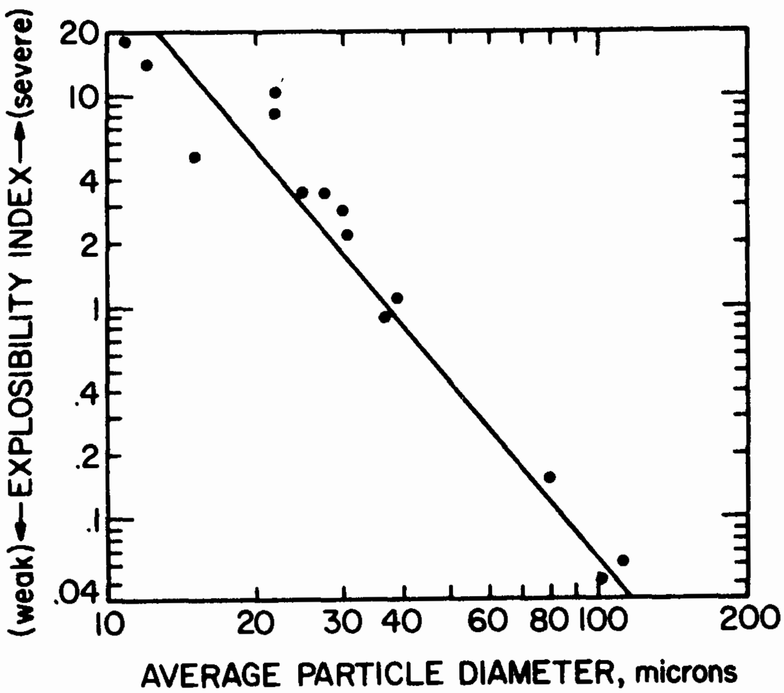


Figure 2.7. Effect of Average Particle Diameter of Atomized Aluminum on Explosibility Index (from Jacobson et al., Ref. 32).

Figure 2.7, the particle size, concentration, and energy input effects are shown in Figure 2.8.

Dust explosions occasionally occur in fabric filters as the result of the accidental admission of a spark from tramp iron, welding or grinding operations, or during maintenance or repair. Disastrous effects of explosions can be minimized by providing burst diaphrams or pressure reflief panels and large vent ducting to the outside of the plant. The loss-prevention staff of most major insurance companies can recommend adequate designs, and fabric filter manufacturers can supply proper components.

The extensive specific surface area associated with powdered materials is also used as a reaction surface for the recovery of SO_2 or SO_3 from flue gases. By generating an aerosol of reactive powdered material, such as $CaCO_3$, and collecting it on a fabric filter, the filter-dust combination functions as a fixed bed reactor for partial

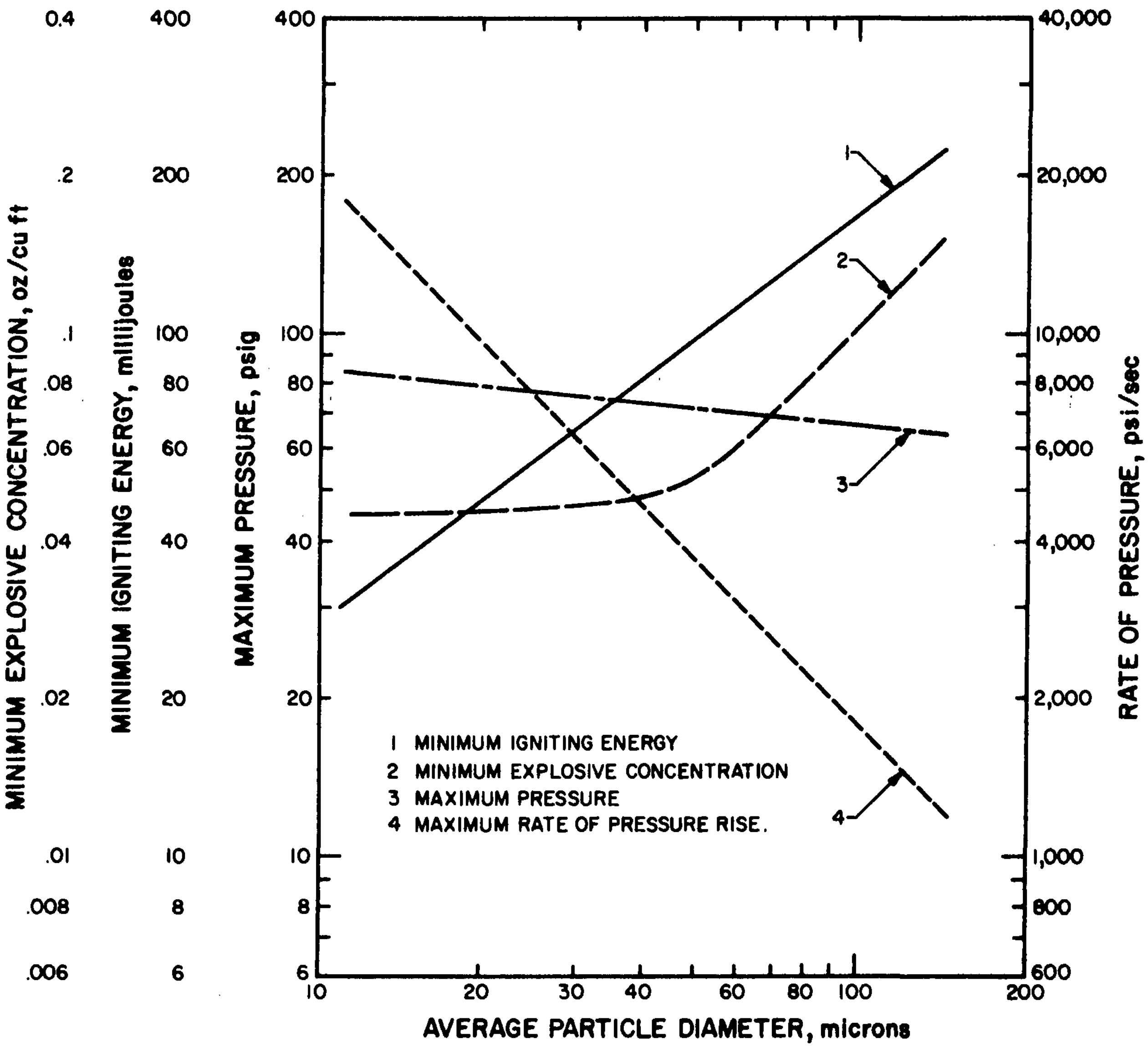


Figure 2.8. Effect of Average Particle Diameter of Atomized Aluminum on Explosion Parameters (from Jacobson et al., Ref. 32)

removal of sulfurous flue gases. Other relevant characteristics of fine particulates associated with size and specific surface, and not necessarily restricted to filter applications, include pigment color and cover properties, flow properties, caking characteristics, drying, heating, surface cover, abrasiveness, potency of therapeutic properties, setting time of cements, bulk powder density, magnetic properties and solubility.[37,38]

2.2.2.6 Electrostatic Charge.- Electrostatic charge associated with suspended particles consists of an excess (-) or deficiency (+) of electrons on the particle. Most small particles have naturally acquired charges from electron transfer during contact and separation or because of free ion diffusion. This charge may be assumed to reside on the particle surface.[13,39,40,41]

Mechanisms[39] that usually produce a charge on aerosol particles are:

- Electrolytic Mechanisms - Electron exchange at a high-dielectric liquid-solid interface followed by separation as from a jet, over a surface, or by impact of liquids on solids.
- Contact Potential - Free electron transfer across a potential barrier because of a differential work function of two metals in contact.
- Spray Electrification - Separation of liquids by atomization leads to formation of charged droplets due to ion concentration in the drops.
- Contact-Separation (Tribo-) Electrification - Separation of contacting, dry, non-metallic surfaces (surface work function).
- Ion Diffusion in Gases - Air ions may be created by electrical discharges in air, by natural radioactivity, or by flame ionization. These ions diffuse rapidly in air and become attached to particles.

Charges of both signs usually appear in equal number after dispersion of small particles so that the net charge of the aerosol may be quite small even when individual particles in the cloud are highly charged.[42,43,44] Collision and adhesion of oppositely charged particles affect behavior of dust clouds and therefore bear upon the interpretation of size analyses.

Representative charge levels on dusts of interest are given in Table 2.6.[40] The number of charges acquired by particles is limited by the breakdown strength of the surrounding medium. In the case of dry air, this is about 8 esu per cm^2, or 1.66×10^{10} electrons per cm^2. It is possible to create charges on particles which exceed this value under certain conditions, e.g., electrostatic precipitation, but observed levels are usually considerably less.

Figure 2.9 shows maximum likely particle charge based on 8 esu/cm^2 and some experimentally determined values.[13,40,43,41] Figure 2.9 illustrates two important characteristics of electrostatic charge phenomena in aerosols: 1) charge levels can exist up to the theoretical maximum as set by breakdown environment and particle surface area and 2) charges observed on natural and artificial aerosols are usually of the order of 1/10th of the maximum value. For estimating purposes, when measurements are not available, the data of Figure 2.9 allow an approximation of the likely charge level. The accompanying notes indicate the methods used in the generation of the particulate charge carriers. Liquid break-up and dry powder dispersal are seen to produce high residual charge on particles (e.g. see items 5,6). Presence of an excess ion cloud tends to reduce residual charge, and conversely, residual small particles remaining airborne, after electrical charging and partial precipitation of the larger fraction, are observed to carry larger numbers of electrons (e.g. see items 19, 20).

Whitby and Liu[46] calculated the theoretical distribution of charge on particles between 0.01 and 1.0 μm in equilibrium with a bipolar ion atmosphere based on diffusion charging, as shown in Table 2.7. The probabilistic nature of the acquisition of particle charge has been considered by Boisdron and Brock,[41] who illustrate the spectrum of particle charge for various conditions and the underlying analysis.

When particles greater than about 1 μm in diameter are passed through a corona discharge, they acquire charges from electrons and adsorbed gas ions in proportion to the square of the particle diameter, D_p, and the strength of the charging field, E_o.[42] For conducting particles:

$$ne = (3/4)\, E_o D_p^2 \qquad (2.4)$$

TABLE 2.6

CHARACTERISTIC CHARGES ON SOME REPRESENTATIVE DISPERSOIDS*

Dispersoid	Method of Dispersal	Charge Distribution (%) Pos.	Neg.	Neutral	Specific Charge (esu/g)** Positive	Negative
Raw cement mix	Agitation in air stream	35	35	30	0.7×10^4	0.7×10^4
Gypsum dust (Schumacher Plant, L.A.)	Grinding, drying in flash dryer	44	50	6	1.6	1.6
Copper smelter dust (Tooele, Utah)		40	50	10	0.2	0.4
Fly ash (Stateline, Chicago)		31	26	43	1.9	2.1
Fly ash (Rochester Electric)		40	44	16	4.8	4.2
Gypsum dust (U.S. Gypsum Phila, Pa.)	Grinding and drying in a rotary kiln				0.2	0.2
Lead fume (Tooele, Utah)	Dwight-Lloyd sintering machine	25	25	50	0.003	0.003
Laboratory oil fume	Condensation from vapor	0	0	100	0	0

*From White, Ref. 40.

**1 esu = 2×10^9 electron charges

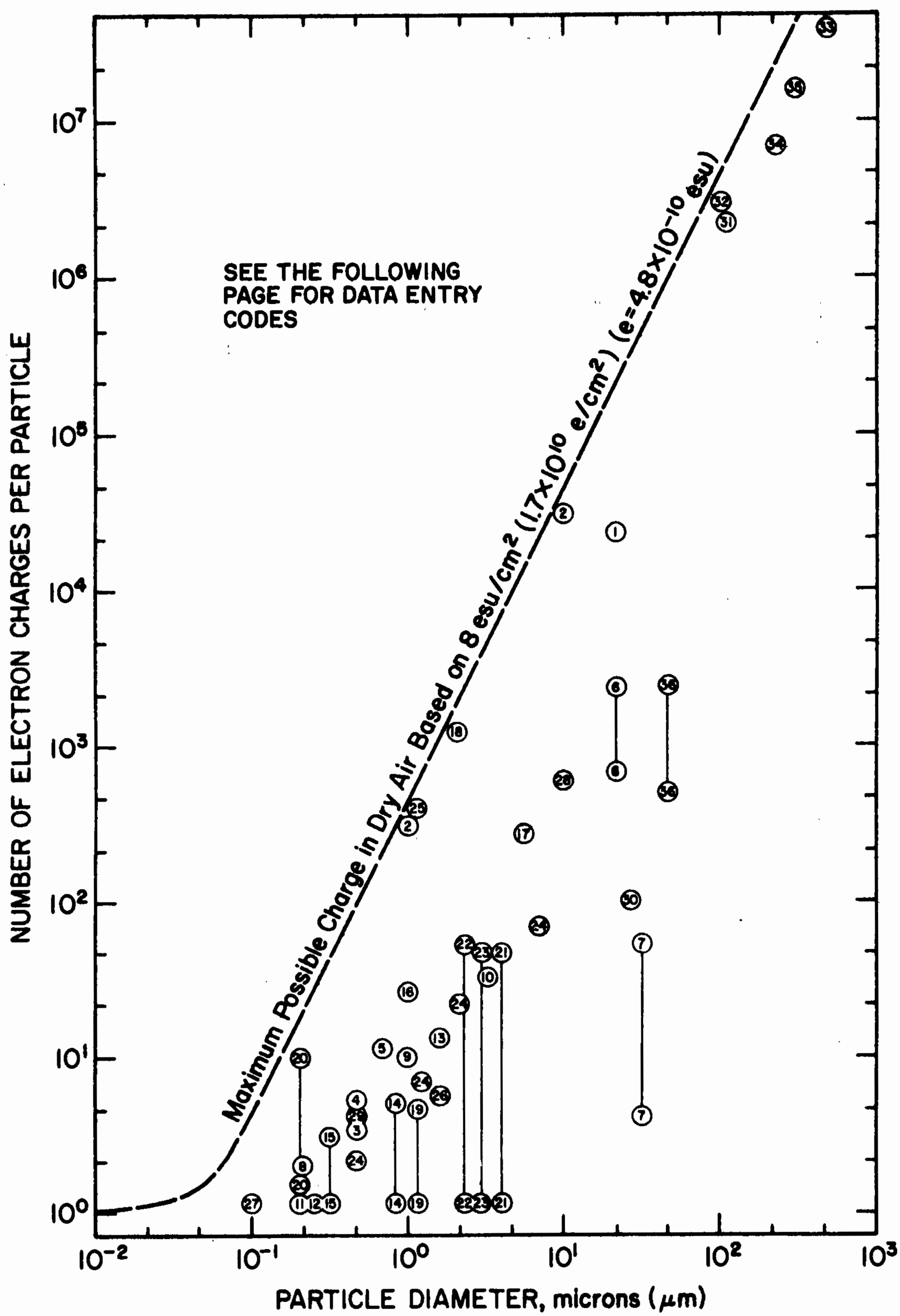


Figure 2.9. Calculated and Measured Single Particle Electron Charges.

Notes for Figure 2.9

No.	Ref.	Source	Material	Remarks, Generation Method
1.	13	Green & Lane	Theor.	2 kV/cm, Field chg.
2.	13	Green & Lane	Theor.	6 kV/cm, Field chg.
3.	13	Green & Lane	Ammonium Chloride	Thermal cond. (Gillespie)
4.	13	Green & Lane	MgO	Combustion fume (Gillespie)
5.	13	Green & Lane	Silica	25 psig air jet redispersion (Gillespie)
6.	13	Green & Lane	H_2O	Fog, dry (Wigand)
7.	13	Green & Lane	H_2O	Fog, damp, unstable (Wigand)
8.	43	Dalla Valle	Tobacco Smoke	Combustion
9.	43	Dalla Valle	MgO	Combustion
10.	43	Dalla Valle	Clay	Air jet redispersed, elutriation
11.	43	Dalla Valle	Stearic Acic	Laller-Sinclair vap'n-cond'n generator
12.	43	Dalla Valle	Ammonium Chloride	Laller-Sinclair vap'n-cond'n generator
13.	43	Dalla Valle	Ammonium Chloride	Spray alcohol solution
14.	45	Megaw & Wells	Dow PSL	Sprayed, measured ion equil distbn.
15.	46	Whitby & Liu	Theor.	Equil. charge, bipolar ion atmosphere
16.	40	White	Theor.	515 ions/cm^3, t>> 1, diff. limited
17.	40	White	Theor.	6.7×10^4 ions/cm^3, t >> 1, diff. limited
18.	40	White	Oil spray	Exptl. ESP, 506 kV/cm, t << 1 field limited (p. 145)
19.	47	Schroter	MgO	Combustion fume, naturally occur.
20.	47	Schroter	MgO	Comb. fume, after charging and propnl. larger fraction
21.	47	Schroter	Plexiglas (PMMA)	Spray dried from benzene
22.	47	Schroter	PVC	Spray dried from cyclohexanone
23.	47	Schroter	PSL	Spray dried from benzene
24.	48	Mercer	Theor.	Sprayed distilled water, 10^{14} ions/cm^3

Notes for Figure 2.9 (Continued)

No.	Ref.	Source	Material	Remarks, Generation Method
25.	49	Lundgren	Meth. Blue: Uranine	4:1, Spinning disc as generated
26.	49	Lundgren	Meth. Blue: Uranine	Neutralized, 10% > 6 e/p
27.	49	Lundgren	Meth. Blue: Uranine	1:1 Collision sprayer and impactor
28.	66	Kunkee	Quartz	Quoted in Zimon, p. 78
29.	66	Jutzi	Quartz	Quoted in Zimon, p. 78
30.	66	Jutzi	Quartz	Quoted in Zimon, p. 78
31.	66	Jutzi	Quartz	Quoted in Zimon, p. 78, 15 kV corona discharge, 7.6×10^{-5} A
32.	66	Jutzi	Zinc	Quoted in Zimon, p. 78, 15 kV corona discharge, 7.6×10^{-5} A
33.	66	Jutzi	Zinc	Quoted in Zimon, p. 78, 15 kV corona discharge, 7.6×10^{-5} A
34.	66	Jutzi	Zirconium	Quoted in Zimon, p. 78, 15 kV corona discharge, 7.6×10^{-5} A
35.	66	Jutzi	Aluminum	Quoted in Zimon, p. 78, 15 kV corona discharge, 7.6×10^{-5} A
36.	65	Deryagin & Zimon	Glass	Blow-off surface, quoted in Corn p. 380.

TABLE 2.7

DISTRIBUTION OF CHARGES ON PARTICLES IN EQUILIBRIUM
WITH A BIPOLAR ION ATMOSPHERE*

D_p (μ)	Number of Charges on particle											
	0	1	2	3	4	5	6	7	8	9	10	Average Charge
0.01	0.993	0.007										0.007
0.015	0.955	0.045										0.045
0.02	0.900	0.100										0.10
0.03	0.763	0.236	0.001									0.238
0.06	0.550	0.430	0.020									0.470
0.1	0.424	0.48	0.09	0.006								0.677
0.3	0.241	0.41	0.232	0.093	0.024	0.005						1.247
1.0	0.133	0.253	0.214	0.162	0.109	0.065	0.035	0.017	0.007	0.003	0.001	2.36

*From Whitby and Liu, Ref. 46.

where n = number of electron charges

e = charge on one electron (4.8×10^{-10} statcoulomb)

Particles of insulating materials acquire charges to 50 to 60 percent of this value. For particles less than about 0.2 μm, diffusion charging predominates[40,46] according to the following relation:

$$n_p = \frac{D_p kT}{2e^2} \ \ell n \left(1 + \frac{\pi D_p c N_o e^2 t}{2kT}\right) \qquad (2.5)$$

where n_p = charges on an initially neutral particle after time, t

k = Boltzmann constant, 1.38×10^{-16} ergs/molecule ^oK

N_o = ion density, ions/cm^3

c = ion velocity (root mean square), cm/sec.

t = time, sec.

T = temperature, ^oK

The theoretical charges acquired by particles of various sizes for a rod and cylinder precipitator assembly are shown in Table 2.8.[50] These agree approximately with reported experimental values.[40] Since particles acquire sufficient charge to precipitate rapidly in a parallel field condenser, this method has formed the basis for the design of several electrostatic particle-size classifiers.[46,49,51] The migration velocity of a charged spherical particle, V_e, in the direction of a collecting electrode can be obtained from the following expression, assuming that air resistance is given by Stokes Law:

$$V_e = C_c \ E n_p e / 3\pi \ \mu_f \ D_p \qquad (2.6)$$

where E = field strength in the collecting space (esu/cm), and C_c is the slip correction factor.

Effective electrical precipitation depends upon the particle charge level (n_p) and a strong collection field gradient (E) which, in turn, is attained by providing a large value for the product $N_o t$, or a reasonable number of ions (N_o) over a realistic time to charge (t). A practical constraint is that the charging time, t, must be less than the gas residence time in the system as determined by the volume-flow

TABLE 2.8

NUMBER OF UNIT CHARGES ACQUIRED BY PARTICLES*

Particle Diameter µm	Field Charging				Diffusion Charging			
	Exposure Time, Sec.				Exposure Time, Sec.			
	0.01	0.1	1	α**	0.01	0.1	1	10
0.2	0.7	2	2.4	2.5	3	7	11	15
2.0	72	200	244	250	70	110	150	190
20.0	7200	20,000	24,000	25,000	1100	1500	1900	2300

*From Lowe and Lucas, Ref. 50.

**Limiting Charge

Note: Calculated from equations (2.4) and (2.5) under the following conditions typical of a rod and cylinder assembly; $T=300^{o}K$, $N_o = 5 \times 10^7$ ions/cm^3, E_o = 2 kV/cm, in air at atmospheric conditions, at 40 kV with a discharge current of 40 µA/ft.

relationships. Practical devices utilizing electrical precipitation must take into consideration the physical and chemical characteristics of the carrier gas, and particle deposition, adhesion, bounce, and reentrainment caused by fluctuations in the flow field.

Acquisition of maximum theoretical charge gives rise to strong attractive coulombic and dipole forces which can be used to collect, separate, or classify particles. The presence of electrostatic charges is often a severe problem when handling particles less than 10 µm having relatively low mass, as fine particles tend to clump together. This makes it difficult to produce good air dispersions for subsequent sedimentation, prevents dry screening of powders with electro-formed sieves, and complicates particle removal from fabrics. Undesirable charge effects may be counteracted by exposing the aerosol to emanations from a nuclear radiation emitter to produce excess air ions for neutralization, or by humidification which enhances charge leakage. The latter process, however, will also accelerate particle clumping.

Powdered materials which are good electrical conductors (e.g. carbonyl iron spheres) can be grounded before and during sieving to reduce charge effects. Fugitive electrostatic charge accumulation in powdered materials handling systems is one source of ignition for explosive reactions, as indicated above.

The presence of electrostatic charge on a particle gives rise to forces influencing its aerodynamic behavior in an electrical field and classifiers have been designed to take advantage of the fact that a charge may be placed on a particle in proportion to its size. Theories of particle charging by diffusion and electrostatic field charging mechanisms have been reviewed by White[40] and Whitby and Liu.[46]

Measurements of particle electrostatic charge can be obtained experimentally by methods illustrated schematically in Figure 2.10. The Faraday ice pail method shown at (a) consists of an insulated filter holder connected to ground through an electrometer and a bucking circuit (Figure 2.11), and measures the total aerosol net charge.[52,53] From an independent measure of particle numbers (as with an automatic light scatter aerosol particle counter, particle size analyzer, or by counting particles on a membrane filter sample), the average charge per particle (+ or -) can be obtained. Millikan's oil drop experiment (Figure 2.10) provides a means for measurement of the motion of a particle in an electrical field. Individual particles are suspended by an electrical field in a parallel plate condenser and their motion observed by light scatter in a microscope. Differential velocities under the action of gravitational and electrical fields are used to compute individual particle charges. The method requires great patience on the part of the observer. Other modifications of the motion of particles in electrical fields are illustrated in Figure 2.10, c and d. Stroboscopic photographs of particles are taken in a defined field and serial tracks are used to compute size (from falling velocity) and charge (transverse displacement).

Charge spectrometers have been employed to sort out particles by electrical mobility in a parallel field configuration,(Figure 2.10 e,f) With an independent measure of size (as by automatic analyzers), the spectrum of charges can be deduced. Whitby and Liu have used the method in reverse by diffusion charging the aerosol particles to a known level, ($0.01 \leq D_p <$ 0.5 μm) and measuring collection of species of known charge at various

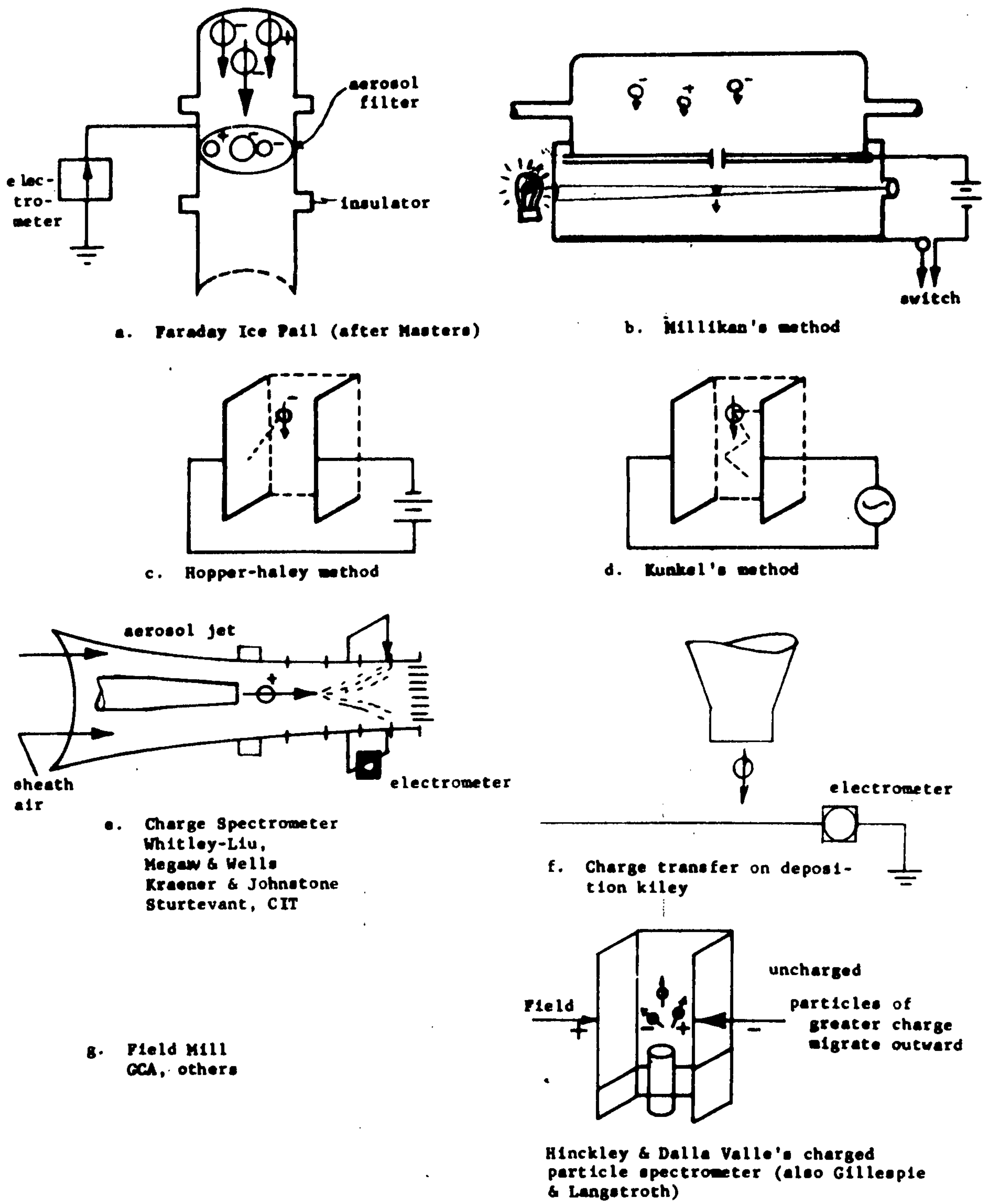
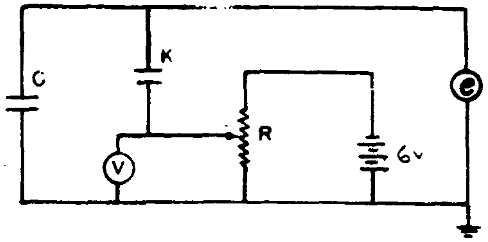
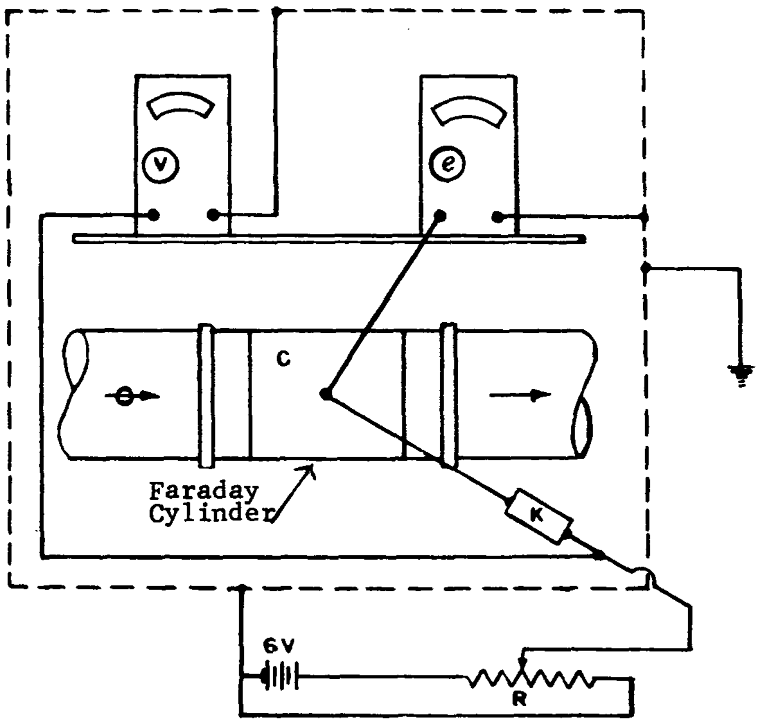


Figure 2.10. Experimental Measurement of Particle Electrostatic Charge.

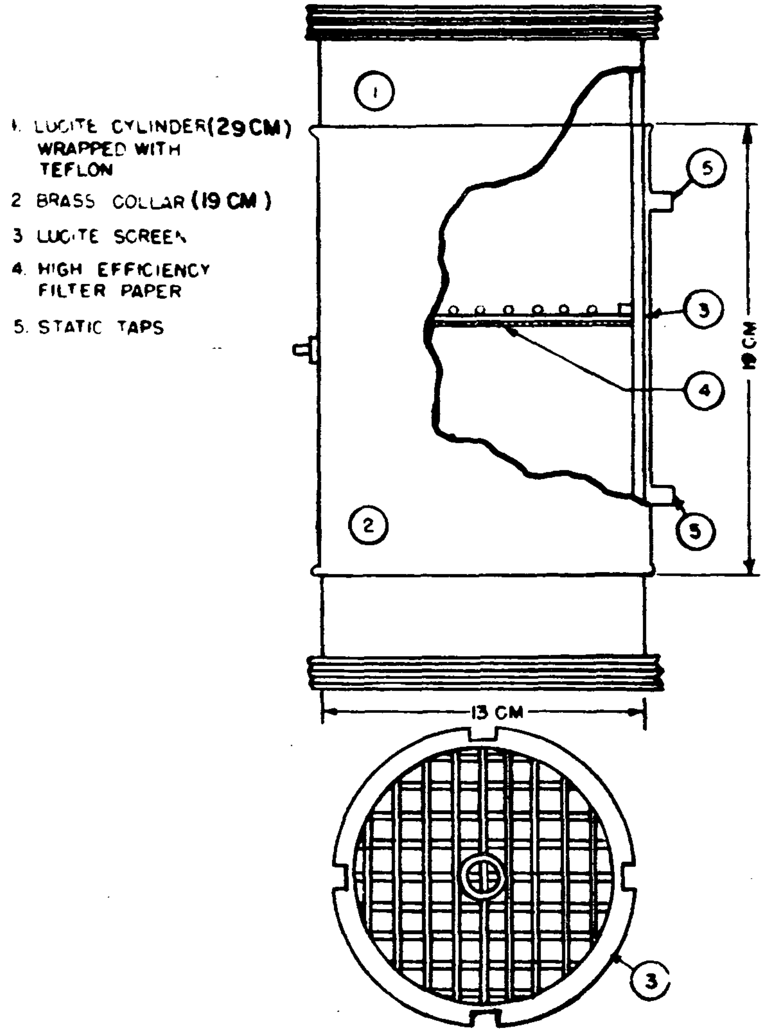


(a) CIRCUIT OF MASTERS

C ~ 50 μμf   e ~ 10 μμf; ELECTROMETER, HI LKG
K ~ 500 μμf   V = VTVM



(b) EXPERIMENTAL DUPLICATION OF MASTERS CIRCUIT



(c) - Faraday Cylinder for Net Aerosol Charge Measurement

Figure 2.11. Simple Method for Measurements of Aerosol Net Charge (From Anderson and Silverman, Ref. 53).

velocities to deduce the size distribution. The field mill (Figure 2.10,g) and the spectrometer method of Hinckley and Dalla Valle (Figure 2.10,h) measure the spectral distribution of charge in a flowing aerosol cloud. Other methods of charge measurement include deflection of a charged particle at high velocity in a magnetic field, charge transfer upon deposition, etc. Although none of these methods is commercially available for field investigation of particle charges they are frequently adapted for laboratory measurements of charges in simulant aerosol clouds. In conjunction with an independent measure of number-size distribution, the system of Masters is readily adaptable to stack sampling for field measurement.

The subject of electrostatic effects in filtration, the production of charge in aerosols or on fibers to promote collection, and the use of electrets (the electrical analog of a permanent magnet) are discussed in subsequent sections.

Particle charge measurement and charge phenomena in dispersed powders has been the subject of extensive research on powder dissemination properties during the past ten years. A summary of the present state of knowledge is included in a recent treatment by Lapple.[54]

2.2.2.7 Adsorption.- Suspended solid and liquid particles are surrounded by a surface film of gas molecules held by imbalanced electrical or chemical valence forces arising from interactions with the surface or near-surface molecules. Gas or vapor molecules may be adsorbed in proportion to their concentration in the surrounding gas phase up to saturation of one monomolecular layer. Additional layers have been demonstrated in typical aerosol systems of interest.[55] The quantity of adsorbable vapor on particle surfaces may be used to estimate surface area and average particle size under controlled conditions, and instrumentation for powder surface area determination is commercially available.[56,57] Atomic or molecular configuration, electrical charge, and particle shape, structure, and fissures affect surface adsorption. Presence of adsorbed vapors on ambient aerosol particles will modify the surface characteristics of particles such as charge, adhesion, and evaporation. The kinetics and mechanisms of adsorption of gases and vapors on solid surfaces are treated extensively in recent texts on the physical chemistry of surfaces,[58,59] the solid-gas interface,[60] and from the standpoint of technological considerations in recent symposia on particle surfaces.[61]

Adsorption is described practically[59] in terms of the empirical adsorption isotherm:

Volume of gas adsorbed = f (partial pressure of the adsorbent).

Typical adsorption isotherms are indicated in Figure 2.12.[59] Type I represents the Langmuir type isotherm in which the vapor is adsorbed as a monolayer. Since the capacity is surface limited, the amount of adsorbed material rapidly becomes independent of its partial pressure in the vapor phase. If a multilayer prevails, a common occurrence in the case of physical adsorption, the Type II curve is more representative of the adsorption process. Type III is a rather unique case where the heat of adsorption appears to be less than the heat of vaporization of the absorbate. Both Type IV and Type V curves tend to reflect capillary condensation phenomena since they level off before the saturation pressure, p_o, is reached. The volume of vapor adsorbed is a function of the vapor pressure and adsorbent properties. Typical values of surface area of several commercial carbon blacks are shown in Table 2.9,[62] (Columns 4 and 5). Estimates of surface area calculated from particle size measurements with the electron microscope (Column 3) are seen to be generally lower than area measured using a nitrogen adsorption method. The wide range of areas is typical of variations in methods of producing particulate materials and of the spectrum of particle sizes. Column 2 indicates the bulk (or apparent) density of the powders, $0.1 \leq \rho < 0.75$ gm/cm^3. True density of amorphous carbon is 1.8 to 2.1 gm/cm^3, and of graphite is 2.25 gm/cm^3. The conversion to the powdered state produces a density of the order of 1/10th to 1/3rd of the true density, as indicated previously (Tables 2.3 and 2.4).

Powder porosity (void fraction, $\epsilon = 1 - \alpha$) is higher with finer particle sizes, i.e., $\epsilon = 0.93$ at $D_p = 10^{-2}$ μm (high color channel black) and ϵ = 0.625 at D_p = 0.5 μm (MT thermal black). Specific surface area also varies from $10^3 m^2/gm$ ($D_p = 10^{-2}$ μm) to about 1 to 10 m^2/gm (0.5 μm).

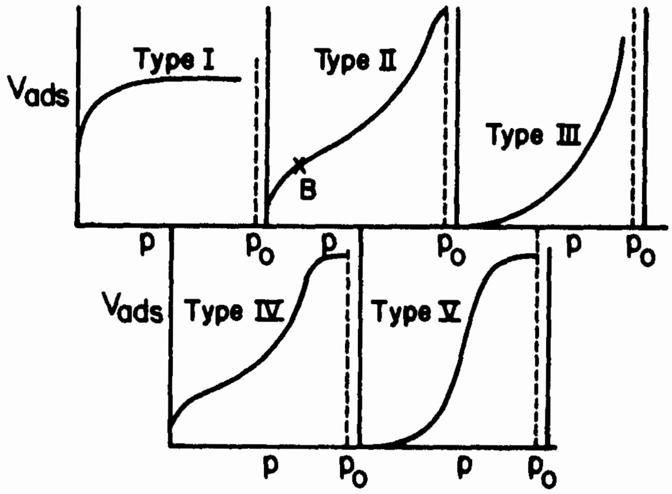


Figure 2.12. Brunauer's Five Types of Adsorption Isotherms (From Adamson, Ref. 59).

In many technical systems of interest, behavior of small particles on contact or at separation is observed to be a direct function of adsorbed ambient moisture. The role of gas adsorption on atmospheric particulate is largely unstudied and poorly defined at present. It is recognized that these processes are influenced by many factors including concentration, humidity, catalytic effects, and natural irradiation levels.[9,63]

2.2.2.8 Adhesion.- Contact of small solid aerosol particles with solid surfaces often results in very strong bonding forces. The phenomena of attachment of solid particles to surfaces is called adhesion, and the force applied to overcome the attachment is called the particle adhesion force.* Since adhesion is an important characteristic of small particles (high surface to volume ratio) it must be considered in many practical aerosol systems; e.g., generation or dissemination of powders, the collection of particles from disperse systems, the control of pollu-

TABLE 2.9

PHYSICAL PROPERTIES OF TYPICAL CARBON BLACKS*1

Carbon-black type	Bulk Density g/cc*2	Av. Particle diam, mμ*3	E.M. Surface Area sq m/g*4	N_2 Surface Area sq m/g*5
A. Color and ink channel blacks:				
High color	0.1-0.2	10-14	218-186	1000-860
Medium col.	0.2	18	130	400
Low color	0.2	30	95	110
Long flow	0.2	30	100	350
B. Rubber grade channel blacks:				
CC	0.35	25	110	225
HPC	0.35	26	105	140
MPC	0.35	28	106	120
EPC	0.35	30	95	100
C. Gas furnace blacks:				
SRF	0.45	70	25	25
HMF	0.42	50	40	35
FF	0.46	40	60	75
D. Oil furnace blacks:				
GPF	0.40	55	40	25
FEF	0.33	40	60	40
HAF	0.35	28	75	75
ISAF	0.33	24	120	130
SAF	0.35	20	140	140
CF	0.32	19	120	220
E. Thermal blacks:				
FT	0.50	185	16	16
MT	0.75	520	6	6
F. Other carbons:				
Acetylene black		43	60	64
Graphite		Large platelets		

*1 From Smith, Ref. 62

*2 Bulk density as commonly supplied to industry. Color black may also be supplied in densified pellet form.

*3 Average value from electron micrographs for arithmetic mean diameter.

*4 Calculated assuming spheres from electron micrograph surface average diameter.

*5 Calculated from adsorption in nitrogen at -195°C by method of Brunauer, Emmett, and Teller.

tants, the assessment of quantity of suspended material, and in the build-up of deposits on filters and duct surfaces. Although adhesion phenomena are commonly displayed and of great technical importance, the calculation of adhesion forces in any given situation may be difficult. Their estimation must include the effects contributed by solid and surface properties, gas constitutents, interface geometry, and history of the environment or system under study.

Consider two 50 μm solid spherical quartz particles brought into contact under ambient conditions. From classical considerations,** the force of gravitational attraction between the two particles by virtue of their mutual masses is equal to (approx.) 2×10^{-16} dynes. If the particles are oriented vertically in the gravitational field of the earth, and the upper particle is held fixed (for example, by a glass fiber), the gravitational force of the earth on the lower particle is ($F_g = mg$) of order of 2×10^{-2} dynes, thus indicating that the lower particle should fall away. In fact, the lower particle will probably not fall, but be held firmly to the upper one. If a separating force is applied to the two particles (e.g. in a centrifuge, or by a microbalance technique), the actual adhesion force can be estimated to be of the order of about 0.5 dynes. This additional adhesive force arises as a consequence of several adhesion mechanisms that operate at and near the interface between the two particles. If two particles having a common contact area of 1 sq μm were assumed to be bonded intimately through chemical or physical means, the force required to overcome the molecular attraction would be approximately 10 dynes. This corresponds to the mechanical strength of the parent materials, of the order of 10^9 dynes/cm^2. Thus, the magnitude of adhesion forces encountered in situations of interest for particulate

---

*The study of adhesion in friction, lubrication, and wear of surfaces in relative motion is not considered here.

**Newton's law of universal gravitation, $F_N = G\, m_1 m_2/r^2$, $G \simeq 7 \times 10^{-8}$ dyne cm^2/gm^2. For two bodies of different size, $r_2 >> r_1$, $F_N \sim r_2$, and the attractive force is directly porportional to the size of the larger.

control technology are usually less than those estimated from consideration of the strength and areas of materials in contact, but apparently somewhat greater than predicted classically. The problem of the analysis or estimation of adhesion forces in aerosol deposits in fabric filters is more complex because the particles are usually packed in close juxtaposition to one another as well as attached to a substrate. This leads to additional forces arising from particle to particle interactions, and also to considerations of the actual geometry of the deposit.

A summary of the major effects in adhesion phenomena is presented in the discussion which follows with empirical relations and observations suitable for technical or engineering estimating purposes. The following aspects are briefly treated:

- Adhesion forces for individual particles including effects of particle size, relative humidity and time-dependency.
- Effects of electrostatic charge on particle adhesion.
- Effects of particle and surface shape.
- Effects of surface roughness.
- Adhesion phenomena in ensembles of particle deposits.

(1) Adhesion Forces for Individual Particles - According to Krupp's[64] unified analytical treatment, the phenomenon of particle adhesion to a surface proceeds as follows:

> "1) At first, particle and substrate come into contact at one point by a contact area of atomic dimensions.
>
> 2) By long-range attraction forces between the two, the particle... is subject to a moment of force so that several contacts are formed... between non-perfectly smooth adherents.
>
> 3) By the interaction forces the ... area at these contacts increases until the attractive forces and the forces resisting the further deformation at the interface are in equilibrium. An adhesive area of finite size is formed between the adherents."

The effectiveness of the contact between particle and substrate also depends upon the magnitude of the force acting on the particle at the instant of contact; i.e., the kinetic energy given up by the particle through its stopping distance, or by the pressure or gravitational force applied by the particle to the substrate to provide intimate contact.

Upon application of a separating force, separation takes place as follows:[64]

> "1) The external forces of separation exerted on... the particle... cause a partial or complete recovery of the deformation at the interface.
>
> 2) Generally, the centre of attack of the separating force will not be symmetrical to the location and strength of the individual contact sites, so that the particle is subject to a moment of force and individual contacts may become broken separately.
>
> 3) Finally, the last contacts are separated; the particle is set free.
>
> The adhesive area, ... is ... the area of the common interface between the adherents effective during this last step."

The adhesive force is defined as that force applied perpendicular to the center of gravity of the particle necessary to remove the particle from the substrate in a fixed period of time. Krupp[64] classifies the interaction forces as follows:

> "Class I - long-range attractive interactions resulting from: Van der Waals forces, electromagnetic fluctuation phenomena between the elementary oscillators of a solid; and electrostatic double layer forces, arising when two solids in contact charge each other by electron transfer (differential surface energy), the contact potential difference at equilibrium being of order 0.1 V for conductors.
>
> Class II - short-range attractive interactions resulting from the various types of chemical bonds and hydrogen bonding mentioned below, and
>
> Class III - interfacial reactions such as diffusion, dissolution, and alloying."

The exact analytical prediction of adhesion forces from physical models is difficult because adhesion results from mechanisms operative at the molecular level leading to chemical and non-chemical bonding at the interface, and to the establishment of a complex field of mechanical stresses, strains, and deformation around the interface.

These interrelationships change with time and with the application of the separating force, leading to requirements for a kinetic model.[64] Forces that produce an attractive interaction between solids in contact include those which provide intermolecular cohesion in solids, such as metallic, covalent and ionic primary chemical bonds, and secondary van der Waals attractions having energies of 1 to 10 and 0.1 eV, respectively. Intermediate energies arise from hydrogen bonds, electronic charge transfer bonds, and the electrostatic double layer forces.

As discussed below, adhesion forces in practical systems are also related to ambient relative humidity or absolute humidity in the surrounding gas, as a consequence of capillary condensation of moisture in the interfacial space.

Analytically tractable geometries of technical interest include sphere-to-wall (half-space), sphere-to-sphere, and sphere-to-cylinder contacts. Present knowledge is limited to estimates of adhesion for particles between 1 and 10^3 μm. The lower limit arises because all real solid surfaces contain numerous irregularities (asperities) under 10 μm such that particles of the same order are effectively embedded in a fissure or crack. In the case of larger particles, gravitational forces are greater than the adhesive forces, because the true contact area, which defines the adhesive forces, is determined by the relatively small dimensions of the surface irregularities.[64] The theoretical bases of particle adhesion have been systematically presented by Krupp.[64] Substantial reviews of the fundamental relationships, technical estimations, and measurements of adhesion forces have been given by Corn[65] and Zimon.[66]

The following experimental methods[65-71] have been used to measure the adhesion force of single particles on surfaces, as indicated in Figure 2.13:

- Microbalance technique for particles that can be manipulated (diameter 75 μm)
- Pendulum method which requires that the gravitational force, F_g, exceed the adhesive force, F_a

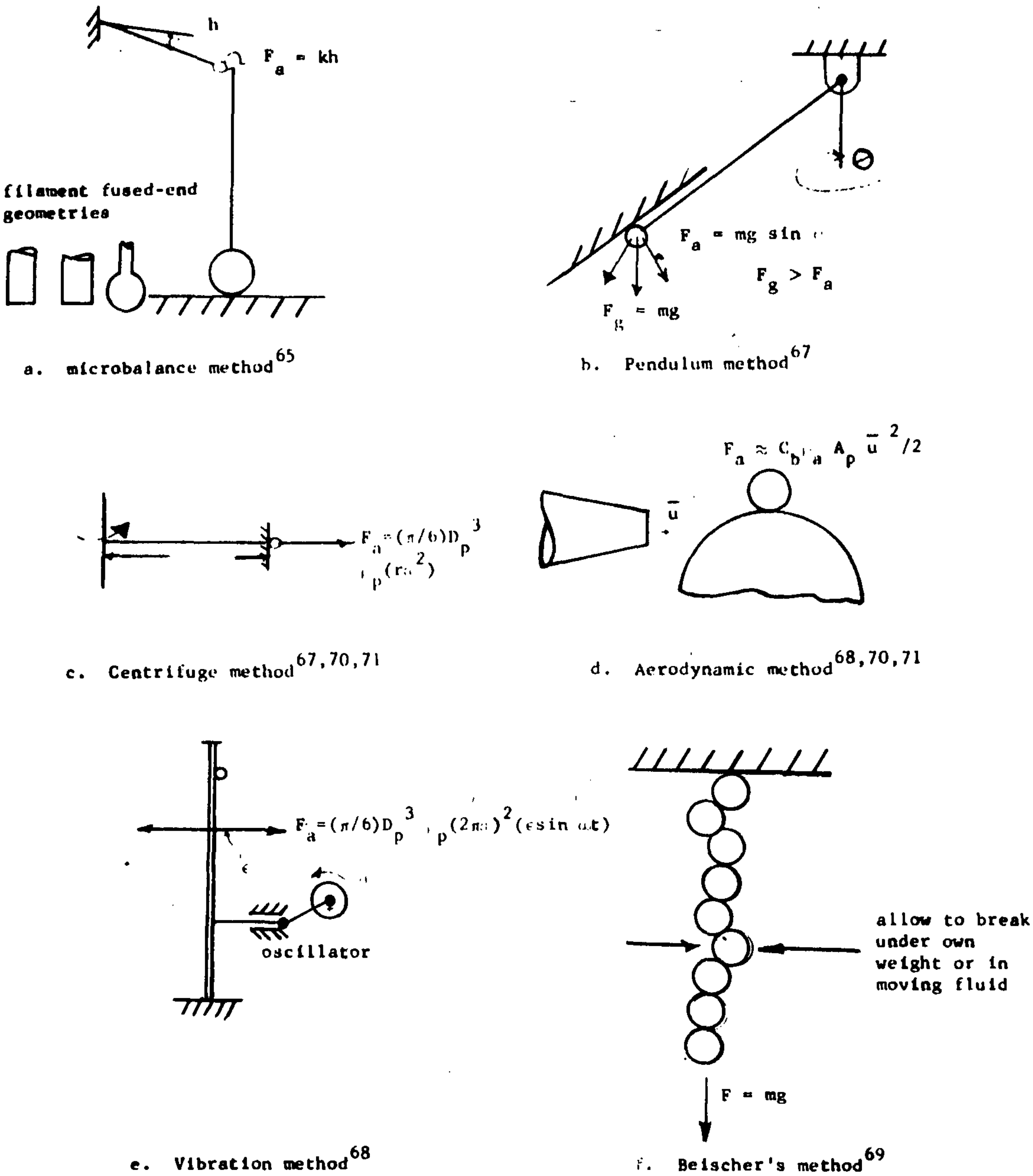


Figure 2.13. Experimental methods for measurement of particle adhesion forces.

- Centrifuge method which requires that particle mass be known
- Aerodynamic method which requires definition of velocity gradients surrounding the contact regions
- Vibration method in which the particle interface is subjected to an alternating compressure force

The following discussions relate to adhesive forces determined by each of the several methods. A modification of the microbalance technique was used by Beischer[69] who allowed coagulating threads of individual Fe_2O_3 particles of 0.5 μm diameter to break under their own weight. The force required was estimated from the size of the separated fragment. His work indicated that for submicron particles the adhesive force was of the order of 0.5×10^{-4} dynes.

If several identical particles are dispersed separately upon a substrate the force required to remove each one will not be the same. Application of a fixed force will remove but a fraction of the particles. Complete separation of all particles may require a significant increase in the force field. The probabilistic nature of this phenomenon is presented in Figure 2.14,[64] in which the relative number of particles

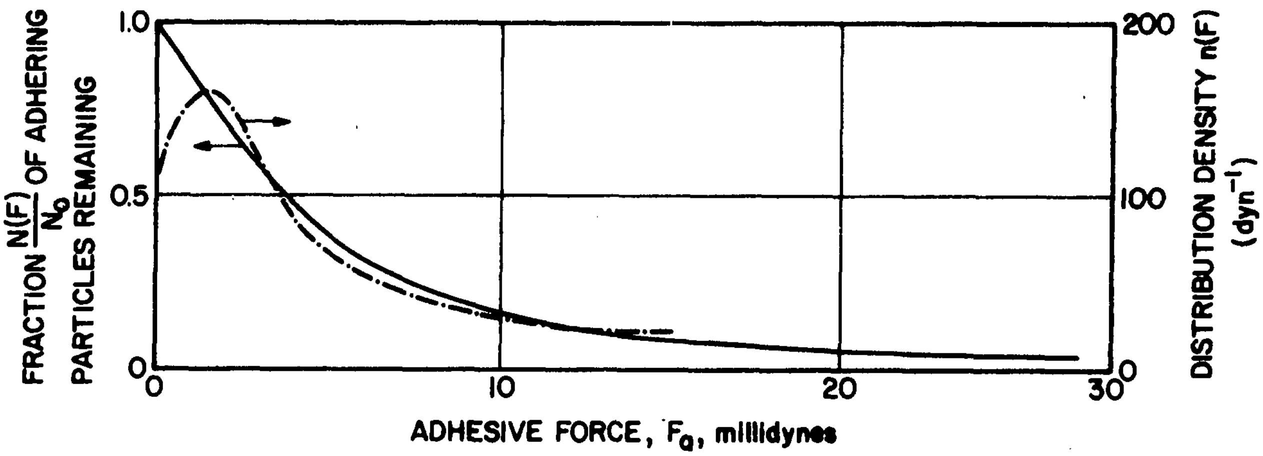


Figure 2.14. Adhesion of Spherical Fe Particles of 4 μm Diameter to Fe Substrate at Room Temperature in Air as a Function of Applied Force (from Bohme, et al., Ref. 67).

remaining after sequential application of discrete centrifugal forces is shown. Whereas fifty percent of 4μm iron particles were removed at approximately 4×10^{-3} dynes, 98 percent removal required a force in excess of 3×10^{-2} dynes. Thus the actual adhesion forces for a large number of identical particles must be represented by a cumulative distribution function of the form $N = N(F_a)$. The number of particles removed by the application of a given force can be represented by its derivative, the distribution density function

$$n(f) = -\frac{1}{N_o}\frac{dN(F)}{dF} \qquad (2.7)$$

where N_o is the initial number present and dN(F) is the fraction of particles whose adhesion force lies between $F \pm 1/2\ dF$, with $n(F) = 0$ at $F = 0$ and $F \rightarrow \infty$.[64] Since n(F) is highly skewed, a logarithmic probability distribution function, or other two-parameter distribution function, will enable presentation of the median detaching force and standard deviation in any given experiment, e.g.,

$$\frac{dN}{N} = \frac{0.43}{F_a \cdot \sigma\sqrt{2\pi}} \exp\left[-\frac{(\log F_a - \log \bar{F})^2}{2\sigma^2}\right] dF_a \qquad (2.8)$$

as suggested by Zimon.[66]

Loffler[70,71] describes the adhesive properties of small granular quartz particles (5 to 15 μm) collected on different fiber filters (50 μm nylon, polyester, and glass fibers) with a logarithmic probability distribution, Figure 2.15. Median forces required to remove 50% of adhering particles from 50 μm nylon fiber ranged from 10^{-3} to 6×10^{-3} dynes, for 5 to 15 μm particles, respectively. The median force required to separate 5 μm irregular quartz particles (~ 1.0 m dyne) was less than that reported by Krupp (Figure 2.14) for smoother 4 μm spherical iron particles (~4 m dyne). The geometric standard deviation, (σF), of the forces representing Loffler's data (Figure 2.15) was about 4.0 for each

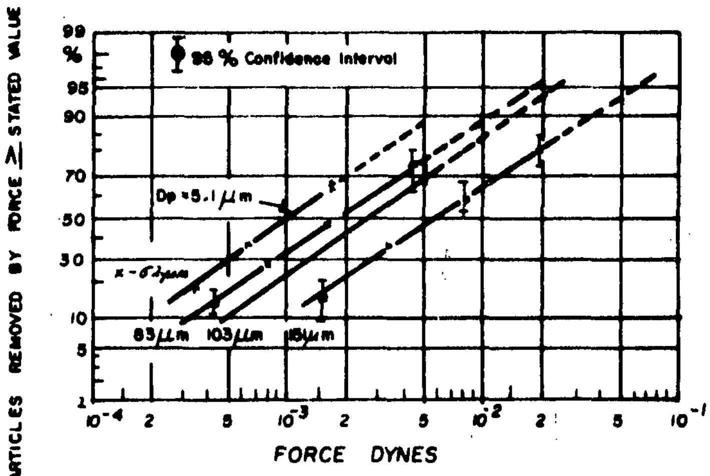


Figure 2.15. Distribution of adhesion forces, logarithmic-probability plot, for classified crushed quartz particles collected by filtration at V = 42 cm/sec on polyamide (nylon) fiber, 50 μm diam., at ~ 50% R.H. (From Loeffler, Ref. 71.).

of the size ranges studied. The high degree of skewness in the distribution was consistent with Krupp's findings, Figure 2.14. The median force required to remove 50% of the particles represented by the data shown in Figures 2.14 and 2.15, leads to an approximate force-size relation given by

$$F_a \approx 10\ D_p \qquad (2.9)$$

where the coefficient has the dimension of surface energy, dyne/cm, and particle diameter is expressed in cm. For removal of nearly all particles, the constant would be of order 10^2. The effect of particle size on adhesion of glass and quartz particles on flat glass plates at 95 percent relative humidity is shown in Figure 2.16, from the extensive measurements of Corn.[72] Corn's results can be represented by the empirical equation

$$F_a \approx 10^2\ D_p \qquad (2.10)$$

at 95 percent R.H. for $5 \leq D_p \leq 200$ μm. He also gives the relationship by

$$F_a = 2\pi\ \gamma_{H_2O}\ D_p \approx 600\ D_p \qquad (2.11)$$

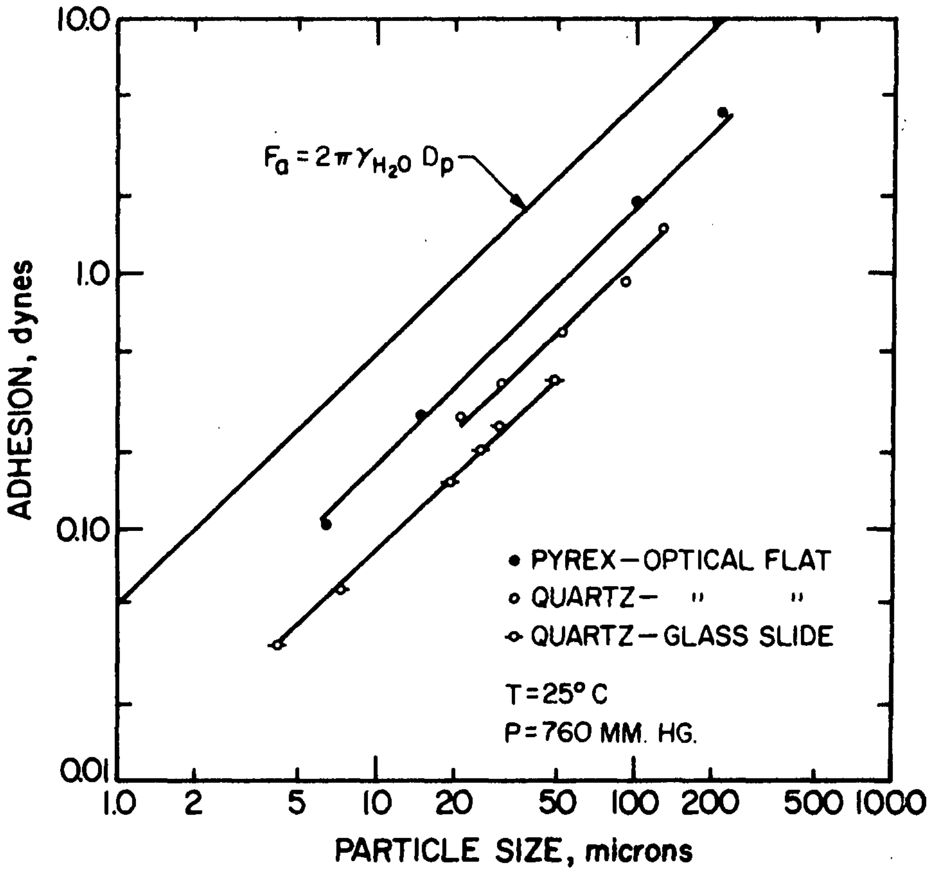


Figure 2.16. Adhesion of Quartz and Pyrex Particles at 95% Relative Humidity (from Corn, Ref. 74).

where γ_{H_2O} is the surface tension at a water-air interface, for γ_{H_2O} = 70 dynes/cm. Similar results were obtained by Bradley[73] for pairs of quartz spheres having diameter D_1 and D_2:

$$F_a = 212\left(\frac{D_1 D_2}{D_1+D_2}\right) \tag{2.12}$$

over the range $200 \leq (D) \leq 600$ μm, and for sodium tetraborate

$$F_a = 434\left(\frac{D_1 D_2}{D_1+D_2}\right) \tag{2.13}$$

over the range $500 \leq (D) \leq 1700$ μm.

As a first approximation, particle adhesion force is proportional to particle size at or near 100 percent relative humidity. The coefficient of proportionality is of the order of 10^2 multiplied by a small integer. For particles less than 1 μm, the coefficient may be as low as 1, as reported by Beischer.[69]

Forces arising from molecular interactions are modified in practical aerosol systems by the presence of substantial (unknown) amounts of adsorbed or condensed molecular species from the constituents of the gas phase.[65] The open region found at the point of immediate contact between a perfect sphere and flat surface represents a microfissure of small radius of curvature. The capillary condensation of vapor at this location in accordance with the Kelvin equation,[13] produces a minute pool of liquid in the interface. The theoretical force of adhesion due to this film of liquid can be shown to be:[65]

$$F_a = 2\pi \gamma_{H_2O} D_p \qquad (2.14)$$

Since the surface tension of water (γ_{H_2O}) is of the order 70 dynes/cm, the constant in equation 2.14 should be of the order 10^2, and seldom greater than 500. The effect of equilibrium relative humidity (surfaces pre-exposed before contact) on adhesion of quartz and glass particles to glass plates is shown in Figure 2.17. The adsorption isotherm for water vapor on quartz is also shown, together with earlier data of Bowden and Tabor[75] for glass spheres on glass plates (also see Figure 2.12). Effects of capillary condensation are reported to diminish below about 60 percent R.H.,[66] although Corn[65] and Larsen[68] both reported effects ascribed to moisture substantially below 60 percent R.H. The effect of relative humidity on adhesion force can be estimated from a linear approximation to Corn's data in Figure 2.17 as:

$$F_a = 10^2 D_p \left\{ 0.5 + 4.8 \times 10^{-3} (\%\ R.H.) \right\} \qquad (2.15)$$

which will be reasonably consistent for $50 \leq \%\ R.H. \leq 95\%$ for particles with $D_p > 20$ μm.

Zimon[66] (p. 82) presents the following data (Figure 2.18, Zimon's Figure 1.2) for effects of particle size with $50 \leq \%\ R.H. \leq 65$, for spherical glass particles on steel surfaces:

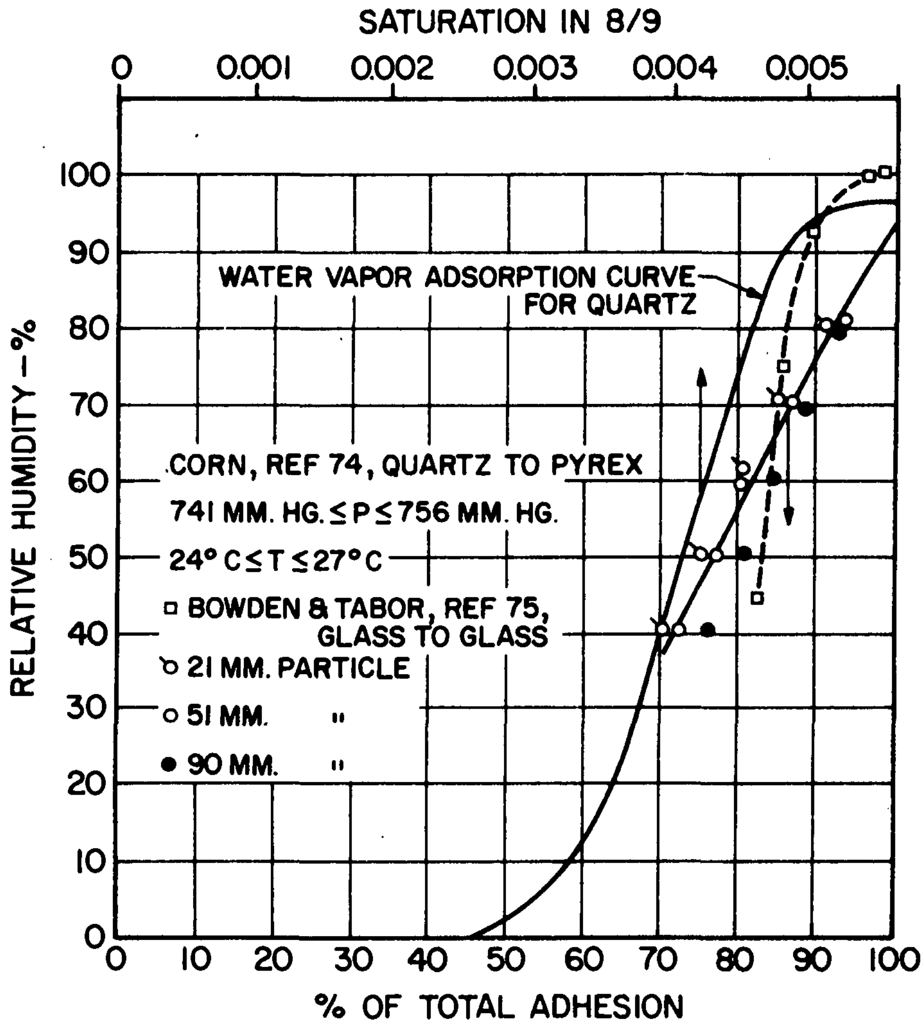


Figure 2.17. Variation of Particle Adhesion With Relative Humidity (From Corn, Ref. 74, and Bowden and Tabor, Ref. 75).

Dp, μm	40-60	20-30	10-20	5-10
F_a, dynes				
Calculated from Equation 2.14:	2.3	1.2	0.7	0.3
Measured, for 50% removed:	2.1×10^{-4}	2.1×10^{-3}	6.1×10^{-3}	1.3×10^{-2}

Zimon concludes from these data that R.H. ≤ 50% has no effect on adhesion. Figure 2.18[66] also illustrates the effect of varying force on detachment of particles of varying sizes, and the shapes of the cumulative force-removal curves for different particle size classes in the same experi-

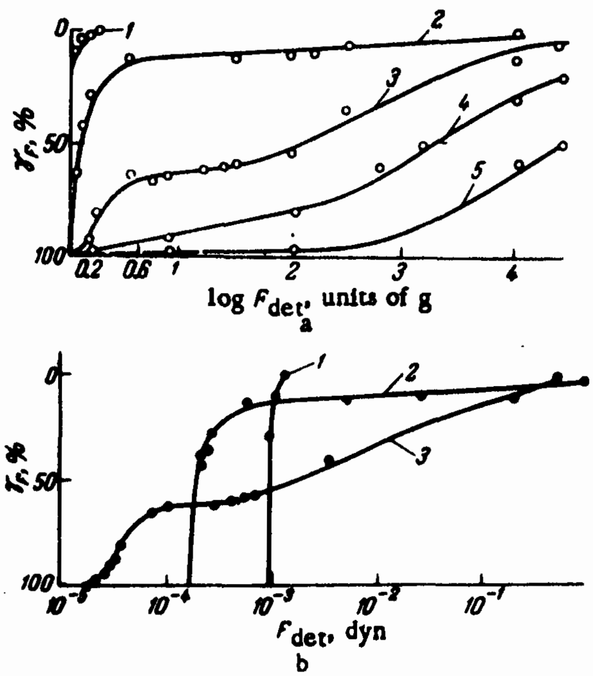


Figure 2-18. Integral adhesion curves for spherical glass particles of different diameters adhering to a steel surface of the 13th class of units of g (a), and in absolute measure (b). 1) dp = 80-100; 2) 40-60; 3) 20-30; 4) 10-20; 5) 50-10μ (from Zimon, Ref. 66)

mental system. In a similar study at R.H. near 100 percent, Zimon[66] reported:

D_p, µm	40-60	80-100	100-200
F_a, dynes			
Calculated from Equation 2.14:	2.3	4.1	5.1
Measured	0.9	4.3	4.7
% Removed	59	78	75

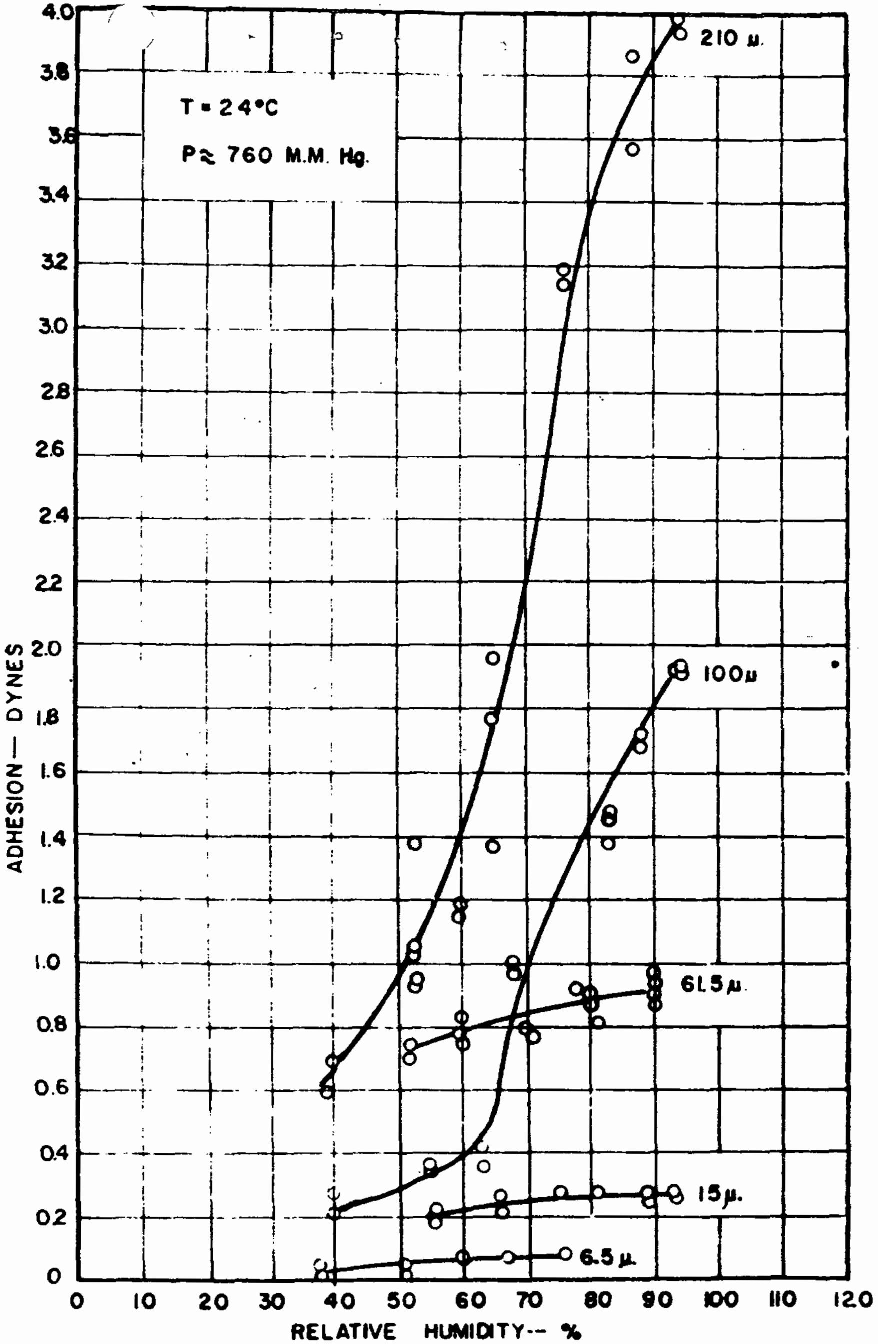
Condensation effects also depend upon particle size and fiber or substrate surface as shown in Figure 2.19 a, b, c, small particles apparently being less affected by humidity in these studies.[70,71,74] Both polyamide and polyester indicate much less capillary condensation effect on adhesion, as expected from the contact angle (< 90^o vs 0^o for glass).

In spite of apparent differences between results presented by various investigators, the data are in reasonable agreement in confirming the relationship between adhesion and particle size and relative humidity. Very low humidity air would be expected to produce relatively low adhesion, from the above data. Reduced humidity, however, removes the adsorbed vapor layer between the particle and substrate. This leads to closer approach and hence the formation of stronger bonds between the two materials. Since the electrostatic charge on the particle or substrate is less mobile or less shielded at low humidity it may be a major reason for increased adhesion at low relative humidities.

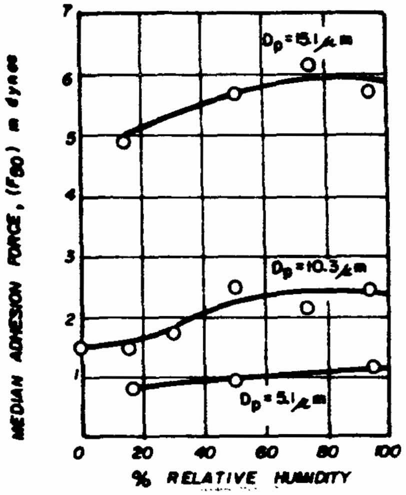
Effects of capillary condensation which depends upon exposure time of the interface to the vapor, require about one hour to approach the full effect.[66] Other time-dependent effects include stress-strain and deformations of the particle-substrate interface under the action of the adhesion force. In general, adhesion forces tend to increase with time with a time constant of the order of an hour or more.[64] Dust removal processes, therefore, should be more effective if applied as soon as possible. The magnitude of time effects on adhesion may be of the order of 25 percent or more.

(2) Effects of Electrostatic Charge on Particle Adhesion

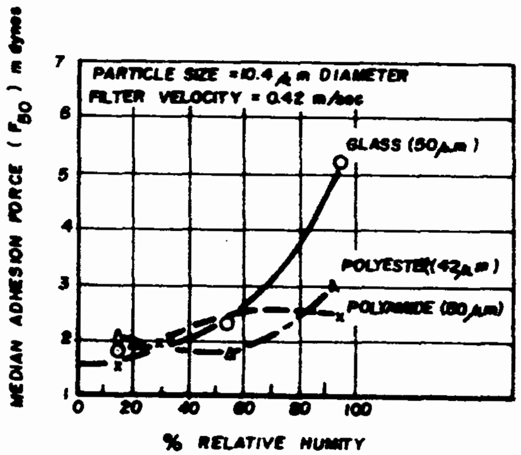
Electrostatic charge on a particle might be expected to cause a marked



(a) From Corn, Ref. 74, Pyrex-Pyrex.



(b) From Löffler, Ref. 70, Granular Quartz on 50 μm Nylon Fiber



(c) From Löffler, Ref. 71, Granular Quartz on Indicated Fibers.

Figure 2.19. Effect of Particle Size and Relative Humidity on Adhesion for Various Materials.

increase in adhesion force. To a first approximation, the charge effect on adhesion force should be given by Coulomb attraction:

$$F_a = \frac{Q_1 Q_2}{K_e r^2} \qquad (2.16)$$

where K_e is the permittivity of the intervening dielectric, and $Q_{1,2}$ are the charges separated by distance r. To find the approximate affect of particle charge on attractive force, consider a 10 micron particle attached to a conducting plane surface, with an expected fugitive charge of the order 100 electrons (from Figure 2.9).

The image force will be of the order $(Q^2/4r^2)=10^{-9}$ dynes, or substantially less than the observed adhesion forces. On the other hand, if the particle were charged to its maximum possible amount, the charge would be 5×10^4 e. The resulting image force of attraction upon deposition on a grounded conductor would be approximately 10^{-4} dynes, or the same order of magnitude as found experimentally by Zimon, for low humidity tests data. Since the image force increases with the square of the charge, and the charge, in turn, as with the square of the particle size, adhesive forces arising as a consequence of particle charging will be larger than those for uncharged particles. This applies to practical situations such as electrical precipitation, flocking, and xerography, where charges are high.

Electrical forces also arise as a consequence of the contact potential from different electronic states of the contacting surfaces, in the form of an electrical double layer. The charge will depend upon the particle electrical conduction properties and the state of the interface. Glass particles (50 to 70 μm) successively detached from a painted surface[66] were found to produce residual charges as shown in Figure 2.20. The higher charges were associated with a higher particle retention after application of a given force. The electrostatic charges upon separation of 50 μm particles were $3000 \leq Q_p \leq 12{,}000$ e. If a high voltage is applied to a conducting substrate, the particles can be caused to leave. However, no application of this observation to fabric filter cleaning has been reported.

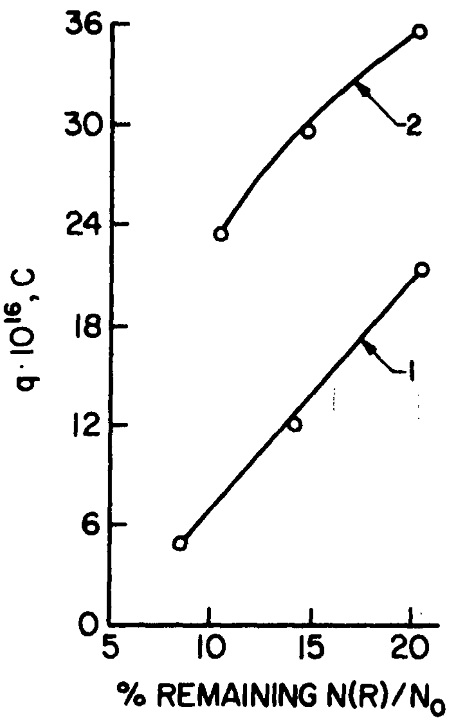


Figure 2.20. Adhesive Force as a Function of the Charge Determined on Detaching Glass Spheres of Various Diameters (by the Vibration Method) From a Painted Metal Surface. 1) d = 50±5μm F_{det}=3.6 · 10^{-3} dyn; 2) d=70±5μm F_{det}=1.9 · 10^{-2} dyn (From Zimon, Ref. 66).

(3) Effects of Particle and Surface Shape - As shown by Zimon (Ref. 66, Chapter 10), the shape of particles in contact and the substrate geometry influence the magnitude of the adhesion force. For two spheres of diameters D_1 and D_2 in contact, the adhesion force can be shown to be as given above:

$$F_a \simeq 10^2\left(\frac{D_1D_2}{D_1+D_2}\right) \tag{2.17}$$

If $D_1 = D_2$,

$$F_a = 10^2 \frac{D_1^{\,2}}{2D_1} = \frac{10^2 D_1}{2} \tag{2.18}$$

or one-half the value expected for dissimilar sizes. For the case of $D_2 >> D_1$,

$$F_a = 10^2 D_1 \left(\frac{1}{1+D_1/D_2} \right) \tag{2.19}$$

Therefore as $D_2 \to \infty$, the force between a plane and sphere becomes

$$F_a \approx 10^2 D_1 \tag{2.20}$$

as found by Corn.[72]. Note that the force between two equal spheres is about one-half of that between a sphere and a plane. For the case of a sphere resting in liquid on a cylinder (as on a filter fiber), Larsen[68] derived the adhesion force from geometric considerations as

$$F_a = 2\pi K_L \gamma_{H_2O} D_p \tag{2.21}$$

where

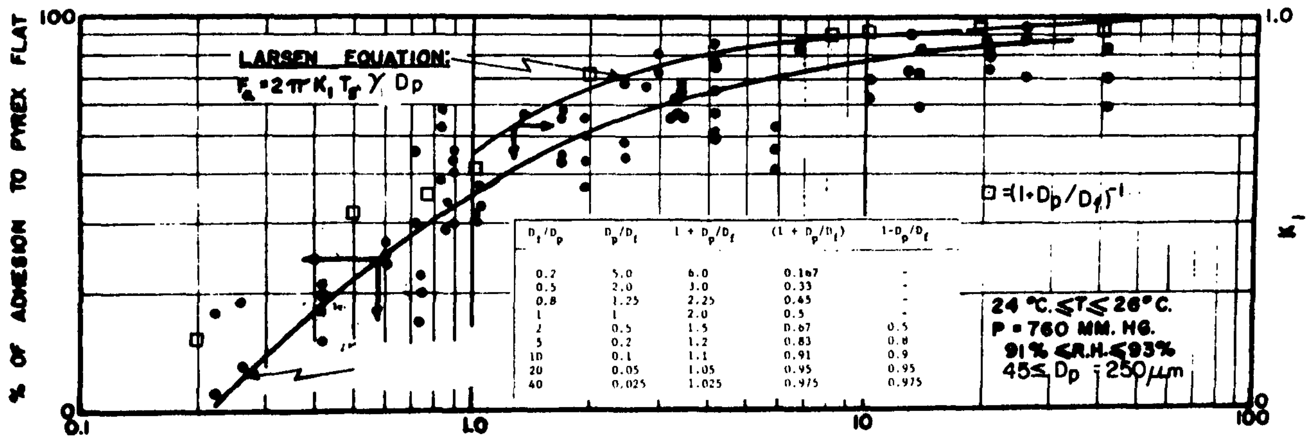
$$K_L = \left[\frac{k_d}{(k_c^2 + k_d^2)^{1/2}} + \frac{1}{(k_c^2 + 1)^{1/2}} \right] (1 + \frac{1}{k_d})^{-1} \tag{2.22}$$

and

$$k_c = \frac{\text{diameter of liquid layer}}{\text{diameter of particle}} = \frac{2\rho}{D_p} \tag{2.23}$$

$$k_d = \frac{\text{diameter of fiber}}{\text{diameter of sphere}} = \frac{D_f}{D_p} \tag{2.24}$$

Larsen's derivation for the sphere- cylinder case is presented in Appendix 2.1. An experimental verification of the Larsen equation is not possible without a measure of the size of the liquid pool layer which cannot be readily measured experimentally. On the other hand, knowledge of the experimental separating force for fiber-sphere geometry would provide information on the interfacial pool size, contact angle, etc. Corn studied the adhesion forces between spherical quartz particles and Pyrex fibers with a microbalance technique at 90% R.H. These data are shown in Figure 2.21 as percent of adhesion to a flat surface vs D_f/D_p. The probabilistic nature of adhesion forces discussed above for a group of particles on a substrate is also evident in the data of Figure 2.21. Here attachment and separation of a single particle to the same surface resulted in a distribution of forces. This observation supplements the data presented previously by Krupp and by Zimon, for a single particle attached several times to the same surface and then separated. Corn also plotted the Larsen equation (2.21) in Figure 2.21 for the fiber and particle sizes of his experiment ($0.2 \leq D_f/D_p \leq 40$; $50 \leq D_p \leq 250$ μm) in terms of the fraction of adhesion to a flat plate. He found agreement with the form



D_f/D_p	D_p/D_f	$1 + D_p/D_f$	$(1 + D_p/D_f)$	$1 - D_p/D_f$
0.2	5.0	6.0	0.167	-
0.5	2.0	3.0	0.33	-
0.8	1.25	2.25	0.45	-
1	1	2.0	0.5	-
2	0.5	1.5	0.67	0.5
5	0.2	1.2	0.83	0.8
10	0.1	1.1	0.91	0.9
20	0.05	1.05	0.95	0.95
40	0.025	1.025	0.975	0.975

DIAMETER FIBER (D_f)/DIAMETER PARTICLE (D_p)

Figure 2.21. Effect of Fiber Size on Adhesion of Quartz Particles to Pyrex Fibers (From Corn, Ref. 74).

of the function within 10 percent. It is evident that Larsen's equation (2.21) is of limited usefulness without data on the third (unknown) parameter, i.e., the diameter of the interfacial liquid geometry. Under the assumption that the pool diameter is small with respect to either the fiber or particle diameter such that $K_c \ll 1$, Larsen's equation can be satisfactorily approximated for computation by

$$F_a \approx 10^2 D_p \left(1 + \frac{D_p}{D_f}\right)^{-1} \tag{2.25}$$

Data calculated for this approximation are indicated by squares in Figure 2.21. For $D_p \ll D_f$, the leading term of the series expansion $(1 - D_p/D_f)$ provides a reasonable estimate, as shown in the calculations. Larsen's equation represents essentially the solution to the two-sphere problem, but approximates the sphere-cylinder data produced by Corn.

Since irregular shapes are less tractable, resort to experiment is required. Data for various surfaces and particles are presented in Table 2.10 (from Zimon, Ref. 66, p. 111). The adhesive properties of flat platelets (graphite, kish, mica) which may have many points of contact, approach theoretical values. These forms are less frequently encountered than irregular, three-dimensional shapes.

Engineering estimates of the force of adhesion for many cases of practical concern at or near 95 percent R.H. can be approximated by:

$$\text{2-sphere;} \quad F_a = 10^2 \, D_1 D_2/(D_1+D_2) \qquad (2.26)$$

$$\text{Sphere-plane;} \quad F_a \approx 10^2 \, D_p \qquad (2.27)$$

$$\text{Sphere-cylinder;} \quad F_a = 10^2 \, D_p(1+D_p/D_f)^{-1} \qquad (2.28)$$

Reduction in R.H. reduces adhesion as indicated approximately in Equation (2.15). Adhesion for small particles (< 20 μ) may be little affected by humidity (c.f. Figure 2.19).

(4) Effects of Surface Roughness on Particle Adhesion - Larger particles ($200 \leq D_p \leq 10^3$ μm) and most plane surfaces of technical interest have surface irregularities (asperities) of the order of a few microns or less, depending upon manufacturing and finishing processes. The effect of surface roughness was studied by Corn and by Bowden and Tabor, Table 2.11. Corn's data were obtained with a Stylus profilometer on optical flats and glass slides. Bowden and Table used polishing techniques with various finishing compounds. All data indicate a consistent reduction of the predicted adhesion force as asperity size increases. A physically acceptable model (assuming a single contact) would be the force relationship between two spheres with the apparent size of the smaller sphere approximately equivalent to the size of the asperity ($h \ll D_p$). Therefore:

TABLE 2.10

ADHESIVE FORCE OF PARTICLES DETERMINED BY VARIOUS METHODS FOR VARIOUS AIR HUMIDITIES*

Substrate material	Particle Material	D_p, μm	Fa, dynes for air humidity 50-60%	90%
Pyrex	Detachment of individual particles			
	Quartz (fused ends of filaments)	25	0.28	0.37
		36	0.3	0.55
		63	0.6	0.76
		88	0.88	1.38
Glass	Glass	400	22	-
		800	30	-
	Centrifuging for γ_F = 2%			
Glass	Glass	50	0.37	1.83
	Sand	50	0.76	0.06
	Coal	50	0.55	0.94
Plexiglas	Glass	50	1.44	1.97
Teflon	Sand	50	0.65	1.28
Brass	Coal	50	0.90	2.85
	Centrifuging for γ_F = 50%			
Starch	Starch	7-9	0.2	-
		13-15	0.2	-
		18-21	0.2	-
Gold	Gold	4	0.07	-
		5-6	0.09	-
		7	0.1	-
		8	0.16	-
	Vibration method for γ_F = 2%			
Steel	Glass	40-60	1.64	-
	Vibration method for γ_F = 50%			
Steel	Glass	5-10	$1.33 \cdot 10^{-2}$	-
		10-20	$6.12 \cdot 10^{-3}$	-
		20-30	$2.15 \cdot 10^{-3}$	-
		40-60	$2.13 \cdot 10^{-4}$	-

Note γ_F = fraction of particle numbers remaining attached after application of indicated force.

*From Zimon, Ref. 66.

TABLE 2.11 EFFECTS OF SURFACE ROUGHNESS IN ADHESION

Plate	RMS Depth μm	Force,* Dynes	% Fa**	$h/D_p \times 10^2$	$1 + 10^2 h/D_p$	Remarks
Pyrex flat 1	0.21	0.27	27	0.42	1.42	From Corn, Refs. 72, 74
Pyrex flat 2	0.29	0.17	17	0.58	1.58	50 μm quartz particles
Microscope Slide	0.34	0.15	15	0.68	1.68	95% RH
Pyrex flat 3	0.48	0.12	12	0.78	1.78	
Glass, highly polished	0.015	9.2	~100	0.006	1.006	From Bowden and Tabor
Glass, 500 Carborundum Paper	0.10	7.3	79	0.04	1.04	Ref 75, cited by Corn
Glass, 320 Carborundum Paper	0.40	4.7	51	0.15	1.15	Ref 73, 260 μm glass particles
Glass 150 Carborundum Paper	10.0	~0	~0	4	5	

* From Corn, Ref. 72, or calculated from $F_a = 2\pi\gamma_{H_2O} D_p$.

** % of $F_a = 2\pi\gamma_{H_2O} D_p$, theoretical value for perfect sphere and plane with capillary condensate.

$$F_a \simeq 10^2 \left(\frac{h\,D_p}{h + D_p} \right), \qquad (2.29)$$

i.e., condensation of moisture at the radius of curvature is determined by the size of the pip. Using the same argument as that for the sphere-sphere case, let D_a = pip (asperity) height and D_p the particle diameter:

$$F_a \sim D_p \cdot f\ (1+C_1 \frac{h}{D_p})^n \qquad (2.30)$$

The ratio h/D_p was multiplied by 100 (arbitrarily, to fit data to a curve) and plotted vs the reduction of adhesion from $2\pi\ \gamma H_2O\ D_p$ as shown in Figure 2.22. A function suitable for technical estimation of the effect of surface roughness at 95% R.H. is obtained from Figure 2.22 as

$$F_a = 2\pi\ \gamma_{H_2O}\ D_p\ (1+10^2 h/D_p)^{-4} \qquad (2.31)$$

where $50 \leq D_p \leq 250$ μm, and h is the mean asperity height, $0.01 \leq h \leq 10$μm. Further work is required to improve the prediction of adhesion on surfaces encountered in practical devices. A contributing factor to surface roughness in practical systems is the deposition of fine fugitive dust from the ambient atmospheric aerosol and from industrial processes. Corn[72] studied the effects of carbon coatings on his quartz particles (to Pyrex flat). Typical results of interest are:

	D_p μm	R.H.	Measured Force, dynes	$2\pi\gamma_{H_2O}D_p$ dyne	$\%F_a$	$1+10^2 h/Dp$
Vacuum evaporated carbon	36	93	0.26	1.5	17	--
	36	46	0.23	---	--	--
Acheson "Dag" colloidal graphite, dip and dry	79	93	0.03	3.3	2.4	2.3
	51	90	0.08	2.1	3.8	3.0
	79	46	0.03	---	---	---

The average sized particle in the colloidal graphite was reported to be 1 μm.[72] The lower adhesion in this instance was attributed by Corn to

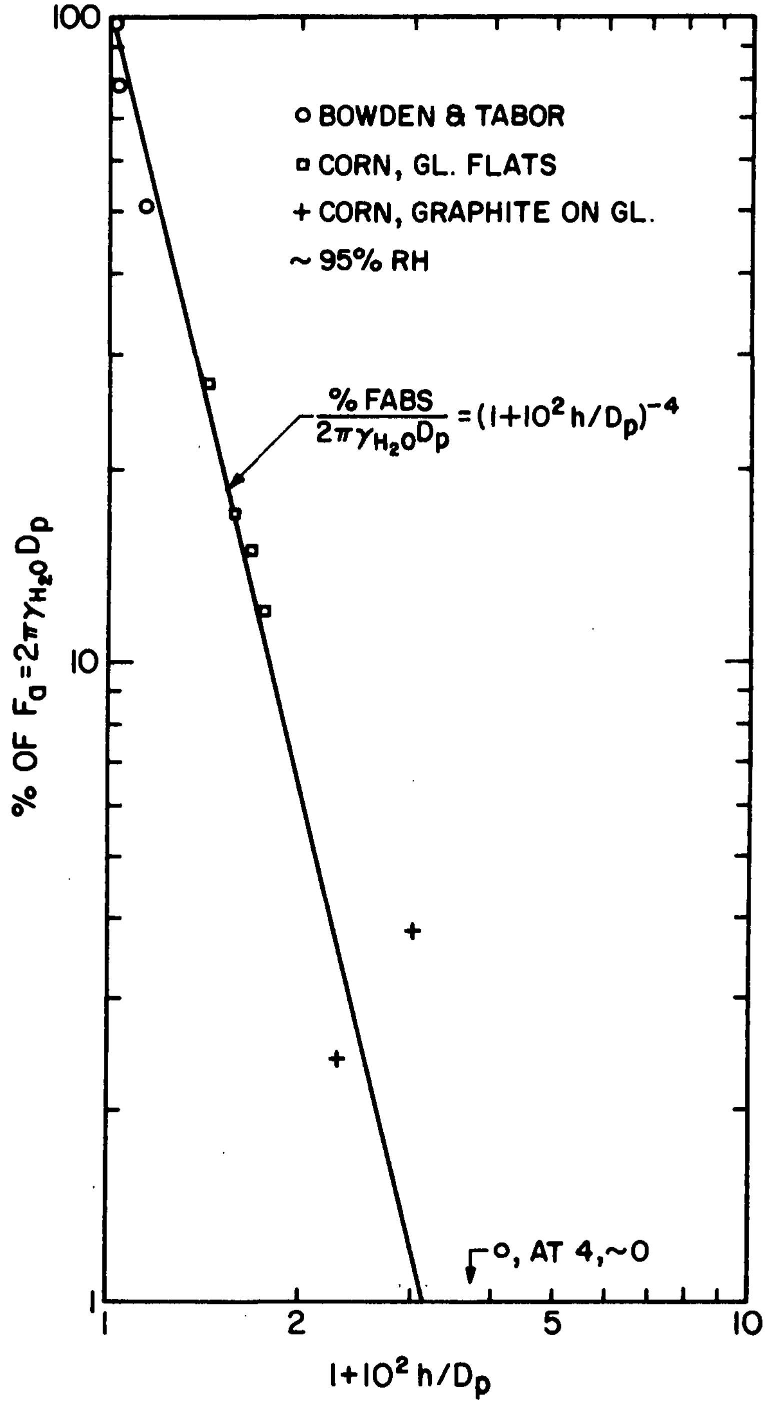
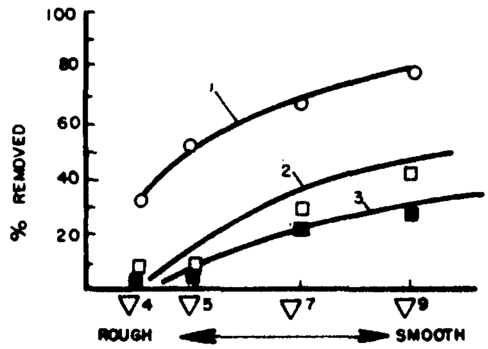


Figure 2.22. Effect of Surface Roughness on Particle Adhesion. (From Corn, Ref. 72).

surface roughness. Using the data above, h/D_p is approximately 1/79 or 0.0126 and $(1 + 10^2 h/D_p)$ is of the order of 2.3. Adhesion was observed to be approximately 2.4 percent of that predicted from condensation expectations. Selected data from Corn's experiments on surface coatings which are indicated on Figure 2.22, tend to support the computational approximations given above. The effect of the evaporated carbon coating on reduction of adhesion may be related to the change in contact angle for water on a hydrophobic carbon surface ($\theta \approx 86^\circ$ for graphite, to 180° for carbon black, vs 0° for glass).[76,77] The evaporated carbon film depth in Corn's study was probably at least a few 0.01 μm.

Additional experimental data on effects of surface roughness are presented by Zimon (Ref. 66, p. 93 et seq.) but with only qualitative estimates of roughness height, Figure 2.23 a, b and c. Three conditions are proposed. In the first, where the plane and sphere are ideally smooth, the forces can be calculated from fundamental considerations. In the second case, where the substrate contains microscopic asperities generally smaller than the particle dimension, the adhesion force is decreased. In the third case, the roughness depth is of the order of the particle size and the particle rests in a trough, leading to increased contact area and greater adhesion.

Surface coatings (i.e., paints) and viscous adhesive films (e.g., oil or adhesive-coated high velocity filter fibers, impactor or settlement plates for fallout catch) modify the adhesion phenomena described above. Penetration of particles into the viscous film will, in general, be expected to produce adhesion forces in proportion to the viscosity.[68] Tacky or oily surfaces provide much larger adhesion forces, depending largely on the depth of the film, and degree of particle penetration. Condensible components in the gas may accumulate on fibrous filter collections, leading to such high adhesion forces that simple mechanical (shaking) or pneumatic (jet or pulse) cleaning mechanisms, developed for dry dusts in non-condensible gases, are unable to provide sufficient dislodging energy. This does not imply that such deposits are unfilterable (or uncollectable), but only that cleaning techniques com-



(a) Adhesion of spherical glass particles $40 \pm 5\ \mu$ in diameter as a function of the class of finish on cast iron surfaces for various detaching forces. (1) $F_{det} = 2.2 \cdot 10^{-2}$; (2) $9.3 \cdot 10^{-2}$; (3) $22.4 \cdot 10^{-2}$ dyn.

(b) Profilograms of steel surfaces (magnification: horizontal, 1050X; vertical, 2000X).

(c) Types of substrate roughness associated with the adhesion of particles.

Figure 2.23. Effects of Surface Roughness on Particle Adhesion (from Zimon, Ref. 66)

monly employed are inadequate to overcome the forces present. Typical combustion effluents in which condensation of moisture occurs (incinerator, boiler plant) are generally not amenable to filtration with present cleanable industrial filters for this reason. Similar restrictions apply to tarry deposits, but in stationary applications recourse to continually washed or wetted collecting surfaces can prevent buildup of thick viscous deposits. Attempts to use fibrous filters or electrical precipitators on particulates from internal combustion engine exhaust with widely varying moisture content (cold to hot cycles) have generally been unsuccessful because of condensation problems associated with the capture or disposal of the particulate components. The collection of non-wettable carbon black particles in electrical precipitators is related to the adhesion and moisture adsorption character of the deposit. The particles build up to large, fluffy aggregates and blow-off the collecting plates (because of the low charge conduction and few adhesion points). Adhesion of carbon black aggregates to surfaces should be low, based on the relatively low affinity of the carbon surface for water, (i.e, large contact angle, $\geq 90^{o}$, for the interface carbon-air-water). These same aggregates are subsequently recovered satisfactorily in filter collectors with tightly woven fabrics where adsorbed moisture effects on particulate accumulation mechanisms are less significant.

(5) Adhesion Phenomena in Ensembles of Particle Deposits - Adhesion phenomena in ensembles of particles are related to the size distribution of the components in the deposit, to the manner in which the particles attach to each other and the substrate, and the relative adhesive forces that occur. Typical deposits of particles on fibers in the early stages of filtration before formation of a complete cake are discussed below. Aggregates of particles build up outward from the fiber surface and form bridges over interfiber openings. As deposition continues, and particularly in repetitive filtration as in cleanable fabric filters, fibers will presumably become dust coated. On the limiting case, extended fabric use with certain polydisperse aerosols may plug the fabric to the point that effective filtration is no longer possible. There are no reported microscopic observations of the history of deposition, aggregate formation, and location of residual dust deposits in fabric filters operated cyclically. At the particle-fiber (fabric) level, the deposit

probably appears approximately as indicated in Figure 2.24a. Removal forces are applied to overcome adhesion and clean the fabric by either vigorously shaking the fabric as in (b) or by directing air flow backward through the fabric, as in (c). In either cleaning mode, fabric flexure and local deformations occur, tending to separate adjoining particles and fibrils. In the shaking mode, a reciprocating motion is produced on the fabric, causing an acceleration of the fabric and dust, which at the maximum displacement is

$$a = 2\pi^2 \delta \omega^2 \qquad (2.32)$$

where a = acceleration, cm sec^{-2}

δ = displacement, cm

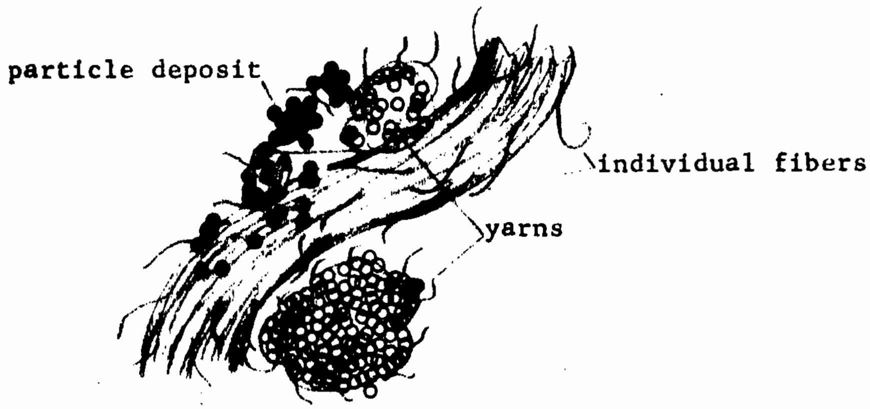
ω = cycle frequency, sec^{-1}

The force applied to the deposit is

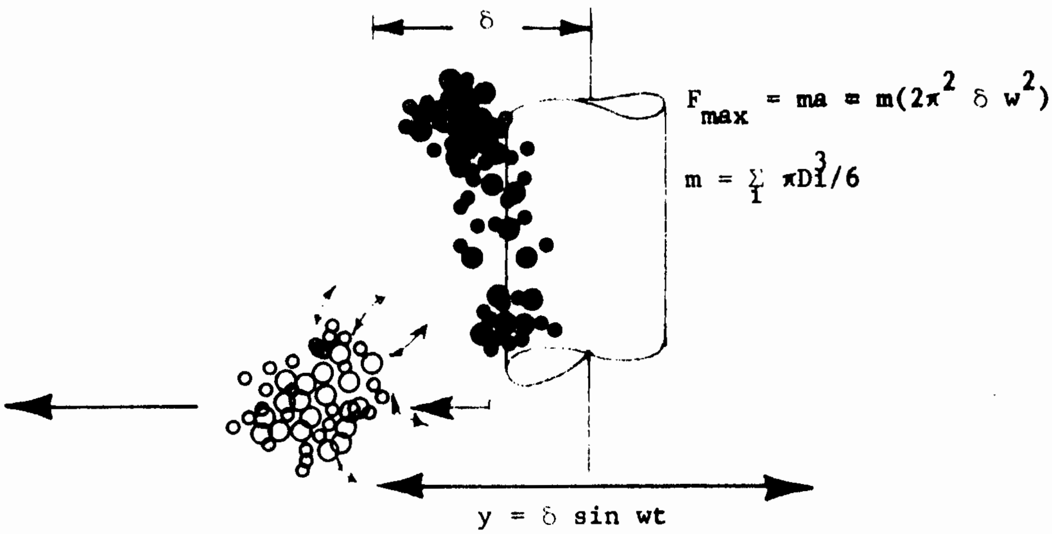
$$F = ma \approx a\rho \sum_i \pi D_i^3/6 \qquad (2.33)$$

The mass set in motion is illustrated schematically in Figure 2.24 (b) and is equal to the sum of the masses of the individual particles separated. Points of prior attachment are indicated by small arrows, each having an adhesive force overcome by the inertial force developed within the deposit. The deposit is actually three-dimensional, but estimates of the mass removed for typical accelerations produced in shaker-type cleaning can be made from the schematic model. If particles were 10 μm, and 10 attachments were involved, for 3g acceleration (typical) the mass of the aggregate removed would be approximately ($F_a \approx 0.1$ dyne x 10 particles) 10^{-4} grams or about 10^6 particles (i.e., ~ 100 μm spatial extent). When the dust deposit is large in amount and extent, gravitational effects will be expected to produce additional forces. The analysis of the forces arising on a granular deposit, from gas flow backward through the layer as in Figure 2.24 (c), can be approximated for estimating purposes as

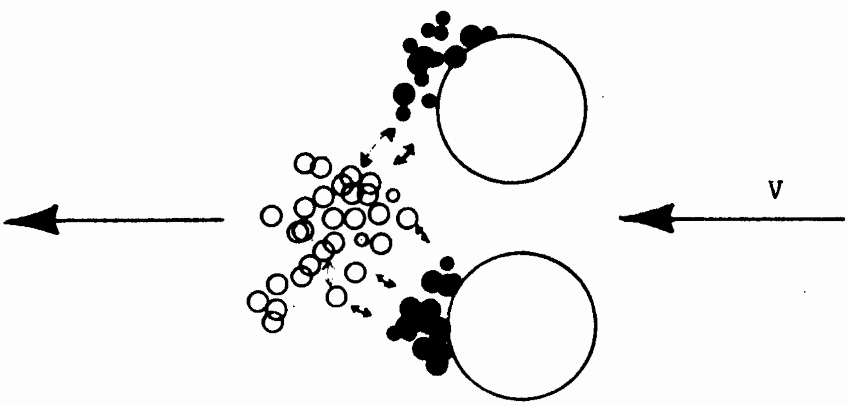
$$F \approx n(3\pi D_p \mu V) C_2 \qquad (2.34)$$



(a) Schematic, Particle Aggregate Development in Fabric Filter Cake



(b) Model of Shaking Method for Removal of Dust Cake in Fabric Filter



(c) Model of Reverse-air Cleaning Method for Removal of Dust Cake in Fabric Filter

Figure 2.24 Schematic of Cake Build-Up and Removal in Fabric Filter where n = the number of particles in the layer and C_2 is a cake drag factor. For the same 10^6 particles of 10 μm diameter as calculated above, flow of air backward through the deposit at the same velocity (~3 ft/min) as the forward filtering flow (after filter flow has been stopped) would be estimated to produce a force of the order of one dyne, or sufficient to overcome adhesion forces at 10 particles. These estimates are intended to illustrate the type of calculation that could be made if observations or data were available on deposit geometry and aggregate structure in fabric filters during deposition and cleaning. Very few studies have been made on the size of aggregates removed upon filter cleaning as a function of deposit geometry or cleaning energy. None affords sufficient data for a detailed analysis as suggested above, however. Those observations that are available (e.g. E. Anderson,[78] Billings et al.,[79] Larsen,[68] Corn,[80] Taub,[81] indicate that the material removed from filter surfaces (by air flow, jet action, or shock flow) consists of aggregates of many individual particles, of substantial aggregate size, and further, that aggregate size removed tends to be smaller upon application of greater cleaning energies.[79] These studies suggest the use of a primary filter screen as a particle agglomerator prior to secondary inertial collection, followed by tertiary filtration.

Air velocities required to remove single particles (~20 μm) from individual filter fibers are generally greater than 10 m/sec (> 2000 ft/min). Velocities of this order are used in reverse-jet cleaned fabric filters, but are not typical of other commercial cleaning methods. All practical methods utilize fabric flexure as well as an applied force. The possibility of cleaning fabric filters by means of air flow directed along the dust cake (parallel to it) has been suggested in certain commercial cleaning methods, but Zimon (Ref. 66, p. 308) indicates that flow velocities of the order of 20 m/sec are required (but without citation as to source of experiments). The discussion of fabric filter cleaning in Zimon's comprehensive test is limited to 6 pages (303 to 309) illustrating the lack of knowledge on this subject. Table 2.12 (from Zimon, Ref. 66, p. 112) illustrates adhesive forces observed experimentally for separation

TABLE 2.12

ADHESIVE FORCE OF A POWDER LAYER*

Substrate Material	Particle Material	D_p, μm	F, dynes (referred to 1 cm^2)
Steel	Glass (spherical particles)	60-90	1.1
		40-60	21.7
		20-30	208.0
		10-20	370.0
Steel	Aluminum oxide	324	37
		163	42
		97	67
		81	90
		68	85
		47	103
		35	143
		25	223
Steel	Lime dust, ordinary non-wetting type	-	520
Glass	Magnesite	200-300	39
		150-200	56
		88-150	83
		75-88	116
		60-75	169
Magnesite	Magnesite	200-300	29
		150-200	40
		88-150	60
		75-88	89
		60-75	103

*From Zimon, Ref. 66, p. 112.

of powder layers of various materials from various materials from various substrates. No filter fabrics were represented in Zimon's Table 2.12. Corn[73] studied removal forces for individual quartz, particles from wool felt fabric and all-glass filter paper (used in high-volume samplers) with results as shown in Figure 2.25. Cleaning methods in commercial fabric filters are developed entirely empirically, without regard to fundamental properties of the particle-fabric system.

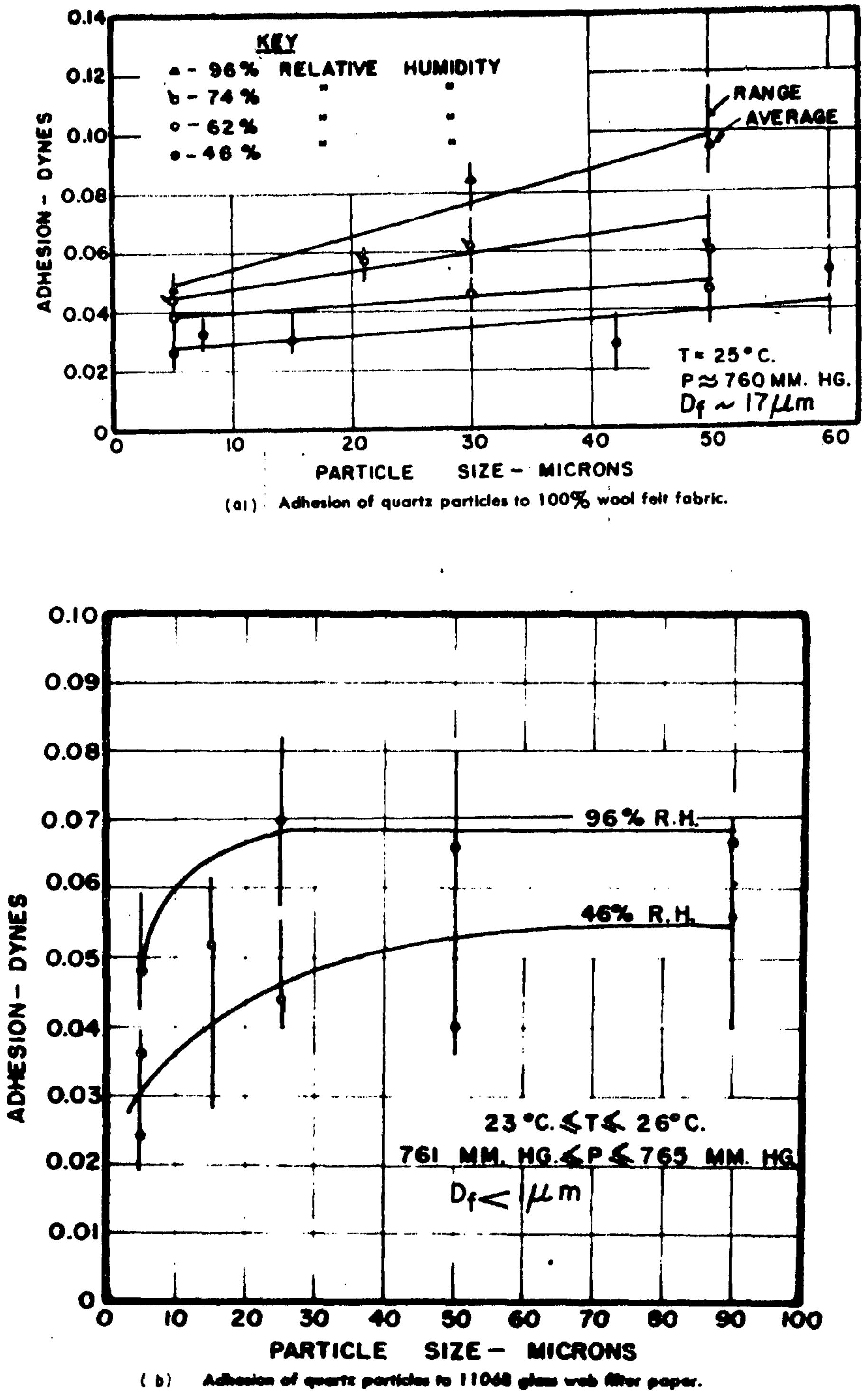
The coefficient of friction of powdered materials sliding on themselves is an index of particle internal adhesion. A technical measurement of such property is easily performed. Typical values for several materials are given in Table 2.20a. Carr[134] discusses technical measures of powder adhesion indices by simple spatula-dip and angle of response techniques. The relationship of these simple tests to actual adhesion forces at the particle and aggregate level are not available.

2.2.2.9 Summary of Particle Properties.- The above discussions indicate that there are two major characteristic groups of properties of particulates that affect the development of a filter cake on a fabric and its subsequent removal:

1. Particle size, size distribution, structure, density, and the shape (morphology) of aggregates affect collection efficiency and pressure drop of the layer.
2. Particle charge, electrical characteristics, adsorptive properties (especially with respect to ambient water vapor) and adhesion affect the cleanability, in conjunction with properties of the fabric substrate and cleaning mechanisms and kinetics.

Electrical charge and adhesion also affect aggregate morphology, collection efficiency,and pressure drop, as discussed below.

These aerosol and powder properties are not simply measured in fabric filter systems of practical interest and little data are available relating these properties to filter performance, i.e, pressure drop, efficiency, life, and costs. Further investigations of particle properties in relation to filter performance would be required for cost-benefit analysis.



(b) Adhesion of quartz particles to 1106B glass web filter paper.

Figure 2.25. Adhesion of Quartz Particles to Wool Felt Fabric and all-glass filter paper (from Corn, Ref. 73)

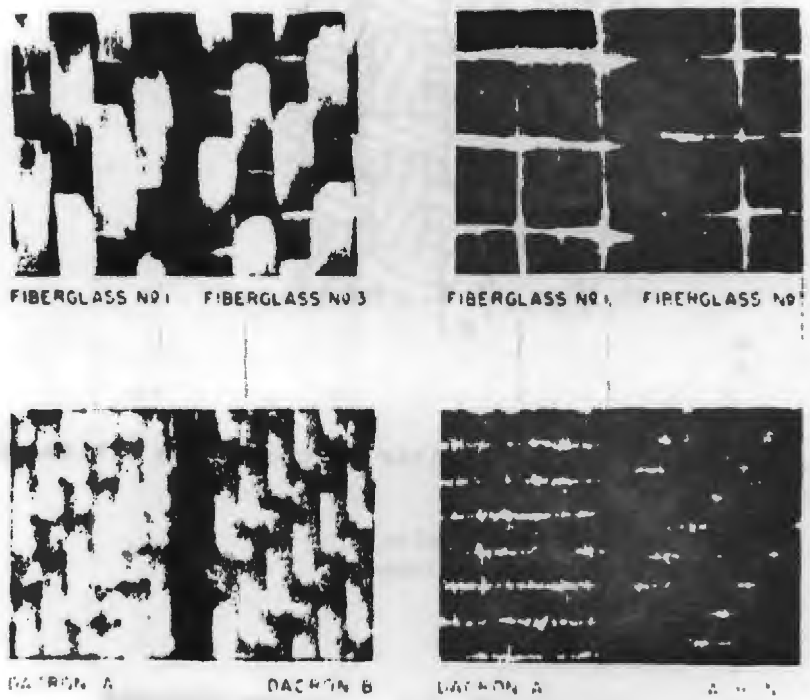
This treatment of aerosol technology covers only those areas judged to be significant for fabric, fibrous, and granular filtration. Appendix 2.2 contains references to further sources of information on the properties, characteristics, and occurrences of aerosols and the relationships of aerosol technology to contemporary engineering and science.

2.3 FABRIC FILTRATION PROCESSES

2.3.1 Introduction

The fabric filtration process is concerned with filtration of solid particles (usually) by fibrous, woven fabric, and granular obstacles placed in the flow stream. A fabric is a porous flexible textile material made by weaving yarns (twisted fine fiber strands of many individual filaments or staple long fiber) or by felting a random array of fibers. The appearance of typical woven filter fabrics is shown in Figure 2.26(a)[82]. Yarns are composed of spun staple or continuous monofilament stranded fibers. Yarns are visible to the eye, as in any common woven textile material, and are of order 100 to 500 microns in diameter. At the relatively low (20x) magnification of Figure 2.26(a), filter fabric appears quite dense, with reflected light. Illumination from below with transmitted light indicates a regular pattern of openings between the yarns (Figure 2.26(a), right-hand side).

In the case of spun yarns, individual fibrous filaments (the basic textile elements within the strands) occur within the interyarn (interstitial) spaces, as shown diagramatically in Figure 2.26(b).[83] Similar projecting filaments, 5 to 10 μm diameter, and 5 to 20 μm long serve as exterior obstacles for the initial capture of dust materials in the interweave spaces. Figure 2.26(c) illustrates the appearance of cotton (sateen) filter fabric at high magnification. The interstitial filaments (individual cotton fibers) can be seen projecting between the yarns. It is evident from the appearance of these woven fabrics that the majority of gas flow during each filtration must pass between the tightly twisted yarns, that is, through the interstitial spaces. If the optical density distributions in the photographs of typical fabrics in Figures 2.26(a) and (c) are any index of the local permeability of the fabric, it would appear that little flow could pass through the yarns. Therefore the



(a) Comparisons of structural characteristics of fabrics (20X)
(from Spaite and Walsh, Ref. 82)

Construction Details of Test Fabrics

Filter Fabric	Fiberglass			Dacron	
	No. 1	No. 2	No. 3	A	B
Air Permeability (cfm/ft² at ½" H_2O)	13.84	11.67	7.86	28.06	14.62
Weight (oz/yd²)	8.41	8.67	9.06	5.51	6.06
Yarn Count	55 x 50	55 x 54	55 x 58	82 x 62	82 x 76
Filament Diameter (in.)	0.00025			0.00113	
Filaments Per Strand	408			50	
Strands Per Yarn	2			1	
Twists Per Inch	3.8			3.5	
Weave	3/1 Crowfoot			3/1 Twill	
Finish	silicone			silicone	
Approx Yarn Diam (μ m)	200				

Figure 2.26. Typical Woven Filter Fabrics

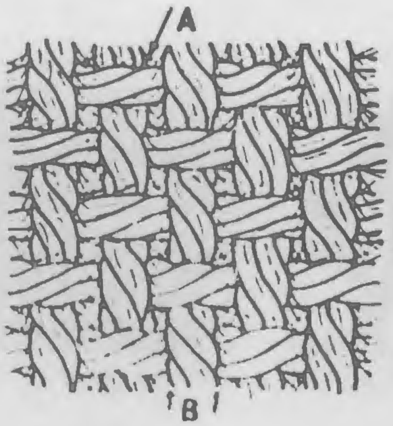


Figure 2.26 (b) Diagram of Plain-weave Filter Fabric. (From Stairmand, Ref. 83)

A. Hairs, 5 to 10 u diameter
B. Main strands, 500 u diameter

Figure 2.26 (c) Typical Sateen-weave Cotton Filter Fabric, 60 x. (Engineered Fabrics Corp., Style 1210, plain finish, 15-20 permeability, 310 Mullen burst, 9.70 oz./sq. yd. 96 x 60 count.)

Figure 2.26. Typical Woven Filter Fabrics (Continued)

process and the progress of filtration at least initially, depends upon the characteristics of the interyarn spaces, and not necessarily on yarn count or weave design.

Fiberglass yarns, and other man-made continuous filament yarns probably present few interstitial fibers in the woven form. Therefore they are expected to be poorer fabrics from the standpoint of reduced collection efficiency and greater seepage of deposits. Lower flow rates are required for satisfactory field performance. Deposits that build up in these fabrics have fewer locations in the interstitial spaces to build bridges on, and are probably more susceptible to pressure drop forces in deposit collapse and bleed (seepage) in the effluent. The use of staple yarns, or bulked or texturized glass yarns, with many projecting filament ends would be expected to improve the collection efficiency and stability of deposit at higher flow velocities. Effects of interstitial fibers on improved dust-holding capacity and pressure drop should also be evident. Repeated filtration and cleaning cycles will cause a gradual accumulation of residual deposit in the interstices, between yarns, and later in the interfiber spaces.

The initial phase of the filtration process begins with the capture of individual particles by single fibers within the flow field (presumably in the interyarn spaces). Particles that deposit on fibers projecting into the flow then act as additional obstacles for future capture of particles. A deposit accumulates on the individual fibers in the form of loose chain-like aggregates projecting into the flow.

Observations of particle deposits during initial stages of filtration before formation of a complete cake are illustrated in Figures 2.27 through 2.31.[84-88] Table 2.13 summarizes microscopic observations on the structure of solid particle deposits on fibers, including data pertaining to certain of the figures (2.28, 2.29, 2.30, 2.31).

Figures 2.27(a) and (b) indicate the effect of time on particle deposition and aggregate growth at constant loading (uniform 1.3 μm particles, $10^3 p/cm^3$) and constant filtering velocity at the same site on isolated untreated fibers.[84] Structure of aggregates indicates that deposition occurs primarily on previously deposited particles (filtering

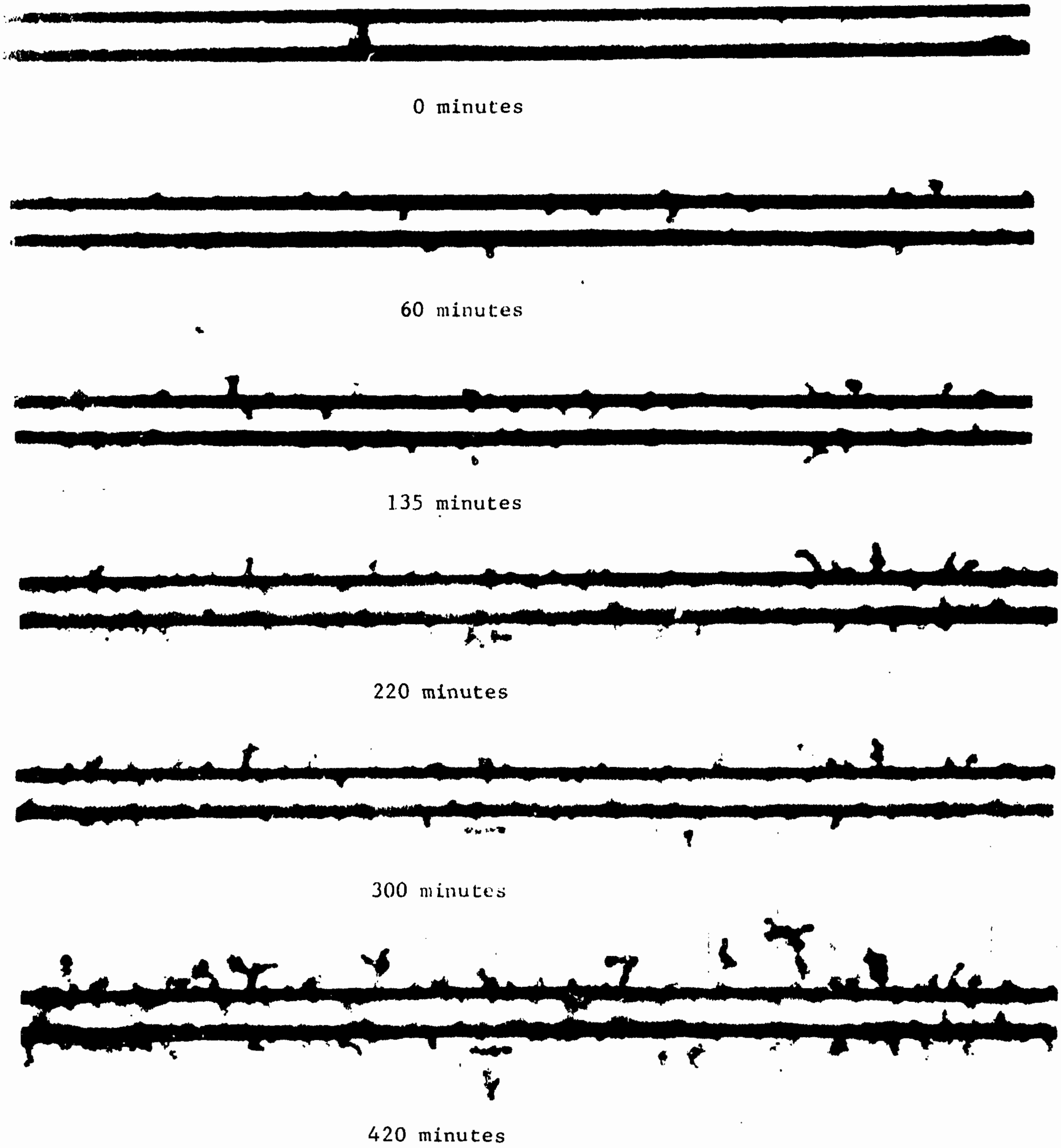
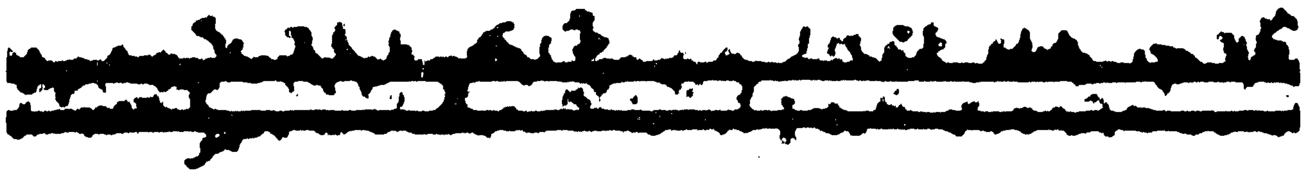


Figure 2.27a. Deposits of 1.305-micron Polystyrene Latex Spheres on 8.7-micron Diameter Glass Fiber operated at 13.8 cm/sec at an approximate concentration of 1000 p/cm^3. Aerosol flow into photograph. (From Billings, Ref. 84).

(a) 120 minutes



(b) 220 minutes

Figure 2.27b. Same as 2.27a, but 9.7 micron diameter fiber and 29 cm/sec. (From Billings, Ref. 84).

efficiency increases). Higher velocities appear to produce more compact aggregates, closer to the fiber. Tomaides[92] has reported that projecting aggregates tend to bend in the flow and become detached at higher velocities, when aggregate length exceeds about 10 particle diameters. Figures 2.28 and 2.29(a) and (b) illustrate the formation of aggregate deposits on sub-micron glass fibers in filtration of methylene blue (filter test aerosol)[85] and metallurgical fumes (Mg ZnO).[86] The tendency for aggregates to form on previously deposited particles is evident in these figures. Substantial amounts of bare fiber remain in each case. Figure 2.30 illustrates formation of particle aggregates of oil orange dye (aerosol L-1) and NH_4Br (S-1) on

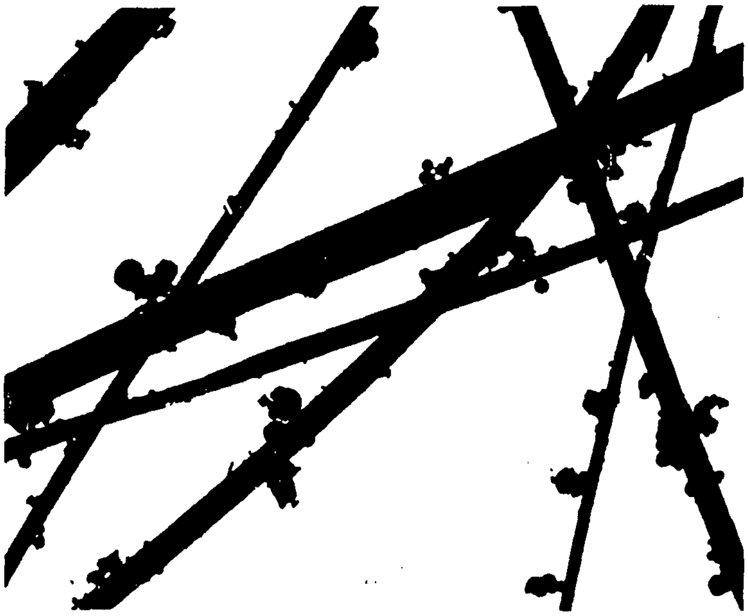


Figure 2.28. Electron micrograph of methylene blue particles caught on glass fibres (from Dorman, Ref 85).

glass fiber at velocities from 1 to 23 ft. per sec[87] (aerosol flow from left to right). Aerosol L-1 formed long hairy filaments projecting upstream into the flow. Note that the rear side of the fiber, away from the flow, is completely bare, a typical observation. Aerosol S-1 formed short chains and clumps at the lower velocity (75 ft/min) and a denser, more uniform deposit at higher velocities (600 and 1400 ft/min). The morphology structure and density of aggregates formed during filtration are a function of aerosol material and deposition velocity. The deposit structure, which influences the porosity and permeability of the filter cake, has important consequences in the estimation of fabric filter pressure drop. As indicated previously, aerosol particles reaching the filter face may also consist of aggregated structures (typical metal oxide fumes). Figures 2.31a-d illustrate the formation of substantial accumulated deposits on filter fibers.[87] These large deposits are presumably the immediate precursors of the more or less continuous filter cake typical of normal operating conditions. Pressure drop observed by Wright et al, at the stage of accumulation shown in Figure 2.31 ranged from 2 to 8 times

Figure 2.29a. Magnesium Oxide Fume on Glass Fiber Filter Paper
V = 2.5 cm./sec Magn x 6500, (from Cheever, Ref 86)

Figure 2.29b. Zinc Oxide Fume on Glass Fiber Filter Paper
V= 2.5 cm/sec, Magn x 6500 (from Cheever, Ref. 86)

Aerosol: L-1
Velocity: Approximately
3 - 10 ft./sec.

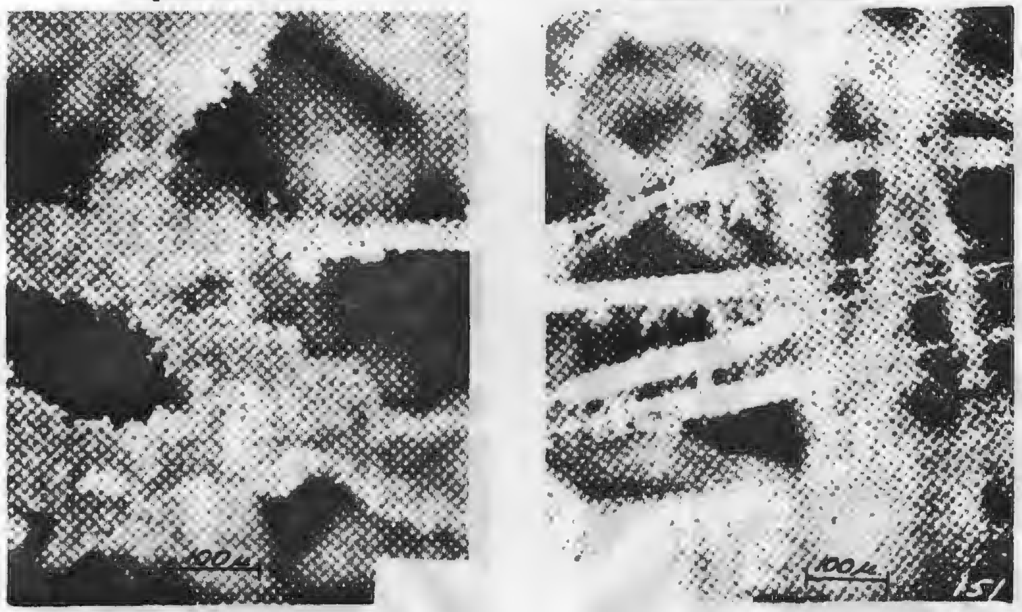
Aerosol: S-1
Velocity: 1.5 ft./sec.

Aerosol: S-1
Velocity: 10 ft./sec.

Aerosol: S-1
Velocity: 23 ft./sec.

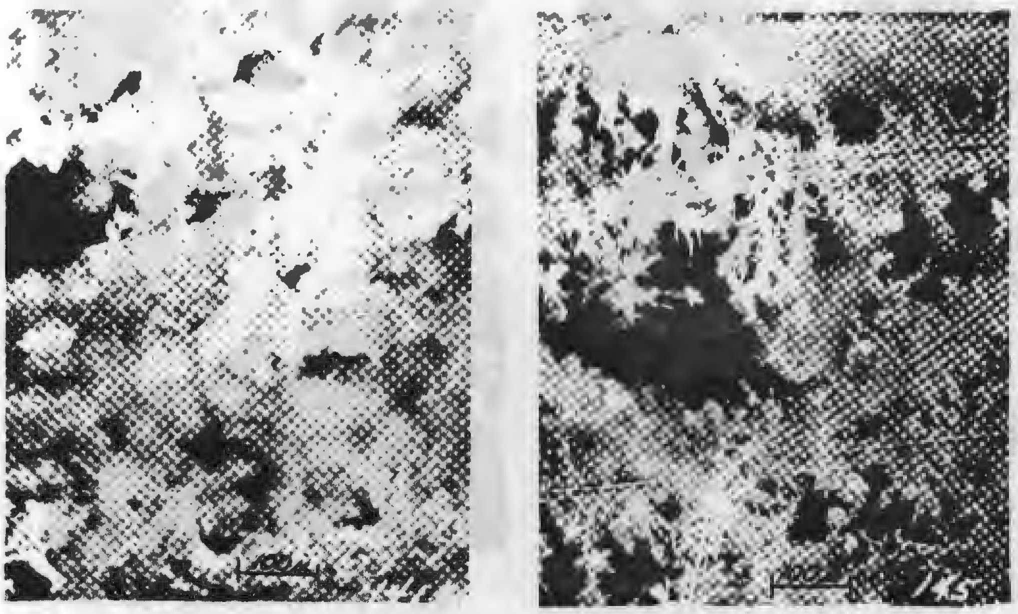
Figure 2.30. Photomicrographs of Fiber 30G loaded in observation chamber (Aerosol flow from left to right).
(from Wright, et. al., Ref. 87)

Upstream face | Downstream face



Aerosol Flow into Photograph | Aerosol Flow out of Photograph

Figure 2.31a. Photomicrographs of Pads Containing Aerosol Special Low Concentration Run; 30 ft./sec. (From Wright, et.al., Ref. 87)



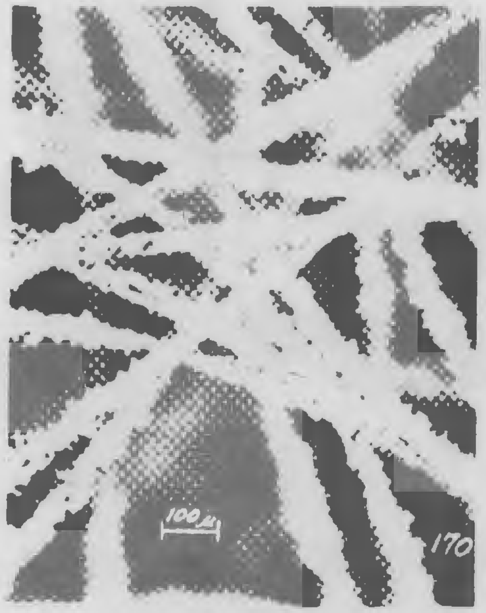
Aerosol Flow into Photograph

Upstream face 1st pad
Velocity: 60 ft./sec.
Pressure drop ratio: 3
Loading: 0.160 cu.ft. aerosol material/cu.ft. fiber

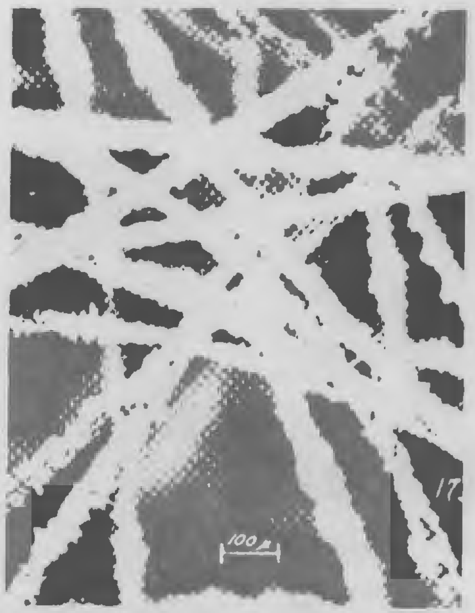
Aerosol Flow out of Photograph

Downstream face 1st pad
Velocity: 1 ft./sec.
Pressure drop ratio: 8
Loading: 0.130 cu.ft. aerosol material/cu.ft. fiber

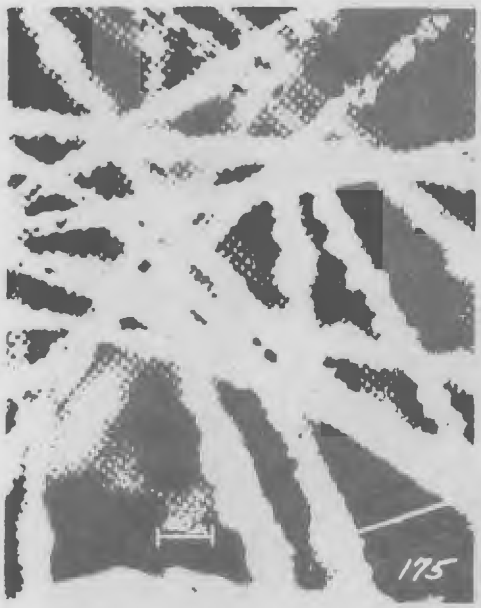
Figure 2.31b. Photomicrographs of Pads Containing Aerosol Various Velocities and Loadings. (From Wright, et.al., Ref. 87)



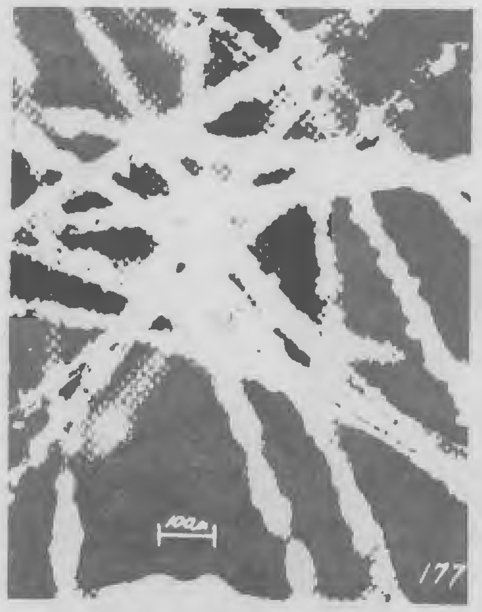
After loading at 1 ft./sec.



After clean air at 3 ft./sec.



After clean air at 10 ft./sec.



After clean air at 30 ft./sec.

Figure 2.31c. Photomicrographs of Pads Containing Aerosol Loaded at 1 ft./sec., followed by Clean Air at 3, 10, and 30 ft./sec. (From Wright, et.al., Ref. 87).

After loading at 1 ft./sec.

After clean air at 3 ft./sec.

After clean air at 10 ft./sec.

After clean air at 30 ft./sec.

Figure 2.31d. Photomicrographs of Pads Containing Aerosol. Same conditions as (c), but 8 times the initial load. (From Wright, et.al., Ref. 87).

TABLE 2.13

OBSERVATIONS OF THE STRUCTURE OF SOLID AEROSOL PARTICLE DEPOSITS ON FIBERS

Investigator	Fiber Material (Diameter)	Particle Material (Diameter)	Particle Shape	Deposit Velocity cm/sec	Structure	Magnific.
Watson (89)	Cellulose	Meth. blue	Sph.	-	Chains and clumps	4,700
	Rubber	NaCl	Cub.	-	Chains and clumps	2,300
	Glass	Carb. bl.	Sph.	-	Chains and clumps	10,000
Leers (90)	Cellulose-Asbestos	NaCl	Cub.	10	Chains	100 (est)
Wright et al. (87)	Glass (30 μm)	Oil Orange (0.3 μm)	Cryst.	200	Chains	100
	Glass (30 μm)	NH_4Br (1.2 μm)	Cub.	45	Short chains	100
	Glass (30 μm)	NH_4Br (1.2 μm)	Cub.	300	Short clumps	100
	Glass (30 μm)	NH_4Br (1.2 μm)	Cub.	700	Unif. deposit	100
Cheever(86)	Glass (0.5 μm)	MgO	Cub.	2.5	Chains and clumps	19,000
	Glass (0.5 μm)	ZnO	Stellar Cryst.	2.5	Needles and clumps	12,000
Dorman(85)	Glass	Meth. blue	Sph.	-	Chains	4,000
Radushkevich and Kolganov(91)	Asbestos (0.06 μm)	Polystyr. (0.25 μm)	Sph.	0.5-25	Chains of 2 or 3	-

the initial clean value for the filter. Such values for accumulation pressure drop are common for high velocity roughing filters (ventilation air cleaning of atmospheric dust) and for high efficiency all-glass filter media (high efficiency papers required for collecting radioactive aerosols, biological sterilization of air in hospitals, production of pharmaceuticals, and in clean-room air supply. Typical pressure drop values for fabric filters are:

Clean, new woven glass fabric ~ 0.06 to 0.02 inches water at 2 ft/min); (permeability, 15 to 50 cfm/ft^2 at 1/2 inch water),

Residual drag, 4 inches of water at 2 ft/min.

The pressure drop ratio: (terminal value in service prior to cleaning/clean, new fabric value) is approximately 200 to 1, and ~100 to 1 after cleaning. It is evident that the characteristic appearance of a filter fabric during service is associated with at least 10 times the amount of dust shown in Figures 2.31a-d. A more or less continuous deposit of accumulated material forms having the appearance of a uniform cake.

The only photomicrographs of the fabric filter cake formation process that have been located are shown in Figure 2.32.[88] The final deposit appears as an undulating layer having surface features reflecting the underlying structures of the fabric, yarns, and projecting fibers. The observations of Figure 2.32 were apparently obtained at relatively low magnification (est. X 10).

Removal of deposited aggregates was achieved in the study of Wright et al,[87] subjecting the system to higher air velocities. Figures 2.31(c) and (d) illustrate the effect of progressively higher blow-off velocities. Substantial cleaning effects occurred only at velocities of the order of 10 meters/sec, which agree with data reported by Zimon and others cited in Section 2.2.2.8(4). Wright tests also included effects of vibration on deposit removal, and studies of efficiency, pressure drop, and depth effects.

Effects of fabric construction on the depth-distribution of deposit is considered below with respect to pressure drop. Felted fabrics, either wool or man-made fiber needle-punched felts, which consist of random orientations of individual filaments having no consistent directional char-

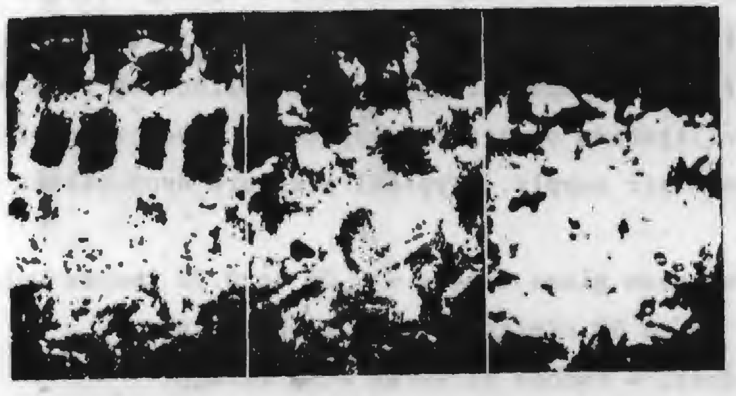


Figure 2.32. Five-ounce cotton cloth, the lower half partially plugged with silica dust. The unplugged meshes in the upper half average 0.2 to 0.4 mm. (After Page) (From Drinker and Hatch, Ref. 88).

acteristics, are more nearly typified by construction of the type shown in Figure 2.31. Phenomena of deposition illustrated in Figures 2.27 to 2.31 are exactly the processes which occur in felts used in fabric filters. The actual deposit formed in a fabric filter has not been carefully observed or reported.

To recapitulate, the process of initial filtration in a clean fabric filter occurs through contact of individual particles with single fibers, then subsequent contact of additional particles with those already deposited, leading to the formation of long chain-like filamentous aggregates, or short stubby clumps. These aggregates continue to grow outward from the fiber. They form more or less continuous interconnections along the fiber, until the fiber is totally covered with a large hairy loose-grained deposit. Fiber junctions fill in, interfiber volume gradually decreases, and probably a more or less continuous deposit or cake forms having an outward appearance at its surface similar to the underlying surface contour. As dust structures become larger, fluid flow is constrained to smaller channels, and pressure effects probably begin to modify, consolidate, and tend to bend, compress, reorient, or compact the underlying structures. Pressure drop rises during accumulation (smaller channels or more obstacles in the flow field) causing a decrease in total flow below some desired value (as a function of the pressure-volume characteristics of the blower used and the system under ventilation). In describing the filtration processes, starting first with a clean (unused) filter and continuing through the final step where the approaching aerosol is filtered by a dust cake or layer, one can establish three distinct filter regimes. These have been characterized by Borgwardt and Durham[177] as blocking or straining (n=2), depth or intermediate filtration (n = 1.5) and finally cake filtration (n = 0). The n term cited parenthetically for each step is the exponent for the resistance change, ΔP, in the following differential equation

$$\frac{d\ (\Delta P)}{dV} = K\ (\Delta P)^n \qquad (2.34a)$$

where dV represents the incremental gas volume passing through filter and K a dimensional constant. If the system flow is nearly constant, it is seen that the rate of resistance rise is most rapid and depends upon the instantaneous ΔP value during the blocking and depth filtration phases. Once the dust cake has developed, however, the pressure term drops out and the classical cake filtration theory applies. A detailed discussion of the latter process is presented in Section 2.4. The accumulated dust is removed from the fabric by stopping the flow and vigorously shaking the element (or by on-line reverse-air or jet cleaning, etc.). Within the limits of available observations, dust structures removed are quite large. However, under usual cleaning circumstances, substantial amounts of the dust deposit remain within the fabric interstitial (inter-yarn, inter-fiber) spaces. Residual pressure drop after cleaning is substantially greater than the original clean fabric value. Complete cleaning is possible, but usually is uneconomical in terms of power or time required, or because of detrimental fabric deterioration.

Upon resumption of flow, after cleaning, on the second filtration cycle, the incoming dust particles presumably see a combination of some bare fiber and a great deal of residual deposited particulate aggregates. The process of filtration then resumes by particle collection on fibers in some locations, and on previously deposited particles and aggregates in other locations. These processes have not been observed at the microscopic level, so the discussion of cake mechanics is in the nature of hypothesis or speculation. The amount of flow will vary locally (over terrain distances of the order of a few hundred microns) depending upon the amount of collected dust that has been removed by the cleaning action. Locations where large amounts of dust have been removed will permit greater initial flow. Pin holes permitting high flow and dust penetration or leakage are commonly observed in the initial stages of filter operation with nearly new woven fabric. However, the high flow velocity through the more open areas also raises the local particle flux (concentration x velocity), causing greater deposition to occur and eventually providing a self-closing tendency for the more open pores. Aggregates again form around fibers, and presumably a more or less continuous dust cake is again formed during deposition and accumulation, as in the initial filtration cycle.

During the initial stages of reconstruction of a continuous particle matrix, efficiency and pressure drop rise rapidly, while the open locations are accumulating a deposit. Filtration proceeds presumably by the interaction of oncoming particles with those already deposited in granular (or cake) filtration. Large pressure drop (or diminished flow) eventually becomes unacceptable in terms of the system requirements, flow is stopped, and the fabric is again shaken to remove a portion of the accumulated deposit. Substantial residual deposited material remains after cleaning, usually more than that remaining after the first cleaning cycle. In typical industrial applications of fabric filters, repeated filtration and cleaning cycles occur over time intervals of a few minutes to a few hours. After some 24 hours (but possibly as much as ~100 hours) the residual deposit after cleaning arrives at a more or less constant value, as governed by the parameters of the cleaning method (energy input). Continued filtration beyond this priming or ageing period results in a relatively constant pressure drop cycle during use and after cleaning. The fabric is essentially saturated or at equilibrium with the deposited residual material, such that no more can be added than is shaken out upon cleaning. If an equilibrium residual deposit does not occur after many filtration and cleaning cycles, residual pressure drop may continue to rise, (slightly less material is shaken off at each cleaning than is added during filtration), causing the condition known as blinding of the fabric. As a result, residual pressure drop is set by blower and system characteristics. More cleaning is then required to remove the residual deposit than is furnished by the original combination of cleaning parameters in use. Fabric can be shaken more vigorously (greater frequency, amplitude, or duration) if this does not damage the fabric. Reverse air can be used to augment shaking, or, depending upon length of time in service, the fabric may be replaced, or laundered, to remove more of the residual deposit. Both seeping and blinding in fabric filters are manifestations of the adhesion between particles and substrate fibrous material (especially man-made monofilament fibers). Therefore, effective bridging of interyarn gaps is difficult to maintain causing material seepage through the fabric during much or all of the filtering cycle. Plugging or blinding of the fabric is the inverse problem, where adhesion forces are greater than removal forces applied by the cleaning method.

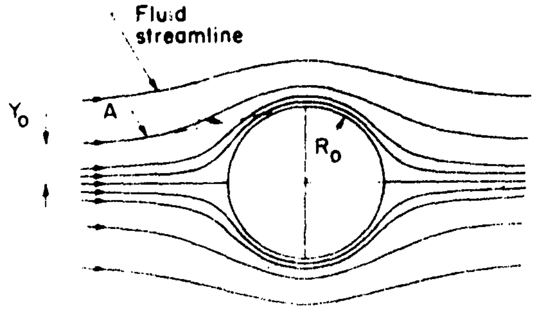
In fabrics that remain in satisfactory service for many cleaning cycles ($10^4 \sim 10^7$), yarns begin to deteriorate from the mechanical flexure and relative motion of adjacent internal fibers in the presence of dust as an abrasive. Individual filaments break, become shorter, the fabric wears thinner at flexure points, and dust penetration increases in these areas. Eventually a thin spot or tear develops that cannot be repaired by the dust buildup during filtration so that the fabric no longer has sufficient integrity for continued service. The fabric is then replaced, or occasionally repaired.

2.3.2 Particle Capture in Fibrous, Fabric, and Granular Filters

Particle collection in filtration occurs as a result of one or more of the following mechanisms:

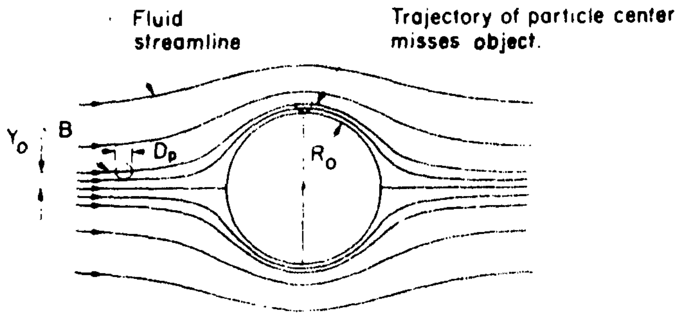
1. inertial deposition as a consequence of the relative velocity between the particle and the fluid as the fluid streamlines separate to pass an obstacle in the flow field (a fiber, or a previously deposited particle);
2. diffusion to surfaces of obstacles as a result of Brownian motion;
3. direct interception or streamline contact with a surface in the flow, arising as a consequence of finite particle size;
4. gravitational sedimentation;
5. electrical separation attributable to particle or obstacle charge, and polarization and space charge effects.

Mechanisms (a) (b) and (c) are illustrated in Figure 2.33.



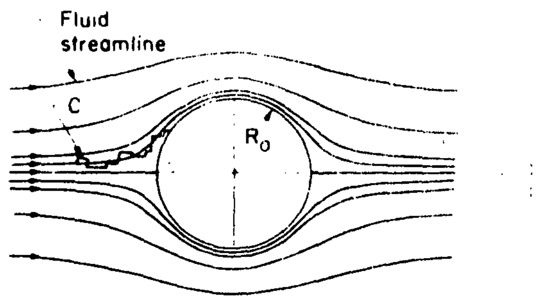
A is trajectory of particle center which just touches **stationary object**.

INERTIAL IMPACTION



B is trajectory of particle center and fluid streamline Particle surface touches object at point of closest approach

DIRECT INTERCEPTION



C is path of particle center due to fluid motion and random diffusion

DIFFUSION

Figure 2.33. Mechanisms of Mechanical Filtration

Theories of particle capture by these mechanisms are based on the following assumptions:

1. collecting obstacles situated in the flow are sufficiently far apart so that the fluid flow in the vicinity of a single obstacle can be represented by the flow near an isolated obstacle, i.e., flow interference effects from adjacent obstacles are neglected;
2. the particles approaching a surface do not interact with or distort the flow to produce additional hydrodynamic lift or drag; and
3. the particles always adhere on contact, i.e., bounce, surface migration, and reentrainment are neglected.

The first assumption is required to define the fluid flow field approaching the object. While it is a reasonable assumption for certain very open fibrous filter geometries, in all cases of interest in operating fabric filters, deposits of large numbers of adjacent particles present on the substrate completely dominate the flow field. Collecting obstacles are close together, and in the case of a deposited layer or cake formation, filtration is presumed to be by deposition of a particle on a previously deposited particle present in a large deposit aggregate.

The assumption regarding particle-surface interaction and hydrodynamic lift or drag is always accepted, but recent studies on particles in laminar shear flow indicate that a lift force may exist.

The third assumption has been investigated with single obstacles and test grids of parallel wires exposed to aerosol flow. Not all particles adhere on contact, and they may bounce, roll, migrate or become reentrained at some later stage in the filtration cycle. Larger aggregates formed during filtration appear to bend in the flow to seek a more stable configuration, or pieces of an aggregate may break off and become reentrained in the flow to deposit further within the filter bed. In continuously cleaned filter fabrics, gradual migration of dust to the outlet side of the fabric has been observed after many filtration and cleaning cycles. Particles deposited at a given velocity may be removed by a higher velocity, as indicated in Figures 2.31(c) and (d). Effects of adhesion of particles to surfaces and to each other upon deposition have been discussed above. For purposes of analysis, it is possible only to define a surface accommodation coefficient, β, related to the ratio of adhesion force to hydrodynamic force. Presumably $0 \leq \beta \leq 1$, where $\beta = 1$ is equivalent to assumption (3) and $\beta = 0$ implies elastic collisions. Although $\beta \neq 1$ in all cases for isolated obstacles, it appears to be close to one for the total filter.

The current theories of filtration have been extensively developed over the past 30 years for bare fibers at the start of the process and are briefly summarized in the following discussion. Effects of deposited material on subsequent performance of filters has not been studied to anywhere near the same extent.

2.3.2.1 Inertial Impaction.- As fluid approaches an immersed obstacle, elements of the fluid accelerate and diverge to pass around the object. A particle suspended in the fluid may not be able immediately to accommodate to the local fluid acceleration and a difference in velocity between fluid and particle may develop. Inertia tends to maintain the forward motion of the particle while the diverging fluid tends to drag the particle aside. Subsequent motion of the particle is the resultant of the inertial projection and the fluid drag. From dimensional considerations, it can be shown that the solutions to the equation of particle motion depend upon the impaction group, defined as:

$$I = 2mV/D_p f \qquad (2.35)$$

where m is the particle mass and f is the resistance of the fluid to the particle motion per unit of velocity. For small spherical particles of diameter D_p, the fluid resistance can be assumed to be given by Stokes' approximation, so that:

$$f = 3\pi\, u_f\, D_p/C_s \qquad (2.36)$$

where μ_f is the fluid viscosity and C_s is the (Cunningham-Millikan) aerosol particle slip correction factor, (Figure 2.34 indicates the variation of C_s with the particle Knudsen Number $Kn = 2\lambda/D_p$).[94,95] The impaction parameter for small spherical particles becomes:

$$I = C_s\, \rho_p\, D_p^2\, V/9\, \mu_f\, D_o \qquad (2.37)$$

where ρ_p is the particle density, V is the undisturbed stream velocity approaching the obstacle, and D_o is the diameter of the collecting ob-

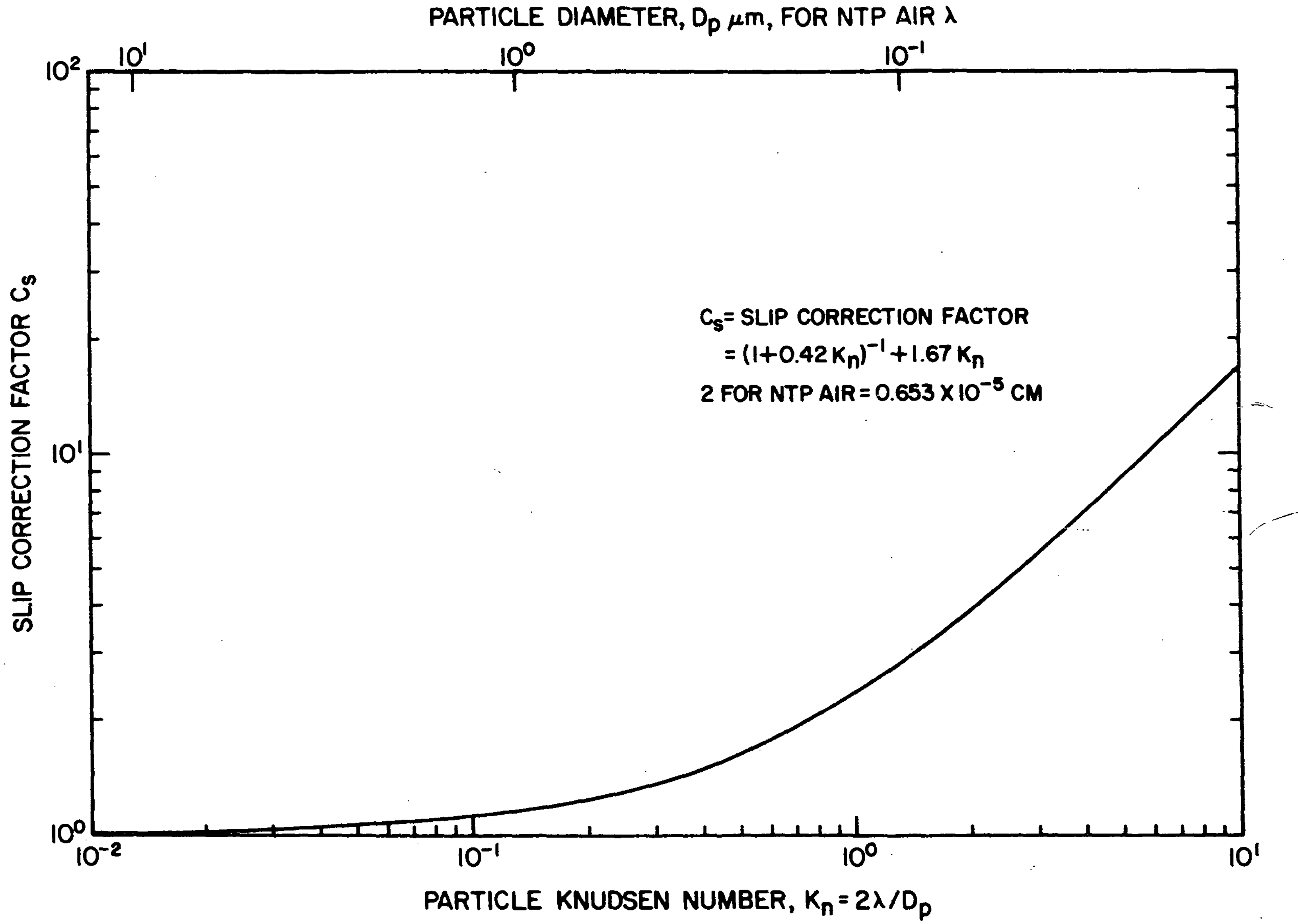


Figure 2.34. Particle Slip Correction Factor (from Fuchs and Stechkina, Ref. 94)

stacle. This parameter also represents the ratio of the distance a small particle will travel in a still fluid when projected with an initial velocity of V to the characteristic dimension of the obstacle, (stopping distance/D_o).

Several numerical and empirical solutions have been presented for inertial collection of particles by spheres or cylindrical fibers. Most of these solutions have been discussed in recent reviews.[13,93] In general, the particle collection efficiency is a function of the impaction parameter and the Reynolds number based on obstacle size.

Numerical solutions for the collection efficiency (η_I) of a spherical particle approaching a spherical collector are summarized in Figure 2.35.[96] In the case of filtration through a granular layer of deposited particles of the same size as the approaching aerosol particles (say 10 μm) at a filtering velocity of order 2 fpm (1 cm/sec), ($C_s = 1$), ($\rho_p = 2$), the impaction parameter is of order 1. Impaction efficiency increases with an increase in velocity, if all other factors remain the same, according to Figure 2.35. Impaction efficiency for the collection of spherical particles by cylindrical fibers and flat ribbons are shown in Figure 2.36.[97]

2.3.2.2 <u>Diffusion</u>.- The transport of suspended particles to an object in the flow under the combined effects of diffusion and fluid motion can be determined from solutions to the equation of convective diffusion. From dimensional considerations, the solutions can be shown to be a function of the Peclet number, defined as:

$$Pe = D_o V/D_{se} \qquad (2.38)$$

where D_o is the object diameter, V is the undisturbed stream velocity, and D_{se}* is the (Stokes-Einstein) particle diffusion coefficient. The Peclet number is the characteristic parameter for the relative magnitude of the effects of convection and diffusion in particle transport.

Several theoretical solutions have been proposed for the efficiency of cylindrical fibers for particles of vanishing size. They are of the form:

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* $D_{se} = kT\, C_s/3\pi\, \mu_f\, D_p$.

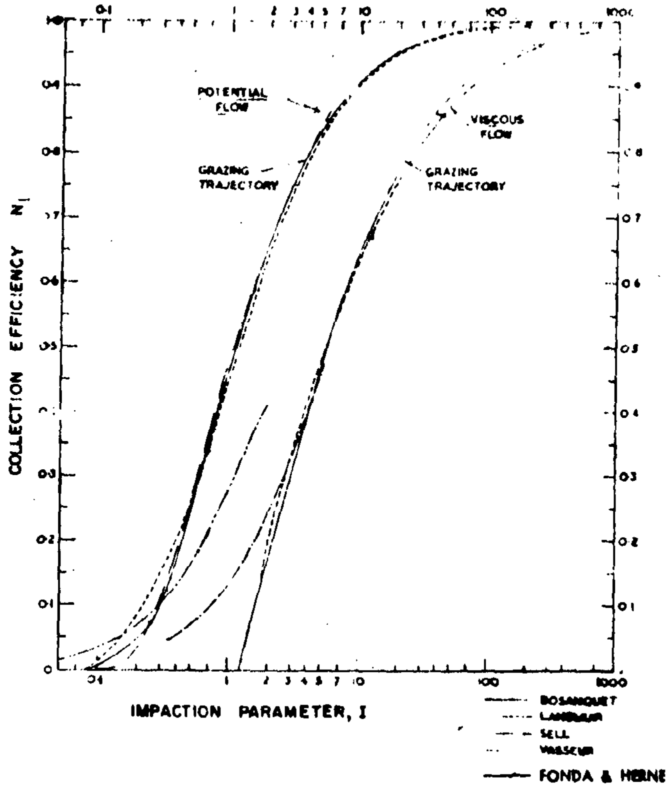


Figure 2.35. Impaction Efficiency for Sphere-Sphere System (from Herne, Ref. 96.).

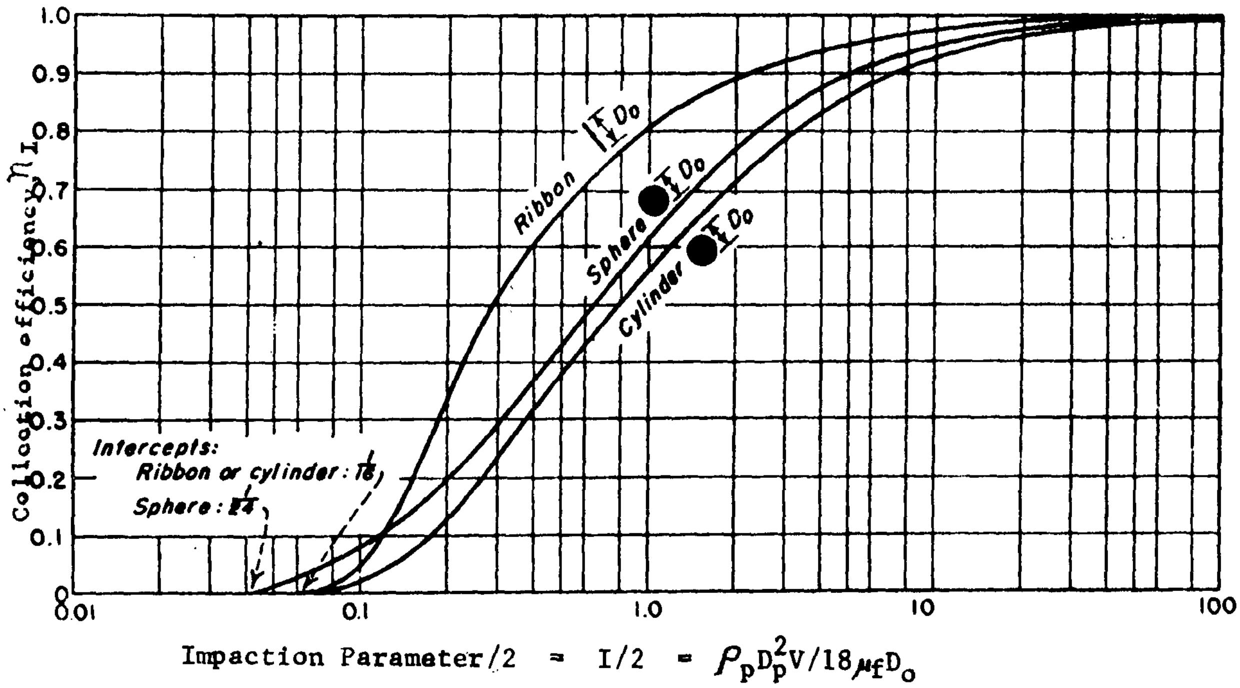


Figure 2.36. Impaction Efficiency for Spherical Particles and Various Obstacles in Potential Flow, After Langmuir and Blodgett (from Perry et al., Ref. 97, p. 20-68).

$$\eta_d \sim P_e^{-n} \quad (2.39)$$

where $1/2 \leq n \leq 1$. It is generally accepted by specialists in mass transfer that $n = 2/3$ is the correct dependence for diffusion alone.

The solutions also depend upon the character of the fluid motion as measured by Reynolds number based upon obstacle size:

$$Re_o = D_o V/\nu \quad (2.40)$$

where ν is the kinematic viscosity of the fluid. For most filters in which diffusion is an important mechanism of removal, $Re \leq 10^{-1}$. The dependence upon Re is logarithmic, and its influence is slight over the usual range $(10^{-4} \leq Re \leq 10^{-1})$.

Effects of diffusion in fabric filtration of particles through a granular layer of previously deposited particles will be of significance for particles less than about 1 μm. The analytical problem has not been solved specifically for granular media. Diffusional collection improves at reduced filtration velocity for smaller particle sizes, since the collection efficiency is inversely proportional to Peclet number.

2.3.3.3 Direct Interception.- Particle capture arising from diffusion or inertial impaction can be determined by assuming the particle is a mathematical point having the property of random molecular motion or inertia. If a particle of finite size passes near an obstacle as a result of (a) diffusion, or (b) inertia, or (c) because of fluid motion alone, contact can occur if the path of the center of the particle comes within a distance of one particle radius (a_p) of the surface. The effect of finite particle size on capture is called direct interception. Collection efficiency can be shown to be a function of the direct interception group:

$$R = D_p/D_o \quad (2.41)$$

It is possible to treat the effect of direct interception as a boundary condition in the solutions for collection efficiency by diffusion and impaction. The solutions then contain the interception group as an additional parameter. If the particle passes near a fiber surface as a result of fluid motion alone, fiber efficiency because of direct interception is:

$$\eta \sim R^2 \tag{2.42}$$

for $R < 1$ and $Re < 1$.

The above three mechanisms of filter efficiency have been extensively developed and analyzed for fibrous filters with bare fibers having no prior deposit. Collection efficiency by the diffusional mechanism decreases with increasing particle size, whereas impaction efficiency tends to increase. These effects lead to a minimum in the efficiency-particle size curve for fibrous filters. Stairmand[83] has calculated the efficiency of a fabric filter at the start of filtration (using as a model the geometry shown in Figure 2.26(b) as a function of particle size, with results as shown in Figure 2.37. Stairmand's discussion related to this calculation follows:

> "A method of calculating the collection efficiency of a fabric or fiber filter has been given in detail..., though, as with electrostatic precipitators, the exercise serves mainly to help in understanding the mechanism of operation of fiber filters, rather than to provide accurate design data. A worked example is given ..., which show that a normal fiber filter exhibits a grade-efficiency curve with a pronounced "dip" at about 0.9 μ, where both impingement and diffusional efficiencies are lowest (Figure 2.37). The formation of an effective floc, or the use of suitable compressed felt in an appropriate design of filter, would obviate this difficulty."

It should be emphasized that the Stairmand calculation illustrated in Figure 2.37 is based on the relationships presented above for a clean filter at the start of filtration. Operating efficiencies observed in fabric filters are usually greater than 99.9 percent for most particles of interest, as will be discussed below. The use of Stairmand's curve to represent fabric filter operating efficiency is entirely erroneous and misleading, and should be discontinued (see for example Figure 20 of Ref. 98, lower right hand corner). Stairmand's curve is typical of performance for a fairly open fibrous filter, and many experiments have shown a dip in filter efficiency caused by a crossover from primarily diffusional separation to impaction collection. Most fabrics used for industrial gas filtration are quite dense and will have a grade-efficiency curve higher than shown in Figure 2.37.

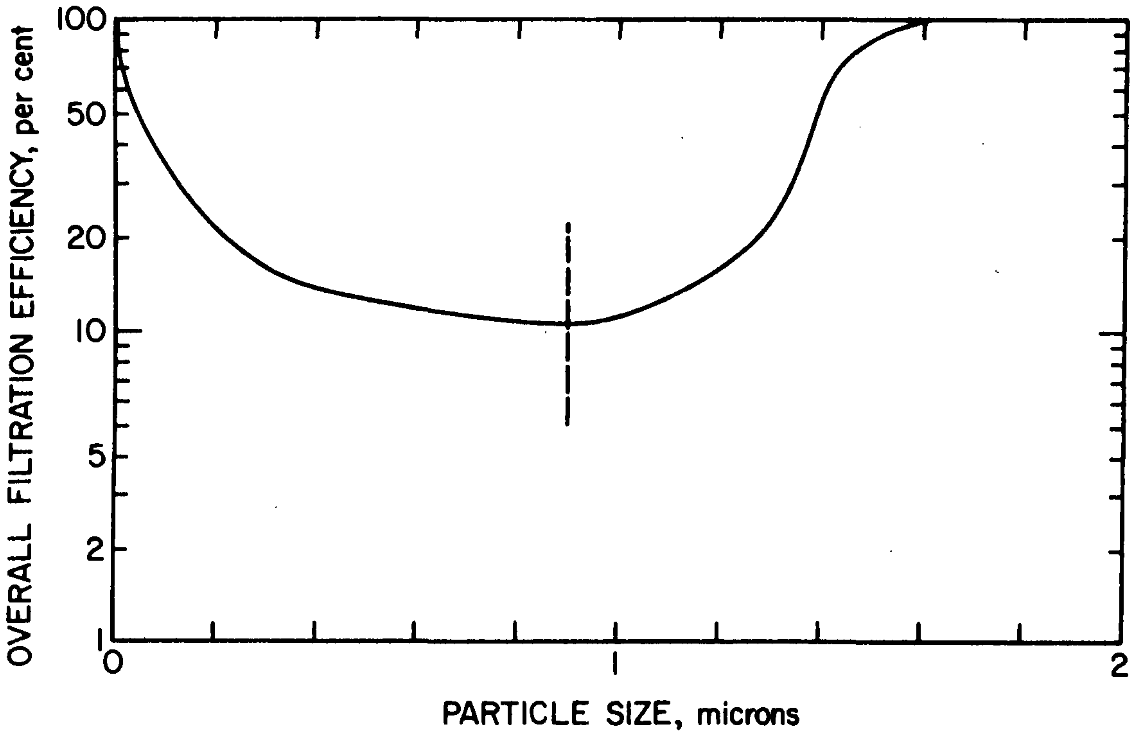


Figure 2.37. Grade-efficiency Curve for Fibre Filter before Particles Accumulate (from Stairmand, Ref. 83).

2.3.2.4 <u>Sieving or Straining</u>.- Operating fabric filters contain extensive deposits of granular particulate material in the form of a more or less continuous layer. Filtration is presumed to occur as a consequence of the flow field between or around granules. If the grains deposited are of the same size as the incoming gas-borne dust particles, then the pores between deposited grains are smaller than the grains themselves. Particle removal can then occur by direct interception of a surface of the incoming particle with the surface of a deposited particle. This model for filtration in a granular layer is usually referred to as sieving (or straining) (particle size > pore size). Since most dust dispersions of practical concern contain particles distributed over a broad spectrum of sizes, pore openings also vary widely in size. Sieving is probably important for the larger grains (or agglomerates), say greater than 10 or 20 μm. For the finer particles found in metallurgical fumes, carbon black, oil combustion ash, etc., collection is probably achieved by the mechanisms of mechanical filtration. Sieving as a mechanism of collection implies an efficiency of 100 percent for the granular layer, and this is never achieved in a practical industrial gas filtration system. Characteristics of granular packings are discussed below. The difficulty in providing an analytical model for filtration in an operating fabric filter is a consequence of lack of quantitative observations on the characteristics of the deposited layer.

2.3.2.5 Collection by Electrostatic Mechanisms.- The effects of electrostatic charge on particle collection in fibrous filters have been considered in several studies. Electrostatic mechanisms in the capture of particles by granular filters have been discussed by Anderson.[53] Analytical and experimental studies have not been attempted for the process of fabric filtration. Measurement of particle and substrate charge distribution and location is difficult and is not usually done as part of the experimental determination of fabric filter efficiency. A number of experimental studies have been performed on the effects of particle charge, object charge, and impressed fields in filters (see Reference numbers 13, 49, 53, 93, 99-112). In most cases, substantial improvements in collection efficiency result from the added effects of electrostatic charge. Effects of electrostatic charge on fabric filter pressure drop are under investigation.

2.3.2.6 Sedimentation.- Sedimentation of particles as a method of collection in fabric filters is usually assumed to be negligible. A general effect of gravity on filtration has been proposed as[53,113]

$$\eta_g = \frac{nV_t \cdot (\text{cross section of collector in vertical direction})}{nVo . (\text{cross section of collector normal to flow})}$$

$$= G = Cs\ \rho_p\ g\ D_p^{\ 2}/18\ \mu_f\ Vo \qquad (2.43)$$

where n = the number of aerosol particles per unit volume, and V_t is the terminal settling velocity of the particles. For a spherical collector in a fabric filter deposit, G is the ratio of the terminal settling velocity to the local stream velocity. Table 2.14 indicates the terminal settling velocity for particles likely to be of interest in fabric filtration.[13]

For a 10 μm particle of unit density (ρ_p = 1) terminal settling velocity is 0.3 cm/sec. At a typical filtration velocity of 1 cm/sec (2 fpm), the esti-

TABLE 2.14

TERMINAL VELOCITIES AND DIFFUSION COEFFICIENTS OF RIGID SPHERES OF UNIT DENSITY IN AIR AT 760 mm Hg PRESSURE AND 20°C*

Diameter μ	v cm/sec	D cm^2/sec
0.1	8.71×10^{-5}	6.84×10^{-6}
0.2	2.27×10^{-4}	2.02×10^{-6}
0.4	6.85×10^{-4}	8.42×10^{-7}
1.0	3.40×10^{-3}	2.76×10^{-7}
2	1.29×10^{-2}	1.28×10^{-7}
4	5.00×10^{-2}	6.16×10^{-8}
10	3.03×10^{-1}	2.41×10^{-8}
20	1.20	--
40	4.71	--
100	24.7	--

*From Green and Lane, Ref. 13.

mated collection efficiency for a granular spherical obstacle in the flow (10 μm), will be of order 0.3, and substantial separation by this mechanism would be expected. In a packed bed of spheres with upward aerosol flow, the effect of gravity opposes collection, as illustrated in the lower part of Figure 2.38, whereas collection with downward flow is improved by gravity (upper part). Effects of gravity on submicron aerosol filtration through fiberglass, sand and lead shot (1500 μm) were studied by Thomas and Yoder[113,114,115], with typical results as shown in Figure 2.39. It is apparent that penetration was reduced (greater efficiency) for downflow, even for aerosol particles less than 1 μm as used in these studies. (Experimental verification of the effects of collection by diffusional and impaction mechanisms at different particle sizes may also be observed in these data, maximum penetration or minimum efficiency occurring in the vicinity of 0.35 μm). Effects of shear flow on particle motion in the vicinity of a collector have been cited above. Effects of gravity on particle flow and stratification inside a filter bag are discussed below.

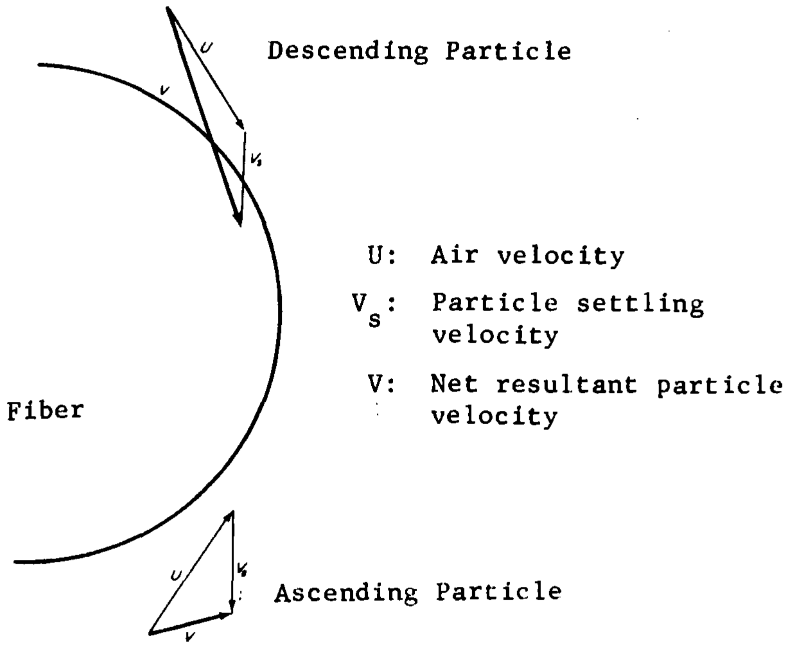


Figure 2.38. Deposition of Particles in Ascending and Descending Streams (From Thomas and Yoder, Ref. 114).

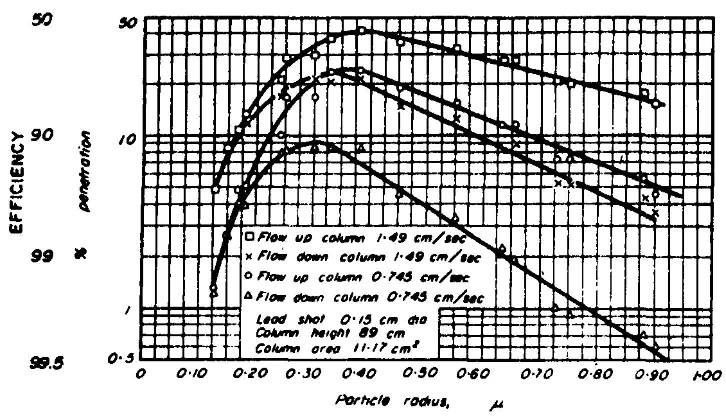


Figure 2.39. Filtration of aerosols through lead shot (From Thomas and Yoder, Ref. 114)

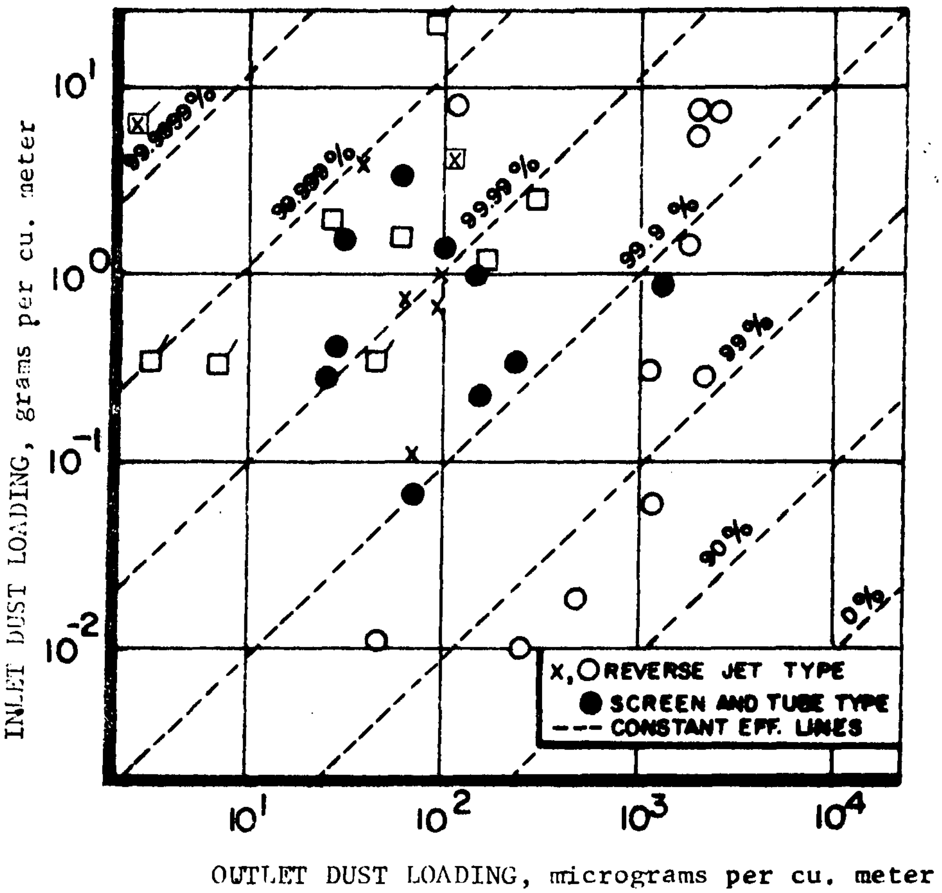
2.3.3.7 Other Collecting Mechanisms.- Turbulent deposition of particles on obstacles and boundary walls (ductwork, flues, checkers, sampling lines) in dust collection systems are of particular importance in system design. Impaction by the randomly varying transverse fluid velocity is the principal mechanism, and particle adhesion, particle bounce, and reentrainment are the particular problems of interest. Collection of particles by this mechanism in fabric filters operated at low velocity is probably negligible. If current experiments on high velocity (100 to 1000 fpm) cleanable industrial filters become of importance, recent analyses of turbulent deposition may be of significance in interpretation of the process.

Thermal forces occur on an aerosol particle in a temperature gradient in hot gases flowing over cold walls. As such, these become important in dust deposits on heat exchanger surfaces in system design for heat transfer coefficients. Thermal effects are not normally expected in usual fabric filters, but have been cited as a mechanism in cool granular filtration of high temperature gases by Strauss and Thring.[116]

2.3.3 Measurements of Fabric Filter Collection Efficiency

Measurements of collection efficiency in operating fabric filters are illustrated in Figure 2.40. Typical values are presented for inlet and outlet concentrations in screen and tube type collectors (intermittently cleaned, woven fabric, field data), reverse jet collectors (continuously cleaned felts, field data) a pulse jet collector (continuously cleaned felt, laboratory results), and a pulsed woolen fabric type. Low efficiencies reported are characteristic of low inlet concentrations with continuous cleaning, usually accompanied by poor maintenance or seeping dusts.

Dennis, et al,[117] in discussing their field measurements of efficiency in operating fabric filters (open and full circle data in Figure 2.40) indicated that "Test results do not necessarily show optimum or expected performance since many collectors were poorly maintained or operated in excess of design capacity." Such tests reflect the degree of maintenance rather than the inherent performance of the fabric filter. In no case was there any correlation observed between efficiency and particle size. Dennis, et al concluded that "For collectors with no obvious leak-



○ ● Dennis, Johnson, First & Silverman, field tests, USAEC Report No. NYO-1588 (1953)

× Caplan & Mason field tests, USAEC Report No. WASH-149 (1954)

□ Pulse-jet laboratory data; USAEC Report No. NYO-4816 (1962), resuspended vaporized amorphous silica powder

□✓ Same; resuspended fly ash

☒ Caplan, Collection Efficiency of Reverse Jet Filters and Cloth arrestors, Report to NAPCA (Sept., 1968), CS filter, pearl starch, 15 μm.

☒✓ Ground limestone, 4 μm.

Figure 2.40. Operating Fabric Filter Efficiency.

age the effluent dusts had 98 percent of their mass represented by particles smaller than 5 microns." Collection efficiency in operating fabric filters is very dependent upon cleaning mechanisms and cleaning cycles, as will be discussed below.

The data of Whitby and Lundgren[118] are of some interest at this point. They evaluated a unit-type filter (Torit model 64) upon which a dust cake of resuspended fly ash was deposited. This cake was then tested with monodisperse test aerosols, uranine and methylene blue dyes.

Collection efficiency for uranine and methylene blue test aerosols with the clean fabric and for a fly ash deposit are shown in Figure 2.41. Particle size efficiency of the clean cotton sateen fabric (at 7 fpm) was essentially as that predicted by Stairmand's analysis. Figure 2.37 illustrates the operation of diffusional and inertial mechanisms. After loading with fly ash (N.B.S. Air Filter Test Dust, ~ 15 μm) the particle size efficiency was observed to be greater than about 99.5 percent for all sizes greater than 0.08 μm (filtering velocity not stated, but calculated to be approximately 5.2 fpm). The collector was shaken (by foot pedal-operated rapping bar) for 10 and 35 individual cycles. The major reduction in pressure drop and collection efficiency occurred with the initial 10 shakes. Collection efficiency at 10 shakes remained greater than 85 percent for all sizes. An additional 25 shaking operations produced relatively less reduction in pressure drop and efficiency (> 75%). This series of tests corresponds to only the first three cycles of operation of a cleanable industrial filter (estimated from the data presented in Ref. 118), and illustrates the initial steps in the accumulation of a residual dust deposit within the fabric. The Whitby-Lundgren tests are of value to illustrate start-up phenomena in a practical fabric filter. However, they probably do not reflect fabric filter performance after an extended period of operation through many ($> 10^2$) filtering and cleaning cycles, when the fabric has achieved an equilibrium residual dust deposit. The test procedure is artificial because collection of fly ash having few particles below about 1 μm would not be likely to result in particles below this size in the effluent.

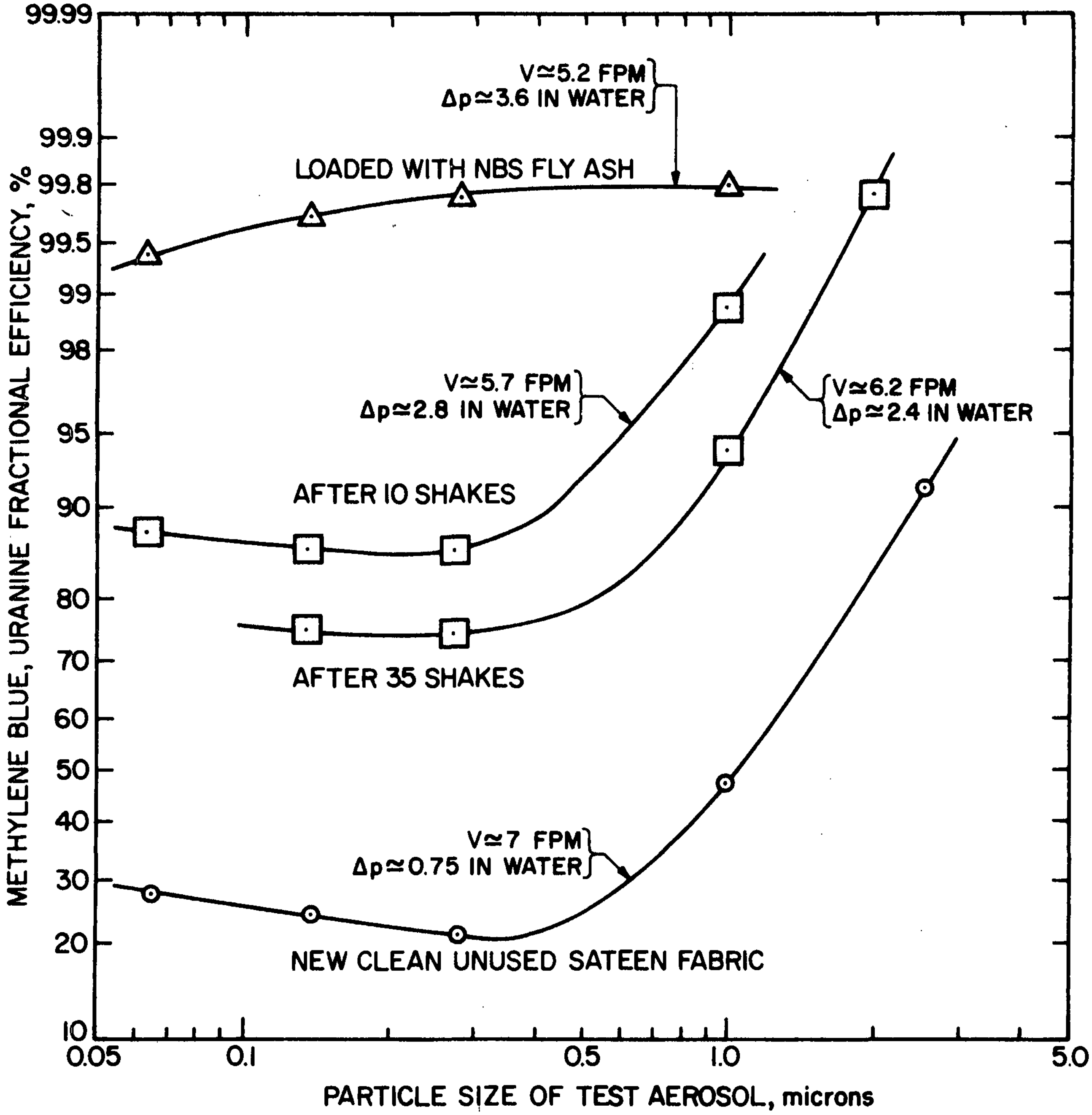


Figure 2.41. Fractional Efficiency of Collector-N.B.S. Fly Ash Layer on Cotton Sateen using Methylene Blue and Uranine Test Aerosols. (From Whitby and Lundgren, Ref. 118).

In other words, for the fly ash test aerosol with no particles below 1 μm, collection efficiency starts at 90 percent even after 35 shakes (> 99.8 at > 2 μm). The efficiency for test aerosols below 1 μm in a fabric filter deposit of fly ash particles substantially greater than 1 micron is not a true reflection of the filter capability. Similar results on a 0.3 μm test aerosol were reported by Stairmand[119] from the data of Skrebowski and Sutton[120] as shown in Table 2.15.

TABLE 2.15

EFFECT OF DEPOSITED DUST ON FILTRATION EFFICIENCY*

Fabric	Aerosol Efficiency**		
	New clean cloth %	After dust deposition %	After cleaning by blowback %
Lightweight plain cloth (synthetic fibre)	2	65	13
Heavy raised-surface cloth (synthetic fibre)	24	75	66
Heavy raised-surface cloth (natural fibre)	39	82	69

* From Stairmand, Ref. 119.

** Test aerosol 0.3 μm radioactive particles.

Particle size-efficiency data for operating fabric filters is discussed in Chapter 6.

2.4 FLOW THROUGH POROUS MEDIA

2.4.1 Introduction

The relationship between the pressure drop across the cloth and dust cake, the velocity through the cloth and cake, the gas viscosity, etc. involving fundamental filtration mechanics, is a basic part of the economics of operating a fabric filter system. For practical purposes, the pressure-velocity relationship can be expressed as Darcy's law. Although more sophisticated relationships can be extracted via fluid mechanics theory through solutions of the Navier-Stokes equation, there is little application for such refinement at the present time.

The principle that pressure drop across a porous bed is proportional to the flow through is basic to intragranular flows. Darcy's equation* can be written simply as

$$\frac{\Delta p}{L} = \frac{\mu_f V}{K} \tag{2.44}$$

which states that the pressure difference across the bed depends on the bed depth L, on the gas viscosity μ_f, and on the permeability of the bed, K, as well as on velocity, V. All variables are readily-obtained engineering parameters except for permeability K which is the subject of a following section.

Note that V in Equation 2.44, refers to the superficial gas velocity through the bed and not to the velocity through the individual pore structures. V is equal to the volumetric flow approaching the bed divided by the area of the bed i.e., by the cloth area. V is the apparent or superficial velocity through the bed; the true velocity averaged across a single passageway in the bed is greater by the factor $1/\epsilon$ where ϵ is the volumetric porosity of the bed.

Darcy's law relating pressure drop and overall velocity applies to a wide variety of beds and fluids with only a few restrictions. The flow should be only slightly compressible or not at all, i.e. the pressure drop across the bed should be but a small percentage of the ambient pressure level. The flow should be steady, that is, there should be no sharp pulses that could excessively compress the gas. The viscosity of the gas mixture should be Newtonian, and the flow rate low enough so that the resistance to flow is determined by viscous and not inertial effects. The test for viscous flow is to compute Reynold's number for a typical deposited particle or fiber, whichever is larger:

$$Re = \frac{\rho_f V' D_o}{\mu_f} \tag{2.45}$$

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* Darcy's equation is usually expressed in differential form.

where ρ_f and μ_f apply to the gas and V' equals V/ϵ, the average velocity past the particle or fiber whose diameter is D_o. As long as the Reynold's number for particle and fiber are both less than unity the resistance to flow through the cake and cloth is mainly viscous and Darcy's law applies. This will be the case in most fabric filtration. In the case of high Re values, another term should be added to Darcy's equation to allow for inertial effects, i.e. pressure loss a function of V^2 as well as v.

2.4.2 Permeability of Rigid Media

The permeability K for use in Darcy's equation is fairly well understood for rigid porous beds, that is, beds whose passageways do not bend or collapse during the flow. (Unfortunately particulate beds and cloths often do change during the flow and this will be discussed in the next section). Permeability is the openness of a material to the transmission of fluid and is defined by Equation (2.44). It is also experimentally determined by measuring pressure drop across a fixed bed length and at a given velocity. Since there is an infinite number of different dust cakes, cloths, packed towers, petroleum shales, ceramic clays, etc., one needs a way of predicting permeability based upon a knowledge of particle sizes, shapes, and arrangements.

From practical fabric filtration experience, K's computed from laboratory and field measurements on different dust cakes vary by a factor of 1000 or more with the larger permeabilities usually being associated with the larger dust particles. Photomicrographs presented above suggest that smaller particles often pack together in feathery clusters while only the largest particles pack closely like marbles. This indicates that there are apparently large differences in the porosity of dust accumulations and that there are differences in cake structure and or arrangement of adjacent particles. These same observations are made in many other kinds of porous beds. Analysts have traditionally concentrated on size, porosity, and structure in trying to predict permeability.

Although many permeability theories have been proposed, none have been widely accepted, partly because of the difficulties in predicting porosity and bed structure. Perhaps the most widely used theory is the Kozeny-Carman equation, which is sufficiently simple and reliable to have at least some utility in most kinds of porous beds. It is derived by applying the concept of hydraulic radius to a capillary passageway through the bed. The Brinkman equation for permeability is less widely used but is derived specifically for loose assemblages of spheres exerting a drag on a flowing fluid.

2.4.2.1 Kozeny-Carman Theory.- Consider a fluid flowing slowly through a tube of diameter d and length L. From Poiseuille's law for capillary flow, the pressure drop across the tube will be $\Delta p/L = \mu_f V'/(d^2/32)$ where V′ is the velocity averaged across the passageway. If the tube is replaced by wide plates L long and spaced d apart, $\Delta p/L = \mu_f V'(d^2/12)$. The hydraulic radii m for these two configurations, defined as

$$m = \frac{\text{passageway cross sectional area}}{\text{passageway perimeter}} \qquad (2.46)$$

(which for a straight passageway is equal to: $\frac{\text{passageway volume}}{\text{passageway surface}}$)

are d/4 and d/2 respectively. When d is replaced by hydraulic radius in these two expressions, the denominators become $m^2/2$ and $m^2/3$ for the tube and plates respectively. By analogy with Darcy's law, Equation 2.44, the permeabilities for these two configurations are precisely $m^2/2$ and $m^2/3$. Since the configurations are quite different in cross section, one might suspect that almost any passageway configuration might be represented by $K = m^2/k$ where k should be of the order of 2.5.

If one had a material composed of many such passageways, arranged in parallel, the overall permeability would clearly depend on the number of passageways, that is, on the relative openness of the material or the porosity ϵ such that $K = \bar{m}\,\epsilon/k$ where $\bar{m}$ is the average hydraulic radius for all passageways now defined as

$$\bar{m} = \frac{\text{void volume for all passageways per unit of dust particle vol.}}{\text{surface area of all passageways per unit of dust particle vol}}$$

Here the denominator is simply S_o, a standard bed property defined as the specific surface of the porous material. The numerator is the volume ratio $(\epsilon/1-\epsilon)$. Thus finally

$$K = \frac{\epsilon^3}{kS_o^2(1-\epsilon)^2} \quad (2.47)$$

which is the Kozeny-Carman equation for permeability.* Note that although simple in concept and form it contains the three ingredients sought from fabric filtration experience; particle size (S_o is closely related to size), bed porosity ϵ, and arrangement structure (chiefly k, but also S_o). Carman in a related study determined a shape factor for a number of non-spherical particles, as a means of predicting S_o when particle size is known. (Ref. 122, page 334-5). Just as K absorbed everything that was difficult to measure when the Darcy equation was written, so now k absorbs the uncertainties remaining in this expression for K, since ϵ and S_o are distinctly defined and reasonably measurable. Kozeny believed k should have a value of 2; Carman[123,124] derived the value of 5 for k. As one might expect, experimentally it turns out to depend on the bed structure. A number of efforts to predict k by introducing such concepts as tortuosity have not been universally useful although these efforts may help to predict permeability in materials of specific type, e.g., packed rings, cylinders perpendicular to the flow, etc. Happel and Brenner[125] discuss several models designed to evaluate k and indicate a significant dependency of k on porosity for porosities above 0.7. They say that theoretically k ranges from 1 to 70 for very porous beds depending on the type of particle and the model used. Table 2.16 and Figure 2.42 illustrate the calculated variation of k with porosity for spheres and cylinders. In view of the great variation in fabric filter dust cakes it must be said that for present purposes k is not well understood. The value of 5 is probably a good starting point for making estimates of permeability in beds of spherical particles. Although k may vary from this either way by a factor of 2, anticipating the amount of variation in bed structures, this uncertainty in k is far smaller than the range of 1000 in experimentally determined K values. The Kozeny-Carman theory cannot apply to anisotropic materials unless k, ϵ and S_o are assigned values that take direction into consideration. K is a local property of the

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* This derivation of Kozeny-Carman theory follows the important concepts. A more rigorous development can be found in Scheidegger.[121]

TABLE 2.16

THEORETICAL VALUES OF THE KOZENY CONSTANT (k) FROM DIFFERENT CELL MODELS (From Happel and Brenner, Ref. 125).

Fractional Void Volume, ε	Flow Parallel to Cylinders	Flow Perpendicular to Cylinders	Flow through Random Orientation of Cylinders	Flow through Assemblages of Spheres
0.99	31.10	53.83	46.25	71.63
0.90	7.31	11.03	9.79	11.34
0.80	5.23	7.46	6.72	7.22
0.70	4.42	6.19	5.60	5.79
0.60	3.96	5.62	5.07	5.11
0.50	3.67	5.38	4.97	4.74
0.40	3.44	5.28	4.66	4.54

material which may well vary from point to point, as in a fabric for example. Thus in Equation 2.44 it is understood that either K is averaged over the entire distance L or else the material is homogeneous. It is reported that K does not apply to high porosity materials presumably because the theory is based on discrete passageways; thus Kozeny-Carman theory should be used with particular caution for ϵ values >0.7.

2.4.2.2 Brinkman Theory.- Brinkman addressed himself to the permeability of a swarm of spheres not quite touching but so close together as to affect the fluid drag on one another. That is, each particle deforms the flow field around itself and the closer the particles are together the sharper the field deformation, and the larger the drag. An array of particles close together form a more impermeable front than the same number of particles widely separated. For example, in sedimentation, a cloud of particles fall together as a large but extremely low density body, i.e., the cloud falls more slowly than a single particle having density and size similar to the cloud constituents because the drag is higher.

By vector calculus Brinkman found the drag on one sphere among a swarm of spheres to be

$$F_1 = 6\pi\, \mu_f\, V\, r_p \left(1 + \frac{r_p}{\sqrt{K}} + \frac{r_p^{\,2}}{}\right) \qquad (2.48)$$

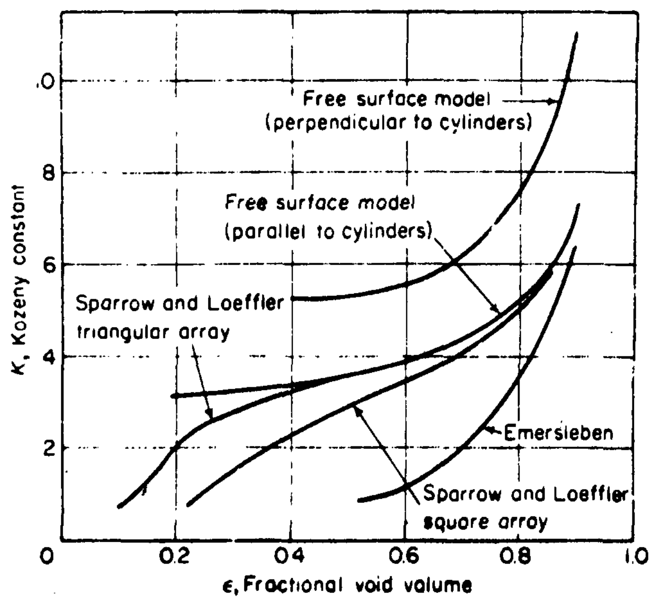

Figure 2.42. Comparison of Theories for Flow Relative to Circular Cylinders. (From Happel and Brenner, Ref. 125).

The first term is simply the Stokes drag on an isolated sphere, but the drag is increased by two other terms involving particle radius r_p and the swarm permeability, K, which was then solved for as follows. Using n the number of particles per unit volume equal to $(1 - \epsilon)/(4/3\pi\, r_p^{3})$, the drag on a unit volume of cloud is:

$$F_n = \frac{dp}{dx} = \frac{\mu_f V}{K} = nF_1 \qquad (2.49)$$

$$K = \frac{r_p^{2}}{18}\left(3 + \frac{4}{(1-\epsilon)} - 3\sqrt{\frac{8}{(1-\epsilon)} - 3}\right) \qquad (2.50)$$

This expression of Brinkman's for permeability must obviously be less universal than the Kozeny-Carman equation since bed structure is not taken into account. However, the Brinkman model should apply to near-spherical particles in very loose, high porosity beds which is most convenient since the Kozeny-Carman model fails at high porosities. The Brinkman theory is less widely quoted and appears to have received less experimental testing.[125] A comparison of the two theories can be made by replacing S_o (the ratio of particle surface to particle volume) by $3/r_p$ (for spheres barely touching) and setting k = 5 in the Kozeny-Carman expression:

$$\text{K-C:} \qquad K = \frac{r_p^2}{18}\left(\frac{0.4\epsilon^3}{(1-\epsilon)^2}\right) \qquad (2.51)$$

The curves are plotted in Figure 2.43.

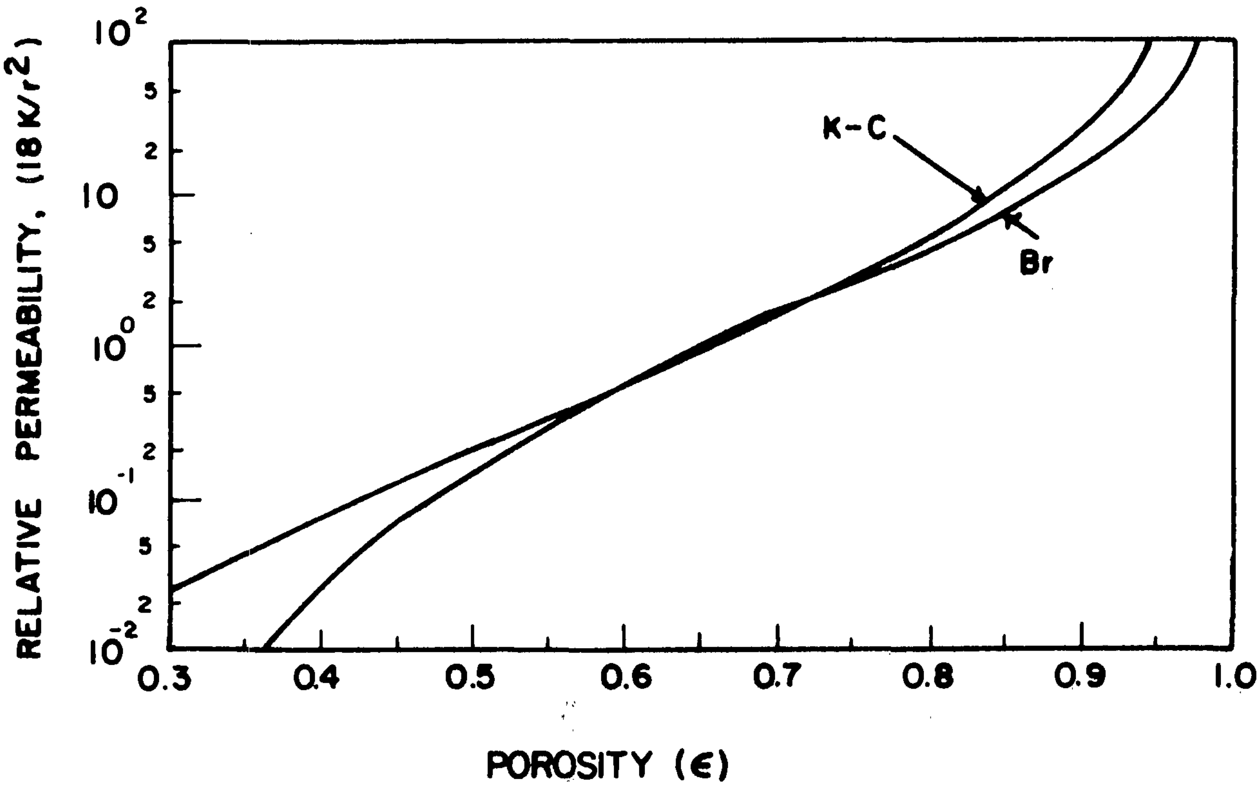

Figure 2.43. Permeability-porosity Relationships for Kozeny-Carman and Brinkman Models.

We gain confidence from Figure 2.43 in that despite the different approaches the two theories predict remarkably similar permeabilities. The importance of porosity is evident; over the range of porosities expected in fabric filtered dust cakes the cake permeabilities may well vary by a factor of 100 due to porosity.

2.4.2.3 Other Permeability Theories.- As already mentioned a great deal of effort has been spent in trying to unify observations of permeability.

Scheidegger[121] discusses the claims for many of these attempts under the groupings of empirical correlations, capillaric models (e.g., Poiseuille's law), hydraulic radius theories (e.g., Kozeny-Carman), drag theories (e.g., Brinkman), and statistical theories of passageway arrangement and molecular kinetics.

2.4.3 Permeability of Changing Media

Since K is a point property of the porous bed, the fact that the filtration dust layer is growing thicker is no limitation to permeability theory nor to Darcy's law. This theory assumes that one may state the structural arrangement adopted by the particles as they land on the cake and hence determine the value of the permeability. This value plus the slowly changing layer thickness make it possible to determine the slowly changing relationship between pressure drop and velocity at any time.

A much more difficult situation arises when the dust structures formed within the cake collapse because of higher pressures. The dust at the immediate surface of the cake is under no mechanical stress, except for a small momentum flux from the landing of later particles. However, as soon as particles land they exert a drag on the fluid which has to be supported by a pressure from the particles underneath. Likewise the underneath particles exert a drag on the particles supporting them plus the pressure from all particles which they support. This accumulation of particle-to-particle pressure results in a maximum approximately at the bottom of the cake where the compressive stress on the cake equals the pressure drop across the dust cake (typically a few inches of water). This compressive stress is always higher than the stresses at the surface of the dust cake, perhaps even including the stress during the initial landing shock. As a result some reorientation or compaction deep in the cake is apt to occur. If it does, the resistance to flow through the collapsed layer rises, increasing the compressive stress on the cake below this area.

The equations governing this process are as follows. The compressive stress p_c at depth x in the cake will be

$$p_c = p_{co} + \int_0^x \left(\frac{dp}{dx}\right) dx \qquad (2.52)$$

where p_{co} is any surface stress associated with the landing particles. The pressure gradient comes directly from Darcy's law in differential form:

$$\frac{dp}{dx} = -\frac{\mu_f V}{K} \tag{2.53}$$

where now we include provisions for a dependency of permeability on the compressive stress:

$$K = K(p_c) \tag{2.54}$$

This latter dependency involves the rheology of the dust cake about which very little is known at present. One could hypothesize that a typical dust cake may be fairly plastic as opposed to being elastic or viscous, that is, it may not collapse at all until a certain threshold of compressive stress is reached.

A napped fabric may also exhibit an increasing flow resistance as the pressure drop across it increases, that is, as the dust cake pressure on the cloth surface increases. One would surmise that this would be basically an elastic process, resulting in a slow exponential increase in pressure drop in addition to any other increases during the filtering cycle.

Evidence for cloth or cake compression during filtration is seen from time to time. J.P. Stevens Co.[126] plotted the pressure drop across clean cloths as a function of filter velocity and found approximately exponential pressure increases in practically every case; velocities ranged up to 20 FPM. Borgwardt, et al[127] report that the resistance of a cake of fly ash formed at 2.26 FPM was increased irreversibly about 20% by simply slowly doubling the flow rate and then reducing it to its original value, all the while using clean air. At doubled air flow, the resultant pressure drop across the cloth and cake was increased 3 to 4 times on again increasing the flow, the resistance didn't change appreciably until the previous velocity maximum was exceeded whereupon the resistance again began to slowly increase. No recovery of permeability was observed. Earlier in the same laboratory, Stephan, et al,[128] found similar phenomena, observing 60% changes in permeability when velocity was approximately doubled; but the interesting thing is that the changes appeared to happen in 4 or 5 discrete steps as if the collapse were not entirely plastic. In the related field of liquid filtration cake collapse is a well known phenomenon.[129,130]

Still further evidence of cake deformation due to excessive drag is the familiar observation that once a cake has formed it may puncture, especially with fairly coarse cloths and fine dusts. This we can conceive as a collapse of the cake very close to a high-velocity spot in the cloth. The result is that the cake in that vicinity does not reform but is pulled right through the cloth.

From observations of fabric filter equipment in use it seems that there is too often little regard for excursions in pressure and velocity as long as they are brief. Closing off one compartment raises the drag suddenly on the dust cakes in adjacent compartments; fan blades create pressure shocks considerable distances away. Some cloths are deliberately cleaned by pressure pulses. There is nevertheless some preliminary evidence that 10% or more of the filtering pressure may be saved in certain cases by carefully preventing unnecessary collapse of the dust cake.

2.4.4 Permeability in Non-uniform Beds

To obtain overall permeability K of a cloth-dust cake combination in which the local permeability K_x varies from point to point through the bed, one must in effect add the resistances, or the reciprocals of permeability, for each successive layer in the bed. From Equations 2.44, 2.52, and 2.53, neglecting p_{co};

$$K = \frac{L\mu_f V}{\Delta p} = L\mu_f V \left\{ \frac{1}{-\int_0^L \left(\frac{-\mu_f V}{K_x}\right) dx} \right\} \qquad (2.55)$$

or

$$\frac{1}{K} = \frac{1}{L}\int_0^L \left(\frac{1}{K_x}\right) dx \qquad (2.56)$$

While a theoretical treatment may be able to express K_x as a function of x through the dust cake and cloth, more often K_x will be estimated for two or more layers of the laminate. In this case

$$\frac{1}{K} = \sum_i \frac{1}{K_i} \qquad (2.57)$$

2.4.5 Resistance vs Permeability

Theoreticians customarily speak in terms of the permeability of a porous bed rather than its reciprocal concept resistance. On the other hand, in fabric filtration practice the standard term is specific resistance which has the commonly accepted units of inches of water per FPM-lb/ft^2. The two are related by the following identity:

$$\text{Specific resistance} = \frac{1}{(\text{permeability})}\left(\frac{\mu_f L}{W}\right) = \left(\frac{1}{\text{Perm}}\right)\left(\frac{\mu_f}{\rho_c}\right) = \left(\frac{1}{\text{Perm}}\right)\left(\frac{\mu_f}{\rho_p(1-\epsilon)}\right) \qquad (2.58)$$

where μ is the gas viscosity, L is the cake or cloth thickness, W is the cake or cloth weight per unit area of cloth, ρ_c is the apparent density of the cake or cloth, ρ_p is the density of the individual particles or fibers, and ϵ is the porosity.

In this middle ground between theory and practice an example of a conversion may be helpful. If the permeability is 2×10^{-8} cm^2, viscosity is 2×10^{-4} poise, and ρ_c is 30 lbs/ft^3, then the specific resistance can be computed as follows:

1. Convert the permeability to 2.09×10^{-11} ft^2
2. Convert the viscosity to 6.05×10^{-9} lb min/ft^2
3. Use density as 30 lbs/ft^3
4. Compute Sp. Res. $= 11.1\left(\frac{\text{lb}}{\text{ft}^2}\right)\left(\frac{\text{min}}{\text{ft}}\right)\left(\frac{1}{\frac{\text{lb}}{\text{ft}^2}}\right)$

   Since 1 $\frac{\text{lb}}{\text{ft}^2}$ equals 0.193 inch of water,

   the Sp. Res. $= \frac{2.14 \text{ inches of water}}{\text{FPM - lb/ft}^2}$

2.4.6 Characteristic Geometric Properties of Porous Media

Three types of porous material are of importance in the analysis of pressure drop of fabric filters: woven and felted fibrous materials, and granular porous media cake (deposited particles). The most usual configuration is a textile fabric woven of multifilament or spun staple yarns of natural (cotton, wool) or man-made fiber (glass, Orlon^R, Dacron^R, nylon, Nomex^R, etc). Typical plain, twill, and sateen weaves are illustrated schematically in Figure 2.44. Basic appearance of representative fabrics has been indicated previously in Figure 2.26a, b, c.

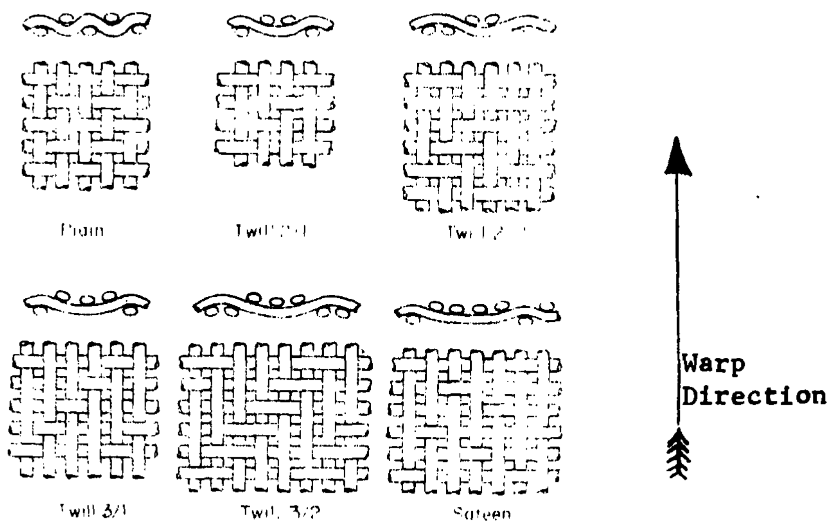

Figure 2.44. Typical Filter Cloth Weaves.

Filter fabrics woven with spun yarns will have many fibrils projecting into the interyarn spaces, so that the flow geometry in a new fabric will be through a semi-fibrous aperture. Aperture size depends upon weave design, yarn diameter, and thread count. Characteristics of the flow through the aperture will depend upon the quantity of interstitial fibrils (interstitial packing density), their sizes, the flow geometry (weave dependent), and the degree to which flow occurs between the yarns (within the aperture) and through the tightly twisted fibers of the yarns themselves. Fabrics with no interyarn fibrils are generally poorer media for gas filtration because of the inability of the dust to form bridges over the pores. A typical research model for this flow geometry is a woven monofilament fabric or a woven wire screen, in which dust builds up on the wires and then sloughs off as larger aggregates (depending upon weave tightness). (Sieves, screens, wire gauzes, punched perforated metals, or sheets or grids of metal plates are not usually employed in gas filtration of fine particles, although they are widely used for size-separation of powdered or granular materials. They are occasionally used as stilling screens for turbulence reduction, or for subsequent gas flow profile modifications or control, in fluid mechanics studies and as straighteners in pipe flow or in electrostatic precipitators after inlet ductwork elbows to cause a duct to flow full or with a more uniform velocity profile.)

Napped woven fabric, such as cotton flannel is produced by mechanically abrading the surface of a woven fabric to separate and withdraw fibrils of the individual yarns, producing a soft, furry surface of many fibers (of order 1/8 inch long) projecting into the upstream gas flow. Napped fabric provides a greater amount of fine fiber for better capture of dust particles. The (permanent) residual deposit may be greater in this type of fabric with certain methods of cleaning, which may not be able to separate the interfiber deposits from the fabric. Napped configurations such as cotton flannel or napped sateen weave cotton are intermediate in filtration characteristics between woven and felted textile fabrics.

Natural wool felt and needle-punched felts of man-made fibers (a barbed needle is inserted and withdrawn from a loose woven filament scrim to separate and withdraw longer fibrils) are other common types of media used in dusty gas filtration. Felt appears microscopically as a dense mass of randomly intertwined fibers, and is quite similar in many respects to fiber filters of paper, metal wools, slag or mineral wool, glass batts, paper, and other non-oriented long filamentous fibrous media. Felts require pneumatic pulse or reverse-jet cleaning for satisfactory pressure drop regulation and control. They cannot be cleaned by mechanical shaking. Their basic efficiency for particle capture is high.

To be able to predict the pressure drop during operation of a fabric filter on a given dust, the filtration engineer requires some knowledge of several properties of the dust and fabric which are essentially physical geometric quantities. (In addition, other characteristics of the dust-fabric system may be required such as, electrostatic charge properties, adhesion, humidity or condensation effects, temperature, etc, and the specific actions of the components of the dust collector associated with periodic cleaning.) In practice, the dust-fabric properties are estimated by the filter design engineer based on his experience with a previous application on the same or a similar dust. There is no substitute for this experience, at present, in the development of the understanding of the mechanics of fabric filtration.

The intrinsic or Darcy permeability of an homogeneous isotropic porous material in slow viscous flow ($Re_p < 10$) is a property defined by the Darcy equation (2.44) as:

$$K = \frac{L \, \mu_f \, V}{\Delta p}$$

with dimension cm^2 (c.g.s), where $\Delta p = \rho_f \, g \, \Delta h$, and h = cm fluid flowing. Permeability (K) depends upon the following geometric properties of the porous material:

1) Porosity, void fraction
2) Specific surface
3) Pore size distribution
4) Particle (grain) size
5) Pore structure
6) Shape factor
7) Granule surface roughness

and is presumably independent of the fluid flowing.

Table 2.17 presents a summary of these geometric properties with methods for measurement. Typical permeability values for various

TABLE 2.17

MEASUREMENTS OF CHARACTERISTIC GEOMETRICAL PROPERTIES OF POROUS MEDIA

	Characteristic Property	Remarks
A.	Porosity	(See Table 2.18 for typical values)
	1. Direct Method	Measure bulk volume of porous material and compact to remove all voids (for soft materials only, e.g., organic materials)
	2. Optical Methods	Microscopic measurement of plane porosity of a random section, photograph, planimeter; also statistical
	3. Density Methods	$\epsilon = 1 - \alpha = 1 - \rho_a/\rho_p$ where ρ_a = bulk (packing) density of a known volume of the porous material, ρ_p = true density of the material, α = fraction of solids
	4. Gas Expansion Methods	Direct measurement of gas contained in pore spaces of known volume of porous medium, by evacuation to lower pressure
	5. Other	Resistance to flow using Kozeny-Carman model
B.	Specific Surface	(See Table 2.22 for typical values)
	1. Optical Methods	Microscopic measurement of circumference of pores to total area of random plane section, photomicrograph, planimeter; also statistical
	2. Adsorption	Adsorbed gases or vapors by Brumauer, Emmett, Teller (BET) method
	3. Fluid Flow Methods	Resistance to flow using Kozeny-Carman model
	4. Other Methods	Thermal conduction, fluidization, ionic adsorption, chemical reaction rate, heat of wetting, isotopic exchange
C.	Pore Size Distribution	
	1. Mercury Intrusion	Capillary pressure ~ pore size
	2. Surface Adsorption	
	3. Capillary Condensation	
	4. X-ray Scattering	

Table 2.17 (cont)

	5. Optical Method	Microscopic, photograph
	6. Other Methods	Surface adsorption, capillary condensation, x-ray scattering, sequential crushing and porosity measurement.
D.	Particle (Grain) Size	
	1. Sieve Method	Serial sieving of sample of powder, average diameter retained on one sieve = $\sqrt{d_1 d_2}$ where d_1 = sieve opening on retained screen, d_2 = sieve opening on screen passed just above. Suitable for granular materials down to ~325 woven mesh (44 μm); for <44 μm use electoformed micromesh sieves down to < 5 μm
	2. Microscopic Method	Microscope, photograph, can use light optical for ~1 μm < D_p < 44 μm, electron microscope to ~0.005 μm; sampling and specimen preparation technique important
	3. Centrifugal Aerosol Spectrometers	Inertial classifier, Bahco for > 5 μm, starts with powder, disperses in air, subjects to centrifugal winnowing action, others available for finer sizes, small powder volumes.
	4. Gravitational Spectrometer	Gravitational classifier, Timbrell
	5. Other Methods	Sedimentation or elutriation in air or liquids, cascade impactors for segregation of air-borne cloud particles, light scatter instruments, etc. (see Figure 2.2)
E.	Pore Structure	
	1. Theoretical Packings of Uniform Spheres	ϵ = 0.0931, (hexagonal lattice) ϵ = 0.259 (rhombohedral or face-centered cubics densest stable packing) to ϵ = 0.875
	2. Packing of Natural Materials	Pore Size ~ grain size; shape, non-uniform sizes present fill interstitial spaces, angularity promotes bridging
F.	Shape Factors	
G.	Granule Surface Roughness	

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* Adapted from Scheidegger, Ref. 121.

granular and fibrous materials are indicated in Table 2.18 from measures of flow and pressure drop.[121] These values are of little value for analytical generalization without additional information on the geometry of the flow system. Measured and calculated permeabilities specific to the requirements of porous media filtration of dust and fumes are treated below.

2.4.6.1 Porosity.- Consider a homogeneous isotropic filter of packing (bulk) density ρ_b (gm/cm^3) composed of granular (or fibrous) material of density ρ_m (gm/cm^3). The fraction of solids in the filter is defined as

$$\alpha = \rho_b/\rho_m \tag{2.59}$$

and the porosity, or void fraction, as

$$\epsilon = 1 - \alpha \tag{2.60}$$

TABLE 2.18

TYPICAL VALUES OF PERMEABILITY FOR VARIOUS SUBSTANCES*

Substance	Permeability range (Permeability in cm^2)	Literature Reference
Berl saddles	1.3×10^{-3} -3.9×10^{-3}	Carman, 1938
Wire crimps	3.8×10^{-5} -1.0×10^{-4}	Carman, 1938
Black slate powder	4.9×10^{-10}-1.2×10^{-9}	Carman, 1938
Silica powder	1.3×10^{-10}-5.1×10^{-10}	Carman, 1938
Sand (loose beds)	2.0×10^{-7} -1.8×10^{-6}	Carman, 1938
Soils	2.9×10^{-9} -1.4×10^{-7}	Aronovici and Donnan, 1946
Sandstone ("oil sand")	5.0×10^{-12}-3.0×10^{-8}	Muskat, 1937
Limestone, dolomite	2.0×10^{-11}-4.5×10^{-10}	Locke and Bliss, 1950
Brick	4.8×10^{-11}-2.2×10^{-9}	Stull and Johnson, 1940
Bituminous concrete	1.0×10^{-9} -2.3×10^{-8}	McLaughlin and Goetz, 1956
Leather	9.5×10^{-10}-1.2×10^{-9}	Mitton, 1945
Cork board	3.3×10^{-6} -1.5×10^{-5}	Brown and Bolt, 1942
Hair felt	8.3×10^{-6} -1.2×10^{-5}	Brown and Bolt, 1948
Fibre glass	2.4×10^{-7} -5.1×10^{-7}	Wiggins et al., 1939
Cigarette	1.1×10^{-5}	Brown and Bolt, 1942
Agar-Agar	2.0×10^{-10}-4.4×10^{-9}	Pallmann and Deuel, 1945

*From Scheidegger, Ref. 121.

A typical value of clean porosity for a wool felt swatch* (17.2 cm long x 12.4 cm wide x 0.25 cm thick) weighing 11.1017 gms (ρ_m = 1.4 gm/cm^3 at 75% R.H.) is thus $\epsilon = 1 - \alpha = 1 - (0.208/1.4) = 1 - 0.148 = 0.842$. This is a reasonably typical value for porous fibrous media ($\epsilon > 0.8$).

Since woven fabric is not homogeneous, because of the presence of yarns, interstitial hairy voids, and non-planar geometry, porosity is not obtainable from a simple geometric model as above for felts. Using a plain-weave wire screen as a reasonably well-behaved geometrical model of a fabric, Robertson[131] reported porosity values (% open area) of the order of 50% (range 25 to 65%) for wire diameters in the range of 75 μm to 0.2 cm. Open area is defined (for a square or plain weave) as:

$$A_o \approx (1 - td)^2 \text{ per square inch} \qquad (2.60)$$

where t = threads per inch and d = yarn diameter. In a subsequent study[132] of 45 textile fabrics, porosity (% open area) ranged from 0.2% to 40.8% for fabric weights from 13.8 to 2.5 oz/yd^2, respectively (air flow permeability at 1/2 in. water ranged from 23.5 to greater than 700 cfm/ft^2 for these same fabrics). Figure 2.45 presents Robertson's data on air

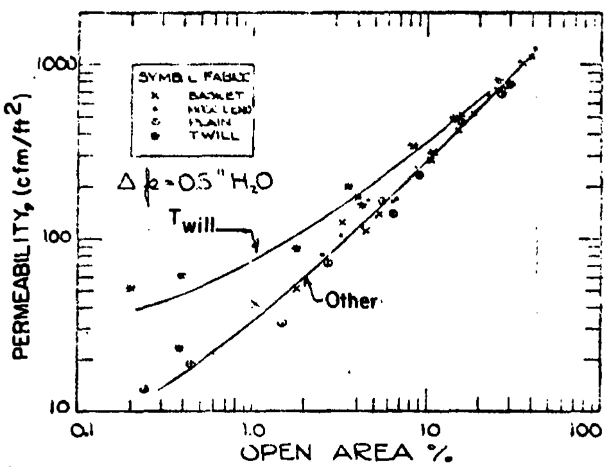


Figure 2.45. Air Flow Permeability vs Fabric Open Area (at 0.5 water pressure differential across fabric) (after Robertson[131]).

*Style No. 1753; Gurley air flow permeability 25-30 (cfm/ft^2 at 1/2 in. water pressure drop; 255 psi Mullin-Burst; 16-17 oz/yd^2; plain, Engineered Fabrics Corporation.

flow permeability and open area (porosity) for four major weave designs (of bright, continuous filament viscose rayon). For a typical sateen weave cotton fabric shown in Figure 2.26C**, with permeability 15-20 cfm/ft^2, the porosity is approximately 0.5% (using "other" curve, Figure 2.45). Further discussion of fabric weave design, material characteristics, and air flow is given below and in Chapter 4.

The porosity of granular powders can be obtained from ($\epsilon = 1 - \alpha$) the bulk density (weight of a specified volume of the powder) and true density of the material. Typical values of interest are presented in Tables 2.19[121], 2.20[133] and 2.21[134]. Porosity of usual granular packings (e.g. sand) is of order 40 to 50%. The actual porosities of dust deposits on operating fabric filters have never been measured. Based on dust structures presented in Figures 2.27 through 2.31 above, and the agglomerate particle densities of aggregated fine particles given in Tables 2.3 and 2.4, porosity of the dust deposit on fabric filters will probably range from greater than 0.9 to of order 0.4, depending on particle size, pressure drop, drag forces on the aggregates, deposition velocity, and effects of adhesion, humidity and electrostatic forces.

The effect of particle size on porosity is shown in Figures 2.46[135] and 2.47[136]. (Also see effect of porosity on permeability, Figure 2.42.) Particles below about 30 μm tend to form much bulkier aggregated structures, due presumably to the varying interrelationships of adhesion forces and particle mass. Search limitations have prevented development of more of these data from the powder literature. It is easily obtained in practice from measures of bulk density (true density assumed known or easily obtainable by pyncnometer) and particle size. No data were found for dusts on actual fabric filters in service.

Additional data and information on packing porosity is presented below in discussions on pore structure.

**Style No. 1210; 310 psi Mullen-Burst; 9.7 oz/yd^2; 96 x 60; sateen; plain finish; Engineered Fabrics Corporation.

2.4.6.2 Specific Surface.- The Carman specific surface of a granular porous medium (or other configuration of the flow field) is defined as the surface area exposed to the fluid per unit volume of solid (not porous) material.

$$S_o = \frac{\text{surface area of solids in a given total volume}}{\text{volume of solids in a given total volume}} \qquad (2.61)$$

$$= \frac{\text{surface area of one particle}}{\text{volume of one particle}} = \frac{A_p}{V_p} \qquad (2.61a)$$

TABLE 2.19

REPRESENTATIVE VALUES OF POROSITY FOR VARIOUS SUBSTANCES*

Substance	Porosity range (Porosity in %)	Literature reference
Berl saddles	68-83	Carman, 1938 ($1 < D_p < 5$ cm)
Raschig rings	56-65	Ballard and Piret, 1950
Wire crimps (5 ~)	68-76	Carman, 1938 (D_p 328 μm x 0.6 cm)
Black slate powder	57-66	Carman, 1938 ($2 < D_p < 80$ μm)
Silica powder	37-49	Carman, 1938 ($2 < D_p < 80$ μm)
Silica grains (grains only)	65.4	Shapiro and Kolthoff, 1948
Catalyst (Fischer-Tropsch, granules only)	44.8	Brotz and Spengler, 1950
Spherical packings, well shaken	36-43	Bernard and Wilhelm, 1950
Sand	37-50	Carman, 1938 ($D_p \sim 200$ μm)
Granular crushed rock	44-45	Bernard and Wilhelm, 1950
Soil	43-54	Peerlkamp, 1948
Sandstone ("oil sand")	8-38	Muskat, 1937
Limestone, dolomite	4-10	Locke and Bliss, 1950
Coal	2-12	Bond et al., 1950
Brick	12-34	Stull and Johnson, 1940
Concrete (ordinary mixes)	2-7	Verbeck, 1947
Leather	56-59	Mitton, 1945
Fibre glass	88-93	Wiggins et al, 1939
Cigarette filters	17-49	Corte, 1955
Hot-compacted copper powder	9-34	Arthur, 1956

*From Scheidegger, Ref. 121

TABLE 2.20

APPARENT DENSITY AND POROSITY FOR SOME INDUSTRIAL DUSTS COLLECTED IN FABRIC FILTERS**

	SW	BW	ε	CODE
Alfalfa meal	34	17	.51	N
Alum	103	55	.47	N
Alumina	250	60	.76	VA
Aluminum	165	160	-0-	M
Ammonium chloride, xln.	94*	52	.45	M
Antimony	414	417	-0-	VA
Asbestos, shred	153	23	.84	M
Ashes, Hard Coal	31	35	-0-	VA
Ashes, Soft Coal	43	43	-0-	VA
Asphalt, crushed	87	45	.48	VA
Ammonium sulfate	113	45	.60	M
Bagasse	20	8	.60	M
Bakente, powdered	100*	40	.60	N
Baking powder	80	41	.49	N
Bauxite, crushed	158	80	.50	VA
Beans, meal etc.	82*	41	.50	N
Bentonite	110*	51	.54	VA
Bicarbonate of Soda	137	41	.30	N
Bonemeal	75	55	.27	M
Bones, ground, minus 1/8"	100*	50	.50	M
Boneblack	65	23	.65	M
Bonechar	80	40	.50	M
Borax, powdered	109	53	.51	VA
Bran	35	15	.57	N
Brass	530	165	.69	M
Brewers grain, spent, dry	65	28	.57	N
Brick	118	135	-0-	A
Calcium Carbide	137	80	.56	A
Calcium Carbonate	169	147	.13	A
Carbon, amorph., graph.	260	130	.50	M
Carbon black, channel	15	5	.67	M
Carbon black, furnace	15	5	.67	M
Carborundum	250	195	.22	VA
Casein	80	36	.55	M
Cast Iron	450	200	.55	VA
Caustic Soda	88	40*	.55	M
Cellulose	94	80*	.17	M
Cement, portland	100	80	.20	VA
Cement, clinker	131	78	.40	VA
Chalk, minus 100 mesh	143	73	.49	A
Charcoal	25	21	.16	N
Cinders, Coal	46	43	.06	A
Clay, dry	85*	63*	.26	A
Coal, bituminous	87*	50	.43	A
Coal, anthracite	100*	55	.45	A
Coca, powdered	70*	35	.50	N
Coconut, shredded	45*	22	.51	N
Coffee	48	25	.48	N
Coke, bituminous	83	30	.64	A
Coke, petroleum	110	40	.64	A
Copra (dried coconut)	45	22	.51	NCor
Cork, fine ground	30	15	.50	M
Corn, cracked, etc.	70	50	.28	N
Cornmeal	80	40	.50	N
Cullet (broken glass)	140*	100	.28	A
Dicalcium phosphate	144*	43	.70	M
Dolomite	181	100	.45	A
Ebonite, crushed	72	59	.82	N
Egg powder	35*	16	.45	N
Epsom salts	162*	45	.72	M
Feldspar	160	70	.56	A
Ferrous sulphate	118	60	.50	A
Fish meat	80*	40*	.50	N
Flour	50	35	.30	N
Flue dust, dry	235	117	.50	M
Fluorspar	200	82	.59	A
Fly ash	85	40	.53	VA
Fullers earth	95*	47	.50	A
Gelatine, granulated	65*	32	.50	N
Glass batch	162*	95	.41	A
Glue, ground	80	40	.50	M
Gluten meal	80*	40	.50	N
Grains, distillery, dry	70*	30	.57	N
Graphite	132	40	.70	A
Gypsum	145	75	.48	A
Ilmenite ore	312*	140	.55	VA
Iron oxide	330	100*	.70	VA
Lead	710	710	-0-	A
Lead arsenate	400	72*	.82	A
Lead oxide	567	180*	.68	A
Lignite	85	50*	.41	A
Lime, ground	87	60	.31	VA
Lime, hydrated	81	40	.50	A
Limestone	163	85	.48	VA
Litharge	560	180*	.68	A
Magnesite	187	187*	-0-	VA
Magnesium	109	100*	-0-	VA
Magnesium chloride	138	33	.76	A
Malt, dry	44	26	.41	N
Manganese sulphate	125	70	.44	A
Maple, hard	4	43	-0-	N
Marble	168	96	.43	A
Marl	120	80	.33	A
Mica, ground	175	15	.914	M
Milk, dried, powdered	70	35	.50	N
Monel metal	554	550	-0-	M
Muriate of potash	160	77	.52	M
Naphthalene flakes	71	45	.37	N
Oak	47	15	.68	N
Oxatic acid crystals	104	60	.42	N
Phosphate rock	160	80	.50	VA
Phosphate sand	190	95	.50	VA
Porcelain	150	75	.50	M
Quartz	165	100	.40	VA
Resin	67	35	.48	M
Rubber, ground	72	23	.68	N
Rubber, hard	74	59	.20	N
Rubber, soft	69	55	.20	N
Salt, rock	136	45	.67	A
Salt, dry, coarse	138	50	.64	A
Salt, dry, pulverized	140*	75	.48	A
Saltpeter	138	80	.42	N
Sand	150	100	.67	VA
Sandstone	144	95	.34	VA
Sawdust	35	12	.66	N
Shale, crushed	175	87	.50	A
Slag, furnace, granulated	132	62	.53	VA
Slate	172	85	.50	A
Soap, chips, flakes	30	15	.50	N
Soap powder	50	25	.50	N
Soapstone talc	175	62	.65	M
Soap ash, light	74	35	.53	M
Soda ash, heavy	134	65	.50	M
Sodium Nitrate	134	70	.52	A
Sodium Phosphate	94	45	.52	A
Soybeans, meal	90	45	.50	N
Starch	96	40	.58	N
Steel	487	100	.80	A
Steel chips, crushed	487	60	.88	A
Sugar	105	53	.50	N
Sulphur	126	60	.52	N
Talc	169	60	.64	M
Tanbark, ground	110	55	.50	M
Tin	457	459	-0-	A
Titanium	280	100	.64	VA
Tobacco	50	25	.50	N
Vermiculite ore	160	80	.50	A
White lead	120	74	.42	A
Zinc Oxide	360	35	.903	A

CODE: VA-very abrasive A-abrasive M-midly abrasive N-less abrasive
SW-specific wt. lbs/ft^3 BW-bulk wt. lbs/ft^3 ϵ-porosity.

*Estimated

**From Ref. 133.

TABLE 2.21

PARTICLE SIZE DISTRIBUTION, BULK DENSITY, POROSITY, AND FLOWABILITY OF SOME TYPICAL POWDERS*

Solid**		Average Particle Size Microns	Mesh Size Powder %	Mesh Size Granule %	Bulk Density Loose	Bulk Density Packed	Bulk Density Working	True Density gm/cm^3	Loose*** Powder Porosity (Void Fraction)	Flowability	Floodable (or can be fluidized)
Aluminum	Granules	840	0.0	100.0	99	114	101	2.65	.40	Excellent	No
	Powder	<30	100.0	0.0	48	74	57		.71	Poor	Very
Coal	Granules	3000	5.0	95.0	43	54	46	1.45	.53	Good	No
	Gran. Pwd.	<74	80.0	20.0	28	36	30		.69	Poor	Very
Limestone	Granules	2000	1.0	99.0	85	105	89	2.62	.48	Excellent	No
	Gran. Pwd.	<30	80.0	20.0	55	81	62		.66	Poor	Yes
	Powder	<30	100.0	0.0	42	66	51		.74	Poor	Yes
Salt	Granules	250	0.0	100.0	74	86	75	2.22	.46	Good	No
	Pwd. Gran.	70	25.0	75.0	63	79	67		.54	Passable	No
	Gran.&Pwd.	30	65.0	35.0	46	62	50		.67	Poor	Yes
Silica	Granules	80	0.0	100.0	97	108	98	2.65	.41	Excellent	No
	Gran. & Pwd.	60	60.0	40.0	51	79	61		.69	Poor	Yes
	Powder	<74	100.0	0.0	51	73	58		.69	Poor	Yes
	Powder	5	100.0	0.0	27	44	34		.84	Very Poor	Yes
	Powder	0.01	100.0	0.0	2.1	2.7	2.4		.9872	V. Very Poor	Yes (dusty)
	Pwd. (porous)	3.5	100.0	0.0	1.9	2.7	2.0		.9885	V. Very Poor	Yes (dusty)
Soda Ash	Granules	250	1.0	99.0	63	76	65	2.15	.53	Excellent	No
	Pwd. Gran.	100	20.0	80.0	36	47	39		.73	Passable	No
	Gran. & Pwd.	74	60.0	40.0	33	51	37		.75	Poor	Yes
Sugar	Granules	150	0.5	99.5	50	57	51	1.69	.53	Good	No
	Gran. Pwd.	74	72.0	28.0	29	43	33		.72	Poor	Yes
	Powder	<74	100.0	0.0	23	36	28		.78	Very Poor	Yes
Sulfur	Pwd. Gran.	220	8.5	91.5	70	86	73	2.02	.45	Passable	No
	Pwd. & Gran.	74	52.0	48.0	35	46	38		.72	Poor	Possible
	Pwd. (lumped)	<74	100.0	0.0	36	50	40		.71	Very Poor	No

*From Carr, Ref. 134

*** ϵ = 1 - Bulk Density/True Density

**Carr defines: particles > 200 mesh (74 μm) as granular, free-flowing units for average weight material of average M.W. (inorganic) of 25-40 lb/cu. ft. → : particles < 200 mesh as "powders", non-flowing. The lighter a material, the coarser is its powder; a heavier material will have finer powdered entities.

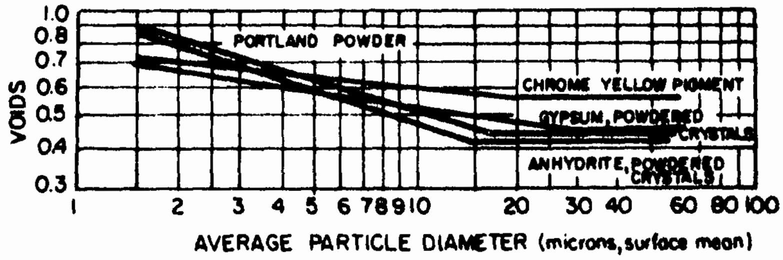


Figure 2.46. Bulking Properties of Various Powders, Roller's Data, from Dalla Valle, Ref. 135.

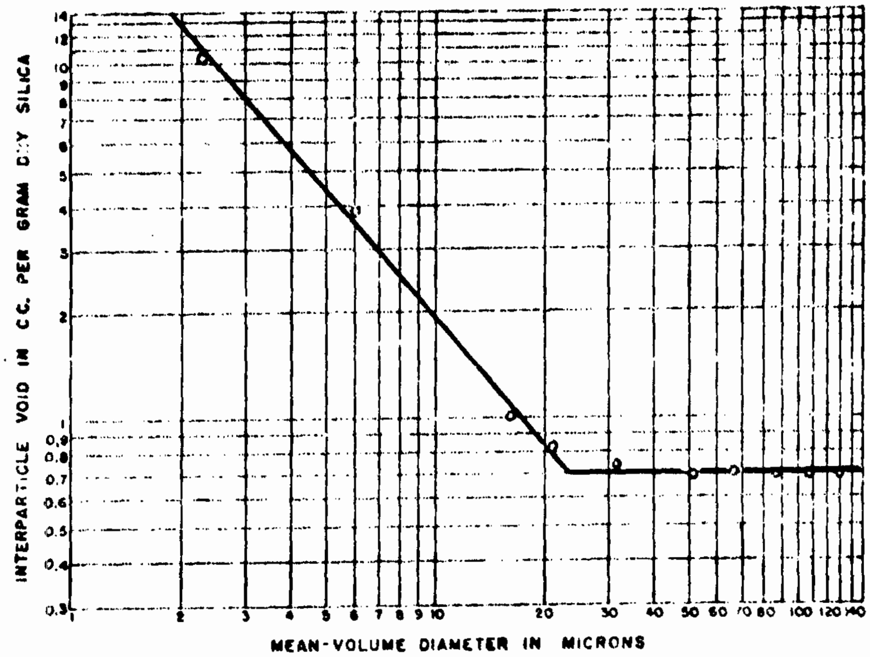


Figure 2.47. Bulkiness of Powders, data by Shapiro and Kolthoff on Silica (Ref. 136).

For spherical particles, $A_p = \pi D_p^2$ and $V_p = \pi D_p^3/6$ and $A_p/V_p = 6/D_p$, with dimension cm^{-1}. For non-spherical particles, an empirical shape factor (greater than 1) is derived, as discussed below. Some representative values of S ($\frac{S_o}{1-\epsilon}$ = surface area of the pores of a unit bulk volume of the porous medium) are indicated in Table 2.22[121].

TABLE 2.22

REPRESENTATIVE VALUES OF SPECIFIC SURFACE FOR VARIOUS SUBSTANCES*

Substance	Specific surface range (Specific surface in cm^{-1})	Literature Reference
Berl saddles	3.9-7.7	Carman, 1938
Raschig rings	2.8-6.6	Ballard and Piret, 1950
Wire crimps	2.9 x 10 -4.0 x 10	Carman, 1938
Black slate powder	7.0×10^3-8.9×10^3	Carman, 1938
Silica powder	6.8×10^3-8.9×10^3	Carman, 1938
Catalyst (Fischer-Tropsch, granules only)	5.6×10^5	Brotz and Spengler, 1950
Sand	1.5×10^2-2.2×10^2	Carman, 1938
Leather	1.2×10^4-1.6×10^4	Mitton, 1945
Fibre glass	5.6×10^2-7.7×10^2	Wiggins et al., 1939

*From Scheidegger, Ref. 121

For computational estimates of granular bed pressure drop to be considered below, values of A_p/V_p for spheres ($= 6/D_p$) are presented in Table 2.23. Note that the range of $(A/V)^2$ is from 10^4 to 10^{10} for particles ranging from 500 to 0.5 μm respectively. A typical value for sand (from Table 2.22) is $S_o = 2 \times 10^2/0.6 = 3 \times 10^2$ (for an assumed particle size of 60-90 mesh sand approximately 200 μm, as given in Table 2.19 and from Carman, Ref. 123). Note that the value for spheres is 3×10^2, in Table 2.23.

2.4.6.3 Pore size distribution.- Pore size distribution depends upon the nature and state of a given packing, and is determined from a mercury-injection method involving flow and pressure measures and capillarity, or by bubbling pressure (bubble point test).

TABLE 2.23

VALUES OF A_p/V_p FOR SPHERICAL PARTICLES IN FABRIC FILTER DUST CAKE

Particle Size μm	cm	A/V* cm^{-1}	$(A/V)^2$ cm^{-2}
500	5×10^{-2}	1.2×10^{2}	1.44×10^{4}
300	3×10^{-2}	2×10^{2}	4×10^{4}
200	2×10^{-2}	3×10^{2}	9×10^{4}
100	10^{-2}	6×10^{2}	3.6×10^{5}
50	5×10^{-3}	1.2×10^{3}	1.44×10^{6}
30	3×10^{-3}	2×10^{3}	4×10^{6}
20	2×10^{-3}	3×10^{3}	9×10^{6}
10	10^{-3}	6×10^{3}	3.6×10^{7}
5	5×10^{-4}	1.2×10^{4}	1.44×10^{8}
3	3×10^{-4}	2×10^{4}	4×10^{8}
2	2×10^{-4}	3×10^{4}	9×10^{8}
1	1×10^{-4}	6×10^{4}	3.6×10^{9}
0.5	5×10^{-5}	1.2×10^{5}	1.4×10^{10}

*$S_o = (A/V) = 6\ \pi D_p^{\ 2}/\pi D_p^{\ 3} = 6/D_p$, cm^{-1}

The true nature of the openings responsible for fluid flow in woven textile fabrics is not actually known. Pore size distributions in 14 tight cotton textile fabrics (6 water repellent) were measured by Wakeham and Spicer[137] using a mercury intrusion technique. These are given in Table 2.24. Total free volume (V_t) was obtained from

$$V_t = \text{total volume of fabric} - \text{volume of fibers}$$

$$V_t = \text{area} \times \text{thickness (at 1 psi)} - \text{wt. of sample}/\rho_f \text{ for cotton.}$$

Yarn to yarn spacing (interyarn) openings were indistinguishable from internal yarn pores between individual (interfiber) cotton fibers when y-y distance was less than about 50 μm. Wakeham and Spicer describe the sizes of pores in terms of

> "... the arbitrary designation of 50 μ as the upper limit of diameter of interfiber pores, as distinguished from interyarn openings."

TABLE 2.24a

PHYSICAL PROPERTIES OF FABRIC SAMPLES INVESTIGATED (DESIZED AND SANFORIZED)

Sample no.	Description	Nominal yarn no.		Thread count		Weight (oz./sq. yd.)	Thick-ness in 1/1000 in.	Air permea-bility*	Hydrostatic permeability	
		Warp	Filling	Warp	Filling				Height	Flow
Group I										
1	Plain weave	13/1	10/1	82	52	9.2	20	2.56	--	--
2	Oxford	13/1	10/1	85	54	9.7	22	3.41	--	--
3	Sateen	13/1	10/1	84	71	11.2	30	5.10	--	--
4	Herringbone twill	13/1	10/1	82	64	10.6	23	2.19	--	--
5	Modified herringbone twill	13/1	10/1	82	63	10.6	24	2.17	--	--
Group II										
6	2/1 twill, 7/8-in. average cotton	13/1	10/1	82	53	9.8	24	5.83	10	>10,000
7	2/1 twill, 1-in. average cotton	13/1	10/1	82	53	9.3	23	5.70	--	--
8	2/1 twill, 7/8-in. average cotton	13/1	10/1	82	53	9.4	23	7.07	--	--
Group III	(water-repellent treated with Norane)									
9	Oxford A	80/2	40/2	166	81	6.6	13	1.57	54	1,219
10	Oxford B	80/3	40/3	136	63	8.3	16	1.58	54	801
11	Oxford C	80/3	40/3	159	64	9.0	17	0.80	80	65
12	Oxford D	60/3	45/3	142	63	9.5	18	0.84	68	397
13	Oxford E	60/3	30/3	140	52	10.0	20	1.00	75	307
14	Oxford F	30/3	15/3	82	39	13.3	25	1.21	50	846

*Air flow in cu. ft./sq. ft./min.
Hydrostatic pressure in cm. of water on the fabric.
Permeability in water flow in cc. through a 5 1/2-in. circle in 50 min.
From Wakeham and Spicer, Ref. 137.

TABLE 2.24b

FABRIC POROSITY DATA

Sample no.	Description	Specific volume of fabric (cc./g.)	% Total free volume (cc./g.)	Interfiber pore volume (cc./g.)	Volume of interyarn spaces (cc./g.)	Median diameter of interfiber pores (μ)
Group I						
1	Plain weave	1.69	1.02	0.503	0.52	9.0
2	Oxford	1.70	1.04	0.600	0.44	10.4
3	Sateen	2.04	1.37	0.828	0.54	14.0
4	Herringbone twill	1.70	1.03	0.609	0.42	10.0
5	Modified herringbone twill	1.65	0.98	0.592	0.39	10.2
Group II						
6	2/1 twill, 7/8-in. average cotton	1.93	1.27	0.770	0.50	13.2
7	2/1 twill, 1-in. average cotton	1.92	1.25	0.686	0.57	12.6
8	2/1 twill, 7/8-in. coarse cotton	1.94	1.27	0.732	0.54	14.8
Group III						
9	Oxford A	1.55	0.88	0.440	0.44	9.6
10	Oxford B	1.57	0.90	0.477	0.43	10.2
11	Oxford C	1.45	0.78	0.386	0.40	8.0
12	Oxford D	1.47	0.81	0.386	0.42	8.6
13	Oxford E	1.54	0.87	0.420	0.45	9.0
14	Oxford F	1.46	0.79	0.518	0.28	10.0

"Microscopic observations and measurements of the observable interfiber and interyarn spaces in fabrics have supported the distinction between these two types of pores. When interyarn pores are appreciably smaller than 50 μ in diameter, they are no longer recognizable as interyarn openings because cotton fibers 20 μ or so in diameter constitute the interyarn-pore walls. In Table (2.24b), therefore, the interfiber pore volume is that for all pore spaces in the fabric less than 50 μ in diameter."

"The difference between the total free volume in the fabric and the interfiber pore volume has been designated the volume of interyarn spaces. In view of the fact that all fabrics studied in this investigation were tight fabrics with practically no observable interyarn pores through the fabric, the interyarn volumes shown in Table (2.24b) may appear to be rather large. This result is due to the definition of the total free volume in the fabric. ...these total free volumes are based on a thickness measurement with a pressure of 1 lb/sq. in. on the fabric. At this pressure the fabric undergoes only a slight compression or distortion, and the total free volume, therefore, includes interyarn spaces which are due to the surface unevenness of the fabric (such as ridges and mounds) in addition to the spaces between yarns and pores within. The interyarn volume as given in Table (2.24b) includes, therefore, interyarn "pores" parallel to the fabric surface as well as those perpendicular to it."

Considering these reservations, pore area estimated from data in Table 2.24a and b, yields an average interyarn space of 2.2×10^{-2} cm or 220 μm. This figure is of the same order or magnitude as discussed by Stairmand (see Figure 2.26). Wakeham and Spicer indicate no such pores visible in the microscope.

Average pore sizes of fibrous <u>felted</u> materials, papers, and the like can be estimated from the porosity, ϵ, (as calculated above), with a geometric model of the fibrous medium and the fiber size, as in typical photomicrographs (Figures 2.28 and 2.29, for example).

Pore sizes of <u>granular media</u> depend upon grain size, shape, and packing arrangement. The general assumption made for relatively large grains (e.g. sands)>> 100 μm, is that the pore size is approximately equal to granule size.

Pore sizes for some typical fibrous, granular and gauze filter materials are given in Table 2.25[138].

2.4.6.4 Particle (grain) Size.- Particle size in granular media affects porosity, surface area, and pore geometry. Particle size measurement is discussed in several texts.[8,9,13,37,38,135] In all cases of practical concern, particles will be present over a range of sizes. Formation of a granular porous medium will involve grains at the larger end of the spectrum present, which may form a loose network with inter-grain openings filled in to some certain extent with the finer sizes.

2.4.6.5 Pore Structure.- The physical shape and appearance of pores in a granular porous medium of natural materials is presumably related to particle size distribution, shape, and surface, as well as to the degree of compaction or compression applied. The only cases analytically tractable are spheres, for which certain broad conclusions can be drawn to assist in interpretation of estimates in non-spherical cases (similarly, cylindrical models are used in analysis of fibrous felted porous media). Pore geometry and structure in spherical (model) arrays are illustrated in Figure 2.48. These studies lead to the conclusions that:

(a) For any one mode of packing (for spheres all the same size) the porosity of the bed is independent of sphere size.

(b) The porosity of stable beds of uniform spheres varies upward from about 0.259 (rhombohedral or face-centered-cubic configurations shown in Figure 2.48c and d); with uniform spheres, simple cubic packing yields $\epsilon = 0.476$.

(c) The densest packing of non-overlapping uniform circles that can be achieved (0.9069) on an area basis yields a porosity of $\epsilon = 0.0931$ in a hexagonal lattice.[140]

(d) If interstitial spaces are partially closed by smaller particles touching at three points (stable) (see Figure 2.49) the resulting packing factor is

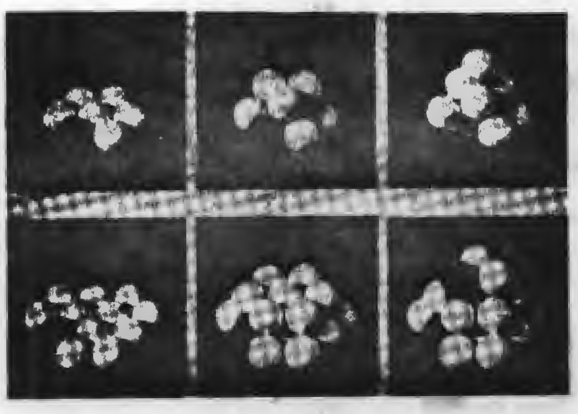
TABLE 2.25

PORE SIZES OF VARIOUS FILTER MEDIA*

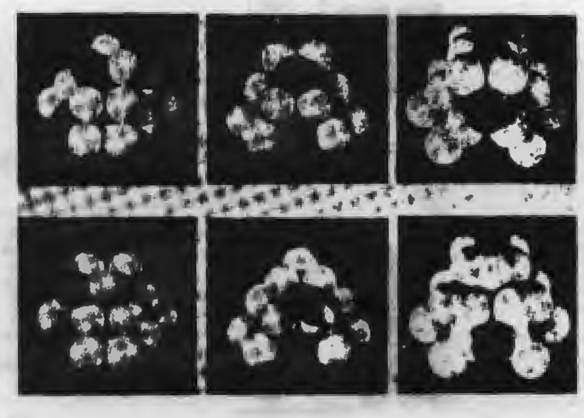
Material	Grade	Average pore size, μ	References
Micro-porous porcelain[a]	XF	50	G.V. Jordan, Jr., Selas Corp. Mech. Eng., 75, 559-63, 566 (1953)
	XFF	20	
	10	4.4	
	015	1.4	
	03	0.60	
	05	0.34	
Porous Teflon filters	CPS-40	Retains 40 μ and larger	Porous Plastic Filter Co., Glen Cove, New York
	CPS-25	Retains 25 μ and larger	
	--	Pore size 9 μ	
Filter papers	S & S 604	4.5	Carl Schleicher & Schuell Co., Keene, New Hampshire
	595	4	
	597	3	
	602	2.2	
	576	1.5	
Membrane and Cella filters	Coarse	3-0.75	Carl Schleicher & Schuell Co., Keene, New Hampshire
	Medium	0.75-0.5	
	Dense	0.5 -0.2	
	Very dense	Below 0.2	
Ultrafine and Ultra Cella filters	Coarse	0.2 -0.08	Carl Schleicher & Schuell Co., Keene, New Hampshire
	Medium	0.08-0.05	
	Dense	0.05-0.01	
	Very dense	0.01-0.005	
	Super dense	Below 0.005	
18-8 stainless-steel filter elements (porous)	C	165	
	D	65	Micro Metallic Corp., Brooklyn, New York
	E	35	
	F	20	
	G	10	
	H	5	
Porous stainless-steel filter plates	5	6.5	Metal and Plastics Compacts, Ltd., Birmingham, England
	10	12	
	20	18	
	50	33	
	100	46	
	250	70	
Carbon	Fine	20-40	Filtros, Inc., East Rochester, New York
Calcined refractory clay Type B	Medium	70-100	
	Coarse	100-200	
Thermoplastic porous media (German Plexolith)	Plates & sheets	15	Filtros, Inc., East Rochester, New York
	Diaphragms	8	
Fused diatomite filter candles	N	3.4	Berkefeld-Filter G.m.b.H., Celle, Germany
	W		Prausnitz, Glas und keramische Filter im Laboratorium fur Filtration, Gasverteilung, Dialyse, Extraction. Akadem. Verlagsgesellschaft, Leipzig, 1933
	V	9.9	
Filterstones, quartz, pantel, carbon, chamotte	10	15-20	Wilhelm Schuler G.m.b.H., Eisenberg, Germany
	20	20-40	
	50	50-70	
	100	100-150	
	130	100-200	
Quartz filter plates	Superfix	10	
Pyrex fritted glass filters	Extra-coarse	170-220	Corning Glass Works, Corning, New York
	Coarse	40-60	
	Medium	10-15	
	Fine	4-5.5	
	Ultra-fine	0.9-1.4	
Metal cloths			
Mykro-Pore (can be supplied with openings from 30 μ up in pure Ni or other metals such as Fe and Cu which can be electrodeposited)	Class XL	30	Multi-Metal Wire Cloth Co., New York
Plain Dutch	24 x 110	245	
Twilled	20 x 250	100	
	30 x 250	65	
	50 x 600	70	
	100 x 1000	50	
Standard testing sieves	100 x 100	149	Newark Wire Cloth Co., Newark, New Jersey
	140 x 140	105	
	200 x 200	74	
	325 x 325	44	
	400 x 400	37	
Sintered fiber glass filters	A	145-175	Ace Glass, Inc., Vineland, New Jersey
	B	70-100	
	C	25-50	
	D	10-20	
	E	4-8	

[a] Pore size determined by bubbling pressure.

*From Cummins and Nato, Ref. 138



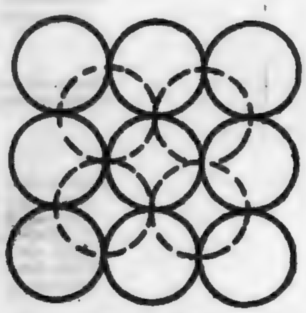
(a)



(b)

Figure 2.48(a) Packing of Spheres: Illustration of "square" and "triangular" holes.

Rhombohedral packing of spheres.



Face-centred cubic packing of spheres.

Figure 2.48(b) Packing of Spheres: Hexagonal close-packed (top) and cubic close-packed (bottom).

(From Kolthoff, Ref. 139.)

$$\alpha = 1 - (1 - 0.9069)^K \quad (2.62)$$

and $\alpha \to 1$ as $K \gg 1$, i.e., $\epsilon \to 0$.

(e) Packing of non-spherical natural particles will lead to bridging and increases porosity, offset partly by the tendency of smaller particles to accumulate in larger interstitial spaces.

No studies of pore morphology have been reported for fabric filter deposits.

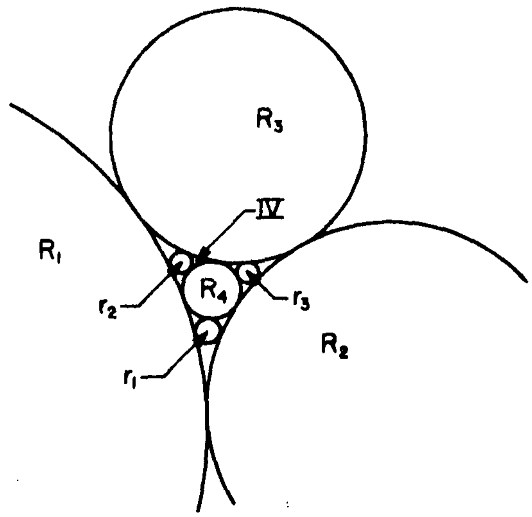


Figure 2.49. Tricuspid Interstices in the Osculatory Packing of Finite Areas with Circles (from Ref. 140).

2.4.6.6 Shape Factors.- If particles are not spherical, the specific area-volume relationship is given as $A/V = \lambda\, 6/D_p$, where the particle shape factor λ is applied, $(1 < \lambda < 10)$. Typical shape factors are given in Table 2.26 as taken from Leva, et al.[141]

Leva's discussion of his shape factor is given below:

"In order to define the shape factor, λ, ... let

D_m = average diameter of a particle of any arbitrary shape;

D_p = diameter of a sphere of equivalent volume;

A = surface area of a particle of arbitrary shape, and

A_p = surface area of a sphere of equivalent volume.

Then, $A = \alpha D_m^2$, where α is an area shape factor, and $A_p = \pi D_p^2$.

TABLE 2.26

SHAPE FACTOR, λ, FOR TYPICAL GRANULAR POROUS PACKING MATERIALS[141]

Shape	Nominal Dimensions, Inches	Shape Factor	Remarks
Spheres	all	1.00	
Rounded Granules	0.170	1.10	Aloxite
Rounded Granules	0.1875	1.10	MgO, Oman and Watson
Sharp Granules	0.165	1.10	Aloxite
Cylinders	0.180	1.15	Alundum
Cylinders	5/16 x 3/8 in. D.	1.16	Tungsten sulfide catalyst Pellet $h/D_c = 0.833$
Raschig Rings	0.252	1.50	Clay
Raschig Rings	0.400	1.90	Clay, Oman and Watson
Raschig Rings	0.944	2.19	
Berl Saddles	0.480	2.07	
	0.765	2.71	
Cylinders	0.247 x 0.236 in. D.	1.145	Copper Pellet $h/D_c = 1.048$
Cylinders	1/2 x 5/16 in. D.	1.175	Copper Pellet $h/D_c = 1.60$
Lessing Rings	0.953	2.67	

$$\therefore, \alpha_p = \pi$$

for the sphere of equivalent volume.

"By earlier definition, V was designated as the volume of the particle. Then,

$$V_p = \gamma D_m^3 = \frac{1}{6} D_p^3,$$

where γ is a volume shape factor.

$$\therefore, \gamma_p = \frac{\pi}{6}$$

for the sphere of equivalent volume.

By definition let

$$\lambda = \frac{A}{A_p} = \frac{\alpha D_m^2}{\pi D_p^2} \qquad (6)$$

Since

$$V_p = \gamma D_m^3 = \frac{\pi}{6} D_p^3,$$

solution for D_p yields

$$D_p = 1.211 \gamma 1/3 D_m \qquad (7)$$

Substituting (7) into (6) yields

$$\lambda = \frac{0.642\alpha D_m^2}{\pi\gamma 2/3 D_m^2} = 0.205 \frac{\alpha}{\gamma 2/3} \qquad (8)$$

For any particle,

$$\frac{A}{V_p} = \frac{\alpha}{\gamma} \frac{1}{D_m^2};$$

substituting this into (8) and recalling that $D_m \gamma 1/3 = V_p^{1/3}$, yields

$$\lambda = 0.205 \frac{A}{V_p^{2/3}} \qquad (9)$$

2.4.6.7 Granule Surface Roughness.- For particulate granular bed systems in slow viscous flow ($Re_p < 10$), Leva et al and other workers have found no dependence of permeability on surface roughness of the granules composing the bed. This is analogous to the situation observed in flow through cylindrical tubes in the so-called streamlined range ($Re_{tube} < 1000$). Surface roughness is only significant in the onset and character of tubulence developed at higher Reyholds numbers, at least as far as is now known. Since much of the work in fabric filtration has been performed in the slow vicous flow regime, no studies of effects of grain roughness are available. As technological application of fabric, fiber, granular, or grid filtration devices goes to higher gas velocities ($V > 100$ ft/min), effects of roughness may be of significance in analyses of filter performance. Surface roughness effects at Re_p greater than 10 are indicated below.

2.4.7 Working Equations

Pressure drop equations have been extensively investigated for various types of porous media.

For a single layer of a plain-weave rectangular mesh wire screen, the (Lapple-duPont) pressure drop equation cited in Reference 97 is:

$$h = \frac{1 - \epsilon^2}{c^2 \epsilon^2} \cdot \frac{V^2}{2g} \qquad (2.63)$$

where h = head loss in cm fluid flowing

c = screen discharge coefficient, dimensionless

ϵ = fractional free projected area of screen; porosity, dimensionless

V = free stream velocity approaching screen, cm/sec

g = gravitational constant, 980 cm/sec^2

Note the use of $V_{pore} = V_{free}/\epsilon$, in equations (2.63) and (2.64) below.

For a series of screens, the overall head loss is directly proportional to the number of screens and is unaffected by spacing or orientation. There are several other studies on screen pressure drop that have not been included here, primarily in wind and water tunnel flow systems. The screen discharge coefficient is a function of the modified Screen Reynolds number

$$Re_{sc} = D_s V \rho_f / \mu_f \epsilon \qquad (2.64)$$

where D_s = the aperture width, cm

ρ_f = fluid density gm/cm^3

μ_f = fluid viscosity, gm/cm-sec

The (Lapple-duPont) discharge coefficients are given in Figure 2.50 and are stated to predict the head loss to within ±20%. A value of C greater than 1 implies pressure recovery downstream of the screen.

Use of plain weave wire screens as models for regular, open textile materials was studied by Robertson, who found

$$C' = \frac{Q}{A_2 \left[\frac{2gh}{1-A_o^2}\right]^{1/2}} \qquad (2.65)$$

where C' = discharge coefficient, dimensionless

Q = volumetric flow rate per pore, cm^3/sec

h = pressure drop, cm of fluid flowing

g = as above

A_1 = upstream flow channel area, cm^2

A_2 = pore projected open area, cm^2

$A_o = A_2/A_1 = \epsilon$

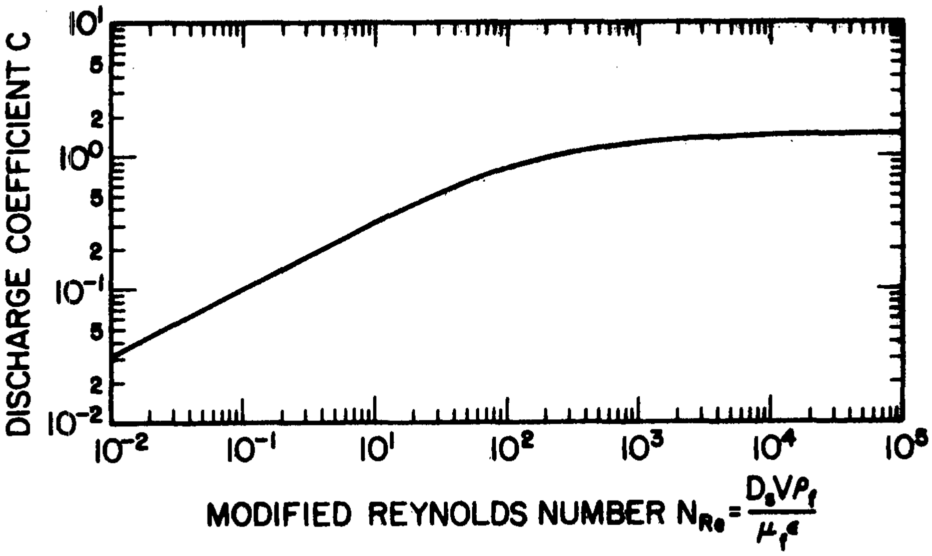


Figure 2.50. Screen Discharge Coefficients, Plain Rectangular-Mesh Screens. (From Perry, et al., Ref. 97).

The discharge coefficient is a function of screen Reynolds number

$$Re_s = D_s V \rho_f/\mu_f \qquad (2,66)$$

where D_s = diameter, or width of square orifice.

Robertson's plot of C vs Re_s is shown in Figure 2.51 (which confirms the 1944 data of G. I. Taylor and R. M. Davies[142]) for the screen configurations shown in Table 2.24 and for plain-weave rayon fabric (yarn, 900 den.) of 25 x 25 ypi (15.6% open area).

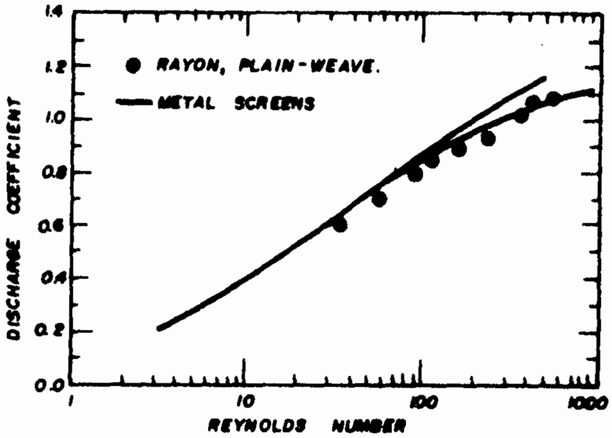
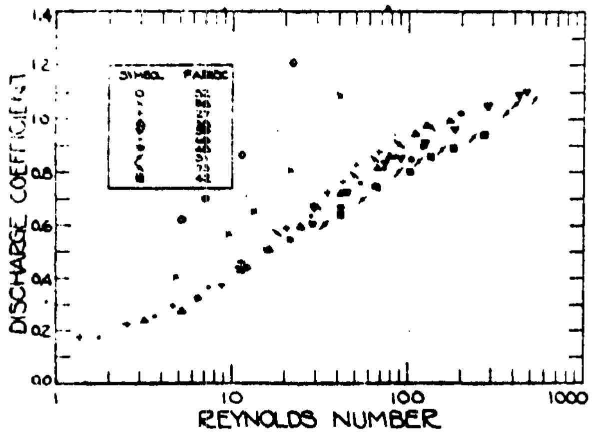


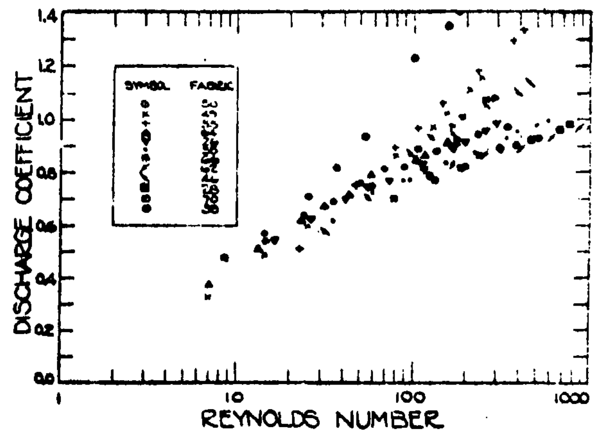
Figure 2.51. Screen and fabric data. (from Robertson, Ref. 131.).

Robertson[132] extended his study to some 45 rayon fabrics using the same equation, with values of the discharge coefficient as indicated in Figure 2.52 for a number of different fabrics. Presumably, Robertson's data can be extrapolated downward (to $Re_s \sim 0.1$) by reference to the Lapple-dePont data in Figure 2.50. As will be shown below, the C~Re relationship is linear for porous media having Re < 10. Note that these correlations are essentially pore-related models (i.e. a capillary flow model is assumed). Robertson indicates[132] that "... even in the tightest weaves tested the yarns can be considered to be impermeable barriers"... to flow, all the flow passing essentially through the inter-yarn spaces.

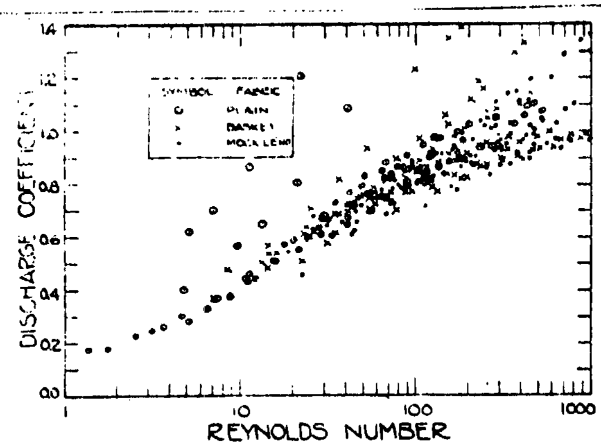
For random felted fibrous media, the flow of clean gas can be considered as a part of the general problem of flow through homogeneous isotropic, porous media. At the usual velocities and ambient pressures encountered in filtration, the gas can be considered incompressible. The volume occupied by fibers is usually small (<10%) in contrast to granular porous media (>30%). The average distance between fibers is several times larger than the fiber diameter, again in contrast to granular media where pore and particle size are approximately equal. The macroscopic flow is one-directional and fibers lie essentially perpendicular to the flow.



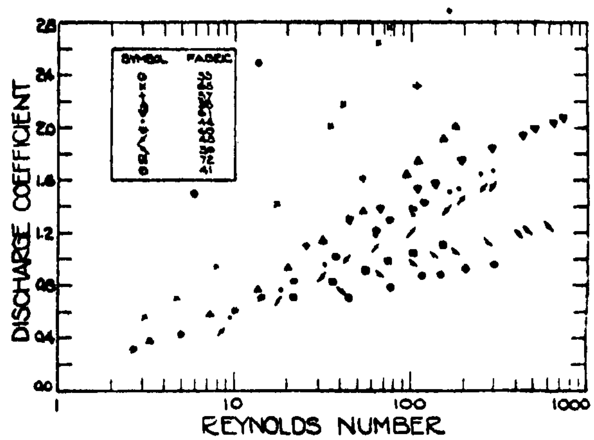
(a) *Experimental porosity data for plain-weave fabric construction.*



(b) *Experimental porosity data for basket-weave fabric construction.*



(e) *Porosity data for plain, basket, and mock-leno fabrics.*



(d) *Experimental porosity data for twill-weave fabric construction.*

Figure 2.52. Discharge Coefficient - Reynolds Number Relationships for 45 Fabrics (from (Robertson, Ref. 132).

For steady flow through fiber filters under consideration here (D_f < 20 microns, V_o < 100 cm/sec), the Reynolds number based on fiber size is less than about one. Therefore, Darcy's Law applies, namely:

$$\bar{U} = -\frac{k'}{\mu}\Delta p \qquad (2.44)$$

where k' is the intrinsic permeability of the medium, and Δp is the pressure gradient. For flow in fiber filters, it is usual to express Darcy's Law in the form:

$$\frac{\Delta p}{L} \cdot \frac{a_f^2}{\mu U_o} = K_o(\alpha) \qquad (2.67)$$

where Δp is the resistance to flow or pressure drop across the medium, a_f is the fiber radius, and $K_o(\alpha)$ is the theoretical resistance coefficient. The intrinsic permeability is related to this coefficient by $k' = a_f^2/K_o(\alpha)$. For theoretical values of the coefficient, use Table 2.16.

There have been a number of experimental determinations of the fiber filter resistance coefficient, defined as:

$$K_o' = \frac{\Delta p}{L} \cdot \frac{a_f^2}{\mu U_o} \qquad (2.68)$$

using measured values of the variables to calculate K_o'. Results of several of these studies are summarized in Table 2.27. The correlation of Davies is shown in Figure 2.53 for $Re_c < 1$ (Reynolds number based on fiber cylinder diameter), (p,269 Ref. 112). An equivalent Reynolds number - resistance coefficient relationship is included in the discussion below.

The pressure drop for flow in granular beds has been shown to be[141]:

TABLE 2.27

EXPERIMENTAL RESISTANCE COEFFICIENTS FOR FIBER FILTERS

Investigator	Experimental Coefficient (K_o')	Remarks
Sullivan	$K'\alpha^2/K''(1-\alpha)^3$	K' = shape factor K" = orientation factor
Blasewitz et al.	$\alpha^{3/2}$	Glass fiber
Davies	$16\alpha^{3/2}(1 + 56\alpha^3)$	Many materials
First et al.	$(29/4)\alpha^{1.4}$	Glass fiber $10^{-3} \leq Re \leq 10^2$
Wong and Johnstone	$(C_D Re/2)(1/\pi)\alpha$	Glass fiber C_D = fiber drag coef. $C_D Re \sim 10$
Chen	$K_1\alpha/\pi(1-\alpha)(-\frac{1}{2}\ln K_2\alpha)$	Glass fiber $K_1 \sim 6.1$, $K_2 \sim 0.41$
Wright et al.	$(C_D Re/2\pi)\alpha$	Glass and tungsten fibers $C_D Re \sim 4\pi$
Kimura and Iinoya	$(2Re\alpha/\pi(1-\alpha)^2)(0.6 + 4.7Re^{-\frac{1}{2}} + 11Re^{-1}$	Glass and steel wool fibers $10^{-3} \leq Re \leq 10^2$
Aiba	$C_D Re\,\alpha^{3/2}/2\pi(1-\alpha)^2$	Glass fibers $C_D Re \sim 50$
Wheat	$K_3\alpha/4(1-\alpha)^2$	Sub-micron glass fiber K_3 corrects for slip flow (~30 at STP).
Werner and Clarenburg	$180 C_s^{-5/2}\alpha^{3/2}$	Sub-micron glass fiber C_s is a function of the fiber Knudsen No, $Kn = \lambda/a$

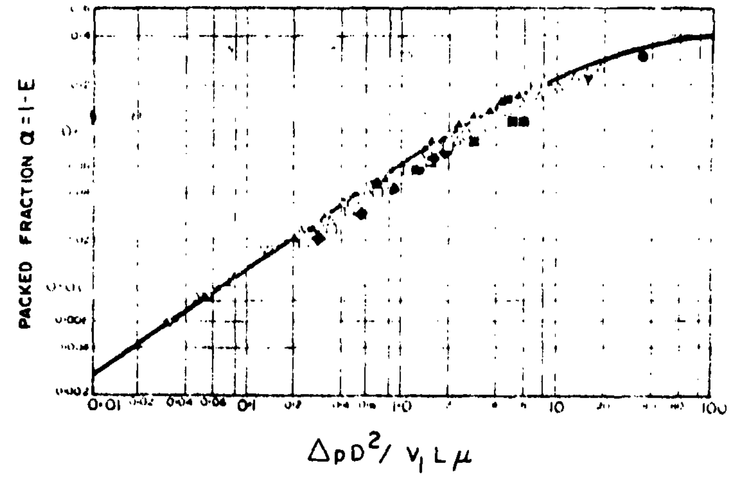


Figure 2.53. Correlation of Bed Density (1 - ε , where ε = Voidage) with a function of pressure drop Δp and superficial gas velocity: $(\Delta p D^2/V_f L \mu_f)$, (from Strauss, Ref. 112).

Fluid flow through fibrous material

o Glass wool	△ Kapok	□ Cotton wool
● Glass wool and copper wire	▲ Merino wool	■ Camel hair
+ Glass (fibres perpendicular to flow)	◇ Cotton wool	▽ Down
x Glass (fibres parallel to flow)	◆ Rayon	▼ Glass wool

$$\frac{\Delta p}{L} = \frac{k}{g} \left(\frac{D_p V \rho_f}{\mu_f} \right)^n \frac{\mu_f^2}{\rho_f} \frac{\lambda_s^{3-n}}{D_p^3} \frac{(1-\epsilon)^{3-n}}{\epsilon^3} \qquad (2.69)$$

where n = flow factor, = 1 for slow viscous flow at low granule (particle) Reynolds number < 10, and → 2 for Re>> 1

k = the Kozeny - Carman constant.

For slow viscous flow (the usual case in fabric filtration) the equation reduces to:

$$\frac{\Delta p}{L} = \frac{k'}{g} \cdot (V \rho_f) \left(\frac{\mu_f}{\rho_f} \right) \cdot \frac{\lambda s^2}{D_p^2} \cdot \frac{(1-\epsilon)^2}{\epsilon^3} \qquad (2.70)$$

where Δ p = pounds per square foot pressure drop.

This is identical to the Fair and Hatch[143] equation, derived experimentally and later on dimensional grounds (with $n = 1$):

$$\frac{h}{L} = \frac{k}{g} \cdot \frac{\mu_f}{\rho_f} \cdot V \left(\frac{A_p}{V_p}\right)^2 \cdot \frac{(1-\epsilon)^2}{\epsilon^3} \qquad (2.71)$$

Leva, et. al,[141] compare their equation to the form commonly used in chemical engineering for flow in terms of the usual Fanning friction factor, f,

$$\frac{\Delta p}{L} = \frac{2f\ G^2}{\rho_f\ g\ D_p} \cdot \frac{(1-\epsilon)^2}{\epsilon^3} \qquad (2.72)$$

where $G = V\rho_f$ = mass flux, pounds/ft^2-sec, from which it follows that

$$f = C(D_p\ G/\mu_f)^{-1} \qquad (2.73)$$

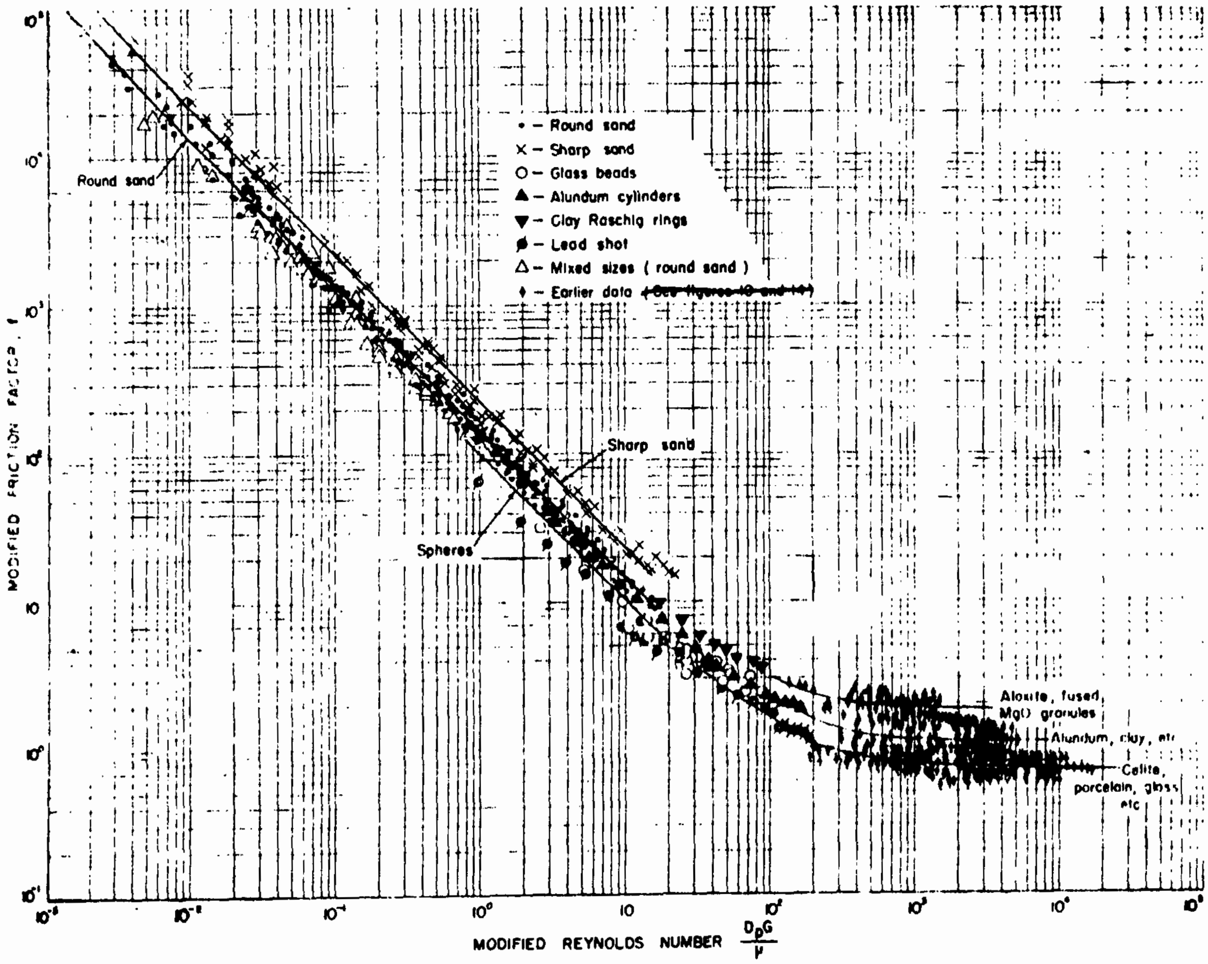
in slow viscous flow, where the constant C is experimentally derived. The friction factor-Reynolds number (Re_p) relationship found by Leva, et al[141] is shown in Figure 2.53a and their smoothed form in Figure 2.53b. It is apparent from these correlations that the pressure drop of a granular layer can be predicted to within a factor of 2 at best, unless the particles are smooth spheres.

The k in the Hatch equation is related to the usual Fanning friction factor by:

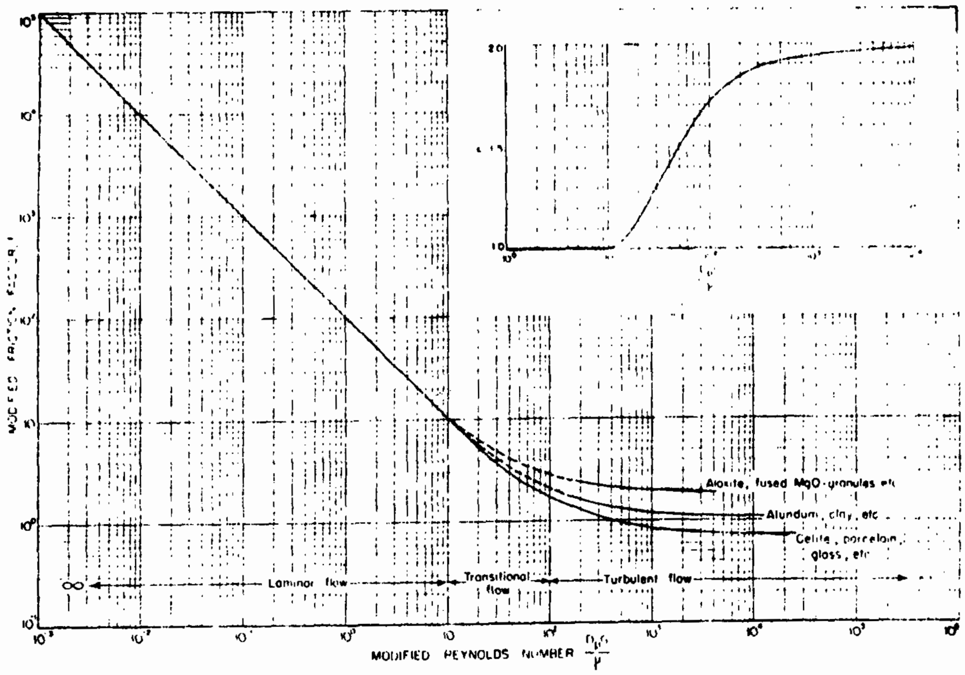
$$k = 2f\ \lambda_s^2 \qquad (2.74)$$

noting that f above in the Fanning form contains λ_s^2. For slow viscous flow ($Re_p < 10$) the Leva, et al,[141] form becomes:

$$\frac{\Delta p}{L} = \frac{200\ G}{g} \cdot \frac{\mu_f}{\rho_f}\ \frac{\lambda_s^2}{D_p^2} \cdot \frac{(1-\epsilon)^2}{\epsilon^3} \qquad (2.75)$$



a —MODIFIED FRICTION FACTORS vs. MODIFIED REYNOLDS NUMBER.



b . MODIFIED FRICTION FACTORS VS. MODIFIED REYNOLDS NUMBER.

Figure 2.53 Friction Factor - Reynolds Number Relationship for Granular Beds (from Leva, et al., Ref. 141) for shape factors $\lambda_s = 1.00$ for smooth spheres, to 1.50 for sharp sands. We note that the equivalent value for the Hatch equation with the Kozeny-Carman constant = 5 and $(A_p/V_p)^2 = 36/D_p^2$;

$$2f = 5 \times 36 = 180$$

which is well within the estimation accuracy of these correlations (for λ_s^2 of order 1). The smoothed data of Leva, et al, (Figure 2.53b) are equivalent to the usual presentations in chemical engineering texts, which arise from similar studies and analyses (by Burke-Plummer, for example). Note that the velocity used in the particle Reynolds' number is modified by the solids fraction $(1 - \epsilon)$ in the definition of pore velocity (Dupuit - Forscheimer assumption) in some correlations.

Effects of particle roughness are seen in the Leva, et al, data at Reynolds numbers (Re_p) greater than about 10, and arise as a consequence of the actions of surface asperities on the inertial motion of the fluid near the granule surface. Surface roughness apparently has no effect for $Re < 10$.

Estimation of pressure drop in fabric filters depends upon the porosity function $(1 - \epsilon)^2/\epsilon^3$, which is generally unknown in an operating system. The general relations for granular packings of various geometries are shown by Leva, et al., vs. the granule/container diameter ratio. For very small particle sizes ($D_p < 30\mu m$), surface adhesion forces dominate gravitational forces and the porosity rises sharply as shown previously in Figures 2.46 and 2.47, but is not observed in the data of Leva, et al, for granules greater than 50 μm. Porosity functions $(1 - \epsilon)^2/\epsilon^3$ and $(1 - \epsilon)/\epsilon^3$ are indicated in Table 2.28 with an approximate range of particle sizes likely to be associated with the indicated porosity, from the Roller data (Figure 2.46).

Porosity also depends upon compaction forces or vibrational effects on the packing, and in fabric filters appears to be a function of the deposition velocity. Aspects of compaction are discussed in Appendix 2.3, in terms of pressures on beds of particles and from the data of Leva, et al, on "dumped, pounded" (vibrated) packings.

TABLE 2.28

POROSITY FUNCTION FOR GRANULAR POROUS MEDIA

Porosity ϵ	Solids Fractions $\alpha = 1-\epsilon$	ϵ^2	ϵ^3	$\frac{1-\epsilon}{\epsilon^3}$	$\frac{(1-\epsilon)^2}{\epsilon^3}$	Probable Particle size* microns
0.90	.10	0.81	0.73	.137	.014	1.0
0.85	.15	0.72	0.62	.24	.036	1.5
0.80	0.20	0.64	0.51	0.39	.078	1.5
0.75	0.25	0.56	0.42	0.60	.15	2.0
0.70	0.30	0.49	0.34	0.88	.26	2.5-3.0
0.65	0.35	0.42	0.28	1.27	.45	3.5
0.60	0.40	0.36	0.22	0.85	.74	5.0
0.55	0.45	0.30	0.17	2.70	1.22	8.0
0.50	0.50	0.25	0.12	4.0	2.0	10-12
0.45	0.55	0.20	0.09	6.0	3.3	20
0.40	0.60	0.16	0.06	9.4	5.8	25-30
0.35	0.65	0.12	0.04	15.1	9.8	> 30
0.30	0.70	0.09	0.03	25.9	18.1	> 30
0.25	0.75	0.06	0.02	48.0	36.0	> 30

*Estimated from Figure 2.46.

2.4.8 Flow and Pressure Drop in Fabric Filters

The quantity of air or process gas, dust concentration, and the specific flow-resistance properties of the particulate deposit determine the amount of cloth area required for any desired value of operating pressure drop. Cloth area is generally selected to provide an operating pressure drop in the range of 3 to 4 inches of water, but some designs can operate substantially in excess of 10 inches of water. Average filtration velocity (total air volume filtered/total cloth area), commonly called air-to-cloth ratio, is generally in the range of 1 to 15 cfm/ft^2, (i.e., 1 to 15 ft/min). However, values in excess of 50 ft/min can be achieved at moderate pressure drop with certain cleaning devices.

The resistance of clean fabric prior to filtration of dust is determined by fabric design and construction, and is reported by fabric manufacturers as air flow permeability, equal to the air flow through the fabric in cfm/ft^2 at 0.5 inch water pressure drop (Appendix 2.4). In general, gas flow through fabrics is viscous at low velocities and pressure drop is directly proportional to flow,

$$\Delta p = K_1 V \qquad (2.75a)$$

where Δp = pressure drop across fabric, inches of water

K_1 = resistance of the fabric, inches of water per ft/min

V = filtration velocity, ft/min.

Based on above correlations for Reynolds number vs. discharge coefficient for square and rectangular openings, this equation assumes that slow viscous flow obtains (i.e., $n = 1$). The factor K_1 is related to either a discharge coefficient (as defined above) or to a friction factor (or Kozeny-Carman factor). K_1 is a coefficient of resistance to flow and, for the simpler weave fabrics, can be calculated from fabric parameters as indicated above, (e.g., see Figure 2.52). In operating fabric filters, at usual dust loadings, the basic fabric resistance is negligible ($< 10\%$ of the total Δp).

Effects of dust deposition on pressure drop and collection efficiency have been analyzed for various dilute cases in aerosol minutes; and the fluid viscosity, μ_f, in lbm/ft-sec. Williams, et al., suggested that the bracketed term, and some of the constants, be lumped into a specific dust-fabric filter resistance coefficient, K_2, as:

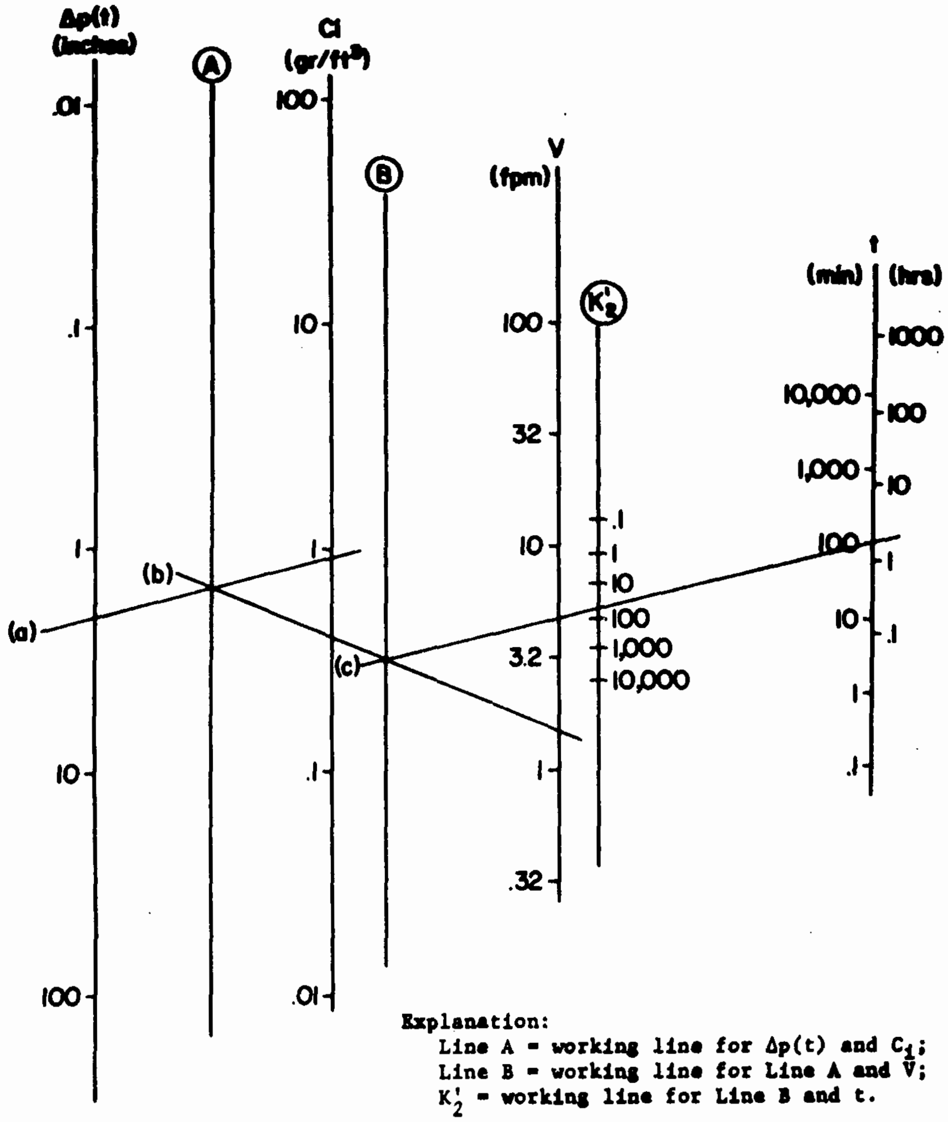
$$\Delta p(t) = K_2 \cdot \frac{C_i V^2 t}{7000} \qquad (2.80)$$

for C_i = grains/ft^3, V = ft/min, and t = min. The resistance coefficient then has the dimensions:

K_2 = inches of water/(lb dust/ft^2 cloth area)-(ft/min filtering velocity),

where K_2 = the specific dust-fabric filter resistance coefficient, presumably calculable by the terms in brackets above. The coefficient, which can also be derived from observations on an operating fabric filter will be referred to below as K_2', the experimentally determined value. It may be computed via the nomograph in Figure 2.54 which is equivalent to Equation 2.80 in relating K_2' to p(t) or vice versa. Such determinations are required in designing a new fabric filter installation in order to predict the relationship between operating pressure drop, filtering velocity, time between cleaning cycles and required fabric area.

Values of the theoretical area per unit volume of dust for particle sizes of interest are shown in columns 1 and 3 of Table 2.23 under the assumption that particles are spherical. Experimental values of A_p/V_p for Equation 2.80 can be estimated for a specific dust of interest from gas adsorption data obtained with commercially available equipment (cm^2 area/gram) and the true density of the material (grams/cm^3), (see Section 2.4.5, b(1) (22)). Porosity or void volume in a particular dust will have a range approximately as indicated in column 5 of Table 2.28. The term $(1 - \epsilon)/e^3$ in Equation 2.79 varies from about 0.4 to 48 as shown in column 5. Void volume is proportional to the range of particle sizes present in the dust, as indicated previously. It is also affected by the forces acting on the deposit producing consolidation as a consequence of the drag caused by the gas flow through the layer. Typical experimental values of void volume as a function of particle size for sized powders are shown in Figure 2.46. They are also readily



Explanation:
Line A = working line for Δp(t) and C_i;
Line B = working line for Line A and V;
K_2' = working line for Line B and t.

Example #1. Find K_2' from observed values of Δ p(t), Ci, V, and t
(a) Line a between the value for Δ p(5) and C_i determines a point on Line A.
(b) This point on Line A and the value of V determines a point on Line B.
(c) This point on Line B and the value for t determines K_2'.

Example #2. Determine Δ p(t) from values of K_2', C_i, V and t.
(a) The values for K_2' and t determine a point on Line B.
(b) This point on Line B and the value for V determine a point on Line A.
(c) This point on Line A and the value of C_i determine Δ p(t).

Figure 2.54. Nomograph for K_2' and Δ p(θ)

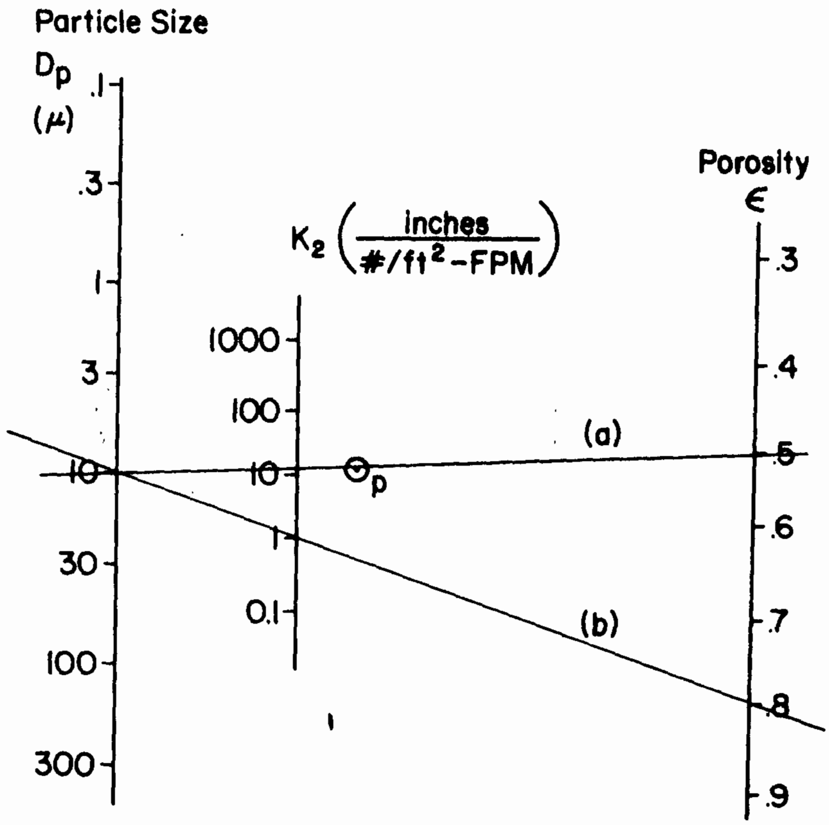
obtainable experimentally from the weight of a known dust volume, in conjunction with a particle size analysis.

The relationship between void volume (ϵ) and particle size shown in Figure 2.46 can be approximated by a single point (P) in Figure 2.55. For example, spherical dusts with an average size of 10 microns typically deposit with a void volume of 0.5 (line a). This approximation, together with Table 2.23 for the dust area per unit volume, enables the bracketed expression for K_2 in Equation 2.80 to be evaluated from particle size alone. This is demonstrated by line (a) where K_2 is estimated to be 10 inches of water per lb/ft^2-FPM. If on the other hand the dust is not spherical or is not typically consolidated, then point (P) does not apply, and K_2 is estimated from particle size and a more appropriate value of void volume. For example, line (b) in Figure 2.55 for non-typical dust gives a value of K_2 of 1. As noted in the Figure, the values of K_2 thus obtained should be scaled upward or downward, depending on fluid viscosity and particle specific gravity.

The depth of the dust layer removed is an important characteristic of the deposit structure and can be used to calculate forces in the cake during shaking or other methods of cleaning. Layer depth may be computed simply by Equation 2.76 from deposit weight, particle density, and deposit porosity. This has been done in Table 2.29 for a variety of filtration conditions and particle sizes. The data indicates that depth ranges from a few microns (7) to a few millimeters (6) for usual dust concentrations (1-30 $gr./ft^3$), particle sizes (1-30 μm) and operating times (1-100 min.). For a typical pressure drop increment of the order of two inches of water, the depth of the dust layer ranges from 100 to 2000 microns for operating velocities of 1-10 fpm. In accordance with the earlier assumptions, K_2' is seen to vary only with particle size in the cited examples, 4 to 57 inches of water per lb/ft^2-fpm.

2.4.9 Analysis of the Specific Dust-Fabric Filter Resistance Coefficient (K_2)

The value of the specific dust-fabric filter resistance coefficient has been defined above by the Williams, Hatch, and Greenburg[147],



$$\text{Based on } K_2 = \left[\frac{k\mu_f}{\rho_p}\left(\frac{A_p}{\nu_p}\right)^2 \frac{(1-\epsilon)}{\epsilon^3}\left(\frac{1}{5.2}\right)\left(\frac{1}{3600}\right)\right] \qquad \text{(Eqn. 2.78)}$$

where

$k = 5$
$\mu = 1.8\times10^{-4}$ d sec/cm^2
$\rho_p = 1$ gm/cm^3
$(A_p/\nu_p) = 6/D_p$

Example (a) Many spherical dusts are deposited with porosities such that the lines connecting size and porosity happen to pass through point (P). For such dusts, point (P) enables an estimation of specific resistance or of porosity, based on particle size alone.

Example (b) A particle size of 10μ and a porosity of 0.8 would indicate a specific resistance of 1 in. $H_2O/(\#/ft^2$ -FPM), using the above constants.

Figure 2.55. Specific Resistance Determined by Particle Size and Deposit Porosity.

TABLE 2.29

CALCULATED VALUES OF THE SPECIFIC DUST-FABRIC FILTER RESISTANCE COEFFICIENT, K_2', THE DEPTH OF DEPOSIT, AND RESULTING PRESSURE DROP

P.S. D_p	ϵ	ρ_p gm/cm^3	C_i gr/ft^3	V ft/min	t min	W lbs/ft^2	W gm/cm^2	L cm	L μm	K_2' in/#ft^2-FPM	$\Delta p(t)$ in.
1 μm	0.9	1	1	1	10^0	1.4×10^{-4}	7×10^{-5}	7×10^{-4}	7	58	.008
		1	1	1	10^1	14×10^{-4}	70×10^{-5}	70×10^{-4}	70	58	.08
		1	1	1	10^2	140×10^{-4}	700×10^{-5}	700×10^{-4}	700	58	.82
		1	1	2	10^0	2.8×10^{-4}	14×10^{-5}	14×10^{-4}	14	58	.033
		1	1	2	10^1	28×10^{-4}	140×10^{-5}	140×10^{-4}	140	58	.33
		1	1	2	10^2	280×10^{-4}	1400×10^{-5}	1400×10^{-4}	1400	58	3.3
		1	1	3	10^0	4.2×10^{-4}	21×10^{-5}	21×10^{-4}	21	58	.073
		1	1	3	10^1	4.2×10^{-4}	210×10^{-5}	210×10^{-4}	210	58	.73
		1	1	3	10^2	420×10^{-4}	2100×10^{-5}	2100×10^{-4}	2100	58	7.3
		1	1	10	10^0	14×10^{-4}	70×10^{-5}	70×10^{-4}	70	58	.82
		1	1	10	10^0	140×10^{-4}	700×10^{-5}	700×10^{-4}	700	58	8.2
		1	1	10	10^2	1400×10^{-4}	7000×10^{-5}	4000×10^{-4}	7000	58	8.2
1	0.9	1	1	3	10^1	42×10^{-4}	210×10^{-5}	210×10^{-4}	210	57	0.73
		1	3	3	10^1	126×10^{-4}	630×10^{-5}	630×10^{-5}	630	57	2.19
		1	10	3	10^1	420×10^{-4}	2100×10^{-5}	2100×10^{-4}	2100	57	7.3
		1	30	3	10^1	1260×10^{-4}	6300×10^{-5}	6300×10^{-4}	6300	57	2.19
1	0.9	1	1	3	10^1	42×10^{-4}	210×10^{-5}	210×10^{-4}	210	57	0.73
		3	1	3	10^1	42×10^{-4}	210×10^{-5}	70×10^{-4}	70	57	0.24
		10	1	3	10^1	42×10^{-4}	210×10^{-5}	21×10^{-4}	21	57	0.073
1	0.9	1	10	3	10^1	420×10^{-4}	2100×10^{-5}	2100×10^{-4}	2100	57	7.3
3	0.7	1	10	3	10^1	420×10^{-4}	2100×10^{-5}	700×10^{-4}	700	41	5.1
10	0.5	1	10	3	10^1	420×10^{-4}	2100×10^{-5}	420×10^{-4}	420	16.8	2.1
30	0.4	1	10	3	10^1	420×10^{-4}	2100×10^{-5}	350×10^{-4}	350	4.4	0.54

Assumptions: Kozeny constant k (in kS^2) ≅ 5

Air viscosity ≅ 2.2×10^{-4} dyne sec/cm^2 (200°F)

Equation 2.79. Other calculated values of K_2 are shown in Figure 2.56, as a function of particle size, and parametric in porosity (ϵ).

Calculated values of K_2 for particle sizes of interest in fabric filtration which include the approximate variation of ϵ with particle size below 30 μm, are given in Table 2.29. These values may be compared directly to the original data of Williams, Hatch and Greenburg presented in Table 2.30. The deviation of K_2' (measured) from the calculated value reflects the difficulty of measuring or establishing the effective particle size (distribution), shape, specific surface, and porosity and the appropriate fabric parameters in an operating fabric filter-dust deposit. Although these parameters are measurable quantities, they are not often reported in the literature.

In an attempt to assess the state of engineering technology available to the designer of fabric filtration devices, a large amount of published and unpublished data was retrieved, as tabulated in Appendix 2.5. This has been analyzed for K_2' in the following pages as a function of:

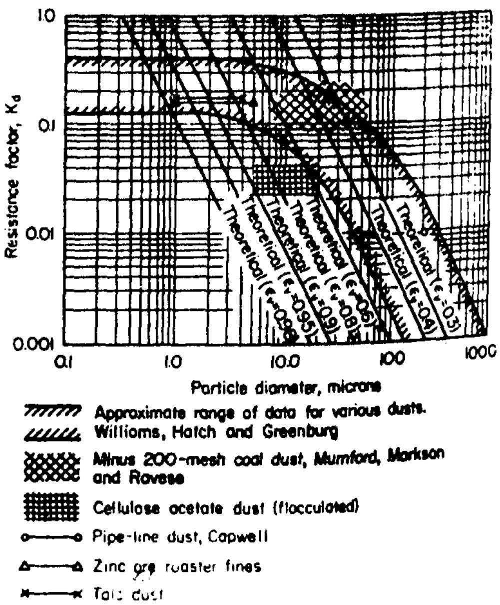


Figure 2.56. Resistance factors for dust layers. Theoretical curves given are based on a shape factor of 0.5 and a true particle specific gravity of 2.0. (From Perry, et al., Ref. 97).

TABLE 2.30

FILTER RESISTANCE COEFFICIENTS K_2' FOR CERTAIN INDUSTRIAL DUSTS[a*]
(Industrial Cloth-type Air Filters)

MATERIAL	PARTICLE SIZE: Coarse <20 Mesh (~800μm)	Coarse <140 Mesh (~100μm)	Coarse <375 Mesh (~44 μm)	Medium <90μm	Medium <45μm	Fine <20μm	Fine <2μm
Granite	1.58	2.20	-	-	-	19.8	-
Foundry	0.62	1.58	3.78	-	-	-	-
Gypsum	-	-	~ 6.30	-	-	18.9	-
Feldspar	-	-	6.30	-	-	27.3	-
Stone	0.96	-	-	6.30	-	-	-
Lamp Black	-	-	-	-	-	-	47.2
Zinc Oxide	-	-	-	-	-	-	15.7[b]
Wood	-	-	-	6.30	-	-	-
Resin (cold)	-	0.62	-	-	-	25.2	-
Oats	1.58	-	-	9.60	11.80	-	-
Corp.	0.62	-	1.58	3.78	8.80	-	-

[a]Inches, water gage, per (pound dust per square foot cloth) per foot/minute filtering velocity.

[b]Flocculated material not dispersed, size actually larger.

[c]Theoretical size of silica; no correction made for materials having other values of ρ_p.

[*]From Williams, et al., Ref. 147.

particle size

particle type

filtering velocity

fabric surface effects

clean fabric permeability

other parameters, (e.g., compression effects,
cleaning method, electrical phenomena)

2.4.9.1 Data for K_2 - Approximately 600 reference sources dealing with fabric filtration were retrieved and reviewed for sufficient data to compute K_2'. About 10 percent of these articles were selected for further analysis. A total of 31 sources had sufficient information to enable computation of K_2' for a variety of applications, dusts, fabrics, etc. These data are summarized in Appendix 2.

In addition to data computed from literature reported values, a questionnaire-interview survey was conducted (1969) among users of 40 operating fabric filters across a broad range of industrial applications for some 31 applications. K_2' values completed from the data furnished are provided in Table 2.31.

2.4.9.2 Effect of Particle Size - Data presented in these two Tables has been plotted against reported or estimated particle size as shown in Figure 2.57. Although methods of particle size determination were not investigated during the present study, they would appear to have a strong bearing on the relationship of K_2' to deposit properties. It must be emphasized that the data reported were obtained in many different configurations, extending from "square-foot" bench scale laboratory experiments (e.g., Williams, Hatch, and Greenberg data (Ref. 147) c.f. Table 2.30) through single bag tests, (e.g., Durham data, Ref. 149, and including multi-compartmented fabric filters operating in actual field situations. There are a multitude of factors operating among these data that have not been adequately quantified.

The data for K_2' vs D_p shown in Figure 2.57 indicate wide spread. The data also tend to confirm the finding of Williams, et al., (as indicated in Figure 2.56), regarding a bend in the curve in the vicinity of 20 to 30 μm. This finding is consistent with the increase in bulk density for particles below this size (Figures 2.46 and 2.47). Data of Williams, et al., are regraphed as enveloped curves in Figure 2.58 (from Figure 2.56) to establish the regression line form. NAPCA-GCA Fabric Filter System Study data (from Table 2.31) are shown as individual data points. It is evident from both figures that estimation of particle size alone is inadequate to provide sufficient information for

TABLE 2.31

SPECIFIC DUST-FABRIC-FILTER RESISTANCE COEFFICIENTS FOR OPERATING COLLECTORS SURVEYED IN FABRIC FILTER SYSTEM STUDY (1969)

Dust	Operation	Dust Loading gr/cu.ft.	Filtering Velocity fpm	Operating Drag In H_2O/fpm Residual	Operating Drag In H_2O/fpm Maximum	K_2'*	Particle Size** µm	Fabric Characteristics Material, Remarks	Cleaning Method	Temp. °F
Carbon black	Oil-furnace	14	1.6	4.4	5.0	56	< 1	Glass, Silicone	Reverse Flow	425
Carbon black	Oil-furnace	26	1.1	4.0	6.2	38	< 1	Glass, -	Rev. flow & sh.	375
Fe_2O_3	Elec. furnace	(1.5)	3.3	1.4	1.6	(3)	< 1	Dacr.®-Orl.®, 2.2tw., 12.5 oz.	Sh. & rev. flow	215
Fe_2O_3	Elec. furnace	1.5	3.0	-	-	(10)	< 1	Orlon®, -	Shake	330
Fe_2O_3	Elec. furnace	0.8	3.0	1.0	2.6	45	< 1	Orlon®, -	Shake	110
Fe_2O_3	Elec. furnace	0.3	1.4	3.5	4.9	715	< 1	Dacron®, -	Rev. flow	225
ZnO	Brass smelter	8.1	0.6	0.9	5.4	40	< 1	Glass, -	Sh.& rev. flow	600
ZnO, PbCℓ	Blast furnace	1.2	1.2	7.2	7.3	18.5	< 1	Glass, tw., 9 oz.	Shake	375
Fly Ash	Oil-fired fce.	0.01	6	1.0	1.1	127	< 1	Glass, 10 oz.	Rev. flow, collapse	260
PbO	Smelter	2.3	1.0	2	3	57	0.5-10	Dacron®, 10 oz.	Sh.& rev. flow	275
Fe_2O_3	Cupola	(< 1)	12.5	-	0.7	(10)	0.5-50	Nomex®, -	Pulse jet	240
Fe_2O_3	Cupola	0.7	2.1	2.9	4.3	121	0.5-50	Glass, -	Shake	450

TABLE 2.31 (continued)

Dust	Operation	Dust Loading gr/cu.ft.	Filtering Velocity fpm	Operating Drag In H_2O/fpm Residual	Maximum	K_2'*	Particle Size** μm	Fabric Charac-teristics, Material, Remarks	Cleaning Method	Temp °F
Fly Ash	Mun. incin.	0.3	2.5	1.3	1.7	180	3	Glass, plain	Collapse	480
Fly Ash	Mun. incin.	0.5	4.5	0.9	1.1	50	(10)	Glass, -	Pulsed rev. flow	425
PVA	Matl. handl-ing	0.05	10.4	0.1	(0.1^+)	25	3	Wool, felt	Pulsed rev. flow	70
$CaSO_4$	Dryer	( )	7.5	( )	( )	0.4	5	Dacron, felt	Pulse jet	220
Cement	Bagging	(10)	2.5	(4)	(6)	(350)	10	Cotton	Rev. flow	70
Cement	Kiln	0.5	1.5	2.0	3.3	12	15	Glass, tw., 9 oz.	Collapse	525
Lime	Kiln	7.5	2.3	(2)	(2^+)	8.8	10	Glass, 14 oz.	Rev. flow & for. pulse	500
Fe_2O_3, ZnO	Elec. furnace	0.5	1.9	2,8	3.1	66	10	Glass, -	Collapse	195
Gypsum wallbd	Trim saw	0.7	3.4	( )	( )	9.2	> 10	Cotton, tw.	Shake	140
Flour	Milling	14	8.6	0.2	0.6	(4.3)	1-30	Wool, felt	Rev. jet	110
Resin, fiber	Matl. Handl.	2.9	2.7	(1)	(1^+)	(8)	1-100	Cotton, flannel	Shake	70
Cement	Milling	5	1.8	1.0	1.6	70	20	Cotton, 17oz.	Shake	325
Dolomite	Kiln	7	3.3	2.9	5.0	670	40	Dacron, -	Collapse	150
Cement	Clinker cooler	4	2.5	1.8	2.6	9	50	Glass, 3x1 tw., 54x56	Collapse	500

TABLE 2.31 (continued)

Dust	Operation	Dust Loading gr/cu.ft.	Filtering Velocity fpm	Operating Drag In H_2O/fpm Residual ↓	Maximum ↓	K_2' *	Particle Size ** μm	Fabric Characteristics Material, Remarks	Cleaning Method	Temp °F
Kish	HM pour	0.4	2.5	2.4	4.2	230	80	Dacron, silicone, monofil	Shake	200
Hypochlorite	Matl. Handl.	2.3	3.3	0.8	1.0	15	(50)	Dynel, -	Shake	70
Alum. hydrate	Natl. Handl.	$>10^3$	1.0	0.8	1.1	0.2	100	Dacron, felt, 18 oz.	Pulse jet	70
Sinter dust	Sinter disch. crusher	1.9	2.3	1.5	2.9	12.5	(100)	Glass, -	Collapse	287
Sand, iron scale	Casting clng	6.7	5.0	0.8	1.6	3	<200	Cotton, -	Rev. jet	70

*$K_2' = 7000\ \Delta p/LV^2t$, inches of water per pound of dust per square foot of fabric, per foot per minute filtering velocity.

**Particle size as stated by user or estimated from process characteristics. The terms in parenthesis are estimated values.

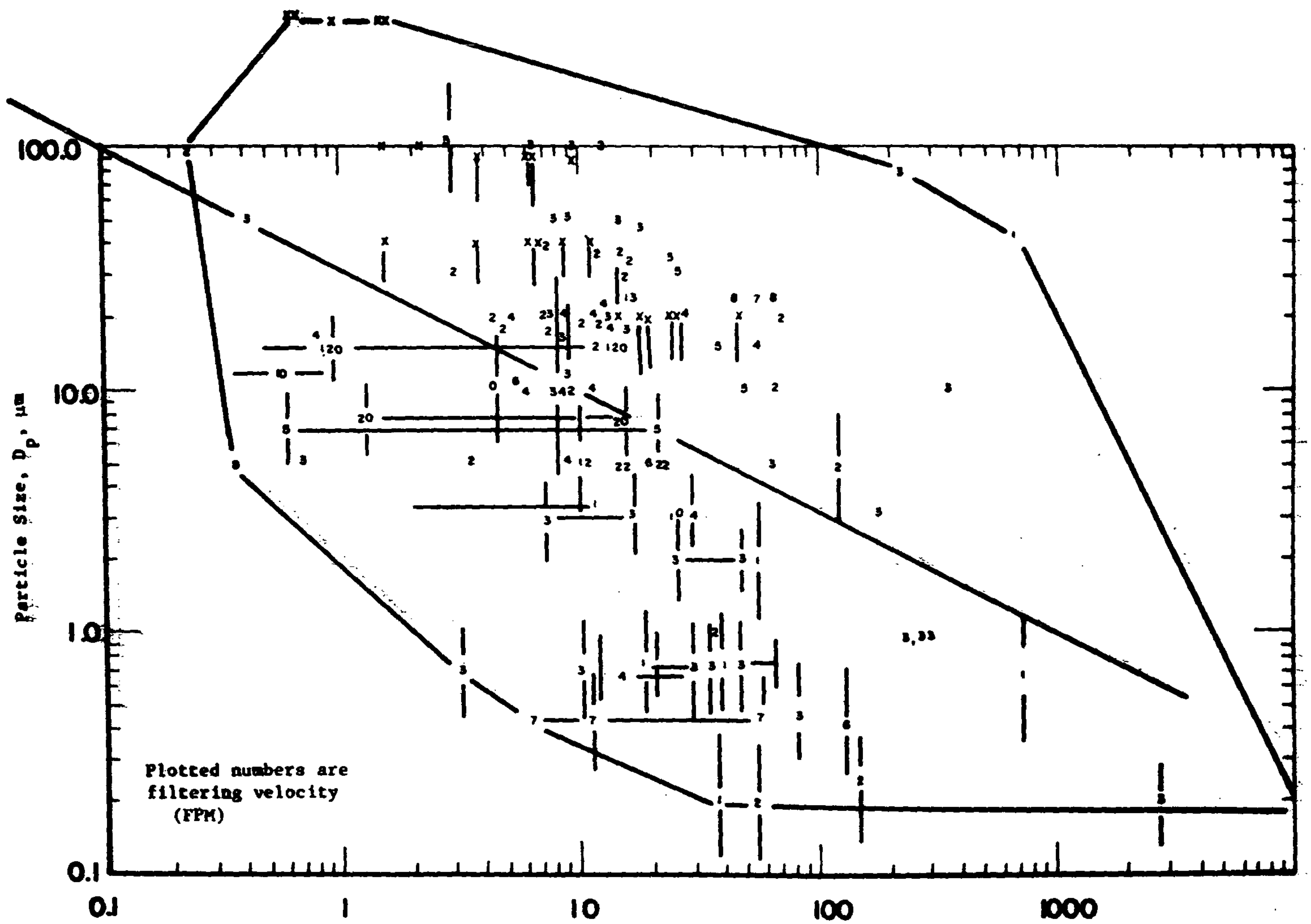


Figure 2.57. Measured Filter Resistance Coefficient vs Particle Size.

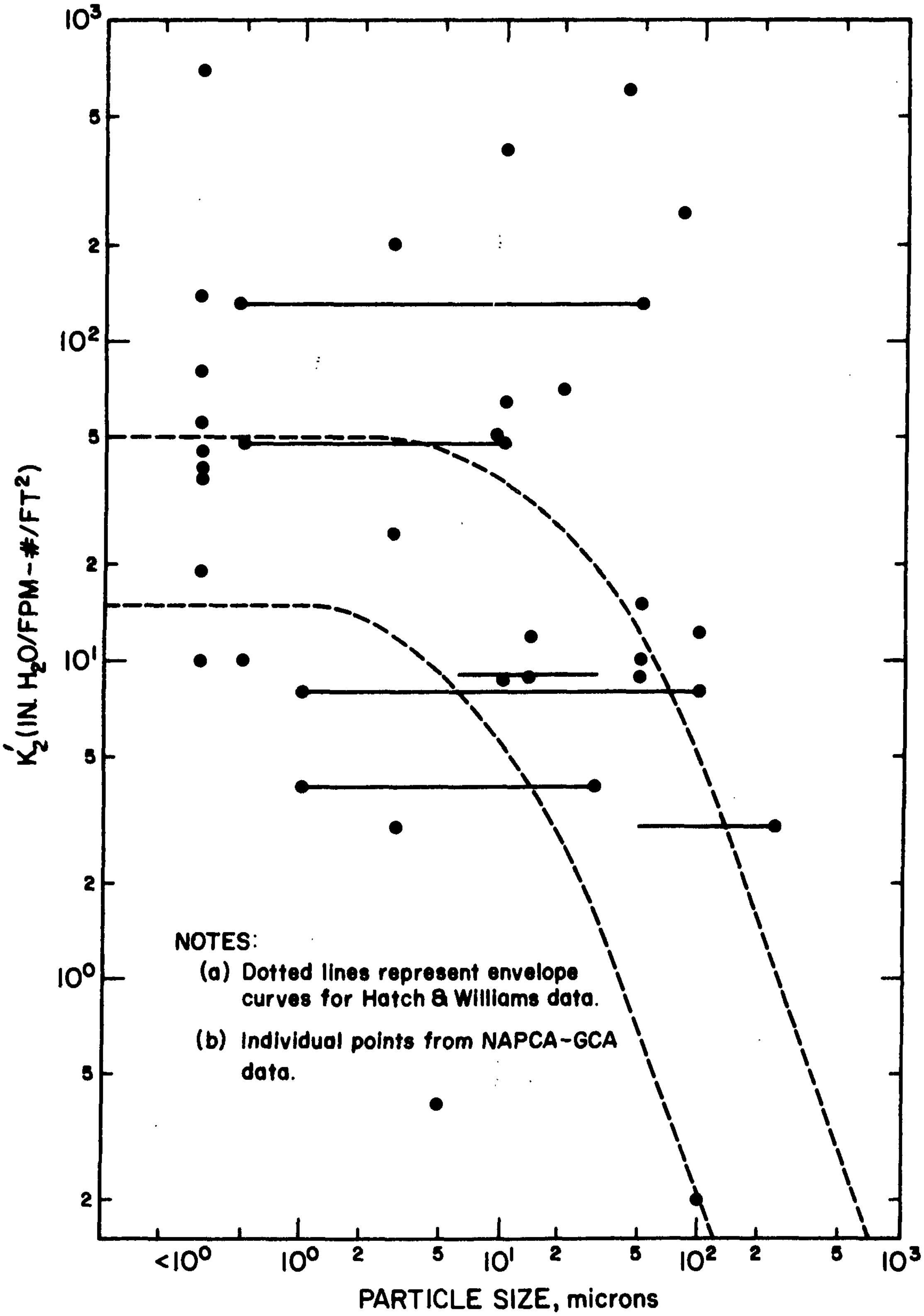


Figure 2.58. Resistance Coefficient (K_2^1) vs Particle Size for operating Fabric Filters Surveyed in 1969.

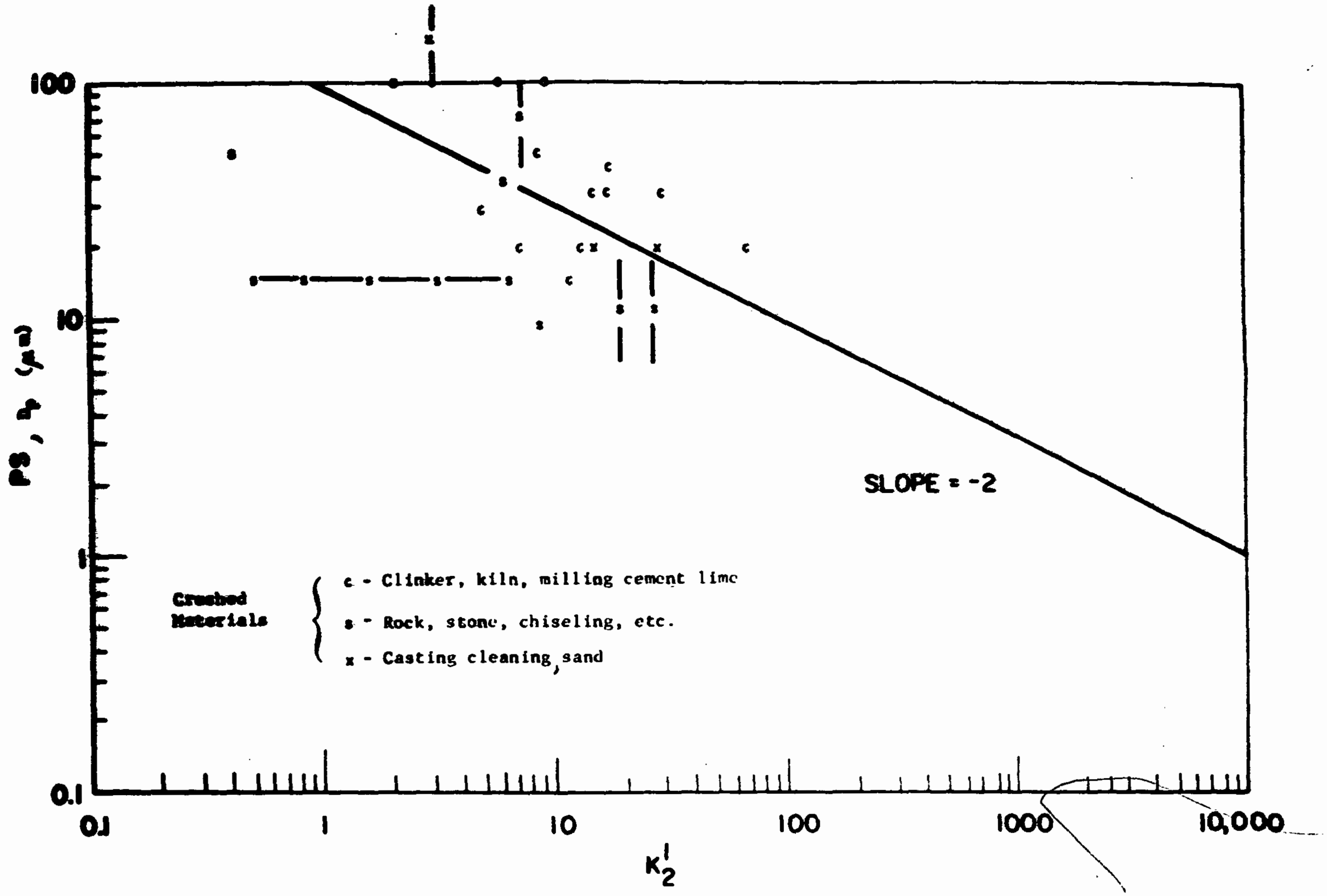


Figure 2.59. Resistance Coefficient (K_2') vs Particle Size for Crushed Materials.

an unambiguous estimate of K_2'. Bulk density data on the specific dusts tested would be expected to improve the correlation. Bulk density from Tables 2.19, 2.20 and 2.21 was used to estimate void volume, and K_2 was computed from Figure 2.55b. The actual bulk density that exists in the dust-fabric deposit would be expected to improve the correlation even more, but will be affected by fabric fiber population (Figure 2.55). These data are not available, but may be measurable under appropriate experimental conditions. Typical K_2' values are given in Ref. 135. For a first approximation of K_2' from Figure 2.57,

$$K_2' \approx \frac{1000}{D_p^2} \qquad (2.81)$$

with D_p in microns, for $30\,\mu m < D_p < 1000$ m.

2.4.9.3 Effect of Particle Shape - Particle shape effects are expected to modify K_2' directly in the shape factor. The data appearing in Figure 2,57 have been classified according to particle materials in the following broad categories which relate to their packing morphology characteristics:

- Crushed Materials (Figure 2.59) - Clinker, kiln, cement milling, lime, stone crushing, rock drilling, finishing, sand, casting cleaning. These materials are relatively hard with single individual large irregular grain shapes.
- Fumes (Figure 2.60) - Metallurgical and other fine metal vapor condensation fumes, and other floccs. These materials are relatively fine aggregates of sub-micron particles, presumably collapsible under pressure, with low initial bulk density, $\epsilon > 0.9$ probably.
- Fly Ash (Figure 2.61) - Pulverized coal fly ash, laboratory redispersion and resuspension of Cottrell precipitated fly ash, freshly formed fly ash, and fly ash plus limestone additive for SO3 control. Fly ash particles tend to be silicate cenospheres and iron oxide spheres, of sizes predominantly above 1 micron. Cement, lime, and dolomite values from Figure 2.32 have been replotted with fly ash data.
- Irregular Particles (Figure 2.62) - Sinter dust, ground mica platelets, mixed fibrous material, corn oats, flour, wood dust, kish, paint, aluminum flake.

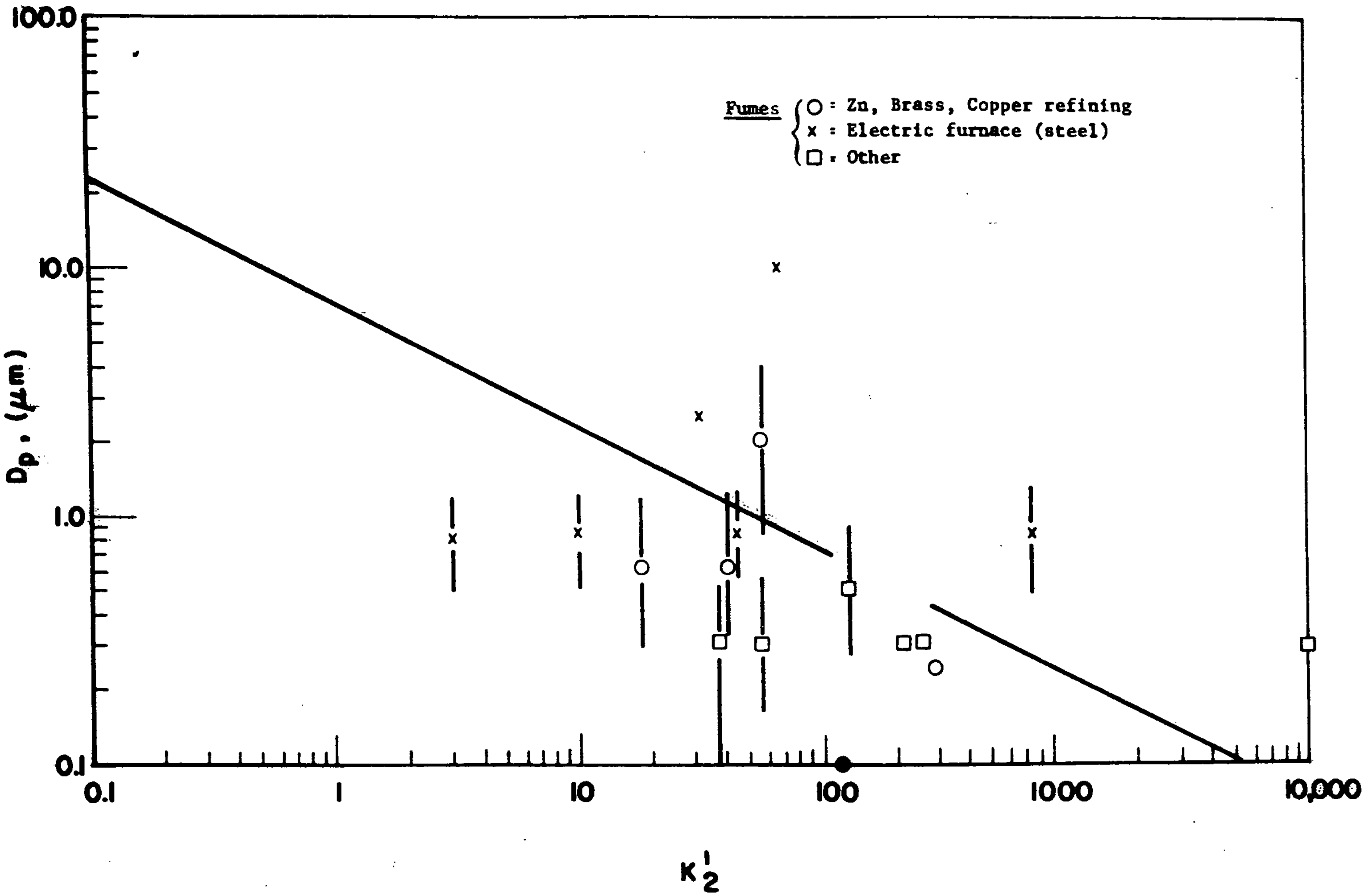


Figure 2.60 Resistance Coefficient (K_2') vs Particle Size for Fumes

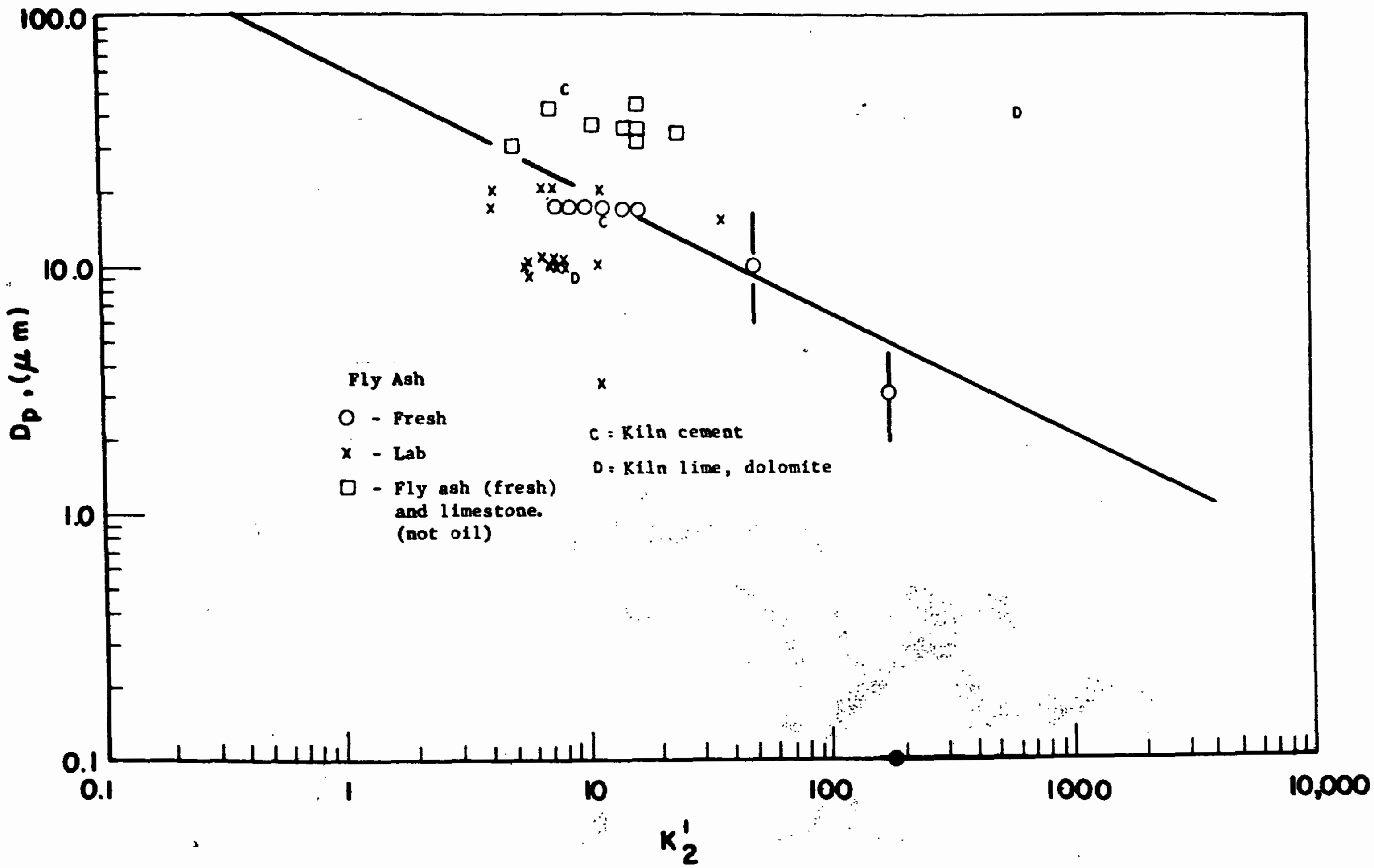


Figure 2.61. Resistance Coefficient (K_2') vs Particle Size for Fly Ash; slope = -2 positioned by eye.

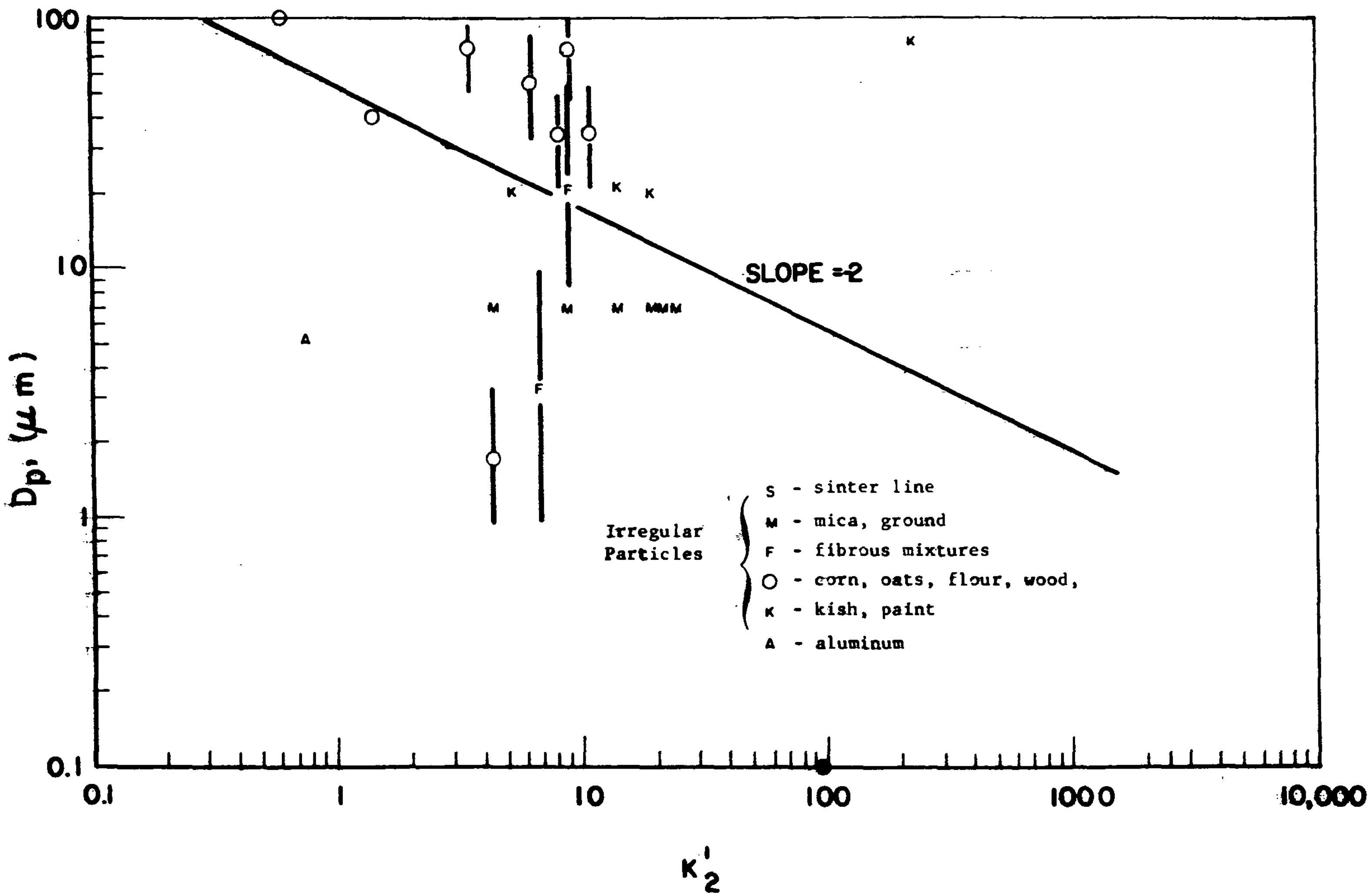


Figure 2.62. Resistance Coefficient (K_2') vs. Particle Size for Irregular Particles; slope = -2; positioned by eye.

- Miscellaneous Soft, or Collapsable Materials (Figure 2.63) - Talc, ZnO, carbon black, $CaSO_4$, aluminum, amorphous silica fume.

Inspection of Figures 2.59 through 2.63 indicates that correlations between K_2' and D_p with respect to gross particle morphology are still fairly scattered. Based on the slope of a line of -2 through most of the data in each of the Figures 2.59 through 2.63 (at $D_p = 10\,\mu m$), we conclude that variations due to particle type on K_2' can be approximated in the following fashion:

Type of Granule	K_{sh} (= Relative Factor in K_2')
Total Correlation	1, i.e., $K_2' = 10^3/D_p^2$
Crushed	10
Fumes	0.05
Ash	4
Irregular	3
Soft, or collapsable	0.2

These correlating factors are applied to the straight line shown in Figure 2.57, to reflect the different locations of the (-2 slope) curves shown. None account for effects of ϵ on K_2 at $D_p < 30\,\mu m$.

2.4.9.4 Effect of Filtering Velocity. - The velocity of deposition (or filtering velocity) is hypothesized to have some effect on K_2, due to the kinetic energy a particle imparts to the cake structure upon landing and also, as a consequence of the greater pressure forces set up in the cake at higher velocity. Both tend to produce compaction of the layer and hence, a lower value of porosity.

Effects of V on K_2 are shown in Figure 2.64 in the form of the relative increase in K_2 $(K_2)_2/(K_2)_1$, as a function of the relative increase in V, (V_2/V_1). It is evident from most of these data that increases of velocity by factors of 2 or 3 tend to produce similar increases in K_2. Unfortunately, data are not sufficiently well-behaved to enable the extraction of a single functional relationship. (Pressure effects on cake porosity are expected to be of the form $\epsilon_p = \epsilon_o e^{-k_i p}$, p = pressure, k_i = a constant, c.f. Appendix 2.3). Fabric substrate compressibility and particle cake compressibility are both anticipated to be parameters in a relationship between K_2 and V. No data were located on porosity of filter dust cakes as a function of V or p. Observations by Borgwardt, et al., of NAPCA[127] indicate in some studies that $K_2 \sim V^{1.5}$. These

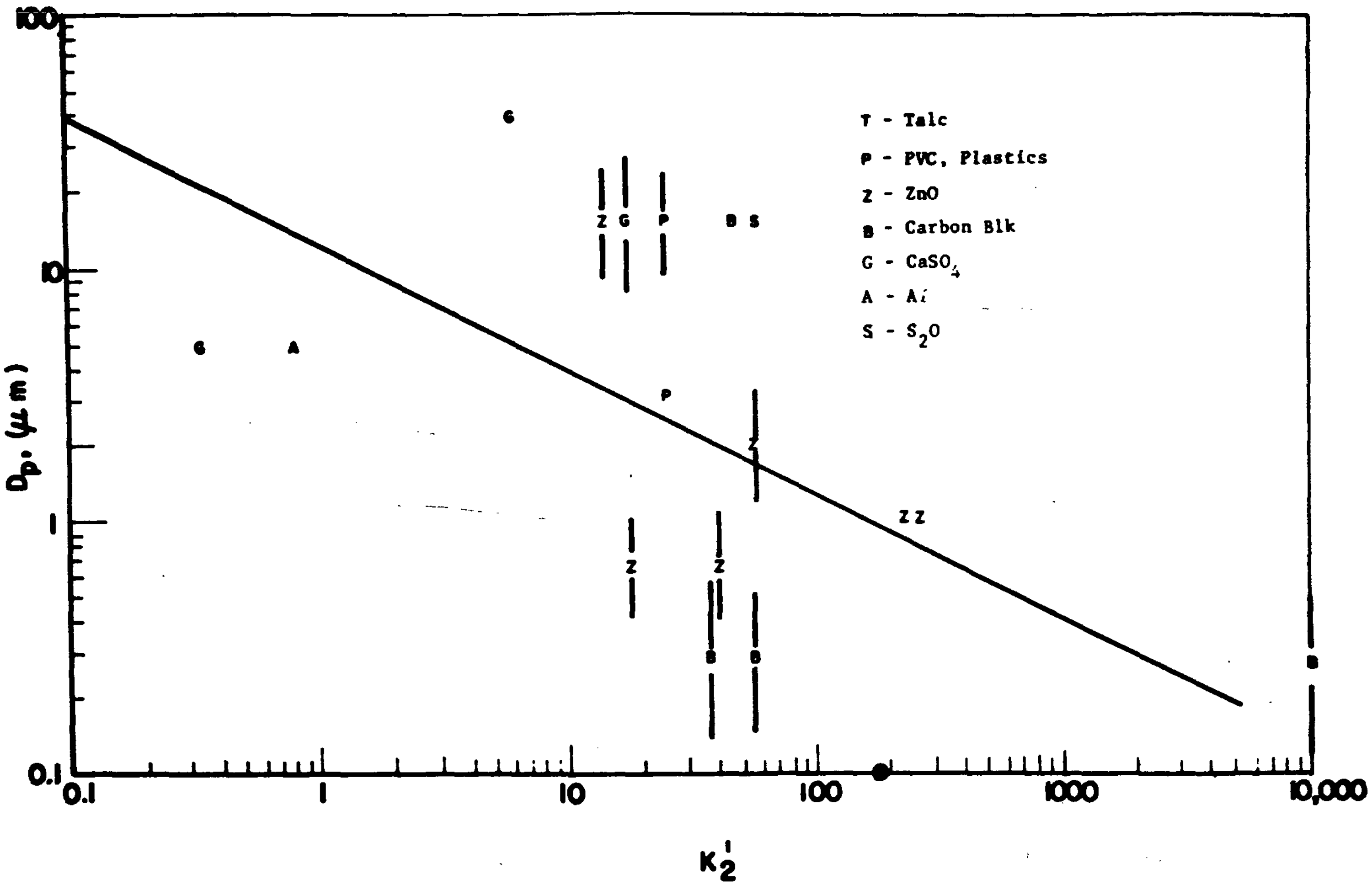


Figure 2.63. Resistance Coefficient (K_2') vs Particle Size for Soft Collapsible Materials; slope = -2; positioned by eye.

findings, however, are not supported by other data shown in Figure 2.64 where the exponents appear to be nearer one for all other data.

Effects of filtering velocity on the dust resistance coefficient are illustrated in Figures 2.65 and 2.66 for three woven fiberglass fabrics of indicated design and properties, from Spaite and Walsh data[82]. Averaged values of K_2 computed here from Figure 2.65 (at 400 grains/ft^2) are as follows:

V, fpm	$(K_2)_1$(inches water/pounds of dust per ft^2 of fabric)·(ft per min. filtering velocity)	V2/V1	$(K_2)_2/(K_2)_1$
2	3.5	1	1
4	8.8	2	2.5
6	19.3	3	5.5

These three values are shown by asterisks in Figure 2.64. Similar computations of K_2 and velocity ratios for data shown in Figure 2.66 (K_2 = 7000/dust permeability) are indicated by the dashed lines in Figure 2.64. While there does seem to be a non-linear dependence of K_2 on V from these data, these relationships are not monotonic at higher V. As an approximate estimating figure for the effect of V on K_2 we suggest:

$$K_v \sim V_2/V_1 \qquad (2.81a)$$

(for V usually about 3 ft/min.) which implies $K \sim V^1$, until further data become available.

2.4.9.5 <u>Fabric Surface Effects</u>. - Fabric effects on K_2 are readily apparent in experimental studies, but are not easily quantified at present (e.g., see data of Durham, Table 2.38, item 3). Characteristic effects of fabric nature are indicated approximately in Figures 2.67 and 2.68. For initial deposition of dusts on clean fabrics Davies[167], in discussing Figure 2.68, says "Fibrous dust filters operating by sieve action are rarely used, since thin, sieve-like materials rapidly become clogged and the filtration and air resistance characteristics are those of the cake of solid that is built up, rather than those of the clean

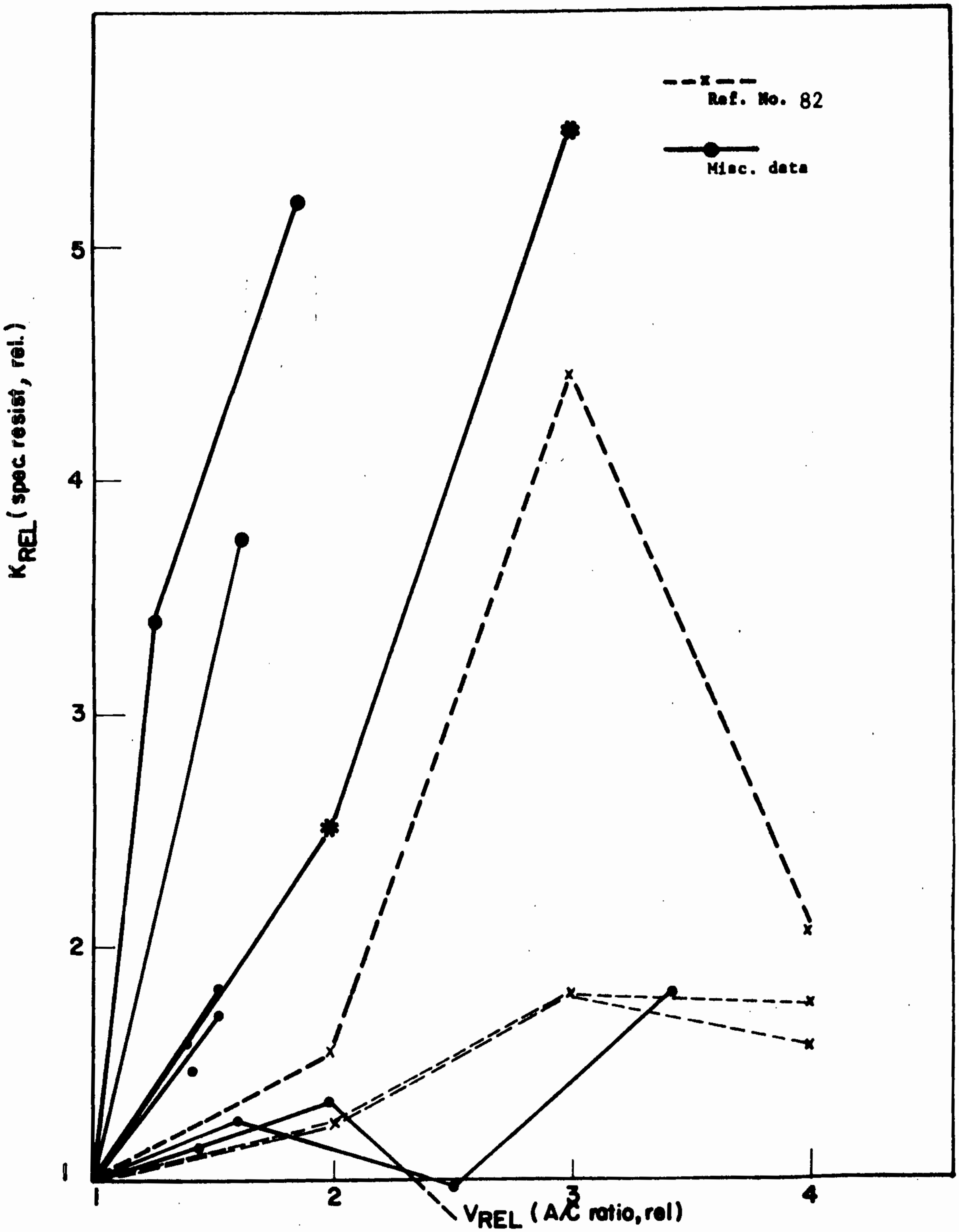


Figure 2.64. Effect of Filtering Velocity on Resistance Coefficient (K_2).

Construction Details of Test Fabrics (also see Figure 2.26).

Filter Fabric	Fiberglass			Dacron	
	No. 1	No. 2	No. 3	A	B
Air Permeability (cfm/ft² at ½" H_2O)	13.84	11.67	7.86	28.06	14.62
Weight (oz/yd²)	8.41	8.67	9.06	5.51	6.06
Yarn Count	55 x 50	55 x 54	55 x 58	82 x 62	82 x 76
Filament Diameter (in.)	0.00025 ~ 6μm			0.00113 ~25μm	
Filaments Per Strand	408			50	
Strands Per Yarn	2			1	
Twists Per Inch	3.8			3.5	
Weave	3/1 Crowfoot			3/1 Twill	
Finish	silicone			silicone	

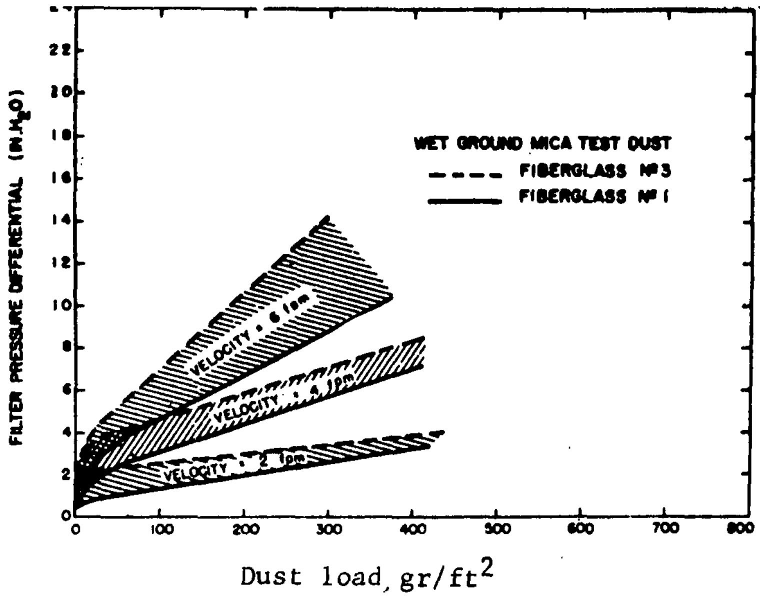


Figure 2.65. Effect of fiberglass construction on filter pressure (From Spaite and Walsh, Ref. 82).

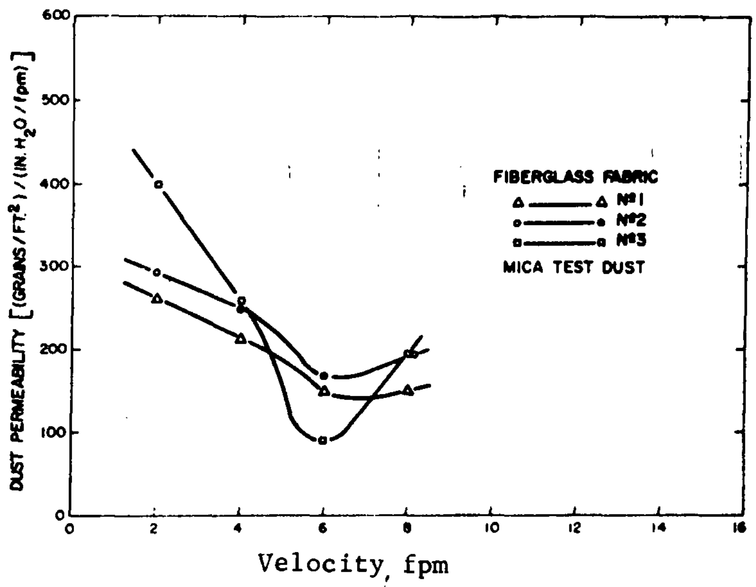


Figure 2.66. Effect of nominal velocity on dust permeability for Fiberglass fabrics, (From Spaite and Walsh, Ref. 82)

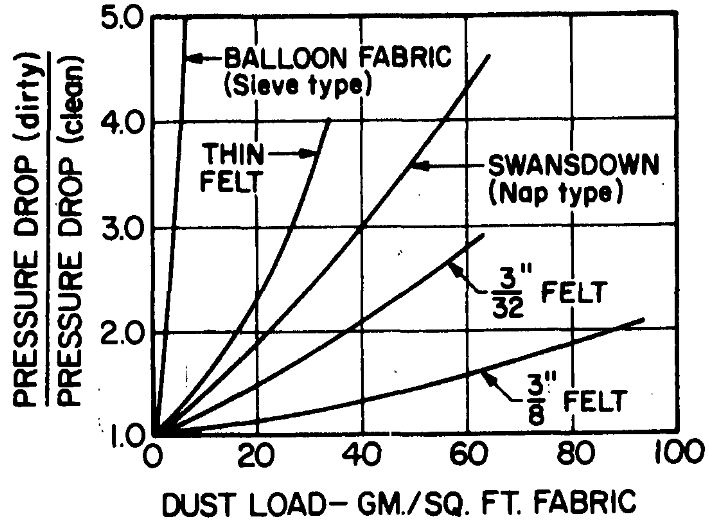


Figure 2.67. Effect of Dust Load on Pressure Drop of Various Fabrics (from Billington and Saunders, Ref. 171).

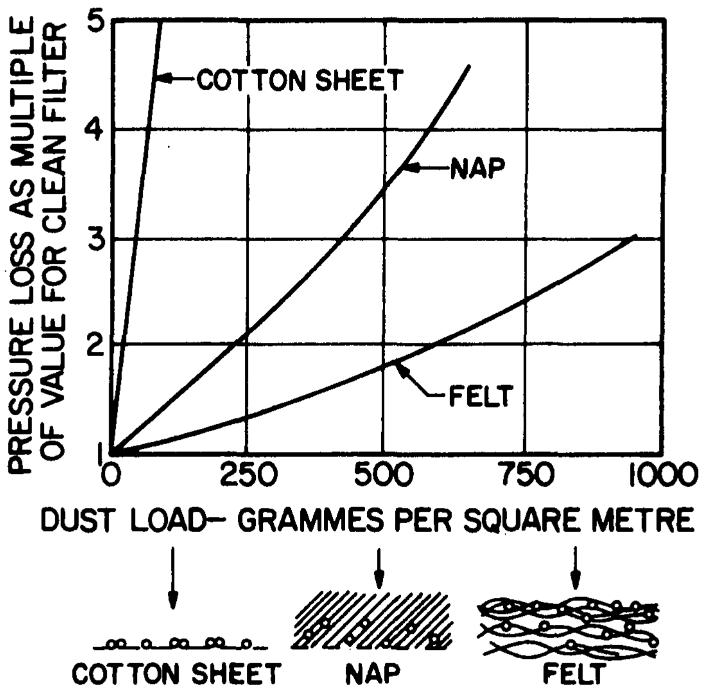


Figure 2.68. Clogging of Various Types of Filter Material (from Davies, Ref. 163 adapted from Billington and Saunders Ref. 171).

material. Cloth, with a nap raised on the side facing the flow is better, because some dust particles are entangled before reaching the finer pores of the base, and the life of the filter is consequently extended. Better still are homogeneous fibrous pads of felt-like consistency, as they can be made effective against fine particles, which deposit in depth, even though the pores are much greater in size than the particles."

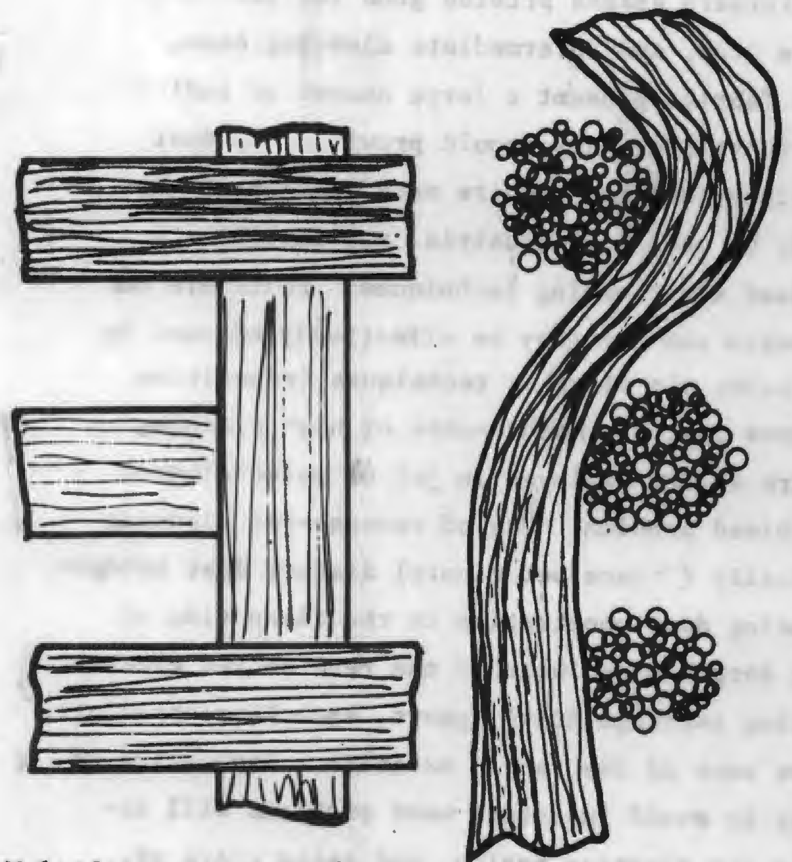
The phenomenological description of the formation of particle deposits on fibers and granules leading to a more or less continuous cake in fabric filtration is apparently not yet quantitative. Indications are however that the interyarn spaces, interfiber spaces, and fabric surface characteristics will all affect the formation and nature of the cake. Although we use the word cake, and the concept of a more or less continuous cake in analyses for K_2, calculations presented above indicate such a cake is probably less than about 1 mm thick for usual inlet dust concentrations ($<10 gr/ft^3$) and filtering velocities (<10 fpm). In continuous on-line cleaned collectors, the cake formed between hydrodynamic cleaning actions (<1 min) is probably less than 0.1 mm (100 μm thick).

Provision of a deep fibrous mat provides larger storage area for dust, more fibrils for formation of a more open, less dense cake, lower pressure drop per unit of dust deposit, and initially intrinsically higher collection efficiency. This approach to aerosol filtration has been termed defense in depth.

Tightly woven yarn fabrics provide less interstitial dust storage capacity in the inter-yarn spaces. The deposit presumably forms nearer the surface with somewhat higher pressure drop per unit of dust deposited. (Flat sieve-like geometries presumably result in highest pressure drop if pores are effectively plugged by depositing particles).

Monofilament weaves, twisted continuous monofilament yarns (glass and man-made polymer fibers) with few projecting interyarn fibrils should result in lower dust storage capacity, somewhat higher pressure drop per unit of dust deposit, and reduced efficiency at start of filtration, during formation of a dust collecting deposit, but should be relatively cleanable by vibration or shaking. Typical staple yarns with projecting fibrils in the interyarn spaces provide good initial efficiency, intermediate pressure drop, and intermediate cleaning ease. Felts and napped staple yarn fabrics present a large amount of individual fiber for filtration. Therefore, they should provide good dust retention and storage capability, but may require more cleaning to remove deposit. Felts can only be used for industrial applications in conjunction with jet and pulsed air cleaning techniques. Felts are not sufficiently strong to be shaken nor can they be effectively cleaned by this method. Use of jet or pulse air cleaning techniques (repetition rate < 1 min, on-line) requires felt for maintenance of high cleaning efficiency. Woven fabrics are seldom employed in jet or pulse-cleaned devices because of the dust bleed problem. Use of reverse-jet cleaning on woven fabric will periodically ($\sim$ once per minute) disturb dust bridges in the interyarn spaces, causing dust penetration to the clean side of the media. This can lead to abrasion and wear of the reverse jet cleaning ring (blow-tube), cleaning ring carriage drive (gears, sprockets, bearings, etc.,) and probably excessive wear of the fabric exterior. Separation of the ring from the bag surface to avoid interface wear problems will reduce the effectiveness of the jet cleaning action, and raise costs of power per unit of dust removed (or per unit of air treated by the filter). These general observations are illustrated schematically in Figure 2.69, with the probable implications (hypotheses) of fabric structure and morphology on performance as indicated. Effects of finishes on filaments, strands and yarns on dust holding or cake release characteristics are at present unknown, except qualitatively. Probably to a first approximation, finishes have no effect on cake build-up properties, but may have an important effect on residual dust deposit retained within interyarn and interfiber spaces, which in turn modifies cake build-up from the substrate. Finishes are occasionally applied to retain material and prevent seeping. Finishes also are employed to improve deposit release during cleaning.

Technically, a plain weave wire screen should be a poor filter, since dust passes easily through the openings upon start of filtration.



Multifilament yarns (long continuous fibers)

Interyarn and interfiber spaces relatively free of projecting fiber ends, or fibrils.

Interfiber spaces determined by filaments per strand, strands per yarn, and twists per inch, and probably of order of 10 μm or less (see Wakeham and Spicer, Ref. 137).

Probable effects on performance

Particle layers primarily particle to particle, slow bridging of smooth open pores, dust holding capacity low.

Relatively high K_2 and pressure drop per unit of dust deposited.

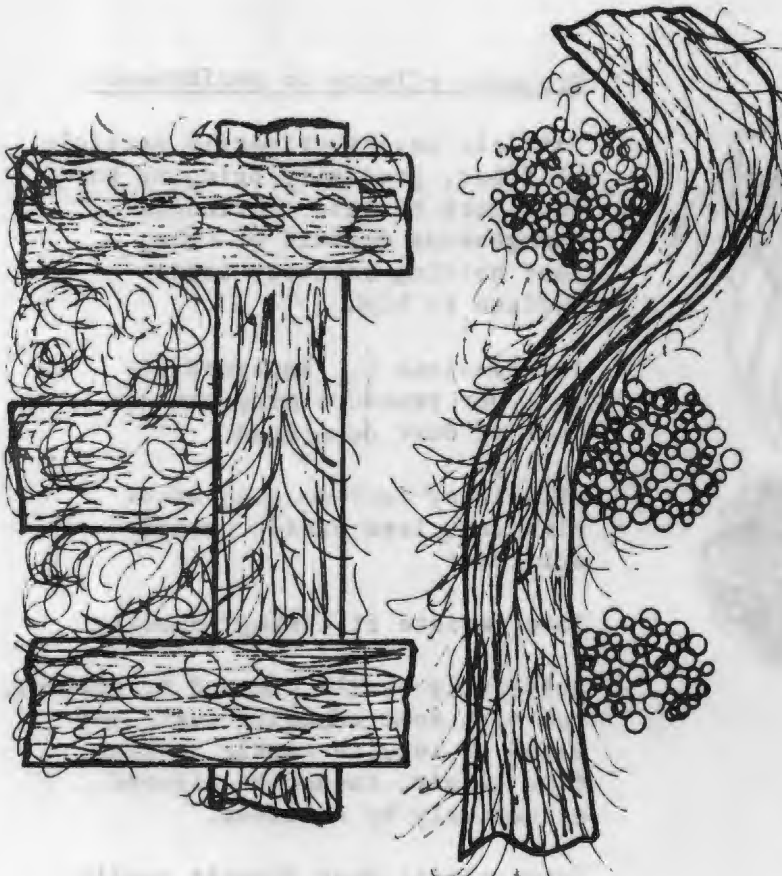
Efficiency lower after cleaning, pores open easily under cleaning.

May require lower filtering velocity to achieve acceptable efficiency.

Relatively easily cleaned by gentle reverse flow of air, by collapse pucker, easy cake release.

Interstitial dust deposit retained less easily, except as modified by finish and its adhesive character (i.e., silicone, graphites).

Figure 2.69(a) Probable effects of Fabric structure on K_2, the specific dust-fabric filter resistance coefficient, and performance in service during filtration.



Probable effects on Performance

Particle layers primarily particle to fiber, but soon bridges form over pores, as supported by hairy fibrous substrate; dust holding capacity intermediate.

Intermediate K_2, intermediate pressure drop per unit of dust.

Efficiency lower after cleaning, but pores open less after cleaning.

Low to intermediate filtering velocity.

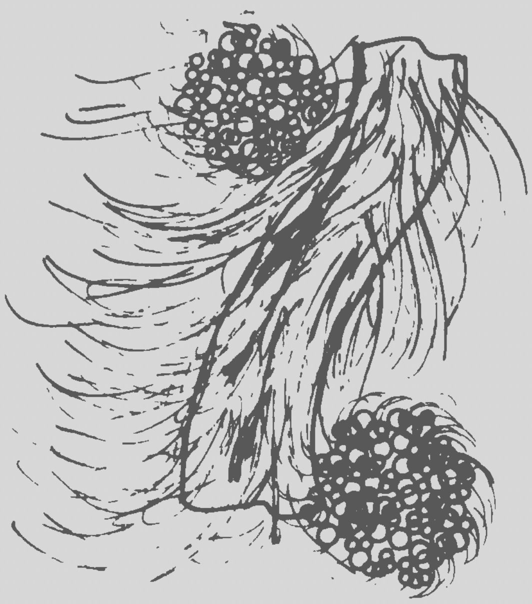
Relatively easily cleaned by shaking, not very cleanable by collapse, gentle reverse air flow improves cleaning.

Spun Staple Yarns (twisted shorter fibers)

Interyarn and interfiber spaces have many projecting fibers, fiber ends, and fibrils.

Interfiber space determined by yarn and strands as above; but substantially modified by presence of many available fibrils for dust deposition. Yarns probably more open, more porous.

Figure 2.69(b)



Napped Fabric (Surface filaments)

Interyarn and interfiber spaces have many projecting fibrils.

Interfiber spaces determined by yarn, strands as above but probably less important on effects as nap provides first order influence on performance.

Intermediate in construction and morphology between woven staple and felted fabrics.

Probable effects on performance

Particle layers primarily particle to fiber, gradually bridging to form more or less continuous homogeneous deposit or cake, dust holding capacity intermediate to high.

Intermediate K_2, intermediate to lower pressure drop per unit of dust deposited.

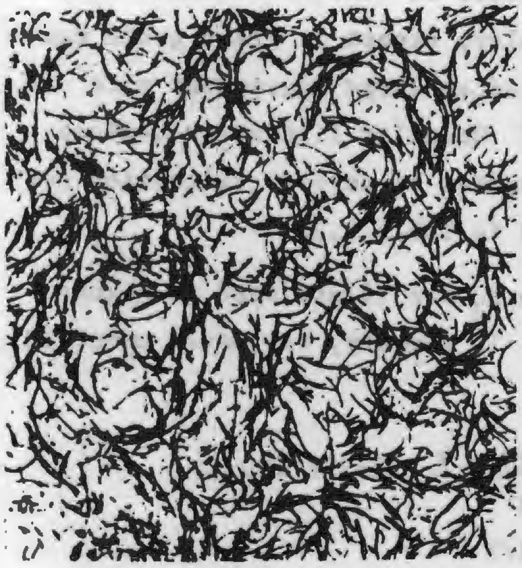
Efficiency fair to good after cleaning, less easily opened substrate.

Intermediate filtering velocity

Relatively easily cleaned by shaking, but with some adhesive dusts may blind or require gentle reverse flow of air, cannot be cleaned effectively by collapse.

Interstitial dust deposit easily retained.

Figure 2.69(c)



Felted Fabric
(wool or needled man-made)

Interfiber spaces always adjacent to a free fiber

Random orientation of individual fibers, many projecting ends

<u>Probable effects on Performance</u>

Particle layers primarily particle to fiber, gradual penetration of felt by migrating interstitial deposit, no straight-through passages.

Low K_2, large dust holding capacity.

Efficiency intrinsically high.

Filtering velocity high, when aggressively cleaned.

Effective cleaning requires high velocity reverse-jet or pulse-jet mechanisms to control porosity, permeability, and cake depth and structure.

Interstitial dust deposits retained to large extent, except migrate as indicated above. Basic character of fiber surfaces different in wool (scaly) and man-made (smooth) affects dust deposit retention, except as modified by finishes and treatments e.g. silicones, resins for effective dust control and reduction of seeping in continuously cleaned designs.

Figure 2.69(d)

However, dust deposits accumulating on grid wires should build up to some more-or-less critical size. After resuspension as relatively large chunks, they can be more easily collected by secondary and tertiary (e.g., inertial device followed by fabric) treatments. Limited work on filtering performance of screens as model filters has been conducted by Gallily[172], Mercer[173], Marshall[174] and Corn[80].

The same general statements should be true for relatively large granular filters (1000 μm) in service on fine particles. Dust bridges will be formed only with difficulty, except at grain-grain contact areas, and dust deposits are detached as large aggregates more easily collected by a secondary stage.[81] Granular filtration devices have been reviewed by AVCO[175]. Other studies of aerosol filtration performance of granular beds are summarized in Table 2.32.

Effects of fabric character on K_2 are illustrated in Figure 2.70 for the data previously presented. In summary, estimated numerical values for K_2 appear as follows:

Fabric Surface Effect	Relative K_2 Values (K_{FS})
Smooth, unnapped	1
Napped	1/2
Felted	1/4

Fuchs (Ref. 93, p. 231) summarized similar findings as follows:

> "Filters in which the specific surface area of the fibres is high have a low value of (K_2). Fabrics with a nap, for example, have (K_2) smaller than similar ones without a nap. Using the same aerosol, a glass fabric had (K_2) 10 times, and an Orlon® fabric with a small nap 4 times, larger than a similar fabric with a large nap. It is possible for (K_2) to vary a thousandfold in different fabrics and for various aerosols."

The implication that the specific surface area of available fibers in the fabric should enter the coefficient K_2 is apparent from Fuchs' comments and from the arguments presented in Figure 2.69. It is evident that surface area characterization of available filtration fibers in fabrics requires consideration in interpretation of K_2 values.

TABLE 2.32

SUMMARY OF STUDIES ON GRANULAR BEDS USED FOR AEROSOL FILTRATION

Author	Ref.	Date	Granules
Katz & Macrae	(***)	1947	Charcoal
Egleson	(*)	1954	Coke
D.M. Anderson	53	1958	Sheet, plastic spheres
Thomas & Yoder(1)	113	1956	
Thomas & Yoder (2)	114	1956	
Yoder & Empson	115	1958	Sand
Strauss & Thring	116	1960	Crushed refractory
Cheever, et al.	(**)	1966	Sand
AVCO	175	1969	Review
Ducon Co.	(****)	1969	
Squires & Graff	APCA paper	1970	Sand
Schoenburg	(175)	1969	Review
Taub	(81)	1970	Research on filter with granular beds

*G.C. Egleson, H.P. Simons, L.J. Kane, and A.E. Sands, The Moving-bed Coke Filter, U.S. Dept. of Interior, Bur. of Mines. Rpt. of Investigations 5033, 1954.

**C.L. Cheever, C.R. McFee, J. Sedlet, and T.L. Duffy, ZPPR Roof Sand Filtration of Uranium, Plutonium, and Uranine Aerosols, Proc. 9th AEC Air Cleaning Conf., Boston, Mass. (13-16 Sept. 1966).

***S. Katz and D. Macrae, J. Phys. Coll. Chem. 52, 695 (1948).

A.M. Squires and R.A. Graff, City College, N.Y., Panel Bed Filters for Simultaneous Removal of Fly Ash and Sulphur Dioxide: III. Reaction of Sulphur Dioxide with Half-Calcined Dolomite, presented at the 63rd Annual APCA Meeting, St. Louis, No. (June 14-18, 1970)

****Chem. and Eng. News, 57 (15 December 1969).

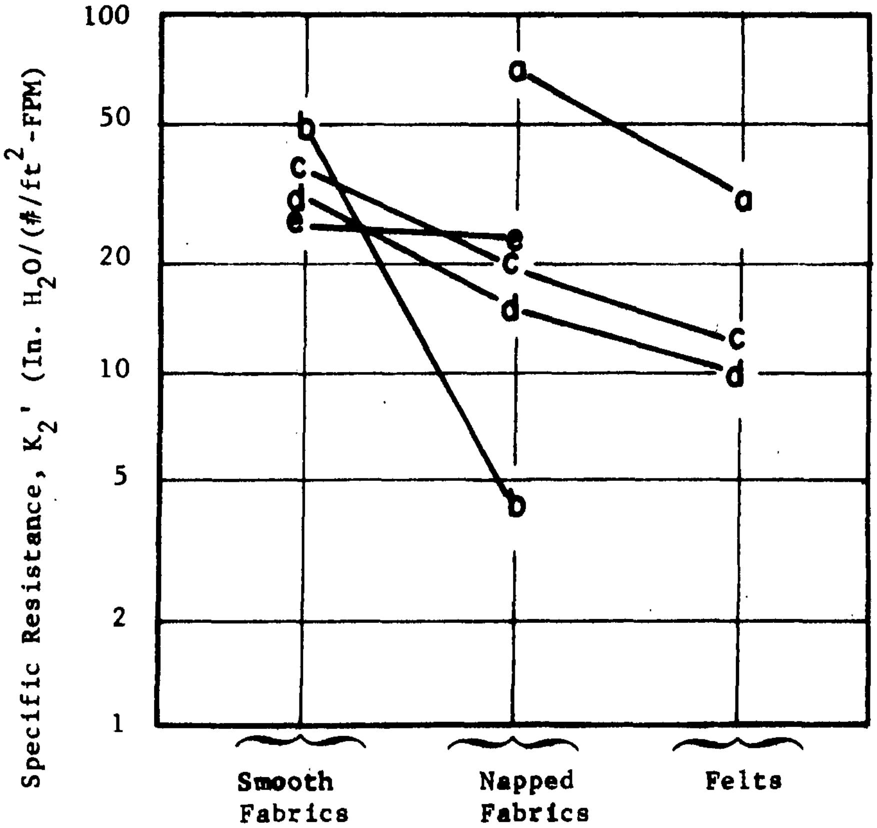


Figure 2.70. Changes in Specific Resistance Due to Fabric Surface. (From published results of 5 separate studies, in each of which fabric surface was the primary variable.) (See also Appendix 2.6).

2.4.9.6 <u>Clean Air-Flow Permeability</u>. - The air flow permeability of new clean unused fabric furnished by the manufacturer (as cfm/ft^2 at 1/2 inch of water pressure drop) was examined as a variable in K_2. Data relating K_2 during filtration and the original clean cloth permeability are shown in Figure 2.71. Although the data are not as consistent as desired, an approximate relationship for estimating indicates that K_2 changes by a factor of 2 for a 50 cfm/ft^2 change in clean permeability;

Initial Clean Cloth Permeability (cfm/ft^2 @ ½ inch water)	K_{perm}
10	1.3
20	1.2
30	1.1
40	1.0
50	0.9
60	0.8
70	0.7
80	0.6
90	0.5

2.4.9.7 <u>Other Effects</u>. - Other possible physical factors that affect K_2 include typical pressure differentials (Δp) encountered in a compartmented filter and the associated compression and decreased porosity, e. Effects of cleaning modify porosity, residual deposit, deposit length, and permeability, and electrostatic charge effects[176], as indicated in Figure 2.72.

Summarizing the above effects, K_2 can be predicted approximately as follows:

$$K_2 \approx D_p^{-2}$$

K_{sh}

Material	K_{sh}
Crushed	10
Fumes	0.05
Ash	4
Irregular	3
Collapsible	0.2

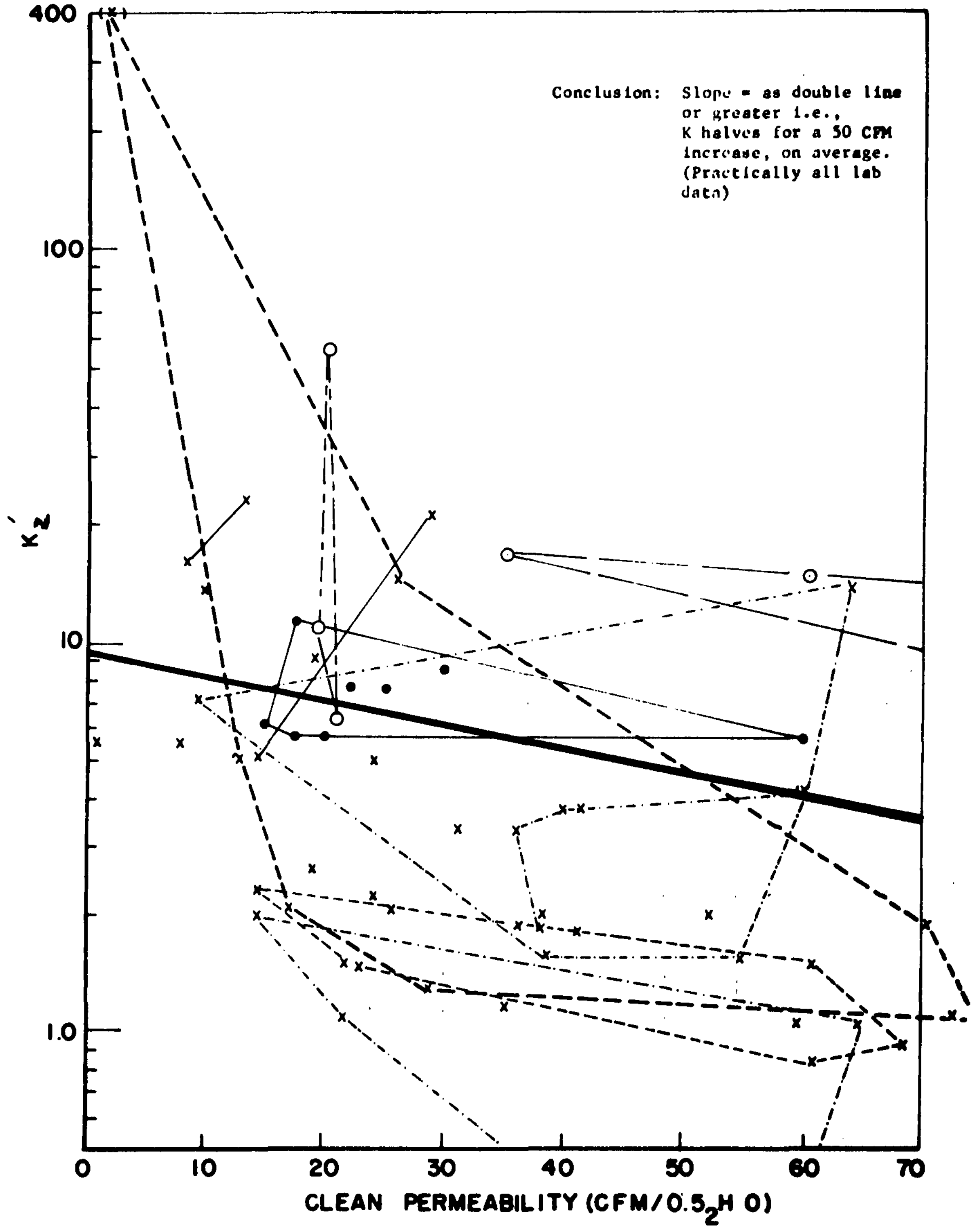


Figure 2.71. Influence of new fabric air-flow permeability on resist. coef. (K_2').

Comparison of efficiencies obtained by giving a filter fabric positive and negative charges

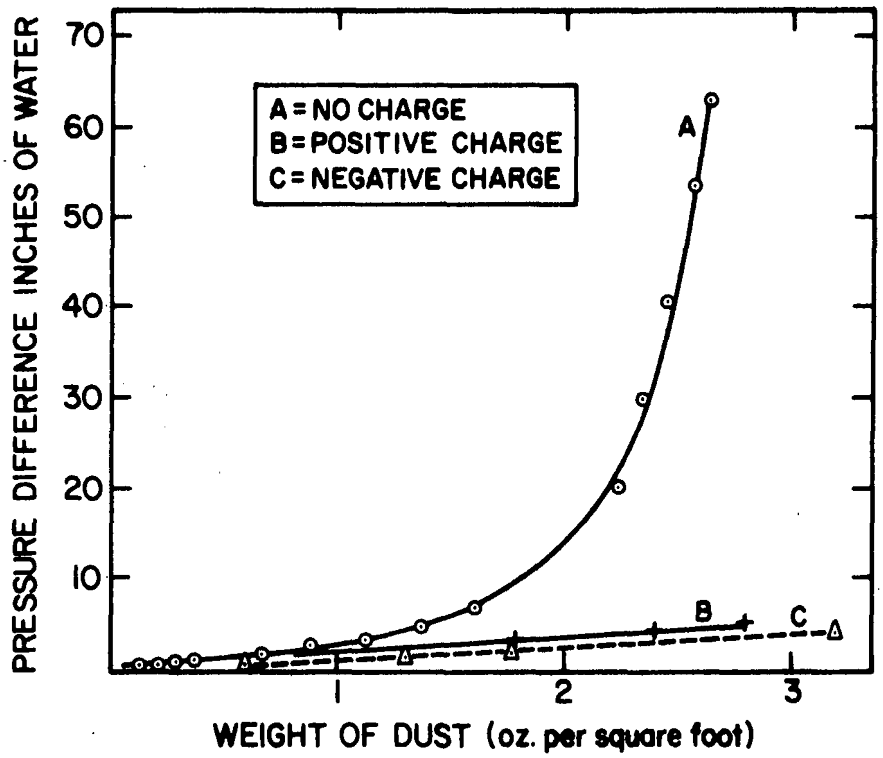


Figure 2.72. Effect of Fabric Charge on Pressure Drop.

$K_v \approx (V/3)^1$ or $(V_2/V_1)^1$.

K_{FS}

Fabric	K_{FS}
Smooth	1
Napped	1/2
Felts	1/4

K_{perm}

Permeability	K_{perm}
10	1.3
20	1.2
30	1.1
40	1.0
50	0.9
60	0.8
70	0.7

(2.81b)

80	0.6
90	0.5

from which (K_2) predicted = $1000\ D_p^{-2}\ (K_{sh} \cdot K_v \cdot K_{FS} \cdot K_{perm})$. For example, for fly ash of 20 μm particle size at a filtering velocity of 4.5 cfm/ft^2, on a napped fabric of new permeability 30:

(K_2) predicted = $\frac{1000}{(20)^2} \cdot 4 \cdot (\frac{4.5}{3}) \cdot \frac{1}{2} \cdot 1.1$ = 8.2 inches water per (pound per square foot) (ft/min). (The value of K_2 calculated from the Williams, et al., relationship at ρ_p = 2 is K_2 = 4, Figure 2.55b).

Values of (K_2) predicted were plotted against K_2 observed for all the field data in Table 2.39, as shown in Figure 2.73. With some reestimation of particle diameters in certain isolated instances, 80 percent of the data lie within a band bounded by a factor of 5. The estimation of friction factor for a packed bed (Figure 2.53, Leva et al.[141]) can only be obtained to within a factor of about 2. Since diameters in these present data are estimates (or for unknown analyses), the spread is not surprising. The data indicates that more detailed information is required on both particle-bed variables and fabric variables.

For comparison with the foregoing multi-factor prediction method, K_2 values were also predicted by the Williams, et al. relationship (Figure 2.55b) and also plotted against the observed field data - obtained K_2 values. The correlation, however, was poorer than that shown in Figure 2.73. Still another attempt at prediction might include a function of dust deposit porosity as one factor in the multi-factor method.

The multi-factor prediction method for (K_2) was further tested by using all NAPCA data for fly ash (or fly ash plus granular additive) as shown in Figure 2.74. Much of the data lie within a 5x band width as found above, but no clear trend is evident. Since NAPCA data were obtained by the same group using similar experimental methods for the most part, the lack of improvement in agreement between predicted and observed apparently reflects the limitations of the approximation scheme.

Further discussion of K_2 and the effect of fabric, geometry, and collector design factors is contained in Chapters 4 and 6.

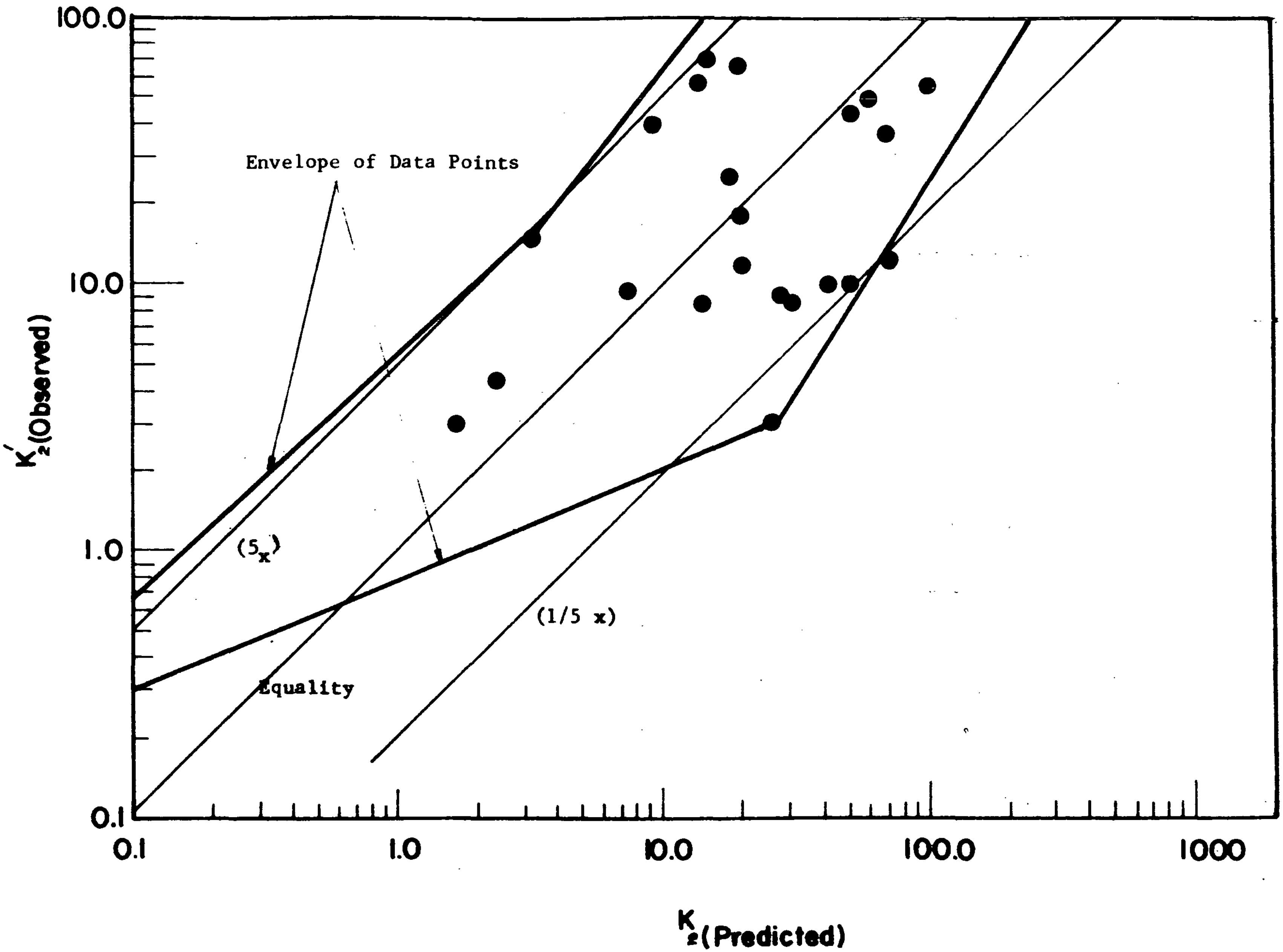


Figure 2.73. K_2 as obtained from prediction vs $K_2{}'$ observed from field data

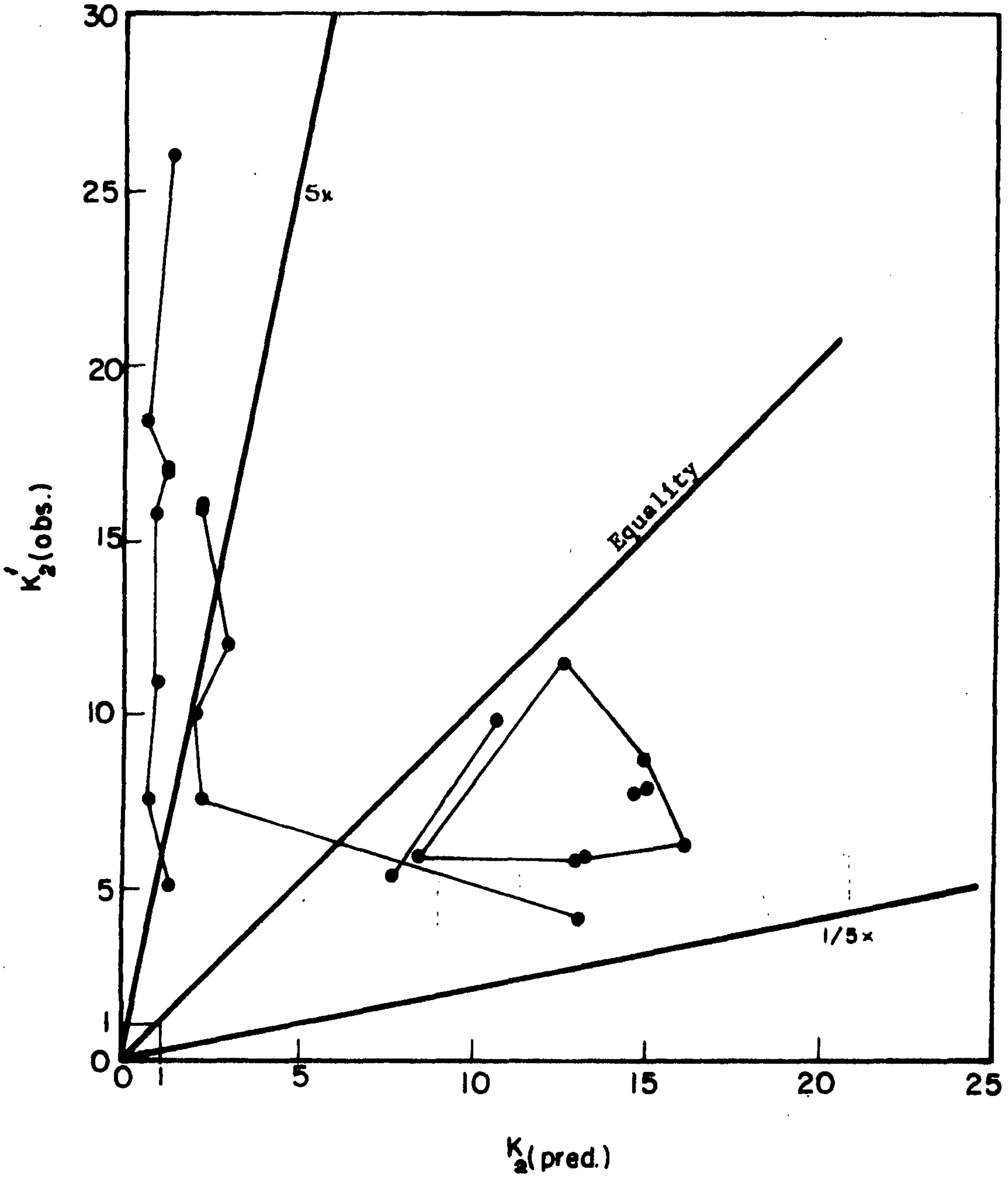


Figure 2.74. Comparison of Specific Resistances, Predicted and Observed, for NAPCA Data.

2-5 SYSTEM PRESSURE AND FLOW

Sections 2.4.7 to 2.4.9 describe the relation between filtration velocity and pressure drop across the cloth. By bringing in other parts of the fabric filter system, ducting, fan, etc. the relationship between fan pressure and total flow can be estimated. This will be seen to depend on factors such as the length/diameter ratio of the bag, the location of the gas inlet to the baghouse, reverse cleaning air, etc. For a first approximation, however, the pressure drop at the fan can be estimated at about twice the pressure drop across the cloth. The total flow will be the product of the amount of cloth being used, which will usually change from time to time in a multi-compartmented fabric filter using automatic sequential compartment cleaning, and the average filtration velcoity. Velocity will also change with time and be different at different parts of the baghouse, so that average velocity may differ considerably from measured velocity at any specific location in the filter.

2.5.1 Flow in a Single Bag

After entering the bag or tube, the flow continually decreases as part of it filters through the cloth; or, if the dust is collected on the outside of the tube, the flow continually increases inside the tube. The same principle applies to frame-type filter elements unless they are Vee shaped. In cases of horizontal flow through the baghouse this change in velocity probably doesn't make much difference. In cases of downward flow where the dirty gases move slower and slower as the bottom of the tube approaches, more large particles will tend to fall into the hopper without touching the cloth. Furthermore, if the downward flow continues during the cleaning cycle it may hasten the fall of collected dust into the hopper. In cases of upward flow, all dust particles carried into the filtering tube reach the cloth, the largest ones collecting near the bottom of the tube, whereas only the smallest ones reach the top where the upward velocity approaches zero.

The expected consequence of this elutriation would be a higher filtration resistance near the top of the fabric collector so that the filtration velocity would drop off even more sharply in the upper region. In fact, however, the flow is usually fairly turbulent in the entrance region and more cleaning energy is imparted to the top of the bag. This can result in over-permeability of the top cloth and under-permeability of the bottom. As a result of both efforts, the middle of the bag should probably collect the heaviest loadings as confirmed by NAPCA in about 1960 during some tests. These show differences of a factor of three in cloth loading along the bag. One concludes that since the behavior of dust on the cloth is not generally predictable the longitudinal flow in the bag is not completely predictable either. The velocity V_e of flow entering a tube is 4L/D x V or entering an evelope, 2L/W x V where L is distance from inlet to dead end, D is diameter, and W is entrance slot width. Since V is usually 1 to 10 FPM, the entrance velocity ranges from 100 to 1000 FPM. Table 2.33 lists the particle sizes that can be supported by velocities of this order. To a first approximation, all larger particles stay below the bag entrance and all smaller ones rise to a point of smaller velocity. Table 2.34 and Figure 2.75 indicate typical transport velocities required to support and convey common industrial dusts. Since all are $>$1000 fpm, much dust of larger sizes will be deposited in the hopper of an operating fabric filter.

There is a small, often negligible pressure loss associated with velocities of $\sim$100 fpm as the flow first suddenly enters the bag and then moves along the bag. The entrance loss is on the order of $\rho_f V_e^2$ or typically 0.01 inch of water. Fluid density, ρ_f, is the sum of gas and particle cloud densities, but except for concentrations above about 50 gr/ft^3 (typical of pneumatic conveying) the latter is negligible since normal gas densities are on the order of 500 gr/ft^3. In the case of filtering outside the bag the head loss is even smaller.

Flow moving through a straight porous duct undergoes a pressure change due to friction (viscous drag at the walls of the duct), gravity,

Table 2.33. Spherical Particle Sizes Transported by Indicated Upward Air Velocities (Terminal Settling Velocities) (cm/sec)

ρ_p*	Particle or Aggregate Diameter, D_p (μm)									
	1	2	5	10	20	50	100	200	500	1000
0.01	.000033	.00012	[illegible]	.0028	.012	.07	.28	[illegible]	[illegible]	[illegible]
0.02	.0007	.00026	.0015	.006	.026	.15	.60	2.3	10	[illegible]
0.05	.00018	.0007	.004	.016	.07	0.4	1.6	5.5	23	51
0.1	.00037	.0014	.008	.032	.14	0.8	3.0	11	39	83
0.2	.00074	.0028	.016	.064	.28	1.6	5.9	19	65	130
0.5	.0018	.007	.04	.16	0.7	3.9	14	42	121	250
1.0	.0037	.014	.08	.32	1.2	7.6	25	70	195	390
2.0	.0074	.028	.16	.64	2.5	14	45	114	310	625
5.0	.018	.07	0.4	1.5	6.4	35	97	223	575	1100
10.0	.037	.14	0.8	3.1	12.5	60	166	352	890	1730

*The density of a dust particle can be substantially lower (<0.1) than the true density of the material from which it is made, as a consequence of air inclusions in aggregates - see Tables 2.3 and 2.4, for typical particle densities, Tables 2.19, 2.20 and 2.21 for typical dust bulk densities, and Figures 2.46 and 2.47 for the variation in bulkiness with particle size.

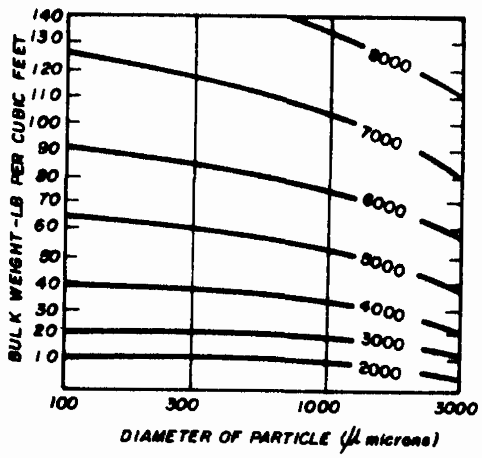


Figure 2.75. Conveying Velocities (from Fan Engineering, Buffalo Forge Co.)

Table 2.34(a). Conveying Velocities for Dust Collecting*

Material	Velocity — F.P.M. From	Velocity — F.P.M. To
Wood flour — sander dust	1500	2000
Sawdust, light, dry	2000	3000
Sawdust, heavy, wet or green	3000	4000
Shavings, light, dry	2000	3000
Shavings, heavy, wet or green	3000	4000
Wood blocks, edgings, heavy, wet or green	3500	4500
Hog waste	3500	4500
Grinding dust	3000	4000
Foundry dust, tumbling barrel, shake-out	3500	4500
Sand blast dust	3500	4000
Buffing lint, dry	2500	3000
Buffing lint, sticky	3000	4000
Metal turnings	4000	5000
Lead dust	4000	5000
Cotton	2500	3000
Cotton lint, flyings	1500	2000
Wool	3000	4000
Jute lint, flyings	2800	3000
Jute picker stock, shredded bagging	3000	3300
Jute dust shaker waste	3100	3400
Jute butts (conveying)	3600	4500
Grain	2500	4000
Ground feed, ½-in. screen (conveying)	4500	5000
Grain dust	2000	3000
Coffee beans	3000	3500
Shoe dust	3000	4000
Rubber dust	2000	2500
Bakelite molding powder	3000	3500
Bakelite molding powder dust	2000	2500
Granite dust and surfacer chips	3000	4000

From Alden, Ref. 178.

Table 2.34(b). Velocities for Low Pressure Pneumatic Conveying*

Material	Velocity, F.p.m. From	Velocity, F.p.m. To
Wood flour	4000	6000
Sawdust	4000	6000
Hog waste	4500	6500
Pulp chips	4500	7000
Tanbark, dry	4500	7000
Tanbark, leached, damp	5500	7500
Cork, ground	3500	5500
Metal turnings	5000	7000
Cotton	4000	6000
Wool	4500	6000
Jute	4500	6000
Hemp	4500	6000
Rags	4500	6500
Cotton seed	4000	6000
Flour	3500	6000
Oats	4500	6000
Barley	5000	6500
Corn	5000	7000
Wheat	5000	7000
Rye	5000	7000
Coffee beans, stoned	3000	3500
Coffee beans, unstoned	3500	4000
Sugar	5000	6000
Salt	5500	7500
Coal, powdered	4500	6000
Ashes, clinkers, ground	6000	8500
Lime	5000	7000
Cement, Portland	6000	9000
Sand	6000	9000

and change of velocity, Comparing points 1 and 2 along the tube,

$$p_1 + \rho_f V_1^2 + F_r = p_2 + \rho_f V_2^2 + \rho_f g \Delta L \qquad (2.82)$$

where F_r is the frictional drag, ΔL is the difference in height beween the points, and ρ_f is the aerosol density being lifted through this height. In the gravity term, normal dust loadings are insignificant but 500° filtration can add 0.5 inches of water at the top of a 40 foot bag just from the added gas buoyancy. (Buoyancy doesn't contribute to pressure drop across the cloth, just across the baghouse). The friction term is probably negligible, since even a nonporous bag having an L/D ratio of 40 and carrying gas at 300 FPM would only have a .05 inch pressure drop from end to end.* Furthermore, the process of filtering continually reduces the boundary layer thickness (and related drag loss). The velocity-squared terms in Equation (2.82) are normally negligible. Thus an analysis of all terms in Equation (2.82) shows that there is usually not much pressure difference between the ends of a vertical or horizontal filtering tube, and likewise for a frame filter. Abrasion and turbulence associated with high entrance velocities are discussed in Chapter 8.

2.5.2 Flow in a Single Compartment

Air velocity within a hopper or other expanded inlet plenum decreases since the product of average velocity and cross-sectional area of a duct remains constant. As the vertical component of velocity decreases, all particles settle faster, in accordance with Table 2.41, so that in a very spacious hopper considerable material may never reach the cloth. Turbulence, however, which is present with or without baffles, retards this settling and may even re-aerosolize some of the dust from the bottom of

*In a non-porous pipe, $\Delta p = f(\Delta L/D)(V^2/2g)$, where f is the pipe friction factor, a function of Re_{pipe} and wall roughness, typically 0.05 ± a factor of 2. (Hunsacker and Rightmire, p. 126).

the hopper. (Air in-leakage through hopper seams, valves, etc., also will resuspend part of the dust and increase the dust load to the fabric). Most particles caught in the accelerating flows rushing into the filter chamber cease to settle appreciably and eventually they reach the filter cloth.

Some baghouse inlets direct the flow tangentially around the inside of the hopper either to reduce the loading to the cloth or to protect the cloth from very large particles. The particles in a rotary flow are thrust radially outward with an acceleration equal to V^2/R where R is the radius of curvature. Since acceleration is of the same order as gravity, Table 2.41 gives very rough estimates of the velocity of outward travel of the particles. Whether they move outward quickly enough to reach the vicinity of the wall where they can quietly settle depends on their size, on velocity, on the inlet configuration, and the degree of turbulence.

If clean air were blown into a compartment where all filter elements had uniform permeability, the flow would probably be essentially uniformly distributed among the elements. In actual practice, however, perfect distribution is probably rare, due to some elements receiving fine particles than others, variability in cleaning intensity, and differences; in local operating temperatures, etc. The resulting mal-distribution of flow which is generally hard to analyze can lead to variable bag life.

In small hoppers or inlet plenums, the flow may bend abruptly as it enters the filter entrance so that the centrifugal effect described above may reduce the concentration of large particles reaching the cloth.

Flow enters the filtering portion of the compartment at fairly high velocity and, except in tapering filter elements, slows down as it approaches the dead end. On the clean side of the cloth, however, the reverse happens; the flow accumulates and accelerates toward the compartment exit. As it does so, small pressure changes take place similar to

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*From Alden, Ref. 178.

those described in 2.5.1.

Flow suddenly entering a large chamber from a small one, such as from an inlet duct to the hopper, undergoes pressure increase as the velocity slows down. The increase is given by $(p_2 - p_1) = \rho_f V_1^2 \left(\frac{A_2}{A_1}\right)\left(1-\frac{A_1}{A_2}\right)$. For example, with an area ratio of 1/5 and an inlet velocity of 3000 FPM, the pressure increase would approximate 0.2 inches of water. If the entrance were very gradual the pressure increase would be larger and given by $(\frac{1}{2})\rho_f V_1^2 \left(1-A_1^2/A_2^2\right)$. In the example, the increase would be 0.6 inches; thus the sudden expansion causes a flow-to-heat energy "loss" equivalent to 0.4 inches of pressure.

2.5.3 System Flow

The baghouse, usually consisting of a group of compartments, has an overall drag or resistance to air flow that depends on that of each compartment. Each compartment with its lead-in ducting has its own flow resistance which, as discussed above, depends on where it is in the cleaning filtering cycle, among other things. Since the compartments are arranged in parallel, the resistances combine as in conventional electrical circuitry:

$$\frac{1}{R_t} = \sum_i \frac{1}{R_i} \quad , \quad i = 1, 2, \ldots n \qquad (2.83)$$

where R_t is the overall baghouse resistance for n compartments. The resistance of any one compartment plus lead-in ducting is to a first approximation the ratio of the flow through the compartment to the pressure across it. The pressure across the compartment is approximately the same for all compartments. Thus equation (2.83) could be written:

$$\frac{1}{R_t} = \frac{Q_t}{\Delta p_t} = \frac{1}{\Delta p_t} \sum_i Q_i \quad , \quad i = 1, 2, \ldots n \qquad (2.84)$$

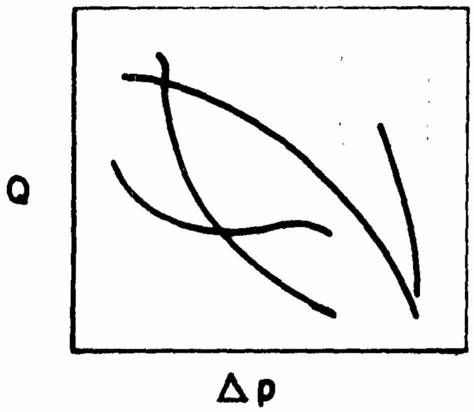
where Q_t is the total flow through the baghouse and Δp_t is the pressure across it. The pressure across the primary fan is greater than the pressure across the baghouse because of friction in the ducting which can be several inches of water for high duct velocities or large L/D duct ratios. The pressure across the fan is the sum

$$\Delta p_F = \Delta p_D + \Delta p_t \tag{2.85}$$

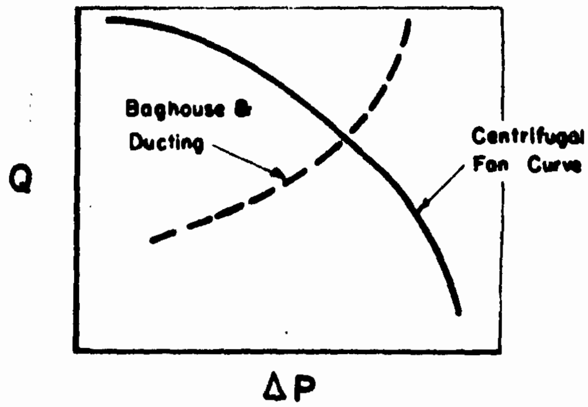
where F, D, and t refer to fan, duct, and baghouse respectively.

The pressure across the fan, however, is uniquely related to the flow through the fan by the fan manufacturer's operating curves. The fan curve is different for each fan type, see Figure 2.76. A curve for a centrifugal blower is given in Figure 2.76(b). Although one has the option of operating a fan on a variable speed basis, a constant operating speed is the more usual practice.

The dotted line in Figure 2.76b represents the relationship between baghouse flow and baghouse-plus-ducting pressure drop determined as above. This curve depicts a transient condition since the drag of individual compartments is continually changing (although at a slow rate in some systems). The slope of the curve represents 1/R for the baghouse-duct combination. In order for Δp to be given by both the fan curve and equation (2.85), that is, for both curves in Figure 2.76(b) to apply simultaneously, Q and Δp must be at the intersection of the curves. In other words the flow through the entire baghouse system is determined by the baghouse-ducting flow resistance and by the fan curve.



(a) Typical fan performance curves



(b) Gas flow-pressure system curves for the usual fabric filter system.

Figure 2.76. Typical Fan Curves.

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CHAPTER 3

TYPES OF FABRIC FILTERS

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TYPES OF FABRIC FILTERS

Approximately 50 U.S. manufacturers produce over 100 fabric filter models, each of which is available over a range of sizes. The term "model" is used to distinguish principally between: (a) the configuration of the cloth filter element; (b) the method of cleaning the cloth; and to some extent (c) the way the cloth is held in place. These variations constitute the main differences between the available fabric filter designs. This chapter briefly describes the models of fabric collectors currently available and in addition considers the reasons for the designs of presently available equipment; for example, the relationship between the filter bag length/diameter ratio and the performance of the collector as a whole.

3.1 STANDARD AVAILABLE FABRIC FILTER EQUIPMENT

Following a 1969 mail survey and a series of subsequent technical discussions, the data presented in Appendix 3.1 was assembled listing the fabric filtration equipment available in the U.S.* The equipment is described in the appendixed tables across the design characteristics discussed below.

3.1.1 Configuration

Nearly every fabric filter is of one of two types, envelope or cylindrical. In the envelope filter, flat panels of cloth are

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* It should be emphasized that the following discussion and the information presented in Appendix 3.1, is based upon the information provided by the manufacturers included in the survey. We attempted to include all known manufacturers of fabric filter systems by including all companies in the survey that were listed in the appropriate categories in the 1969 Product Listing in Environmental Science and Technology and the Journal of the Air Pollution Control Association. In addition, we cross checked the membership roster of the Industrial Gas Cleaning Institute and other known sources of listings of fabric filter manufacturers. We are unable to fully evaluate the completeness of the product information provided in the survey, but are confident that we have received a large percentage of the non-proprietary information available from these companies.

stretched over a frame. The panels are usually in pairs, or more rarely, pleated. The cylindrical filter is either open at both ends or more frequently closed at one end in the shape of a bag. Both envelope and cylindrical tube elements are nearly always vertical, so the accumulated dust can fall to a collecting point for disposal. Usually, many such elements are located side by side in the dust collector.

As Figure 3.1 indicates, the configuration of the filter element is related to the flow of gases through the element; dirty gases usually enter the bottom of the compartment and flow upward. Also basic to the filter operation is whether the dust will collect on the inside or the outside of the filter element, and this fixes the number and location of tube sheets and plenums in the compartment. Consequently, the configuration of the filter element determines the configuration of the entire baghouse compartment.

3.1.2 Cleaning Methods

A second way to distinguish between fabric filter models is by the manner in which the cloth is cleaned. The cleaning process may be entirely manual, or it may be initiated manually and then completed automatically. Larger systems usually completely automatically clean the elements by using a timer or pressure limit switch. The most common methods are by shaking or by reversing the flow through the cloth in some manner. Shaking methods include horizontal or vertical shaking of one end or all of the filter element; vibrating or rapping; fluttering with air currents; snapping the cloth with a pulse of compressed air;and sonic cleaning. Methods of flow reversal include forcing the dust cake off the cloth with back pressure; collapsing the cloth with associated flexure and cracking of the dust cake; snapping the cake off with a pulse of compressed air; and blowing it off with a jet of air through the cloth. Many of the available equipment models use a combination of cleaning techniques. An example is horizontal shake with partial collapse. The most common single method is horizontal shake with about half the models using this cleaning technique. In comparison, sonic cleaning is a relatively new approach with more limited utility.

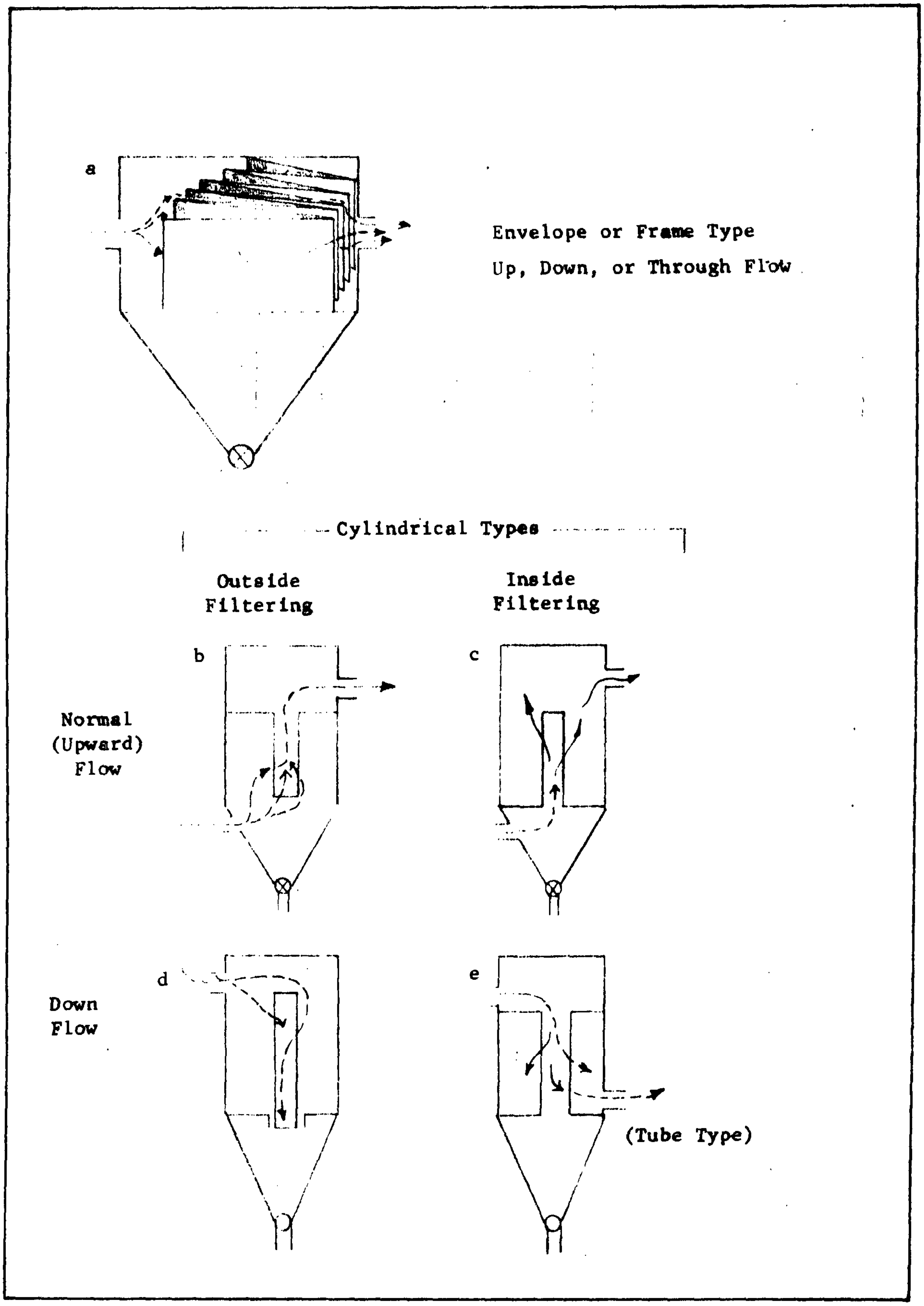


Figure 3.1. Configurations of Fabric Filters

3.1.3 Filter Fastening Techniques

Associated with the filter configuration and cleaning method is the way the filter element is held in place. An envelope is typically buttoned to a frame, part of which may be movable to tighten the cloth. The tubular filter is clamped to a thimble plate at one or both ends. If there is no flow through the other end, it is hooked or buckled to a common cross bar or infrequently left free. There must be some way to tension the tube and the adjustment is not always easy. If the filter is to be stationary during cleaning, it will be supported on one side by wire mesh or spaced rings. Appendix 3.1 does not show how the filter element is held in place or supported, but this can be estimated from consideration of the configuration and cleaning method.

Figure 3.2 depicts some of the alternate techniques for installing the fabric collector in the collection system.

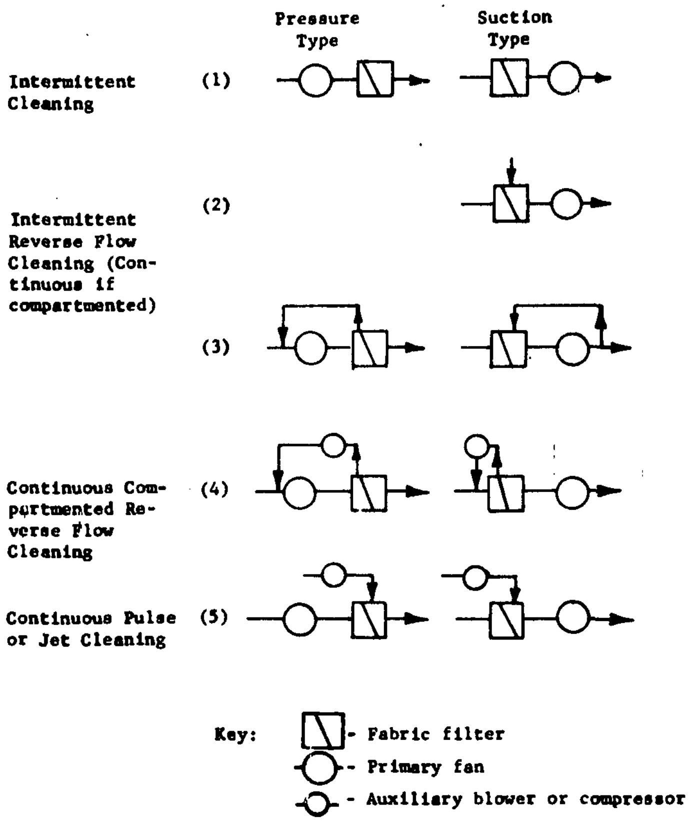


Figure 3.2. Types of Fabric Filter Systems Depending on Cleaning Method.

For example, intermittent equipment (Type 1) may either be proceeded or followed by the primary fan and requires no other flow branches in the system. Reverse flow equipment can be operated with the fan after the collector to provide the needed suction, (Type 2), but more often an additional fan or additional ducts to the separate compartments are used to achieve the reverse flow (Types 3,4). The cleaning methods requiring higher pressure air use additional blowers or compressors (Types 4,5). In order of popularity based on the numbers described in the manufacturer's brochures, Types 1 and 5 are most common while Types 3 and 4 are less often installed. Except for intermittent equipment, most collectors can be installed in any of the ways shown.

3.1.4 Size

While filters called "unit" models come in standard sizes down to that of ordinary vacuum cleaners, many other models range upward to whatever size is desired. The largest known filter has about 1,000,000 ft^2 of cloth and is located at a Canadian asbestos plant. Large (5,000 ft^2 or more) baghouses are nearly always assemblies of compartment modules for economy in design, shipment, assembly and maintenance. Individual module sizes are usually a few hundred ft^2 of cloth, as Appendix 3.1 indicates, but this appears to depend on the market around which the manufacturer has built his line. Also, the choice of number of compartments, and hence compartment size, is a factor in the service to be provided by the baghouse system. For example, the more compartments the steadier (more uniform) the total system flow may be.

3.1.5 Typical Fabric Filter Equipment

To illustrate the variety of the available equipment, the following examples have been selected and are described, based on brochures received from the manufacturers.

- High temperature glass cloth baghouse
- Unit collector manually cleaned

- Typical shake-type baghouse
- Pulsing flow baghouse
- Reverse flow envelope collector
- Reverse jet collector
- Reverse flow cylindrical collector
- Reverse pulse collector
- Ultrafiltration equipment.

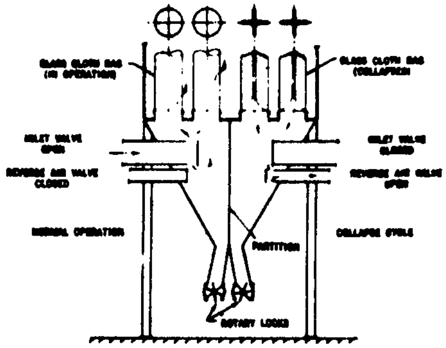
A brief discussion of these different design approaches is presented, because each design approach demonstrates a type of fabric filter used extensively for air pollution control.

3.1.5.1 High Temperature Glass Cloth Baghouse.- This equipment, as depicted in Figure 3.3a, is designed to operate with glass cloth for high temperature applications and moderately large gas flows. A typical dust would be electric furnace fume (fine particles) filtered at a fairly low velocity. Most dusts would be expected to release fairly easily from the smooth glass cloth. In order to preserve the cloth, as gentle a cleaning method as possible is used, including collapse or collapse plus gentle reverse flow air. This collector might be located outdoors where space is less expensive, in which case the added ducting could provide advantageous cooling of the gases.

3.1.5.2 Unit Collector Manually Cleaned.- The system presented in Figure 3.3b is typical of many relatively small unit dust collectors which range approximately from the size shown down to one-bag designs of a few ft^2. The construction is usually light, as the unit is usually intended for indoor service adjacent to the dust source. These units may contain an integral blower and frequently are used in combination with inertial precleaning equipment such as a cyclone. The equipment need not be at floor level, but can be mounted under, on a workbench, or overhead as long as the shaker and cleaning part are accessible. Since the equipment is close at hand and simple, it offers good reliability. It is widely used on small production operations, frequently for nusiance dusts from buffing, grinding, etc., or for bin vent, material transfer point, etc., applications.

GLASS CLOTH COLLECTOR AIR VOLUME RATING CHART (CFM)

Length Tube	No. Tubes	Net Area Sq. Ft.	Air/Cloth Ratio (FPM/Ft.² Cloth) 1½	2
14		1320	1,980	2,640
16		1560	2,340	3,120
19		1800	2,700	3,600
21	32	2040	3,060	4,080
24		2280	3,420	4,560
26		2520	3,780	5,040
29		2760	4,140	5,520
19		2995	4,493	5,990
21		3350	5,025	6,700
24	52	3705	5,558	7,410
26		4095	6,143	8,190
29		4485	6,728	8,970
24		4560	6,840	9,120
26	64	5040	7,560	10,080
29		5520	8,280	11,040
24		5985	8,970	11,970
26	84	6615	9,923	13,230
29		7245	10,868	14,490
24		7980	11,970	15,960
26	112	8820	13,230	17,640
29		9660	14,490	19,320



ARR. B-2
GLASS CLOTH COLLECTOR-HOPPER AND DAMPER OPERATION

SEQUENCE OF OPERATION

The tubes to be cleaned are isolated from the rest of the system by means of valves and collapsed by creating a negative pressure inside the tubes. This negative pressure inside the tubes is created by the collapse exhauster.

The sequence of operation is:

1. **Inlet valve closes, isolating section to be cleaned.**
2. **Reverse air valve opens, collapse exhauster evacuates gas from tubes and hopper, after a short time interval, reverse air valve closes.**
3. **Inlet valve opens momentarily, partially reinflating glass tubes, and then closes. In addition to opening the tubes for removal of dust, this action imparts an inertial cleaning action.**
4. **A null period of zero pressure follows the collapsed phase, allowing the collected material to fall into the hopper.**
5. **The inlet valve opens, and glass tubes are back into operation.**

Manufacturer: Am. Air Filter Co.
Model No: Amertherm
Brochure No: 283A

Filter Element Type: Bag
Diameter/Spacing: 11.5"
Length: 14 to 29
Flow Direction: Up
Dust Caught on the in side.
Retainment: Hung and clamped
Cleaning method: reverse, collapse, flutter
Control method: automatic
Power required: valves only

Baghouse shape: cyclindrical, 2 or 4 comp.
Filter elements per compartment: 8 to 56
Baghouse size: (45 ft x 12 ft x 12) max
Cloth Area: 1300 - 10,000ft^2
Operation: Continuous
Accessibility: Intermittent
Fabric types: Glass
Normal air/cloth ratio: 1½-2
Applications: Hi temperature fumes, dusts
Temperatures: Hi temperature fumes, dusts
Loadings: moderate
Cleaning frequency: moderate
Dust types:
Efficiency:

Figure 3.3a. High Temperature Glass Cloth Baghouse

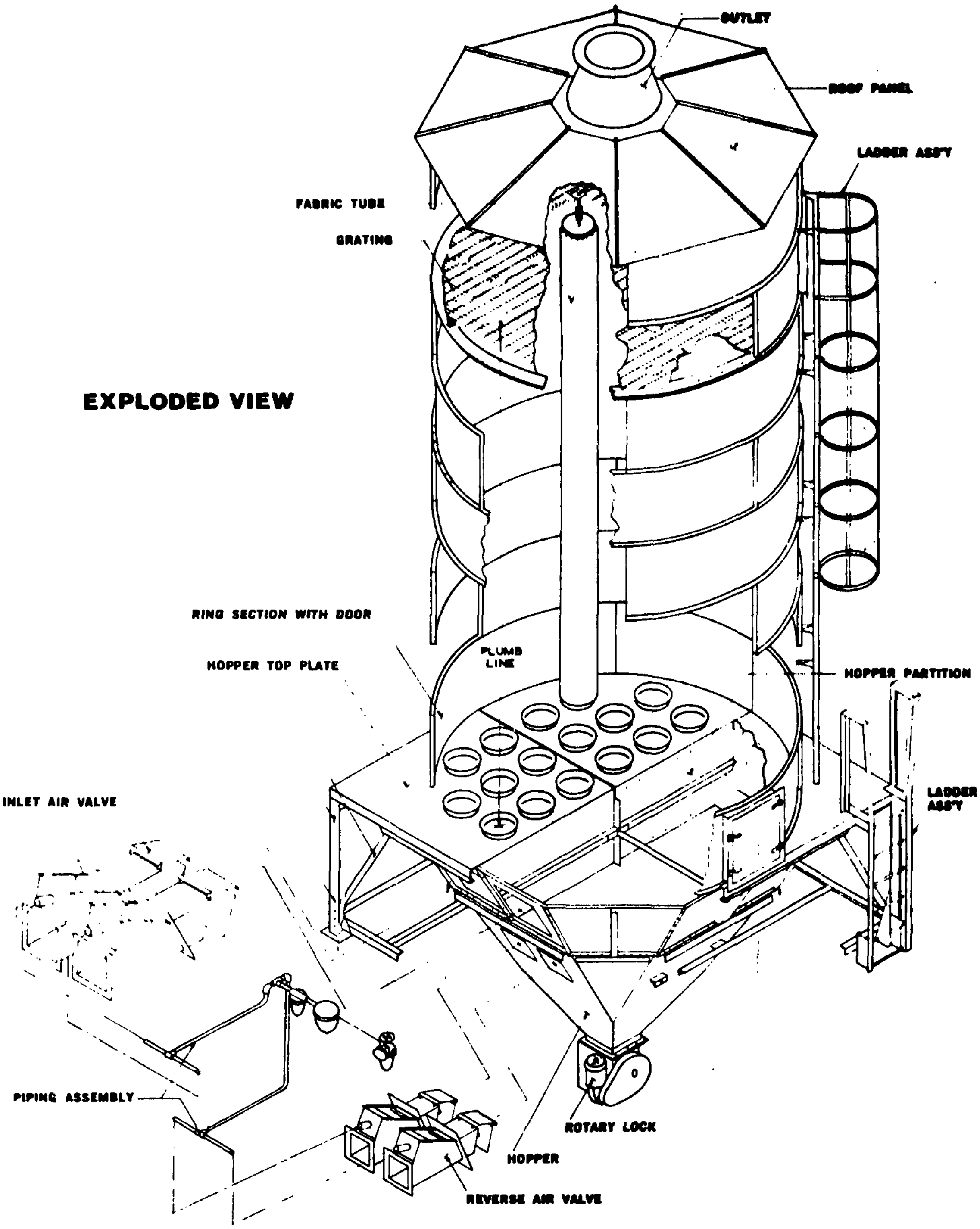


Figure 3.3a. High Temperature Baghouse (continued)

FT-40

For "In plant" locations to recirculate cleaned air . . . Available totally enclosed for outside venting or outdoor locations.

The Model FT-40 Filter was designed for use with the 3000 Series DUSTKOP where the fiberglass filter is not usually employed such as in woodworking or other applications involving large volumes of very fine dust. It can also be used with "N" units smaller than the **3000 Series** where a very large area of filter is required.

Dust laden air enters the top chamber through an inlet that can be placed either on the end or on the side. The air then passes downward through forty 5" diameter cloth filter tubes which remove all remaining dust. At intervals, dust may be manually shaken from the inside of the tubes by use of the shaker bar accessible from either end of the unit, motorized shaker is available. Dust falls into the undisturbed air of the lower chamber where it can be removed when this area becomes about two-thirds full. Dust removal is from either end.

The FT-40 has 40 filter tubes with a filtering area of 383 square feet. Tubes are sealed top and bottom with the same rubber grommet seal used in the FILTERKOP at the right. It is shipped completely assembled; shipping weight 697 pounds.

Manufacturer: Aget Mfg. Co.
Model No: FT-40
Brochure No: 736-2

Filter Element Type: Tube
Diameter/spacing: 5"
Length: (6')
L/D ratio: 14
Flow Direction: Down
Dust caught on the inside.
Retainment: clamped top and bottom
Cleaning method: shake
Control method: manual
Power required:

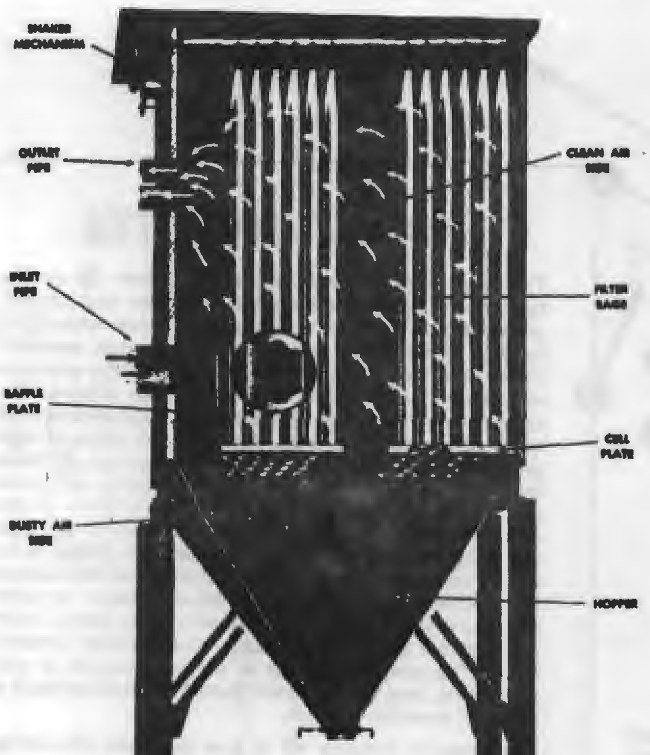
Dust disposal: Manual
Baghouse Shape: Rectangular
Filter elements per compartment: 40
Baghouse size: (8 x 2 x 4)
Cloth Area: 383 ft^2
Operation: Intermittent
Accessibility: Intermittent
Fabric Types: Low temp. cloths
Normal air/cloth ratio: any
Normal pressure across cloth: any
Applications: low temperature emissions
Temperatures: low temperature emissions
Loadings: low
Cleaning frequency: infrequent
Dust types: usually large, dry
Efficiency:

Figure 3.3b. Unit Collector Manually Cleaned

3.1.5.3 <u>Typical Shaker Type Baghouse</u>.- While equipment of the type shown in Figure 3.3c is available in all sizes, most of the larger baghouses are of the shaker type because of the relatively low initial investment. The equipment is suitable for a wide range of conditions, although less so at high dust loading, because the baghouse compartment must be shut down during the cleaning cycle. On the other hand, compartmentization enables entry for inspection and repair without stopping the system. This equipment is similar to that in use for the last 50 years or more and this long experience has resulted in a fairly good performance/cost ratio. Shake cleaning, however is not suitable for some fabrics and for some dusts.

3.1.5.4 <u>Pulsing Flow Baghouse</u>.- Pulse cleaning equipment of the type depicted in Figure 3.3d has been introduced by many manufacturers as the most recent improvement in fabric filter cleaning technology. Systems of nearly any size are made possible, as with most of the larger types of equipment, by simply adding more sections onto the baghouse. Various kinds of pulsing are used, including the reverse compartmental pulse shown here. Designs employing separate pulses in each bag are discussed below. Pulse cleaning is effective with little or no additional attrition to the cloth compared with other cleaning methods. Felted fabrics are usually used in pulse equipment. For these two reasons the air/cloth ratio in pulse equipment is typically two or three times that of most other equipment and the size of the baghouse is porportionately smaller. The initial baghouse cost, per CFM of gas cleaned, should be less than for other equipment, but this is somewhat offset by the need to purchase and operate an air compressor. A clear advantage of pulse equipment is the virtually continuous operation during cleaning because the pulse time is so brief. This means either a smaller baghouse or steadier operation, or both, and an almost unlimited dust concentration capability.

3.1.5.5 <u>Reverse Flow Envelope Collector</u>.- Flat-panel filter equipment offers several advantages over bag and tube type equipment and is widely used in certain industries. For one thing the flat arrangement, as shown in Figure 3.3e, packs 20 to 40 percent more cloth in the same



1 No coarse dusts reach the tubes.
To protect cloth where coarse dusts are encountered, a built-in impingement chamber deflects air dowward into a hopper which acts as a settling chamber.

2 Maximum efficiency maintained under all conditions
through Dustube design. Top end of cloth tube closed by sewing — bottom of tube seated snugly in recessed metal cell plate by gasketed spring steel ring. Dimensional changes of cloth occurring in service cannot cause leakage.

3 Maximum cloth life
(especially important in the use of the new and costlier synthetics). No metal contacts or abrades the filtering area of the cloth *dustube*. Tubes are adjustable so cloth need never be under tension. Gentle but effective shaking action does not subject cloth to strain.

4 Simple installation, rapid tube replacement.
One man working alone on clean air side can install tubes — no tools required. The cloth tubes can be replaced in groups as time permits during off hours, causing no interruption in production use of equipment.

5 Easy inspection — Simplified maintenance
from walkway on clean air side of collector — inspection can be made during operation on many jobs.

6 Bridging and clogging are prevented
by the circular shape, flexible walls, and ample diameter of the tubes.

7 Lower power costs.
Dustube design gives minimum static loss.

8 Adaptable to all cloths
including Orlon, Nylon, Fiberglas, Dacron, Dacron, Nomex.

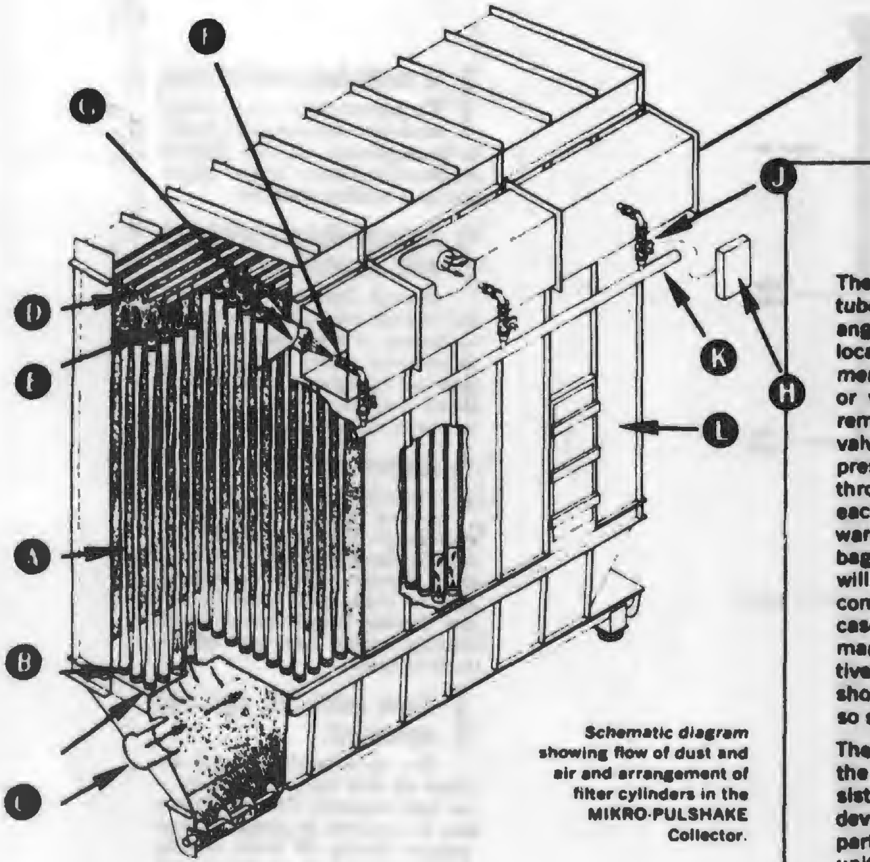
9 High operating temperatures
Temperature range up to 550° Fahrenheit.

Manufacturer: Wheelabrator
Model: Dust Tube
Brochure No: 565E

Filter Element Type: Bag
Diameter/spacing: 5½"
Length: 13½'
L/D Ratio: 32
Flow Direction: Up
Dust caught on the inside
Retainment: hung and snapped in
Cleaning method: shake
Control method: automatic
Power Required: ½ - 4 hp

Baghouse shape: Rect.
Filter Elements per Compartment: 72-960
Baghouse size: (22 x 10 x 50) max std.
Cloth Area: 200 - 12,000
Operation: Intermittent
Accessibility: Continuous
Fabric types: Cotton or other
Normal air/cloth ratio: 3:1
Normal pressure across cloth:
Applications:
Temperatures:
Loadings: Moderate
Cleaning frequency: Moderate
Dust types:
Efficiency:

Figure 3-3c. Typical Shake-Type Baghouse



Schematic diagram showing flow of dust and air and arrangement of filter cylinders in the MIKRO-PULSHAKE Collector.

HOW IT OPERATES

The filter bags are clamped to collars on the tube sheet and suspended from the bag support angles by lengths of chain. A blow tube is located opposite the outlet duct of each compartment. Dust laden air enters the collector under pressure or vacuum and cleaning takes place as follows: The remote cyclic timer actuates the solenoid-controlled valve causing it to open. A momentary pulse of high-pressure air (100PSI) from the air supply pipe flows through the blow tube and into the outlet duct from each compartment. The result is an interruption of outward flow and reversal of flow during which the filter bags begin to collapse. In some cases, the single pulse will permit release of accumulated dust and the cleaned compartment is immediately back on stream. In other cases, the valve must be pulsed on a cycle basis, which manipulates or shakes the bags several times consecutively. The pulse, or series of pulses, occur in a very short time, and the net down time of a compartment is so small as to be ignored.

The collector housing is dust tight and divided by the tube sheet into two plenums. The lower section consists of a hopper and inlet, with some dust disposal device. The hopper can be large and service all compartments, or it can be separated into more individual units as desired. The upper plenum houses and supports the filter bags and provides exhaust outlets and pulsing valve system for continuous cleaning.

A Manometer shows the pressure drop across the filter bags and indicates filter performance.

Manufacturer: Pulverizing Machinery
Model No : Mikro-Pulshake
Brochure No. 3M/2/68

Filter Element type: Bag
Diameter/Spacing: 5¼"
Length: 10'
L/D Ratio: 23
Flow Direction: Up
Dust caught on the inside.
Retainment: hung, clamped
Cleaning method: pulse, collapse
Control method: automatic
Power required: 6-16 SCFM @ 100 psi

Baghouse shape: Rect.
Filter elements per compartment: 80
Compartment size: 19 x 6 x 6
Cloth Area: 3200 - 8800 ft^2
Operation: Continuous
Accessibility: Continuous
Fabric Types:
Normal air/cloth ratio:
Normal pressure across cloth:
Applications:
Temperatures: to 550^o
Loadings: High
Cleaning frequency: Frequent
Dust types:
Efficiency:

Figure 3.3d. Pulsing Flow Baghouse

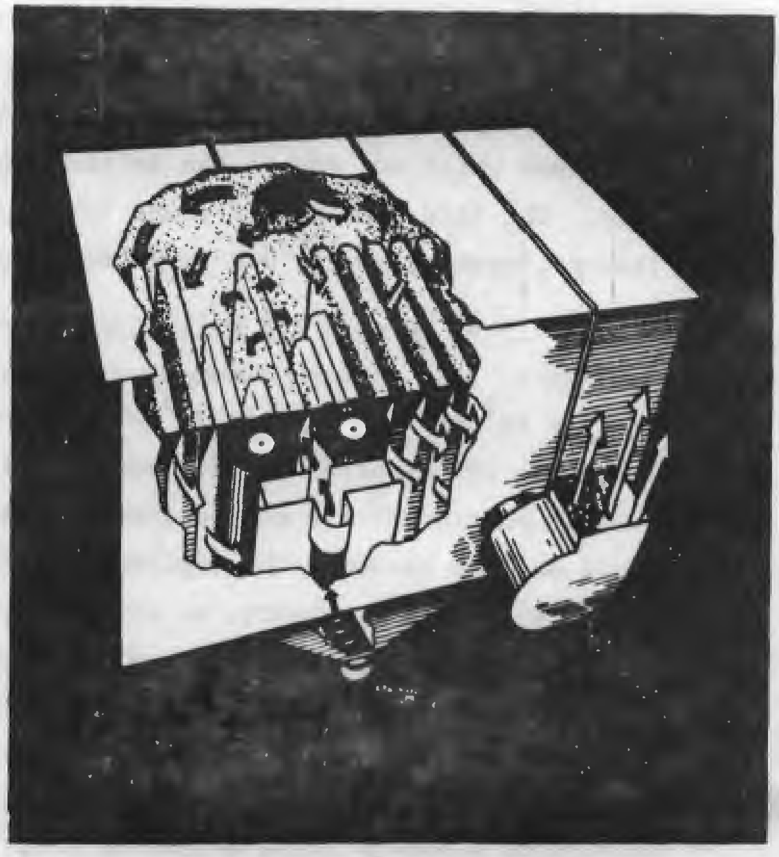
HOW DYNACLONE OPERATES

In drawing, Dynaclone is under suction from the fan. Area in blue indicates normal filtering of air from dust source through flat cloth bags. As air passes into each bag, the dust is left on the outside surface, and only clean, filtered air (clear arrows) is drawn through fan.

Dynaclone continuously cleans the deposited dust from filter bags, one at a time. Bags not being cleaned remain in operation. Exhaust fan keeps the filter under negative pressure. This causes air from dust source to flow through the bag; it also draws air in from outside atmosphere for cleaning the bags.

Cleaning air (dark arrows) comes through flexible hose to traveler, which moves back and forth across open ends of filter bags. Cleaning air gently forces dust from outside surface of the bag. Dust drops directly into hoppers at bottom of filter.

Cleaning air is then picked up at the main air stream and filtered through the active bags.



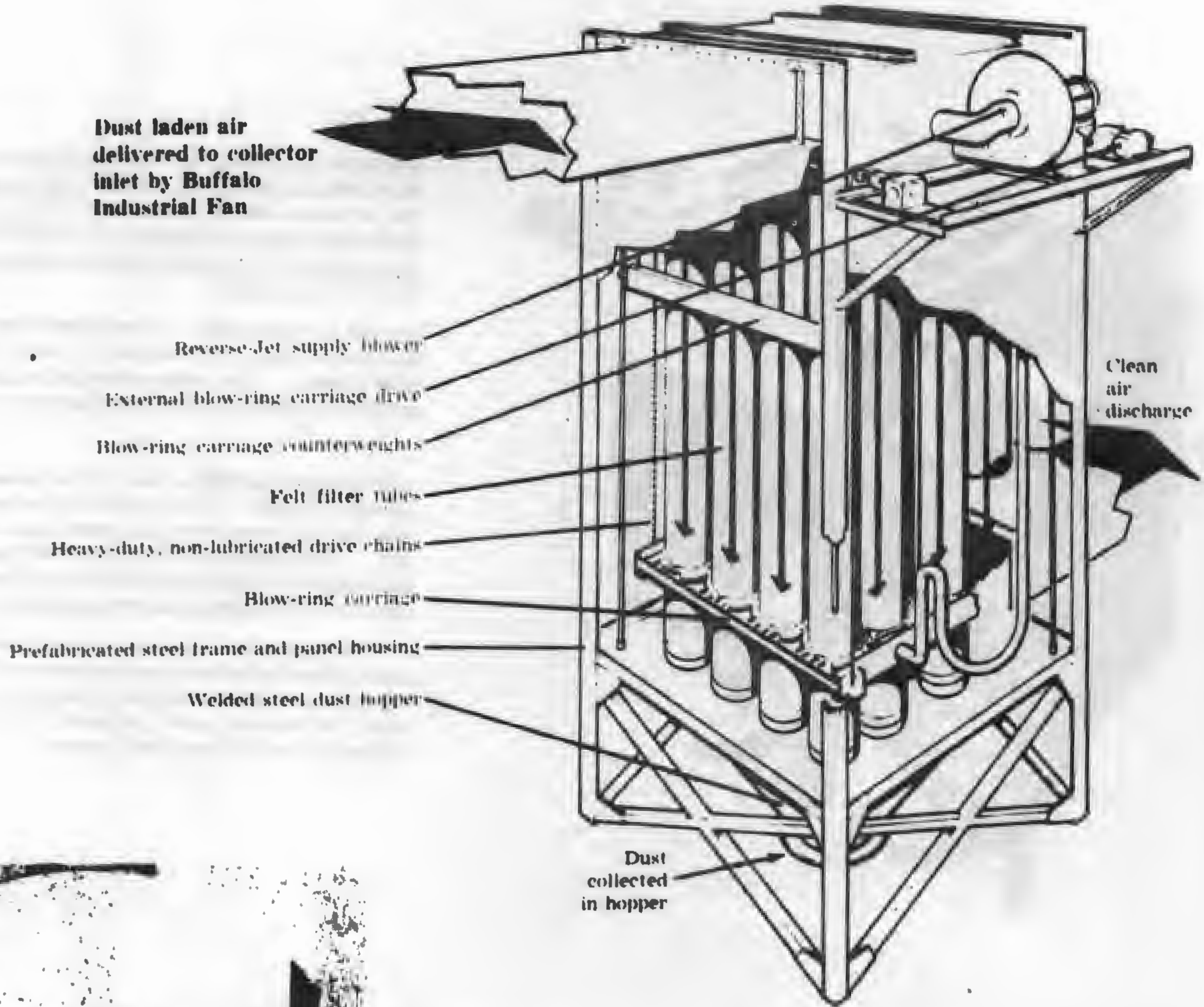
Manufacturer: W. W. Sly Co.	Baghouse shape: Rect.
Model : Dynaclone	Filter elements per compartment: 34-400
Brochure No: 104	Baghouse Size: (24 x 16 x 8') max
	Cloth area: 700 - 10,000 ft^2
Filter Element Type: Envelope	Operation: Continuous
Diameter/spacing: 2.1"	Accessibility: Intermittent
Length: 3.6'	Fabric Types: Cotton and Other
L/D ratio: 20	Normal air/cloth ratio: 2.
Flow direction: Horizontal	Normal pressure across cloth:
Dust caught on the outside	Applications:
Retainment: Buttoned	Temperatures: Low temperature
Cleaning method: Reverse flow	Loadings: Moderate
Control method: Automatic	Cleaning frequency: moderate
Power required:	Dust types:
	Efficiency:

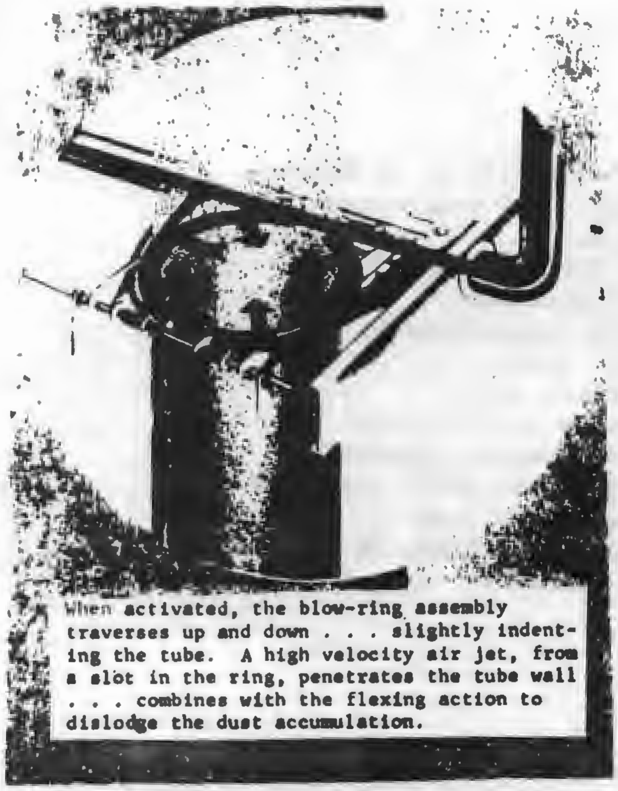
Figure 3.3e. Reverse Flow Envelope Collector

dust collector volume. The air entering the space between the panels is usually moving slower than the air entering a cylindrical filter. This may reduce fabric wear if the dust is abrasive. Access to each filter panel can be easier than access to a large number (50 to 100) of bags packed close together and panels can be brushed down if necessary. Disadvantages of having a moving carriage in the collector include wear and maintenance needs. The panels are usually supported by a mesh which may add to the initial baghouse cost, but extends cloth life. The life does appear to be longer than that of cylindrical collectors, perhaps partly due to differences in applications.

3.1.5.6 Reverse Jet Collector.- Reverse jet equipment, such as shown in Figure 3.3f , became known in the 50's for its high capacity in CFM per ft^2 of floor or per ft^3 of collector volume, and also for the high filtering efficiencies the equipment achieved with felted fabrics. Operation is continuous and can be almost steady, or the cleaning carriage can cycle only as needed. The equipment is frequently used where very high efficiencies are necessary, as with toxic or radioactive dusts. The cleaning mechanism requires careful maintenance to prevent undue wear of the cloth tubes, because the carriage mechanism can be seriously damaged by abrasive dusts if the cloth is once broken. In some cases the downward flow of gases entering this equipment may be an advantage in tending to distribute particle sizes uniformly along the tube.

3.1.5.7 Reverse Flow Cylindrical Collector.- A few models of cloth dust collectors are distinct departures from the typical, as were both the pulse and the reverse jet types until they became popular. The recently introduced collector in Figure 3.3h is different. It combines several features of other collectors, notably reverse flow plus reverse pulse cleaning, a traveling carriage and flattened filter elements. The result is a fairly compact collector capable of high filtration velocities and good efficiency. The cylindrical housing enables the filter casing to withstand substantial gas pressures.





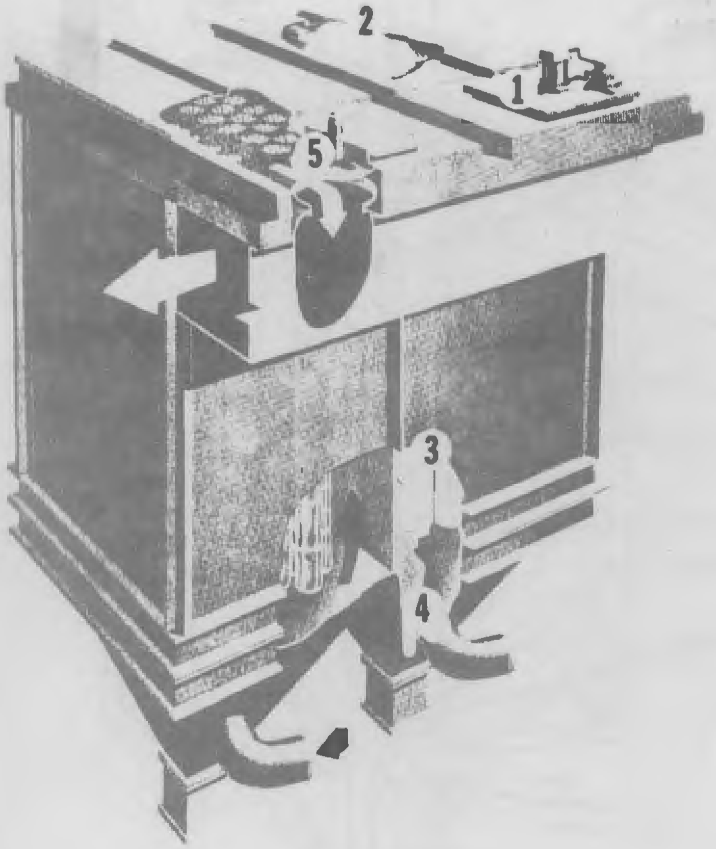
When activated, the blow-ring assembly traverses up and down . . . slightly indenting the tube. A high velocity air jet, from a slot in the ring, penetrates the tube wall . . . combines with the flexing action to dislodge the dust accumulation.

Manufacturer: Buffalo Forge
Model: Aeroturn B
Brochure No: AP 650

Filter Element type: Tubular
Diameter/spacing: 12"
Length: 8-20'
L/D ratio: 8-20
Flow direction: down
Dust caught on the inside
Retainment: clamped top and bottom
Cleaning method: Reverse jet
Control method: Automatic
Power required: 5 hp blower plus 1/2 hp carriage

Baghouse shape: Rect.
Filter elements per compartment: 16
Compartment size: (32 x 7 x 7) max
Cloth: 400 - 945 ft^2
Operation: continuous
Accessibility: continuous
Est. FOB Cost:
Fabric types: Felt, tight cloths
Normal air/cloth ratio: 8-24
Normal pressure across cloth:
Applications:
Temperatures: moderate
Loadings: moderate to high
Cleaning frequency: moderate
Dust types:
Efficiency:

Figure 3.3f. Reverse Jet Baghouse



Dust laden air enters the collector hopper and travels upward uniformly about the tubular filter bags in each zone. The air penetrates the felted filter media, depositing the dust on the outside of the bags. Clean, filtered air continues upward inside the bags and into the clean air plenum from which it is exhausted.

To clean the filter bags, the poppet valve on the zone to be cleaned closes; this isolates the zone. After the poppet valve closes, the solenoid controlling passage of compressed air to the isolated zone opens for approximately 1/10 second, emitting a burst of compressed air into the plenum chamber. This pulse of air, expands rapidly down into the filter bags, sets up a shock wave which flexes the felt. Dislodged dust drops into the hopper, where it is discharged through either trickle valves, rotary locks or screw conveyors depending upon the application requirements.

The poppet valve on the isolated zone then reopens, putting the cleaned zone back on stream. The entire cleaning sequence takes less than 3 seconds in most applications. The cleaning cycle is repeated in the next zone until all bags in the unit have been cleaned.

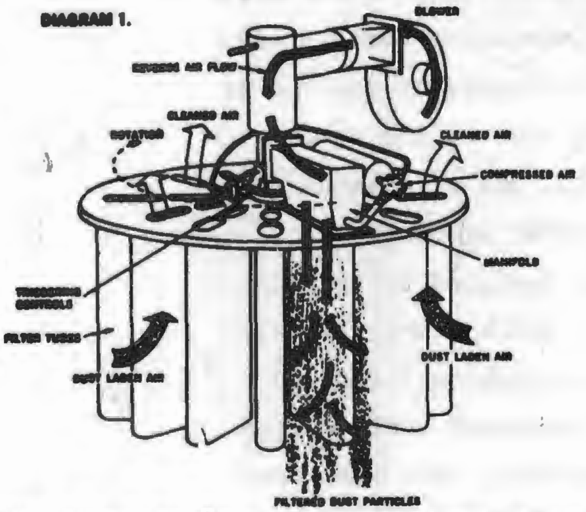
Manufacturer: Fuller Company
Model No: Dracco Plenum Pulse
Brochure No: DCB - 14A

Filter Element Type: Bag
Diameter: 5"
Length: 5' and 8'
Length/Dia. ratio: 12 or 19
Flow Direction: Up
Dust caught on the outside
Retainment: Supported by clamped wire cage
Cleaning Method: Outlet plenum pulse
Control Method: automatic
Power required: 10 to 18 SCFM at 100 psig per 1000 ft^2 of fabric.

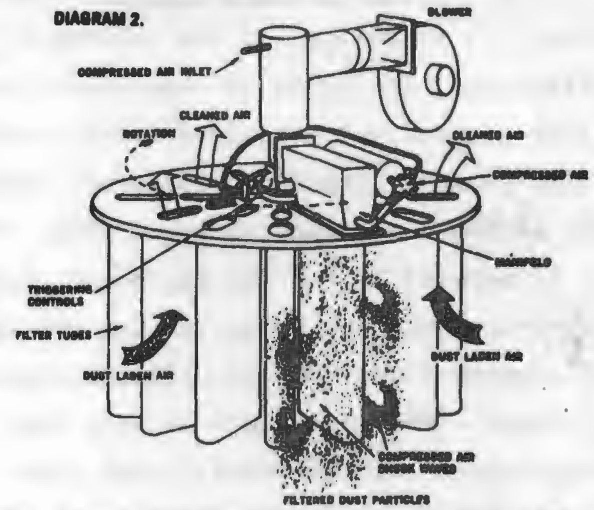
Collector Shape: Cylind. or Rectang.
Filter elements per compartment: 12 to 48
Collector size: 4' x 4' x 16' (min)
Cloth area: 156 ft^2 and up
Operation: continuous
Accessibility: intermittent, outside
Fabric types: felts
Normal air/cloth ratio:
Normal pressure across cloth:
Applications: compact, continuous
Temperatures: up to 450°F (felt limit)
Loadings: medium to high
Cleaning frequency: high, or as needed
Dust types: any size
Efficiency:

Figure 3.3g. Reverse Plenum Pulse Collector

These diagrams illustrate the unique DUAL reverse air cleaning system of the Type "CS" dust filter



The design of the Type "CS" dust filter incorporates two supplies of reverse air. Diagram 1 above shows path of air supplied by pressure blower to manifold which rotates from bank to bank of fabric filter tubes. Reverse air from the pressure blower causes the tubes to expand or "puff" so that the filter fabric is held in a taut position.



This diagram shows path of compressed air shock wave. When filter tube has been expanded by air from the pressure blower, a burst of compressed air is released. This air sets up a shock wave which dislodges accumulated particles from the filter fibers. Dislodged particles are swept away by the continuously flowing air (as shown in Diagram 1) from the pressure blower to the hopper located beneath the filter tubes.

Manufacturer: Carter-Day Co.
Model No: "CS"
Brochure No: L-1126R2

Filter Element Type: Flattened bag
Diameter/spacing: (2-5")
Length: 2-8'
L/D ratio:
Flow direction: up
Dust caught on the outside
Retainment: suspended
Cleaning method: reverse flow, pulse
Control method: automatic
Power required: 1/4 hp plus 4 to 14 SCFM @ 80 psi
Baghouse shape: cylindrical
Filter elements per compartment: 12-72
Baghouse size: (24 x 10 x 10) max
Cloth Area: 60 - 1500 ft^2
Operation: continuous
Accessibility: Intermittent
Fabric types: Felts, normally
Normal air/cloth ratio: 10 to 25
Normal pressure across cloth:
Applications:
Temperatures: moderate (to 425°F)
Loadings: high
Cleaning frequency: High (30 sec)
Dust Types:
Efficiency:

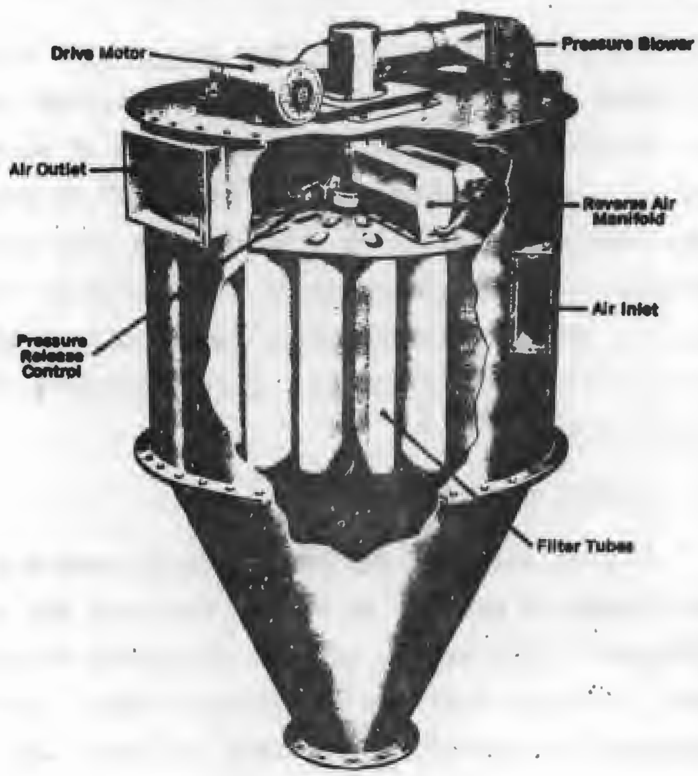


Figure 3.3h. Reverse Flow Cylindrical Collector

3.1.5.8 Reverse Pulse Collector.- Installations such as depicted in Figure 3.3i are typical of the equipment now increasing most rapidly in application. The pulse of compressed air is released at the top of the filter element and travels downward removing most of the deposited dust. The pulse is usually quite sharp initially, but attenuates as it travels, losing its effectiveness. Thus, the filter elements are limited to several feet. The equipment shown is designed to entrain additional air with the pulse, giving not only a shock front, but also a brief reverse flow. The two effects apparently combine for added effectiveness. The advantages of this kind of equipment include high air/cloth ratios and thus small plant floor occupancy, very high dust loading capability and high efficiency by virtue of the felts used. The compressed air requirements may cost as much as the power to achieve filtration, although initial costs are generally fairly low. This kind of equipment comes in practically all sizes.

3.1.5.9 Ultrafiltration Equipment.- Ultrafiltration equipment, such as shown in Figure 3.3j, achieves efficient removal of low concentrations of submicron particles by an extension of standard fabric filtration technology. In this process a "filter aid" is used to provide the initial dust cake and subsequently to provide good cake release. By adding a means of introducing the filter aid as a powdered or fibrous material ahead of the filter, several manufacturers have modified their standard equipment lines to include this capability. Ultrafiltration is further discussed in Section 3.5.4.

3.2 FILTER CONFIGURATIONS

Filter elements are available in numerous shapes, styles and sizes. This range of choices is due to the need for equipment to serve totally different applications and the different relative evaluations of space, power, initial cost and maintenance time. Filter cloth is now arranged in panels or envelopes, in tubes and bags and in variations on these. Looking ahead, it is not likely that any radical new geometry will be developed, although somewhat more cloth per cubic foot of baghouse

Manufacturer: Flex-Kleen (Research Cottrell)
Model No: (several)
Brochure No: T-7

Filter Element Type: Bag
Diameter/spacing: 5 3/4"
Length: 18 to 84"
L/D ratio: 3 to 15
Flow direction: Up
Dust caught on the outside.
Retainment: hung and clamped; supported
Cleaning method: reverse pulse
Control method: automatic
Power required: approx. 10 SCFM, 100 psig per 500 ft^2 of fabric
Baghouse shape: Rect. or cyclindrical
Filter elements per compartment: 8 and up
Baghouse size: variable
Operation: continuous
Accessibility: Intermittent
Fabric Types: various felts
Normal Air/cloth ratio: 6to 15
Normal pressure across cloth:
Applications: High loadings continuous service
Temperatures: moderate
Loadings: high, moderate
Dust types:
Efficiency: good

FLEX-KLEEN filter bags are constructed of quality materials to precise dimensions with double stitched french-fell seams. Felted materials are used for their high filtering efficiency at high air-cloth ratios.

EASY TO ASSEMBLE—Filter bags are slipped over the bag cages with the top 2 inches turned in over the top of the cage to form a seal on the bag cup. The bag-cage assembly is slipped over the bag cup and clamped with a quick-acting clamp. A split ring on the cage engages with a groove on the bag cup to form a positive lock.

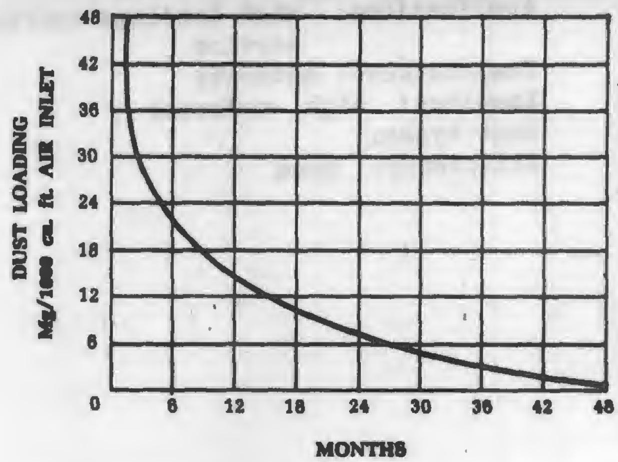
Figure 3.3a. Reverse Pulse Collector

HOW THE TOTALAIRE FILTRATION SYSTEM OPERATES

The basic operating unit of the Totalaire system is a standard Pangborn cloth tube type dust collector which is adapted for ultra high efficiency air filtration by coating the tubes with a special, inexpensive filter aid at the rate of .075 lb/sq ft. Even the finest particles of atmospheric dust and tarry materials are collected and entrapped in the resulting filter mat. As these particles are fine and light, they cause no holding problem and they actually increase filtration efficiency. In a National Bureau of Standards Spot Dust Test, Totalaire filtration proved 94% efficient. By weight, the efficiency of the unit will exceed 99%. It will clean atmospheric air to below .04 mg per 100 cu ft with intake concentration of 9 to 12 mg per 1000 cu ft.

Filter aid material is supplied in 30 and 50 lb bags. Under normal conditions one application will last from 2 to 3 years. On units operating under suction, air moving equipment of the ventilating system is used to feed the filter aid through the hopper sections. On units operating under pressure, it is fed into the system ahead of the fan. Charging time ranges from a few minutes on small collectors up to an hour or two on larger units.

Filter aid material adheres to the inside surfaces of the tubes when fed into the collector. After a few hours of operation, it can only be removed by operating the shaker mechanism. Under normal conditions, removal of the filter aid material and accumulated dust is required only after 2 to 3 years of 24-hour-a-day operation. Obviously maintenance costs are extremely low.



This graph shows the typical operating time before shakedown for a Totalaire unit under various dust loads, when the unit is started at 1" wg and shaken down at 3.5" wg. For example, if the dust loading is 6 mg per 1000 cu ft air, the unit should be cleaned every 28 months.

Manufacturer: Pangborn
Model: Totalaire
Brochure No: 931

Fabric types: standard
Normal air/cloth ratio:
Normal pressure across cloth:
Applications:
Temperatures: Ambient
Loadings: Very low
Cleaning frequency: very seldom (years)
Dust types: Small particle
Efficiency:

Figure 3.3j. Ultrafiltration System

volume may be obtained by closer folding, pleating, or packing. Possibly new designs that simplify cloth replacement will be introduced and higher entrance and exit velocities will be developed for those baghouse systems not limited by particle abrasion. At the present time, however, we must continue to examine filter configurations on the basis of: (1) panels vs tubes or bags; (2) upward vs downward flow; (3) inside vs outside collection; and (4) length, diameter, and length/diameter ratio.

3.2.1 Panel vs Tube Filters

About 20 percent of the collector models available use flat panels, the rest using either tubes or bags. The advantages of one type over the other seem to depend on the application, since both are widely used. One major manufacturer of panel type filters cites these advantages:

(1) The flat filter gets 20 to 40 percent more cloth per ft^3 of collector volume.

(2) The air is moving more slowly when it enters the panel, than air at cylindrical bag entrances, hence abrasion is less.

(3) A set of panels can be inspected more easily since both sides of the cloth on every panel can be seen.

(4) A single panel can be changed more easily than a single tube, although it may be easier to completely rebag the tube collector once it is cleaned out.

(5) Dust getting through any leak in the cloth piles up under the panels where it is more easily removed than dust piled around the lower ends of tubes.

(6) There are more choices of inlet and outlet locations on a panel baghouse than on a bag type, where inlet must be at the bottom and outlet must be at the top (or vice versa).

(7) The panel may be shaken or pulsed more uniformly than a bag which is shaken or pulsed from one end only.

(8) In the event fibrous materials are encountered, the panels can be brushed down on the dirty side, whereas the dirty side of the bag may be inaccessible. If the dust bridges between the panels, every other one can be removed.

A manufacturer of bag or tube filter equipment might counter with the following opinions:

(1) Since bags can be very long, more cloth can be installed or otherwise serviced per ft^2 of floor space.

(2) In most installations, abrasion is not a problem and when it is it can often be alleviated by suitable fabric design.

(3) It is easier to repair a leaky bag in place without removing it than a panel.

(4) A single tube can be changed more easily than a single panel.

(5) Dust piled around the base of the tube is often the quickest way to locate a leak.

(6) Unless the baghouse inlet and outlet are located logically from the standpoint of air distribution and dust settling, expensive baffles or plenums are necessary. Standard inlet and outlet locations reduce costs.

(7) Shaking a baghouse takes less power and is quieter than shaking a panel collector.

(8) The spaces between panels, being smaller, are more apt to clog with coarse fibrous matter or in the event of a high surge of dust than the relatively open bag or tube.

The views of both manufacturers obviously have merit in certain instances, and have to be considered against the collector application of interest.

3.2.2 Upward vs Downward Flow

Traditionally, the collector inlet was located at the bottom of the baghouse where the heaviest dust settled immediately to the hopper, thereby minimizing fabric abrasion and extending the period between fabric cleanings. Since the compartment or entire baghouse was shut down for cloth cleaning, the dust never had to fall against an upward gas flow. Furthermore, downflow required the use of an extra tube sheet and perhaps even more expensive, the use of an extra bottom plenum (see Figures 3.3b and 3.3f). Thus, the upward flow design was logical, simple and least expensive.

The introduction of reverse jet cleaning, and with it continuous on-line operation, brought in the extra tube sheet and introduced downward flow to encourage the dust to fall during filtration. Otherwise, the dust might collect again on the nearby cloth. In fact, this may happen even with downward flow, especially near the bottom of the tube where the downward air velocity approaches zero. The four reverse jet models available today all use downward flow.

It would seem that the same principle of downward flow for continuous filtering would apply to pulse cleaning as well, but in fact less than 10 percent of the approximately 30 pulse type models use downward flow. The contradiction is partly explained by the theory that pulse cleaning removes the cake without breaking it up as much as the reverse jet does, so the dust falls as larger pieces. Also, when the pulsed air is directed downward, as it usually is, it tends to carry the dust downward although only briefly.

Because the settling velocity and primary flow velocity are additive in downward flow, all sizes of particles tend to travel farther in downward flow than in upward flow before being caught by the fabric. Particles in downward flow have some probability of falling completely through the filter tube to the hopper without being caught. This is true of all particle sizes, whereas in upward flow only particles larger than a size determined by the tube entrance velocity can escape the fabric (Section 3.2.4.2; for most filter applications this size is of the order of 3 μm.) Consequently, it would appear that the choice of upward or downward flow might reduce the average cake weight, depending on the particle size distribution. Dusts predominately larger than the limiting size might be more suited to upward flow filtration. Smaller dusts, if filtered downward, might result in slightly lighter cake weights.

A consideration that probably overrides the minimization of cake weight is the distribution of particle sizes along the filter surface and the effect this has on dust deposit permeability and subsequent local filtering velocities. Both large and small particles would be distributed more evenly over the length of the tube in the case of downward flow. This should result in a more uniform use of the entire filtering surface than in upward flow.

Another important consideration is that the upward flow collector is generally less expensive, having one less tube sheet or plenum. It is harder to adjust the tube tension with two tube sheets. In addition, with downward flow there is dead air in the hopper which increases danger of condensation.

Some panel types are distinctly upward or downward flows, in which case the above considerations apply, even though the panels may be small in dimension. However, most panel-type filters tend to use horizontal flow, that is, the inlet and outlet are approximately at the same height on the baghouse.

These are the considerations in selecting the direction of flow. To summarize, although the upward flow collector is slightly less expensive initially, the downward system should give slightly the better filtering performance and lower power requirement. However, the data available are insufficient to quantitatively confirm this conclusion.

3.2.3 Inside vs. Outside Filtering

While this is not a consideration in most panel filters, bag-type equipment offers the choice of filtering on either the inside or the outside of the cylinder as was shown earlier in Figure 3.1. Of course, reverse jet equipment provides inside filtering, as does all but one model of downward flow equipment. About 60 percent of all upward flow equipment is the inside filtering type. Clearly, the choice has nothing to do with the fabric which can be sewn with either side out. An important advantage to inside filtering is being able to enter the filter compartment for inspection and maintenance during operation. Also, inside filtering does not usually require the use of supporting mesh which can increase maintenance difficulties. However, inside filtering tends to involve more fabric flexure during cleaning.

3.2.4 Length, Diameter and Length/Diameter Ratio

Most filter bags are 5 to 12 inches in diameter and 5 to 40 times the diameter in length. The choice of diameter and length does affect filter performance, but the dimensions are more traditionally determined by their effect on the initial cost of the bags and that of the baghouse.

3.2.4.1 Tube Diameter.- Filter cloth is usually woven in standard widths, and in general, bag diameters are constrained by the available widths of fabrics as woven. One common size is approximately 38 or 39 inches wide, from which two 5 or 6 inch diameter bags can be obtained, allowing for the necessary overlap at seams. For certain applications, an 11½ or 12 inch diameter glass fabric bag is the most economical size from the available 38 inch wide glass cloth. A few baghouses are designed for use with 7 or 8 inch diameter bags. This size is probably based upon a 54 inch wide cloth from which two bags can be obtained from a single width. Wool felts, used in reverse jet baghouses, are generally either 9, 10 or 18 inches in diameter.

The diameter of the filter bags also influences the size of the baghouse. For example, about 1,750 square feet of filtering area can be provided in about 80 square feet of floor area by using 6 inch diameter by 10 foot long bags. If 12 inch diameter bags were used instead, they would need to be about 14 feet long to provide the same filtering area in the same floor space, though 12 inch diameter bags can easily be obtained 20 feet long or more when there is adequate head room. This (12 in. x 20 ft.) would result in a baghouse having about 2,500 square feet of filtering area in the same floor space (80 ft^2).

While using a smaller diameter increases the filter capacity per unit occupied floor area, there are disadvantages associated with small bags. Small bags may bridge across, particularly in cases of unusually coarse collected dust or extreme surges in dust loading. If the hopper plugs, any bag can become filled at the bottom with collected dust and the smaller bag is less easily emptied afterward. Smaller bags require a larger number of clampings, tension adjustments and inspections for the same cloth area, but they are easier to handle during maintenance and repair.

3.2.4.2 Length-Diameter Radio and Tube Entrance Velocity.- The air (and dust) velocity at the entrance of a cylindrical filter tube is given by:

$$Ve = V_f \times 4 \left(\frac{L}{D}\right)$$

For example: Filtration velocity = 3.0 FPM, V_f
Length/Diameter ratio = 25, L/D
Entrance velocity = 300 FPM, Ve

This velocity is typical of many collector installations.

In upward flow, the greater the entrance velocity the more large particulate will be carried into the tube, (The largest particle that can be lifted by an air current of given velocity and viscosity is discussed in Chapter 2). Thus, the greater the entrance velocity, the faster the dust deposit increases. The permeability of the deposit may be expected to be diminished by the larger particles, however, as discussed in Section 2.4.8.

The upward velocity will decrease along the tubular filter to zero. Thus, the size of particles that can be lifted (in upward flow) decreases along the tube. This results in a partial distribution of particle sizes and a consequent variation in deposit permeability and weight along the tube. These variables are affected by the entrance velocity and the size distribution of particles entering the collector.

The cost of power required as a consequence of entrance head loss is negligible, being less than one dollar per KCFM-year at 300 FPM. However, in the case of abrasive dust, the bag may be scoured and excessively worn near the entrance tube sheet, (Attempts to define the potentially abrasive entrance velocity have not been successful; see Section 4.5.1).

Length/diameter ratio affects the swaying stability of the vertical tube. Bags should not rub together either during filtering or during the cleaning cycle. Thus, the higher the ratio the greater the advisable bag separation, partly offsetting the floor-saving advantages of long tubes. Also, the lengthwise seam of the bag will stretch differently than the rest of the cloth, making the high length-diameter ratio bag bend as the tension or dust load changes.

The short stocky tube may shake more easily than the thin longer bag, but the stresses at the shaking end may still be higher. There is no accepted way to generalize this at present, as amplitude, frequency, dust weight and several cloth parameters are involved. Also, the relation between fabric stressing and fabric life is not clear.

Length/diameter ratios are usually between 5 and 40, but more typically between 10 and 25. In purchasing, the choice of length/diameter ratio seems to be mainly determined by whatever equipment is available, and this is more dependent on other considerations.

3.2.4.3 Tube Length.- In addition to its relation to diameter, tube length is also limited in other ways:

(1) The tension along the length of the bag increases as a function of height, starting with whatever tension is being applied at the bottom. It may be so large at the top as to pull holes in the cloth at the cuff seams or otherwise damage the fabric, in cases of heavy dust deposits.

(2) The longer the bag, the more expensive it is per square foot, because of the difficulty of handling and sewing a long bag. The choice of long bags requires a more elongated dust collector for the same fabric area and since elongated housings require more siding and stronger structural members, the collector cost will generally increase.

(3) Some cleaning mechanisms are length limited, notably air pulse and shaking, wherein sufficient energy for the entire length of the tube must be applied at one end to the detriment of that end. The energy requirement increases faster than length, in general.

(4) Continuously cleaned dust collectors require the removed dust to fall to the hopper during filtration. Instead

of falling, many particles must be caught again on the fabric. This results in relatively heavy deposits near the bottom of the bags. The longer the bags, the heavier this deposit will be. In a similar sense, intermittently cleaned collectors require a pause after cleaning to allow the dust to settle to the hopper. The shorter the bags, the sooner the collector compartment can be returned to service.

(5) Different thermal expansions between cloth and baghouse require latitude in the bag fastenings or shorter bags, or both. For example:

	Diff. Length*	Resulting Stress Change**	Tension***
Steel-Glass:	.00042 ft/ft of bag	4.2 psi	2.5 lbs

(6) Very long bags may require two or more people to install and inspection and other maintenance may also be difficult.

(7) The baghouse may be ceiling limited if it is to be installed indoors.

(8) One claim is made that bag surface scouring increases, due to sliding of the loosened deposit downward along the bag surface. Scouring may assist the cleaning process, but it may also damage the fabric surface fibers. It is not clear which in general, is the more important.

A review of bag lengths in a number of specific filter installations has indicated the use of slightly longer bags where smaller particles are involved. There is no clear physical reason for this. Recent air pollution control applications are chiefly concerned with small particles. There is also apparently a slight trend in the fabric filter industry toward longer bags and tubes, which may be coincidental.

As will be seen from a review of typical costs of fabric filtration (Chapter 7), plant overhead and especially the cost of plant

*Assuming the fabric expands as a solid; per 100°F.

**Assuming tensile modulus of 10^4 psi and no bag fastening latitude; per 100°F.

***Assuming a 6-inch diameter bag and .03-inch thickness; per 100°F.

floor space are very important factors. It is entirely possible that two collectors may be intended for almost identical service, the only difference being that one will be used where floor space is plentiful and free, and the other where floor space will contribute as much as 10 percent to the annual cost of operation. One would prefer to select equipment with longer bags in the second case.

3.2.4.4 Panel Geometry.- The average velocity entering a space (W) between two filter panels of distance L from entrance to closed end is given by $V_e = V_f \times 2 (L/W)$. For example, if the filtering velocity is 2 FPM and L and W are 3 ft and 1.5 inches respectively, the average entrance velocity is 96 FPM. It is generally less than for bag and tube filters and consequently, many of the above comments relating to entrance velocity do not apply. Furthermore, as the flow is often horizontal, there may be more settling. There should be less abrasion of the fabric surface because of the lower velocities.

In the normal interest of saving floor and plant space, panels will be designed as close together as possible. This is subject to the need to inspect and replace the cloth; clogging of the space between the panels; touching during cleaning, such that the dust cannot fall or such that one panel abrades against the next; entrance abrasion; and structural requirements. Most panel spacings are between one-half and three inches and equipment using oval bags or envelopes have inside dimensions on about the same scale.

Panel length and height vary from a few inches to a few feet. In addition to the above limitations, the manufacturer's choices are determined by such things as the width of the original bolt of cloth; the need to maintain tension over the panel; the ease of installation and replacement of panels; and thoroughness of cleaning, which depends on cleaning methods.

3.2.5 Other Configurations

Panel type filters vary from single flat fabric sheets to oval envelopes with only one end open, really more like a bag than a panel. A standard item with Pangborn is the multi-tube filter element, two panels sewn together at intervals so that when inflated six cylindrical filter elements result, fastened together side by side. This approach packs more fabric in a given collector volume, but may increase maintenance costs, since a failure of one tube requires maintenance or replacement involving all six. Also, tension adjustment of such a large filter element may be slightly more difficult.

Reported in some of the early literature, and perhaps still in common use in Europe, is the conical filter element which tapers from a circular bottom of ordinary diameter to an apex at the top of the baghouse. This design should give nearly constant upward velocity the entire length of the element and,therefore, a more uniform particle size deposition. The elements can also be packed more closely together without danger of inter-abrasion, as long as they are not made too long, except that space must be provided for their maintenance just as with any filter element. Tapered elements are relatively expensive to construct. A thin cone may bridge across the inside and be difficult to clean. The shake dynamics of a cone are no doubt substantially different than for a cylinder.

A few other novel fabric filter configurations are discussed in Section 3.5

3.3 CLEANING MECHANISMS

Except for studies of specific air pollution control problems, most development toward better fabric filter equipment appears to go into improved methods of removing the accumulated dust deposit from the fabric. As a result, we have the variety of cleaning mechanisms already mentioned in this chapter. Just as the dust particles cohere to one another, the deposit cake adheres to the surface fibers of the cloth, or in the case of deep or napped surfaces, among the surface fibers. The problem is to remove the desired amount of the deposit from the fabric quickly and uniformly without either:

- removing too much of the residual deposit which greatly improves the collection efficiency at start-up on a subsequent filtering cycle, for woven fabrics
- damaging the cloth, or using too much power, either of which can be a substantial part of operating cost
- excessively dispersing the removed dust particles, as these would probably then have to be re-filtered.

The standard cleaning methods are listed in Table 3.1 along with a number of superficial characteristics frequently, although not always, associated with those methods. More quantitative discussion of some of these characteristics (efficiency, cost, filtration velocity, etc.) can be found elsewhere in this handbook. The cleaning principles are discussed here.

The time required for completion of the cleaning process is an important consideration in comparing cleaning methods. This time should be much shorter than the time between cleaning periods, which as shown in Section 2.4 is determined by filtering velocity, dust loading, pressure drop tolerances and the "K" value of the dust. For a high dust loading, the cloth might have to be cleaned very often - perhaps every 30 seconds, for example. For this, a manual cleaning process would be out of the question. Likewise, a shaking process which might require 1 minute or more just to accomplish the cleaning, would mean that at least two thirds of the fabric in the system would be out of use at all times. On the other hand the reverse jet method accomplishes the cleaning quickly, but is limited in repetition by the slowness of the carriage. Pulse cleaning is very fast, but also has comparative disadvantages. It seems that every cleaning method in use has at least one advantage over each of the others, and conversely.

TABLE 3.1

COMPARISONS OF CLEANING METHODS*

Cleaning Method	Uniformity of Cleaning	Bag Attrition	Equipment Ruggedness	Type Fabric	Filter Velocity	Apparatus Cost	Power Cost	Dust Loading	Max. Temp.**	Sub-Micron Efficiency
Shake	Ave.	Ave.	Ave.	Woven	Ave.	Ave.	Low	Ave.	High	Good
Rev. Flow, no flex	Good	Low	Good	Woven	Ave.	Ave.	M.Low	Ave.	High	Good
Rev. Flow, Collapse	Ave.	High	Good	Woven	Ave.	Ave.	M.Low	Ave.	High	Good
Pulse-compartment	Good	Low	Good	Felt, Woven	High	High	Med.	High	Med.	High
Pulse-bags	Ave.	Ave.	Good	Felt, Woven	High	High	High	V. High	Med.	High
Reverse jet	V. Good	Ave.-Hi	Low	Felt, Woven	V.High	High	High	High	Med.	V. High
Vibration, rapping	Good	Ave.	Low	Woven	Ave.	Ave.	M.Low	Ave.	Med.	Good
Sonic assist	Ave.	Low	Low	Woven	Ave.	Ave.	Med.	--	High	Good
Manual flexing	Good	High	--	Felt, Woven	Ave.	Low	--	Low	Med.	Good

*These value judgments do not permit comparison of performance aspects, only of methods.

**Fabric limited.

3.3.1 Shake

Bags are most commonly shaken from the upper fastening. Several combinations of horizontal and vertical motion are used. The bags may all be fastened to a common framework which moves horizontally. The frame may have slight additional upward or downward swing, depending on the linkage holding the framework. The framework may instead be oscillated vertically. Alternatively, the bags may be attached in rows to a rocking shaft. In this case the location of the point of attachment with respect to the center of rotation determines whether the motion is predominantly horizontal or vertical.

Rarely are the bottoms of the bags shaken instead of the tops. Panel filters on the other hand, are usually shaken top and bottom, that is, the entire filter bank moves from a single drive point. The shake amplitude is usually designed into the equipment and may be anywhere from a fraction of an inch to a few inches. The frequency of shake is usually several cycles per second and can often be adjusted to obtain the most suitable fabric motions. Most shaking is essentially simple harmonic or sinusoidal motion. When it is, the peak acceleration may be easily computed; it is usually from 1 to 10 g's.

During the shake, the filtering should be stopped. Otherwise, the dust will work through the cloth, reducing the efficiency and possibly damaging the cloth by internal abrasion. In some equipment, the flow is slightly reversed during shaking, both to prevent penetration and to aid in cake removel. Still more elaborate, but possibly more effective, cleaning procedures involve a series of alternate flows and shakes which take time, but are claimed to give a gentler net treatment to the cloth, plus more uniform and thorough cleaning.

In a typical cycle, the inlet flow to the compartment is first dampered off by an automatic timer and valve mechanism. If necessary, the outlet vent is also closed (Figure 3.4). In the absence of an air lock between adjacent hoppers it may be necessary to close a damper

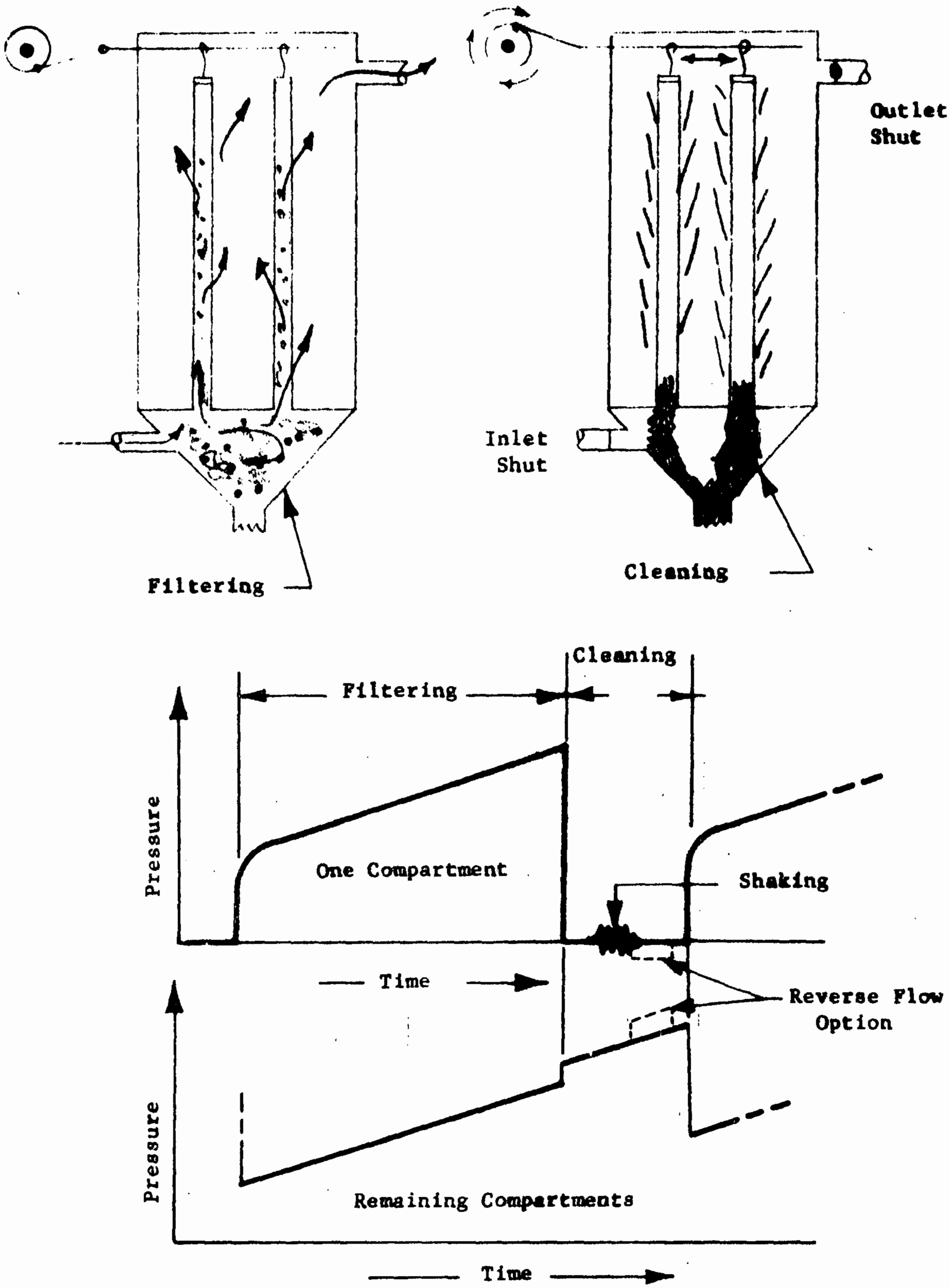


Figure 3.4. Shake Cleaning Process and Associated Pressure Cycles.

there to prevent the intrusion of dirty air from hoppers still operating. There should be zero forward pressure across the fabric during shaking, since otherwise dust will work through the fabric. The timer starts the shaker motor and the bags are shaken horizontally at 1 to 5 cps with an amplitude of up to 2 inches; that is, the shaker imparts accelerations on the order of a few g's. Shaking continues for 10 to 100 cycles. Then the timer may start a small flow of clean reverse air using an auxiliary blower or a secondary duct-and-damper system for 10 to 20 seconds. The shaking may be repeated, this time during the small reverse flow. Finally, the cleaning is stopped and after pausing to allow the dust to settle, the inlet and outlet dampers are opened and the compartment begins its filtering again. The entire cleaning cycle may take from 30 seconds to a few minutes. Some installations do not return the compartment on line until the next one is ready to be cleaned, thereby achieving a fairly steady overall flow through the baghouse system at the expense of some over-capacity.

The pressure across the compartment during the cleaning cycle is sketched in Figure 3.4. If there are only a few compartments in the baghouse system, shutting one down will increase the flow and pressure drop across each of the others, the amount depending on the fan curve. The pressure across the baghouse while the above cleaning is performed is also indicated in Figure 3.4. This increase in filtering velocity and pressure across the fabric in the other compartments can be expected to have some effect, adverse but probably slight, on the filter cakes forming in those compartments.

The mechanics of cleaning by shake have apparently not been studied in any detail. The cloth is flexed to some extent and the cake is thereby cracked or loosened from the cloth fibers. Shaking produces inertial stresses at the cake-cloth interface, both shear and tensile, and if these exceed the adhesive strength, then some of the dust cake falls off. It is reported that a fine balance of bag tension, shake frequency and shake amplitude is necessary in order to obtain the "s" shaped wave in the moving bag giving best results. On the other hand, simple manual shaking equipment seems to work with a minimum of science, although careless manual cleaning is hard on the fabric. The amount of shake energy transmitted along the bag decreases from a maximum at the shaken end (usually the top) to a smaller value as the energy is absorbed along the bag. A heavy residual dust cake,not removed by the cleaning process (usually in the case of sticky fine dusts), changes both the mass and the flexibility of the bag and must affect the rate of energy absorption locally. Further, the added residual dust weight accumulates upward and increases the tension toward the top of the bag, affecting the shape of the shake "wave" for better or for worse.

Shake equipment has few limitations in application. As noted above, the dust loading time cannot be too short. The dust should be fairly easily removable from the cloth as it is easy to damage the cloth by over-shaking. This is especially true of glass bags. Although it was at first believed that glass could not be shaken, the introduction of certain glass finishes has made this possible on some dusts which separate fairly easily from glass fibers. Shake baghouses are popular for both very small systems (manual shake) and very large continuous systems.

Two problems in particular are often reported with shake equipment. First, in an effort to keep manufacturing costs down, a number of shaker mechanisms are underdesigned. They wear and as they do, they shake less effectively. The bags load up or the operator intensifies the shaking, and the mechanism then destroys itself unless given an inordinate amount of maintenance. Second, as the free end of the bag is shaken, the cloth must flex extensively at the fastened end, resulting in fiber-fiber abrasion. This may explain the common occurrence of bag failures within the first couple of feet of bag. These entrance end bag failures may also be related to dust deposit weight, which is often heavier at the lower end of the bag and may result in a higher rate of cleaning energy absorption in this region. Another possible factor is particle entrance abrasion.

3.3.2 Reverse Flow - No Flexing

If the dust releases fairly easily from the fabric, a low-pressure reversal of the flow may be enough to loosen the cake without flexing or mechanical agitation. To minimize flexural attrition of the fabric, it is supported by a metal grid, mesh or rings, and is usually kept under some tension (Figure 3.5). The support is usually on the clean side of the tube or bag, although dirty-side support can help to keep the sides of the bag or the panels sufficiently apart to allow the cake to fall to the hopper. Some filter equipment relies solely on low pressure flow reversal, while other models use it in conjunction with another method, shaking for example, or use the much higher reverse pressures of pulse or jet cleaning.

There are several ways of accomplishing flow reversal. In addition to the standard dampers on each compartment, each one can have its own reversing fan. A few models have a traveling apparatus that goes from bag to bag or from panel to panel, blocking off the primary flow

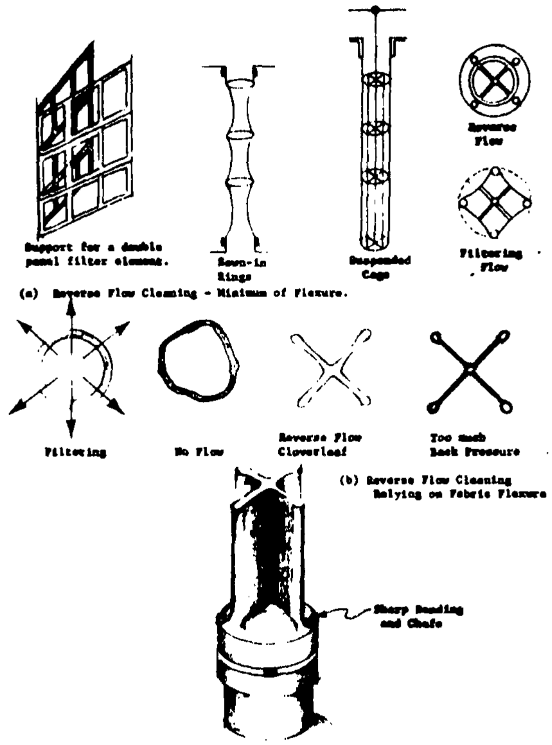


Figure 3.5. Reverse Flow Cleaning.

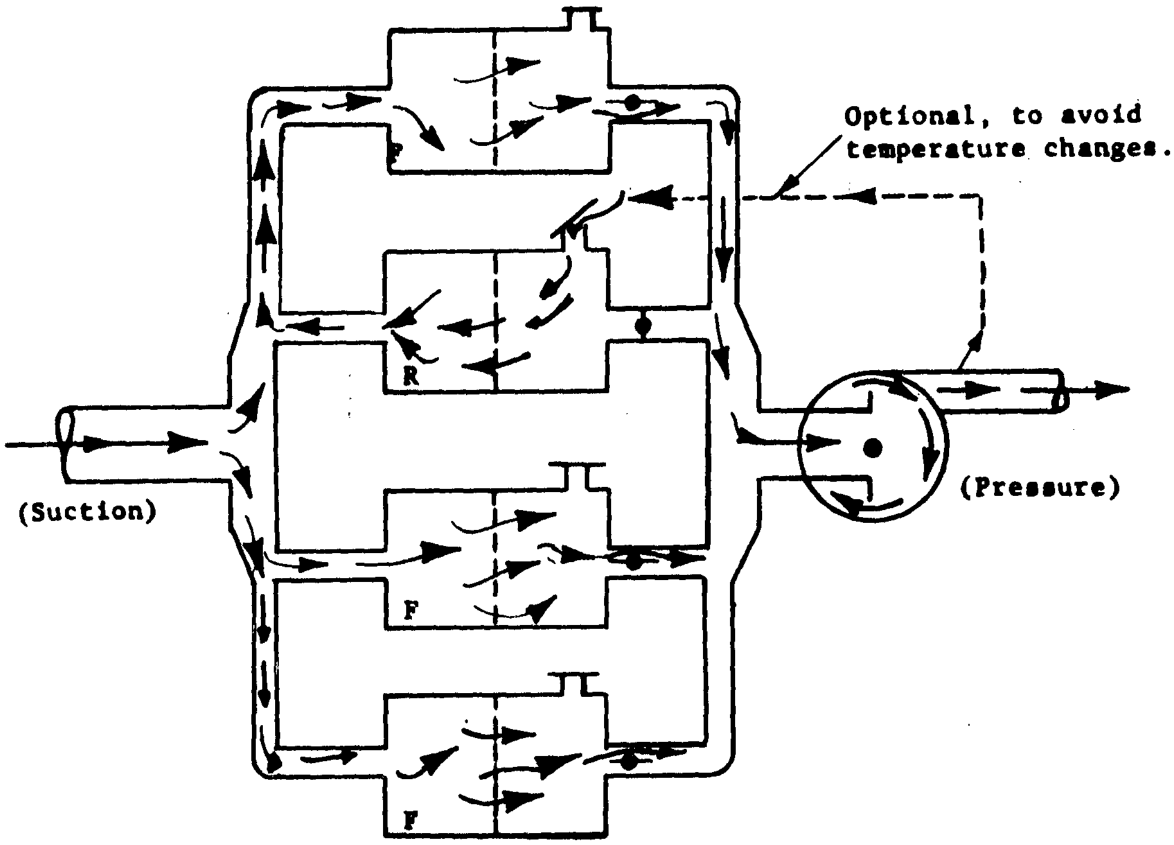
and introducing some air in the reverse direction with a secondary blower (Figures 3.3e and 3.3g). Perhaps a simpler method is to take advantage of a suction on the dirty side, or a relative pressure on the clean side, without using another blower as sketched in Figure 3.6. If in using this cleaning system it becomes necessary to increase the suction or pressure being used for cleaning by partially closing off the inlet or outlet primary duct, then to avoid the added power consumption, it may be better to use a small secondary fan or fans.

Any flow volume reversed through the filter must be refiltered. This means that in addition to taking cloth out of the system for cleaning, this cleaning method increases the total air flow in the remainder of the system. The net increase in air/cloth ratio is normally 10 percent or less, but this may cause a large (perhaps 40 percent) increase in power consumption. This is partly through a decrease in cake permeability.

The pressure across the compartment and baghouse will be similar to that sketched in Figure 3.4. However, some equipment users believe repeated reverse flows introduced suddenly to "pop" the cloth are beneficial, in which case the pressure-time cycle will be different.

Reverse flow equipment with a minimum amount of cloth flexing finds the same wide range of general applications as shaking equipment, the one main requirement being that the dust release easily from the fabric. Thus, felts are not cleaned by low pressure reverse flow.

Disadvantages of reverse flow equipment include the increased filtration velocity (or alternatively a proportionally larger installation), the costs of any additional fans, ducts or dampers, and when necessary the cost of a support grid. This grid tends to be a nuisance when it comes to changing the bags or panels and considerable effort has gone into its design. The grid or rings may chafe against the cloth unless the cloth is so tight it can't move, which introduces



F: Compartments filtering

R: Compartment being cleaned by dampered control from suction side of system.

Figure 3.6. Schematic for Reverse Flow Cleaning During Continuous Filter Operation.

tension problems, or unless the cloth is fastened to the support, as for example, rings sewn to the tube. Even such hard fibers as glass can apparently fail by chaffing. Chaffing is such a problem that the supports are occasionally done away with at the risk of excessively flexing the cloth.

3.3.3 Reverse Flow With Collapse

Even though cloth flexure is detrimental, especially when the fabric is penetrated by grit, flexure is frequently the preferred means of cloth cleaning. It is sometimes used in conjunction with other methods. The cleaning method excludes panel type filters and felts, but cloth bags having the dust cake on the inside are often cleaned this way. The cylinder is often reported as collapsing for some reason into a cloverleaf pattern (see Figure 3.5). The collapse is not 100 percent, however, or the cake could not fall to the hopper. There should be just enough reverse flow to crack and shear the cake until it falls off. It may then be carried to the hopper by the reverse air current, depending on collector design.

With this kind of cleaning there is an optimum tightness of the cloth, said to be somewhat between 25 and 100 lbs for a standard 11.5 inch diameter glass bag. More tension than this is hard on the fastenings, or prevents the bag from collapsing enough. Less tension results in too sharp a cloth bend at the tube thimble where the cloth is fastened (see Figure 3.5). The tension of a suspended bag can be automatically changed during the cleaning cycle if necessary, by adjusting the position of the hanger frame.

The collapse method of cleaning uses essentially the same damper, fan and ducting equipment as the method of reverse flow without collapse. Just as repeated shaking is standard practice, the bag or tube may be collapsed more than once. It may also be "fluttered" by lightly and rapidly pulsing the reverse air to give a shaking effect, at some risk of damage to the cloth. Such flow changes may also transmit pressure pulses to adjacent compartments and damage the cake structure there.

Chief disadvantages of collapse cleaning are flexural and chaffing attrition of the cloth, and some lack of control of cleaning intensity. For instance, if the cake fails to come off sufficiently and begins to stiffen the cloth, there will be still less cleaning and consequently, extra flexing in adjacent areas and faster wear. There is little one can do to increase cleaning intensity, although one can repeat the process or change the rate of flexure.

3.3.4 Pulse Cleaning

This method attempts to overcome several of the difficulties associated with other methods of cleaning. In this kind of equipment a sharp pulse of compressed air is released in the vicinity of the fabric giving rise to some combination of shock, fabric deformation and flow reversal. Depending on the design, and there are over 25 models of pulse cleaned equipment. The result is the removal of the dust deposit without more than a brief interruption of the filtering flow. The fabric receives a minimum of flexural wear and the filter installation is smaller because the fabric is in use practically all the time. Also, for reasons on page 3-46, most pulse equipment utilizes felt rather than cloth. With felt the filtration velocity can be typically 3 to 4 times that used in shake or reverse flow equipment, so the pulse filter installation is smaller.

The main distinction of pulsed equipment is the brief cleaning time, typically around one-tenth of a second. The very low ratio of cleaning time to filtering time makes pulsed equipment uniquely useful at very high dust loadings, up to several hundred grains per cubic foot on large particles. Thus, this equipment is widely used for pneumatic conveying systems, and it also has application at moderate and low dust concentrations.

The earliest designs of this kind, as shown in Figure 3.7, use open top bags with a pulse nozzle in or just above the top of each bag. A timer controlled solenoid valve releases 60 to 120 psi air through the nozzle for a small fraction of a second. As the air pulse moves down the bag, it may draw in other air and the combination tends to bulge the bag. In one variation the filtering is on the inside of the bag and the dust is partly removed by reverse collapse, but then a pulse similar to the one shown above snaps the bag open and completes the dust removal. Note that this forward pulse cleans without apparently plugging the fabric. A second variation in pulse cleaning design is the compartment pulse, in which several bags or envelopes are served by the same nozzle located in a plenum at one end of the group; or, the entire compartment is served by one or more nozzles. For example, at least one model injects a reverse air blast into the compartment inlet, which temporarily stops the flow and reverses it, causing partial collapse of the filter elements.

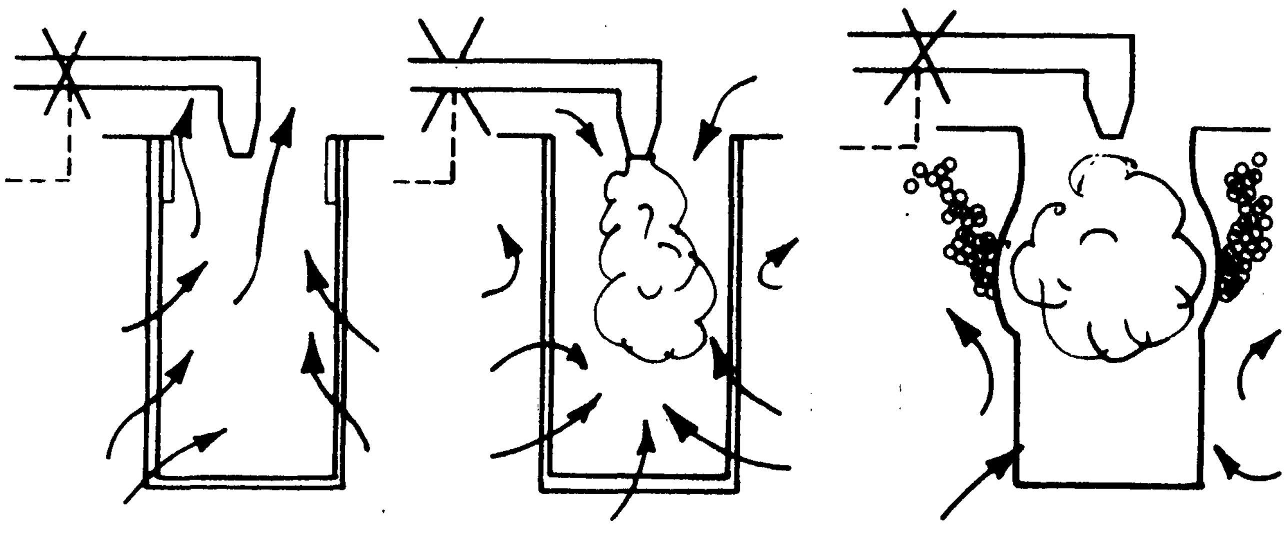


Figure 3.7. Reverse Pulse Cleaning.

These variations in clean vs. dirty side pulsing and inside vs. outside-the-bag pulsing, raise the question of the mechanism or mechanisms of dust removal. Several mechanisms appear possible depending on design:

1. The bag or tube stretches as the air balloons through it, cracking and blowing off the cake, (inside pulses only).
2. The air pressure change, even after expansion and dilution, is still long enough and intense enough to cause a flow reversal which blows off the cake, (clean side pulses only).
3. The inertia of the air mass pulls a vacuum behind it which pulls off the cake, (dirty side pulses only).
4. The shock of the pulse accelerates the fabric away from the dust cake, even though the distance traveled by the fabric is very small, (probably dirty side pulses only).
5. The fabric and dust accelerate outward together, but only the fabric has the elasticity to snap back into shape. Outside dust is left behind; inside dust is thrown off at the end of the snap-back, (inside pulses only).

Among the approximately 25 pulse-type collectors the pressure-time function varies considerably from a true shock to little more than a quiet reversal of flow, so it is entirely possible that several of these mechanisms apply.

Efficiency of use of compressed air is important because the electric power needed to run the compressor can equal that for the primary fan. Some models claim improved efficiency by using venturis surrounding the pulse nozzles as was shown earlier in Figure 3.3.i. These entrain a certain amount of additional air which expands the bag, causing the collected dust to drop off the outer surface. The entrainment may also set up a shock wave which accelerates or flexes the filter cloth.

It is expecially interesting that only one of the approximately 25 available pulse-cleaned models uses downward flow. Apparently, the dust is able to fall through the upward flow to the hopper despite upward velocities typically 3 to 4 times those in shaker and reverse flow equipment. Evidently the pulse-removed deposit falls in large pieces, but even so, a large quantity of dust must be redeposited on the fabric. Possibly, these large pieces are beneficial in acting as filter aid, but on the other hand they increase the total deposit on the filter.

The components of a pulse cleaning filter include an air compressor, a storage or surge tank, piping, solenoids and nozzles, and some models use venturis and fabric support gridwork as well. Few, if any, ducting dampers are needed along with their associated controls. As there are no moving parts required, the pulse method has an advantage in terms of maintenance.

Just as in shake cleaning, in which all the cleaning energy must be applied at one end of the bag, so in pulse cleaning the effectiveness of cleaning decreases with length of bag. This is evident in the short bags typically used in pulse equipment, rarely if ever over ten feet in length. Since there is little fabric motion, the bags or tubes can be packed slightly closer without interchaffing. Even so, large installations still occupy more floor space than types with 30- to 40-foot bags.

Both the intensity and frequency of pulse cleaning are easily adjusted, but there is little control of top to bottom uniformity of cleaning. Woven cloths tend to be over-cleaned by pulsing, resulting in excessive leakage following cleaning, whereas felts are more easily maintained at a satisfactory level of residual dust deposit over the entire bag length with excellent cleaning efficiency.

There are several other reasons for using felts rather than woven cloths, although in a few rare cases tightly woven fabric is used. The dimensional properties of felts may make them more amenable to pulse cleaning involving "ballooning". Bag inlet velocities are high in pulse equipment and felts having softer surfaces may withstand more abrasion than cloths. Felts form a more porous dust cake having lower specific resistance, so they can be cleaned less often than cloths for the same pressure build-up. Equipment using felt can be smaller because higher filtering velocities are possible. Finally, felts can be used even though they are initially more expensive, because there is little mechanical wear of the fabric in pulsed equipment.

Like other types of equipment pulsed cleaning has its disadvantages. It is limited in temperature to around 450°F at present, because felt materials are not available for higher temperature. High pulse pressure can damage the fabric by over-stretching it. Felts tend to plug in depth rather than blind. They may have to be cleaned rather than discarded because of their greater value. Felt, compressed air, power and the compressor are all relatively expensive so that economic balances are different for pulse equipment. As a result, equipment sizes and shapes are different. Pulsed equipment may be best for some applications and simply not economical for others.

3.3.5 Reverse Jet Cleaning

Introduced in the early 1950's, this method of cleaning became known for its high filtering efficiency and high filtration velocities. It was the first method to give felted materials a good, uniform cleaning. It did this by using a small-volume jet of moderately pressurized air spaced at moderate time intervals. Figure 3.3f shows how this can be done. A carriage carrying the jet rings moves up and down the filter tubes, driven originally by chains and sprockets, or by cables controlled by limit switches. On the carriage a slotted ring close to the fabric surrounds each filter tube. Most of the jet air goes through the felt toward the dirty side, blowing the dust out of the deep felt surface.

Since the four reverse jet models on the market are based on the original Hersey patents, the models are much the same. One type uses adjustable segmented rings around the tubes, another uses a flat plenum through which are cut holes about the same diameter as the tubes. The traveling carriage is easily designed for either cylindrical or rectangular baghouses. Tube lengths are in the range of 6 to 30 feet. In all models the flow is downward and outward. For this reason, the collector can be open sided, but as reverse jet equipment is often used on toxic materials because of its high efficiency, health codes usually require that the filtered gases be contained until exhausted outdoors.

There are times when a very low dust concentration must be filtered, e.g., valuable or toxic dusts. At such times the reverse jet collector is an early consideration, not only because of high efficiency, but because of high air capacity, typically 10 to 30 FPM depending mainly on particle size. The time required for cake buildup can be as long as a month, depending on concentration. To prevent useless running of the carriage the limit switches may be over-ridden either manually or by a pressure switch. Once the carriage starts to move, it travels at its normal rate of a few feet per minute. It pauses between trips for cake buildup, thus lengthening the mechanical life of the equipment.

Conversely with moderate dust loadings, the carriage usually runs continually. On higher loadings it can be speeded up to a limited extent if necessary. Note that in continuous operation the pressure drop across the compartment is not quite steady, since compared with the midpoint of the tubes the end of the tube is first cleaned too soon and then cleaned late on the next pass. How much this causes the primary flow through the system to fluctuate depends on rate of pressure buildup, rate of carriage travel, the fan curve, etc.

Reverse jet equipment offers control of both intensity and frequency of cleaning, and even offers the possibility of adjusting the intensity according to carriage position if necessary, although there is no report of this being done. The cleaning is practically uniform from top to bottom, the more so since the deposit tends to be uniform due to downward flow. For these reasons the felt should last longer without plugging than with any other method of cleaning. Unfortunately, these advantages are partly offset by wear problems in both the felt and the moving parts.

Reverse jet equipment is well suited to fine particles, expecially if these cohere well. Otherwise, there is considerable re-entrainment when the deposit is removed and the collector operates at a higher pressure drop. This equipment is also suited to coarse particles, especially non-abrasive ones.

Regarding wear, it is good design policy and almost necessary to have as much of the moving mechanisms as possible outside the compartment. Even the clean side of the compartment sooner or later gets dusty, if not from seeping dust then from perforated fabric. When this happens the mechanism tends to wear and, eventually, to stick and jump. The limit switches may become fouled and unless fail-safe the drive chains will break, cocking the carriage and probably ruining the fabric tubes. Once fouled it is very hard to get the mechanics back into the original clean and unworn condition. Consequently, the frequency of maintenance increases.

In a number of installations a hard deposit of dust and fiber bits has built up on the jet rings over a period of time so close to the cloth as to cause abrasion. This deposit can wear through the fabric unless removed.

The air required to clean the fabric is usually supplied by a high-speed blower at pressures of 5 to 20 inches. The volume required is roughly 5 percent of the primary filtering flow which increases the filtration velocity only slightly.

3.3.6 Vibration and Rapping Cleaning

Although several methods of cleaning involve motion and even fluttering of the fabric, higher frequency agitation with little cloth travel can also be effective. In vibration and rapping, either transverse or longitudinal elastic waves travel over the fabric, accelerating the fabric surface through displacements that are usually small. The inertia of the dust cake causes stresses at the cake-fabric interface which detach the dust cake from the fabric. Since it is easier to vibrate or rap a compact group of taut filter elements, envelope filters are the most commonly rapped type.

This method of cleaning is especially successful with deposits of medium to large particles adhering relatively loosely. Since larger particles are typically from low or moderate temperature sources, high temperature fabrics are not usually used. Woven fabrics rather than felts are used because they clean less expensively and even paper filter material can sometimes be used.

The vibrating mechanism should be located outside the housing to minimize dusty abrasion. At least one end of the frame supporting the filter envelopes is floating and attached to an eccentric arm or vibrator. If the cleaning is to be done manually, a common rod may protrude or the housing may be opened to strike each filter frame.

The compartment is shut off during the vibrating or rapping. If continuous filtering is necessary, several compartments can be used with sequential automatic cleaning. The length of the vibrating time varies. However, as with shaking, about 100 vibration cycles should be sufficient. Longer vibration is probably not as detrimental to the cloth as in shaking. The power requirement is low and the cloth life can be several years barring heat, chemical, or other problems.

For larger particles, for which this equipment is especially suited, the filtration velocity can be higher than with other types of intermittent equipment. Therefore, vibration/rapping equipment is compact.

With the larger particles, higher pressure drops across the cloth can be tolerated without as much danger of blinding the cloth or blowing the cake through the cloth. For this reason small, light, unit-type intermittent equipment may operate safely without attention for relatively long periods, even without instrumentation. Eight hours is a typical operating period between cleanings. Even though the cost of filtering power at higher pressure drops across the small collector is high, it is frequently only a small part of the plant process cost.

The main disadvantage of this kind of equipment is probably the relatively few dusts for which it can be used. If the equipment is located in a confined space it can be noisy.

3.3.7 Sonic Cleaning

Agitation frequencies still higher than those used in vibration and rapping have been attempted with ultrasonic and sonic cleaning methods. Although these frequencies are known to slightly improve the preagglomeration of a few fine dusts, they have not, on the whole, been very effective in fabric cleaning. Lower sound frequencies are used, however, with success in a few installations. The Fuller Company (Dracco) has installed sonicly cleaned equipment in cement plants for over ten years. They also used a successful combination of reverse flow-collapse plus sonic cleaning in Bethlehem Steel's open hearth furnace baghouse about 1964-65.[2] Usually, sonic cleaning must be supplemented by some other method.

The frequency band used can be estimated from the sound, described as low and mixed like a fog horn or railroad whistle. The cloth motion is not apparent, but the vibration can be felt by touch. At the Bethlehem installation the sound was generated by compressed air, with less than 300 SCFM needed for 50 horns serving about 80,000 ft^2 of cloth. The pressure required was not determined. Following reverse flow and collapse the horns gave three five-second blasts, after which the collapse and horn blasts were repeated a second time.

In all reported installations of sonic cleaning (cement and open hearth fumes), glass cloth has been used, at filtration velocities of 2 FPM or less. However, it was claimed in 1959 that use of sonic cleaning would reduce the normal cloth pressure drop of 4 inches by 25 to 50 percent, raising the possibility of a higher filtration velocity.

Sonic cleaning costs have been reported as lying between those of reverse air and shaking systems. The compressed air equipment is apparently less than for pulse cleaning equipment. However, sonic cleaning has never achieved the popularity of most of the other cleaning methods, for reasons which have not been reported.

3.3.8 Manual Cleaning

Any of the automatic cleaning cycles can be initiated manually at convenient times, as between shifts. An even simpler method of cleaning is to approach each bag or panel and remove the cake by hand as in beating a rug. The method has no hardware to wear out and is as reliable as maintenance can be. However, the cloth itself generally wears rapidly and endures fewer cleaning cycles than other methods.

This method is only practiced on smaller dust collectors having, at most, only a few filter elements. They can be brushed in place, or thumped to knock the cake loose. Alternatively, they can be removed and turned inside out for more thorough cleaning.

When the more expensive fabrics blind or plug, well before their other qualities are depleted, they are reclaimed by various methods such as vacuum cleaning, dry cleaning, or laundering. An advantage here is that weak spots may be detected and repaired before a hole in the fabric actually occurs. A certain amount of skill goes into removing dust without damaging the fabric. Manual cleaning of any large amount of ordinary cloth is not economical.

3.4 CONSTRUCTION AND MATERIALS

Fabric filter manufacturers are rarely able to guarantee the performance of their equipment, because performance depends so much on how the equipment is installed and used. Any manufacturer can, however, guarantee the quality of his dust collector as sold. As a check on quality, the manufacturer has standard specifications for the production of the equipment. These specifications include a large amount of detail for construction and materials, an example of which is presented in Appendix 3.2.

3.4.1 Housing

External framework and configuration design is available in three types, the choice depending mainly on moisture condensation considerations. The open-sided pressure design (inside filtering) is cheapest and used mainly below 135°F. The closed pressure type is next, and followed by the slightly more expensive closed suction installation. Above 160°F, the equipment is usually closed and insulated. The cost increases with the area and thickness of metal used, which depends on the pressure the walls must withstand. Cost will also reflect any necessary weather protection, insulation, etc., as well as gas corrosiveness and temperature.

Most small unit collectors are assembled at the factory, usually welded, while larger units may be either assembled at the factory or on location. The largest unit that can presently be shipped by railcar is approximately 10' x 40' x 12' high; consequently many larger designs are assembled from standard preassembled modules by either welding or bolting on location. It is difficult in field assembly to make good pressure or vacuum-tight seals between panels, modules and flanges and seal quality is a chief complaint among fabric filter users.

To create a strong structure and provide good seals against weather and condensibles, under the large deformations due to changes in temperature and pressure, some variations in construction are necessary. Several styles of housing joints and sealants are indicated in Figure 3.8. For steel, one manufacturer uses galvanized 14 gauge sheet, others use 10 gauge welded hot-rolled steel. Much heavier material can be used, up to one-quarter inch or more. The open hearth FF installation at Bethlehem Steel used 3/16 inch for walls, roof and partitions, 1/4 inch for floor plates and 5/16 inch for hoppers and inlet plenum (Fuller-Dracco design)[2]. In passing, let it be noted that competition forces many manufacturers to underdesign unless otherwise instructed (see Section 8.3).

Materials other than steel may be used for housings; for example, cement plant collectors are often made of concrete and one fabric filter manufacturer has a design for precast reinforced concrete panels. An aluminum company stated it feels that aluminum is definitely the best all-round material to use. Corrugated asbestos cement paneling is often used for exterior roofing and siding, with the interior walls and partitions made of steel. Various other composite panels can be used. Insulation can be sandwiched in the paneling or added to the outside at factory or later as needed. The main precautions in selection of material are corrosion and changes in temperature that cause thermal stresses in the seals and even in the bags.

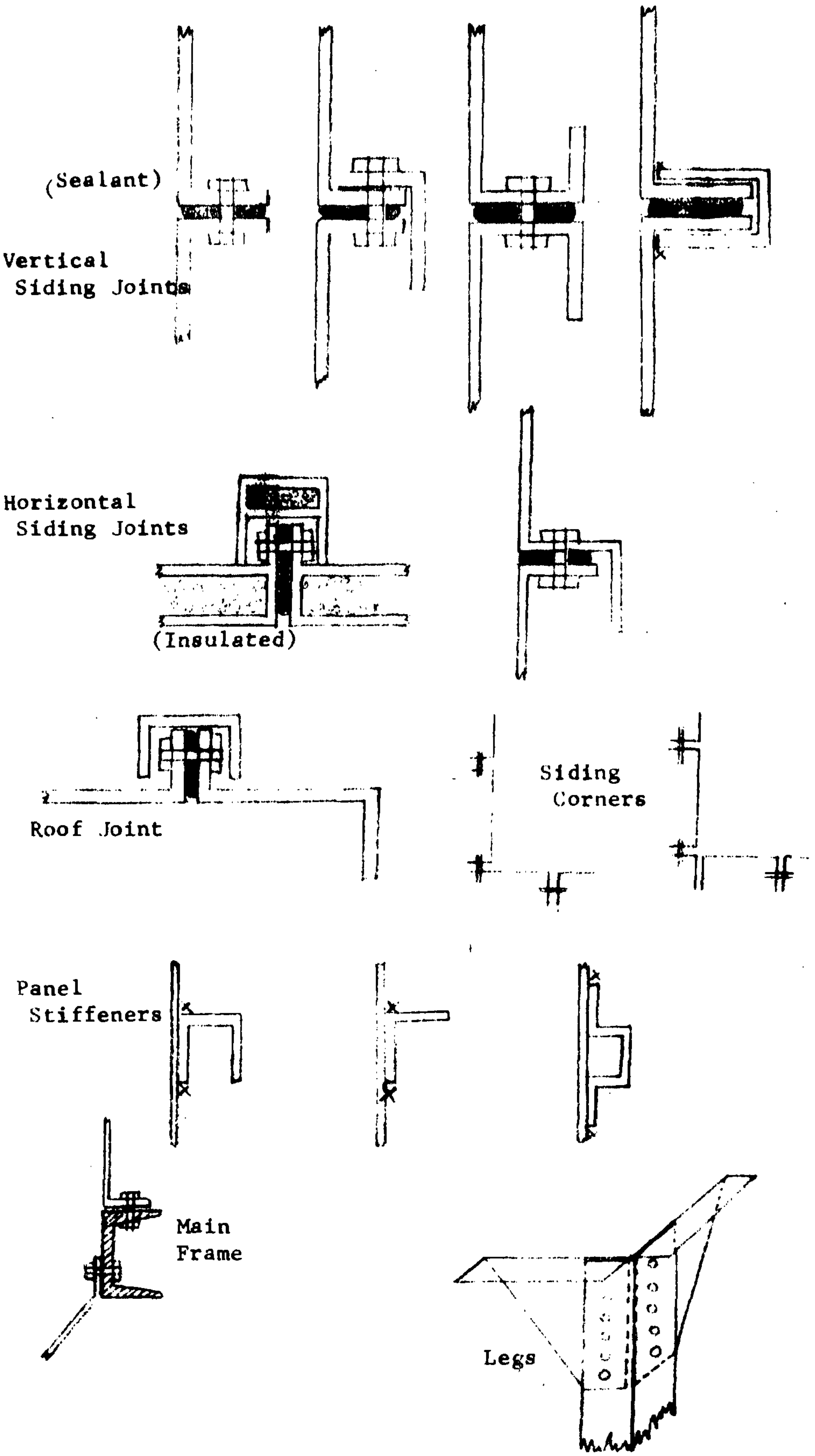


Figure 3.8. Examples of Some Styles of Fabric Filter Compartment Joints.

3.4.2 Hopper and Disposal Equipment

Hopper material is usually similar to that used for the housing with similar joints and seals. The inside may be treated to minimize adhesion of the dust. Hoppers are commonly available with either 45^o or 60^o slope depending on the need to conserve height or to provide adequate sliding, as affected by the plugging properties of the dust.

Most hoppers are under a few inches of pressure or vacuum. Consequently they require some kind of valve at the bottom to let the collected dust out without admitting air to reentrain dust and redeposit it. Automatic filter equipment usually uses a rotary valve consisting of a sealed paddle wheel as depicted in Figure 3.9. These valves rotate at about 5 RPM, and are typically 6 to 12 inches in diameter. Thus they handle around 2 CFM of collected material. If the solids flow is higher, the valve can be run faster or more or larger valves can be used.

For low solids flow,and for many non-automatic installations requiring periodic attention,sliding gates may be used. Unless the hopper is under practically zero pressure these gates are used only when the compartment is shut off. When the hopper is under no pressure a gate may not be necessary. A stocking perhaps 6 feet long reaches from the hopper bottom to the dust bin. Likewise, the rotary valve or gate seldom discharges with an open cascade of dust. A stocking is used or more commonly the solid flow enters a conveyor, usually screw-type.

If for reasons of compartment cleaning or maintenance the compartments must be completely isolated then the rotary air lock valves are located between the conveyor and the hoppers. Otherwise it may be less expensive to install the conveyor directly on the hoppers and use one valve at the end of the conveyor. The air slide, bucket, and belt methods of conveying powdered materials are normally used only for high solids flow. There are,however, times when the screw conveyor doesn't work as with gummy dusts and those that lock up under pressure.

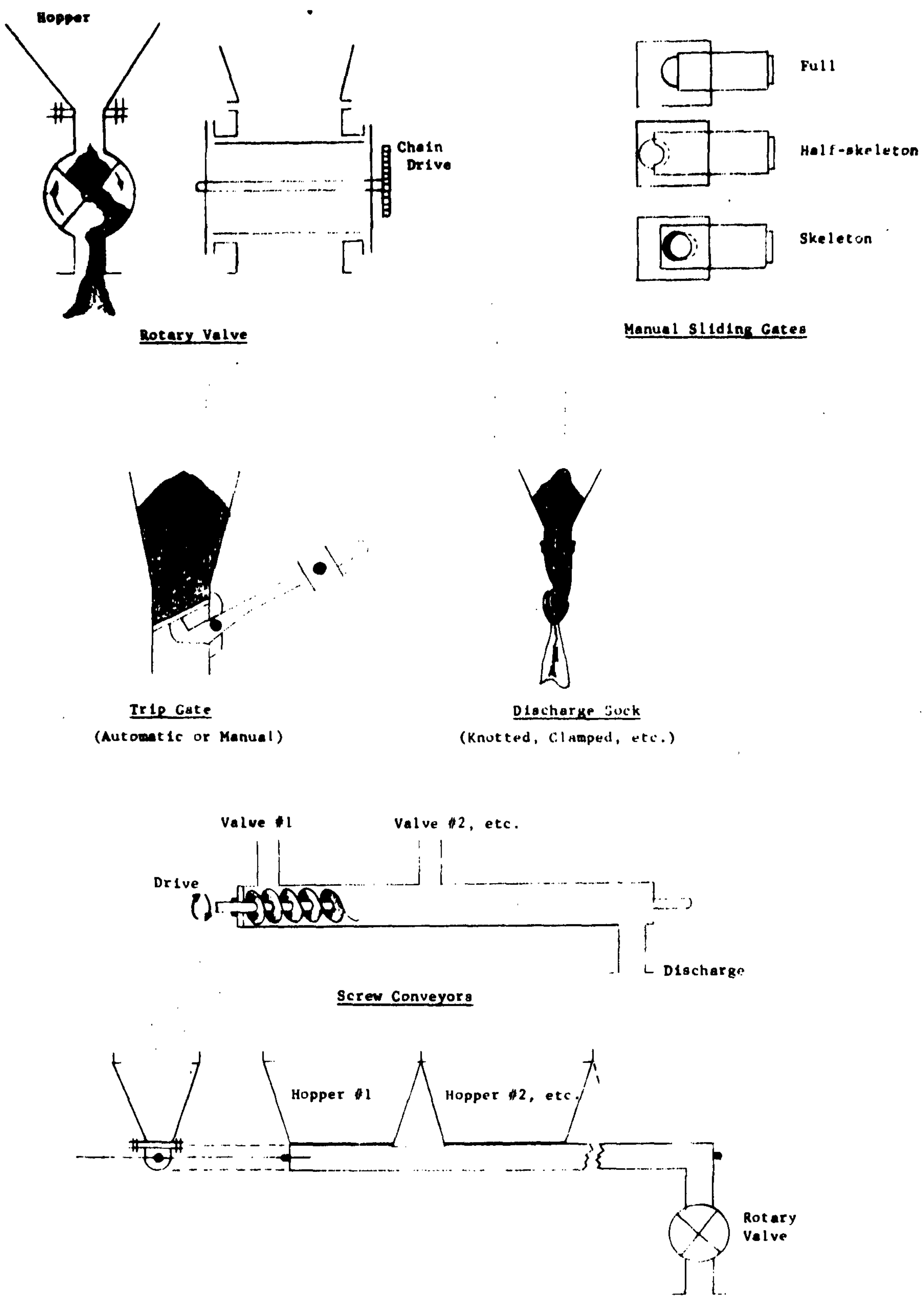


Figure 3.9 - Types of Hopper Discharge Equipment

3.5 EXTENSIONS OF FABRIC FILTRATION EQUIPMENT

In addition to the standard FF designs already discussed, from time to time novel filter equipment arouses interest among those acquainted with the limitations of standard equipment as indicated earlier in Chapter 1. The patent literature records a fascinating history of design variations, of which only a small percentage are now in practice. Besides these efforts to control dust, fabric filtration has demonstrated other capabilities including control of gases and perhaps odors, control of mists, and ultrafiltration for very fine particulates in atmospheric dusts.

3.5.1 Variations in Standard Fabric Filter Designs

3.5.1.1 Bourdale Rotary Filter.- The filter media surrounds a central shaft and rotates "until such time that the cake of dust has such a mass that its centrifugal force exceeds the fan suction, when it flies off the surface and settles down into the hopper."[5] This is a compact unit in use on a wide variety of dusts up to 210°F. It is made by Wheelabrator Allevard of Paris.

3.5.1.2 Tower Collector.- Two tiers of glass cloth bags are used, one above the other, in a 60 foot or higher cylindrical chamber. The flow is downward; cleaning is by sonics. Although the brochure of the company that produces this configuration is not specific, the bags are probably butted end to end on an intermediate tube sheet to relieve the tension that would otherwise be extreme on a single 60 foot bag.[6]

3.5.1.3 Self-Emptying Bag.- In one such design[7] up to 8 bags, each about 6 ft by 1.5 ft dia., are held at the top by a guy cord during filtering. For cleaning the cord is released and under the weight of the dust the bag sinks through the lower tube sheet, turning itself inside out and cracking off the cake. In another design used in a copper mine in Zambia the bags are held up by inflation pressure, and their top is guided up and down by a taut wire through a grommet in the top center of the bag. Dust dumped as the bag inverts itself is later washed away by a stream through the inlet plenum.[8]

3.5.1.4 Granular Bed Plus Screen.- This equipment uses pulses to clean a combination sand bed plus filtering screen, as sketched in Figure 3.10. Large particles form a cake on the screen(s), and fine particles

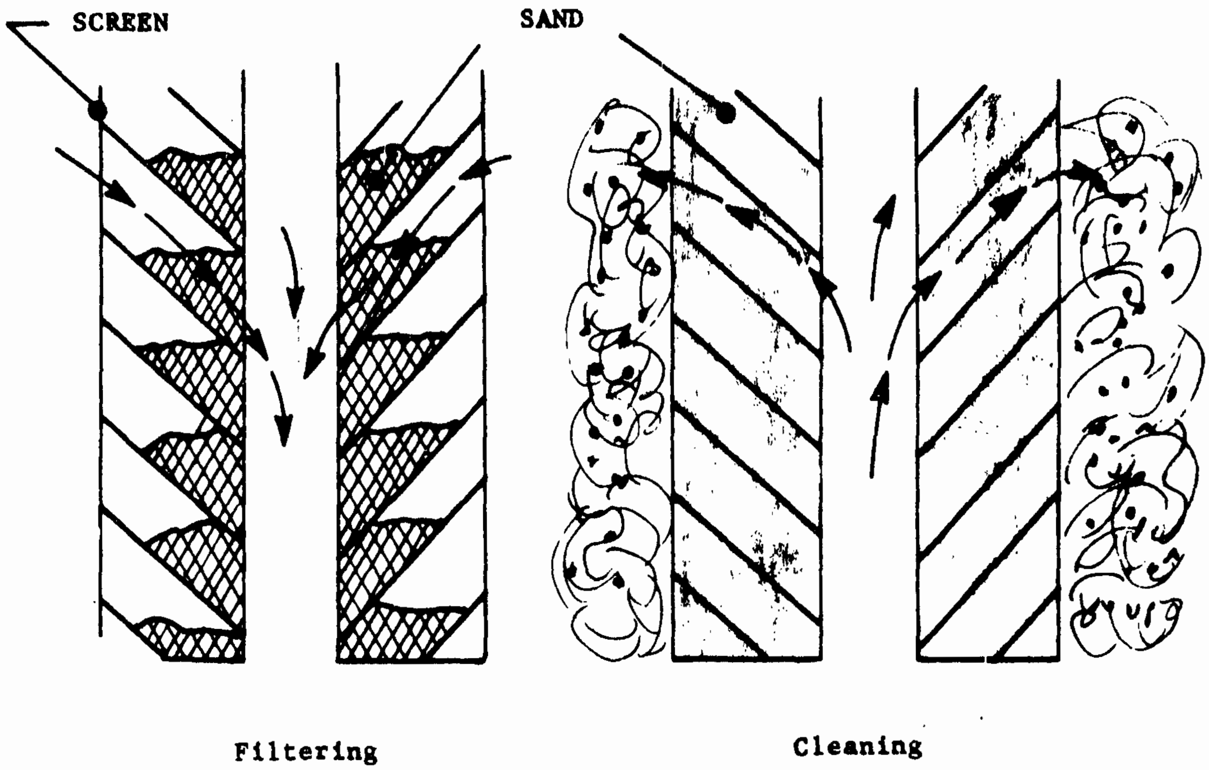


Figure 3.10. Ducon Sand and Screen Filter Cleaned by Back Flow.

are caught in the sand(s). "The channels in the filter element are not completely filled with sand. Thus, during the cleaning cycle, short blasts of high-pressure air expand the beds. The air dislodges filter cake from the outer screen and restructures the granular material into a filtering bed essentially the same as the original."[9] The Ducon Co. says the device can operate at filtering velocities of 30 to 40 fpm at temperatures well above 1000°F and on sticky dusts.

3.5.1.5 Foreign Equipment.- Filtration and Separation, a British publication, regularly lists developments in dust control equipment in Great Britain and Europe. Much of this equipment is slightly different from U. S. Designs although several U.S. manufacturers have subsidiaries in Europe, and this handbook survey of available equipment styles could be extended to include European equipment.

3.5.2 Control of Gases and Odors

Several experimental studies have shown that finely divided absorptive or adsorptive granular materials aerosolized into the gas stream entering the fabric filter, can effect the removal of certain gaseous components. The combination of good powder control with high specific surface, and long, intimate gas-powder contact especially on the fabric, are advantages offered by fabric filtration equipment over most other equipment. Most recently the removal of up to 98.4% of SO_2 by sodium bicarbonate has been demonstrated at a coal-fired power plant by Air Preheater Co. under NAPCA contract. Fly ash and NO_2 are also removed at the same time. The optimum equipment design for gaseous control would probably not be much different from present filter designs, except for the system for introducing and possibly recirculating the powdered material. This addition is estimated to be a small part of the fabric filter system cost.

The addition of particle aggregates to a filter cake should reduce power costs by reduction of the cake porosity. The partial recirculation of agglomerates from the collector hopper seems attractive but there is no report of this practice. It would appear that agglomerate recirculation in conjunction with absorptive powder recirculation would be attractive in numerous possible gas and odor control applications.

Similarly, although as far as is known absorbing additive in fabric filter equipment has not been used to control odors, it is a likely prospect. Granular charcoal, catalysts, or fritted impregnated material could be introduced to and removed by the filter, regenerated in special closely confined equipment, and then recirculated.

3.5.3 Control of Mists

It is widely observed that the fabric in an ordinary fabric filter collector must be kept dry or it will rapidly plug with dampened dust.

This may be reversible, however, as shown by pilot plant experience at a Southwest Portland Cement Company plant some years ago using siliconized glass fabric, collapse without shake cleaning, and cement kiln effluent normally about 500°F: "...During subsequent months of testing, the bags at times were saturated with water from condensation during normal variations of atmospheric and kiln conditions (wet-process) and were even deliberately wetted. In all cases, rising temperature dried the bags and, at the next collapsing cycle, they discharged readily and returned to normal pressure drop. Inspection of the fabric showed that no blinding had occurred, and the lack of deterioration suggested an entirely satisfactory life of at least one year."[11]

Other filter beds, more open than normal filter fabrics, are used for large particle demisting in a number of processes. These are usually self draining, but if they are of intermediate porosity and there is danger of clogging they can be kept open with water sprays. One such study obtained effective removal of submicron TiO_2 particles plus around 90% removal of sulphuric acid mist, by irrigating synthetic felts.[12] Filtration was at 70 to 165 FPM, the spray rate was around 10 gal. per KCFM, and felts fairly similar to felted fabric filtration materials were used. The pressure drops encountered were 8 to 10 inches of water and were nearly independent of filter velocity, possibly because the air permeability of the wet felt depended on the amount of water remaining in the felt. Projected initial costs of a complete 56,000 CFM system were cited as $2.40 per CFM plus minor installation costs.

These examples of effective particulate control with fabric at conditions below dewpoint may point the way to solution of condensation problems in fabric filtration, enabling cooler and more economical operation without fabric blinding and plugging. There are many possibilities for research and development in this area including the opportunity for coincidental wet-process odor control. Although the field is not a new one by any means, new synthetics and changing economics make it a viable and inviting challenge.

3.5.4 Ultrafiltration

The high efficiency made possible by filtering with a dust cake is used to obtain very low effluent concentrations of toxic and radioactive dusts, bacteriologicals, and atmospheric dust. Very low concentrations of liquid or tarry particles may also be controlled. Aside from a system for introducing the filter aid, the equipment is much the same as that for any fabric filter system. Since the fabric is cleaned only very infrequently, however, perhaps once a year or longer, the cleaning mechanism and dust disposal equipment can be minimal. A high fabric packing density can be used without concern of chaffing. Maintenance is low and the equipment is available for operation with a number of filter aids.

3.6 REFERENCES FOR CHAPTER 3

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CHAPTER 4

FABRIC SELECTION

CHAPTER 4

FABRIC SELECTION

4.1 INTRODUCTION

Satisfactory performance of a fabric filter on a specific application requires selection of a fiber material compatible with the gas-particle environment, and a fabric design appropriate to dust collector geometry and collector cleaning requirements. Fiber, yarn, and fabric parameters influence the ability of the fabric to collect dust at a reasonable pressure drop. A brief summary of developments in fiber, fabric, treatments, and applications has been presented in Chapter 1. Man-made fibers have been developed over the past 30 years with superior resistance to physical and chemical environmental requirements. While traditional fabrics of cotton and wool are still employed for many fiber applications, the impact of man-made fiber fabrics has extended the range of application of fabric filters to a much broader gas cleaning market. Continuing developments in fiber and fabric technology, as in dust collector design, can be anticipated.

The purpose of this chapter is to present information on fiber and fabric properties important to their application for industrial gas filtration. In addition, pressure drop during fluid flow through fabrics and dust deposits has been considered in Chapter 2; effects of fabric structure on filter performance has been discussed in Chapter 6; and fabric costs in dust collection have been considered in Chapter 7. In what follows, a number of terms unique to the textile industry are used, and these are defined in Appendix 4.1.[1]

4.2 MATERIALS

Production of textile fabrics begins with the basic structural unit, a single fiber. Fibers are obtained from traditional natural vegetable or animal sources, such as cotton (cellulose) or wool (protein). Fibers are also produced from man-made or modified natural organic polymeric materials through modern chemistry and chemical engineering. Industrial filtration fibers are indicated in Table 4.1 by generic group manufacturer, and Trade names.[2] A more complete index has been compiled by Dembeck.[3] The internal molecular orientation and crystallite structure of the fiber determines its basic physical and chemical properties. End use fiber characteristics are substantially controlled by additives and treatments. Within a generic group, polymers, co-polymers, and homo-polymers may be produced. For all these reasons, there are differences in physical properties and chemical resistance for each manufacturer's product in each group.[2]

Fibers are produced as staple (relatively short lengths ($1 \leq$ length $\leq$ 10 inches long), as monofilament (single long continuous filament $L \gg 10$ in.) and as multifilament (many continuous parallel filaments). Natural fibers are used for industrial filtration staple. Man-made filtration fiber is used in both staple and filament lengths. Cross sections of typical natural and man-made fibers are shown in Figure 4.1. Fiber microscopy such as this is a useful technique in textile identification and filtration research, as discussed in various references.[5,6]

4.2.1 Natural Fibers

Cotton and wool fibers are commonly used in fabric filter dust collectors. Cotton fibers are elongated single hollow cells, often flattened (Figure 4.1), with characteristic irregular lengthwise twists. Cotton fibers from different varieties of plants vary in length from 1/2 to 2 inches, and in width from 12 to 25μm.

Sheep wool also varies with specie and with geographical location. The surface of a wool fiber is made up of flat scales (cuticle) which overlap like shingles. These scales are spaced approximately 20 μm apart along the fiber. They are very important in determining the mechanical properties of wool fiber assemblages, and probably influence dust collection and release properties as well. Wool fibers are 10 to 70 μm in diameter, and 1 1/2 to 15 inches in length. They are almost uniformly cylindrical except for the ends which are tapered.

TABLE 4-1

MANUFACTURERS AND TRADE NAMES OF INDUSTRIAL FILTER FIBERS**

ACETATE AND TRIACETATE
Celanese--"Acetate", "Arnel"*
DuPont--"Acele"*
Eastman Chemical--"Estron"*
F.M.C Corp., American Viscose Division--"Avisco"*

ACRYLIC
American Cyanamid--"Creslan"*
Chemstrand--"Acrilan"*
Dow Chemical--"Zefran"*
DuPont--"Orlon"*

MODACRYLIC
Eastman Chemical--"Verel"*
Union Carbide--"Dynel"*

POLYAMIDES
Allied Chemical--"Caprolan 6"*
American Enka--Enka nylon 6
Chemstrand--Chemstrand 6.6
DuPont--nylon 6.6 "Nomex"* nylon
Nylon Industries--Celanese Nylon
Firestone Synthetic Fibers--Firestone nylon 6
U.S. Rubber--nylon 6.6
Vectra--nylon 6.6 nylon 6

POLYESTERS
American Enka Corporation--Enka Polyester
Beaunit Fibers--"Vycron 2.5"*
DuPont--"Dacron"*
Eastman Chemical--"Kodel 2.4"*
Fiber Industries (Celanese)--"Fortrel"*
Metlon--"Crystal Mist"*
Vectra--Polyester

POLYETHYLENE
Alamo Polymer Corporation--"Reevon"*
American Thermoplastic Products--"Amerfil"*
Dawbarn--"DLP"*
Firestone Synthetic Fibers--Firestone Polyethylene
G.F. Chemicals--"Gerfil"*
Industrial Plastic--"Tuff-Lite-L"*
Vectra--"Wynene"*
Vogt Manufacturing--"Voplex"*

POLYPROPYLENE
Alamo Polymer Corporation--"Reevon"*
American Thermoplastic Products--"Amerfil"*
Dawbarn--"DLP"*
Firestone Synthetic Fibers--Firestone Polypropylene
Hercules Powder--"Herculon"*
Industrial Plastic--"TuffLite-P"*
Vectra --Polypropylene
Vogt Manufacturing--"Voples"*

RAYON VISCOSE
American Enka--"Superenka"*, Fiber 700"
Beaunit Fibers--Beaunit Rayon
Celanese--Celanese Rayon, "Fortisan"*
Courtaulds North American--"Fibro"*
F.M.C. Corporation, American Viscose Div.--"Avisco"*, "Rayflex"*, "Super Rayflex"*, Fiber 40"*, "XL"*
Industrial Rayon--"Lekroset"*, "Tyron"*, "Villwyte"*

SARAN
Dow Chemical--"Rovana"*
Firestone Synthetic Fibers--"Velon"*
Vectra--Saran

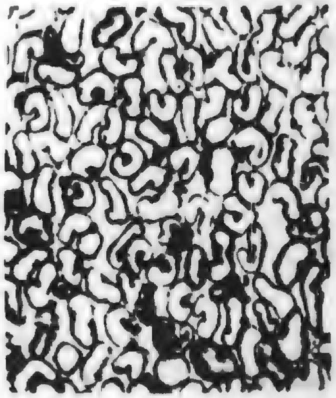
TEFLON
DuPont--"Teflon"*

VINYON
F.M.C. Corporation, American Viscose Division--"Avisco Vinyon HH"*
Rhodia Aceta (France)--"Rhovyl"*
Vogt Manufacturing--Voplex Vinyon

GLASS
Famco--Famco Fiber
Johns Manville--Fiber Glass
Owens-Corning-Fiberglas Corp.--"Fiberglas"*
Pittsburgh Plate Glass--Fiber Glass
Ceramic, Asbestos, Metal

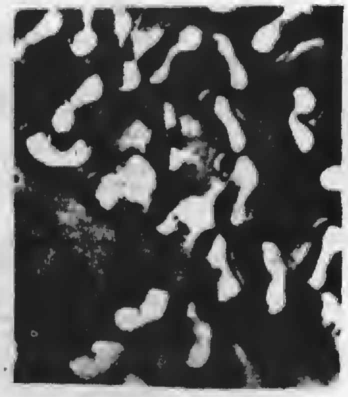
COTTON AND WOOL
Available as natural fibers

* Registered Trade Mark
** from J.P. Stevens, Inc., Ref. 2

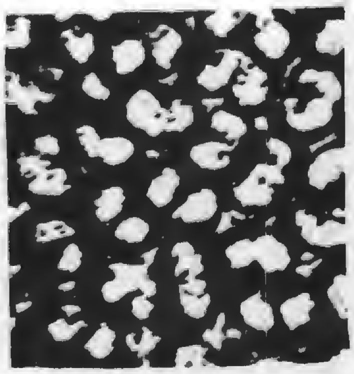


(a) Cotton (X280)

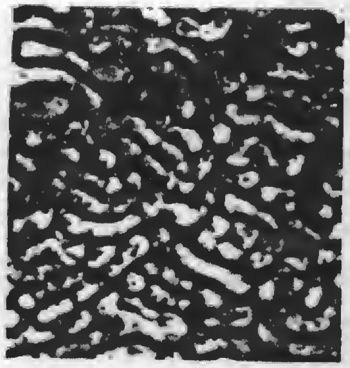
(b) Wool (X410)



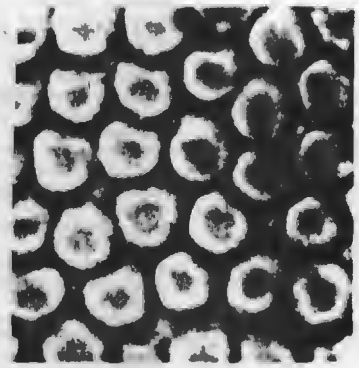
(c) Polyacrylonitrile (Orlon^R) (X380)



(d) Acrylic (Acrilan^R) (X410)

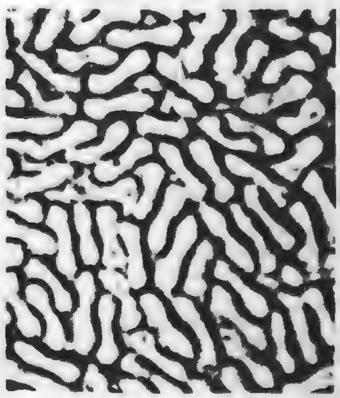


(e) Modacrylic (Dynel^R) (X410)

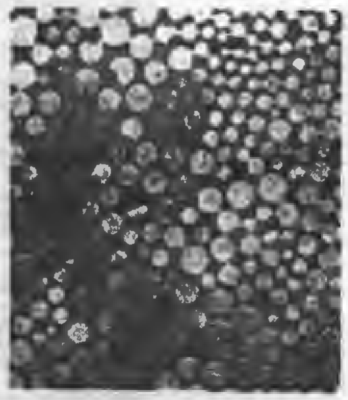


(f) Polyamide (Nylon) (X380)

(g) Polyester (Dacron^R) (X380)



(h) Vinyl (Vinyon) (X380)



(i) Glass (X150)

Figure 4.1. Cross Sections of Filtration Fibers, (From Harris, Ref.4.)

4.2.2 Man-Made Fibers

"Certain (man-made) fibers offer outstanding resistance to acids, others to alkalies. Most are impervious to mildew. Some.... have high temperature resistance so that....operations such as cooling of exhaust gases can be reduced or eliminated. Because of their inherent toughness and resistance to abrasion and other environmental conditions, many....offer substantial overall savings due to increased service life and reduced equipment down-time. The initial cost of fabrics made from (man-made) fibers may be greater than fabrics made from natural fibers. However, the increased service will make them the most economical in the long run.....A careful choice of filter or dust collection fiber for each application can pay dividends in efficiency and economy."[2]

While the chemical processes used to manufacture the various polymeric materials used as filtration fibers may differ,[4,7,8] the fibers themselves are made by somewhat similar processes.[3,4,8] The liquid material is spun (wet, dry, or extrusion) to mono- or multifilament, stretched to orient the constituent molecules, then processed into yarn strands; and by spinning, texturizing or through-tow and staple, to yarn.

4.2.2.1 Acrylic Fibers.- An acrylic fiber is designated[9,10] as "A manufactured fiber in which the fiber-forming substance is any long chain---polymer composed of at least 85% acrylonitrile units---", $(-CH_2-\underset{CN}{\overset{}{CH}}-)_n$, the remainder frequently being a copolymer such as vinylidene chloride to provide dye sites. Process steps in the production of acrylic fibers are discussed in References 4 and 7. Among other acrylics commonly used in fabric filtration are Orlon^R and Acrilan^R. Both are somewhat dumbell-shaped in cross section (Figure 4.1) and their surfaces are irregularly striated to various degrees. Acrylic fiber diameters are about 15 to 35 μm.

Characteristics, properties, and available producer's forms are given in Table 4.2. The acrylics offer a good combination of

> "....abrasion resistance and resistance to heat degradation under both wet and dry conditions. An outstanding

TABLE 4-2

CHARACTERISTICS, PROPERTIES, AND FORMS OF ACRYLIC FIBER FOR INDUSTRIAL FILTRATION*

HEAT RESISTANCE:

Dry Heat: Inferior to "Teflon" and Nomex" nylon, which are outstanding in this respect. Inferior to polyesters, but superior to nylon and natural fibers.
Moist Heat: Rated below "Teflon" and "Nomex" nylon, but considerably superior to polyesters, nylon, rayon and natural fibers.

CHEMICAL RESISTANCE:

Acids: Satisfactory resistance to most mineral or organic acids. Superior to polyamides, polyesters and cellulosic fibers but less resistant than other synthetics.
Alkalies: Inferior to most fibers in this respect, except natural protein fibers, silk and wool.
Oxidizing agents: Fair to good resistance to most oxidizing agents. Superior to polyamides, polyethylene and natural protein fibers.
Organic Solvents: Excellent resistance to most common organic solvents. Superior to modacrylics polyethylene, polypropylene vinyon and protein fibers.

PHYSICAL PROPERTIES:
Tenacity and Elongation:

Filament: Dry and wet tenacity ranges from 3.8 to to 4.8 g.p.d. Dry and wet elongation ranges from 13 to 23.

Staple: Dry and wet tenacity ranges from 1.8 to 3.5 g.p.d. Dry and wet elongation ranges from 20 to 55%.

Specific Gravity: 1.12 to 1.18
Abrasion Resistance: Good, but less resistant than polyamides, polyesters, and polypropylene. Superior to "Teflon."

FORMS AVAILABLE:
DuPONT "ORLON"

Staple: 1.5 to 16 denier/filament. Cut lengths 3/4" to 5½". (Can be converted to spun yarns of many sizes).
Tow: 2 to 10 denier/filament.
All of the above are available in bright, semi-dull and black.
CHEMSTRAND "ACRILAN"
Staple: 1 to 15 denier/filament. (Can be converted to spun yarns of many sizes).
Tow: 2 to 8 denier. Available in high shrink form.
AMERICAN CYANAMID "CRESLAN"
Multifilament: Deniers of 75,150 and 200. Semi-dull only. Special industrial 166 denier--10% shrinkage in boiling water.
Staple: 1.5 to 15 denier/filament. Bright and Semi-dull. Regular and high shrink. (Can be converted to spun yarns of many sizes).
FARBENFABRIKEN BAYER AG. "DRALONG T"
Multifilament: 200-800 denier, bright.
Staple: 2-10 denier, white, dull and doped-dyed light green for identification purposes. (Can be converted to spun yarns of many sizes).
RHODIACETA "CRYLOR"
Multifilament: Denier of 100 to 225.
Staple: Not yet available in U.S. Market
DOW CHEMICAL "ZEFRAN"
Staple: 3 and 6 denier per filament cut 2 inches (Can be converted to spun yarns of many sizes).

*from J. P. Stevens & Co., Inc. (Ref 2)

characteristic is the ability of acrylics to withstand a hot acid atmosphere, making this fiber a good choice in the filtration of exhaust gases. Acrylic fabrics are used for dust collection in the manufacture of ferrous and non-ferrous metals, carbon black, cement, lime and fertilizers.

"Other dry filtration or dust collection applications include the drying of raw flour, sand and coal, mining and ore dressing. Wet filtration applications include the manufacture of dyestuffs, paint, varnish, solvents, storage batteries and mineral oil; also galvanizing and copper mining. Acrylic filters function well in the presence of steam, as in heat exchangers.

".....Acrylic fibers made especially for industrial use, such as "Dralon T" and "Crylor," are available as homo-polymers, composed of 100% acrylonitrile units. The homo-polymers offer a good hydrolytic resistance, and are recommended for temperatures of up to 284°F, while copolymers are recommended for temperatures of up to 248°F. Dow Chemical Company's new acrylic fiber is a homo-polymer and will operate in the higher temperature range recommended for homo-polymer acrylic fibers. Wet performance of Dow's new acrylic is maintained to be superior to other acrylic fibers."[2]

4.2.2.2 Modacrylic Fibers.- Modacrylic fiber is designated[9] as "...a manufactured fiber in which the fiber-forming substance is any long chain...polymer composed of less than 85%, but at least 35% by weight of acrylonytrile units..." For example, Dynel[R] is a 40-60 acrylonitrile-vinyl chloride mixture. The cross sections of Dynel fibers resemble dumb-bells, and their surfaces appear uneven.[4]

Although few gas filtration applications use modacrylics, the one most used for filtration and dust collection is manufactured by Union Carbide Chemicals under the trade name 'Dynel'. 'Verel' (Eastman Chemical Products) is also an important available modacrylic fiber. (Other producers are indicated in Ref. 3.) "Modacrylics have good chemical and abrasion resistance generally, offer excellent dimensional stability and are unaffected by many acids and alkalies, even at high concentrations. Water has no adverse effect on the fiber which retains over 95% of its strength when wet. Dry and moist heat degrade modacrylic more than the other fibers discussed in the brochure, with the exception of vinyon."[2] Characteristics and properties of modacrylic fiber are given in Table 4.3.

4.2.2.3 Nylon, Polyamide.- Nylon fiber is designated[9] as.... "a manufactured fiber in which the fiber-forming substance is any long chain...polymer having recurring amide groups...$(-\underset{\substack{\| \\ O}}{C}-NH-)$...as an integral part of the polymer chain." Table 4.4 indicates the basic polymer in the several types of nylon currently available. Nylon fibers are cylindrical, as shown earlier in Figure 4.1, with smooth surfaces devoid of markings. The fibers are uniform in diameter (10 μm and upward) and appear round in cross section. Continuous filaments and staple fibers (1 to 5 in. long) are produced.[4]

> "Three types of nylon are available for filtration: Nylon 6,6 (DuPont, Celanese and Chemstrand), Nylon 6 (Allied Chemical, Enka and Firestone) and 'Nomex' nylon (DuPont).
>
> " 'Nomex' nylon differs considerably from the other types, and therefore is treated separately.
>
> "Nylon 6,6 and nylon 6 have similar characteristics, except that the latter has a lower melting point and somewhat poorer heat resistance at extreme temperatures. Possibly for this reason, and because nylon 6,6 was introduced in this country before nylon 6, the former is used more widely in filtration. Where elevated temperature is not a factor, however, it would seem that the two types would give comparable service.
>
> "Because of nylon's high abrasion resistance, it is used in filtration of abrasive dusts or wet abrasive solids at low temperatures. Nylon's good elasticity makes it ideal for conditions where continuous flexing takes place. This fiber is a good choice in wet filtration applications, at low temperatures and in an alkaline atmosphere, for example in dyestuffs. Fabrics of nylon provide good cake discharge."[2]

The general characteristics and properties of nylon fibers in use for filtration are indicated in Table 4.5.

TABLE 4.3

CHARACTERISTICS, PROPERTIES AND FORM OF MODACRYLIC FIBER FOR INDUSTRIAL FILTRATION*

HEAT RESISTANCE:

Dry Heat: Shrinkage starts at 250°F but can be heat stabilized at higher temperatures below the stiffening state. For prolonged use, 180°F should be considered maximum. Surpasses acetate, polyethylene, saran and vinyon in heat resistance, but inferior to other fibers. This fiber will not support combustion.
Moist Heat: As with most fibers, moist heat has more effect on the fiber than dry heat.

CHEMICAL RESISTANCE:

Acids: Little effect even at high concentrations for most mineral and organic acids, including aqua regia, chromic acid, nitric acid, phosphoric acid and sulfonic acid. Can be used in the presence of moderate concentrations of nitric and sulfuric acids. Adversely affected by phenol and high concentrations of acetic acid.
Alkalies: The fiber has good alkaline resistance under most conditions.
Oxidizing Agents: Excellent resistance to nearly all oxidizing agents.

Organic Solvents: Softens or dissolves in warm acetone and some other ketones, otherwise would be considered good for organic solvents. Not affected by dry cleaning solvents or gasoline.

PHYSICAL PROPERTIES:

Tenacity and Elongation: Depending on type 2.4 to 3.0 g.p.d. dry and wet tenacity. Dry and wet elongation ranges from 32 to 39%.
Specific Gravity: 1.30 to 1.37.
Abrasion Resistance: Good, but inferior to polyamides, including "Nomex" nylon, polyesters and polypropylene. Superior to "Teflon."

FORMS AVAILABLE:

Staple Only:

EASTMAN ("VEREL") 3-24 denier. (Can be converted to spun yarns of many sizes).
UNION CARBIDE ("DYNEL") 2-24 denier. (Can be converted to spun yarns of many sizes).

*from J. P. Stevens & Co., Inc., Ref. 2

TABLE 4.4

CHEMICAL COMPOSITION OF POLYAMIDES

Nylon-4	Pyrrolidone
5	Valerolactum
6	Caprolactum
6T	Hexamethylene terephthalamide (aromatic)
7	Heptanoamide
8	Caprylamide
9	Amino-nonanic acid
11	Amino-undecanoic acid
12	Lauryl lactum from butadiene
66	Hexamethylene adipamide
68	Hexamethylene-diamine and suberic acid
610	Hexamethylene diamine and sebacic acid
MXD-6	Metaxylylene adipamide (aromatic)

4.2.2.4 Nomex^R Nylon.- Nomex Nylon is a proprietary aromatic-polyamide linked structure developed by DuPont for applications requiring good dimensional stability and heat resistance. "Nomex can be used at temperatures at which other fibers melt. Unlike glass, it is resistant to fluorides and has good abrasion and flex resistance. It has a wide range of filtration applications, including the cement industry, carbon black, non-ferrous metals and steel."[2] Characteristics, properties, and producer forms are indicated in Table 4.6.

4.2.2.5 Olefin.- An olefin fiber is designated as..... a manufactured fiber in which the fiber-forming substance is any long chain... polymer composed of at least 85% by weight of ethylene, propylene, or other olefin units..."[9] Polypropylene is one olefin used for industrial gas cleaning applications.

> "The production of polypropylene fiber varies among the manufacturers....to achieve certain properties, such as dyeability, light stability, heat sensitivity, and shape of the filament cross section. The pro-

TABLE 4.5

CHARACTERISTICS, PROPERTIES, AND FORMS OF NYLON FIBER FOR FILTRATION*

HEAT RESISTANCE:

Dry Heat: Up to 250°F. nylon has reasonably good dry heat resistance. It is superior to acetate, modacrylic and saran. However, the other synthetics are superior to it.
Moist Heat: Nylon performs adequately in moist heat at temperatures ranging up to 225°F. However, its high initial tensile strength and abrasion resistance will make it a preferred choice in a number applications.

CHEMICAL RESISTANCE:

Acids: Most mineral acids cause degradation and partial decomposition. Soluble in formic acid.
Alkalies: Good resistance to alkalies under most conditions. In this respect nylon is better than acrylics but not as good as the olefins.
Oxidizing Agents: High concentrations and temperatures may cause complete degradation.
Organic Solvents: Withstands common organic solvents very well. Some phenolic compounds cause solubility.

PHYSICAL PROPERTIES:

Tenacity and Elongation: Both nylon 6 and nylon 6.6 are produced in a wide range of strengths.
Filament: Dry and wet tenacity ranges from 4.0 to 9.2 g.p.d. with dry and wet elongation running from 16 to 42%.
Staple: Dry and wet tenacity ranges from 3.5 to 7.2 g.p.d. with dry and wet elongation running from 16 to 50%.

Specific Gravity: 1.14.
Abrasion Resistance: One of nylon's outstanding characteristics is abrasion resistance and in this respect nylon is superior to all other fibers.

FORMS AVAILABLE:
NYLON 6.6:
Monofilament: 7 to 30 denier
Multifilament: deniers of 20,30,40,50,60,70,80,90,100,140,200,260,400,420,520,630,780,800,840,1050,1260,1680.
(NOTE: The underlined deniers are those that are used most often).
Staple: 1.5 to 18 denier/filament. (Can be converted to spun yarns of many sizes).
Tow: 3 to 18 denier/filament
Above forms available in bright, semi-dull, dull and black.
NYLON 6:
Monofilament: 15 to 20 denier
Multifilament: deniers of: 30/40/50/70/100/140/200/840/1050/1260/2100/2400/2500/3150/3360/4200/5000/7500/10,000/15,000
Staple: 2.0 to 15 denier/filament. (Can be converted to spun yarns of many sizes).

*from J. P. Stevens & Co., Inc. Ref. 2

TABLE 4.6

CHARACTERISTICS, PROPERTIES, AND FORMS OF NOMEX[R] NYLON FIBER FOR INDUSTRIAL FILTRATION*

HEAT RESISTANCE:

Dry Heat: "Nomex" nylon does not melt, but at temperatures above 700°F degradation sets in rapidly. In dry heat, up to and including 450°F., this fiber may be used satisfactorily, as long as there is no acid dew point problem.

Moist Heat: Small amounts of water vapor at elevated temperatures, and in intimate contact with water or saturated steam, "Nomex" nylon exhibits a progressive loss in strength. However, it withstands these conditions much better than Nylon 6.6 or many other fibers.

CHEMICAL RESISTANCE:

Acids: Withstands both mineral and organic acids much better than nylon 6.6 or nylon 6 but not as well as polyesters and acrylics.

Alkalies: Excellent resistance to alkalies at room temperature (better than polyesters and acrylics) but degraded by strong alkalies at elevated temperatures.

Oxidizing Agents: Like nylon 6.6 or nylon 6, "Nomex" is degraded by oxidizing agents.

Organic Solvents: Highly resistant to most hydrocarbons and many other organic solvents.

PHYSICAL PROPERTIES:

Tenacity and Elongation: Dry tenacity: 5.5 g.p.d. Wet tenacity: 4.1 g.p.d. Dry elongation: 18% Wet elongation: 15%.

Specific Gravity: 1.38

Abrasion Resistance: Superior to acrylic fibers and about equal to polyesters and nylon 6.6.

FORMS AVAILABLE:

Multifilament: Deniers of 100,200 and 1200.

Staple: 2 denier/filament (can be converted to spun yarns of many sizes).

Both filament yarn and staple are available in natural (off-while), international orange and olive green.

* J. P. Stevens & Co., Inc., Ref. 2

duction of polypropylene fiber results in a relatively economical and inexpensive fiber because the basic substance from which it is made is propylene gas--a by-product of petroleum distillation. The most costly aspect is the manufacturer's initial investment in research and plant establishment."[8]

"Polypropylene combines the virtues of lightness, high strength and excellent resistance to most acids and alkalies with the important added attraction of low cost. Having the lowest density of any synthetic fiber in filtration and dust collection, polypropylene offers the greatest cloth yield per pound of yarn and is one of the most economical synthetics.

Polypropylene fibers are manufactured under such trade names as "herculon" (Hercules), "Reevon" (Alamo Polymer) and "Vectra" (National Plastic Products).

The sleekness of the fiber allows for a fabric providing good cake discharge and resistance to blinding. Since its moisture absorption is virtually nil, polypropylene is a good choice for an application such as dye production, where pigment changes can be made with only a light wash between batches.

"Polypropylene has been used successfully at 165°F in the greige, and in the heat set stage at up to 250°F."[2]

Characteristics, properties, and producer forms are given in Table 4.7.

4.2.2.6 Polyester.- A polyester fiber is designated as

"...a manufactured fiber in which the fiber-forming substance is any long chain...polymer composed of at least 85% by weight of an ester of dihydric alcohol and terephthalic acid (p - HOOC - C_6H_4 - COOH)...."[9]

The general characteristics of this material, which is a commonly used dust collection fabric particularly in the cement industry, are presented in Table 4.8. The Dacron^R polyester fibers are round (see Figure 4.1), but variation in shape of the spinnaret holes will affect the appearance

TABLE 4.7

CHARACTERISTICS, PROPERTIES, AND FORMS OF POLYPROPYLENE FIBER FOR INDUSTRIAL FILTRATION*

HEAT RESISTANCE:

Dry Heat: Polypropylene has the lowest heat resistance of all the synthetics except the modacrylics, and loses tenacity in direct proportion to increases in temperature. It should be remembered, however, that the fiber's very high initial tenacity will leave a generous margin for many applications.
Moist Heat: Since polypropylene is non-hygroscopic, its heat degradation characteristics are essentially the same under moist conditions as they are under dry conditions.

CHEMICAL RESISTANCE:

Acids: Very good resistance to both mineral and organic acids. Attacked at high temperatures by nitric acid and chlorasulfonic acid.
Alkalies: Generally good, except poor resistance to sodium and potassium hydroxide at high temperatures(above 200oF) at high concentrations.
Reducing Agents: Good resistance to most reducing agents.
Organic Solvents: Good resistance to most organic solvents. Exceptions are ketones, esters, aromatic and aliphatic hydrocarbons at high temperatures. Soluble at 160°F in chlorinated hydrocarbons.

PHYSICAL PROPERTIES:

Tenacity and Elongation:
Filament: Dry and wet tenacity 4.8 to 8.5 g.p.d. with dry and wet elongation 15 to 30%
Staple: Dry and wet tenacity ranges from 4.5 to 6.0 g.p.d. with dry and wet elongation 15 35%.
Specific Gravity: 0.90 to 0.91 are of the lowest specific gravities of any fiber.
Abrasion Resistance: Excellent abrasion resistance wet and dry.

FORMS AVAILABLE:

Monofilament: 6 to 12 mils round and flat.
Multifilament: 165 to 4000 denier.
Staple: 1.5 to 15 denier. (Can be converted to spun yarns of many sizes)
Available in natural and solution dyed colors.

*from J. P. Stevens & Co. Inc., Ref. 2

TABLE 4.8. CHARACTERISTICS, PROPERTIES AND FORMS OF POLYESTER FIBERS FOR INDUSTRIAL FILTRATION*

HEAT RESISTENCE:

Dry Heat: Polyesters are not comparable to "Teflon" and "Nomex" nylon, which have usually high heat degradation resistance, but they are superior to most other synthetics in this respect, though subject to hydrolytic degradation under certain circumstances. However, polyesters are used for filtration and dust collection under conditions of wet heat, particularly where the initial yarn strength exceeds minimum re-requirements sufficiently to allow for hydrolysis. Below 350°F there is little shrinkage of polyester fiber.

CHEMICAL RESISTANCE:

Acids: Good resistance to most mineral and organic acids except high concentrations of nitric, sulfuric and carbolic acids.
Alkalies: Good resistance to weak alkalies and moderate resistance to strong alkalies at low temperatures. Strong alkalies at high concentrations and temperatures dissolve polyesters.
Oxidizing Agents: Good resistance to most oxidizing agents.
Organic Solvents: Excellent to most organic solvents, but unsuited for some phenolic compounds and affected by cyclohexanone at 313°F.

PHYSICAL PROPERTIES:

Tenacity and Elongation:
Filament: Dry and wet tenacity ranges from 4.4 to 7.8 g.p.d. Dry elongation from 10 to 25%. Water has little effect on either the strength or elongation of polyester fibers.
Staple: Dry and wet tenacity ranges from 2.2 to 5.5 g.p.d. Dry and wet elongation from 18-50%.
Specific Gravity: 1.35 - 1.38.
Abrasion Resistance: Polyester fibers have excellent abrasion resistance ranking next to nylon in this respect.

FORMS AVAILABLE:

Multifilament: Deniers of 30, 70, 100, 140, 150, 220, 250, 420, 440, 840, 880, 1000, 1100, 1680, and multiples of 1100 up to 16,500.
Staple: 1.5, 2.25, 3.0, 4.5, 6.0 8.0, 15. (Can be converted to spun yarns of many sizes).
Direct Spun Yarn: From 4s/1 to 30s/1.

*From J. P. Stevens & Co., Inc., Ref. 2.

and mechanical properties of the fiber, as will the extent to which the fiber is drawn. The usual diameters are 10 to 30 μm. The following quotation provides some additional information on this material.

> "Polyester fibers are manufactured under such trade names as "Dacron" (DuPont), "Fortrel" (Fiber Industries/Celanese), "Vycron" (Beaunit), "Kodel" (Eastman Chemical Products) and Enka Polyester (American Enka Corporation). They can be woven into filter and dust collection fabrics affording very good resistance to chemicals, abrasion and dry heat degradation, plus excellent dimensional stability."[2]

4.2.2.7 Teflon[R] Fluorocarbon.- The characteristics, properties and forms of these fibers are summarized in Table 4.9 and described in the following quotations.

> "Teflon - Dupont's trade name for their fluorocarbon fibers - is available in two forms. The multi-filament yarns are made from the homo-polymer polytetrafluoroethylene (TFE). The monofilament yarns are produced from the co-polymer of tetrafluoroethylene and hexafluoropropylene (FEP). Both polymers are composed of long-chain molecules in which all of the available bonds are completely saturated by fluorine. These carbon-to-fluorine bonds are extremely strong, resulting in fibers which are exceptionally stable to both heat and chemicals. Teflon fiber has no known solvents except certain perfluorinated organic liquids at temperatures above 570°F. The fiber is inert to concentrated mineral acid, organic acid, alkalies, oxidizing agents and organic solvents at elevated temperatures.
>
> "The fiber remains flexible and non-brittle from minus 100°F to plus 550°F. Teflon withstands prolonged exposure at 450°-500°F without degradation. Above this temperature some decomposition results but even at 500°-550°F decomposition is slow. The gaseous decomposition products evolved at high temperatures are highly toxic and must be removed from the work areas through adequate ventilation.
>
> "Teflon fibers have a very low coefficient of friction resulting in excellent cake discharge. This fact, coupled with its chemical inertness and resistance to dry and moist heat degrada-

TABLE 4.9. CHARACTERISTICS, PROPERTIES AND FORMS OF TEFLON[R] FIBER FOR INDUSTRIAL FILTRATION*

HEAT RESISTANCE:

Dry Heat: "Teflon" TFE can be used in continuous service up to 500°F. "Teflon" FEP can be used in continuous service up to 450°F.
Moist Heat: Due to zero moisture absorption, these fibers withstand moist heat temperatures about as well as dry temperature.

CHEMICAL RESISTANCE:

Acids: Inert
Alkalies: Inert
Oxidizing Agents: Inert
Organic Solvents: Inert
The only substances known to react with these fibers are alkali metals fluorine gas at high pressure and temperature, and chlorine trifluoride. This is the most chemically resistant fiber produced.

PHYSICAL PROPERTIES:

Tenacity and Elongation:
Filament and Staple: Dry and wet tenacity for type TFE is 1.6 g.p.d and for type FEP is 0.5 g.p.d. Dry and wet elongation is 15%.

Specific Gravity: 2.1
Abrasion Resistance: Teflon fibers are inferior in abrasion resistance to the acrylic, nylons and polyester fibers, but are superior to glass fibers.

FORMS AVAILABLE:
"TEFLON" TFE
Filament Natural Brown
100/200/400/1200 denier.
2400 up to 26,400 denier plied yarns
Filament Bleached White
225/450/1350 denier.
2700 up to 29,700 denier plied yarns
Staple Natural Brown
6.67 denier/filament
Staple Bleached White
7.50 denier/filament
Staple available in cut lengths of 0.5" up to 5.0" in 0.5" increments (Can be converted to spun yarns of many sizes).
"TEFLON" FEP
Monofilaments (clear, colorless)
3/5/8/11/16/20/32/50/60 mils.

*from J. P. Stevens & Co., Inc., Ref. 2

tion, makes Teflon suitable for filtration and dust collection under severe conditions. Its major weakness is abrasion resistance in which Teflon is inferior to all other synthetic fibers except glass. The high price of Teflon fiber limits its use in the filtration field. However, for uses under extreme temperature conditions, Teflon may prove to be most economical in the long run. It would further be expected that as the demand for Teflon increases and production expands, the price of Teflon will decline."[2]

4.2.2.8 Vinyon.- Vinyon fiber is designated[9] as ..."a manufactured fiber in which the fiber-forming substance is any long chain... polymer composed of at least 85% by weight of vinyl chloride units ($-CH_2-CH C\ell-$)". The characteristics, properties and producer forms of the fiber are presented in Table 4.10. The following quotations summarize these characteristics.

> "Characteristic of vinyon fibers is the dumbbell shape of their cross sections....Fibers with an occasional twist are observed. Both continuous filaments and stable fibers (1-5 in.) occur in trade, the width of all types being 16 to 18 μ."[4]
>
> "Vinyons are made of 100% polyvinyl chloride by the French Societe Rhovyl, and as a copolymer of polyvinyl chloride and polyvinyl acetate by the FMC Corp., American Viscose Division. Vinyons offer very good resistance to most chemicals, even in highly concentrated form. They can be made into fabrics providing extremely smooth cake discharge, and are used for filtration of air and (numerous liquids)."[2]

4.2.2.9 Glass.- Glass fiber is a product of fusion, a non-crystalline silicate analogous to other fiber polymeric materials, ($-SiO_4-$). Selected silica sands, limestone, soda ash, and borax or other ingredients are melted at about 2500°F and the mixture is extruded through spinnarets. The resulting filaments may be drawn while still molten and later twisted and plied into filament yarn. Or, the extruded glass may be drawn and broken by jets of compressed air into staple of lengths 8 to 15 inches.

TABLE 4.10. CHARACTERISTICS, PROPERTIES, AND FORMS OF VINYON FIBER FOR INDUSTRIAL FILTRATION*

HEAT RESISTANCE:

Dry Heat: The maximum working temperature for Rhovyl's type "Clevyl T" is 350°F., provided the fabric is clamped to prevent shrinkage.

Moist Heat: Due to vinyon's low water absorption the effects of moist heat are similar to those of dry heat.

CHEMICAL RESISTANCE:

Acids: Excellent resistance at room temperature to mineral acids, including hydrochloric, nitric, and sulphuric acids, aqua regia and organic acids with the exception of carbolic acid.

Alkalies: Very good resistance to alkalies such as potassium hydroxide, sodium hydoxide and ammonium hydroxide.

Organic Solvents: Dissolved by ketones, and partially dissolved or softened by esters and ethers. Certain other organic solvents cause swelling at certain temperatures. In general, this fiber should not be considered for use with most organic solvents other than mineral oil, aliphatic hydrocarbons, alcohols and glycols.

PHYSICAL PROPERTIES:

Tenacity: Filament and Staple:
"Clevyl T" (Dimensionally stable to 212°F) Staple 1.7 to 2.0 g/d
"Type 55" (55% shrinkage at 212°F) Filament 2.7 to 3.0 g/d.

Abrasion Resistance: Not as resistnat as polyesters or nylons, but comparable to the acrylics.

Specific Gravity: 1.34-1.38

FORMS AVAILABLE:

RHOVYL STAPLE:
"Clevyl T" (Dimensionally Stable to 212°F) 3.5/5/8/15 d/fil.
"Type 30" (30% shrinkage at 212°F) 3d/fil.
"Type 55" (55% shrinkage at 212°F) 1.8/3.0/6.4 d/fil.

RHOVYL FILAMENT:
"Type 55" only: 75/100/200/400 800/1600 denier.

FMC VINYON H.H. STAPLE ONLY
Deniers of 1.5 to 5.5 staple lengths of 1/2 inch to 2 inches but not in all deniers. (Can be converted to spun yarns of many sizes)

*From J. P. Stevens & Co., Inc., Ref. 2

The fibers are then treated with a lubricant which is of great importance in the durability of the eventual fabric. Following drying, the fibers are processed much like the more conventional fibers.

Glass fiber photomicrographs are shown in Figure 4.1. The fibers are perfectly round with very smooth and structureless surfaces. Diameters range from 5 to 16 μm for most textile fibers. Characteristics and forms of glass fibers are given in Table 4.11.

4.2.2.10 Other Man-Made Fibers.- Other generic organic fiber materials that could be used for industrial gas filtration include acetate and triacetate (cellulose acetate), rayon (regenerated cellulose), manufactured rubber, saran (vinylidene chloride), and vinal (vinyl alcohol). They appear to offer no significant advantages for industrial gas filtration in most instances, although saran has some application in spray tower mist elimination. (Other unclassified fibers are summarized in Ref. 3, pp. 218-221).

Several fiber materials and finishes are currently available in pilot plant quantities having potential for high temperature applications or control of electrostatic effects in fabrics. Some metals and ceramics having potential filtration uses are summarized in Appendix 4.2.[3] Fiberfrax[R], and Brunsmet[R], have been laboratory tested and found satisfactory for filtration at high temperatures (> 1000°F), but require further development in filtration systems.

4.2.3 Physical and Chemical Properties

Relative physical and chemical properties of filter fiber materials are summarized in Tables 4.12, 4.13 and 4.14. Table 4.13 shows general quantitative physical properties and a qualitative estimate of chemical, heat, and abrasion resistance.[2] Where both high and low tenacity fibers are produced, the range of strength and breaking elongation is given. Since many fibers are produced in both filament and staple fibers, the general physical properties are shown separately for each form. Fiber resistance to specific chemical compounds is indicated in

TABLE 4.11

CHARACTERISTICS, PROPERTIES, AND FORMS OF GLASS FIBERS FOR INDUSTRIAL FILTRATION*

HEAT RESISTANCE	Fabrics made from glass yarns actually gain in strength as the temperature rises from room temperature to 400°F. From that point, strength and flexibility decrease. The recommended operating temperature is 500°F with surge limits up to 600°F
CHEMICAL RESISTANCE	Glass is resistant to acids of normal strength and under ordinary conditions. It is attacked by hydrofluoric, concentrated sulphuric, and hot phosphoric acids. Overall resistance to acids is slightly above average. Hot solutions of weak alkalies will also attack glass. Overall resistance to alkalies is poor. Operating a glass baghouse at or below the dew point can be particularly damaging if acid anhydrides or metallic oxides are entrained in the gas stream. Fluorides and the oxides of sulfur are particularly damaging to glass.
PHYSICAL PROPERTIES	Glass is considered to be incombustible because it is completely inorganic. In addition, it has a low coefficient of linear expansion and hence is dimensionally stable. Although glass has an extremely high tensile strength it has poor flex-abrasion resistance. Various chemical treatments to the glass fabric improve the flex-abrasion characteristics of glass bags.
FORMS AVAILABLE	Filament Filament and Textured Filament and Spun

*From Albany Felt Co., Ref. 11.

TABLE 4.12. RELATIVE PROPERTIES OF MAN-MADE FIBERS*

Resistance to Acids
"Teflon"
Polypropylene
Vinyon
Modacrylics
Acrylics
Polyesters
"Nomex" nylon
Nylon 6.6 & 6
Rayon

Resistance to Alkalies
"Teflon"
Polypropylene
Vinyon
Modacrylics
Nylon 6.6 & 6
"Nomex" nylon
Polyesters
Rayon
Acrylics

Resistance to Oxidizing and Reducing Agents
"Teflon"
Polypropylene
"Nomex" nylon
Modacrylics
Polyesters
Acrylics
Nylon 6.6 & 6
Vinyon
Rayon

Tensile Strength
Nylon 6.6 & 6
Polyesters
Polypropylene
"Nomex" nylon
Rayon
Acrylics & Modacrylics
Vinyon
"Teflon"

Resistance to Abrasion (Wet & Dry)
Nylon 6.6 & 6
Polypropylene/Polyesters
"Nomex" nylon
Acrylics & Modacrylics
"Teflon"
Rayon
Vinyon

Resistance to Dry Heat
"Teflon"
"Nomex" nylon
Polyesters
Acrylics/Rayon
Nylon 6.6
Nylon 6
Polypropylene
Modacrylics
Vinyon

Resistance to Moist Heat
"Teflon"
"Nomex" nylon
Acrylics
Nylon 6.6 & 6
Rayon
Polyesters
Polypropylene
Modacrylics
Vinyon

Max. Recommended Operating Temp. (F.) For Continuous Service

"Teflon"	500°
"Nomex" nylon	450°*
Polyesters	300°*
Acrylics (homopolymers)	284°
Acrylics	275°
Rayon	275°
Nylon 6.6	250°*
Nylon 6	250°*
Polypropylene	225°
Modacrylics	180°

Price Relationship (Per Pound)** (Highest to Lowest)

STAPLE	FILAMENT
"Teflon"	"Teflon"
"Nomex" nylon	"Nomex" nylon
Glass	Acrylics
Nylon 6.6 & 6	Modacrylics
Polyesters	Polyesters
Acrylics	Nylon 6.6 & 6
Modacrylics	Glass
Vinyon (Rhovyl)	Vinyon (Rhovyl)
Polypropylene	Polypropylene
Viscose Rayon	Viscose Rayon

* These fibers are subject to hydrolysis when exposed in hot, wet atmospheres in varying degrees. Polyesters degrade to the greatest extent. "Nomex" nylon next, then nylon 6, and nylon 6.6 least.
The following is quoted from DuPont's NP-33, "Properties of 'Nomex'." "At elevated temperatures, "Nomex" fiber in intimate contact with water or saturated steam exhibits a progressive loss in strength with water vapor. (Nylon 6,6 completely deteriorates in less than 100 hours under the same conditions)"

** Based on prices per pound at time of publication (1965 est) - See Chapter 7.

* From J. P. Stevens and Co., Inc., Ref. 2.

TABLE 4.13

SUMMARY OF PHYSICAL AND CHEMICAL PROPERTIES OF INDUSTRIAL FILTER FIBERS*

	Acetate	Acrylics	Creslan*	Crylor*	Dralon T*	Orlon*	Modacrylics	Polyamides
FILAMENT								
Breaking Tenacity gpd (Dry)	1.2 1.5	3.8 4.8	3.8	4.2	4.2 4.8			4.1 9.2
Breaking Tenacity gpd (Wet)	0.8 1.2	3.8 4.6	3.8	4.0	4.0 4.6			4.0 7.9
Breaking Elongation % (Dry)	23 44	13 23	23	14	13 15			16 40
Breaking Elongation % (Wet)	30 54	13 23	23	14	13 15			28 42
STAPLE								
Breaking Tenacity gpd (Dry)	1.2 1.5	2.0 3.5	2.0 3.5		3.0 3.5	2.2 2.6	2.5 3.0	3.8 7.2
Breaking Tenacity gpd (Wet)	0.8 1.2	1.8 3.3	1.8 3.2		2.9 3.3	1.8 2.1	2.4 3.0	3.5 6.1
Breaking Elongation % (Dry)	35 40	20 50	40 50		30 33	20 28	33 39	16 50
Breaking Elongation % (Wet)	30 45	26 55	45 55		30 33	26 34	32 39	18 46
Specific Gravity	1.33	1.18	1.18	1.12	1.15	1.14	1.30	1.14
Max Recommended Operating F	175	275	275	275	284	275	180	250
Resistance to Abrasion	G	G	G	G	G	G	G	E
Resistance to Dry Heat	F	G	G	G	G	G	F	G
Resistance to Moist Heat	F	G	G	G	E	G	F	G
Resistance to Mineral Acids	P	G	G	G	G	G	G	P
Resistance to Organic Acids	P	G	G	G	G	G	G	F
Resistance to Alkalies	P	F	F	F	F	F	G	G
Resistance to Oxidizing Agents	F	G	G	G	G	G	G	F
Resistance to Solvents	F	E	E	E	E	E	G	E

	Nomex* Nylon	Polyesters	Dacron*	Kodel*	Vycron*	Polyethylene	Polypropylene	Rayon Viscose	Saran	Teflon	Vinyon	Glass	Paper	Cotton	Silk	Wool
FILAMENT																
Breaking Tenacity gpd (Dry)	5.5	4.4 7.8	4.4 7.8		4.6 5.4	1.0 7.0	4.8 8.5	1.5 5.7	1.1 2.3	1.6	0.7 3.0	6.0 7.3			3.8	
Breaking Tenacity gpd (Wet)	4.1	4.4 7.8	4.4 7.8		4.6 5.4	1.0 7.0	4.8 8.5	0.7 3.6	1.1 2.3	1.6	0.7 3.0	3.9 4.7				
Breaking Elongation % (Dry)	18	10 25	10 25		19 25	10 80	15 30	9 30	15 30	15	12 15	3			17	
Breaking Elongation % (Wet)	15	19 25	19 25		19 25	20 80	15 30	14 40	15 25	15	12 15	2.5				
STAPLE																
Breaking Tenacity gpd (Dry)	5.3	2.2 5.5	2.2 4.0	2.5 5.5	5.3 5.4		4.5 6.0	1.5 4.6	1.0 1.5	1.6	0.7 3.0			3.0 4.9		1.0 1.7
Breaking Tenacity gpd (Wet)	4.0	2.2 5.5	2.2 4.0	2.5 5.5	5.3 5.4		4.5 6.0	0.7 3.6	1.0 1.5	1.6	0.7 3.0			3.3 6.4		0.8 1.6
Breaking Elongation % (Dry)	19	18 50	18 50	24 45	32 40		15 35	9 30	15 25	15	40 60			3 7		25 35
Breaking Elongation % (Wet)	16	18 50	18 50	24 45	32 40		15 35	14 40	15 25	15	40 60			3 7		25 50
Specific Gravity	1.38	1.38	1.38	1.38	1.38	.92	.90	1.52	1.70	2.10	1.34	2.54		1.50	1.25	1.32
Max Recommended Operating F	450	300	300	350	300	150	225	275	1.60	500	350	550	200	225	175	200
Resistance to Abrasion	E	E	E	E	E	G	E	G	G	F	G	P	F	G	G	G
Resistance to Dry Heat	E	G	G	G	G	F	G	G	F	E	P	E	F	G	F	F
Resistance to Moist Heat	E	F	F	F	F	F	F	G	F	E	P	E	F	G	F	F
Resistance to Mineral Acids	F	G	G	G	G	G	E	P	G	E	E	E	P	P	F	F
Resistance to Organic Acids	E	G	G	G	G	G	E	G	G	E	G	E	G	G	F	F
Resistance to Alkalies	G	G	G	G	G	G	E	F	G	E	G	P	G	G	P	P
Resistance to Oxidizing Agents	G	G	G	G	G	P	G	F	F	E	F	E	F	F	P	P
Resistance to Solvents	E	E	E	E	E	G	G	G	G	E	F	E	E	E	G	F

E —Excellent
G—Good
F—Fair
P —Poor

*From J.P. Stevens & Co., Inc., Ref. 2.

Table 4.14. (Additional detailed engineering test data on fiber properties is presented in Appendix 4.3.[2,12]).

> "It is possible that a fiber indicated as being fair within a general chemical class (in Table 4.13) may be rated as good for a particular chemical within the general grouping. Each fiber has its own strong and weak points and must be evaluated on its own merits."[2]

The evaluation of the resistance of fibers to chemical reagents presented in Table 4.14 is based on liquid filtration requirements. However, the data presented in the table have direct applicability to dust filtration as the time, temperature, chemical concentration, type of polymer, treatment of fabric, etc., all have their effect on final selection of a filter or dust collection medium. For these reasons, tests should be made under operating conditions, as a composite table cannot cover all possible conditions to which a filter or dust collection fabric may be subjected.

The maximum temperature, degrees Fahrenheit ($^{\circ}F$), as enumerated in Table 4.14 is the maximum temperature that should be employed normally for dust collection or liquid filtration of dilute solutions. A fiber marked R (recommended) can be expected to usually withstand most conditions reasonably well. S (satisfactory) fibers should be considered only for low concentrations and moderate temperatures. N (not recommended) fibers can be expected to give poor results under any conditions.

> "Chemical composition of synthetic fibers greatly affect their chemical resistance. This is true within a generic family as well as from one type of fiber to another. Chemical resistance of a co-polymer fiber is usually lower than that of a pure homo-polymer base fiber. The co-mono-mers used to form "links" are particularly sensitive to external effects....
>
> Using acrylic fibers as an example, in acidic or oxidizing solutions, in dry or humid air between 275°-$350^{\circ}F$, the difference in behavior between homo- and co-polymers becomes very important. The homo-polymer is superior. The influence of composition of the basic acrylic polymer has little effect when considering organic solvents, weak acids, most mineral salt solutions and cleaning or bleaching agents. In alkaline media up to intermediate concentrations and tempera-

TABLE 4.14

RESISTANCE OF FIBERS TO CHEMICAL REAGENTS*

	Acetate	Acrylic	Creslan	Crylor	Dralon T	Orlon	Modacrylic	Nytril	Polyamides Nylon 6 & 6.6	Nomex Nylon	Polyester	Dacron	Polyethylene	Polypropylene	Rayon–Viscose	Saran	Teflon	Vinyon	Glass	Paper	Cotton	Silk	Wool
Max. Temp. Degrees Fahrenheit	175	275	275	275	284	275	180	300	250	450	300	300	150	250	275	180	500	170	550	200	225	175	200
MINERAL ACIDS																							
Aqua Regia	N	S	S	S	S	S	S	–	N	N	S	S	R	R	N	R	R	R	R	N	N	N	N
Chromic	N	R	R	R	R	R	R	R	N	N	R	R	R	S	N	S	R	R	R	N	N	N	N
Hydrochloric	N	R	R	R	R	R	R	R	N	S	R	R	R	R	N	R	R	R	R	N	N	N	S
Hydrofluoric	N	S	S	R	R	R	R	S	N	N	S	S	R	R	N	R	R	R	N	N	N	S	S
Nitric	N	R	R	R	R	R	S	S	N	S	R	R	S	S	N	R	R	R	R	N	N	S	S
Phosphoric	S	S	S	S	R	S	R	R	S	R	R	R	R	R	N	R	R	R	R	N	S	N	S
Sulfuric	N	S	S	S	S	S	S	R	N	S	S	S	R	R	N	S	R	R	R	N	N	S	S
ORGANIC ACIDS																							
Acetic	S	R	R	R	R	R	R	R	S	S	R	R	R	R	R	R	R	S	R	R	R	R	S
Benzoic	N	R	R	R	R	R	R	R	N	S	R	R	R	R	R	R	R	–	R	R	R	R	S
Carbolic	N	R	R	R	R	R	R	–	N	N	S	S	S	–	R	S	R	N	R	R	R	N	S
Formic	N	S	S	S	R	R	R	N	S	S	R	R	R	R	R	R	R	R	R	R	R	R	S
Lactic	S	R	R	R	R	R	R	–	S	S	R	R	R	R	R	R	R	R	R	R	R	S	S
Oxalic	R	R	R	R	R	R	R	S	R	N	R	R	R	R	R	R	R	R	R	R	R	R	S
Salicylic	N	R	R	R	R	R	R	R	S	S	R	R	R	R	N	R	R	–	R	N	N	N	N
BASES																							
Ammonium Hydroxide	S	N	N	N	S	S	S	R	S	S	N	N	R	R	S	S	R	R	S	S	S	N	N
Calcium Hydroxide	N	R	R	R	R	R	R	R	R	R	R	R	R	R	S	R	R	R	S	R	R	N	N
Potassium Hydroxide	N	N	N	N	S	N	S	N	S	S	S	S	R	S	S	S	R	R	N	R	R	N	N
Potassium Carbonate	N	S	S	S	S	S	R	S	R	R	S	S	R	R	S	R	R	R	N	R	R	N	N
Sodium Hydroxide	N	S	S	S	S	S	S	N	S	S	S	S	R	S	S	S	R	R	N	R	R	N	N
Sodium Carbonate	N	R	R	R	R	R	R	S	R	R	R	R	R	R	S	R	R	R	N	R	R	N	N
SALTS																							
Calcium Chloride	S	R	R	R	R	R	R	R	N	S	R	R	R	R	R	R	R	R	S	R	R	S	S
Ferric Chloride	N	R	R	R	R	R	R	–	S	S	R	R	R	R	N	R	R	R	N	N	N	N	N
Sodium Acetate	N	R	R	R	R	R	R	–	R	S	R	R	R	R	R	R	R	R	S	R	R	S	S
Sodium Benzoate	R	R	R	R	R	R	R	–	S	S	R	R	R	R	R	R	R	–	S	R	R	R	R
Sodium Bisulfite	R	N	N	N	N	R	R	–	S	S	R	R	R	R	R	R	R	R	R	R	R	R	S
Sodium Bromide	S	R	R	R	R	R	R	–	R	R	R	R	R	R	R	R	R	–	N	R	R	S	S
Sodium Chloride	R	R	R	R	R	R	R	–	R	R	R	R	R	R	R	R	R	R	N	R	R	R	R
Sodium Cyanide	S	R	R	R	R	R	R	–	S	S	R	R	R	R	R	R	R	–	S	R	R	R	S
Sodium Nitrate	S	R	R	R	R	R	R	–	S	S	R	R	R	R	R	R	R	R	S	R	R	S	S
Sodium Sulfate	S	R	R	R	R	R	R	–	R	R	R	R	R	R	R	R	R	R	S	R	R	S	S
Sodium Sulfide	S	R	R	R	R	R	R	–	R	R	R	R	R	R	R	R	R	R	S	R	R	S	S
Zinc Chloride	S	S	S	S	S	S	R	R	N	S	N	R	R	R	S	R	R	R	N	S	S	S	N
OXIDIZING AGENTS																							
Bromine	S	S	S	S	S	S	S	–	N	–	S	S	N	R	S	N	R	N	R	S	S	N	N
Calcium Hypochlorite	S	R	R	R	R	R	R	R	S		R	R	R	R	S	R	R	R	R	S	S	S	N
Chlorine	S	S	S	S	S	S	R	S	N	–	S	S	N	R	S	N	R	S	R	S	S	N	N
Fluorine	N	S	S	S	S	S	S	–	N	–	S	S	S	R	N	N	R	N	N	N	N	N	N
(Continued)																							

R Recommended for Most Conditions
N Not Recommended
S Satisfactory for Low Concentration and temperature
– Insufficient Data

	Acetate	Acrylic	Creslan	Crylor	Dralon T	Orlon	Modacrylic	Nytril	Polyamides Nylon 6 & 6.6	Nomex Nylon	Polyester	Dacron	Polyethylene	Polypropylene	Rayon–Viscose	Saran	Teflon	Vinyon	Glass	Paper	Cotton	Silk	Wool
Max. Temp. Degrees Fahrenheit	175	275	275	275	284	275	180	300	250	450	300	300	150	250	225	180	500	120	550	200	225	175	200
OXIDIZING AGENTS (Cont.)																							
Hydrogen Peroxide	N	R	R	R	R	R	R	R	S	–	S	R	N	R	S	R	R	N	R	R	R	S	N
Iodine	S	R	R	R	R	R	R	–	N	–	R	R	N	R	R	S	R		R	R	R	R	N
Ozone	–	R	R	R	R	R	R	–	–	–	R	R	S	S		R	R		R	–		–	N
Peracetic Acid	S	S	S	S	S	S	S	–	S	S	–	–	N	R	S	S	R	S	R	S	S	N	N
Potassium Chlorite	–	R	R	R	R	R	R	R	S	S	R	R	R	R	S	R	R	R	R	S	S	N	N
Potassium Permanganate	–	N	N	R	N	R	S	–	S	–	N	R	N	N	S	S	R	R	R	S	S	N	N
Sodium Hypochlorite	N	S	S	S	S	R	R	R	S	–	S	R	S	R	N	R	R	R	R	S	S	N	N
Sodium Chlorate	R	–	–	–	–	–	R	S	–	–	–	–	R	S	S	R	R	R	R	R	R	S	N
ORGANIC SOLVENTS																							
Acetone	N	R	R	R	R	R	N	N	R	R	R	R	S	S	R	S	R	N	R	R	R	R	R
Amyl Acetate	N	R	R	R	R	R	S	R	R	R	R	R	N	S	–	S	R	N	R				
Benzene	R	R	R	R	R	R	R	R	R	R	R	R	N	R	R	S	R	N	R	R	R	R	R
Carbon Bisulfide	R	R	R	R	R	R	S	R	R	R	S	S	R	N	R	S	R	N	R	R	R	R	S
Carbon Tetrachloride	R	R	R	R	R	R	R	R	R	R	R	R	N	S	R	R	R	S	R	R	R	R	S
Chloroform	N	R	R	R	R	R	R	R	R	R	R	R	N	S	R	S	R	N	R	R	R	R	R
Cyclohexanone	–	R	R	R	R	R	S	–	R	R	R	R	S	S		N	R	R	R	–			
Diethylene Glycol	–	R	R	R	R	R	R	–	R	R	R	N	R	R	–	R	–	S	R	–	–		
Ethyl Acetate	N	R	R	R	R	R	R	R	R	R	R	R	N	S	R	S	R	N	R	R	R	R	S
Ethyl Alcohol	R	R	R	R	R	R	S	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	S
Ethyl Ether	R	R	R	R	R	R	R	R	R	R	R	R	S	R	R	N	R	S	R	R	R	R	R
Furfural Alcohol	–	R	R	R	R	R	R	–	–	–	R	R	N	–		R	R	N	R		–	–	
Methanol	R	R	R	R	R	R	S	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Methyl Ethyl Ketone	N	R	R	R	R	R	N	N	R	R	R	R	S	S	–	S	R	N	R	–	–	–	–
Naptha	R	R	R	R	R	R	R	–	R	R	R	R	S	S	R	R	R	S	R	R	R	R	S
Propylene Glycol	–	R	R	R	R	R	R	–	R	R	N	S	S	R	–	R	R	–	R	–	–	–	–
Stoddard Solvent	R	R	R	R	R	R	R	R	R	R	R	R	S	S	R	R	R	S	R	R	R	R	R
Trichloroethylene	N	R	R	R	R	R	R	–	R	R	R	R	S	R	R	R	R	S	R	R	R	R	R
Tri Cresyl Phosphate	–	R	R	R	R	R	R	–	R	R	R	R	N	–	–	R	R	–	R	–			–
Toluene	R	R	R	R	R	R	R	R	R	R	R	R	N	S	R	S	R	S	R	R	R	R	R
Xylene	R	R	R	R	R	R	R	–	R	R	R	R	N	S	R	S	R	S	R	R	R	R	R
MISCELLANEOUS																							
Acetaldehyde (in water)	N	R	R	R	R	R	R	–	R	R	R	R	–	–	R		R	N	R	R	R	R	S
Benzaldehyde (in water)	N	R	R	R	R	R	R	–	R	R	R	R	–	–	R	–	R	N	R	R	R	R	S
Formaldehyde	R	R	R	R	R	R	R	R	R	R	R	R	R	S	R	–	R	R	R	R	R	R	S
Cottonseed Oil	R	R	R	R	R	R	R	–	R	R	R	R	R	R	R	R	R	R	R	R	R	R	S
Glycerine	R	R	R	R	R	R	R	–	R	R	R	R	R	R	R	R	R	R	R	R	R	R	S
Glycol	S	R	R	R	R	R	R	–	R	R	N	S	R	R	R	–	R		R	R	R	R	R
Lard	R	R	R	R	R	R	R	–	R	R	R	R	R	R	R	R	R	–	R	R	R	R	R
Linseed Oil	R	R	R	R	R	R	R		R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Mineral Oil	R	R	R	R	R	R	R	–	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Nitrobenzene	S	R	R	R	R	R	R	–	R	R	R	R	R	R	R	–	R	N	R	R	R	R	S

*From J.P. Stevens & Co., Inc., Ref. 2.

tures, both types of acrylic polymers behave in a similar manner. As alkaline conditions become more severe the homo-polymer again shows superiority.

Under weak or intermediate conditions of chemical concentration and/or temperature, generic family only will need to be considered. As severity of conditions increase, then special fibers within a generic type become important considerations. "Tailor-made" fibers are being manufactured within a generic family. "Nomex" nylon will withstand 450°F whereas nylon 6 or 6,6, the common types of nylon, are useful up to 250°F."

"In the acrylics, "Crylor" and "Dralon T" can be used at higher temperatures than most other acrylics because of their higher acrylonitrile content. All manufacturers of synthetic fibers are striving to produce better fibers for filtration and dust collection."[2]

4.3 YARN PRODUCTION

The standard definition of a yarn is as follows:

"Yarn: a generic term for a continuous strand of textile fibers, filaments or material in a form suitable for knitting, weaving, or otherwise intertwining to form a textile fabric. Yarn occurs in the following forms:

a. A number of fibers twisted together
b. A number of filaments laid together without twist
c. A number of filaments laid together with more or less twist
d. A single filament,...monofilament
e. A narrow strip of material such as paper cellophane, or metal foil...

Varieties include single yarn, plied yarn, cabled yarn, cord, thread, fancy yarn."[13]

Yarns formed of short staple fibers are called spun yarns. Yarns may also be formed of a twisted bundle of individual fine monofilaments (typically several hundred, each monofilament of order 10 μm diameter), in which case the yarn is called multifilament or filament. Single or monofilament yarns (e.g. as in monofilament fishing line, 5 to 10 lb. test) are not as widely used in fabrics for industrial gas filtration as multifilament yarns and spun yarns.

Multifilament yarns are made directly from individual monofilaments, frequently as they are extruded, in which case the desired number of spinnarets is used. Following varying amounts of thermal and mechanical molecular crystallite orientation, a finish lubricant may be added and a slight twist is given the yarn to maintain multifilament order. This low-twist basic yarn is then coverted to the specific yarn form required for the desired fabric design either by the fiber producer, by an intermediate processor, or by the fabric manufacturer. Man-made fiber staple may be cut from multifilament yarn. Staple yarns are made by the fiber yarn or fabric manufacturer by parallelizing the short fibers and twisting them together for the desired strength.

The method or "system" of yarn production is determined by the type of fabric desired for dust collection. The major fabric types are presented in Table 4.15 based on information provided by Albany Felt Company.

A variation of the woolen system is the worsted system, in which the fibers are given additional parallelizing treatment, or combed, before being spun. As a result the worsted yarn is smoother and of finer quality (Figure 4.2). The type of spinning machine as well as the amount of combining influences the fiber orientation, and thus has an influence on the amount of free fiber available for dust filtration.

4.4 YARN PROPERTIES

Yarns of staple fibers can be made with various fiber lengths and various fiber diameters. The diameter of the yarn itself can range from relatively fine to comparatively heavy and thick. The amount of twist is also variable. All yarns composed of staple fibers must possess sufficient twist to hold the fibers in place. The amount of twist in staple yarns also depend upon staple length, shorter staple requiring higher twist for adequate weaving strength.

Filament yarns are smooth and even unless they have been diliberately formed in an uneven manner for novelty effects. They may be thick in diameter and heavy, gossamer sheer and light, or of any intermediate weight and diameter.

TABLE 4.15

MAJOR FABRIC SYSTEMS *

Woolen System Spun Fabrics

This terminology relates to a manufacturing system and not just wool fibers. Synthetic can be woven on the 'woolen system'.

Woolen System Spun Fabrics are made with soft, lofty, open, heterogeneous, low twist yarns, which result in a fabric with many small pores for high capacity and efficiency. This type fabric is ideal for very fine dust up to and including coarse grades....

This type construction was designed primarily for the Shaker type baghouse.

Cotton System-Spun Fabrics

This terminology relates to a manufacturing system and not just cotton fibers. Synthetic fibers can be woven on the cotton system.

In this type fabric, the yarns are smaller, tighter and of high twist. Because of this, the yarn count is increased to prevent dust leakage and the resulting fabric is generally lighter in weight and offers less capacity than a woolen system spun fabric.

This type fabric could be used for a Shaker type baghouse.

Filament Fabrics

Filament filtration fabrics are characterized by slick yarns without any protruding fiber ends along the yarn and therefore the surface of the fabric is very smooth.

Since this type fabric is completely without a surface "cover" or "nap", the yarns are packed quite closely together, even tighter than a cotton system fabric of equal permeability.

This results in a fabric which has excellent release characteristics, but limited capacity.

This type construction was designed for the Reverse-Air type baghouse.

"Combo" Fabrics (Spun-filament)

This type fabric incorporates some of the advantages of both the woolen system fabric and the Filament fabric. In this unique design, the filament yarns are manufactured in the lengthwise or warp direction of the bag whereas the woolen system spun yarns are manufactured in the crosswise or filling direction.

The "combo" fabrics are a so-called one sided construction whereby the filament yarns are predominant on one side, giving the inherent advantage of cake release. The spun yarns are used to add strength and to cover the interstices of the yarn and thereby reduce pore size.

This fabric was designed primarily for Shaker baghouses, however, it also has limited use in Reverse Air Collectors.

The "combo" fabric offers a good balance of capacity and cleanability where plugging problems are encountered.

Needled Fabrics

This type fabric is manufactured by mechanically interlocking layers of fibers by inserting a multitude of reciprocating barbed needles. Needled fabrics should use a woven base fabric (sometimes referred to as a scrim) for strength and stability.

This type fabric offers excellent capacity and wear with the reverse-jet and pulse jet type collectors.

*From Albany Felt Company, Ref. 11

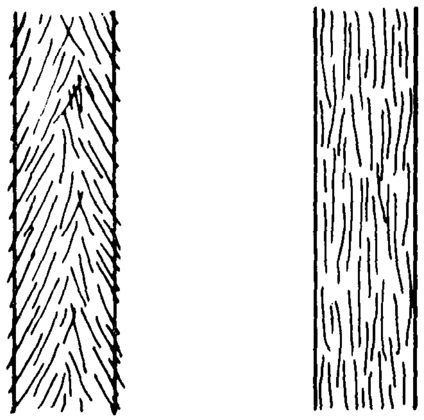


Figure 4.2. Diagram of Fiber Lay- a. Woolen Yarn (note, Fibers Usually Lay in Much More Random Manner); b. Worsted Yarn (Ideal Fiber Lay). (From Joseph, Ref. 14).

4.4.1 Threads and Yarns

Thread and yarn are basically similar. Yarn is the term usually applied when the assemblage of fibers is used in the construction of a fabric. Thread is the product used to join pieces of fabric together in the construction of textile products. Thread is frequently of plied construction. It is fine, even, and strong. Several types of thread are available on the market: there are simple ply threads, cord threads, elastic threads for special use, monofilament threads of the man-made fibers, and multifilament threads.

4.4.2 Yarn Twist

As the staple fibers or filament fibers are formed into yarns, a certain amount of twist is added to hold the fibers together. The amount of twist is measured by the number of turns per inch. The more turns per inch the stronger the yarn becomes, up to a point. Beyond the optimum, which varies depending upon fiber content, staple length, size of the yarn and appearance desired, the yarn will become somewhat brittle and tend to break easily. According to Gurley[15] yarns with low twist have less than 5 turns per inch; medium twist yarns from 5 to 20 turns per inch; and high twist yarns from 20 to 30 turns per inch. It has been suggested that optimum ranges are 3 to 6 turns per inch for filament fiber yarns and 10 to 20 turns per inch for staple fiber yarns.

The direction of twist is also important. Yarns may be twisted either with a right-hand twist or a left-hand twist. The right-hand twist is called a Z twist, while the left-hand twist is an S twist, as in Figure 4.3. Various effects can be obtained by combinations of yarns of different twist direction, and the durability of yarns may be increased by efficient plying of S and Z twist single yarns.

4.4.3 Yarn Number

Yarn number is a measure of linear density. Direct yarn number is the mass per unit length of yarn; indirect yarn number is the length per unit mass of yarn. Yarn number is frequently called yarn count in the indirect system. To some extent the yarn number is an indication of the diameter when yarns of the same fiber content are compared.

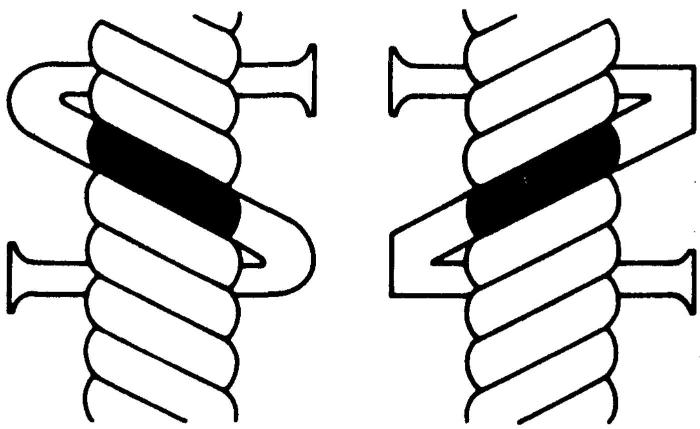


Figure 4.3. Diagram of S and Z Twist in Yarn. (From Joseph, Ref. 14).

Over the years various methods of determining yarn number have been developed. Cotton yarns have been numbered by determining the weight in pounds of 840 yard hanks, or, more frequently, the number of 840 yard hanks required to weigh one pound. For example, if 840 yards weigh one pound, the yarn number is 1s; if it requires 30 such hanks to weigh one pound. the yarn is a 30s. A heavy yarn would be 1s; a medium yarn is considered a 30s, while a very fine yarn might be a 160s.

Woolen system yarn is measured by the number of 300-yard hanks per pound while worsted system yarn is measured by the number of 560-yard hanks per pound. Man-made fiber yarns are usually measured using the denier system. The denier is equal to the weight in grams of 9000 meters of yarn.*

Recently the textile industry has considered among other systems the Tex numbering system for all fibers. A kilometer of yarn is weighed in grams and the weight becomes the yarn number. In this system the larger the number the heavier the yarn and, conversely, the smaller the number the finer the yarn. Note that:

$$\text{Tex} = \frac{\text{Wt in grams}}{\text{1000 meters of yarn}} \tag{4.1}$$

and

$$9 \text{ Tex} = 1 \text{ denier} \tag{4.2}$$

The denier or Tex may be used to determine monofilament fiber size and approximate yarn diameter from the appropriate fiber material density.

Consider for example a Nomex^R nylon yarn stable fiber (see Table 4.6, for forms available) of 2 denier/filament (2/9 tex). The diameter of this fiber is obtained as follows. Since

$$\frac{\pi}{4} D_f^2 \, L \, \rho_f = \text{Wt in grams,} \tag{4.3a}$$

$$\frac{\pi}{4} D_f^2 \, (9 \times 10^3 \times 10^2 \text{ cm})(1.38 \text{ gm/cm}^3) = 2 \text{ grams} \tag{4.3b}$$

from which

$$D_f = 14.3 \mu\text{m}$$

The fiber density, ρ_f, was obtained from Table 4.13 (also see Appendix 4.3).

*This system dates back to early Roman history where a coin, the "Denier" (~ 0.5 gm) was used as a medium for buying and selling silk.

A 100 denier multifilament Nomex^R nylon yarn (Table 4.6) would be composed of approximately 50-2 denier filament ends. The yarn diameter would be of the order

$$(1-\epsilon)\ \frac{\pi}{4}\ D_f^{\ 2}\ N = \frac{\pi}{4}\ D_y^{\ 2} \qquad (4.4)$$

where $1-\epsilon = \alpha$ = the packed fraction, depending upon twist and yarn tightness

D_f = the individual filament diameter

N = the number of filaments in the yarn

D_y = the yarn diameter

from which (assuming $1-\epsilon = 0.6$), $D_y \approx 14.3\sqrt{30} \approx 80\mu m$, or approximately the thickness of a human hair.

Breaking tenacity (c.f. Table 4.13 or Appendix 4.3) in grams/denier can be converted to stress from the fiber size and breaking weight applied. For the 2 denier Nomex^R nylon staple fiber above, breaking tenacity (dry) is 5.3 grams/denier, or 10.6 grams. Stress at rupture is thus determined as follows:

$$\text{Stress} \approx \text{Force/area}$$

Stress = $10.6 \times 980/(14.3 \times 10^{-4})^2\ \pi/4 = 6.5 \times 10^9$ dynes/cm^2 or about 9.5×10^4 psi.

4.4.4 Simple and Plied Yarns

Yarns that are even in size, have an equal number of turns per inch throughout and are relatively smooth, are called simple yarns. A simple, single yarn is the simplest assemblage of fibers suitable for operations such as weaving and knitting. These yarns may be made from any of the fibers and by any of the basic systems.

A simple-ply yarn is composed of two or more simple-single yarns plied or twisted together. In naming a ply yarn the number of singles used precedes the word "ply." For example, if two singles are used, it would be called 2 ply. Typical plied and cord yarn are shown in Figure 4.4.

4.5 FABRIC PRODUCTION

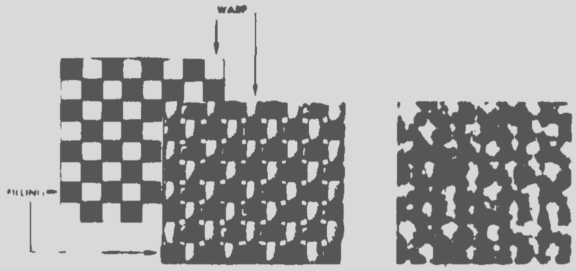
4.5.1 Weaving

The production of a flexible textile fabric for use in filtration systems involves weaving; rarely are completely non-woven materials such as paper used. Most felts used in filtration are first woven, then given further treatment. Figure 4.5 shows the major weaves used in non-felted filter fabrics. Woven fabrics are formed by interlacing yarns at right angles on a loom, after which the raw or "greige" fabric may be further treated. While there are many patterns of interlacing, the fabrics in most common useage in gaseous filtration are classed generally as twill and sateen (satin). Plain weave fabric is also sometimes used. The engineering technology of these and other weaves is discussed in detail elsewhere[16] and the following quotation from Potter and Corbman[8] summarizes the fabric production process:

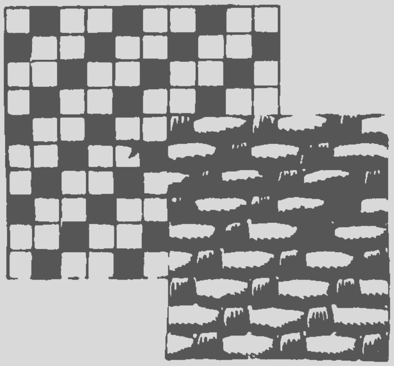
(a) Photograph of Cord, Composed of Four Plies, Each Ply Composed of 7 Single Yarns.

(b) Four Ply Yarn, Slightly Magnified, Showing Fibers Separated in One of the Single Yarns Forming the Ply.

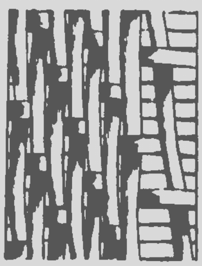
Figure 4.4. Plied Yarns. (From Joseph, Ref. 14).



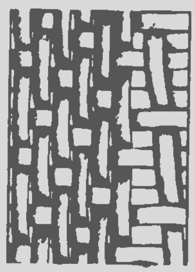
(a) Plain Weave, Showing Loose or Open Construction and Close Construction, Such as Muslin.



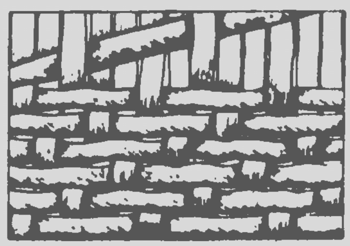
(b) Twill Weave. "This drawing shows a three-shaft twill-two warp yarns in each repeat. This is a right-hand, filling-faced twill because the diagonal moves from the upper right down to the lower left, and more filling than warp appears on the face of the fabric. It is also referred to as a one up and two down twill $(\frac{1}{2})$ because the warp goes over one and under two filling yarns."[8]



(i) Warp Floats are Seen Interlacing Every Eighth Filling.



(ii) Warp Floats are Seen Interlacing Every Fifth Filling.



(iii) Filling Floats are Seen Interlacing Every Fifth Warp.

(c) Satin Weave, Showing (i & ii) Warp-Face and (iii) Filling-Face Construction.

Figure 4.5. Weaving Styles for Filtration Fabrics. (From Ref. 8).

PREPARATION FOR WEAVING

"In the weaving operation, the lengthwise yarns that form the basic structure of the fabric are called the warp. The crosswise yarns are the filling, also referred to as the weft or the woof. The filling yarns undergo little strain in the weaving process. In preparing them for weaving, it is necessary only to spin them to the desired size and give them the amount of twist required for the type of fabric for which they will be used.

Yarns intended for the warp must pass through such operations as spooling, warping, and slashing to prepare them to withstand the strain of the weaving process. These operations do not improve the quality of the yarn. In spooling, the yarn is wound on larger spools, or cones, which are placed on a rack called a creel. From this rack, the yarns are wound on a warp beam, which is similar to a huge spool. An uninterrupted length of hundreds of warp yarns results, all lying parallel to one another. These yarns are unwound to be put through a starch bath called slashing, or sizing. The slasher machine covers every yarn with a starch coating to prevent chafing or breaking during the weaving process. The sized yarns are passed over large steam-heated copper cylinders that remove the moisture and set the size. They are then wound on a final warp beam and are ready for the loom.

TWILL WEAVE

A distinct design in the form of diagonals is characteristic of the second basic weave, called the twill. Changes in the direction of the diagonal lines produce variations, such as the herringbone, corkscrew, entwining, and fancy twills.....The values of the twill weave include its strength and drapability. The diagonally arranged interlacings of the warp and filling provide greater pliability and resilience than the plain weave. Also, twill fabrics are frequently more tightly woven and will not get dirty as quickly as the plain weave, though twills are more difficult to clean when they do get soiled. The yarns are usually closely battened, making an especially durable fabric. Twill weaves are therefore commonly used.....where strong construction is essential.

In the twill weave, the filling yarn interlaces more than one warp yarn but never more than four, as strength would be sacrificed by so doing. On each successive line, or pick, the filling yarn moves the design one step to the right or to the left, thus forming the diagonal. Whichever the direction of the diagonal on the face of the fabric, the design runs in the opposite direction on the reverse side.

When the direction of the diagonal starts from the upper left-hand side of the fabric and moves down toward the lower right, it is called a left-hand twill. When the direction of the diagonal starts from the upper right-hand side of the fabric and moves down toward the lower left, it is called a right-hand twill. Although there is no advantage of one over the other, the direction of the diagonal can aid in the recognition of the face of the fabric.

The steepness of the diagonal can indicate strength and durability in the fabric. In order to obtain a steep twill, more warp yarns must be used than filling yarns. And since warp yarns have a higher twist and are stronger than filling yarns, the steeper the twist the stronger the fabric is likely to be.

Twill weaves are named according to the number of harnesses required to make the design. A three-of four-harness twill is frequently used. The word "shaft" may be substituted for "harness," as in three-shaft or four-shaft twill.

Twill weaves are also classified as even or uneven according to the number of warp and filling yarns that are visible on the face of the fabric. The even twill, for example, shows an equal number of warp and filling yarns in the recurring design, such as two over and two under. This pattern makes what is called a four-shaft twill, and it requires four harnesses.

Most twill weaves are uneven. An uneven twill may show more warp than filling yarns in the recurring design; this is called a warp-face twill. If more filling yarns than warp yarns show on the face, the weave is called a filling-face twill. Warp-face twills are generally stronger than filling face twills because the stronger warp yarns on the face of the fabric can take more abrasion and wear. Warp-face twills generally have much more warp than filling yarns; consequently, such fabrics hold their shape better and drape better due to the warp's greater twist and resilience.

Twills are described in terms of the interlacing of the warp yarns over and under the filling yarns. An uneven four-shaft twill, for example, that has three warp yarns riding over one filling yarn is referred to as a three up and one down, or $\frac{3}{1}$. On the other hand, a three-shaft twill that has one warp yarn riding over two filling yarns is referred to as a one up and two down, or $\frac{1}{2}$.

SATIN WEAVE

In the basic construction, the satin weave is similar to the twill weave but generally uses from five to as many as twelve harnesses, producing a five- to twelve-shaft construction. It differs in appearance from the twill weave because the diagonal of the satin weave is not visible; it is purposely interrupted in order to contribute to the flat, smooth, lustrous surface desired. There is no visible design on the face of the fabric because the yarns that are to be thrown to the surface are greater in number and finer in count than the yarns that form the reverse of the fabric. The satin weave may have a warp- or filling-face construction.

Warp-Face Satin Weave. Warp-face satin is woven so that the warp may be seen on the surface of the fabric. For example, in a five-shaft construction, the warp may pass over four filling yarns and under one; in a twelve-shaft construction, the warp may pass over eleven filling yarns and under one. Since the warp lies on the surface and interlaces only one filling at a time, the lengths of warp between the filling are called floats. These floats lie compactly on the surface with very little interruption from the yarns going at right angles to them. Reflection of light on the floats gives satin fabric its primary characteristic of luster, which appears in the direction of the warp.

The long floats found in the satin weave might be considered a disadvantage because they represent a minimum of interlacings, and therefore a potential weakness in the fabric. Furthermore, to increase the smoothness and luster of the fabric, the yarns are given a minimum of twist and are therefore relatively weak. The longer the float, the greater the chance that the surface of the fabric will snag, roughen, and show signs of wear.....

Satin-weave fabrics drape well because the weave is heavier than the twill weave, which, in turn, is heavier than the plain weave. More harnesses are used for satin weave, thus compressing a greater amount of fine yarn into a given space of cloth. This compactness gives the fabric more body as well as less porosity......

Filling-Face Satin Weave. The filling-face satin weave is also called the sateen weave; however, this sometimes causes confusion because some cotton and rayon fabrics are also identified as sateen. In this construction, the filling yarn lies on the surface of the fabric as it passes regularly over and under the warp yarns. For instance, a filling yarn may pass over four warp yarns and under one. The floats are consequently made up of the filling yarns, and the luster appears in the filling direction.

"On the conventional loom, the warp yarns that are to run lengthwise in the fabric are wound on a cylinder called the warp beam, which is at the back of the loom. The warp also extends to a cylinder called the cloth beam, which is at the front of the loom and on which the fabric is rolled as it is constructed. Supported on the loom frame between these two cylinders, the warp yarns are ready to be interlaced by the filling yarns that run in the width of the cloth, thus producing the woven fabric.

In any type of weaving, four operations are fundamental. They are performed in sequence and are constantly repeated......The essential parts of the loom are: warp beam, cloth beam, harness or heddle frame, shuttle, and reed. These parts perform the following operations.

> Shedding—raising warp yarns by means of the harness or heddle frame
>
> Picking—inserting filling yarns by means of the shuttle
>
> Battening—pushing filling yarns firmly in place by means of the reed
>
> Taking up and letting off—winding the finished fabric on the cloth beam and releasing more of the warp from the warp beam.

CLASSIFICATION OF WEAVES

The manner in which groups of warp yarns are raised by the harnesses to permit the insertion of the filling yarn determines the pattern of the weave, and in large measure the kind of fabric produced. Weave patterns can create varying degrees of durability in fabrics, adding to their usefulness and also to their appearance. In a simple weave construction, consisting of the filling going under one warp and over the next, two harnesses are needed: one to lift the odd-numbered warp yarns, and a second to lift the even-numbered warp yarns. More than two harnesses are required for advanced weaves, and as many as forty for figured weaves.....

PLAIN WEAVE

The plain weave is sometimes referred to as the tabby, home-spun, or taffeta weave. It is the simplest type of construction and is consequently inexpensive to produce. On the loom, the plain weave requires only two harnesses. Each filling yarn goes alternately under and over the warp yarns across the width of the fabric. On its return, the yarn alternates the pattern of interlacing. If the yarns are close together, the plain weave has a high thread count, and the fabric is therefore firm and will wear well."[8]

4.5.2 Felting and Needle Punching

The felts used in fabric filtration in their early stages of production are also woven, but subsequent steps completely change the character of the material from that of a woven fabric. While felts can be made simply by matting fibers together and by other non-woven methods (see below), the use of a woven base fabric called a scrim greatly increases the strength and stability of the fabric.

The production of a felt depends on whether its fibers are naturally binding. Because woolen fibers are scaley, and also shrink when exposed to heat and moisture, a woolen scrim shrinks when mechanically worked in warm water in the presence of certain lubricants and chemicals. The identity of the separate yarns tends to be replaced by a more homogeneous character. The material becomes felt-like in density, stiffer and thicker. Minor amounts of synthetic fibers added to the woolen yarns can modify the properties of the felt thus produced.

To further increase the homogeneous character of the felt surface, it may be napped. This has always required the use of teasels, woody, thistle-like parts for a weed plant, the barbs of which pluck fibers from the surface of the felt. When enough nap has been raised in this way, it may be singed or otherwise trimmed to the desired thickness.

Needle punching is a method of combining two or more layers of fiber into a felt-like fabric. Usually one layer is a scrim for strength, while the other(s) may consist of fibers of almost any description or combination. Thus considerable control over separate properties of the finished material is possible. For example, the scrim may contribute the desired dimensional stability while the top layer contributes the ideal properties for dust control. The surface layer might be 100% dacron, the scrim 100% nylon, for example.

The technique used in needle punching is to prepare a scrim and a batting separately.[3] The batting may be formed by carding, by airlay of fibers, or by other random web-forming equipment. The batting is generally of the same order of weight or lighter than the scrim. It is unrolled or otherwise spread over the scrim. Needles having forward barbs are punched from the batting side into or through the scrim, and the batting fibers thus laced into the scrim remain behind when the needles are withdrawn. Production is at the rate of about 10 FPM. Variations in the needling process include needle angle, number of repetitions, two-sided needling, etc. When a shrinkable scrim is used, the needled material may later be felted in various ways to produce a still more dense and uniform material.

Non-woven production methods include resin bonding, wet bonding (paper-like materials), spun bonding (while the fibers are still tacky from their extrusion stage), heat bonding, chemical bonding, spray bonding, and stitch bonding (a sort of knitting within a matt).[3,16] Nearly all fibers used in fabric filtration can be used in non-woven fabrics. Because non-woven fabrics can often be produced more rapdily than by weaving, it appears that filtration fabric or even filter elements might eventually be produced by non-woven methods.

4.5.3 Fiber Additives, Yarn Treatment, and Fabric Finishes

Natural fibers are produced with an outer molecular film; cotton cellulose fibers are covered with a wax-like adhesive; and wool protein fibers contain oils, fats, and waxes from glandular secretions during growth. Both may contain other agricultural chemicals added to protect or preserve the fibersto aid in the harvesting process, e.g., insecticides, defoliants, etc. Wool will have much of the grease removed in a washing, scouring or solvent extraction process. Additional oil (animal, vegetable, or mineral) may be provided as a lubricant for spinning. The production of fabrics from fibers and yarns involves many chemical, physical and mechanical processes. Properties of the fiber, yarn, and fabric are continually modified through treatment and additives to meet the requirements of production machinery.

Each additive or treatment may result in some residual material attached to individual fibers that ultimately affects its strength in service or its ability to act as a substrate for filtration. The potential combination of additives, treatment or finishes is nearly limitless. Prediction of fabric performance in service (pressure drop, efficiency, life) on a given application is presently empirical through service testing, and thus the science of fabric treatments for improved performance is relatively undeveloped. Furthermore the addition of materials to improve filtration performance, particularly life in service is often proprietary. Many techniques are relatively new, and not subject to competitive or comparative testing procedures. The entire field of the role of finishes and additives in gas filtration requires further analysis before analytical generalizations can be produced for optimization studies.

Each of the generic man-made fiber materials discussed above is a complex chemical structure with varying physical properties and surface characteristics.

These polymeric materials frequently contain one or more of the following additives:[17]

- Plasticizers reduce flow viscosity or temperature in melt spinning the resin, such as DOP in PVC; and are also employed to improve low temperature flexibility.
- Solvents are used in wet spinning as with acrylic plastics or rayons; and in coating, adhesives, etc.
- Organic peroxides are used as polymerization initiators or for cross-linking reactions in thermoplastic materials to transform them into thermosets.

- Antioxidants are added to reduce oxidative deterioration during manufacture, processing or storage, and to provide heat protection especially among vinyls.

These agents may be required in varying amounts.

- Flow-control agents may be required to control melt viscosity and transformation of the polymer to a stable form for end-use.
- Colorants, pigments, and delustrants include powered, colloidally dispersed or dissolved materials added to provide color or reduce brightness.
- Flame retardants are employed to provide fire protection for flammable polymers.
- Stabilizers are used to import thermal stability or mechanical protection during processing and to protect the mix against changes induced by other additives, e.g. by neutralization of contaminants, residues, or impurities.
- Ultraviolet absorbers are added to reduce UV absorption by the polymer or to quench molecular reactions, in order to limit physical degradation of the plastic exposed to sunlight.
- Antistatic agents may be applied as a coating to external fiber surfaces or added internally; the agent acts as a hygroscopic material to assist the charge to leak away (make the fiber electrically conductive) and may modify the charging process, reverse the sign of the charge, or promote dissociation of ionic material present on the fiber.
- Other additives, filters, and processing aids may be employed as viscosity depressants, parting agents, emulsifiers, coupling agents, internal or external lubricants, or adherents.

Many compounds are used in varying amounts to assist in manufacturing and processing operations and to provide stability, compatibility, and other desirable end-use properties. Since filter fiber is a small proportion of the total annual market for man-made fiber textiles, materials used in production and processing are developed, produced, and used primarily for the larger market applications, rather than for fabric filtration objectives. Each producer's fiber, while generically the same (i.e., same basic polymer), will be produced differently and will have different additives which may affect dust particle-fiber attachment, deposit formation, and stability. The reduction of these phenomena to engineering design parameters in filtration will be difficult and complex.

The yarn may be treated as well as the fiber. Yarn treatments now include surface addition of lubricants, antistatic agents, and various mechanical operations such as attenuation or stretching, heat setting, and bulking or texturizing. Warp yarns are subjected to greater strain during weaving and may be sized or coated to prevent chafing and breakage.

Fabric finishing includes those processes to improve appearance or serviceability of the fabric after leaving the textile machine (greige goods). Cotton and wool fabrics are usually cleaned (washed or scoured) and bleached, and may be chemically treated to provide waterproofing, mothproofing, mildewproofing, or fireproofing. Mechanical finishes applied to cotton and wool include singeing, napping, shearing, felting, or shrinking. Synthetic fabrics are usually heat set to relax internal stresses in the yarns set up during weaving. This causes shrinkage, although it enhances dimensional stability for subsequent exposures to temperatures below the setting temperature. Additional moisture protection (water repellants) and antistatic agents may be applied.

Glass fiber fabrics are subjected to high temperatures ($\sim 10^{3}$ °F) to relieve yarn twisting and weaving stresses and to heat clean the weaving size. Glass fabrics are usually lubricated with silicones, graphite and other proprietary finish agents to reduce fiber-fiber abrasion resistance during filter cleaning. Graphite finishes of the order of 5% by weight have been indicated to provide extended service life of glass fiber fabrics at temperatures $\leq 500^{\circ}$F, as illustrated in Figure 4.6. Largely as a result of improved finishes, the use of glass fiber fabrics for applications at temperature $> 275^{\circ}$F has increased greatly. Competitive fabrics now include Nomex^R ($\leq 425^{\circ}$F) Teflon^R ($\leq 450^{\circ}$F), and newer man-made fibers (Brunsmet^R, Fiberfrax^R, and Polyimides). Improved lubricants and finishes for glass fiber fabrics to provide longer life at higher temperatures ($> 600^{\circ}$F) are under continuing development.

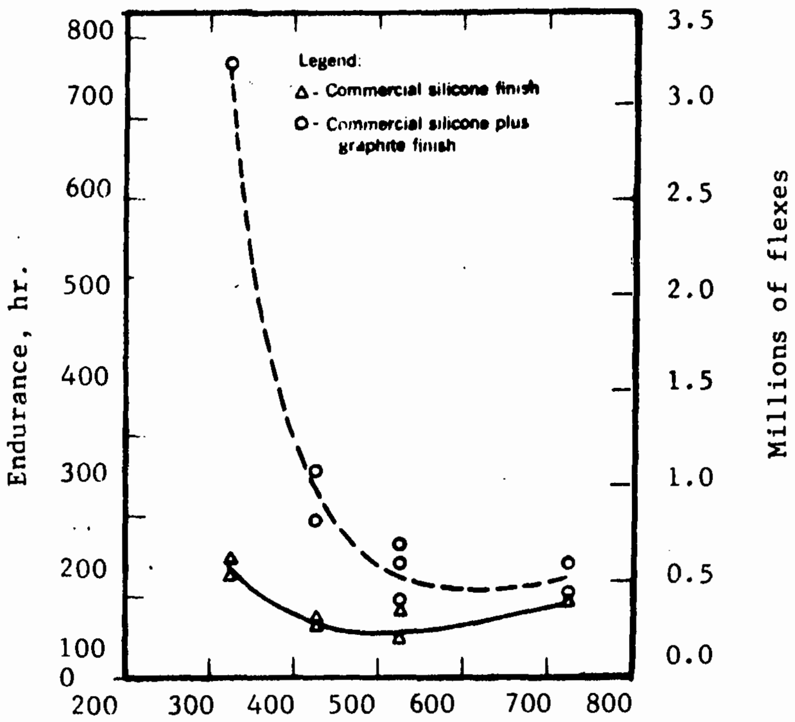


Figure 4.6. Effect of Graphite on Glass Fabric Temperature Endurance. (From Ref. 18).

4.6 FABRIC PHYSICAL CHARACTERISTICS

4.6.1 Abrasion Wear

The mechanical abrasion of fabric is only one of several kinds of wear, other kinds including chemical and thermal degradation, handling, etc. As Table 4.16 indicates, a fabric could conceivably experience many kinds of wear at one time or another during its lifetime of manufacturing and use. Most of these types of wear are terms from popular usage and consequently are ill defined. For present purposes the term "abrasion" will be defined and used as an eroding away of fabric fibers or fiber surface material, through moving contact between (a) the fiber and dust particles or (b) adjacent fibers.

TABLE 4.16

SOME TYPES OF MECHANICAL WEAR IN FABRICS

Fatigue	Migration
Sliding	Slippage
Rubbing	Breaking
Galling	Cutting
Scoring	Grinding
Snagging	Plowing
Picking	Penetrating
Flexing	Rupturing
Welding	Shearing
Compression	Catching
Plucking	Bending
Fretting	Polishing
Fracture	Chaffing

Material science describes the forms of abrasion as either two-body or three-body abrasion. Fiber-to-fiber rubbing or fiber-to-particle collision (sand blasting) are two-body systems. Interstitial dust particles, caught and chaffing under pressure between adjacent fibers or yarns, represents three-body abrasion. The mechanics of the two processes are somewhat related, however, and involve the relative sizes of the bodies, the hardnesses or relative hardnesses, the pressure between the bodies, the coefficient of friction and the nature of the motion between them. The laws of material abrasion are nevertheless only partially determined because of other effects which are more difficult to evaluate such as humidity, rate of oxidation of freshly exposed surfaces, smoothnesses of particles, any accumulation of freshly abraded particles, etc.

The laws of material abrasion are undeveloped, and fabrics, being of complex geometry and having extremely varying stresses and strains, are especially difficult to analyze. Neither can fabrics be analyzed in detail for abrasion during their fabric filtration performance, as abrasion is usually reported simply as "holes" in the filter element (Section 8.3). Even though it appears that abrasion represents up to 25% of fabric failures there is insufficient data relating to particle hardness, coefficient of friction, et cetera, to establish the rules of filtration fabric abrasion.

Manufacturers of filter fabrics have little technology for the abrasion resistance of their fabrics, although they do measure the resistance of fabrics to abrasion by standard testing procedures. Typically a swatch of the fabric is rubbed back and forth over a rough surface, sometimes in the presence of grit,until the fabric becomes perforated.* The fabric abrasion resistance is rated according to the time required for perforation.[19] Other methods include sandblasting, and flexure or tension during rubbing.[20] Thus it appears that fabric manufacturers as well as users rely on an evaluation of the destruction of the fabric without attempting to determine the basic cause or causes of failure. Considerably more analytical approaches have been taken by Backer[21,22] and Hamburger[23], as reviewed by Kaswell[10,24] and Hearle[16].

4.6.1.1 Sandblast or Surface Scour.- Particles entering a fabric collector filter element are apt to strike the fabric surface with sufficient velocity to abrade and remove portions of fibers, eventually perforating the fabric. This is analogous to the process called sandblasting, and although sandblasting involves perpendicular impact while the fabric is struck at a shallow angle, the mechanics should be related. Raleigh[25] studied perpendicular sandblasting. He assumed that the rate of wear is related to the maximum strain produced in a surface by an impact. This strain is proportional to

$$\sim V \sqrt{\frac{\rho}{Y}}$$

where V is the impact velocity, ρ the density and Y the tensile modules of the impacted material. To the extent that this strain exceeds the tensile strain limit of the material, bits of the material will chip out.

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* Another test that is frequently used is to abrade the fabric against itself with a rolling crease. Cycles to failure are an indication of resistance to flexure and two-body abrasion.

Evidently this applies better to hard, brittle materials than to plastic ones, where the mechanism is more probably plowing than chipping.

Zenz and Othmer[26] reported a general agreement that 90° sandblast errosion is proportional to

$$\sim LV^3$$

where L is sand loading or concentration, although the exponent was reported to vary from study to study between 3 and 6. The exponent of 3 can be shown to be consistent with the assumptions that wear rate (depth/time) is proportional to both the particle impact rate (number/time) and the average particle kinetic energy. In the above case it is assumed that the mechanism is plastic plowing, rather than brittle chipping.

Fabric abrasion using sandblast equipment has been studied experimentally. Parker[27] found with approximately 60 mesh granules that harder abrasive (circa silicon carbide hardnesses) and higher blast pressures shortened fabric life; for example:

Pressure (psi):	30	40	50	60
Life (seconds):	100	54	35	23

Unfortunately Parker did not state the rate of sand flow which may or may not have varied with blast pressure.

Generally Parker found the rate of removal of fiber was constant over the life of the fabric, although it slightly accelerated during the life of heavier (8-12 oz/yd^2) fabrics. Kaswell[24] also indicated an approximately linear relationship between fabric strength loss and the time of operation of the abrasion equipment.

Types of surface abrasion test machines other than sandblast are more widely accepted, and their data may be related to filter element scouring. Kaswell[24] reviewed these methods and a large number of studies of fabric surface abrasion made chiefly by the garment industry. He credits Backer and Tanenhaus[22] with an examination of fourteen fabric properties that relate to abrasion resistance:

Geometric Aspects

1. Area of contact between fabric and abradant
2. Local pressures developing on specific yarn points
3. Threads per inch
4. Knuckle height
5. Yarn size
6. Fabric thickness
7. Yarn crimp
8. Float (knuckle) length
9. Yarn cohesiveness
10. Compressional resilience
11. Fabric tightness
12. Cover factor

Abrasion Aspects

1. Direction of abrasion
2. Magnitude and direction of tensions developed during abrasion

In conclusion it appears that fabric surface scouring is related to dust loading and impact velocity, and to particle sharpness and hardness. Fabric designed with a dense surface (level; few knuckles) should retain its strength longer. Nap, pile or sacrificial surface fibers will extend the life of the fabric A soft fiber material, flexible fibers, and resilient yarn and fabric will also reduce the rate of surface fiber degradation.

4.6.1.2 Internal Chaffing.- The rubbing together of two fibers as the fabric is flexed is also two-body abrasion. Glass fibers are notoriously weak in this respect. Originally glass fabric had almost no durability; crossed glass fibers apparently became nicked due to chaffing or due to dissolution at the point of contact and then snapped easily. However when silicone and other lubricants were added, their life extended almost indefinitely in comparison.

When a yarn is bent its elementary fibers slip past one another, unless they are bonded together or under a large lateral pressure from twisting or weaving. In the latter cases the yarn is beam-like in rigidity and liable to rupture in tensile failure if bent. More normally, fibers slip to some extent as the yarn is bent; and also adjacent yarns tend to slip as the fabric is flexed. Thus the shaking or collapse cleaning of a filter fabric is associated with myriad tensile stresses and fiber slippages with chaffing.

To a first approximation, the strain associated with a bending fabric is ($\mathcal{E} = \frac{t}{2} R$) where t is the fabric thickness and R the radius of bend. Also approximately, the amount of slippage (distance) between fibers of diameter D_f in a yarn undergoing bending strain $\mathcal{E}$ is $l \sim \mathcal{E}D_f$, or

$$\ell \sim \frac{tD_f}{R} \qquad (4.1)$$

A precept of two-body abrasion is that the volume of material removed during a rubbing of distance 1 is[28]

$$V = \frac{k\ell L}{H} \qquad (4.2)$$

where k is a wear coefficient, L is the loading between bodies, and H the hardness of the body being abraded. (ν and L may alternatively be expressed per unit area). It appears that k depends on several aspects of the materials and their geometry, but is frequently of order unity.

Rabinowicz[29] discusses four common types of two-body wear, any of which may apply during the fabric deformations active in dust collectors:

- Adhesive wear. One surface adheres so strongly to a second because of atomic bonds at their contact that on sliding, a portion of one is torn loose.
- Gouging wear. A protuberance on one surface plows a groove in the second. It appears that k (wear coefficient) may be of the order of the protuberance size in microns.[28]
- Corrosive wear. Corrosive films that normally tend to resist further corrosion may wear away, exposing fresh surface to corrosive attack.
- Fatigue wear. Tensile stresses trailing the sliding body may crack the supporting surface, leading to chipping of fragments from the supporting surface.

It appears from these brief reviews that chaffing inside the fabric may be reduced by minimizing the:

- number of fabric deformations (cleaning cycles)
- degree (radius) of deformation (cleaning intensity)
- tightness of the fabric weave
- softness of the fiber material
- fabric thickness
- fiber diameter
- fiber roughness
- interfiber friction coefficient.

Table 4.17 lists frictional properties for several fibers. These affect both the rate of wear between fibers and the stiffness of the yarns, to be discussed below.

4.6.1.3 Internal Abrasion.- Many dust particles are abrasive in contact with the fibers ordinarily used in filtration fabrics. Since most industrial dusts and fumes include some particle of sizes substantially smaller than the fiber diameters (10-30μm) there is great likelihood of penetration between adjacent yarns and adjacent fibers. Here the fine particles may be trapped by interfiber pressures, and as the fabric flexes, they cut and gouge the fibers. This is three-body abrasive wear. This wear also follows Eqn. (2) as far as can be determined, except that k may be an order of magnitude smaller than for two-body wear[28].

The evidence for wear of a fibrous structure due to imbedded grit is scant, despite the claims of carpet cleaning services and the manufacturers of laundry detergents. Soiling of carpets and garments has received much attention according to Kaswell[24] but primarily from the standpoint of color changes rather than mechanical degradation. Apparently dust filtration fabrics have not been tested for degradation due to imbedded particles. While reports from filter operation indicate a general weakening of the fabric with time, thermal degradation, surface scouring and other mechanisms are more readily shown to be the causes than imbedded particulates.

4.6.2 Flexibility

The flexibility of a filtration fabric is important for at least two reasons: Removal of the dust deposit may be improved by flexing

TABLE 4.17

FIBER FRICTIONAL PROPERTIES*

THE COEFFICIENTS OF FRICTION OF VARIOUS AIR-DRY TEXTILE FIBERS AND FILAMENTS IN COMMERCIAL CONDITION

Rubbing Surfaces	Coefficient of Friction[a]	Fiber Daimeter(μ)
Nylon/nylon		
Very fine	0.14	18
6 denier	0.15	28
27 denier	0.23	62
Bristle	0.6 (0.5-0.8)	500 approx.
Viscose rayon/viscose rayon	0.19	30 (variable)
Acetate rayon/acetate rayon	0.29	41 (variable)
Cotton/cotton		
--from sewing thread	0.29	
--from cotton wool	0.57	18 (variable)
Wool/wool		
from tops	$\mu 2 = 0.38$ $\mu 1 = 0.24$	20
commercially scoured	$\mu 2 = 0.49$ $\mu 1 = 0.20$	18
coarse, "clean"	$\mu 2 = 0.42$ $\mu 1 = 0.25$	26

STATIC COEFFICIENTS OF FRICTION OF FIBERS (Average Values)

Wool	
With-scale	0.11
Anti-scale	0.14
Wool in water	
With-scale	0.15
Anti-scale	0.32
Cotton	0.22
Jute	0.46
Viscose rayon	0.43
Acetate	0.56
Nylon	0.47
Saran	0.55
Terylene	0.58
Steel	0.29

[a] In the case of wool $\mu 1$ is the coefficient of friction in the direction of the scales (root-to-tip) and $\mu 2$ is the coefficient of friction in the direction against the scales (tip-to-root).

* From Harris, Ref. 4.

of the fabric substrate and conversely, such flexure may cause fabric degradation as noted above. Thus, fabric flexibility may be both necessary and harmful. Since the role of flexibility in fabric filtration is not well established, only the principles of fabric flexibility are stated here.

A single fiber flexes beam-like according to the well-established relation[24]

$$y = \frac{W\ell_s^3}{48YI} \; ; \; I = \frac{D_f^4}{64} \qquad (4.3)$$

where ℓ_s is the span length and y is the center span deflection under center load W. Y is the elastic modulus and I the moment of inertia of the fiber which as expressed above is specifically for a circular fiber.

A parallel group of N fibers with zero friction between them would deflect 1/N as much, under the same load conditions as the single fiber. On the other hand with high friction the bundle would deflect as a single beam, and the deflection would be approximately $1/N^2$ as much as for the single fiber. A yarn of parallel fibers, having intermediate friction, would deflect between 1/N and $1/N^2$ as much as given by Eqn. 4 for only one fiber.

A twisted yarn deflects somewhat more easily, but the exact expression for deflection is highly involved. The amount of inter-fiber friction in a yarn is proportional to the coefficient of friction and to the pressure between fibers. This pressure results from twisting, and it usually changes with bending. One simple measure of the amount of friction in a yarn is the amount of permanent set it acquires when bent; a perfectly frictionless yarn would normally recover elastically.

When woven, each yarn contributes its own stiffness to the fabric. The yarn stiffness will generally be increased however by increased inter-fiber pressures from bending the yarns and packing them together. Thus a section of fabric N′ yarns wide will generally be more than N′ time as stiff as N′ single yarns. Extenuating factors in calculating fabric stiffness are slippage vs. friction between the yarns, the thickness of the fabric, and the position and the straightness of yarn through the fabric.

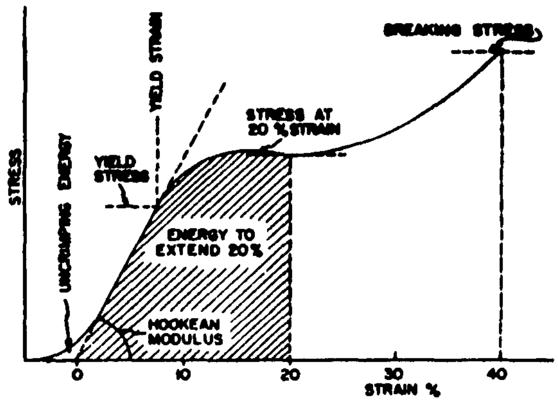
Fabric flexibility as a property of the fabric can be designed via any of the above factors. Other design variations include texturized (teased) yarns, lubricants or bonding agents, fibers of several diameters or lengths, and a variety of finishing treatments including napping and calendering. Many fabrics are designed to be more flexible in one direction than in the other. This opens the possibility in filtration fabrics of using relatively delicate fibers or yarns in one direction for collecting the dust deposit, and using more flexibly durable yarn in the other direction for removing the deposit.

Flexing of filtration fabric is of necessity associated with interfiber tensions and frictional chaffing. Any grit present may cut the fibers during chaffing (Section b). In addition all fibers undergo some molecular fatigue with repeated flexing.

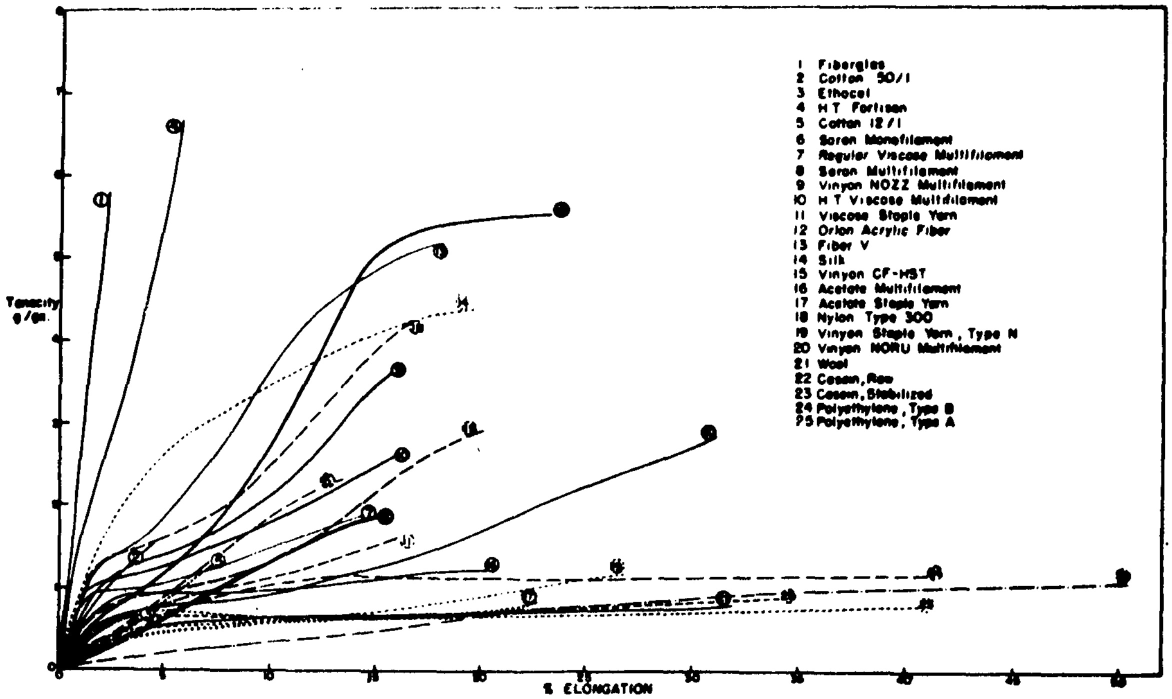
4.6.3 Strength

Although fabric breaking strength is not usually an important parameter in filtration, per se, it is frequently specified because it is one check on the quality of yarns and fibers in the fabric. Strength is also one indication of the aging a fabric has undergone. Filtration fabric rarely tears in use unless the filter element has been sewn in such a way as to concentrate the tension, i.e. at a cuff seam. Tensile modulus is more closely related to the performance of the fabric since it determines the distribution of tension over the filter element and thus the distribution of cleaning energy in mechanical cleaning.

Fabric strength is related to fiber strength or denier, defined as the weight in grams of 9000 meters. Appendix 4.3 lists the denier strengths (i.e. weights) and other fiber mechanical properties of a variety of fibers. Strengths and moduli are also indicated in Figure 4.7.



Typical stress-strain curve for a textile fiber. (Dillon, J. H., Ind. Eng. Chem. **44:** 2115, 1952.)



Stress-Strain Curves of Fibers Tested

Tabulation of stress-strain data on page 146, graphical representation of recoveries on page 148.

Standardized test conditions of above figure

To obtain comparable and reproducible data on the fibers tested, it was necessary to conduct all tests under the same conditions. The conditions for these recovery tests were standardized as follows:

Gage length	**5.0 in. (12.7 cm.)**	**Temperature**	**70°F. (21.1°C.)**
Rate of elongation	**5.0 in. (12.7 cm.) per minute**	**Relative humidity**	**65%**
Removal of elongation	**Immediately after extension**	**Specimens**	**New fibers for every elongation**
Recovery time	**5.0 minutes**		

Susich, G. and Backer, S.: Textile Research J. 21: 482, 1951. Also Textile Series Report No. 64, Office of the Quartermaster General.

The immediate elastic recovery is determined by extrapolating to zero load the initial straight-line portion of the recovery curve.

Delayed recovery is the recovery which takes place slowly and is mathematically defined as: 100 − (immediate elastic recovery (%) − permanent set (%)).

Permanent set is measured after removing the strain and allowing the sample to recover for 5 minutes.

Figure 4.7. Stress Strain Curves for Fibers*

* From Harris, Ref. 4

The strength of a yarn can obviously not be greater than the summed strength of its fibers and actually the yarn strength is practically always less. This is for two reasons: first, the central-most fibers in the yarn are nearly straight and tighten first; hence they break before the outer spiraling fibers reach full load. Second, part of the tension in the outer fibers goes into pressure directed into the yarn rather than into longitudinal tension; hence a tightly twisted yarn may be a very weak one in tension. In the case of staple fibers which must be twisted to obtain yarn strength, there is a twist giving maximum yarn strength; this maximum depends on fiber properties number of fibers, etc.

If a typical fiber in the yarn is examined, it will lie at a twist angle Φ to the yarn axis as depicted in the following sketch:

The stresses (σ) in yarn (y) and fiber (f) are related by

$$\sigma_y = \sigma_f \cos^2 \Phi \qquad (4.4)$$

Thus the strength of the fiber contributes less strength to the yarn. Fiber and yarn strains are also related by a similar but more complex relationship, since the yarn has a widely ranging fiber packing depending on fiber geometry within the yarn.* Consequently even though the fiber tensile modulus is determined (See Figure 4.7 and Appendix 4.3), the expression for the yarn's tensile modulus, that is, the ratio of yarn stress to yarn strain, is not algebraically simple.[16]

The process of weaving further modifies the contributions of yarn strength and tensile modulus to the fabric. The yarn is generally weakened by being bent around orthogonal yarns, depending on its twist and the sharpness of the bend. The tensile modulus of the fabric is generally increased by the weaving process over that of the unwoven yarns, depending

* Loose twisted yarns may elongate considerably before the fibers become tightened, in analogy to the members of a folding gate. Small elastic strains in homogeneous compressible media can be described by Poisson's ratio, but this approach is misleading in fibrous structure applications where the geometric deformations are often large.

on the tightness of the weave. Consequently the fabric is less resilient in tension than a parallel assemblage of the same number of fibers, that is, it absorbs less strain energy before rupture. Kaswell[10] cites the importance of a fabric's elongation-recovery properties in numerous industrial applications.

Strength and modulus are further complicated by dependencies on humidity, mechanical fatigue, and of course the manufacturer's processing and finishing variables. Backer and other at MIT and elsewhere[16,30] have done much to relate fabric and fiber physical properties, and much of this developing science may be useful in obtaining improved filtration fabrics.

4.6.4 Permeability

The resistance to flow of gases through porous materials has been discussed in Chapter 2. The permeability of filtration fabrics is so decreased by the residual dust deposit that the permeability of the clean fabric appears to have little to do with its use.

The objective in fabric design is to maintain a highly permeable residual dust and fabric combination, while yet passing a minimum amount of dust. Toward this end the pores through a fabric must be closely controlled. They must not exceed a certain bridging diameter. (Section 2.3.2). If the pores are too small they will either plug or pass too little gas, which distributes itself according to the square of the pore diameter. In an ideal filtration fabric probably all the fabric pores should be the same size, the size depending on dust properties, etc.

Pore size and thus fabric permeability are dependent on cloth design structure. Kaswell[24] indicates reductions in permeability with increasing pick count and also with pick diameter as would be expected with the decreasing pore sizes. Filling twist was found to have a greater effect on fabric porosity and permeability for a given fabric than any other constructional variable; the tighter the filling yarn the more permeable the fabric. This would be expected for any fabric passing more air between than through the yarns.

Pore size must not be visualized as simply the distance between crossed cylinders, however. For all but filament yarns there will be numerous fiber ends protruding into the pores, and in the extreme case (napped or felted materials) the pores will be primarily between fibers rather than between yarns. In such cases the uniformity of spacing is equally important, but the means of achieving it are less dependent on weave. Yarn texturizing and post-weave surfacing treatments contribute much to the permeability of the clean fabric, and perhaps also to the residual dust deposit permeability.

4.6.5 Dust Deposit Release

The ability of the fabric to release the deposited dust will depend on the mode and intensity of cleaning and also on the adhesive character of the fabric. Cleaning and fabric adhesion are discussed in Chapters 2 and 6. The way in which fabric construction relates to deposit release has not been determined, but is presumed to depend partly on the electrical resistances of selected fibers. Resistance is seen to depend on humidity, which is independently known to have a marked effect on filtration fabric performance (Section 2.2.2)

4.7 AVAILABLE FABRICS

There are at least 50 U.S. manufacturers of dust filtration fabrics or filter elements for dust collectors. The list of manufacturers in Appendix 4.4 resulted from a 1969 survey of nearly 200 companies believed to have interests in the kind of filtration fabrics used in dust and fume collectors.

The list is representative of U.S. fabric manufacturers and suppliers, but undoubtedly does not include all such firms, and may not accurately represent the interests of every firm listed. For example a firm although not specifically mentioning a fabric product in its brochures is often able to supply the product on short notice. Other firms prefer to specialize in certain fibers, filter element types, etc.

Chapter 7 discsses the purchase costs of filter elements, filter fabric, and typical fibers in some detail. As indicated in Chapter 1, the market for dry filtration fabrics is estimated at $15 to 30 million annually, about half the fabric going into new collection equipment and half replacing fabric which has worn out.

The distribution of fabric manufacturers, while not analyzed in detail, may be assumed similar to the distribution of filter equipment manufacturers. That is, the typical fabric manufacturer has one half to one million dollars in sales, and the largest manufacturers have sales of several million annually.

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CHAPTER 5

ENGINEERING DESIGN OF FABRIC FILTER SYSTEMS

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CHAPTER 5

ENGINEERING DESIGN OF FABRIC FILTER SYSTEMS

The design of a fabric filter system is similar to most engineering design assignments in that there is no single rigorous approach to the solution of the problem at hand. Many parameters must be identified and their inter-relationships understood. Placing an important variable in proper perspective whether it be, for example, the fabric cost or gas stream dew point, represents a key step in the design process. The primary purpose of this Chapter is to highlight the many factors that must be considered in designing the overall system. Since many of these inter-relationships are discussed in greater detail in other sections, a very general procedure for selecting and/or designing the system components is presented here, with the emphasis placed upon the pitfalls and expected problem areas.

The overall performance of the filter system will only be as good as that of the poorest functioning component. Therefore, only those well experienced with fabric filter equipment should assume the responsibility for system design, especially of new equipment and new applications. The replacement of existing equipment is somewhat easier since one does have some practical guidelines. In general, the first decision that one must make is whether to do the job in-house, or to contract for a "turn-key" job in which the entire system is provided by an outside firm. In either case, the best available consultation should be sought and the purchaser should retain the responsibility for complete description of the process effluent to be filtered. Once the above groundwork is established, the experienced engineer is presented with a tractable design problem which he can undertake in the conventional iterative manner and which involves the following main design steps:

1. Define the effluent -- mass flow rate, dust properties, gas properties, and process variations with time.
2. Approximate the collector design
3. Approximate the fan and ducting needs.
4. Based on (2) and (3) select peripheral equipment, instruments, and controls.

5. Repeat (2) and (3) to minimize the estimated total system cost.
6. Review for alternative effluent control methods; budget; and procure.

The first three steps can be carried out approximately without the cost data for individual system components by using the guidelines set forth in this handbook. In later stages, specific apparatus must be evaluated, in conjunction with equipment supplier support, to arrive at realistic estimates of initial costs.

Operating, maintenance and overhead costs are also essential considerations in preparing design specifications. Even the accounting practices of the purchasing company may decide the relative attractiveness of one system over another, e.g., the depreciation of a low first cost, higher maintenance system versus that of a higher capital cost installation. Total annual cost is probably the best criterion to use (see Chapter 7). Other criteria of performance that are difficult to assign a cost to, but which affect the overall quality of the system, include the emission level of the equipment, its reliability, simplicity of operation, etc. Although the latter factors are difficult to quantity the design engineer must take them into account.

5.1 DESCRIPTION OF PROCESS EFFLUENT TO BE FILTERED

The definition of the problem, which is common to any engineering design effort, constitutes the basis for its effective solution. In the case of fabric filtration, the crux of the problem is to define as completely as possible the process effluent properties. The minimum information required is listed in Table 5.1. So important are these data that, in almost all cases, preliminary stack sampling should be performed and, in some instances, the entire operation should be simulated on a bench or pilot scale with experimental dust generation and filtration facilities.

If a process is characterized by variations in gas flow and/or gas particulate composition, the equipment must operate at peak loads without media plugging, as well as at reduced flows where condensation may occur. Any potential future increase in effluent loading should be considered in estimating design capacity, since an initial overdesign is often less costly than subsequent reconstruction.

It appears highly advisable to prepare a brief summation as outlined below in which the key properties of the effluent and the control requirements are listed. Most fabric filter manufacturers submit a similar questionnaire to potential customers prior to quoting on new equipment.

TABLE 5.1

EFFLUENT AND FILTERING REQUIREMENTS

1. Process Effluent

(a) Gas flow:
- Average:
- Maximum:
- Temperature:
- Water Content:
- Other Constituents:

(b) Dust flow:
- Average:
- Maximum:
- Size distribution:

Size:	<1	<5	<20	<50	<80	<95	<99 μm
%:	__	__	__	__	__	__	__

- Particle density:
- Bulk density:
- Est. range of K_2:
- Other properties:

2. System

(a) Preferred location - (in) (out)side

(b) Space limitations, if any

(c) Ambient weather
- Range:
- Temperature:
- Snow, water, wind loads

(d) Weight requirements

(e) Cost considerations

3. Exhaust

(a) Particulate level:

(b) Gaseous req'ts:

(c) Visibility req'ts

(d) Preferred exhaust location:
- (in) (out)side
- Distance from collector:

5.1.1 Gas Flow

Determine the volume of gas emitted by the dust generating process prior to any corrective adjustments of temperature or dew point.

Should there be temporal variations, the maximum, minimum, and average flows should be estimated. The cost of the fabric filter system will be approximately proportional to the volume of gas emitted by the process. Therefore, it is imperative that one establish what gas volumes will obtain when practicable process changes and closure or all unnecessary vents of leak points are considered. One should anticipate, and be prepared to defend, process changes that constitute minor expenses relative to the savings achieved through reduced gas handling capacity.

5.1.2 Gas Properties

Determine the temperature and pressure of the carrier gas stream and estimate its approximate water content. Identify any abnormal gaseous constituents such as acid vapors, toxic and/or corrosive fumes, combustible or explosive materials, condensibles, etc. Determine whether composition and/or concentration vary significantly with time, particularly during process start-up or shut-down operations.

5.1.3 Dust Flow

Determine the weight (mass) rate of dust or fume generation by the process, again making certain that the quantity has been minimized as much as possible by process adjustment. Variable load conditions, particularly peak values, must be considered in determining filter capacity if overloading or plugging is to be avoided. Standard procedures for measurement of effluent properties are described in several test manuals (for example, see reference 1).

5.1.4 Dust Properties

The better the system designer understands the properties of the dust particles (see Chapter 2), the easier his task of designing the filtration system becomes. Minimal information for developing a functional system, however, must include a characterization of the particles in terms of mean or median diameter and, if possible, the distribution of sizes. A knowledge of effective densities for discrete and bulk particles as well as an estimated permeability (K_2) for the dust is also useful in establishing filtering conditions.

The value of (K_2), which is thought to reflect the integrated effects of particle dimensions; e.g., length to diameter ratio, cohesiveness between particles, dust cake rigidity, and spatial arrangement of particles in the dust cake, is a valuable design tool. On the other hand, individual measurement of the factors which presumably determine the K_2 are not as yet sufficiently understood to make their quantification possible. Additional dust properties for which no strict quantitative definition is currently made, but which constitute important inputs for system design are; the softness or stickiness of the dust as a function of temperature or humidity; abrasiveness; agglomerating characteristics; "seeping" tendency; adhesion of the dust cake to the fabric.

5.1.5 Variability in Aerosol Composition

Allowance should be made for the fact that, even without intentional modification of the gas temperature or the particle size properties, there may be radiation cooling, moisture leakage into the gas stream, agglomeration of the smaller particles and/or sedimentation of the larger particles, or other changes during transit through the system. Therefore, one must attempt to define the aerosol as it enters the filter unit.

5.1.6 Emission Requirements

The degree of particulate control which must be attained with the overall filter system should be determined early in the design process. This will usually be stated as a maximum tolerable weight emission rate rather than as a system efficiency. The requirements may also specify other factors that must be considered, e.g., toxic gases, odors, or visibility of particulate or steam plumes.

It must also be decided whether the filtered effluent can be discharged directly to the outside environment (with the attendant problems of heat loss, make-up ventilation and visible exhaust) or released within the building. In the latter case, the problems of heat, materials toxicity, nuisance and/or hazard in the event of filter rupture, and noise take on added importance because of confinement.

5.2 DUST COLLECTOR DESIGN

The design criteria applying to the collector itself will, in turn, affect those for other system components. During the early design phase, however, it may not be possible to predict the interrelationships between design criteria and costs. Therefore, until realistic trade-offs can be established among collector size, fan requirements, and hoods and ducting, cost estimation within approximately ± 50 percent is acceptable. As a subsequent aid to cost optimization, it may be helpful to construct a table by which one can estimate how the collector cost will increase with respect to an increase, say 10 percent, in any significant variable:

	Filter Velocity	Temperature	Fabric Pressure Drop	Dewpoint Temperature	Particle Diameter	Effluent Flow Vol.	Dust Loading	Specific Resistance
A 10% increase in this variable:	V	T	p	DT	D_p	Q	L	K_2
Will add this much to the								
INITIAL COLLECTOR COST: ($)								
ANNUAL SYSTEM COSTS: ($)								

The effects of selected variables on the annual operating and maintenance costs may also be estimated, as indicated, since the collector design has a strong affect on the annual costs (Chapter 7).

5.2.1 Pressure Drop

Estimate the average pressure differential across the filter media and deposited dust layer during normal operating conditions. Although the value selected may be somewhat arbitrary, several practical considerations, e.g., collector strength under pressure or vacuum, fan power requirements, and dust cake mechanics, point to a few inches of water as the optimum pressure drop. Lacking any better design guides, 3 inches of water is acceptable as a typical value. On the other hand, the use of high velocity filtration, felted fabrics, or the presence of a sticky or low porosity dust cake often require that optimum pressure drop be of the order of 8 to 10 inches of water. Pressure loss through the collector alone, exclusive of the media drop, is usually small compared to that of the loaded fabric. The pressure loss associated with the duct, hood and stack system will probably be in the same range as that for the collector with fabric.

The pressure drop through the combined fabric and dust layer can be treated as an independent variable in the sense that the design engineer can exercise considerable control over the cleaning mechanism. By increasing the intensity and/or frequency of cleaning it is possible in some cases to reduce pressure drop to levels approaching those of the clean fabrics. If this concept is carried too far, however, the collection efficiency may be lowered, the fabric itself damaged, and the power costs for driving the cleaning mechanism increased to prohibitive levels. Thus, the selection of the optimum operating pressure loss becomes a matter of trade-offs based upon engineering judgement and field trials. Since the final operating pressure loss may not necessarily conform to the original design point, it is not practical to over-refine the preliminary estimates of average and peak pressure drops.

5.2.2 Air/Cloth Ratio

This ratio (CFM of air filtered per ft^2 of cloth filter area) is very important in determining collector performance. The ratio (or its equivalent, filtering velocity) is discussed throughout this handbook in connection with dust deposit characteristics, collector configurations, collector efficiency and pressure drop and maintenance requirements, to mention some principle effects related to air/cloth ratio. Ratios in current use range from less than 1:1 to more than 20:1. The choice depends on cleaning method and fabric, and on characteristics of the particles.

There is no precisely determinable ratio for a given application as the choice also depends on estimates and trade-offs, such as between initial collector cost and recurring power costs. Consequently, there is no precise analytical method for determining the best air/cloth ratio, although Chapters 2 and 6 indicate several approaches to the construction of analytical models. Instead, it is customary to select ratios based on similar previous experience, that is, ratios that have been proven on similar combinations of cleaning method, fabric, and dust.

Each dust collector manufacturer has guidelines for the selection of air/cloth ratio, based on his experience with a variety of applications. These guidelines vary from manufacturer to manufacturer, largely as a result of differences in equipment. Four such guidelines are summarized in Appendix 5.1 for a shaking bag collector, a glass cloth collector employing principally reverse flow plus flexural cleaning, a reverse jet collector, and a reverse pulse collector. These are typical of the guidelines that manufacturers have made publicly available. Normally, these guidelines should enable estimates to within at least 25 percent of the optimum design ratio. In unusual cases, and for a more exact estimate, consultation with an experienced manufacturer is advisable. Frequently, in new applications a pilot study has been used to determine the best air/cloth ratio. Such studies can be misleading, however, unless they accurately model the proposed equipment and use a suitable aerosol.

There is an optimum air/cloth ratio for each set of filter system design parameters: i.e. dust to be filtered, configuration of filter system, cleaning mechanism to be employed, fiber material to be utilized and configuration of the fiber media. However, for a given set of the above parameters, the total system cost versus air/cloth ratio relationship is rather flat near the optimum ratio. Thus there is a tendency to minimize initial costs by selecting an air/cloth ratio toward the high end of the range. On the other hand it is frequently reported that, with lengthy operation at two different filtration velocities, the lower of the two filtration velocities results in lower operational costs. Thus one must carefully weigh the traditionally cited advantages of lowered air/cloth ratio (i.e. lower power costs, decreased maintenance and higher collection efficiency) against the larger initial capital costs associated with increased collector size and the penalty for its space occupancy. Further, as pointed out earlier in Chapters 1 and 2, it is anticipated that with advancing fiber, fabric media and cleaning technology the optimum range of air/cloth ratios, for any set of design and operating parameters, will tend to increase.

5.2.3 Cleaning Mechanism and Fabric

The selection of the cleaning mechanism and the filter fabric are best made together, since both items are closely related (Section 3.3). For example, felted fabrics are almost exclusively cleaned by pulse or reverse-jet air, whereas most woven fabrics are cleaned by other means. Of the relatively few choices of fiber media (approximately eight, see Section 4.2), most will be eliminated for reasons such as poor temperature and/or corrosion resistance or excessive cost. Of the several cleaning mechanisms used in filtration systems, only two or three will meet the specific requirements for a given installation: i.e., high, low or moderate dust loadings; continuous or intermittent operation; ease of removal of dust from the fabric; small floor area; minimal pressure drop; high efficiency; etc.

By a process of elimination, therefore, a review of past successful filtering performance will usually show that only a few cleaning mechanism - fabric combinations are compatible and sufficiently attractive to warrant economic evaluation.* The time required for cleaning also determines the choice of cleaning mechanism. This time should be a small fraction of the time required for dust deposition, since otherwise too large a fraction of the fabric will be out of service for cleaning at any given time. It is common with shake cleaning equipment, for example, to have a cleaning-to-deposition time ratio of the order of 0.1 or less. Applying this criterion, having a ten compart-

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*It is not intended here to exclude or impugn the merits of a hitherto untried combination. The design approaches set forth in this chapter, however, are based upon successful precedent or at least qualitative findings which lend some substance to cost estimates. If it is desired, or is absolutely necessary to consider some novel combination, one should view the problem as a research and development effort and not as a routine fabrication process. The path that should be followed will be more apparent once preliminary cost estimates have been prepared, based upon conventional design approaches.

ment baghouse would mean that one compartment is out of service at all times. Therefore, the choice of cleaning mechanism affects system size as well as fabric life, maintenance, etc.

5.2.4 Cloth Area

The amount of fabric in actual use at a given time is found by dividing the estimated total flow entering the collector by the selected air/cloth ratio. The volume flow rate of the effluent entering the collector will not necessarily be the same as that discharging from the generating process, owing to temperature changes, the added volume of vaporized cooling water, and dilution air which may be added deliberately for cooling purposes or accidentally by air leakage. The latter factor may contribute to a significant flow increase in systems operating under large negative pressures. In filter applications involving a varying flow, some judgement is required to decide whether to size the equipment for the peak flow, the average flow, or for some intermediate point. It is again necessary to seek a compromise between the increased cost of larger equipment and the increased cleaning cost, and the possible risk of fabric damage associated with short term, high pressure drops.

Except for certain systems that are operated intermittently, e.g., a few hours on line followed by cleaning only during down time, most filtration units will require reserve fabric capacity to allow for off-line cleaning, inspection and maintenance. Since it is common practice to isolate temporarily defective filter units until it is convenient to replace them, additional reserve capacity may be required. The total fabric area to be installed can be estimated by multiplying the area to be in actual use at any time by the term

$$(1 + T_R + F) \qquad (5.1)$$

where (T_R) is the time ratio (cleaning to deposition) discussed in the preceding section and (F) the fraction of the fabric area expected to be out of service at any time due to replacement, inspection, or maintenance operations. Judicious timing of the above procedures in relation to peak flow periods may, however, reduce the multiplying factor.

Costs for the installed fabric media as a function of unit size may be estimated from data given in Section 7.3.

5.2.5 Cloth Life

Fabric deterioration often results from the combined assault of several factors (Chapter 8), rather than from any single effect such as thermal erosion, mechanical stress through repeated flexure, chemical attack, abrasion, etc. All possible modes of failure should be considered during the preliminary design phase. Again, previous experience, especially that relating to similar fabric-cleaning-dust applications, may be the best and only guide. Extrapolating from experience, one might estimate that the reduction in fiber life through thermal erosion might double for a 20°F rise in temperature, or that the mechanical attrition rate might double when the frequency of cleaning is doubled.

Generally, it should be possible to estimate fabric life within a factor of two in situations where no direct experience can be cited. If performance data are available, estimated reliabilities may be upgraded to perhaps ± 20 percent, which is the order of dependability of the best pilot plant data. Having established a reasonable estimate of fabric life, one can then reach an annual cost figure for fabric media.

5.2.6 Housing Configuration

5.2.6.1 Number of Compartments. - Selecting the number of separate compartments for a fabric filter installation is a relatively easy decision. The basic information required is the allowable variation in gas flow with respect to process or plant ventilation, the availability of sizes of commercial units (compartments or filter house modules) and the expected frequency of maintenance. In small collectors, individual compartments may contain as little as 100 square feet of fabric surface, although collectors as large as approximately 50,000 CFM capacity may also have only one compartment. Multiple compartments of almost any size may be chosen, subject to availability. With the exception of reverse jet and pulse jet units, at lease one compartment will be out of service during the cleaning cycle. It may also be necessary to provide additional compartments for emergency, extended maintenance, or unexpected increases in process effluent.

5.2.6.2 Fabric Arrangement. - Fabric filter media in panel, tube, and bag form represent the most commonly used industrial configurations. Although the selection of filter geometry may occassionally be a matter of preference, the type of fabric and the cleaning method usually dictate the configuration. Panel filters, for example, cannot be cleaned by flexure, and reverse jet cleaning requires open ended tubes. Other important considerations are discussed in Section 3.3.

Panels, tubes, or bags are commercially available over a broad range of dimensions as discussed in Section 3.1. Once the requirement for fabric surface per compartment is determined, it remains to decide what combination of filter length, diameter, and spacing will be the least expensive. This is too often interpreted as a maximum filter packing and a rather compact filter housing, i.e., a container with no dimension much greater than twice the smallest dimension. Closely packed filter elements tend to wear against one another, and make inspection and maintenance difficult (Section 8.3). Compact housings incur a greater cost for plant floor space than taller units. Recently, one manufacturer has introduced super-long bags (~60 ft), partly to conserve floor space[(3)]. Compact housings may, however, be more suitable in outside locations where land use costs less than the erection of tall structures.

Other considerations in selecting the fabric configuration are downward vs. upward flow and inside vs. outside filtering. The ease and the frequency of fabric replacement, and the uniformity of flow distribution and associated danger of condensation in stagnant air pockets are also considerations.

5.2.6.3 Compartment Structure. - Although many kinds of fabric collectors can, in principle, be operated either under negative or positive pressure, the larger units are often custom designed for one condition or the other to minimize costs. Least expensive is the installation needing no housing at all, in which the particulate is collected on the interior surfaces of a positive pressure bag system. The danger of cooling below the dew point is an important consideration, particularly in a suction housing where infiltration leakage often occurs unless a more expensive gas-tight design is adopted. Thermal excursions of the collector during startup and shutdown can effect the sealing characteristics of critical gasketed connections, depending on the structural materials. Interconnection of compartments via ducting or hoppers and their isolation, especially during the cleaning cycle, are important considerations (Section 3.4). The generalized rules for designing the compartment structure are not well defined. Construction materials are likewise not generally prescribed. The most common housing material is steel, as discussed in Chapter 3. The choice of material depends on the nature of the dust and gas mixture and their flammability, corrosiveness etc. Lacking a more specific guideline, one would do well to follow precedent in selecting materials of construction, metal gages and dimensions.

5.2.7 Capital Cost Estimates

A detailed discussion of initial and annual cost factors is presented in Chapter 7. The cost of the baghouse, including its amortization schedule and plant overhead costs, should now be estimated based upon the tentative equipment selections. The designer should now devote primary attention to initial installation costs with emphasis upon how these initial costs will contribute to the total annual cost of the fabric filter system operation, in accordance with specific company costing procedures. At this time, sufficient information has been acquired to complete the working estimate guide at the beginning of Section 5.2.

Some of the design decisions cited above may have been based upon very limited data. Consequently, one should review the compilation of preliminary estimates, particularly those reflecting choice of fabric, cleaning mechanism, and average pressure drop through the filter media. The objective should be to describe a collector that will be within ~10 percent costwise of the optimum design. It is not advisable, however, to finalize the design until other components of the overall system have been selected and evaluated with respect to their possible influence on collector design.

5.3 FAN AND DUCTING DESIGN

The design and selection of filter system components, other than the collector discussed previously, also require some iterative approaches during the planning phase. Fortunately, the alternatives are fewer, and in most cases, the design features are simpler. The main trade-off area is between the pressure drop through the ducting and stack systems (an inverse function of duct diameter) and the fan size and cost. In many cases, the pressure drop through the fabric filter unit alone will largely determine fan size.

5.3.1 Ducting Layout

The positioning and amount of ducting are determined mainly by the expected locations of effluent source, collector, fan, and venting point. Ordinarily, minimum duct lengths and diameters will be used unless the ducting is also intended to provide radiant cooling of the gases prior to filtration, or to function as settlement chambers to remove the larger particles. The first step in design is to establish the locations and lengths of main, branch and riser ducts showing types of junctions and bends.

The distance from the dust collector to both the dust source and the point of discharge of the filtered effluent, must be considered with regard to duct costs and space availability. The cost of plant floor space may be a reason for locating the collector outside the plant, other possible reasons being ceiling limitations and safety. On the other hand, the outside collector must usually be protected against weather and insulated against temperature changes. Also, not to be overlooked in locating the collector are space clearances for, and accessibility to: the necessary ducting; crane or hoist requirements, especially for fan repair; the weight of the collector; the feasibility of removal and disposal of the collected dust; and plant insurance costs.

In laying out the duct plan, the locations of cleanout doors, dampers, dilution valves and any auxiliary cleaning equipment, i.e., dry inertial collectors, scrubbers, or cooling towers should be taken into consideration. Whenever possible, all ducting should be located so as to be easily installed and maintained.

It is important to use as little horizontal ducting as possible and to select diameters which allow for complete transport of the dust load to the collector. Sharp bends and abrupt changes in dimensions should also be avoided to prevent dust accumulation. Since the above approach suggests high velocity systems, it should be recognized that power costs also increase with higher duct velocities and that abrasive dusts can cause rapid duct erosion, particularly in bends. Useful velocity guidelines have been set forth in Table 2.42(b) and in various engineering manuals to aid in this aspect of system design.

Duct sizes through the system are estimated by the recommended transport velocities and the calculated volume flow rate through each section. The latter value is computed from the source flow, corrected for any added volume attributable to dilution air, and adjusted to the temperature and pressure conditions at the location of interest in the duct system. In cases of fluctuating flow, it is recommended that the ducting be sized for some intermediate flow between average and peak loads.

The ducting sections located downstream of the collector may be sized somewhat larger, owing to absence of settlable particulate in the gas stream. The final dimensions should represent a balance between the increased cost for larger duct size and the lower pressure drop (power cost).

5.3.2 Ducting Costs

Standard steel ductwork is normally used, unless there is danger of corrosion, abrasion, adhesion, high temperature, thermal distortion, need of insulation, or unusual surges in pressure or in temperature. Aluminum, glass, plywood, etc., can sometimes be used as substitutes for steel. While the duct material may be suggested by the collector manufacturer, the ducting is normally made up and installed locally.

Cost estimates or quotations are readily obtained as soon as diameter, length, and guage specifications are available (Section 7.1.3).

One must consider the costs of dampers, ports, Tee sections, elbows, flanges or other special components, keeping in mind the fact that fitting or adapting the ducting to the above parts may involve more cost than that for assembling straight vertical or horizontal runs.

5.3.3 System Pressure Drop

The total system pressure drop is that of the combined losses in the duct and the fabric filter unit. Ducting losses vary approximately as the square of the gas velocity and can be readily calculated by standard formulas or from tabular or graphical data (see Section 2.5). Presure drops for non-linear shapes (elbows, Tee's, reducers, etc.) are usually expressed in equivalent length of straight duct of the same diameter. In conventional practice, one traces the largest branch (usually from the most remote source of dust generation), noting the temperature and gas flow through each succeeding section up to the collector inlet. A similar procedure is followed from the collector exit to the point where the filtered effluent is discharged to the inside or outside atmosphere. Ordinarily, the total pressure drop associated with the ducting alone will be in the range of 3 to 6 inches of water, although other values may apply in some circumstances.

One then adds to the estimated pressure drop through the ductwork, the collector pressure drop and that of any other component of the system, e.g., a centrifugal collector. The result will be the net presure to be supplied by the fan when ambient pressures are the same at system inlet and outlet. Should the ambient pressure at the system inlet exceed that at the outlet, the net pressure requirement for the fan is decreased by this difference.* The opposite applies if the pressure gradient is reversed.

*The kinetic energy or velocity pressure retained by the air leaving the fan may be deducted from the fan static pressure requirement, except when the air is charged to a large stagnant space, e.g., exhausting the fan outdoors. The kinetic deduction is frequently overlooked, however, on the justification that by omitting it, a safety factor is added. See the excellent discussion on fan selection in "Fan Engineering" by the Buffalo Forge Company(6).

5.3.4 Fan Selection

Of the types of fans commonly used in industrial ventilation, centrifugal fans are most often chosen for the primary flow in fabric filtration systems. These are described below and in Figure 5.1:

1. "Forward-curved blade types: A multi-bladed, "Squirrel Cage" wheel in which the leading edges of the fan blades curve toward the direction of rotation. These fans have low space requirements, low tip speeds and are quiet in operation. They are usually used against low to moderate static pressures such as encountered in heating and air conditioning work. Not recommended for dusts or fumes that would adhere to the short curved blades, causing unbalance and making cleaning difficult.
2. Straight or Radial-blade (paddle wheel, long shaving wheel): The "workhorse" for most exhaust system applications, they are used for systems handling materials likely to clog the fan wheel as the name indicates. Such fans usually have a medium tip speed and a medium noise factor and are used for buffing exhaust, woodworking exhaust or for applications where a heavy dust load passes through the fan.
3. Backward blade type: The type in which the fan blades are inclined in a direction opposite to the fan rotation. This type usually has a high tip speed, provides high fan efficiency and has non-overloading characteristics. Except in case of direct driven arrangements, non-over-loading feature is over emphasized in exhaust ventilation work as the exhaust system acts as a load limiting orifice to make overloading of any exhauster motor from variations in system conditions improbable. Blade shape is conducive to buildup of material and fans in this group should be used only on clean air containing no condensible fumes or vapors."(7)

The first consideration in fan selection is which of the numerous fan types is best suited to the estimated air flow and pressure requirements. Reference to manufacturers' data depicting the performance of various types over a range of speeds and delivery volumes will establish this. Another consideration in selecting the fan type is whether it is to be used on the clean side of the filter or on the dirty side where maintenance will probably be higher. (See also the discussion of types of collector construction, Section 5.2.6.)

Although several fan sizes of a specific type can meet the desired pressure-volume requirement by changing the speed, only one size

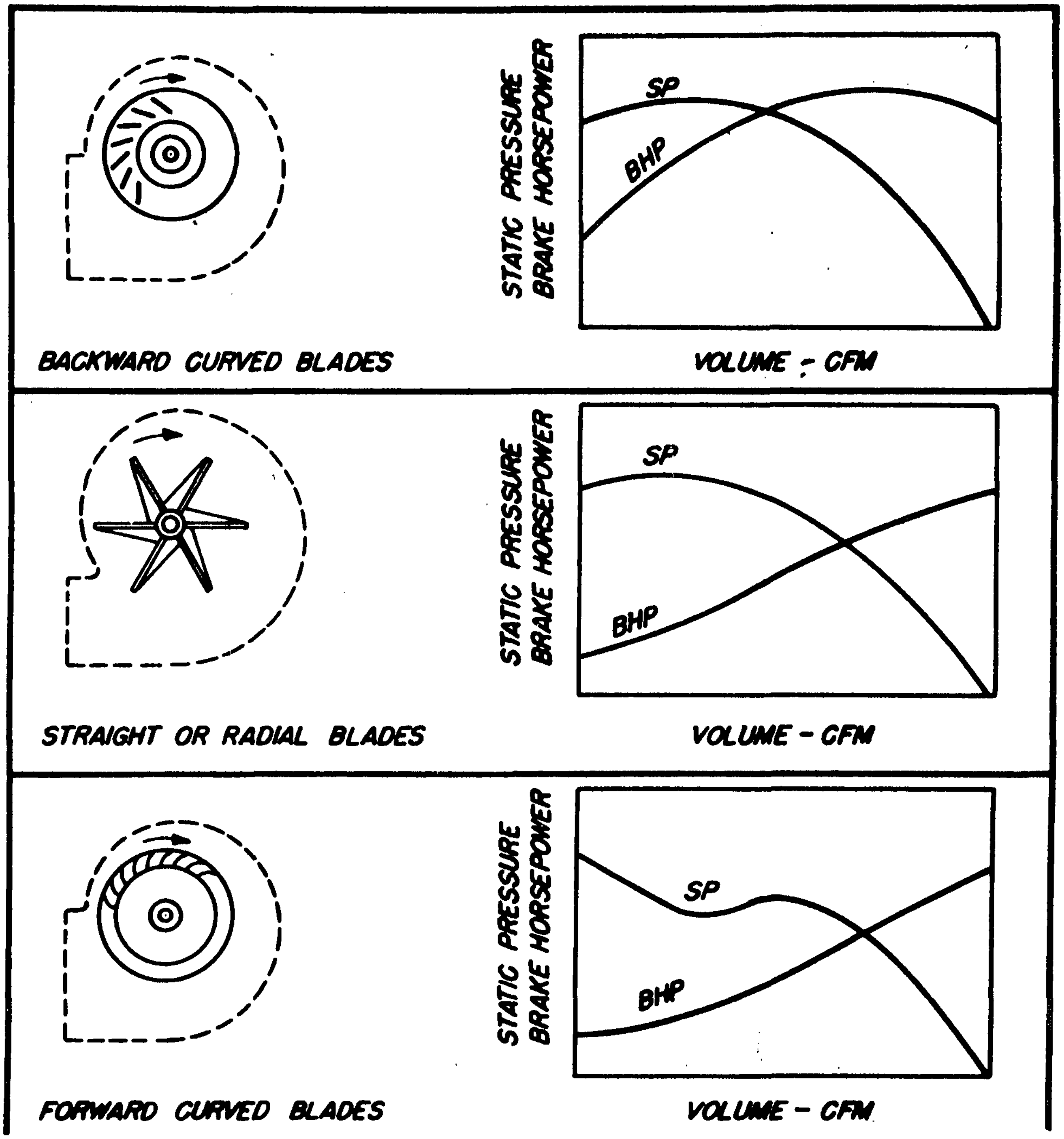

Figure 5.1. Some Fabric Filter System Centrifugal Fans. (From Ref. 7).

will perform at hits peak efficiency. Therefore, there may be no particular economy in selecting a smaller size unit of lower cost, since operation at a higher speed will lend to proportiately greater power consumption. On the other hand, a slight oversizing of the fan will result in lower fan speeds and probably less maintenance without a serious drop in effiency. Extra fan capacity is a safety factor against future process expansion or unexpected peak flow requirements which the fan must be capable of handling. Another consideration in fan selection is the reliability requirement: Can a fan outage be tolerated, or should more than one fan be installed?

The process of fan selection from the several trial sizes involves the following steps. First, choose a maximum rated capacity, roughly 20 percent more than the required capacity. Determine from the table or fan curve the power and speed requirements at the required pressure and flow,* and from these data, estimate the installed fan and motor costs and maintenance costs. Using an acceptable amortization rate, perhaps ten years and the local cost of power, compute the total annual cost of operating this particular fan size. Note that the cost of the drive, mountings, and motor may easily double the cost of the fan alone.

Note that one is limited to available motor speeds if a direct drive is to be used. Direct drives consume less power, need less maintenance, and present no belt slippage problems. On the other hand, many small and moderate sized fans are belt driven, both for reasons of initial cost and to permit future speed adjustments.

This initial cost estimate for fan and associated equipment is probably adequate for the early phase of the system design process. To minimize fan costs, however, the above computation should be repeated for slightly larger or smaller fans until a minimum cost is reached. It may become apparent before undertaking this step that a change in fan style

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*Fan test data is usually based on standard temperature and pressure, i.e., standard air density. If the fan is to handle non-standard density gas, different curves will be used.

or size should be considered, due to revisions in collector design pressure drop and in ducting requirements. Having determined the fan arrangement of minimum cost, again consider whether there is a sufficient margin of capacity and of reliability.

5.3.5 Minimizing Fan and Ducting Costs

Preliminary estimates of ducting requirements and costs should be reviewed. It may be determined, for example, that a small increase in duct diameter, say 5 percent, will allow use of a smaller fan with a net lowering of overall cost; that is, the lower operating and capital costs for the fan assembly overrides the increased initial costs for the ducting. In this example, the decrease in pressure drop through the duct system would be of the order of 20 percent based upon the inverse fourth-power relationship between pressure loss and duct diameter. Having established a revised value for duct pressure drop, new criteria are available for resizing the fan and motor drive. If the combined cost of the duct and fan system decreases appreciably as a result of this reassessment, the process should be repeated until a minimum point is identified.

It also is recommended that the above cost analysis be examined in terms of the key variables affecting the initial and annual costs for the combined fan-ducting system. Again, a tabular array of the system cost increase,as a function of change in the major design variables,constitutes a useful working tool.

5.4 PERIPHERAL EQUIPMENT, INSTRUMENTS, AND CONTROLS

In earlier sections of this chapter, a preliminary design approach has been outlined for the main components of the fabric filter system. As the few remaining system parts are less dependent upon the primary system dimensions, they should now be selected so that the overall fabric filter system design can be finalized (Section 5.5).

5.4.1 Particulate Pre-Conditioning Equipment

The pre-filter particulate treatment process, if any, may be designed for: (a) the enhancement of particulate agglomeration, thereby precipitating out of the gas flow some material prior to deposition on the fabric and/or improving the resistance properties of the dust cake,

(b) the pre-separation of coarse particles by gravity sedimentation or inertial techniques, or (c) the injection of additives to produce a dust cake sufficiently dense to provide high efficiency collection of low concentrations of fine material, or alternatively additives to produce a more porous dust cake with lower resistance.

Use of any of the above techniques may require reappraisal of preliminary cost estimates for the fabric filter system for the following reasons (see Section 2.4.8 for details):

(a) Change of deposit permeability and hence cycle time, due to alteration of particle size distribution.

(b) Change of inlet loading.

(c) Change of cake removability or residual permeability.

(d) Change in properties of the collected material such as bulk density and total volume.

(e) Changes in gas stream properties.

One must balance the economic advantages of changes in dust properties against the costs of installing and operating the pre-conditioning equipment. Of course, if the treatment process is used to elevate collection efficiency to levels satisfying pollution control regulations, the equipment costs become a necessary investment.

5.4.2 Gas Pre-Conditioning Equipment

Hot process effluents are usually partly cooled before filtering to reduce the flow volume which, in turn, decreases the filter fabric area requirement. Lowering the gas temperature toward the dew point often extends fabric life and may permit the use of less expensive or more durable materials. Prior to entering the collector, the process effluent may also be altered through combustion, absorption, chemical reactions or humidification, any of which may influence the design of other fabric filter system components. Temperature conditioning, a common treatment, is usually accomplished by the methods described in Table 5.2. In other situations, it may prove more economical to filter the gas essentially at process effluent temperature, or even at increased temperature, provided that the temperatures do not exceed the upper limit for the fabric.

Table 5.2

METHODS OF TEMPERATURE CONDITIONING*

Radiation-Convection Cooling (long, uninsulated inlet ducts)	
Advantages:	Lowest flow volume of the three methods Smoothing or damping of flow, temperature, pressure or other surges or peaks in the process effluent stream Saving of heat (building space heating).
Disadvantages:	Cost of extensive ducting Space requirements of ducting Possibility of duct plugging by sedimentation.
Evaporation (by water injection well ahead of the filter)	
Advantages:	Low installation cost, even with automatic controls Capability of close and rapid control of temperature Capability of partial dust removal and/or gas control via scrubbing.
Disadvantages:	Danger of incomplete evaporation and consequent wetting of the filter or chemical attack of the fabric or filter Increased danger of exceeding the dewpoint and increased possiblity of chemical attack Increased steam plume visibility, a hazard near highways Possible increase in volume filtered.
Dilution (by adding ambient air to the process effluent stream)	
Advantages:	Lowest installation cost, especially at very high initial temperatures.
Disadvantages:	Substantial increase in total filtering volume Automatic control of both temperature and filtering velocity is not possible Uncontrollable intake of ambient moisture, dust, etc without prior conditioning of the dilution air.

* See also Ref. 8.

Somewhat related to the three cooling methods outlined in Table 5.2 are the special systems for emergency protection of the equipment. These include: CO_2 devices that automatically release high-pressure gas to cool the effluent, should its temperature exceed a critical preset limit; fail-safe dampers held in position by set-point melting links; burst-out panels to prevent duct or collector rupture due to pressure or vacuum excursions; and various types of alarm systems. Such equipment can be reliable and relatively inexpensive compared to the cost of replacing a collector system. Rapid-cool equipment can also serve in shortening the time required to take equipment out of service. Heating equipment may facilitate start-ups by preventing condensation.

5.4.3 Instrumentation

Instrumentation which provides a continuous record and/or direct display of the important factors describing the overall filtration process is an essential part of a good fabric filter system. The cost is relatively low (~ a few percent of the total system investment) and the judicious selection of instrument type and function may permit the use of less expensive fabrics or materials of construction, e.g., ordinary sheet steel rather than a special alloy. A discussion of recommended instrumentation is presented in Section 7.1.5. The measurement of those system characteristics that affect its overall function, e.g., temperatures, pressures (absolute and differential), primary gas and dilution air flow rates, water rates, dew point levels, and possibly continuous monitoring of stack effluent concentrations, all enhance the probability of successful system operation. Any or all these devices can be designed to alert the operator through appropriate warning systems (horn, alarm bell, flashing lights) when abnormal conditions arise.

5.4.4 Control Equipment

Solenoid valves, damper actuators, timers, etc., associated with the filter need not be considered here, since they are usually included in the basic filter price. Auxiliary blowers such as those for reverse cleaning may or may not be included and air compressors for pulse cleaning are seldom included as part of the filtration unit. Special ducting dampers that must open and close rapidly or provide high leak tight integrity (< 0.1 percent leakage under adverse temperature, pressure and corrosion conditions) should be specified in the system design.

5.4.5 Dust Disposal Equipment

The physical and/or chemical properties of the dust collected in the hopper require appraisal at this point. Although the disposal technique is usually independent of the primary system operation, some pretreatment of the process effluent may contribute significantly to the ease of handling of the collected dust. For example, the injection of an inert mineral dust might reduce the tackiness of some resinous materials to the point where bridging problems in hoppers or plugging in screw conveyors could be reduced, and the overall system economics improved.

The final selection of hopper design, hopper outlet valving, vibration equipment (if needed), screw conveyors, chutes, pneumatic conveyors, and other ancillary equipment will depend upon several factors. These may include the angle of repose of the dust, its bulk density and the volume and/or weight to be handled. Another factor is the tendency of the dust to flow freely or to bridge, agglomerate or become sticky under mechanical stresses (stirring, rapid motion, vibration) or under changes in temperature or humidity. One must consider whether the hopper is to operate under positive or negative pressure, and also what labor requirements are necessary for dust handling, i.e., whether the dust is to be reprocessed, sold or dumped as waste. Several types of disposal equipment are discussed in Section 3.4.2.

5.5 FINAL SYSTEM DESIGN

Having established preliminary design features for the individual parts of the system, it is now necessary to integrate these into a compatible system. This process calls for more engineering judgement and experience than that required for the preliminary design phase. In addition, the final planning should be geared to management's philosophy on the relative importance of initial costs and total annual costs.

Summary guideline tables outlined in previous sections should be re-examined to determine whether overall costs can be lowered by adjustments in any of the principal variables. Should any appreciable differences in costing be observed, design optimization procedures should be repeated at this time. Since the basic types of equipment required are now apparent, appropriate manufacturers' equipment lines should be reviewed for preparation of specifications. It is highly advisable to consider standard items when possible. Quality, expected service life, ease of repair and delivery times, as well as initial cost will be evaluated. Where possible, preliminary cost estimates or final quotations may now be obtained.

Before fixing the design specifications, a final search should be made for unique or extenuating factors that could possibly influence performance or total costs, such as safety features, noise, general plant ventilation, insurance, relocation of system components, tax rebates, etc. One should also re-examine future needs with respect to plant expansion or process changes. If there remain some questionable design areas, or if certain design aspects are controversial, it may be advantageous to seek the professional opinion of some competent outside person(s) or agency. Otherwise, final design and cost estimates can be submitted for approval and procurement.

No further design or cost changes of significance are expected. However, it may be possible to trim the overall costs a few percent by the following analytical procedure. Let the total annual cost (C) be expressed as the sum of: power costs (P); all costs related to fabric life including materials and labor (F); annual distributed initial costs including interest, taxes and any other item that is directly related to initial installed cost (I); and fixed costs not considered elsewhere (X)

$$C = P + F + I + X \qquad (5.2)$$

Select a key design parameter, such as filter velocity (V), and introduce it into each of the terms of this equation where applicable. In each term, assign to the parameter its appropriate exponent (Table 5.4).

Power, for example, is approximately proportional to V^2. This means that if a slightly different velocity (V') were chosen, the revised estimate of power cost (P') would be approximated by $P' = P\,(V'/V)^2$. Substitution of the design parameter into the other terms of the equation yields the following expression for a revised total cost (C')

$$C' = P(V'/V)^2 + F(V'/V)^{-0.5} + I(V'/V)^{-1} + X \qquad (5.3)$$

That is, the result of changing from the design velocity previously selected to a new value can be estimated by the expanded equation. Cost factors P, F, I, and X have already been determined by careful design procedures. To estimate the effect of a 5 percent increase in filter velocity, the ratio ($V'/V = 1.05$) is used, and (C') is readily evaluated.

By few repetitions of this process, the velocity that will give the minimum total cost may be estimated. If this new estimate is appreciably different from the original design value, a re-examination of the system design is called for.

By this process, the effect of minor changes in any design parameter may be estimated. For parameters having both positive and negative exponents in Table 5.3 (filter velocity, Ave. Cloth Δp, etc.) an optimum design value may be estimated. Note, however, that the parameter exponents listed in Table 5.3 should be accepted as estimates only, owing to the limited field and laboratory data available from which they derive. With respect to trends, i.e., direct or inverse relationships, and weak or strong dependency of a given cost category, the exponents cited in Table 5.3 may be interpreted as tentative typical values. These exponents will not apply uniformly to all systems. One is also not constrained to use the precise grouping of cost factors cited here.

5.6 PROCUREMENT AND RESPONSIBILITY

The final responsibility for the design, fabrication, procurement of materials, approval of specifications, performance testing, maintenance, and the overall performance of the fabric filter system should fall within one department and preferably with one individual of decision

Table 5.3

APPROXIMATE OPTIMIZING EXPONENTS OF COSTS*

PARAMETER	POWER	CLOTH-RELATED	INITIAL
Filter Velocity	+2	-.5	-1
Temperature	+1	+2.75	+1.75
Particle Size	--	-2	-1
Ave. Cloth Δp	+1	--	-1
Cleaning Intensity	-1	+1	-1
Flow Volume	+1	+1	+1
Loading	+.5	+1	+.5
Humidity	+--	+--	--

Note: Fixed costs (X) are invariant by definition.

*May vary from above, values according to circumstances. Blanks indicate insufficient information.

making capability. Although several departments or divisions within a company may contribute their services, any joint sharing of responsibility should be avoided to minimize oversights, schedule conflicts, or other committee type problems.

Following receipt of quotations for system components and installation costs, one should verify compliance with specifications, including the warranty aspects of all components. This is equally important when a turn-key package has been purchased. Although there will be occasions when completely defensible design changes may be proposed by equipment suppliers, one should not expect any extreme deviations in dollars or design with a carefully executed program.

Fixing the responsibility for on-line fabric filter system performance cannot be overstressed, especially with smaller installations. Frequently, a manufacturer is blamed for faulty equipment operation, whereas the problems have actually arisen because of user abuse and neglect. This has led to dissatisfaction and experimentation in some plants, sometimes leading to the purchase of several fabric filter designs to handle one type of process effluent. This makes maintenance routines unnecessarily complicated. When dissatisfaction has resulted in purchase from several different manufacturers, one cannot expect to receive interested customer service from any of them.

As a final point, few if any manufacturers will guarantee the performance of fabric filter equipment, because its function is highly sensitive to process effluent changes as well as to the quality of the installation job and subsequent maintenance. All of these are difficult to document. Perhaps one of the best procurement policies is to request the manufacturer to provide and guarantee installation and startup as part of a package. He should also provide a set of guidelines for operational routine and maintenance at no cost, and he may provide training for the men who will use the new system.

5.7 REFERENCES FOR CHAPTER 5

1. American Society of Mechanical Engineers, Determining the Properties of Fine Particulate Matter: Power Test Codes, PTC-28, New York (1965).

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CHAPTER 6

FABRIC FILTER PERFORMANCE

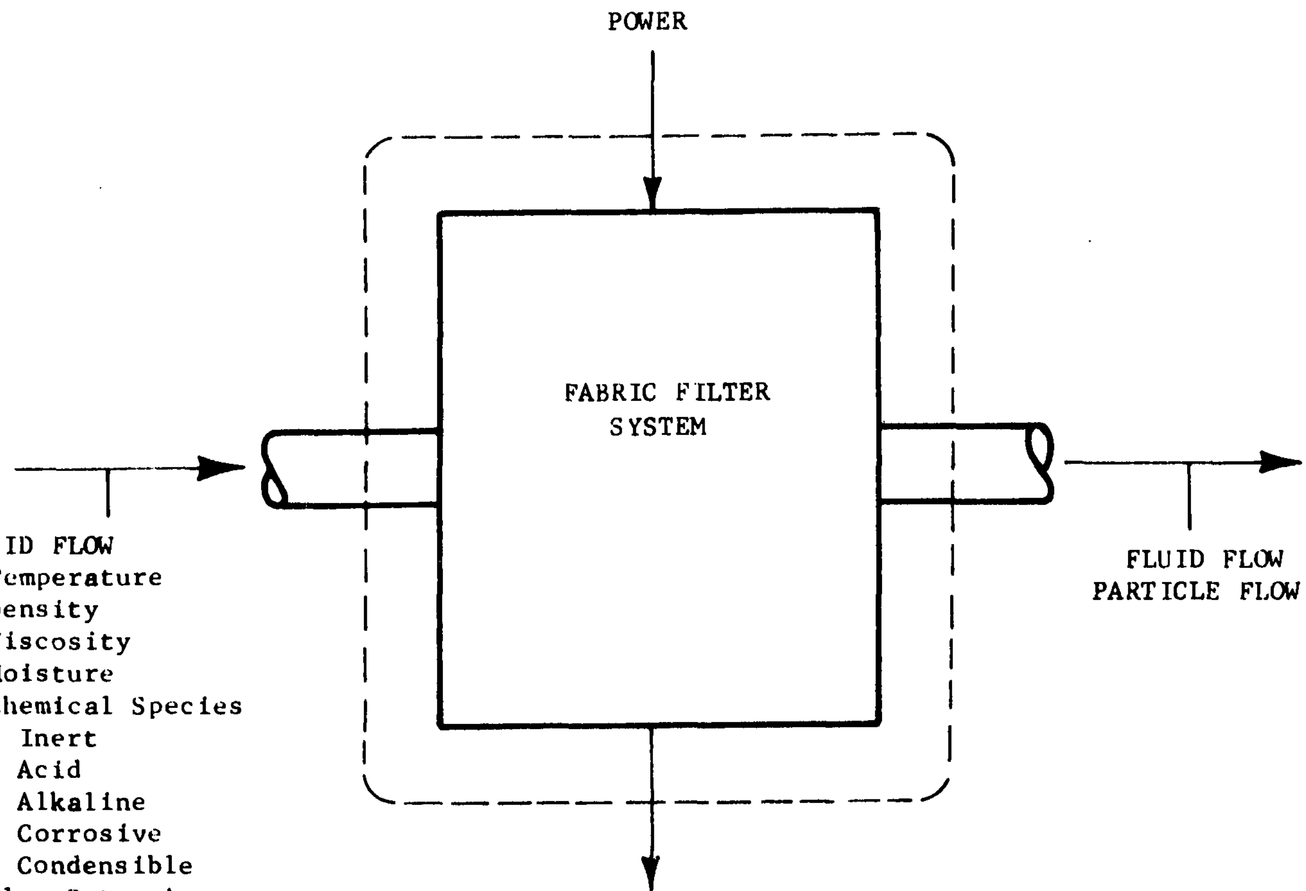
CHAPTER 6

FABRIC FILTER PERFORMANCE

6.1 INTRODUCTION

The determination of fabric filter performance includes the specification of pressure drop, collection efficiency, component life, and costs during operation, in terms of dust, gas, and fabric parameters. Pressure drop with a given dust, gas, and fabric is determined by collector filtering velocity, by the method or mechanisms of cleaning, and by the amount of cleaning. These same factors simultaneously influence efficiency, life, and operating cost. Every fabric filter system in service can, in principle, be described by one or more analytical statements relating pressure drop to dust and gas flow rates, dust-fabric resistance, and cleaning mechanism operating parameters. This Chapter considers pressure drop performance and its variation. Data are also presented on fabric filter efficiency as effected by operating parameters. Efficiency, cost, and life have not been reduced to analytical relationships as has pressure drop and, as a consequence, overall optimization of performance across the several variables has not been reported. Supplementary cost data are contained in Chapter 7, and maintenance, service life, and failure modes of components, principally fabric, are discussed in Chapter 8.

There are approximately 100 fabric filter models commercially available in the U.S. (Chapter 3), each available in a range of sizes. These differ principally in the type and arrangement of fabric used and in the method of cleaning the fabric to control operating pressure drop. The unit operation of all these models can be represented, as indicated in Figure 6.1, by a system into which the particles and gas flow, and to which power is applied to produce external observable changes in gas and particle flow rates. (Additional related system inputs include costs and additional outputs include component life considerations.) With proper quantitative statements about the input parameters shown on the left, the output variables may be estimated with reasonable assurance. Not all the factors indicated are equally important, and in specific instances many may be relatively unimportant to the total performance of the system.



FLUID FLOW
- Temperature
- Density
- Viscosity
- Moisture
- Chemical Species
  - Inert
  - Acid
  - Alkaline
  - Corrosive
  - Condensible
- Flow Rate, Average
- Rate of Change of Flow
- Flow History

PARTICLE FLOW
- Concentration
- Particle Size
- Size Distribution
- Shape
- Density & Packing Char.
  - Bulk Density on Fabric
  - Density Changes with Pres.
- Surface Characteristics
  - Moisture Adsorption
  - Adhesion
  - Electrostatic Properties
  - Oxidation
  - Sintering or Bonding
- Chemical Species
  - Inert
  - Acid
  - Alkaline
  - Corrosive

PRESSURE DROP
COLLECTION EFFICIENCY
POWER EFFICIENCY
COSTS
- Capital
- Operating
- Maintenance
- Repair

COMPONENT LIFE AND FAILURE ELEMENTS
- Operating History
- Fabric
- Seams
- Supports
- Mechanisms

ANCILLARIES
- Dust Handling System
- Control
- Other Systems

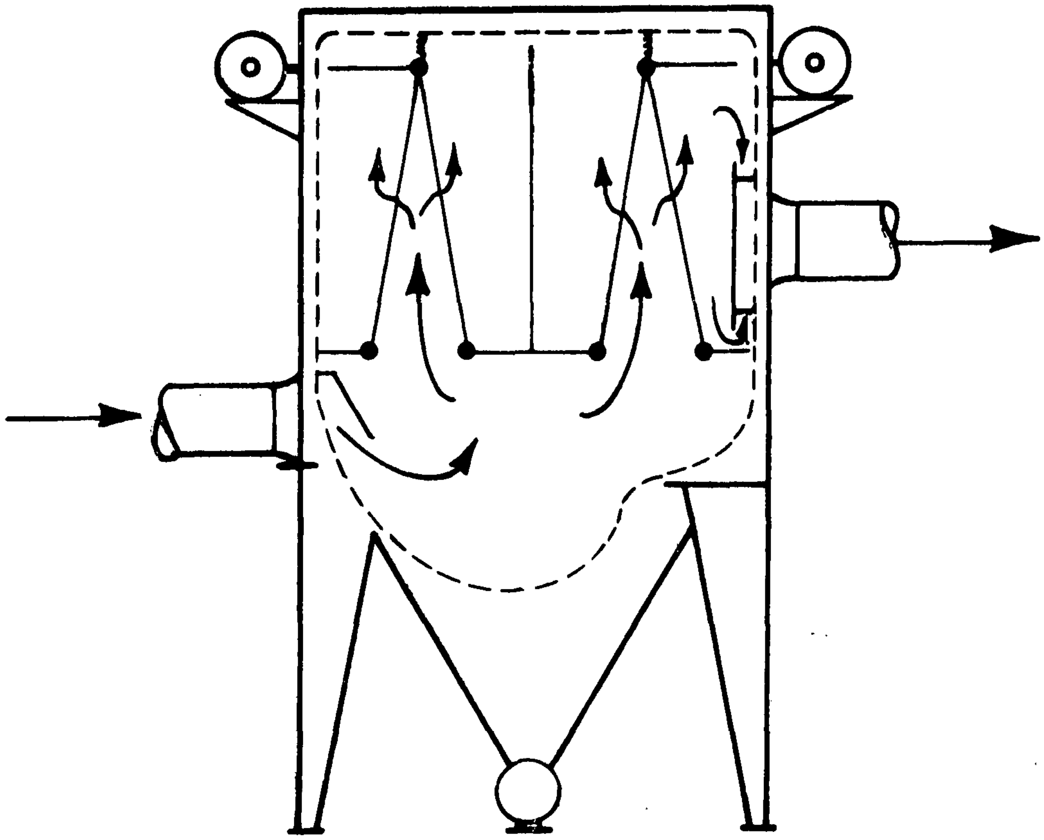
Figure 6.1. Parameters Controlling and/or Describing The Performance of Fabric Filter Systems.

These external system parameters are determined by the functioning of the internal components of the fabric filter, as illustrated in Figure 6.2. Each of the components listed can exist over a range of sizes, shapes, operating variation, and arrangements within the collector. Table 6.1 presents a summary of the effects on performance of fabric filter internal component configuration and operational functioning.

This chapter discusses the relationships of the external performance of fabric filters to the form and functions of the internal components, insofar as this information is available. Performance relationships are highly dependent on properties of the particulate material described in Chapter 2. Chapter 4 contains fabric characteristics which, in conjunction with the deposited dust, also influence performance. Details of the internal configurations of alternate collector systems are discussed in Chapters 3 and 5.

Laboratory testing of fabric filters under controlled conditions has provided much basic knowledge and handbook data for collector design and interpretation of performance. Laboratory or pilot plant research and development studies require a simulant dust for the process to be modeled; dust feeding and redispersion apparatus; flow, pressure, temperature, and humidity measuring instrumentation; appropriate duct work; stack sampling equipment; and other special equipment for measurement and analysis of performance parameters. Most major fabric filter manufacturers have development laboratories available for trials on specific dusts, including particle size measurement instrumentation, one or more commercial filters set up for test, fabric evaluation test rigs at bench scale, dust generation apparatus, etc. Data developed from these sources is usually proprietary. However, summary charts, tables or nomographs are often presented to aid in selection of appropriate fabric area for specific filter applications (Section 5.2).

Discussed below are the data available on filter performance in terms of internal component configuration and function and input parameters. The basic types of collectors for which comprehensive laboratory data are available include:



INTERNAL COMPONENT CONFIGURATION AND CHARACTERISTICS

1. Fabric
   A. Size of Fabric Element, L.D.
   B. Fabric Design, Weave, Arr.
   C. Fabric Structure, Nap
   D. Strand Structure, Arr.
   E. Yarn, Fiber, Fibril Size, Arr.
   F. Fabric Materials, Serviceability
   G. Manufacture, Finishes, Lubricants
   H. Permeability; clean; in-service
   I. Fabric Weight
   J. Fabrication, Sewing
2. Collector
   A. Compartments
   B. Headers, Dust Inlets
   C. Fabric Attachments
   D. Construction Materials
   E. Hoppers, Dust Outlets
3. Cleaning Mechanisms
   A. Mechanical
   B. Gasdynamic
   C. Combined, Sequencing
   D. Coupling Characteristics
4. Performance Relationships
   A. Local Pressure Drop
   B. Local Efficiency
   C. Residual Drag, Local
   D. Deposit Drag, Local
   E. Local Velocity
   F. Local Particle Concentration
   G. Changes in above as related to internal configurations, external system inputs, and microscopic processes.

Figure 6.2. Fabric Filter Internal Component Parameters.

TABLE 6.1

EFFECTS ON PERFORMANCE OF FABRIC FILTER INTERNAL COMPONENT CONFIGURATION

Component	Typical Configurations	Effects, Remarks
Housing	Rectangular, cubical, cylindrical	On outside filtering fabric configurations, the gas approach velocity is determined by housing size, relative to space occupied by filter medium; housing acts as settling chamber in this case, to reduce dust concentration reaching fabric, especially for the larger size particles; and may amount to > 50% reduction in dust load to fabric at $C_i > 5$ gr/ft^3.
Dusty Gas Inlet	Top, bottom, tangential	Inlet at bottom, hopper, or on side usually followed by baffle to prevent direct jet of dusty gas on fabric; inertial effect of baffle reduces the dust concentration reaching the fabric, particularly for larger particles (> 50 μm); tangential inlet enhances this effect; top inlet designs with inside filtering fabric configuration tend to have less stratification of particle size on fabric; bottom inlet designs have larger particles depositing nearer bag inlet, produces wear, scour, and abrasion problem on the fabric with some dusts; in large multicompartmented designs, inlet header must be properly proportioned for flow-pressure balance.
Classifier	Rectangular chamber, one module without cell plate or other internal components	Classifier reduces dust load to fabric by settling and inertial turn effect, especially for the larger more abrasive particles; usual large empty chamber adds little or no increased pressure drop; same function can be accomplished with inertial skimmer or cyclone in smaller space but with greater pressure drop requirement.
Dust Hopper	Inverted pyramidal, conical, see Appendix 6.1	In conjunction with bottom inlet location and inlet baffle, hopper acts as inertial skimmer or gravity settling chamber; sized hopper relative to gas flow determines particles inertially removed; dust build-up in hopper can reduce effective flow to bottom entry bags, hopper dust flow

TABLE 6.1 (Continued)

Component	Typical Configurations	Effects, Remarks
		problems, bridging, etc., associated with high humidity (> 70%) and greater adhesion (see Ch. 2); recent studies on hopper design and dust flow indicated in Appendix 6.1; bin vent and silo filter applications may discharge directly to storage without hopper; hopper must be air-tight when under suction to prevent redispersion of collected dust to fabric.
Cleaned Gas Outlet	Side, top	No effect of configuration on performance except insofar as outlet gas flow related to back flow air utilized for cleaning; large multicompartment units require careful design of outlet header to assure even inlet flow distribution.
Fabric Arrangement	. Bag, tented top, open bottom . Sleeve, open both ends . Sleeve, open top, over wire frame . Multibag . Envelope	Fabric configuration and utilization determined local dusty gas velocity which in turn controls local dust-fabric resistance; fabric arrangement relative to cleaning method and mechanism determines both residual drag and effective drag; too much fabric crowded into housing becomes difficult to service, thereby limiting maintenance and producing poor performance, i.e. dust leaks and accelerated deterioration of fabric and other components.
Fabric Arrangement and Suspension	. Sleeves-clamp, spring insert . Closed ends-hook, buckle, cap . Envelope-button, hook	Tension and tension changes affect cleaning distribution, and indirectly, fabric porosity. Installation and ease of maintenance. Wear often results at stress points.
Tube Sheets, Thimbles		Spacing of elements affects wear, aerodynamics and sedimentation, and maintenance ease. Thimbles can cause wear.
Cleaning Mechanisms	(Numerous)	See Sections 3.3, 8.8.

. Single compartment intermittently cleaned designs
. Multicompartment periodically cleaned designs
. Continuously cleaned designs

(Gradations between available commercial designs tend to make these categories a matter of degree.)

Most laboratory tests are directed primarily at pressure drop, and at ways to control pressure drop within reasonable limits by changes in operation, usually changes in cleaning. Less data on the field performance of fabric filters in specific applications are available, due to the usually limited range of variation of parameters. Performance from such pilot plant or full scale tests is discussed in a final section of this chapter.

6.2 LABORATORY PERFORMANCE OF INTERMITTENTLY CLEANED COLLECTORS

Intermittently cleaned collectors are designed and operated on a relatively light duty cycle. Sufficient fabric area is furnished, in conjunction with low dust concentration, so that the pressure drop increases slowly over a time period in the order of hours. The collector fan (exhauster) is shut off and some form of shaking or vibration is used to clean the fabric. Typically, the filter may operate on its dust source over a full shift, and be shut down for cleaning when the production machinery is idle. Most intermittently cleaned collectors operate with a filtering velocity in the vicinity of 2 to 3 fpm with dust loadings less than about a grain per cubic foot. They are usually employed for relatively coarse dusts on dust control, venting, or nuisance applications.

6.2.1 Bench Scale Performance

6.2.1.1 Pressure Drop-Time Relationship.- Specific dust-fabric filter resistance coefficients (K_2') discussed in Chapter 2 have been obtained in many cases with bench scale apparatus on the scale of 1 ft^2 of fabric.[1,2] The pressure drop increase for a stated operating time may be estimated (see Chapter 2) by the following equation:

$$\Delta p(t) = K_2' \, C_i V^2 t / 7000 \qquad (6.1)$$

where C_i = inlet dust concentration (grains per ft^3), V = filtering velocity (ft/min) and t = time (min). Experimental values of K_2' determined by Williams et al.,[1] for a constant filtering velocity and a single (cotton) fabric, were presented earlier in Table 2.37. They were shown to be a function of particle material and approximate particle size, in accordance with the expected influence of these parameters on deposit porosity.

Later studies by Snyder and Pring[2] demonstrated that K_2' is a function of dust properties and type of yarn or fabric (amount of free fiber surface available to the dust deposit), as shown in Tables 6.2a and b. Their data indicated that K_2' is a resistance coefficient specific for the dust and fabric. The quantitative separation of the effects of fabric from the dust properties in the specific resistance coefficient was not attempted. Effects of dust particle size and shape, and fabric yarn or nap on the resulting pressure drop increment are shown in Figures 6.3a, b and c. Snyder and Pring's pressure drop - deposit curves are seen to be non-linear with a marked upward curvature evident in several instances. Typical K_2' values ranged from 234 for freshly-formed MgO fume on napped Orlon® to 7 for petroleum coke fines on spun staple Orlon napped both sides. Napping resulted in about a 10% reduction in K_2', but usually resulted in a higher residual dust deposit after shaking.

6.2.1.2 <u>Dust Collection Efficiency</u>.- Collection efficiency was found to range from 84% for MgO fume to greater than 99.9% for petroleum coke. However, the Snyder and Pring[2] data are of limited value as they do not represent typical industrial usage. Fabrics were not utilized for long periods to achieve equilibrium priming or aging, and cleaning parameters were not quantified. The principal value of their study was to direct attention to the effects of free available fiber on K_2', and to the non-linear variation of K_2' with deposit weight. They also provided experimental validation of the predicted effect of gas viscosity on pressure drop.

TABLE 6.2a

PROPERTIES OF VARIOUS ORLON FILTER FABRICS*

Dust: fine petroleum coke
Results: average of 5 cycles

Cloth	Weight Oz./Sq. Yd.	Permeability New	Permeability Used	Dust Loading Grams/ Sq.Ft.	Residual Dust, Grams/ Sq.Ft.	Collecting Efficiency	Filtration Constant, K_2'
Napped filament Orlon, 3/1 twill	3.9	35	10	29.00	4.18	99.91	17.1
Knit Orlon, napped	7.6	85	58	15.40	4.58	99.70	12.5
Orlon spun staple	7.5	60	33	18.21	1.48	95.19	15.0
Orlon spun staple, napped both sides	9.0	100	50	19.95	2.15	99.64	7.4
Orlon spun fiber-stock, 3/2 twill	4.9	110	62	17.96	0.99	93.42	13.0

*From Snyder and Pring, Ref. 2.

TABLE 6.2b

FILTRATION CHARACTERISTICS OF NAPPED AND UNNAPPED SIDES OF ORLON*

Orlon: 1 oz. napped filament, 76 x 72 count, 3/1 twill
Results: average of 4 runs
Fume: freshly generated magnesium oxide

	Used Permeability[a]	Dust Loading Grams/ Sq.Ft.[b]	Residual Dust, Grams[c]	Collection Efficiency %	K_2'
Napped side	4.2	12.0	15	89.4	234
Unnapped side	8.1	13.8	4.5	84.0	251

[a]Permeability after shaking, cu. ft/min./sq. ft. at 0.5 inch w.g.

[b]Corresponds to weight of dust removed by shaking, grams/sq.ft.

[c]Dust remaining on cloth after shaking.

*From Snyder and Pring, Ref. 2)

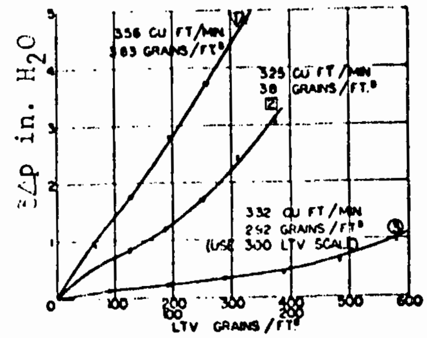


Figure 6.3a. Values of Δp vs. Deposit Weight (LTV) in filtering fine petroleum coke dust.

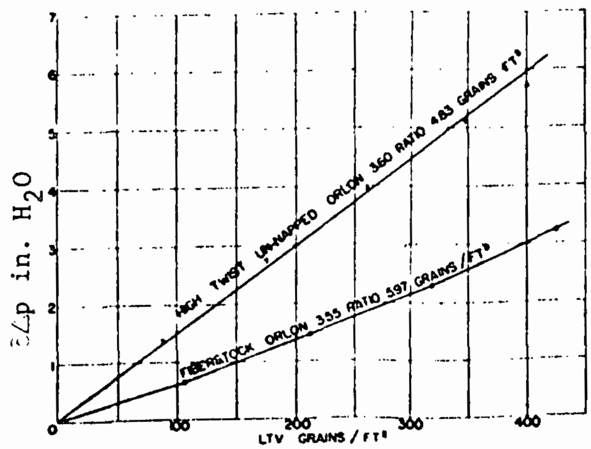


Figure 6.3b. Values of Δp vs. LTV covering dust generated in abrasive blasing of steel paint drums on high twist, unnapped Orlon with an extremely low fiber surface area per square foot and fiberstock Orlon.

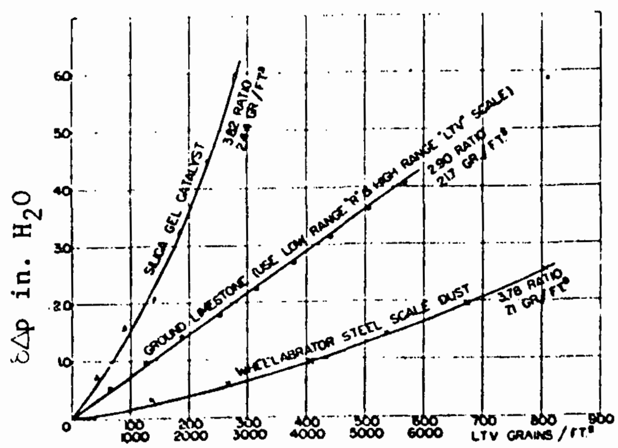


Figure 6.3c. Effect of particle size and shape on filter resistance of cotton sateen cloth. Silica gel dust, 43% less than 10 microns; Scale dust, 2% less than 10 microns; Limestone dust, 32% less than 48 microns.

(From Snyder and Pring, Ref. 2).

6.2.2 Single Bag Performance, Pilot Scale Tests

6.2.2.1 Pressure Drop-Time Relationship

Basic Concepts. - When textile fabric is used as a filter for dusty gas in the form of a bag, tube, or envelope, and then cleaned repetitively, an equilibrium pressure drop-time behavior is observed. After an initial priming or aging period (which may range from < 10 hours to > 10^2 hours for certain dusts and fabrics), the pressure time response appears as illustrated in Figure 6.4. The pressure-time trace will then be repeated cyclically, provided that the gas and dust flow rates are maintained constant and if the cleaning energy patterns, durations, etc., are applied uniformly. The pressure-time curve depends upon the gas viscosity, particle properties, (size, shape, surface phenomena), fabric properties, (fiber, yarn, weave, finish, nap) and operating characteristics of the cleaning mechanisms. If the flow of dust to the fabric filter is stopped at any point, and a pressure-flow curve is determined using clean air, it will be found that

$$\Delta p = S\left(\frac{Q}{A}\right)^n \qquad (6.2)$$

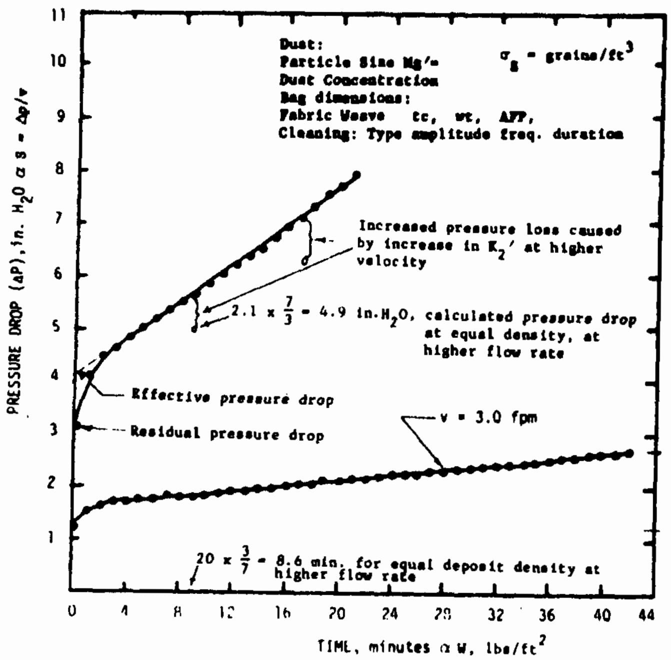


Figure 6.4. Pressure Response in Constant Flow Rate Gas Filtration (Constant Gas and Particle Flux). (From Borgwardt and Durham, Ref. 3).

where n = 1 as long as viscous flow obtains (for a granule Reynolds number < 10). The property S or "drag" is a variable function of fabric, flow, and dust parameters as described in Chapter 2; it is analogous to the resistance in a purely resistive electrical circuit described by Ohm's Law, i.e., Voltage = Resistance x Current.

The drag, S, may thus be defined[4,5] as

$$S = \frac{\Delta p}{V} \tag{6.3}$$

for small Reynolds numbers, which is the case of most fabric filtration. S is a property of the filter and applies to any filter area. If S varies from area to area, due to variations in permeability for example, then the overall effective drag S_e is given by the following, again analogous to the electrical case of resistances in parallel:

$$\frac{1}{S_e} = \frac{1}{S_1}\left(\frac{a_1}{A_f}\right) + \frac{1}{S_2}\left(\frac{a_2}{A_f}\right) + \ldots + \frac{1}{S_n}\left(\frac{a_n}{A_f}\right) = \frac{1}{A_f}\sum_i \frac{a_i}{S_i} \tag{6.4}$$

where the a_i are the incremental component filter areas and the S_i are the local drags.

The use of the drag concept allows direct comparison of filter media from one filtering situation to another, regardless of filtering velocity or unit size.[6]

The Darcy permeability, K_D, which defines the intrinsic permeability of the filter medium in terms of its structural form, is analogous to electrical conductivity. It is related to the specific resistance, K_2, of the filter medium by the relation

$$K_D = \frac{1}{K_2} \cdot \frac{\mu_f}{(1-\epsilon)\rho_p} = \frac{W}{S} \cdot \frac{\mu_f}{(1-\epsilon)\rho_p} \tag{6.5}$$

The ratio, W/S, provides another measure of cake permeability in terms of the density of filter deposit per unit area, W and the resistance to airflow per unit velocity or drag S. The latter description of permeability is merely the reciprical of the previously cited specific resistance, K_2. It should be noted that the permeability is an intensive property (independent of mass) whereas the drag, S, is an extensive property (mass dependent) that relates filter resistance to flow rate. While the drag will always increase as additional material is deposited on the filter, permeability may increase, decrease, or remain constant over the same period, depending upon flow, fabric, and dust interactions.

Utilizing concepts of filter drag and areal density of deposit, the typical pressure-time response during equilibrium operation of a fabric filter element shown in Figure 6.4 can be represented as a drag-density relationship as presented in Figure 6.5. Several typical features

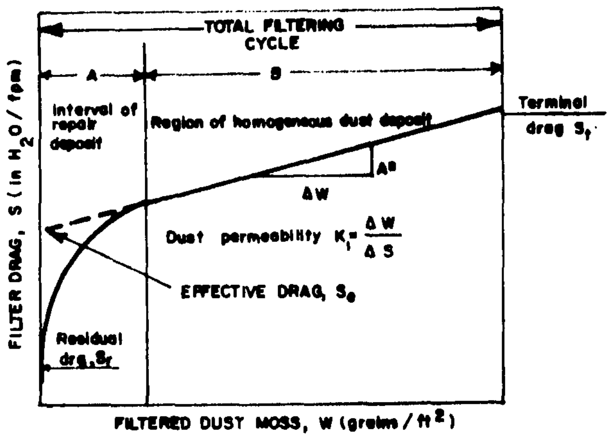


Figure 6.5. Schematic Representation of Basic Performance Parameters for Fabric Filters.

of performance are illustrated. The total drag of the filter medium in service is the sum of the drag produced by the fabric with its irreducible residual deposit plus the drag of the dust deposit added during the filtration cycle.[7]

All practical cleaning methods so far developed result in some nonuniformity in the effectiveness of cleaning obtained in different areas of a filter cloth. Because of this, when filtration is resumed on a recently cleaned cloth area, the rate of change of drag of the medium will vary in the early part of the filtering cycle. The curve in Figure 6.5 indicates that cleaning leaves a nonhomogeneous and discontinuous surface that is subject to rapid increases in resistance when a new deposit is first being formed. Curve segment A represents the increase during this part of the cycle. After the discontinuities have been largely eliminated by preferential flow of the dust-laden gas through low-resistance areas, a relatively uniform deposit has been formed. Subsequent deposition of dust generally results in a linear increase in resistance to flow as dust accumulates, curve segment B. Efficiency of the filter is lowest during the early part of the cycle while the discontinuities are being repaired.

This relationship will hold for any dust-fabric combination but the shape of the curve may be significantly altered by differences in the cleaning or the nature of the fabric. Highly effective cleaning will lower the residual drag value, S_r, and poor cleaning will increase it. For that part of the cycle represented by curve segment B where the homogeneous deposit is formed, the specific properties of the dust tend to control the rate of increase of resistance. The permeability, K, of the dust-fabric combination will be reflected by the slope of the curve. These general relationships relating to pressure loss through the medium in a filtration process apply whether the area being considered is a single bag or many bags in a single compartment, so long as all of the area is put in service at one time.

Because of the dominant importance of pressure drop in equipment of this type, the drag of the filter medium must be given primary consideration. Filter drag, however, is but a single element of the total pressure drop that determines fan and power requirements. In practice, the total pressure drop to be overcome may, because of duct losses, be twice that attributable to the filter medium alone. The total system will contain sections with gas in turbulent as well as viscous flow, so that total pressure drop will vary with flow exponentially by some power between 1.0 and 2.0 instead of directly with flow as it does for the Δp across the medium alone.

The residual drag, S_r, is determined by the properties of the dust and the fabric, in conjunction with the operation of the cleaning mechanism. Cleaning energy input, as distributed through acceleration, frequency, and duration, defines the amount of dust removed down to some irreducible minimum value. The effective drag, S_e, is defined as that value of the drag obtained from extrapolation of the linear portion of the S-W curve to zero W, at the ordinate. For practical purposes, the filtration cycle appears as:

$$S(W) = \frac{\Delta p}{V} = S_e + W/K \tag{6.6}$$

where S_e is some function of S_r, fabric, and dust parameters. The actual shape of the S-W curve in region A has not been presented; instead it is usually approximated by this equation.

In terms of the specific dust-fabric filter resistance coefficient,

$$K_2' = 7000/K \tag{6.7}$$

providing W is calculated as grains of dust/ft^2 of fabric. Then the pressure-time relation is generally of the form

$$\Delta p(t) = S_e V + K_2' C_i V^2 t/7000 \tag{6.8}$$

when the S-W curve is linear from the extrapolated value of S_e. The form of the S-W relation is not always linear, and seems to depend on the amount of fiber available at the fabric surface for dust holding, as will be discussed below.

Liquid Filtration Analogy.- Because investigations of liquid filter performance have been treated in much greater detail in the technical and engineering literature, it is of some value to examine their applicability to fabric filtration. A typical liquid filter utilizing a fabric, as applied in the Chemical Process Industry, operates at constant pressure drop and the flow rate (or total flow volume) is allowed to decrease until a fixed volume has been treated. The filter is then stopped, drained, and the resulting cake (deposit) is removed by manual or semi-automatic means, which may involve the physical removal of the fabric system from the main flow housing. In rotary pressure or vacuum filters, the deposit and removal steps are continuous and automatic. In the manufacture of paper the cake formed from a slurry of wood fibers is continuously withdrawn as product. The use of rapid sand filters (2-3 gpm/ft^2) for water purification (in Sanitary Engineering) involves operation of a fixed bed of granules as a filter for fine particulates until the deposit storage capacity of the bed is exceeded, whereupon the filter is then backwashed.

In each of these areas there are extensive investigations and analyses of the filtration process under a condition of variable deposit and variable flow or pressure drop. However, the following reasons preclude the direct utilization of these data to the processes of fabric filtration of gases, even when the same filtration substrates are employed:

1. The adhesion forces between small particles at a fibrous or granular substrate are several orders of magnitude smaller in liquids. Adhesion forces for particles in air or gases are typically of the order of 1 dyne (Chapter 2, Table 2.10) for sizes in the range of 1 to 100 μm, and are dependent upon humidity, capillary condensation, and surface effects such as contamination, roughness, electrostatic charge, etc. Table 6.3 indicates that adhesion forces in liquids are typically less than 10^{-5} dynes. They depend upon van der Waals forces operative at molecular dimensions ($\sim 10^{-8}$ cm).

2. Pressure drop in liquid filtration is generally much greater than in fabric filtration of air and gases. Typical terminal pressure drop in fabric filtration is less than 15 inches of water, i.e., less than 1/2 psig. Pressures used in liquid filtration in the chemical process industries are generally greater than 10 psi (rotary vacuum filter) and may exceed 100 psi (plate or frame type). Rapid sand filters typically backwash at 3 to 5 psi.

3. The combination of lower adhesion forces and greater pressure drop are believed to have substantial effects on the characteristic of the deposit in liquid filters as contrasted to deposits likely to occur in fabric filtration of dusty gas. In liquid filtration through fabrics, one typically observes a deep cake of order of several millimeters thick, much thicker than the fabric media. Calculated values of deposit thickness in fabric filters

(Table 2.36) are generally less than 1 millimeter. Measurements of deposit thickness in fabric filtration have not been reported.

4. The irreducible residual deposit pressure drop in fabric filters, measured by S_e or S_r as shown in Figure 6.5 is a major portion of the total operating pressure drop in every cycle. In the case of liquid filtration, Ruth (see Appendix 6.2) and other investigators have shown that the pressure drop of the filter medium at the beginning of the filter cycle is of little significance in the resistance of the medium after a cake has formed.[3]

TABLE 6.3

ADHESION OF VARIOUS PARTICLES TO SUBSTRATES OF VARIOUS MATERIALS IN WATER

(for $F_{det} = 7 \times 10^{-5}$ dyn)*

Substrate Material	Particle Material	d_p, μ	γ_F, % **
Glass	Quartz	11.0	0
	Graphite	7.5	20
Steel	Quartz	11.0	33
	Graphite	7.0	40
Bronze	Graphite	7.0	40
Glass	Quartz	5.0	76***
Paraffin	Quartz	5.0	0***

*(From Zimon, Ref. 8).

** γ_F = fraction of particle numbers remaining attached after application of indicated force.

***For $F_{det} = 1.6 \times 10^{-7}$ dyn.

The structure of the deposit formed at the surface of a fabric dust filter is markedly influenced by relative humidity and adhesion, and electrical characteristics of the dust and fabric. The aggregates formed are probably very filamentous and chainlike for fine particles, although more compact, similar to the liquid filtration case, for larger dust particles. For these reasons, deposit formation in dust filtration probably differs from that in liquid filtration. Liquid filtration concepts such as complete pore blockage, standard blocking, cake filtration, and the like, are very likely to be inappropriate models for gas filtration phenomena. While analogies between liquid and gas filtration are attractive to consider, especially the concept of cake formation in the latter case, they require further investigation before their utility can be evaluated. A summary of pertinent studies in the field of liquid filtration applied to fabric filter technology is given in Ref. 3.

6.2.2.2 Dust Profiles.- Pressure-time data shown in Figure 6.4 and S-W curves given in Figure 6.5 represent a macroscopic average over the total fabric surface for a single cylindrical filter tube (or for many bags in parallel). Stephan, et al.,[9] have investigated local interactions of dust, gas, fabric, and cleaning parameters at various locations on a single bag. Local mass deposited (areal dust density) was measured with a β-gaging mass probe and local flow rate with a velocity probe. These two instruments are shown in Figure 6.6a and b, respectively. The improved mass probe containing a β-source directed toward an end window G-M tube is held adjacent to the filter bag. The resulting signal is interpreted through calibration as mass per unit area. The filter velocity probe measures air flowing through a section of the bag. Both devices measure an area of 1 to 2 $in.^2$. Clean unused fabric has an areal density of ~500 gr/ft^2, 10 oz/yd^2, or 0.07 lb/ft^2), so that the dust deposits encountered in practice are 1 to 10 **times** the weight of the fabric. Residual dust weights are typically < 0.1 lb/ft^2.

Typical results obtained with the mass and velocity probes on a 9-inch diameter by 60 inch long bag are shown in Figure 6.7. Deposited mass is greatest at or near the center of the bag height (~ 800 gr/ft^2). Filtering velocity is lowest in this same region ($<$ 1 fpm). Figure 6.8 illustrates the variation of filtering velocity with dust deposit density over the bag. Values of the local relative specific dust-fabric filter resistance coefficient (K_2') have been calculated (assuming a uniform 1 in. H_2O pressure drop over the total bag) as shown in Figure 6.9. Dust resistance is lowest at the bottom (probably as a consequence

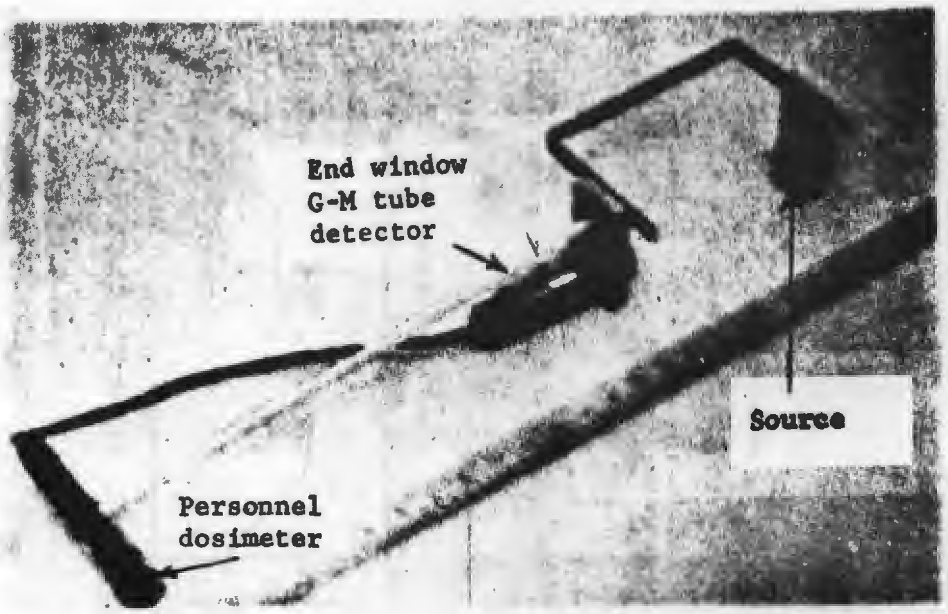


Figure 6.6a. Improved Mass Probe.

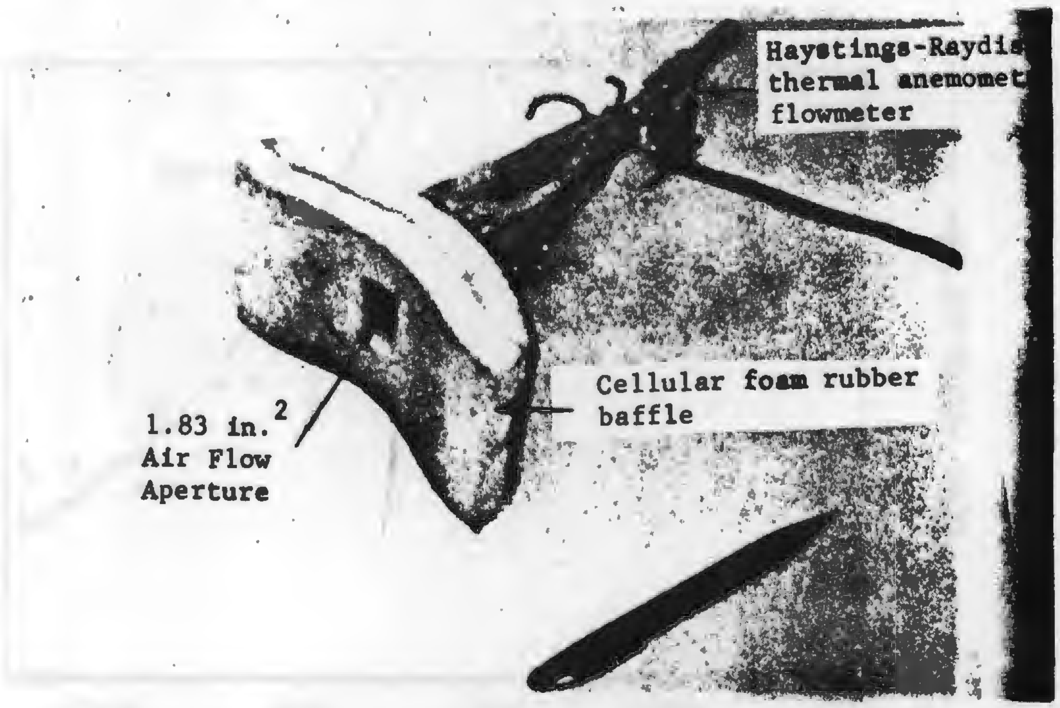


Figure 6.6b. Filter Gas Velocity Probe.

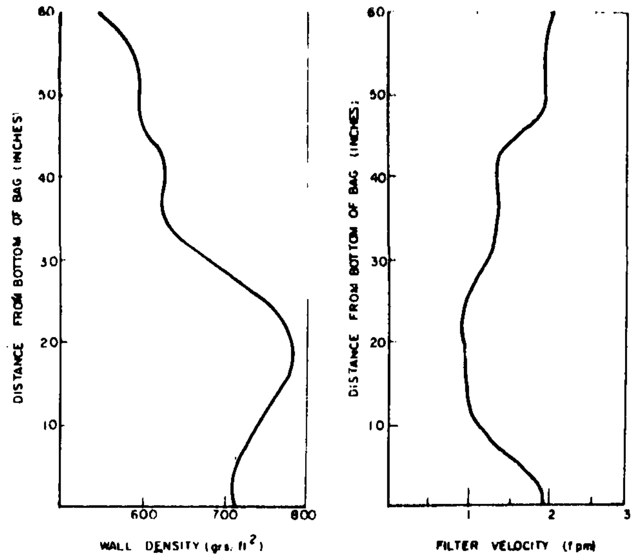


Figure 6.7. Corresponding Mass and Filter Velocity Profiles. (From Stephan, et al., Ref. 9).

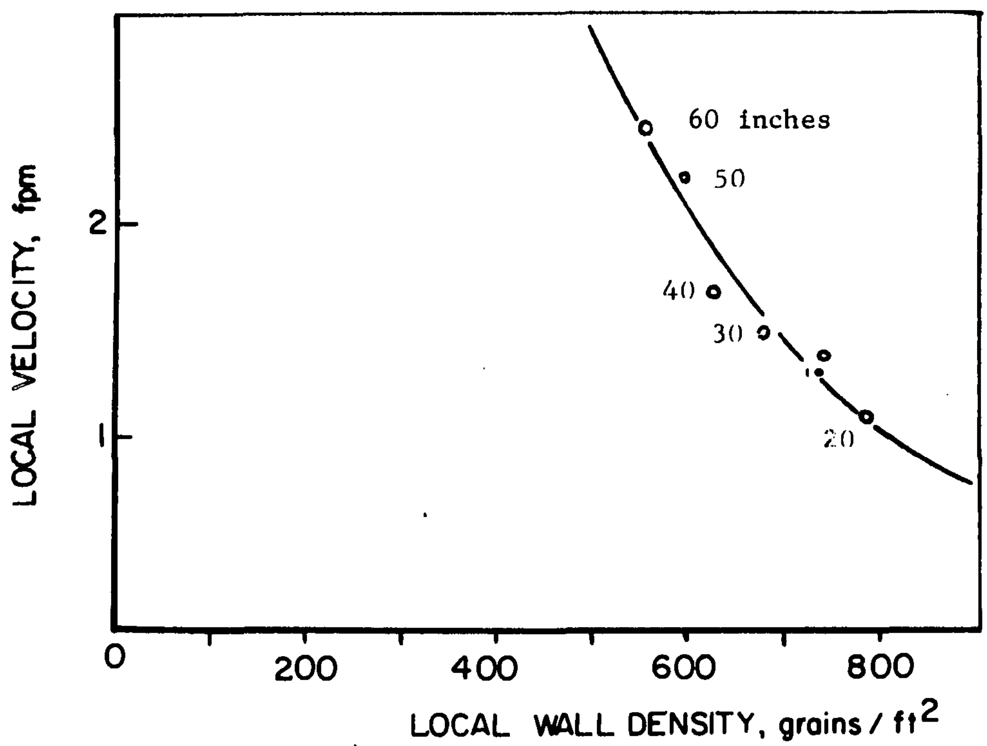


Figure 6.8. Variation of Filtering Velocity with Dust Deposit Density, from Figure 6.7.

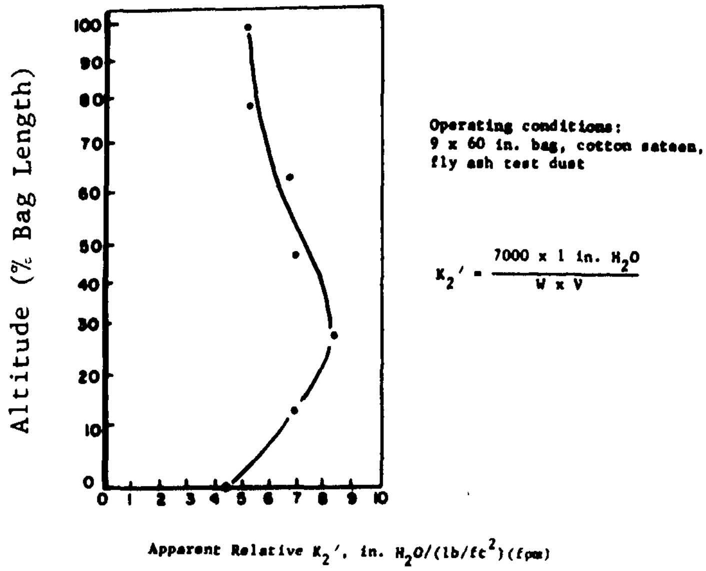


Figure 6.9. Variation in Specific Dust-Fabric Filter Resistance Coefficient with Height in a Filter Tube, from Figure 6.8.

of preferential deposition of larger particles), increases to a maximum value near the center of the bag, and decreases again toward the top of the bag (where dust of finer particle size deposits). This pattern may be characteristic of bottom entry filters.

Using these techniques for measurement of local mass and local velocity, Stephan et al.,[4] and Stephan and Walsh[10] studied dust profiles on filter bags throughout typical filtration and cleaning cycles. Their equipment consisted of a 2-bag laboratory unit cleaned by shaking; further details are given in Figure 6.10.

Figures 6.10a and b illustrate the development of dust mass and filter velocity (drag) profiles during a single filtration cycle, equivalent to local S-W values in space and time. Immediately after cleaning, the profiles ($S_{0,1}$ $W_{0,1}$) are indicative of the degree of cleaning achieved with the one-minute cycle. Upon restoration of dusty gas flow, profiles tend to become more uniform, and by the time the fourth increment has been reached ($S_{0,4}$, $W_{0,4}$) a characteristic profile shape

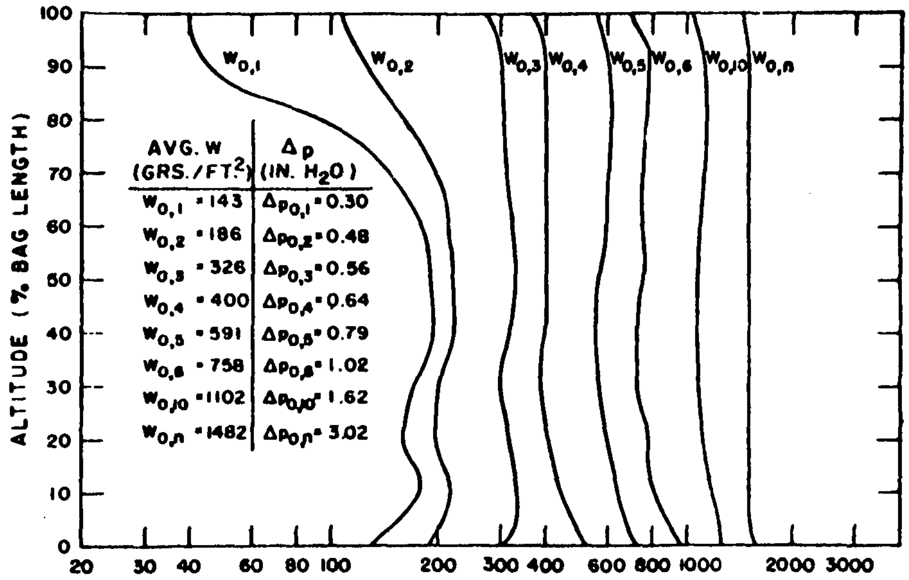


Figure 6.10a. Development of Dust Mass Profile Through a Filtration Period (from Ref. 4)

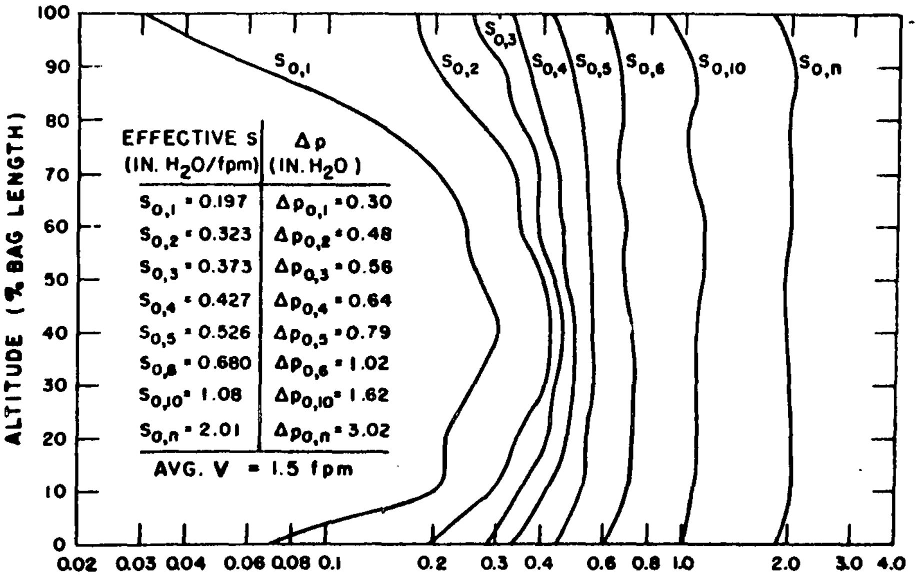


Figure 6.10b. Development of Dust Drag Profile Through a Filtration Period (from Ref. 4)

Notes to Figure 6.10

Filter tubes were 6 in. in diameter by 63 in. long fabricated of standard cotton sateen (National Filter Media Style No. 74, 96 warp x 60 fin, 9.7 oz/yd^2) having a rated Frazier Porosity of about 15 ft^3/min. In terms of resistance and permeability, the fabric would be rates at S_0 = 0.033 in H_2O/fpm and K = 14,300 (grains/ft^2)/(in H_2O/fpm). Shaking action was vertical at the top, with a 2-1/4 in. amplitude at a frequency of 6.75 cps for a duration of one minute. Tests were conducted at average filter velocities ranging from 0.75 to 7.5 fpm, and dust concentrations in the range $1 \leq C_i \leq 10$ grains/ft^3. Test dust consisted of resuspended Cottrell precipitated fly ash elutriated to -7 microns ($\text{MMD} = 3.2$ µm, $\sigma_g = 1.8$).

develops which is maintained for the remainder of the filtration cycle. Both S and W profiles tend to become nearly flat at high mass deposit values. Effects of particle elutriation and of velocity on dust-fabric resistance ($K_2' \simeq V$) are no doubt factors in the departure of the profiles from flatness. The variations in profile slopes near top and bottom of the filters appeared in all experimental runs, indicating that even when starting with a perfectly flat profile, dissimilarities develop along the bag length near the top and bottom of the bags. This investigation indicated that filtration does not occur uniformly over the length of a filter bag. Different quantities of dust are collected and local filter velocities vary by factors greater than 2 in the initial part of the filtering cycle at different locations on the tube. The corresponding values of local permeability vary in space and time.[4] These variations reflect the differences in cake removal by the pattern of cleaning energy applied, the relative adhesion of different fractions of dust as a function of cleaning energy applied, and the differences in dust structure over the length of the tube.

The approach to profile linearity is expected since areas of low resistance will handle higher than average air volumes, and vice versa. Consequently more dust is deposited on the low resistance areas, less on the areas of high resistance, and a self-balancing system exists. It is likely that the period 0,1 → 0,2 (i.e., addition of 50 gr/ft^2) corresponds approximately to the period of deposit repair and non-linear K_2'. Values for the effective average resistance coefficient for the total bag structure, ($K_2' = 7000/K = 7000\ S/W$) are shown in Figure 6.11 for each of the increments, 0,1 → 0,n. The resistance coefficient increases rapidly during addition of the first increment of dust, then falls to a relatively constant value through much of the remainder of the cycle. The terminal value is somewhat higher, possibly because of dust deposit compaction. Dust permeability profiles for another test series are shown in Figure 6.12. Average K_2' increased from 2 to 12.7 during the test. Effects of particle stratification are apparent at the top and bottom of the bag, at the various intervals during filtration.

General conclusions drawn from these studies are:

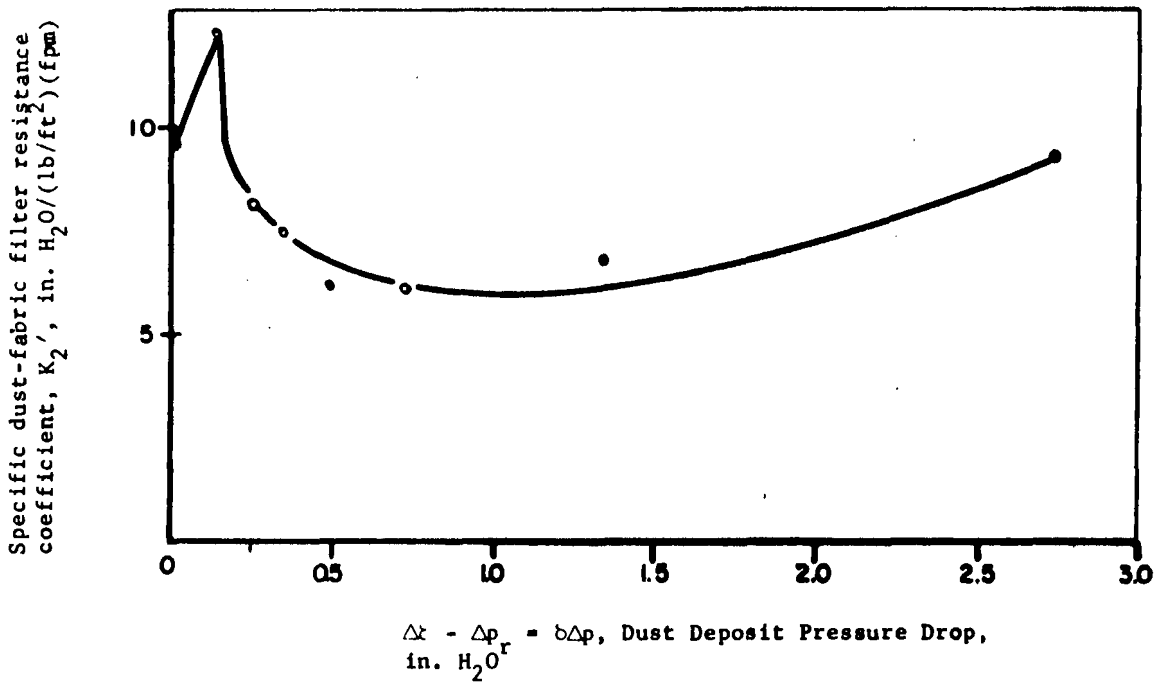


Figure 6.11. Variation of Average Specific Dust-Fabric Resistance Coefficient During a Filtration Cycle.

1. The local specific dust-fabric filter resistance coefficient is a variable with respect to both location on a filter tube, and time or amount of dust deposited.
2. The dust mass and drag profiles reflect interactions of particle size, flow, and structure during deposit formation.
3. The average specific dust-fabric filter resistance coefficient tends to rise during the filtration cycle.

Using the same techniques of mass and velocity measurement, the deposit characteristics may be studied during the process of cake removal. Effects of shaking on dust mass and drag profiles are illustrated in Figures 6.13 a and b. Figure 6.13a shows a mass profile just before cleaning, and after one and 20 minutes of shaking. In this par-

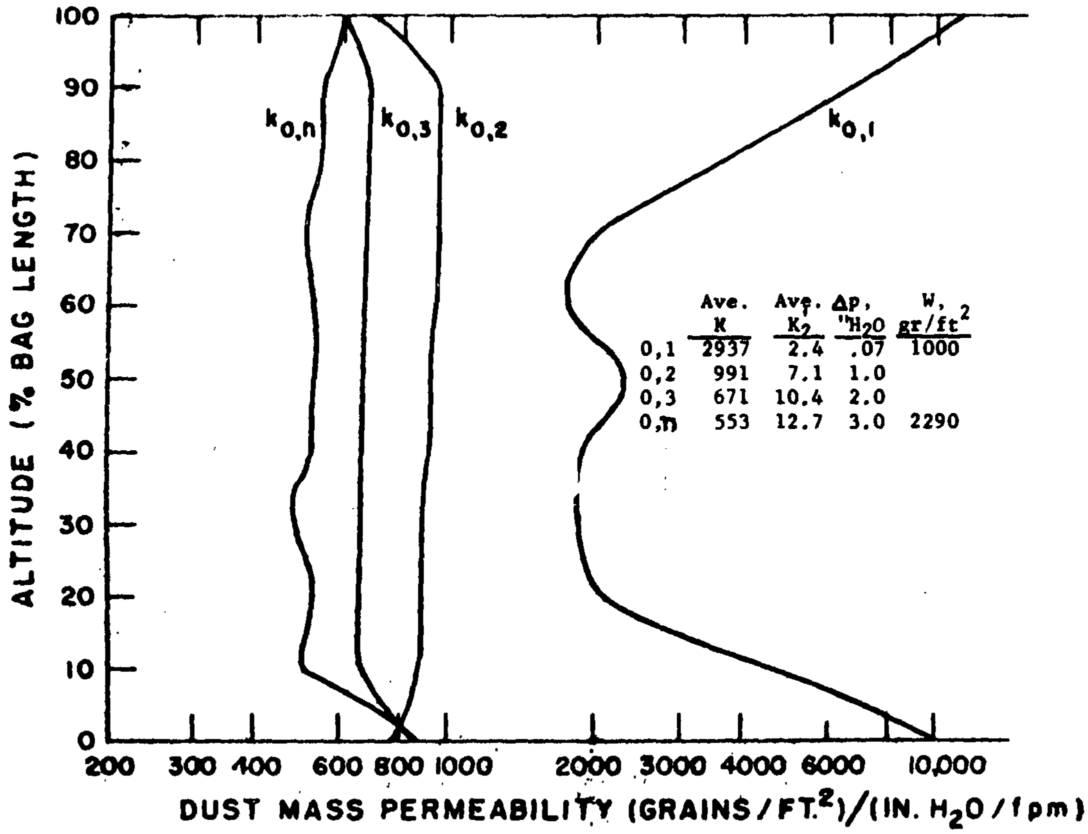


Figure 6.12. Decrease in Dust Mass Permeability through a filtration Period (from Stephan ,et. al., Ref. 4)

ticular case, 89.5 percent of the dust deposit was removed by one minute of shaking and 97.2 percent by a 20-minute shaking period. The reductions in drag are illustrated in Figure 6.13b. The first minute of shaking reduced the pressure drop by 89.7 percent and the next 19 minutes reduced it by only an additional 2.8 percent. However, dust removal itself is of secondary importance to resistance decrease, which determines the pressure drop after shaking. Before shaking, the cake had an average resistance of 7.4 inch $H_2O/(lb/ft^2\text{-fpm})$ and this value was slightly decreased to 7.2 by one minute of shaking. After 20 minutes of shaking, specific resistance was increased to 20. Continued shaking may reduce dust mass proportionally more than resistance. Reduction in effective resistance is more meaningful than quantity of dust removed in determining optimum lengths of cleaning periods.

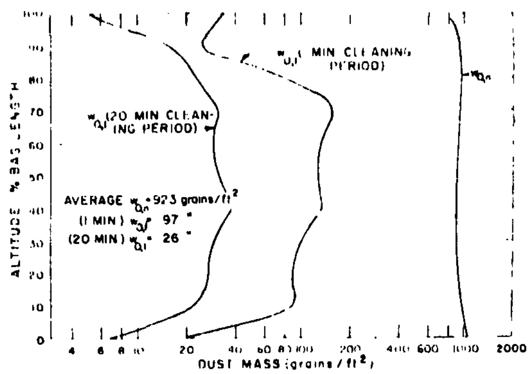


Figure 6.13a. Effect of Cleaning on Residual Dust Mass Profiles (From Stephan, et al., Ref. 4).

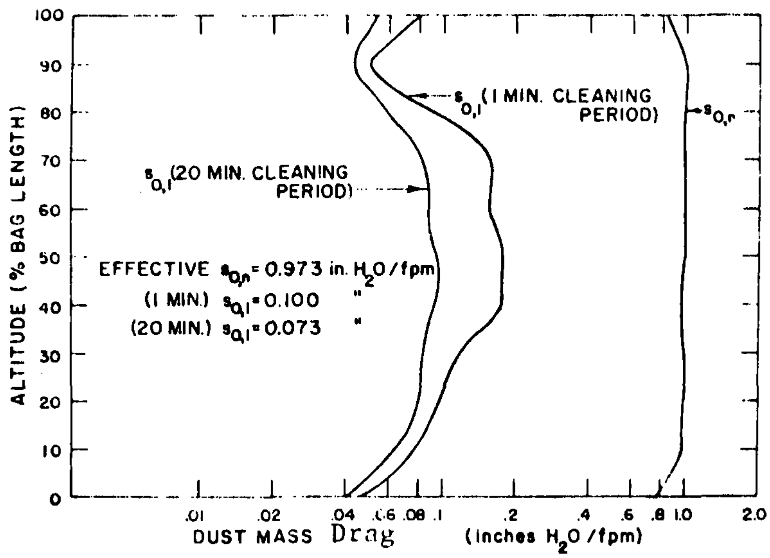


Figure 6.13b. Effect of Cleaning on Residual Drag Profiles (From Stephan, et al., Ref. 4).

Additional data on development of residual dust mass profiles during cleaning are shown in Figure 6.14. An essentially uniform terminal dust mass of 1650 grains per square foot was reached under the filtration conditions given in the Figure. The filters were then shaken for 5 seconds (= "1st shake," consisting of 34 strokes) and the residual profile was measured. Approximately 88% of the terminal dust was removed during this first period. Successive incremental shaking periods were then conducted, and profiles were measured. Only 3% of the terminal dust mass was removed in the second period. The profiles were progressively flattened with further shaking.

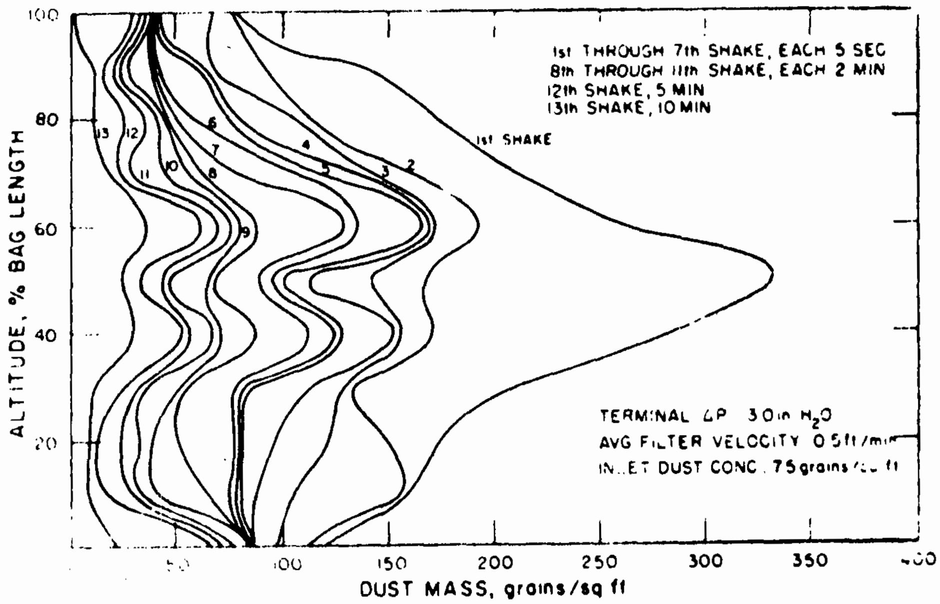


Figure 6.14. Residual Dust Mass Variation with Cleaning Duration. W_T = 1650 gr/ft^2. Shake, 6.75 cps. (From Stephan and Walsh, Ref. 10.)

Stephan and Walsh also discuss aging, equilibrium residual profiles, filtering velocity, and particle penetration into the fabric. They emphasize that a non-uniform residual profile exists at the start of every filtration cycle. Filtration never occurs uniformly over the total filter surface. Different filter velocities, amounts of dust collected, and deposit structure occur at various locations. They conclude that data from laboratory bench-scale determinations of dust-fabric resistance coefficients cannot be equated for design purposes to the effective or average resistance coefficients of the same dust on full-sized filter tubes.

One practical implication of the Stephan-Walsh study:

> "....concerns the differences in local cleaning intensities which exist between very short cleaning periods and appreciably longer ones.... Filter cleaning follows the law of diminishing returns - i.e., each shaking stroke contributes less and less, with the degree of cleaning approaching asymptotically some limiting value for a given set of cleaning conditions."

"This....suggests...the hypothesis that appreciably shorter cleaning periods than are now commonly in use may be employed without proportionately reducing the length of the subsequent filtration periods. Such a situation would have two distinct advantages:

1. "Rate of filter wear, which will always be related in some way to the total number of cleaning strokes experienced by the filter, could potentially be reduced.

2. With the use of shorter cleaning periods at more frequent intervals, increased filter ratios - i.e., smaller equipment size - might well be possible." [10]

This hypothesis is supported by the recent successful development of pulse-jet filters, which are continuously cleaned on-line by a short (< 1 sec) burst of high pressure compressed air (100 psi) every 30 seconds or so. Higher filtration velocities are used (~10 fpm), and fabric life appears to be at least as long as in many shaken designs.

6.2.2.3 Analysis of Mechanical Shaking - Mechanical shaking of a single bag or compartment is discussed below. Analysis of multi-compartment shaking with and without simultaneous reverse air flow, and reverse-jet and pulse-jet cleaning are considered in following sections.

The fabric is cleaned periodically to remove deposited material by any of several possible means (Section 3.3), of which mechanical shaking is one of the more common. A minimum pressure differential at the start of the filtration cycle can be achieved by vigorous cleaning to keep average residual accumulation and drag small (Curve A, Figure 6.15). However, too much energy applied to the fabric to remove accumulated dust shortens fabric life and reduces collection efficiency (Curve B). There is, thus, an economic optimum to be determined (Curve C), which depends on many properties of dust, fabric and cleaning.

Fabric cleaning can be generalized to considerations of force applied to the deposited powder layer as a consequence of: (a) motion induced in the fabric, or (b) interaction of the motion of cleaning gas with the deposit and fabric. Removal forces produced on the deposit are resisted by adhesion (particle-to-fabric) and cohesion (particle-to-

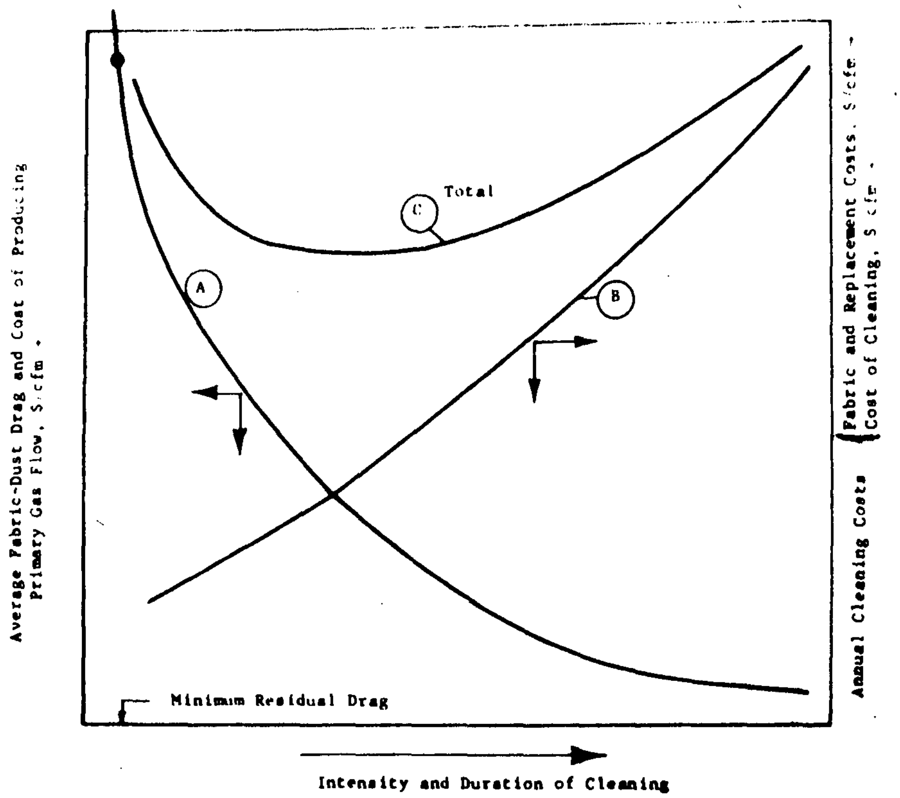


Figure 6.15. Cost Analysis in Fabric Filter Cleaning

particle) forces within the deposit matrix. In principal, the force applied to the deposit can be determined from consideration of the energy applied during cleaning. In practice, cleaning forces are produced by a configuration having fixed frequency and amplitude, or other characteristic patterns of application, and deposit mass variations. The point of optimum cleaning is produced by field adjustments of one or more of these variables.

A comprehensive analysis of mechanical shaking in fabric filtration has been reported by Walsh and Spaite[11]. They studied the effects of shaker amplitude, (ϵ_s) shaker frequency (ω) and duration (number of strokes, ωt) on residual drag (S_r) and filter capacity (weight of dust collected during the filtering cycle, W without exceeding some terminal filter drag, S_t). Tube geometry, fabrics, shaking direction, etc., were held constant. The pilot scale test unit is shown in Figure 6.16. Bags were installed with zero tension and zero slack. The range of variables investigated included V = 3 fpm, $0.05 \leq \epsilon_s \leq 2$ in., $5.2 \leq \omega \leq 56$ cps, and $5 \leq \omega t \leq 700$ strokes. Maximum acceleration produced by the simple harmonic motion is:

$$= (2 \omega)^2 \epsilon_s \qquad (6.9)$$

where ϵ_s = amplitude of the motion, 1/2 the peak-to-peak stroke length. The maximum occurs at the limits of the shake motion. The range of accelerations studied was $0.72 \leq \alpha \leq 15.5$ g's ($10^6 \leq \alpha \leq 22 \times 10^6$ in/min^2). Frequency, amplitude, and acceleration in mechanical shaking are constrained by physical limits as illustrated in Figure 6.17. Shaking

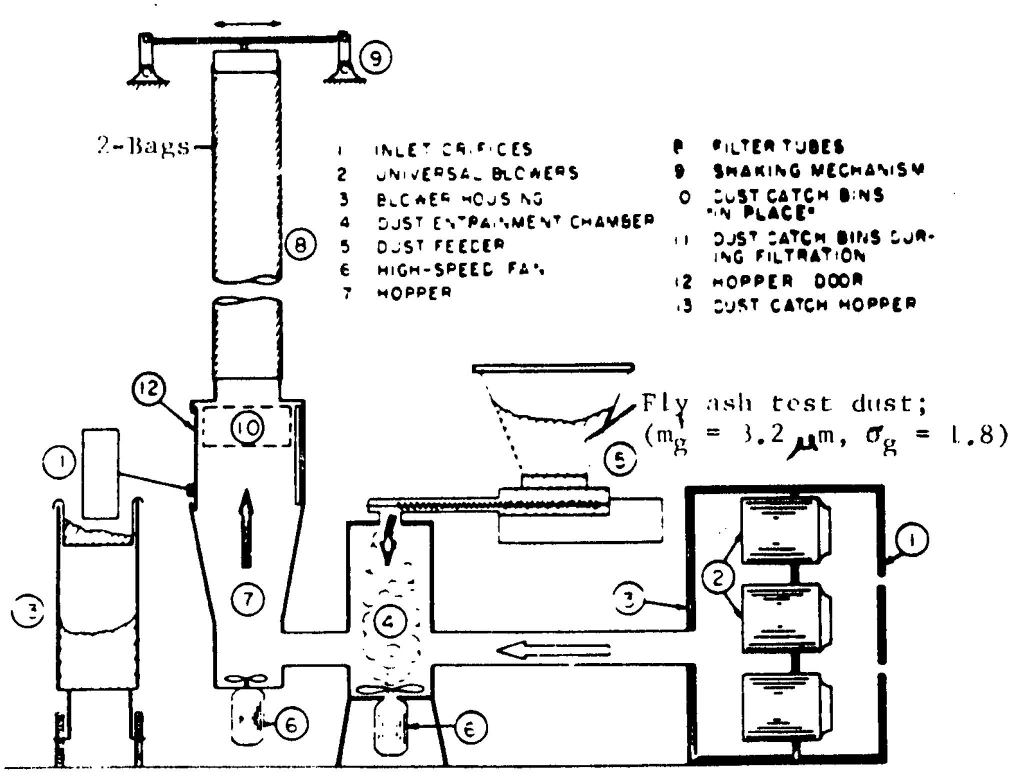


Figure 6.16. Schematic Drawing of 2-Bag Test Unit. (From Walsh and Spaite, Ref. 11.)

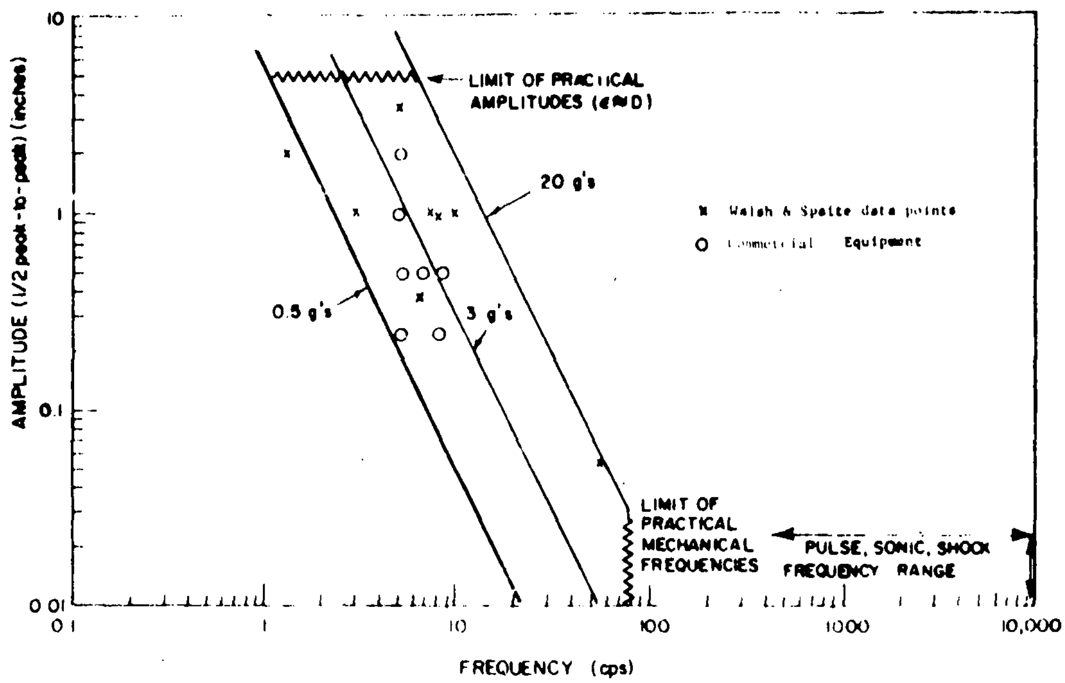


Figure 6.17. Input Accelerations in Fabric Filter Cleaning

accelerations used by Walsh and Spaite include those used in typical commercial fabric filters. Pulse, sonic, or shock wave frequencies applied to the gas are generally greater than those possible with mechanical motion of the fabric.

The analysis of Walsh and Spaite is presented below and additionally developed toward: (a) Residual drag, (b) Filter capacity. The objective is the determination of these important aspects of performance using the basic parameters of cleaning, dust, etc.

Residual Drag - Effects of shaker amplitude frequency and duration on residual drag are shown in Figure 6.18, together with test accelerations (Equation 6.11). (Note the similarity of these curves to the adhesion curves shown in Figure 2.14). Terminal drag (S_t) prior to shaking was held constant at 1.0 in H_2O/fpm. With fixed acceleration input (fixed shaker amplitude and frequency), increasing amounts of shaking (ωt) produce an initial reduction in residual drag, S_r. A point is soon reached when increased duration produces little further reduction in residual drag ($S_r = S_{min}$). The initial cleaning

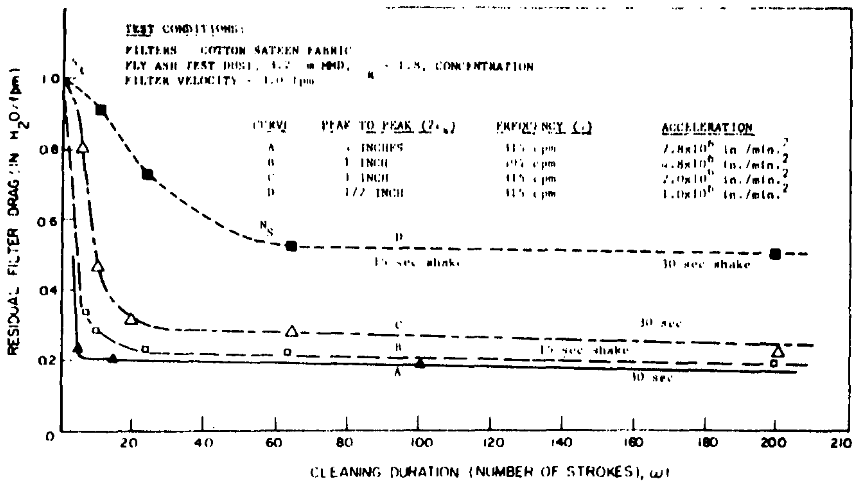


Figure 6.18. Effect of Cleaning Duration on Residual Filter Drag for Several Shaking Conditions. (From Walsh and Spaite, Ref. 11.)

strokes accomplish most of the cleaning. A practical limit exists beyond which increased shaking duration did not substantially decrease residual drag.[11] This limit, indicated at N_s in the figure, ... "was approximately reached when oscillatory motion was developed over the entire filter tube. Physically, N_s was the number of strokes required to produce significant discontinuities in the dust mass structure so that ... drag was at a practical minimum because of low resistance areas."[11] Maximum capacity was achieved with a greater number of strokes. In either case, 15 seconds of shaking was sufficient to achieve an effective minimum drag and maximum capacity. Commercial fabric filters typically shake for 30 seconds or longer.

The effect of shaker acceleration on minimum residual drag (S_{min} at N_s) is shown in Figures 6.19a and b. These data indicate that the minimum drag produced (the nearly horizontal portion of the curves in Figure 6.18) is a function of the acceleration, as

$$S_{min} = \frac{0.45}{\alpha^{1/2}} \quad \text{(in. } H_2O/\text{fpm)} \qquad (6.10)$$

for $0.7 \leq \alpha \leq 6$ g's. For $\alpha > 6$ g's, $S_{min} \rightarrow$ constant, independent of α.

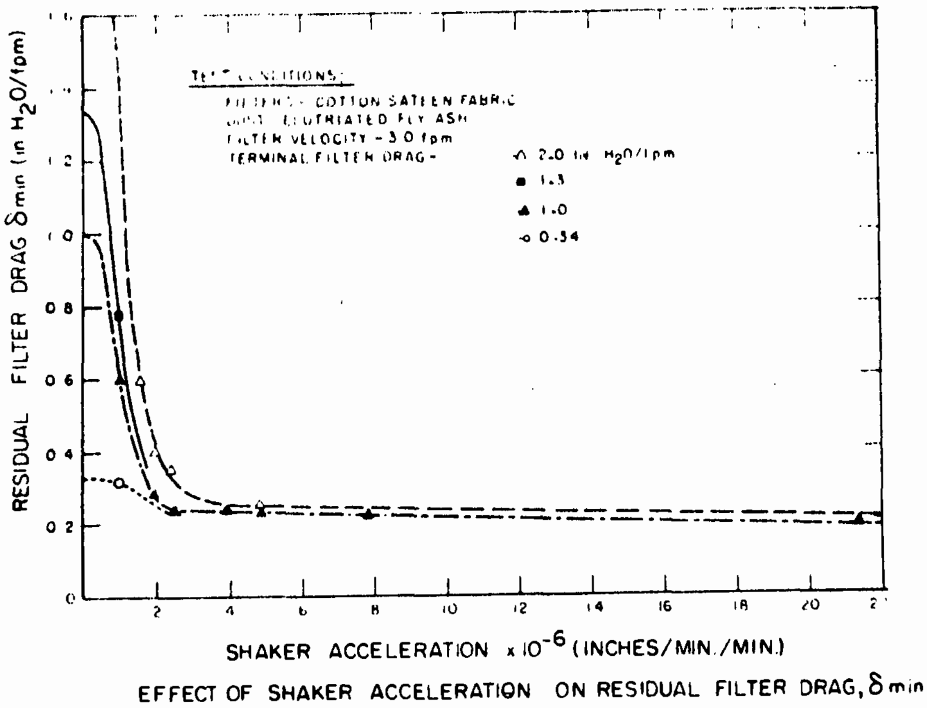


Figure 19a. Effect of Shaker Acceleration on Residual Filter Drag. δ_{min}. (From Walsh and Spaite, Ref. 11.)

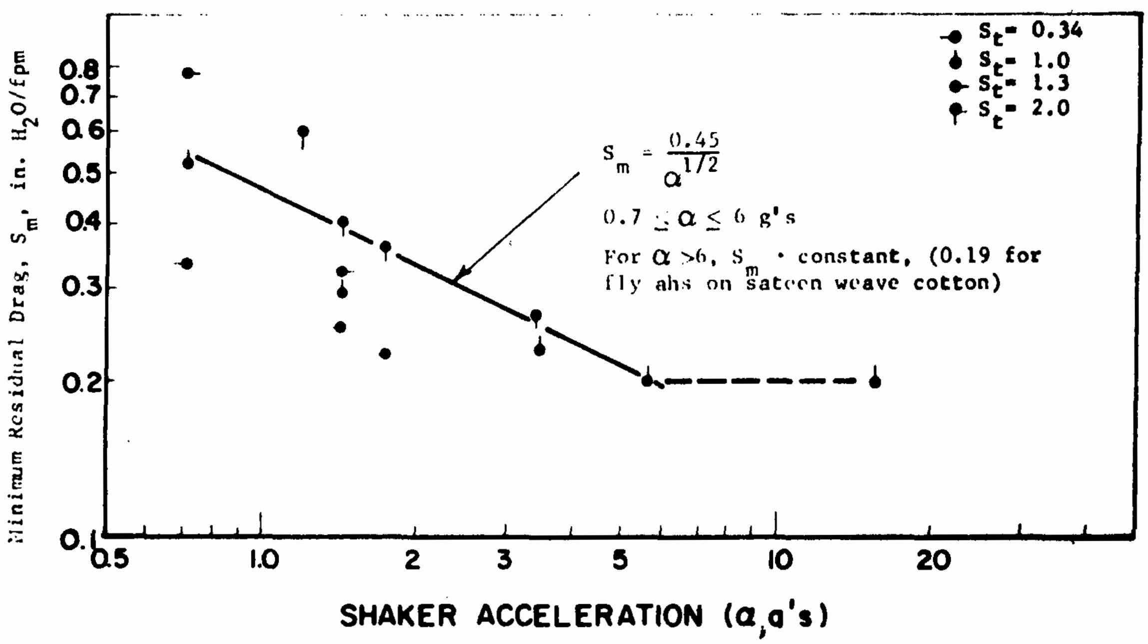


Figure 6.19b. Minimum Residual Drag as a Function of Shaker Acceleration.

The form of the S_r-ωt function appears to be relatively independent of the type of dust (Figure 6.20), within the limits of the data available. Properties of the dust (particle size distribution, shape, adhesion forces, density) and characteristics of the fabric (free available fiber, weave, yarn, fiber material) as well as filtration parameters will affect the S_r-ωt values. Hard-to-clean dusts, or napped fabrics, for example, will require greater shaking duration, but the shape of the drag-duration curve would be expected to be similar to those shown in Figures 6.18 and 6.20.

The path followed by residual drag ($S_r < S_{min}$), as a function of cleaning duration, was analyzed using the data of Figure 6.18 and found to be represented approximately by:

$$\frac{S_t - S_r}{S_t - S_{min}} = \frac{3}{4} \log (\alpha \omega t) - \frac{1}{4} \qquad (6.11)$$

where S_t is the terminal drag prior to shaking, S_r is the residual drag produced by the number of cleaning strokes ($\leq N_s$), and S_{min} is the minimum drag obtainable with a given input acceleration (Equation 6.10). Data points taken from Figure 6.18 (for $\omega t \leq N_s$) are shown in Figure 6.21.

The number of strokes (ωt) required to reach minimum residual drag (S_{min}) is a function of shaker amplitude (ϵ_s) as indicated in Figure 6.22. For these data,

$$N_s = (\omega t)_s = \frac{25}{2\epsilon_s} \qquad (6.12)$$

where ϵ_s is the shaker amplitude (1/2 the peak-to-peak total motion of the shaker).

In summary, residual drag appeared to be determined by (number of strokes x peak acceleration), Equation 6.11. However, residual drags smaller than a certain limit were not obtainable, the limit depending on acceleration, Equation 6.10. At that acceleration, N_s strokes (Equation 6.12) were required to reach the limiting drag.

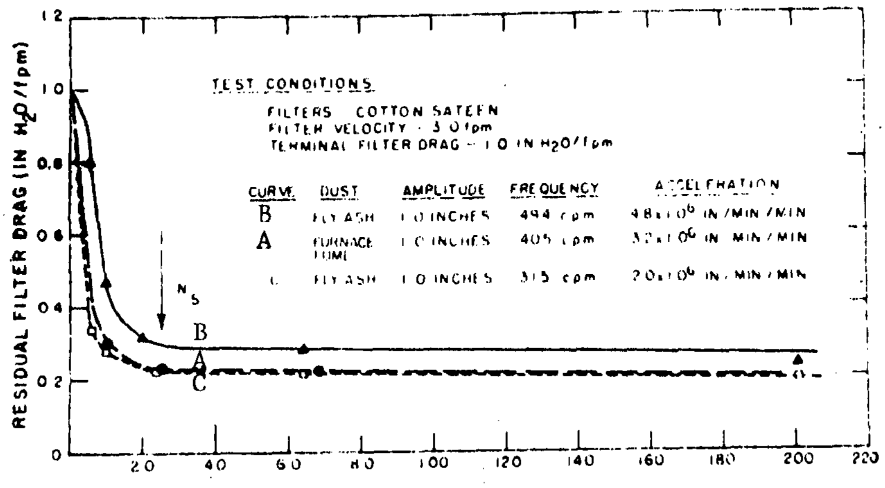


Figure 6.20. Effect of Dust on Residual-Drag-Cleaning Duration (S_r-ωt) Relationship. (From Walsh and Spaite, Ref. 11).

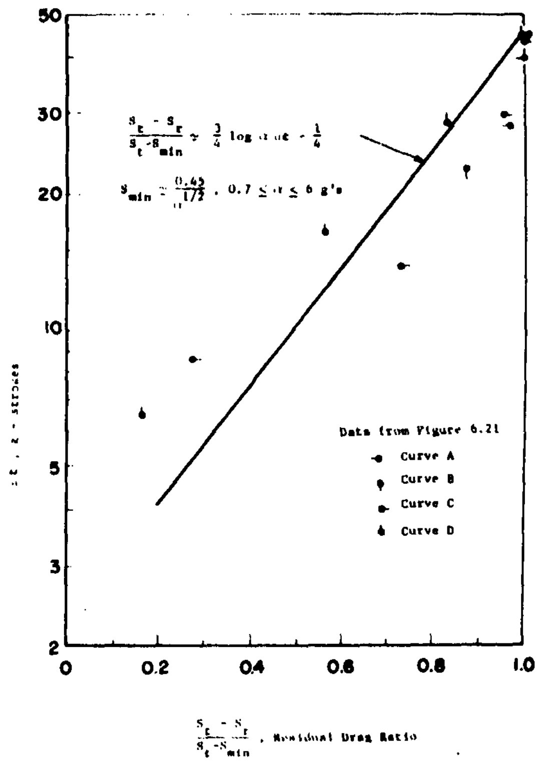


Figure 6.21. Effect of Acceleration and Shaking Duration on Residual Drag.

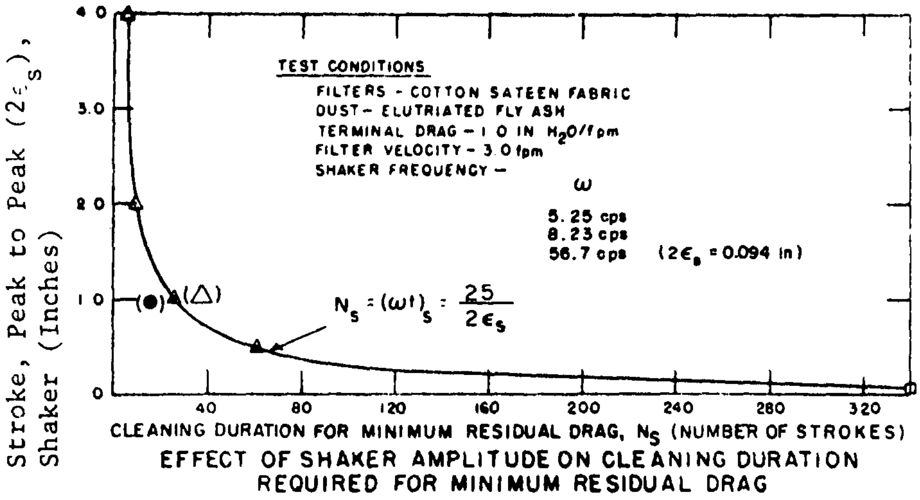


Figure 6.22. Effect of Shaker Amplitude on Cleaning Duration Required for Minimum Residual Drag. (From Walsh and Spaite, Ref. 11.)

Filter Capacity.- Filter capacity is defined as weight of dust per unit cloth area which can be collected in the next filtering cycle without exceeding a given terminal drag. In steady cyclic operation, filter capacity is equal to the amount of dust removed by the cleaning action. Filter capacity is identical to dust mass areal density (W) discussed above.

Effects of shaker amplitude, frequency, and duration on filter capacity are shown in Figure 6.23 for the same tests as in Figure 6.18. Increasing amounts of shaking (ωt) remove additional dust up to some maximum value, beyond which little more can be removed, for a given acceleration. Effect of acceleration on the maximum achievable filter capacity are shown in Figure 6.24.

Maximum filter capacity for a given acceleration can be represented approximately for these data by

$$W_{max} = 810\ (1 - e^{-\alpha}) \qquad (6.13)$$

where α is in g's, as indicated by the dotted line in Figure 6.24.

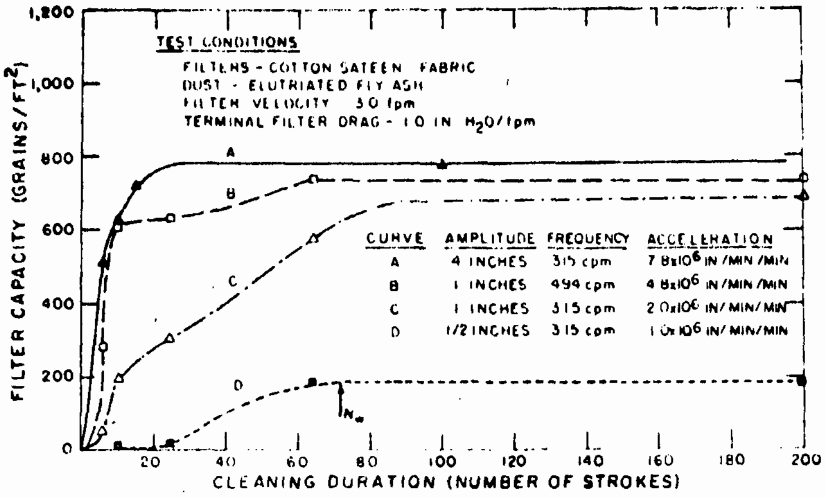


Figure 6.23. Effect of Cleaning Duration on Filter Capacity for Several Shaking Conditions. (From Ref. 11.)

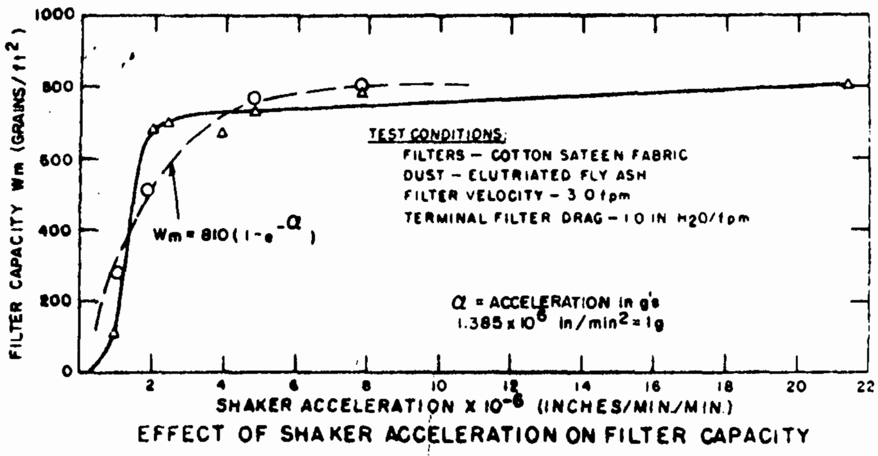


Figure 6.24. Effect of Shaker Acceleration on Filter Capacity. (From Ref. 11.)

The path followed by filter capacity as a function of cleaning duration was analyzed for the data of Figure 6.23 and can be represented approximately by

$$\frac{W_r}{W_{max}} = \frac{3}{4}\log(\alpha\ \omega t) - \frac{3}{5} \qquad (6.14)$$

where W_r is the residual filter capacity produced by the applied cleaning strokes, and W_{max} is the maximum achievable filter capacity (Equation

6.13) for a given input acceleration. Data points taken from Figure 6.23 (for $\omega t \leq N_w$) are shown in Figure 6.25.

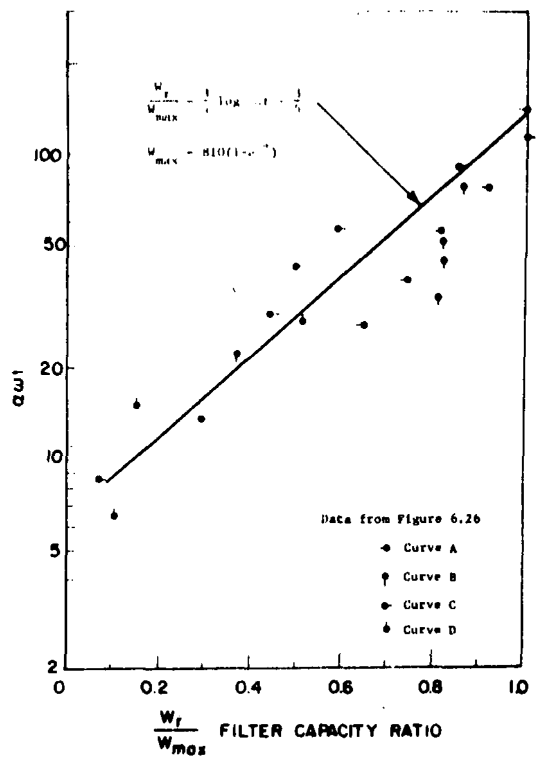


Figure 6.25. Effect of Acceleration and Shaking Duration on Residual Deposit.

The required number of strokes to achieve N_w is given approximately by

$$N_w = (\omega t)_w \approx \frac{70}{2\epsilon_s} \qquad (6.15)$$

for $2\epsilon_s \geq 1$ inch. Smaller amplitudes ($2\epsilon_s < 1$ inch) appear to arrive at N_s sooner than estimated by Equation 6.15.

In summary, Equation 6.13 indicates the maximum amount of dust (W_{max}) that can be removed from the fabric by a given acceleration input. Equation 6.15 indicates (approximately) the number of shaker strokes (N_w) required to reach the maximum dust removal. If the required number of strokes to reach maximum dust removal is not achieved during the shaking cycle ($\omega t \leq N_w$) an estimate of the amount of dust removed (W) is given by Equation 6.14.

These results are indicated in Figure 6.26. Data from curve C of Figures 6.18 and 6.23 have been plotted to indicate the drag-dust mass relationship through a single filtering and cleaning cycle. These represent equilibrium conditions at constant filtering velocity and dust concentration during the filtering cycle. The relationship for drag produced by added dust mass has been discussed above and in Chapter 2. For many dusts and fabric combinations, this is

$$S(W) = \frac{\Delta p(W)}{V} = \frac{K_2' W}{7000} + S_e = \frac{K_2' C_i Vt}{7000} + S_e \qquad (6\text{-}16)$$

where W is in gr/ft^2 of fabric and C_i is in gr/ft^3 of gas. The interval shown at A in Figure 6.26 represents the process of deposit repair when the rate of change of drag (resistance) is a decreasing function of dust deposit. The interval S_e-S_r is approximately 0.2 in.H_2O/fpm. Values of S_e-S_r are discussed below, for various dust, fabric, and cleaning combinations. The corresponding value of W at the point where the linear part of the S-W filtering curve actually starts is approximately 100 grains/ft^2. The filtering cycle (path A & B) can be approximately represented by

$$S(W) = \frac{K_2' C_i Vt}{7000} + (0.2 + S_r) \qquad (6.17)$$

Upon reaching the terminal drag (S_t), the dusty gas flow is stopped and shaking begins. Drag is reduced (path C) according to the shaking mechanism inputs, as given in equations 6.10, 6.11 and 6.12. (summarized in Table 6.4).

Equations 6.9 through 6.17 define the loop shown in Figure 6.26, approximately. For an assumed inlet loading of 5 gr/ft^3 and a filtering velocity of 3 fpm (15 gr/ft^2-min), the pressure drop-time history of the filtering and cleaning cycles appear approximately as shown in Figure 6.27 (from Figure 6.26). Equations and data presented above provide an estimate of the transient conditions in filtering and

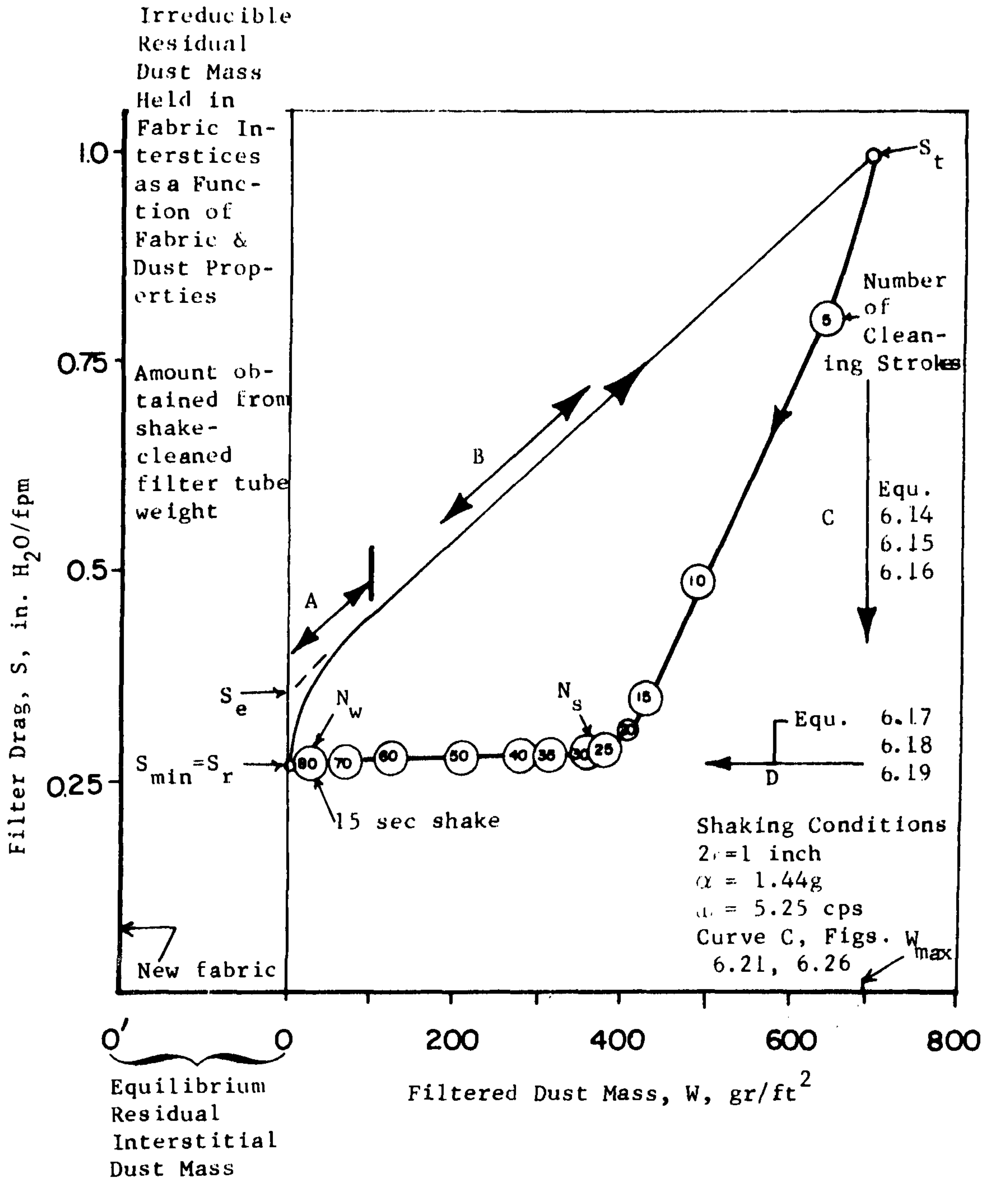


Figure 6.26. Fabric Filter Performance With Intermittent Mechanical Shaking (15 sec shake).

TABLE 6.4

SUMMARY OF CLEANING EQUATIONS FOR FABRIC FILTER DRAG AND DUST DEPOSIT DURING SHAKING WITHOUT AIR FLOW

6.9	$\alpha = (2 \omega)^2 \epsilon_s$
6.10	$S_{min} = \frac{0.45}{\alpha^{1/2}}$; $0.72 \leq \alpha \leq 6$, For $\alpha > 6$, $S_{min} \rightarrow$ Constant (0.19)
6.11	$\frac{S_t - S_r}{S_t - S_{min}} = \frac{3}{4} \log(\alpha \omega t) - \frac{1}{4}$; $\frac{S_t - S_r}{S_t - S_{min}} \leq 1$
6.12	$N_s = (\omega t)_s = \frac{25}{2\epsilon_s}$
6.13	$W_{max} = 810 (1 - \epsilon^{-\alpha})$
6.14	$\frac{W_r}{W_{max}} = \frac{3}{4} \log(\alpha \omega t) - \frac{3}{5}$; $\frac{W_r}{W_{max}} \leq 1$
6.15	$N_w = (\omega t)_w \approx \frac{70}{2\epsilon_s}$; $2 \epsilon_s \geq 1$ inch

cleaning cycles for various values of filter operating and cleaning parameters. As an illustration of their utility, Figure 6.28 has been constructed for a cleaning time of 5 seconds, keeping all other parameters constant (taken from the data shown in Figures 6.18 and 6.23). Much less dust is filtered prior to reaching terminal drag. The corresponding pressure drop history is shown in Figure 6.29. The number of cleaning strokes used per hour for the 5 second cycle is 75, (Figure 6.28), as compared to 108 per hour for the 15 second shake cycle, (Figure 6.26). The amount of dust collected is 900 gr/ft^2-hr with either cycle.

In contrast, a typical pulse-jet collector operated under similar conditions of inlet concentration (fly ash, 5 gr/ft^3) at a filtering velocity of 8 fpm would clean each bag approximately 88 times per hour, and each cleaning cycle (0.16 sec duration, 100 psi jet air) would remove approximately 27 gr/ft^2 of dust. Equilibrium pressure drop for

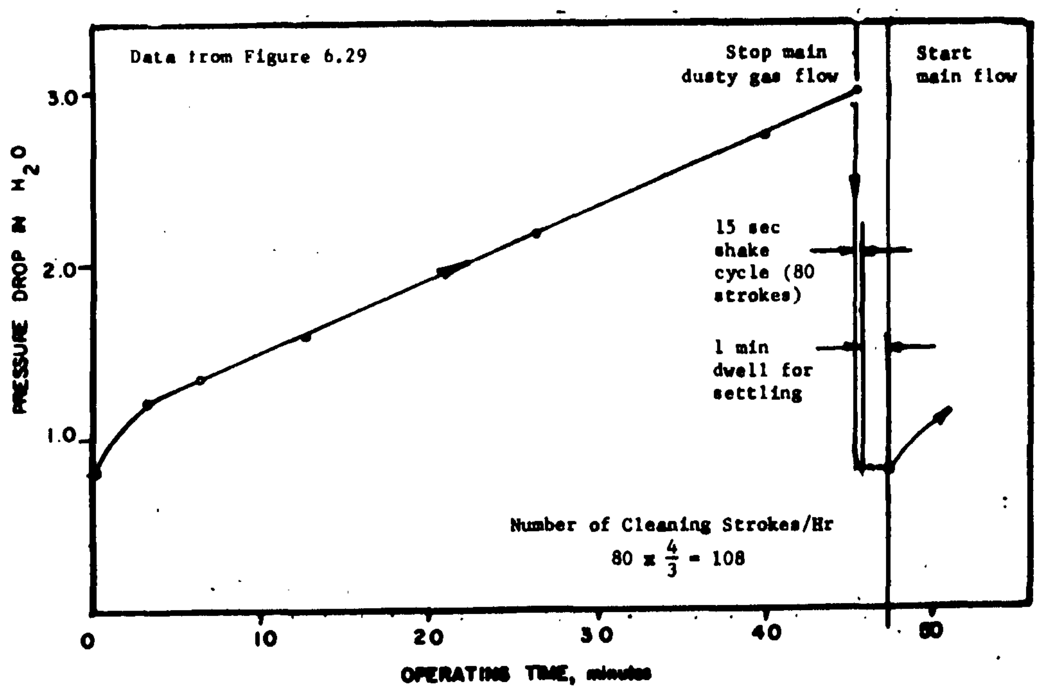


Figure 6.27. Filter Pressure Drop History (Constant Velocity and Dust Concentration).

this collector would be effectively constant at 4.0 in. H_2O. Amount of dust removed would be 2400 gr/ft^2-hr. Short-cycle on-line cleaning has been developed rapidly by filter manufacturers during the past few years. The number of cleaning operations per hour in these designs is approximately equal to or less than the number of cycles required in shaking designs, so fabric life is probably at least as long. Most use felted fabric having inherently high collection efficiency, so that short-cycle cleaning does not adversely affect average collection. Dust handling capacity is much higher per unit fabric area with on-line cleaning.

Walsh and Spaite[11] discussed the effects of the duration of cleaning cycle on filter capacity in terms of practical applications of the research results presented above. They indicate:

> "...that the influence of factors affecting the transmission of motion may be directly related to N_s, and it has been shown that longer shaking amplitudes might be desirable since they favor the transmission of motion. A definitive conclusion cannot be reached, however, until the influence of amplitude on filter wear is known."

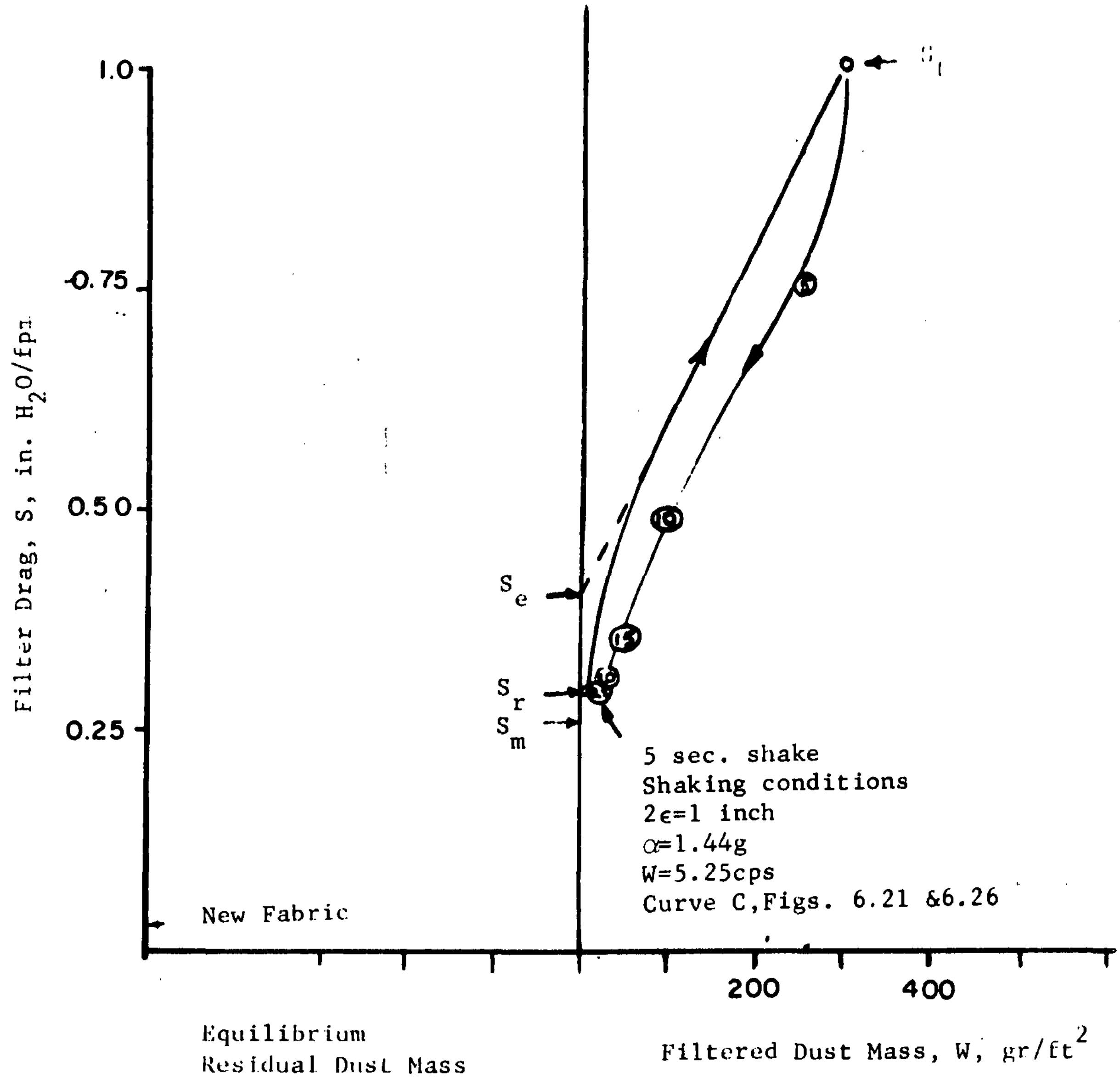


Figure 6.28. Fabric Filter Performance with Intermittent Mechanical Shaking (5 sec).

"Another application of the data is related to reducing filter wear for a given shake by minimizing the total number of strokes applied over a period of time. The cleaning duration which will achieve this effect can be found by drawing a line from the origin and tangent to the curve of a "capacity vs duration" relationship, as shown in Figure 6.30. The duration at the point of tangency will allow the most dust to be filtered per shaking stroke, such that the total

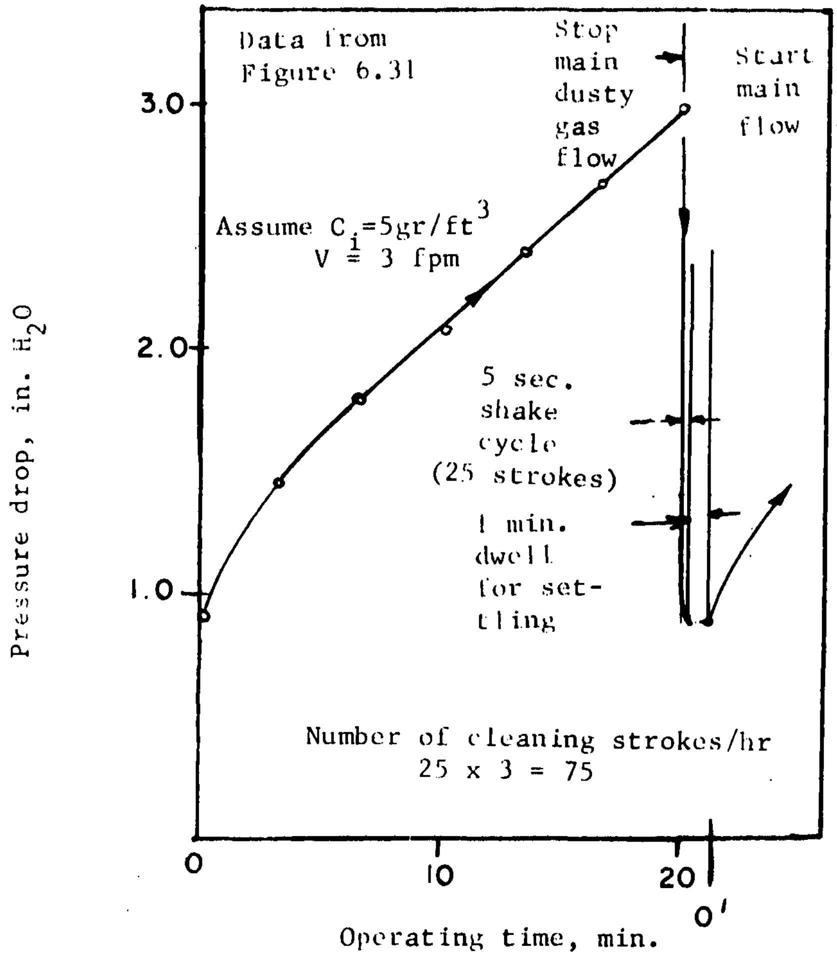


Figure 6.29. Filter Pressure Drop History (Constant Velocity and Dust Concentration.

number of strokes utilized over a period of time (say one week) will be significantly less than the total number used with a duration of N_w strokes. The total amount of dust collected over this period and maximum filter drag for each cycle would be the same in both cases. For the illustration shown, the total number of strokes required for operation at this optimum condition for a 40-hour interval would be approximately one-third the number required if N_w strokes were used for each cleaning period"...(also see a similar comparison in Figures 6.26 and 6.28 using 2/3 the number of strokes in going to N_s vs N_w, respectively).

"In practice, operation under this condition probably would produce a residual dust ...(deposit)... less uniform than that after N_w strokes, so that significant aging (gradual increase in residual drag with time) may complicate operation in this region...The extent of such nonuniformities can be seen by considering local velocities of filtration as shown in Figure 6.31. These data were taken while determining the curve of Figure 6.30 and indicate the degree of nonuniformity that existed after several cleaning durations. For instance, the profile after cleaning with 28 strokes shows velocities on the order of five to six fpm through the upper portions of the filter, while the profile after cleaning with 688 strokes shows a uniform velocity of three fpm over the entire filter surface. The former situation indicates that the shaking motion was effective in reducing local filter drag only at the top of the bag; hence, velocities there are higher than average. Repeated operation with this shake would result in a gradual build-up of drag at the bottom of the filter and a gradual increase in the effective drag of unit. This type of drag increase would not occur when operating with a duration of 688 strokes because the entire filter area would be affected by the shaking motion"...(also see Section 6.2.2.2 above for residual profile uniformity with duration of shaking).

"Figure 6.19a, which contains several curves representing residual drag as a function of acceleration and terminal drag, has certain practical implications. These data indicate that in the region below the optimum acceleration, residual drag was dependent on terminal conditions (see equation 6.11), while in the region above the optimum acceleration it was practically constant (see equation 6.12). In other words, changes in conditions such as increased cycle times or increased dust concentrations, which would increase the terminal drag of a unit, will increase residual drag if the acceleration of the shake is below optimum for the system. Also, if a unit is operated on a time-cycle and the acceleration is below optimum, both residual and terminal drags will increase from cycle to cycle until the drag reduction during cleaning equals the drag increase during filtration. This effect will be in addition to any other normal increases associated with an approach to equilibrium. Assuming that cleaning duration is in excess of N_s, a reduction in residual drag can be accomplished only by increasing acceleration. This type of phenomena may explain the results reported by Lemke, et al., (12) (ZnO from hot dip galvanizing kettles), wherein the residual drag of two pilot-plant filter units, operating on a timed cycle, increased gradually over a period of time. The increase was of such an extent that vigorous hand shaking was periodically required to maintain reasonably low filter pressure differentials. The vigorous shaking by hand, then, was comparable to increasing the acceleration of the shaker. It would seem possible, therefore, that a dependence of residual drag on terminal conditions may be a general indicator of insufficient acceleration, and that the region of operation (i.e., above or below the optimum acceleration) may be determined by varying filtration times and monitoring the effect of such changes on residual drag."[11]

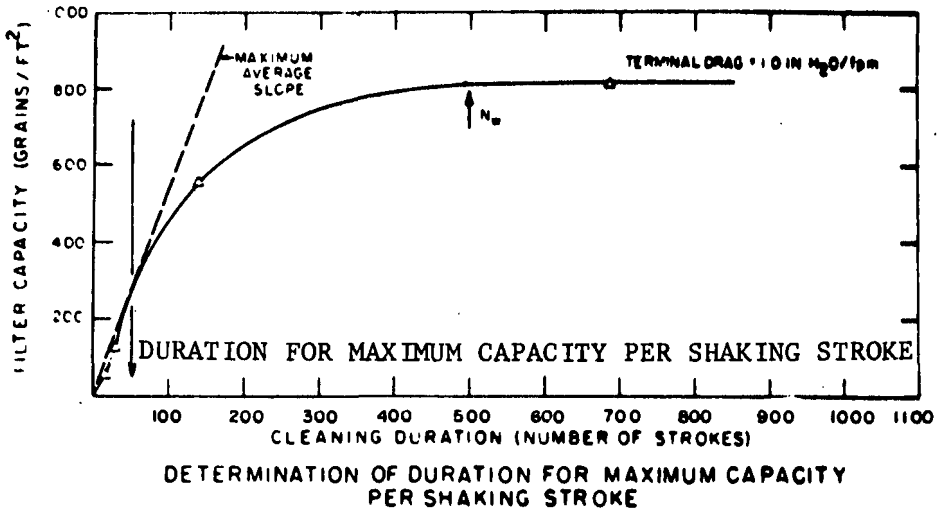


Figure 6.30. Determination of Duration for Maximum Capacity Per Shaking Stroke. (From Walsh and Spaite, Ref. 11).

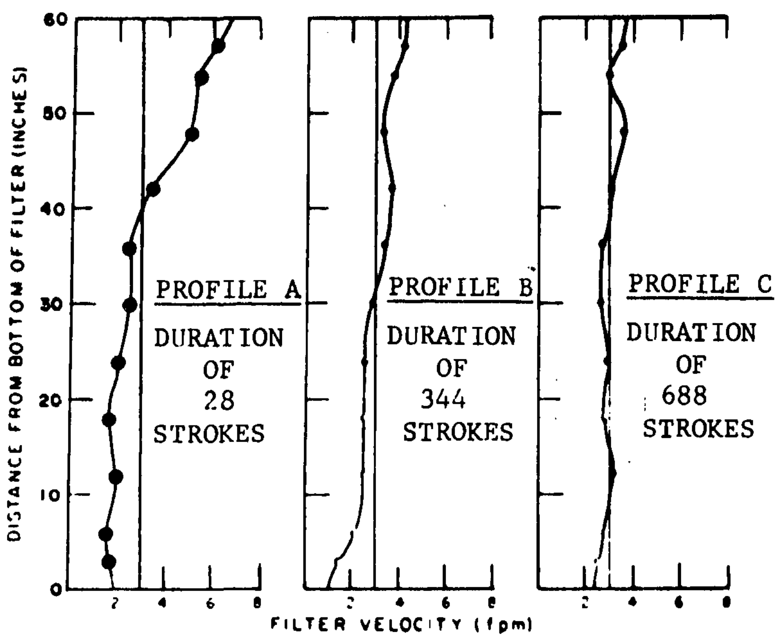


Figure 6.31. Local Filter Velocity after Various Cleaning Durations, with the Same Shake (3/32 in. amplitude, 3400 cpm frequency; average velocity 3 fpm).(From Walsh and Spaite, Ref. 11).

Walsh and Spaite presented the following conclusions:

"1. A well-defined limit will exist beyond which increased shaking with a given shaking stroke will not significantly contribute to further cleaning (see equations 6.11 and 6.14).

2. Filter capacity and residual filter drag are a function of shaker amplitude and the square of shaker frequency (maximum acceleration of bag cap), but again a well-defined limit exists beyond which increases in these factors will not result in further cleaning (see equations 6.10 and 6.13).

3. Shaker amplitude has an influence on the number of cleaning strokes required for a given degree of cleaning. This influence is independent of its effect on the maximum acceleration of the shaking stroke (see equations 6.12 and 6.15).

4. A relative measure of the influence of factors affecting the transmission of shaking motion can be obtained by considering cleaning durations required to produce minimum filter drag.

5. For any given shaking arrangement there will exist a cleaning duration which will produce the least bag wear over a period of time." [11]

There is a definite requirement for study of the effects of these same shaker variables on fabric wear and bag life for optimization of cleaning costs.

6.2.2.4 Effects of Fabric Structure. - There are more than a dozen generic types of man-made fiber materials that can be used in fabric for gas filtration, in addition to cotton and wool. Fiber, strand, twist, yarn, yarn count, weave, and finish parameters are discussed in Chapter 4. The initial studies of Snyder and Pring[2] indicated an effect of fiber material, fabric weave, and mechanical finish on filtration performance (See Figures 6.3a, b, and c, and Tables 6.2a and b). More recent investigations of the effects of fabric structure in pilot scale systems have been presented by Spaite and Walsh[13] (two bag unit,[11] Figure 6.19), Durham[14] and Borgwardt, et al.[15] Other data have been presented in Chapter 2.

Spaite and Walsh[13] studied the performance of three Fiberglas[R] and two Dacron[R] fabrics, woven from continuous filament yarns (specifications and photographs of test fabrics are given in Figure 2.26a).

"Basic performance curves for the Fiberglas^R fabrics when operated at a nominal velocity of 2 fpm are shown in Figure 6.32a. Each set of test bags were exposed over the entire range of nominal velocities investigated (2 fpm to 10 fpm), and two runs were made at low velocity to determine the extent of changes in the residual medium during the tests. The lower curve for each fabric was obtained after new bags were operated at 2 fpm for 48 hours. The upper curve for each pair shows results of a repeat run made at 2 fpm under conditions that were identical, except that the cloth had been exposed for one week to the higher filtration velocities. The higher resistance after exposure is a reflection of the effect of dust penetration into the fabric, or "aging".[13]

Figure 6.32a shows an increased effect of aging on the more open Fiberglas^R fabric No. 1, as compared to No. 3:

"...the tighter weave, No. 3, exhibited a higher resistance to flow when it accumulated a semi-permanent residual dust mass. Much of the advantage in low residual drag shown initially by the open fabric, No. 1, was cancelled out by the effect of aging; ...dust cake permeability was affected, but little by aging.

The importance of changes in filter drag and filter resistance coefficient is most evident when their combined effect is shown as total resistance to flow. In Figure 6.32b, the increase in filter pressure differential that occurs during filtration is shown as a function of the mass of dust filtered. These curves represent the pressure increase during operation at velocities of 2 fpm, 4 fpm, and 6 fpm on the tightest (No. 3) and loosest (No. 1) Fiberglas^R fabrics. The filtration capacity of the fabrics, in terms of the mass of dust than can be collected before a given differential pressure is exceeded, depends on the fabric structure most strongly at high filter velocities. At higher velocities this dependency becomes greater as the mass deposited becomes greater; at lower velocities it becomes less significant as the total mass increases.

The effect of fabric structure and nominal velocity on the specific dust-fabric filter resistance coefficient is shown in (the upper portion of) Figure 6.33. In every instance the dust deposit creates an increase in the specific resistance coefficient as filtering velocity is initially increased.

These changes in the resistance coefficient are substantial over the range of velocities that would exist in multicompartmented units operating at nominal velocities of 2 to 3 feet per minute. Thus, they are an important consideration in any analysis of flow and resistance patterns in such an installa-

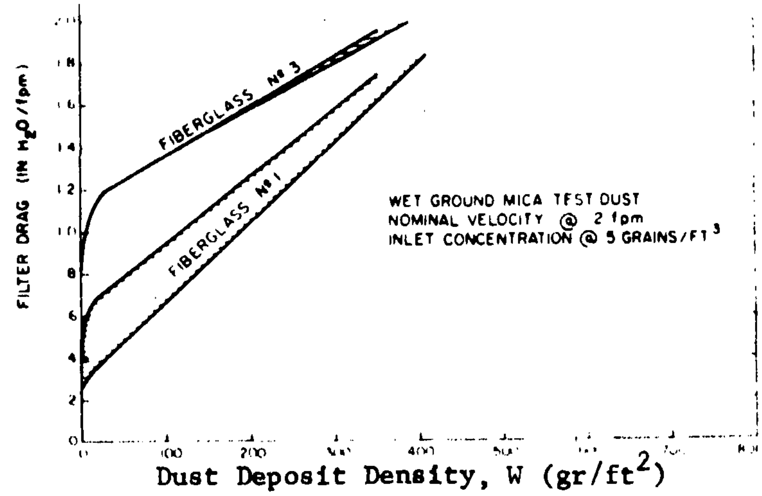


Figure 6.32a. Effect of Fiberglass Fabric Fill Count Variation

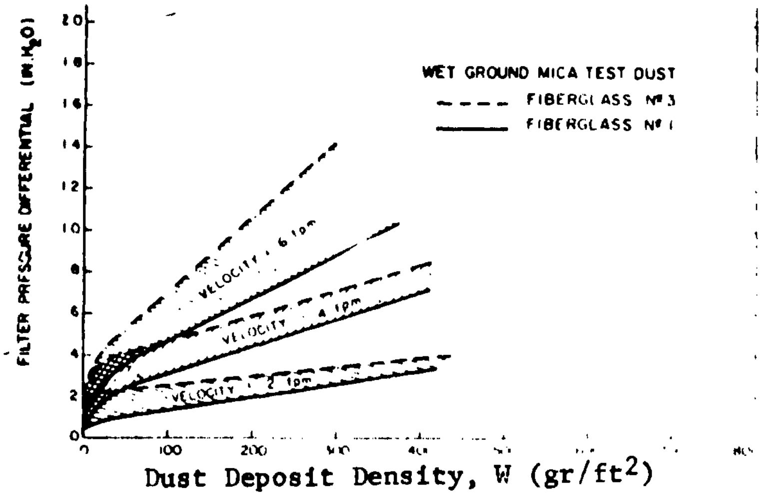


Figure 6.32b. Effect of Fiberglass Fabric Construction

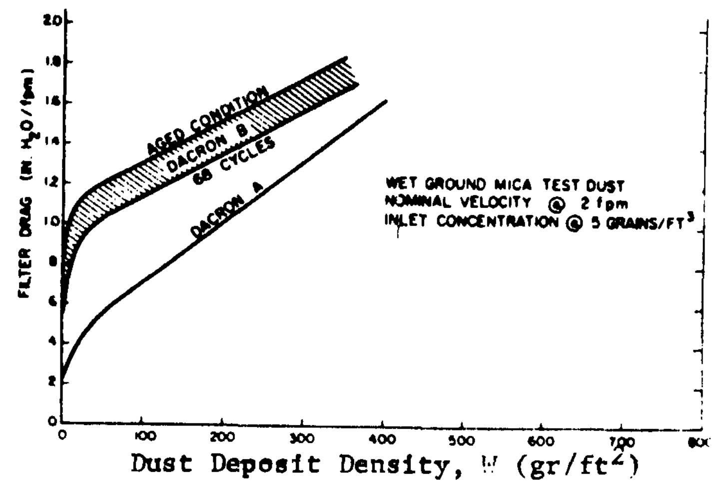


Figure 6.32c. Effect of Dacron[R] Fabric Fill Count Variation.
(From Spaite and Walsh, Ref. 13)

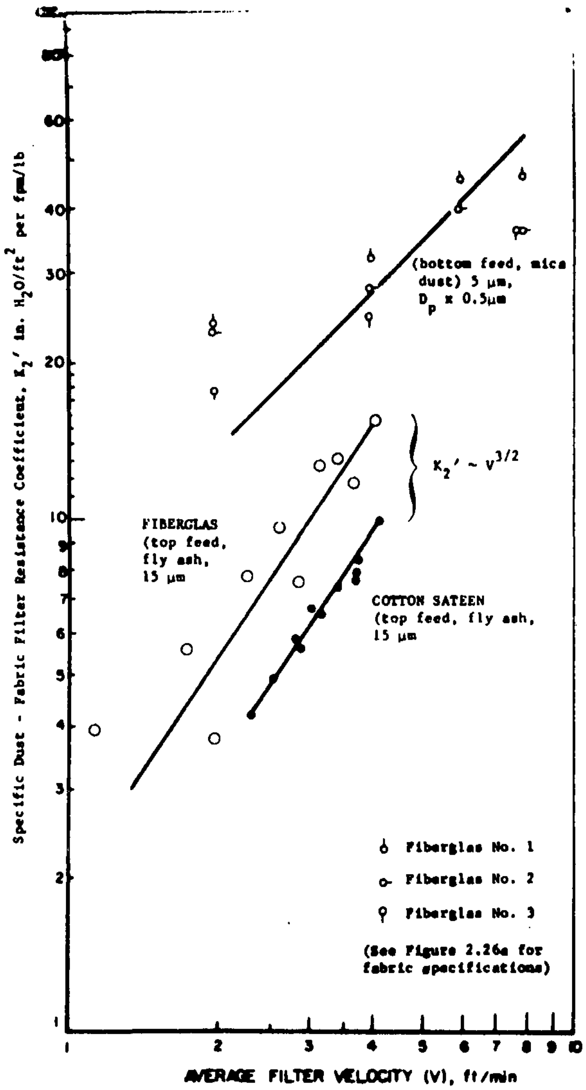


Figure 6.33. Correlation Between Average Specific Dust Fabric Filter Resistance Coefficient and Filtration Rate.

tion. Substantial error will be introduced by an assumption that the resistance coefficient observed in bench scale tests or in a single-compartment pilot unit will be reproduced by conditions in a full-scale unit in the same process.

The data for both Fiberglas[R] and Dacron[R] show analogous trends and patterns when velocity and fill count variations were studied independently. Illustrations No. 2 and No. 3 in Figure 2.26a show the difference in the two Dacrons[R] and the extent to which Dacron[R] B and Fiberglas[R] 1, the two materials with nearly equal clean-cloth air permeability ratings, are similar.

The basic performance curves for Dacron^R, shown in Figure 6.32c are similar to those obtained with Fiberglas^R. The filter drag at the end of the period of deposit repair was again found to be higher for the tighter weave fabric, Dacron^R B. The accelerated increase in initial drag for both Fiberglas^R and Dacron^R indicates that such an effect is characteristic of the continuous-filament yarns.

The effect of velocity on the specific resistance coefficient for the mica dust deposited on Dacron^R followed the same general pattern shown for Fiberglas^R in Figure 6.33 (upper portion).

The increases in pressure differential across the filtering medium during the filtering cycle are essentially the same for both Dacron^R and Fiberglas^R. The previously discussed similarity in the relationships for the individual components of the pressure loss (i.e., loss across the initial dust fabric medium and loss through the deposit...) are reflected here in curves that are so nearly identical to those shown for Fiberglas^R in Figure 6.32b that it is unnecessary to show both sets.

A second measure of performance that must be considered when fabric structure and velocity are varied is the amount of dust discharged through the fabric. Most of this discharge occurs in the early stages of filtration.

Figure 6.34 shows the manner in which dust discharge varied as a function of nominal velocity and Fiberglas^R structure. Each filtering cycle was terminated at a drag level of 1.5 in. H_2O/fpm. Because of this, some cycles were ended before they could progress substantially beyond the region of formation or repair of the uniform filtering medium. Such tests are designated by circles on the curves.

A most interesting aspect of Figure 6.34 is the curve which shows dust discharged per cycle as a function of velocity for Fiberglas^R No. 1. The data points numbered 1 through 7 represent the results of 7 consecutive tests of this fabric, each made after 24 hours of operation at test velocity.

The efficiency was poor in early tests, but showed a marked improvement, associated with the aging of this loosely woven fabric. The interim runs at low velocities (points 5 and 7) indicate that the improvement in efficiency tended to be permanent. During Run 7 the dust discharge changed from 11.8 grains/sq.ft. for the second cycle to 10.9 grains/sq. ft. for the fifty-second cycle. Subjective estimates of filter efficiency support these data: before aging, a number of pinholes and high velocity air jets were in evidence over the surface of the fabric; after aging, these largely disappeared. During the tests, the efficiency of the fabric changed from 85.5 percent for Run 1 to 96.1 percent for Run 7.[13]

The curves in Figure 6.34 show that dust discharge was approximately proportional to velocity and inversely proportional to filling yarn count.

"Conditions that developed in the filter enclosure were similar to those observed in industrial fabric filters. The bags developed a slight dust layer on the exterior surface, and some dust collected on the floor of the clean air side. The weight of this material was not included in the dust discharge data. The dust discharge data are probably higher than would be encountered in actual use because of the intensive cleaning employed for these tests.

For the Dacron^R fabrics, the effect of nominal velocity on dust discharge per cycle is shown in Figure 6.34b. A general linear relation is again shown, but the relationship is different in that the Fiberglas^R fabrics allowed greater dust discharges at low velocities and Dacron^R generally showed a lower rate of increase in dust discharge with velocity. These differences might be attributable to a more even distribution of air flow through the Dacron^R fabric. An indication of the distribution of areas available for high air flow is obtained by considering light transmission through the fabrics (Figure 2.26a).

The most striking point in the comparison of the two cloth types is that the two materials with nearly equal clean-cloth permeability values (Fiberglas^R No. 1 - permeability 15.84 and Dacron^R B - permeability 14.62) have different performance characteristics. The difference is reflected in dust mass vs. filter drag curves (Figure 6.32), and the efficiency curves, (Figure 6.34). The comparisons demonstrate the impossibility of predicting performance of an untried fabric from permeability data and known performance data for a second fabric, even when the same dust is involved. Thus, cloth permeability per se seems to be of less importance to these filtration parameters than the manner in which the fabric structure is changed to alter permeability".[13]

The effect of filtering velocity on the specific dust-fabric filter resistance coefficient was also investigated by Borgwardt, et al[15]. Their flyash data are shown in Figure 6.33 (lower portion). They found that:

$$K_2' \sim V^{3/2} \qquad (6.18)$$

for $1 \leq V \leq 4$ fpm. The earlier data of Spaite and Walsh (Figure 6.33, upper portion, mica dust 5-10 μm D_p x 0.5 μm thick) are less well-

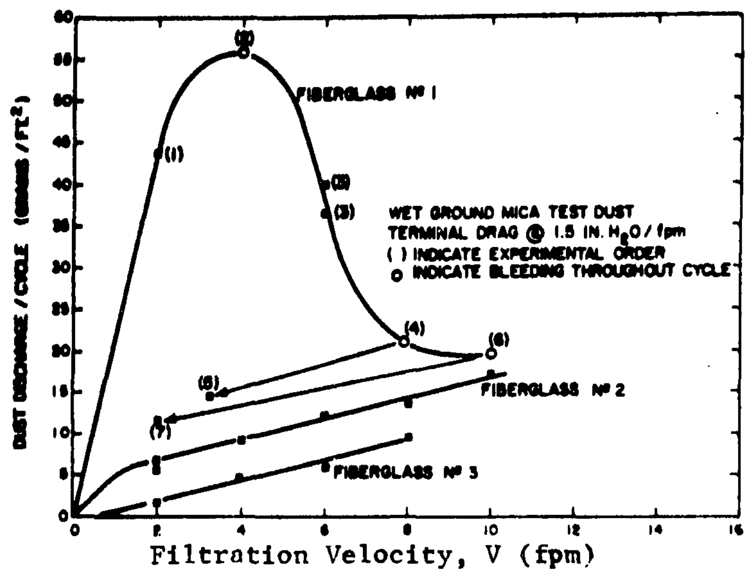


Figure 6.34a. Effect of Nominal Velocity on Dust Discharge for Fiberglass Fabrics.

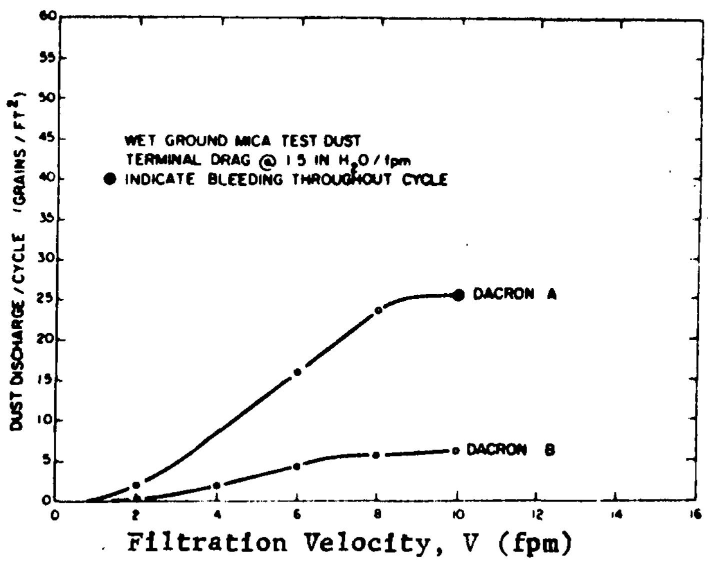


Figure 6.34b. Effect of Nominal Velocity on Dust Discharge for Dacron[R] Fabric.
(From Spaite and Walsh, Ref. 13)

behaved, but indicate that $K_2 \sim V^n$ for $n > 0$ and $2 \leq V \leq 8$ fpm. In each of these studies fabric, dust, and velocity all affect K_2'. (See also Section 2.4.8.4).

Figures 6.32(a) and (c) can be used to determine the unknown interval $(S_e - S_r)$. The nonlinear portion of the S-W curves occurs during the period of dust deposition less than about 100 gr/ft^2. Approximate values of the interval $(S_e - S_r)$ are ~ 0.2 in.H_2O/fpm.

Durham and colleagues[14] have extended the above investigations to nine additional woven fabrics indicated in Table 6.5. Six different fiber materials were tested: Nomex[R], Teflon[R], Polypropylene, Orlon[R]-Acrylic (Microtain[R]), Dacron[R] and Cotton. Yarn configurations included continuous multifilament warp and fill, filament warp and spun fill, spun warp and fill, and napped (Dacron[R]) woolen system yarns-warp and fill. Weaves and thread counts were different for each fabric, as was fabric weight and clean air-flow permeability. Three grains/ft^3 of flyash test dust (~ 10 μm D_p) was filtered at 4 fpm (constant mass flux 1.7×10^{-3} lbs/ft^2 min) in all tests (top entry, single 5.5 in. diam. x 66.6 in. long bag, under suction). Cleaning was accomplished with a mechanical reciprocating shaker attached to a flexible connection at the bottom of the bag (2ϵ = 1.75 in.; ω = 5.6 cps; duration, 0.5, 1, 3, and 5 min; ωt = 170, 340, 10^3, 1.7×10^3 strokes; α = 2.85 g's). (See equations 6.10 through 6.15 for effects of shaking parameters on minimum residual drag and maximum dust capacity per filtering cycle). Filter drag-deposit density $(S-\overline{W})$* curves are shown in Figures 6.35a, b, and c, and 6.36. Fabrics have been grouped qualitatively by yarn free available fiber area, according to the classification hypothesis indicated in Figures 2.69 a-d (Chapter 2). Four classes of fabric were identified according to a qualitative estimate of free available fiber:

(a) Continuous multifilament warp and fill, Figure 6.35a

1. Nomex[R]
2. Teflon[R]
3. Polypropylene

* $\overline{W}$ is dust deposited on the fabric, as calculated from dust fed and hopper fallout (see discussion below).

TABLE 6.5

Fabric Filter Media Specifications and Performance with Constant Particle Flux (1.7×10^{-3} lbs/ft^2-min)

Fabric Number	Yarn Composition	Yarn Type	Weave	Thread Count, threads/in.	Clean Air Flow Permeability	Approx. Clean Drag* in. H_2O/fpm	Fiber Density, gm/cm^3	Fabric Weight oz/yd^2	Terminal drag, S_T in. H_2O/fpm	Residual Drag, S_R, in. H_2O/fpm	Effective drag, S_E in. H_2O/fpm	S_e-S_R in. H_2O/fpm	Terminal Deposit, W_T lbs/ft^2	Storage Capacity, W_t/S_t	Specific Resistance Coefficient, in. H_2O(fpm)$^{-1}$ (lb/ft^2)$^{-1}$	Approximate Filtering Power, HP/1000 cfm
1	Nomex®	Filament warp & fill	3x1 twill	96x78	15-20	0.028	1.38	4.5	1.5	0.40	0.99	0.59	0.045	0.030	11.5	0.85
2	Teflon®	Filament warp & fill	3x1 twill	76x61	20-40	0.017	2.1	8.6	1.0	0.15	0.54	0.39	0.055	0.055	8.7	0.51
3	Poly-propylene	Filament warp & fill	3x1 twill	74x73	10-20	0.033	0.9	4.3	1.5	0.21	0.92	0.71	0.095	0.063	6.2	0.68
4	Nomex®	Filament warp; spun fill	3x1 twill	95x58	20-25	0.022	1.38	5.4	1.0	0.22	0.55	0.33	0.060	0.060	7.8	0.47
5	Dacron®	Filament warp; spun fill	3x1 twill	77x81	20-30	0.020	1.38	5.8	1.0	0.05	0.41	0.36	0.075	0.075	7.7	0.39
6	Cotton	Spun warp & fill	Sateen 5H-W	97x63	15-20	0.028	1.50	9.5	1.0	0.41	0.56	0.15	0.077	0.077	5.8	0.39
7	Orlon®	Spun warp & fill	3x2 twill	85x77	15-25	0.025	1.14	5.7	1.0	0.20	0.32	0.12	0.12	0.12	5.8	0.33
8	Acrylic**	Spun warp & fill	2x2 twill	39x35	60	0.008	1.14	9.8	0.7	0.05	0.25	0.20	0.10	0.14	4.8	0.23
9	Dacron®	Woolen syst. Napped fabric	2x2 twill	41x39	55-65	0.008	1.38	12.5	1.0	0.09	0.20***	0.11	0.205	0.205	2.4***	0.17

* - cfm/ft^2 at 0.5 in. H_2O, assumed linear $\Delta p \sim V$.

** - Albany Felt Microtain®

*** - Estimated from linear portion of S-W curve up to $W \leq 0.1$ lbs/ft^2, then K_2' increasing to 8.5 at $W = 0.2$ lbs/ft^2

Note: Fly ash test dust, 10 μm diam., C_i = 3 grains/ft^3, V = 4 fpm, cleaning time 180 sec, 5.5 in. diam. x 66.6 in. long bags.

(From Durham, Ref. 14).

(b) Filament warp and spun fill, Figure 6.35b

4. Nomex[R]

5. Dacron[R]

(c) Spun warp and fill, Figure 6.35c

6. Cotton Sateen

7. Orlon[R]

8. Acrylic (Microtain[R])

(d) Napped, Figure 6.36

9. Dacron[R]

Effects of increasing amounts of free available fiber should include reduction in K_2' and increased amount of dust storage capacity ($\bar{W}_t/S_t$). More free fiber (A → D) should also reduce the amount of dust deposit released for a given shaking cycle, An increase in ωt on class A fabrics should produce little additional dust removal ($\Delta\bar{W}$ small as ωt) but a similar increase in ωt on class D fabrics should produce a larger amount of dust removal. Fabric performance is indicated in Table 6.5. Effects of fabric structure on K_2, $\bar{W}_t/S_t$, and increased cleaning time are summarized below:

Fabric	No.	K_2'	$\bar{W}_t/S_t$	$\Delta\bar{W}_{30-300}$
Filament	1	11.5	0.030	0.005
	2	8.7	0.055	-
	3	6.2	0.063	-
Filament/Spun	4	7.8	0.060	-
Spun	6	5.8	0.077	0.016
	7	5.8	0.12	-
	8	4.8	0.14	0.014
Napped	9	2.4	0.205	0.030 (60-300 sec)

- The specific dust-fabric filter resistance coefficient (K_2') is relatively larger with filament fabric, (~10) and smaller for hairy or napped fabric (~ 5) (except for fabric No. 3, filament polypropylene, which is somewhat lower than expected). The calculated value of the specific resistance coefficient (K_2') for this dust (10 μm = Dp; ρ_p = 85 lb/ft^3, is 7.3 in $H_2O/(lb/ft^2)$ (fpm), uncorrected for velocity effect ($K_2 \sim V^n$, $n > 0$).
- Dust storage capacity ($\bar{W}_t/S_t$) increases with amount of free available fiber (except for polypropylene, which is higher than expected). Capacity varies from 0.03 to 0.2 lbs dust/ft^2 of fabric per unit drag.

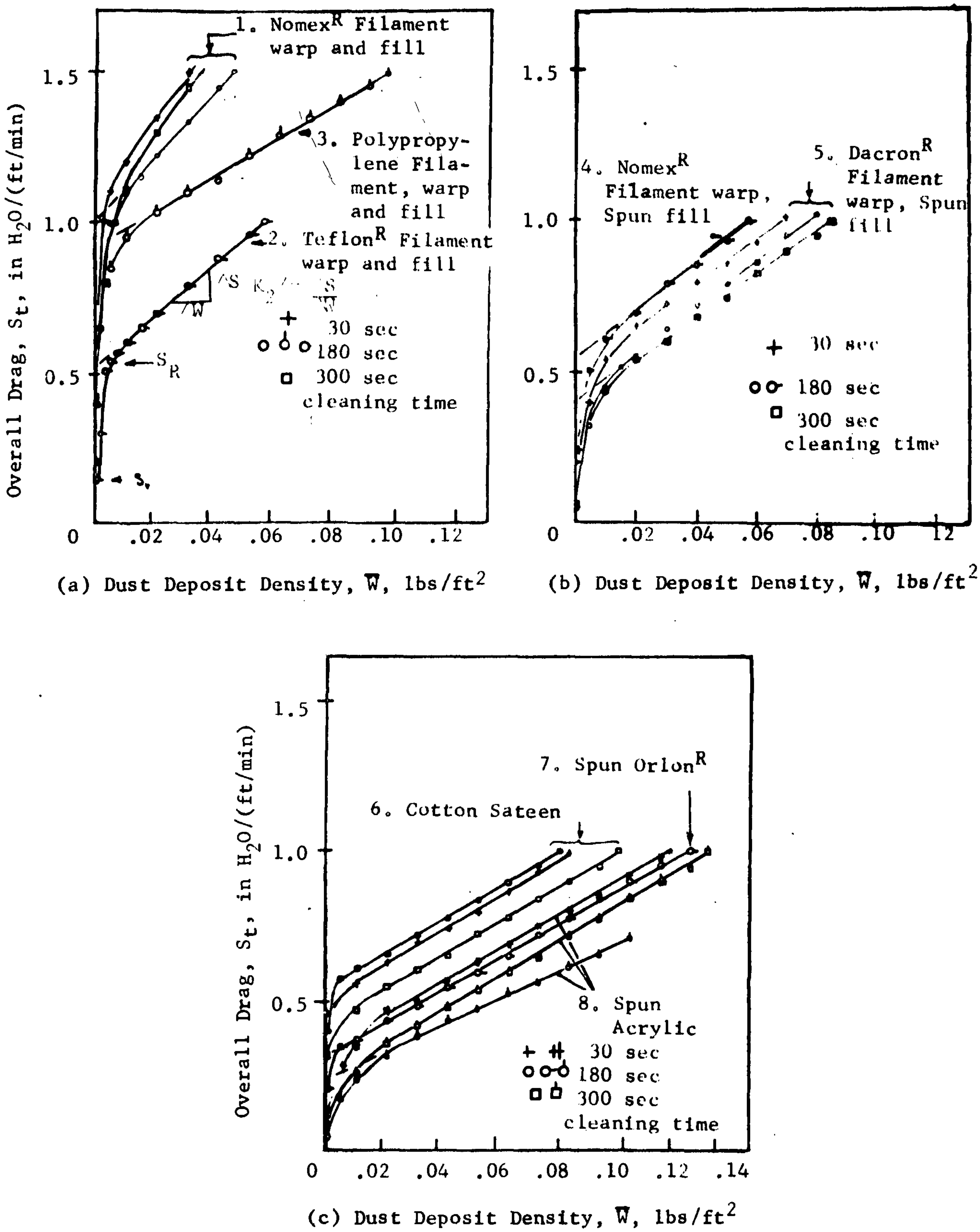


Figure 6.35. Effect of Fabric on Filter Performance (From Durham, Ref. 14).

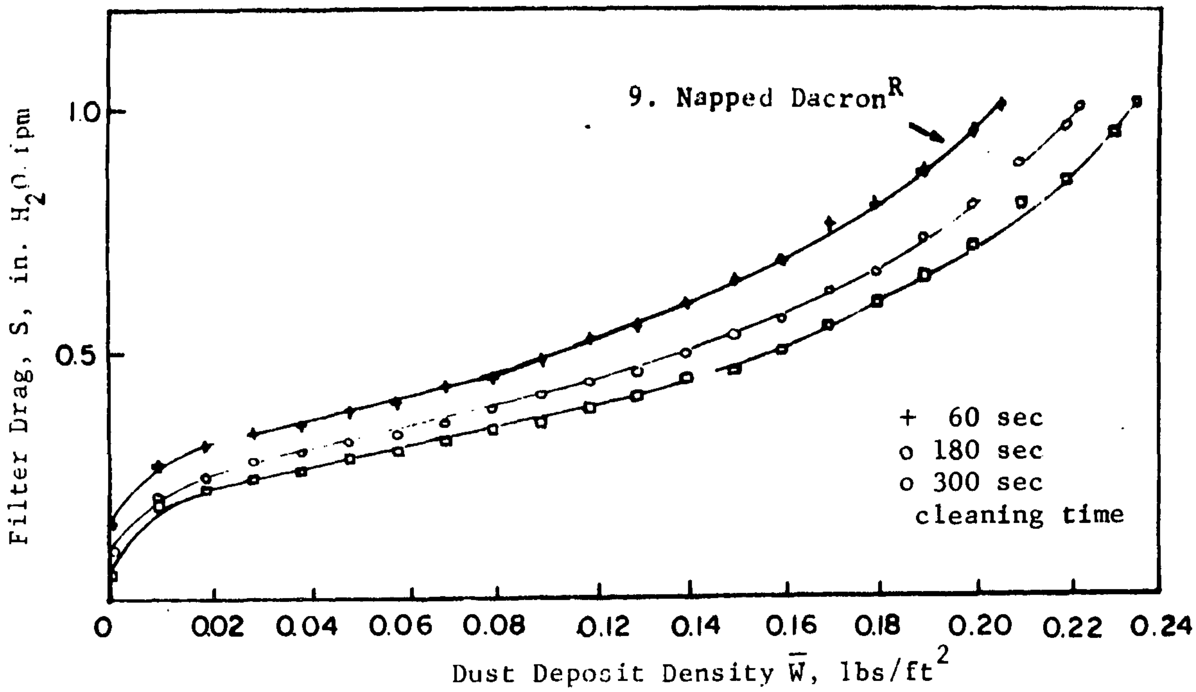


Figure 6.36. Effect of Shaking Duration on Dacron[R] Fabric Filter Performance (From Durham, Ref. 14).

- Amount of dust removed by an increase in shaking duration (ωt) is relatively lower with filament fabric (No. 1). Duration increase from 30 to 300 sec (170 to 1.7×10^3 strokes) produced a 0.005 lb/ft^2 increase in dust holding capacity. Spun yarns (Nos. 5, 6, 8) tend to release dust more slowly, an increase in duration from 30 to 300 sec. producing a 0.015 lb/ft^2 increase in capacity. Napped fabric (No. 9) shows the largest effect of increased shaking duration, 60-300 sec. producing $\overline{W}$ of 0.03 lb/ft^2. At an inlet flux of 1.7×10^{-3} lbs. dust/ft^2-min, these $\Delta\overline{W}$ values correspond to an increase in operating time between cleaning cycles of (Col. 4):

Fabric	No.	$\overline{W}_{30-300}$	Time of $\overline{W}_{30-300}$	Time to $\overline{W}_{t_{180}}$
Filament	1	0.005	2.9 min	26.5 min
Fil./Spun	5	0.015	8.8	44.0
Spun	6	0.016	9.4	45.0
Spun	8	0.014	8.2	59.0
Napped	9	0.03 (60-300 sec)	17.6	121.0

- Increasing cleaning duration from 30 sec. to 5 min. on filament fabric (No. 1) produces about 3 min. longer filtering time in a 26 min. cycle, or no net improvement. The filtering cycle is lengthened less than the amount required for the additional shaking.
- Increasing cleaning duration from 30 sec. to 5 min. on spun yarn fabrics (Nos. 5, 6, 8) produced about a 9 min. longer filtering cycle in a 45 to 60 min. cycle, or about 15 to 20 percent longer filtering cycle.
- Increasing cleaning duration from 1 min. to 5 min. on the napped fabric (No. 9) produced an 18 min. longer filtering cycle (15 percent increase in filter operating time between cleanings).

Dust characteristics will modify the quantitative observations above, but general trends shown are expected to be the same. For most dusts, increased cleaning duration beyond 30 sec. or 1 min. will probably not produce a net increase in filtering time greater than about 10 to 15 percent. The effect of increased cleaning time on reduction of fabric life is assumed to be linear. A five to ten times increase in cleaning duration (30 or 60 sec to 5 min) will probably reduce fabric life by a similar factor. Assume fabric life is of order 5×10^6 shaking cycles. Cleaning for 30 sec uses 170 cycles (5.6 cps). Let the filtering cycle be 45 min long followed by a 30 sec shake and 30 sec dwell for settling. Then every 46 min will require 170 shake cycles. Fabric life is estimated as $(5 \times 10^6 \times 46/170 \times 60)$ 2.8 years. If the cleaning duration is extended to 3 min (6 x, or 10^3 shaking cycles per cleaning cycle) the filtering cycle may be extended about 10 percent or 49.5 min. The complete cycle will consist of 49.5 min of filtering followed by 3 min shake and 30 sec dwell for settling, or 53 min. Fabric life may be estimated as $(5 \times 10^6 \times 53/10^3 \times 60)$ 0.55 years, or about 1/6th of the life obtained with shorter cleaning duration. Pulse jet collectors cleaned on-line every 30 sec (120 cycles/hr) would be expected to have an average fabric life of order 5.2 years, under the above assumptions. None of these estimates include effects of factors tending to reduce fabric life during filtration, such as scour and abrasion, temperature, condensation, acid or alkaline deterioration and other gas or particle factors.

Durham[14] observed anomalies in S-$\overline{W}$ curves for different shaking times for tests at different parts of the year. For example, in

Figure 6.35a, Fabric No. 1, it was found that data produced for 3 min. shaking did not agree with data for 30 sec and 5 min shaking obtained several months later. Similar anomalies are evident in data for fabric Nos. 6 (cotton) and 8 (Microtain^R). The shift in the S-$\overline{W}$ performance curves are positive (Nos. 1 and 8, to the right, higher $\overline{W}_t$ per units) and negative (No. 6, smaller $\overline{W}_t/S_t$).

6.2.2.5 Effects of Humidity - Durham and Harrington[16] have shown that the apparent anomalies in performance just described probably result from changes in ambient moisture content (Relative Humidity, R. H.). Relative humidity was controlled between 20 and 60 percent R.H. in the same experimental configuration described above.[14]

Resuspended fly ash was used as a test dust, and the 11 fabrics enumerated in Table 6.6 were tested. Increasing relative humidity generally reduced overall resistance of the filter. Three responses were calculated to identify the system resistance: effective drag, S_e, specific resistance coefficient, K_2', and terminal drag, S_t. (Figures 6.5 and 6.35 show typical values of these three parameters.)

Table 6.7 presents results of the effects of relative humidity on K_2', S_e and S_t. The specific dust-fabric filter resistance coefficient was significantly reduced by increasing the relative humidity. Effective drag exhibited no particular trend. In most instances, terminal drag was reduced with increasing relative humidity. The specific resistance coefficient determines the rate of increase in resistance during the linear portion of the filtering cycle to achieve any given value of terminal drag. Thus, reduction in K_2' offers potential for increased bag life and reduced maintenance (i.e., less frequent shaking required). Figure 6.37 illustrates the effect of R.H. ($20 \leq$ R.H. ≤ 60 percent) on K_2' for three acrylic fabrics and for polypropylene. An increase in R.H. from 20 percent to 60 percent reduced K_2' by a factor of order 2.

TABLE 6.6
FABRIC CHARACTERISTICS
(From Durham and Harrington, Reference 16)

Fiber Composition*	Type Yarn** Warp	Type Yarn** Fill	Yarn Denier Warp	Yarn Denier Fill	Thread Count, threads/in. Warp	Thread Count, threads/in. Fill	Weave Pattern	Fabric Thickness, Mils	Fabric Weight, oz/yd^2
Nylon	CF	CF	210	210	74	68	2 x 2 Twill	9.4	4.1
Creslan[R]	CF	CF	200	200	80	76	3 x 1 Twill	10.8	4.0
Dacron[R]	CF	CF	250	250	76	66	3 x 1 Twill	9.1	3.9
Polypropylene	CF	CF	210	210	81	69	3 x 1 Twill	12.4	4.6
Crylon[R]	CF	CF	200	200	77	63	3 x 1 Twill	10.2	5.1
Dralon[R]	CF	CF	200	200	76	71	3 x 1 Twill	9.8	4.4
Orlon[R]	CF	CF	200	200	76	62	3 x 1 Twill	8.7	4.3
Cotton sateen	S	S			95	58	Satin	24.1	10
Glass filament	CF	CF			54	56	3 x 1 Twill	9.6	9
Glass Combination	CF	S			48	22	2 x 2 Twill	24.6	16.5
Glass texturized	CF	T			46	24	3 x 1 Twill	16.5	14

* Creslan[R] acrylic, Amer. Cyanamid; Dacron[R] polyester, Du Pont; Crylon[R] acrylic, Crylon S.A.(Fr); Dralon[R], Farberfabriken Bayer (W.Ger.); Orlon[R] acrylic, DuPont.

** CF = continuous filament; S = staple; T = texturized.

TABLE 6.7
EFFECT OF RELATIVE HUMIDITY ON SPECIFIC RESISTANCE COEFFICIENT, EFFECTIVE DRAG, AND TERMINAL DRAG
(From Durham and Harrington, Reference 16

Bag Description*	Specific dust-fabric filter resistance in. H_2O/ft-min / lb/ft^2 — Relative humidity, %					Effective drag, in. H_2O/ft-min — Relative humidity,%					Terminal drag,** in. H_2O/ft-min — Relative humidity, %				
	20	30	40	50	60	20	30	40	50	60	20	30	40	50	60
Nylon	11.2	7.6	6.4	3.9	2.6	0.24	0.23	0.32	0.32	0.30	0.60	0.48	0.55	0.45	0.38
Creslan[R]	9.9	9.6	7.8	5.6	4.0	0.12	0.14	0.23	0.30	0.29	0.45	0.48	0.50	0.48	0.40
Dacron[R]	8.4	7.7	7.2	4.2	3.0	0.69	0.61	0.63	0.60	0.62	0.98	0.88	0.88	0.73	0.75
Polypropylene	9.6	7.8	7.8	5.0	3.6	1.05	0.98	0.99	0.94	0.95	1.37	1.25	1.25	1.10	1.08
Crylon[R]	6.4	3.8	4.2	4.2	2.3	0.12	0.12	0.18	0.21	0.32	0.34	0.33	0.36	0.36	0.30
Dralon[R]	9.3	5.2	4.2	4.1	2.3	0.45	0.40	0.38	0.37	0.32	0.76	0.68	0.56	0.50	0.41
Orlon[R]	6.8	6.5	4.3	3.8	3.4	0.78	0.82	0.74	0.59	0.61	1.00	1.03	0.90	0.76	0.73
Cotton	8.0	7.5	7.3	5.8	5.4	0.46	0.48	0.45	0.45	0.49	0.74	0.73	0.66	0.53	0.74
Filament glass	5.7	5.6	6.5	6.2	5.3	0.53	0.55	0.48	0.63	0.68	0.73	0.75	0.73	0.85	0.88
Combination glass	5.1	4.3	4.4	3.7	3.2	0.25	0.24	0.20	0.18	0.20	0.43	0.38	0.35	0.32	0.30
Texturized glass	7.7	7.0	6.4	5.5	4.3	0.49	0.45	0.40	0.41	0.42	0.75	0.70	0.58	0.58	0.58

* See Table 6.6 for generic fiber description and manufacturer.

** Mass flux 1.7×10^{-3} lbs/ft^2-min, for 20 min. filtering cycle, $\overline{W}_t$ = 0.034 lbs/ft^2

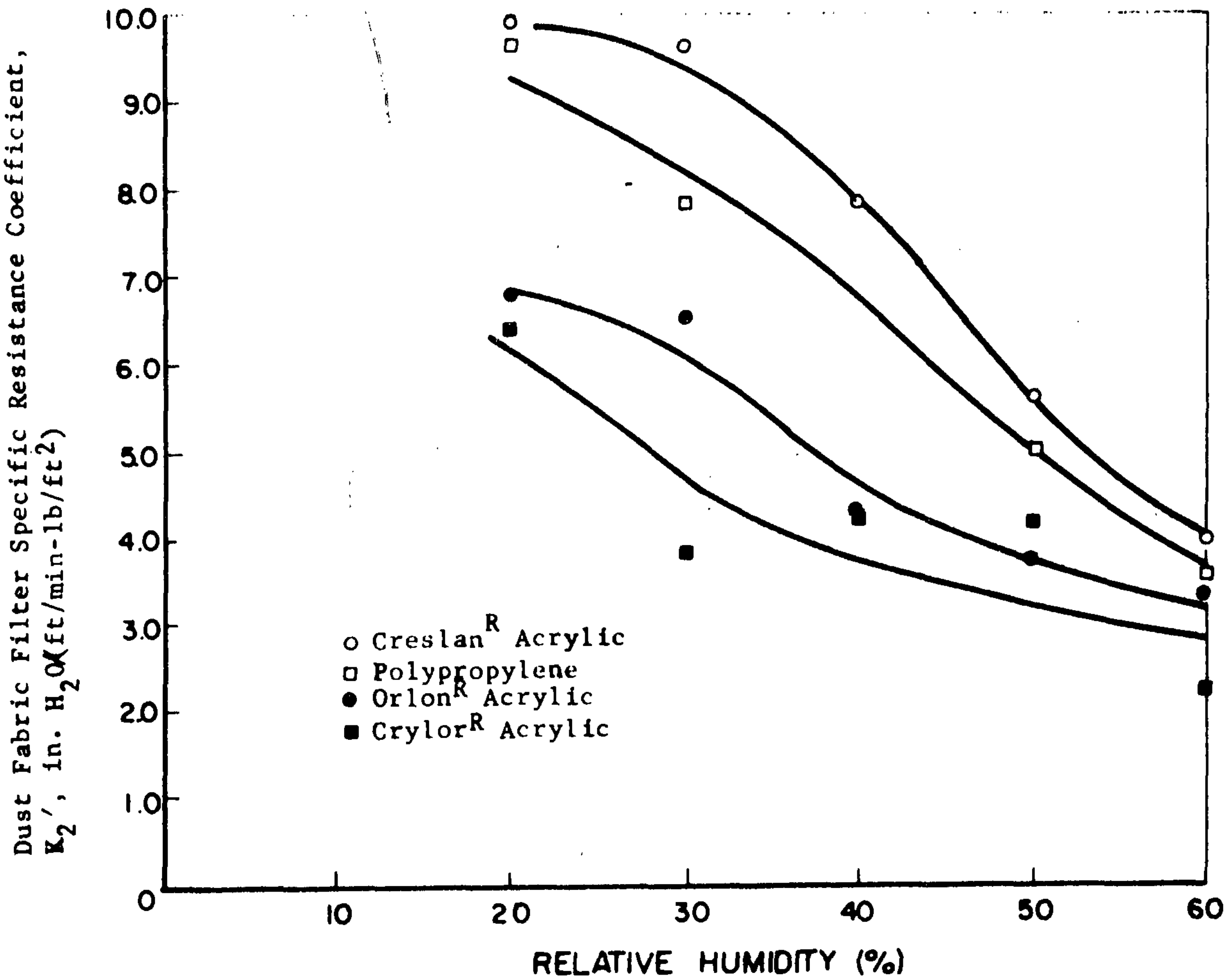


Figure 6.37. Effect of Relative Humidity on Specific Dust-Fabric Filter Resistance Coefficient (From Durham and Harrington, Ref. 16).

The effects of R.H. on dust penetration were also measured, as presented in Table 6.8.

> "All fabrics except cotton sateen exhibited a decrease in efficiency with decreasing relative humidity. The most pronounced changes occurred with the continuous filament fabrics (c.f. Figure 2.69a). Creslan[R], Crylor[R], filament glass, and Nylon fabrics displayed the greatest changes, with efficiencies decreasing from over 99.5 percent at 60 percent relative humidity to about 95 percent at 20 percent relative humidity. (Note: A 9-fold change in penetration.) Cotton was the most efficient fabric evaluated. Its efficiency was 99.99 percent at all humidities. The many fibrous projections on the staple cotton yarn, not present on the smooth continuous filament yarns, are

TABLE 6.8
EFFECT OF RELATIVE HUMIDITY ON OUTLET DUST CONCENTRATION AND EFFICIENCY
(From Durham and Harrington, Reference 16)

Bag Description*	Outlet dust concentration, grains/1000 ft^3					Efficiency, weight %				
	Relative humidity, %					Relative humidity, %				
	20	30	40	50	60	20	30	40	50	60
Nylon	130	148	61	4.4	0.02	95.62	95.02	98.02	99.86	99.99+
Creslan[R]	168	177	100	37	3.1	94.47	94.02	96.35	98.78	99.90
Dacron[R]	34	32	13.1	1.9	0.7	98.86	98.95	99.12	99.94	99.98
Polypropylene	36	32	35	7.0	2.7	98.80	98.96	98.85	99.78	99.91
Crylor[R]	148	89	56	13	1.3	95.12	97.29	98.14	99.56	99.96
Dralon[R]	26	24	17	0.8	0.6	99.11	99.23	99.43	99.98	99.99+
Orlon[R]	12	7.5	6.9	3.9	0.8	99.59	99.75	99.78	99.87	99.97
Cotton	0.04	0.2	0	0	0	99.99+	99.99+	99.99+	99.99+	99.99+
Filament glass	148.1	135.9	106.4	25.4	9.1	95.00	95.31	96.55	99.18	99.71
Combination glass	10.4	10.3	2.2	0.1	0.1	99.65	99.66	99.92	99.99+	99.99+
Texturized glass	63.8	40.2	19.9	6.0	1.1	97.84	98.66	99.31	99.80	99.96

Note: Inlet dust concentration C_i = 3.0 gr/ft^3, fly ash, 4.0 μm median diameter.

* See Table 6.6 for generic fiber description and manufacturer.

(From Durham and Harrington, Ref. 16).

probably the major factor in producing uniformly high efficiency. Figure 6.38 illustrates the effects of relative humidity on the outlet dust concentrations for Crylor^R, Creslan^R, Orlon^R, and polypropylene fabrics.

Relative humidity also significantly affects the outlet particle concentration at various times during the filter cycle. Figure 6.39 indicates an initial outlet particle concentration of about 1.5×10^6 particles per cubic foot at the begining of a 20-minute filter cycle. As the filter cycle proceeds, the particle concentration drops off much faster as the relative humidity increases. Curves similar to those in Figure 6.39 were obtained with all fabrics except cotton sateen. Relative humidity affects the rate at which the interstitial openings of the filter medium are bridged, the structure of the deposit, and the filtration characteristics of the system. The net effect of increasing the relative humidity of the carrier gas was to improve the efficiency of the system."[16]

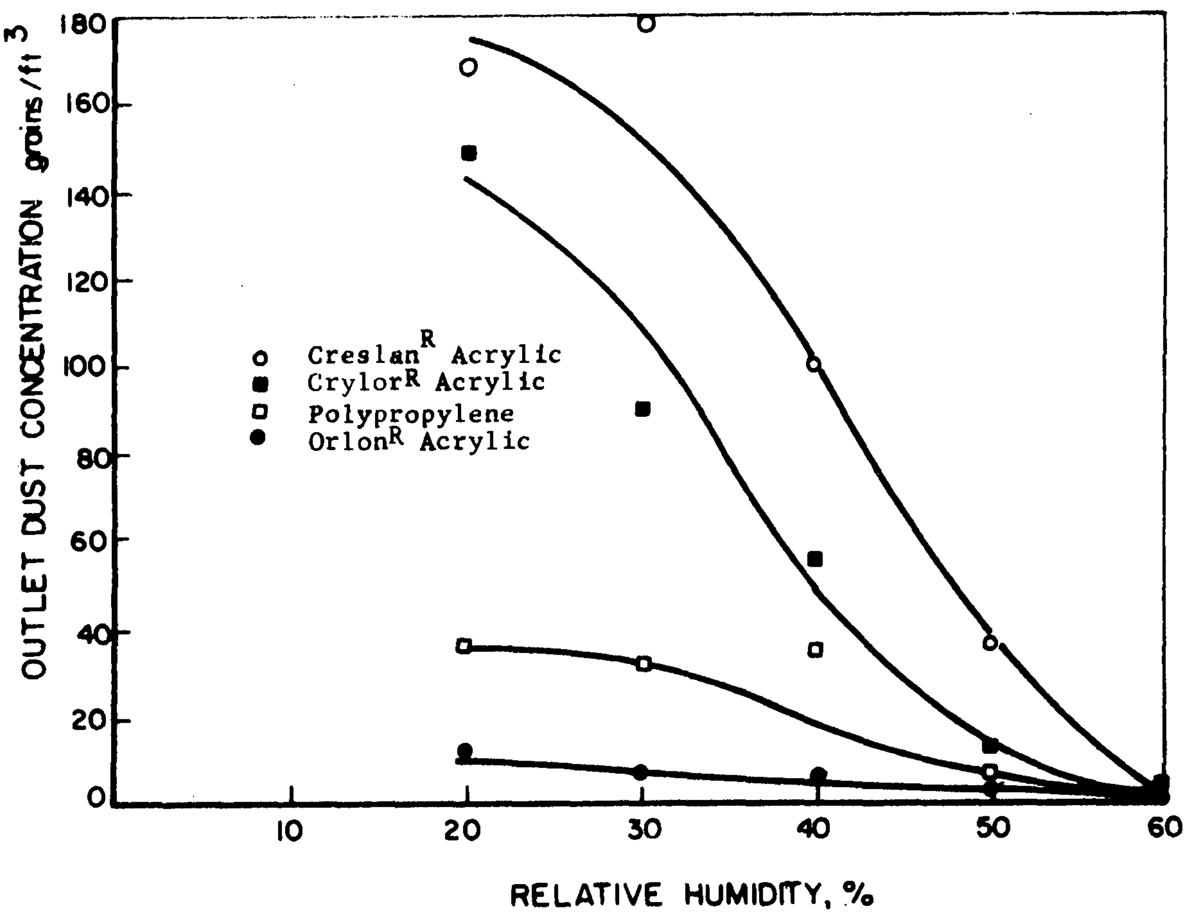


Figure 6.38. Effect of Relative Humidity on Outlet Dust Concentration.
(From Durham and Harrington, Ref. 16).

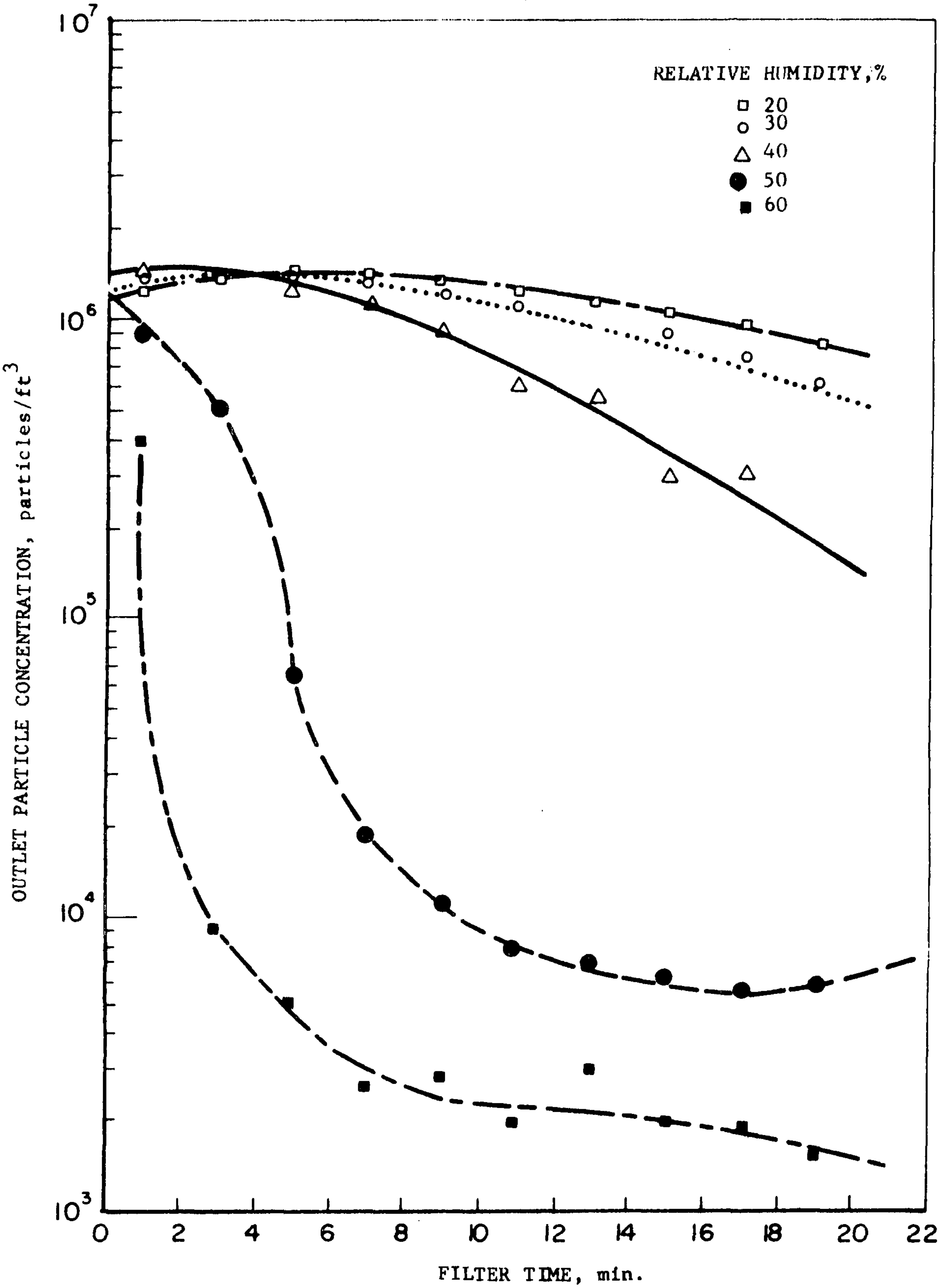


Figure 6.39. Relationship of Particle Concentration and Filter Time at Various Relative Humidities. (From Ref. 16)

These results are consistent with observations of increased particle adhesion force at higher R.H. (c.f. Figures 2.17 and 2.19, and Equation 2.15). The increased force should tend to produce a more open, porous, and filamentous deposit having lower K_2' and better retention (less particle migration and bleed). Humidity may also affect the size of the particles collected on the filter.

It should be noted that the above effects were obtained only with fly ash, while humidity had no apparent effect on resistance or collection efficiency when using cement dust, pulverized limestone, or amorphous silica under identical test conditions. Clearly, further research is needed to determine what aspects of fabric and particles affect, through humidity, the resistance and collection efficiency of a filter system.

6.2.2.6 Effects of Velocity - Several aspects of filter performance have been observed to depend upon total gas flow rate or average filtering velocity. These include:

- Increase in specific resistance with velocity;
- Amount of dust depositing directly in the storage hopper before reaching the filter (hopper fallout);
- Particle size stratification of dust passing to the fabric because of fallout, and within the bag, as velocity (flow) decreases throughout the length of the bag;
- Deposit reorientation or consolidation if velocity increases during filtering cycle (deposit collapse);
- Particle penetration through thin or open areas on the fabric surface (deposit puncture).

Hopper Fallout - Hopper fallout has been observed during single bag and single compartment studies. A fallout factor, γ, has been defined[3] as:

$$\gamma = \frac{\text{amount of dust deposited in hopper, } \bar{W} - W}{\text{amount of dust entering collector inlet, } \bar{W}} \text{, or}$$

$$\gamma = 1 - \frac{W}{\bar{W}} \qquad (6.19)$$

That is, γ is the fraction of the total dust entering the inlet of a fabric filter deposited directly in the hoppers, without being filtered by the fabric. Hopper fallout is reported in the fabric study of Durham[14] above, (but without γ). Values of γ depend upon dust particle size and shape, as related to hopper, inlet, baffle, flow, and collector configuration parameters. Typical values for γ from fabric filter compartment studies (discussed below, see Figure 6.50) are 0.1 - 0.25 over a flow range of four for either top or bottom bag inlet[3].

Particle Size Stratification. - Velocity also affects dust resistance by altering the particle size distribution in the deposit. The bulk flow of gas and dust is parallel to the filter surface and decreases in velocity from a maximum at the entrance of the bag to zero velocity at the other end. Filter arrangement also produces changes in particle size distribution by inertial separation and settling of larger particles as fallout. During bottom feed operation, a greater portion of larger particles enter the bag as the gas throughput is increased (i.e., dust fallout decreases). Thus, the average particle size of the fallout varies with filtration rate, as does the average particle size of the filter deposit. Since the resistance coefficient is sensitive to the porosity of the cake and the surface-to-volume ratio of the particles, as given by the Kozeny equation, size stratification will contribute to changes in the resistance of the dust cake.

The effect of velocity on particle size statification along the length of a single bag is shown in Figures 6.40 and 6.41. In these tests, made on a single filter bag, samples of the dust cake were taken from several different vertical positions along the bag. Figure 6.40 indicates the effect of velocity on median particle diameter deposited at four different elevations (of a 60 inch bag height). Just above the bottom inlet (2 in.), median particle size varies from 8 to 15 μm, as average filtration velocity is varied from 2.5 to 8.5 fpm (approximate upward velocity at bag inlet, 109 to 327 fpm). Just below the top, most of the dusty gas has been filtered, upward velocities are low, and median particle size varies from 5 to 13 μm as average filtering velocity varied from 2.5 to 8.5 fpm. The deposit at the top is composed of finer particles (higher K_2'). Figure 6.41 shows the effect of filtering velocity on particle size distribution at the center of the bag. Higher gas flow supports

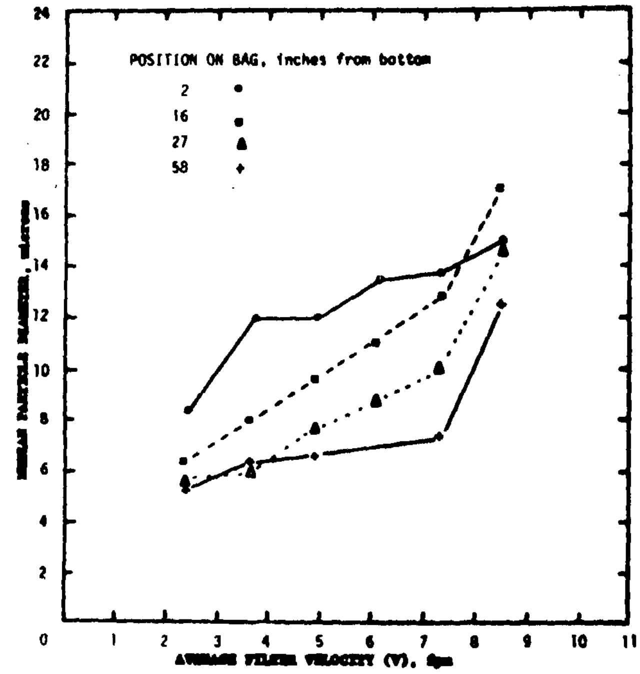


Figure 6.40. Effect of Filtration Rate on Particle Size in Deposit at four bag altitudes (Single bag filter unit, bottom feed) (From Borgwardt and Durham, Ref. 3).

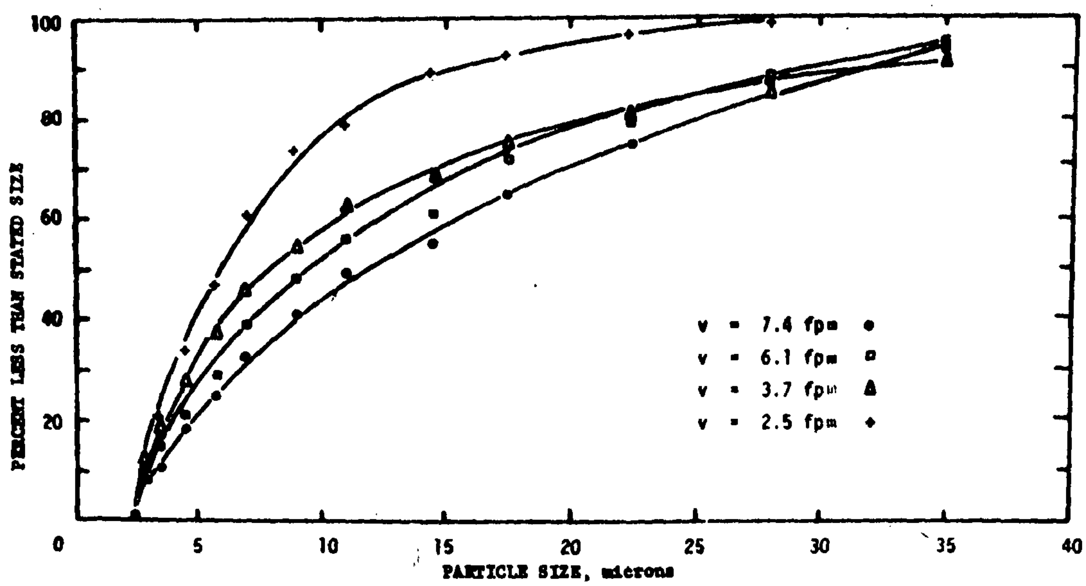


Figure 6.41. Effect of Filtration Rate on Particle Size Distribution in deposit at Center of Bag (Single Bag Test Unit, Bottom Feed) (From Borgwardt and Durham, Ref. 3).

larger particles, the median particle size increasing from about 6 μm at 2.5 fpm to about 14 μm at 7.4 fpm. These figures show that elutriation of the particles has occurred inside the bags and that the degree of elutriation depends upon rate of gas flow. Changes in particle size distribution between different positions on the filter surface result in the formation of non-uniform filter cakes. These phenomena indicate that the specific resistance coefficient will depend upon filtration rate, through effects on particle size.

Deposit Consolidation. - Deposit consolidation (collapse) occurs when forces produced on and in the granular matrix exceed frictional and adhesive forces supporting the particle aggregate structures. Forces tending to produce consolidation arise from static pressure differentials across the deposit (1 in. H_2O = 0.036 psi = 5.2 psf), viscous drag of the fluid on the particles, kinetic energy imparted by depositing particles, flow pulsations, or physical contact with the filter. If these forces are greater than interfacial particle-particle-fiber forces, the structure can shift to a more compact, stable orientation. Permeability is reduced, and pressure drop rises[4].

Deposit consolidation and collapse has been observed experimentally on both bench-scale apparatus and in a pilot-scale 2-bag unit.[4] In experiments with fly ash on bench-scale equipment, cake collapse was produced by gradually increasing air flow through a dust cake supported on a flat circular filter 1.5 inches in diameter. Deformation of the matrix occurs in steps over appreciable intervals of filter velocity. Deposit thicknesses were measured with a microscope having a graduated micrometer fine adjustment. Irreversible compressions up to 50 percent of the original deposit thickness were observed.[4] (Actual deposit thickness was not reported.)

In an experiment with a pilot-scale 2-bag unit, filters were loaded to an average dust mass of 950 grains/ft^2 at an average filter velocity of 3.4 fpm as shown in Figure 6.42. The resultant pressure differential was 3.4 in. H_2O (effective permeability 950 (grains/ft^2)/

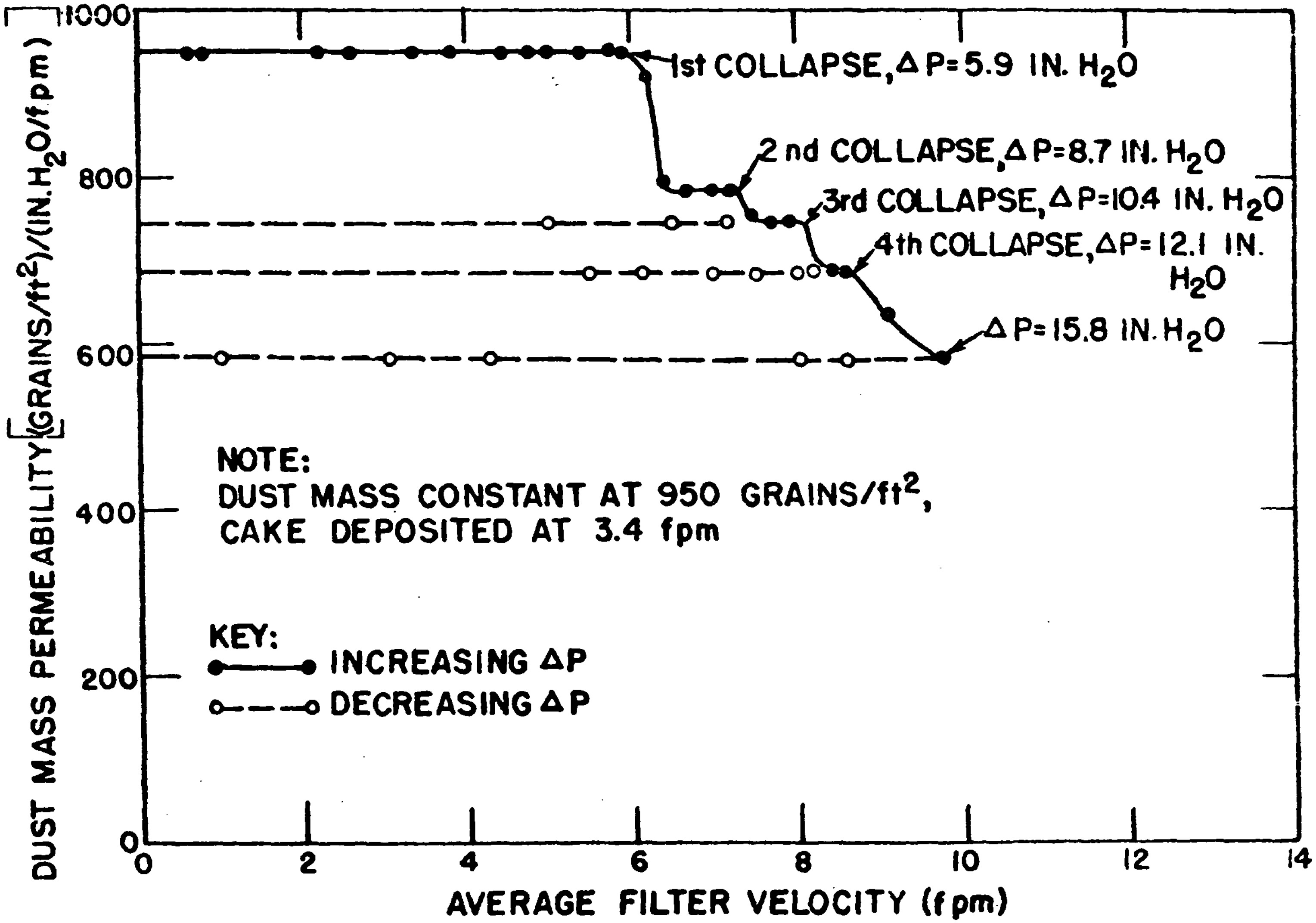


Figure 6.42. Successive Deposit Collapse Observed On Pilot-Scale 2 Bag Filter Unit (From Stephen et al., Ref 4)

(in. H_2O/fpm)). Filter velocity was lowered to about 0.75 fpm and then raised to 5.9 fpm during which time permeability remained constant at 950 ($K_2' = 7.2$). As filter velocity was gradually increased above 5.9 fpm, however, permeability decreased rapidly to 785 ($K_2' = 9.9$) at V = 6.5 fpm. From 6.5 to 7.2 fpm, the permeability of 785 was maintained. Between 7.2 and 7.6 fpm a second collapse occurred, further reducing permeability to 745 ($K_2' = 10.1$), a value which was maintained up to 8.1 fpm. At this point, filter velocity was reduced to 5 fpm to substantiate that a new matrix structure of lower permeability had been created. Two more distinct collapses were observed as filter velocity was ultimately raised to 9.8 fpm, and after each of these, filter velocity was lowered and then raised, to demonstrate that a permanent consolidated structure had been produced in each instance. After the final collapse, permeability had been reduced to 585 ($K_2' = 11.9$), or to about 60 percent of the permeability of the uncollapsed deposit. Filter drag was increased from 1.0 in. H_2O/fpm for the uncollapsed cake to 1.62 for the final collapsed matrix, or by more than 60 percent. The same effect has been observed in single compartment and multicompartment filters, as discussed below. These effects also depend upon R.H. in the gas, and fabric parameters.

Particle Penetration - Woven fabrics are susceptible to pinhole flow leakage, a common phenomena with many types of porous media. Deposit puncture, which occurs when small pinholes are opened through the matrix, should be more prevalent on filament yarns or worn staple fabrics. Local resistance is lowered and high flow occurs through the opening. Local disintegration of the filter deposit is a more severe manifestation of the application of external forces that cause deposit collapse. The puncture may be self-repairing, since increased flow through the area brings more dust to the vicinity of the puncture. Thus, inertial deposition mechanisms are enhanced by the higher velocity. If the holes are too large, however, penetration will continue.

Deposit puncture has been confirmed experimentally as shown in Figure 6.43. On a bench-scale flat filter paper it could not be induced even at very high pressure differentials. However, when a cotton sateen filter fabric was used as the support, puncture occurred as shown in Figure 6.43. It is seen that the unpunctured cake had a drag of 1.0

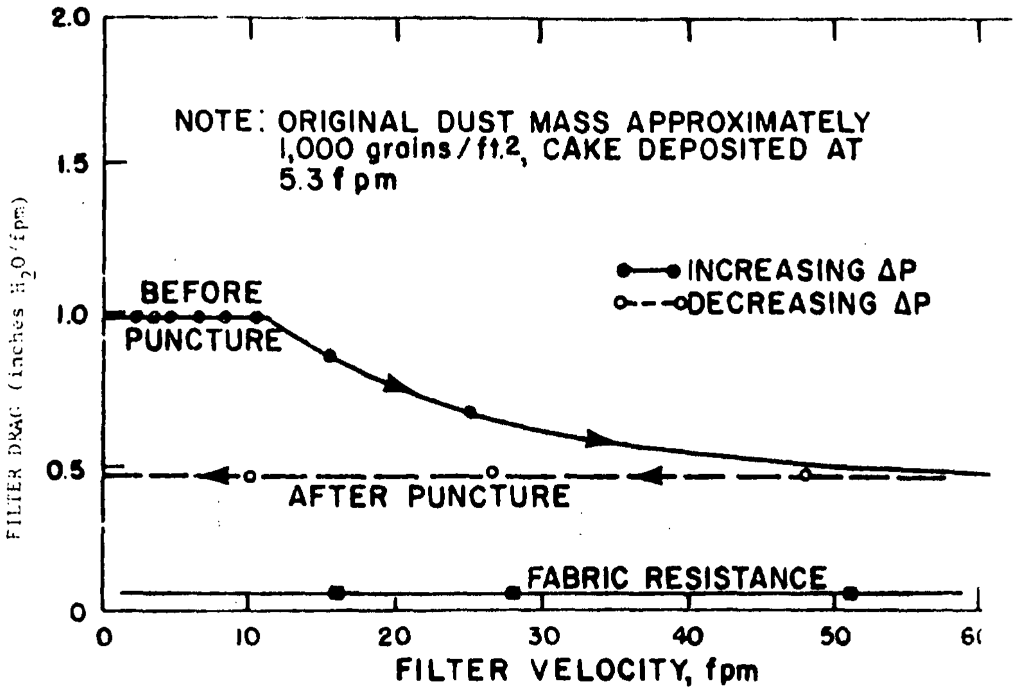


Figure 6.43. Deposit Puncture Observed on Bench-Scale Filter. (From Ref. 4).

in. H_2O/fpm. As filter velocity was raised above 10 fpm, drag began to decrease sharply and continued to decrease, approaching a limit of approximately 0.47. Reduction of filter velocity to 10 fpm verified the constant resistance of the punctured deposit. The pinhole punctures created were easily visible by microscopic examination of the fabric against a bright light.

An example of pinhole healing is described by Stephan, et. al.[4] The air velocity through the perforated area dropped from approximately 100 fpm to about 2.3 fpm during a few minutes of normal filtering.

6.2.3 Single Compartment Performance

The laboratory performance of single compartment intermittently cleaned fabric filters is effectively represented by single bag performance tests discussed above. Differences are associated with scaling and in distribution of flow to each of the several bags.

6.2.3.1 <u>Shake-Type Collector</u> - Billings, et. al.,[17] reported laboratory performance data for a small Wheelabrator Dustube[R] (2 #35A) cloth tube collector (500 ft^2 of fabric, nominal 10^3 cfm capacity). This equipment is representative of several commercial collectors.

The test unit consisted of two identical steel chambers, each containing 32-5" x 70" cloth tubes. In normal operation, one chamber filtered the dusty air while the second was cleaned by mechanical shaking of the cloth tubes. Operational time between cleaning cycles varied with dust loading and desired pressure drop characteristics. Tubes were usually shaken when they attained a pressure drop of 2 to 4 in. H_2O.

As the number of compartments increases, different sections may be shaken sequentially, but the proportion of bags not in operation decreases so that large multi-chambered units operate at nearly constant pressure drop.

The objectives of the test program were as follows:

1. To evaluate the resistance-efficiency characteristics with a variety of aerosols at different dust loadings and filtration rates.
2. To compare laboratory results with those obtained in the field, since only field results indicate service life and the effect of maintenance procedures on filter performance.
3. To investigate the feasibility of this type of unit for removal of low concentrations (e.g. toxic materials such as Be, radioactive dusts, etc.) from air and gas streams by means of augmentation with filter aids.

Efficiency and pressure drop tests were conducted in three operating modes: (a) performance of woven cotton medium with light dust loadings and no bag shaking (i.e., basic cloth performance), (b) performance of asbestos-flocked bags with light loadings and no shaking, and (c) performance with higher dust loadings and frequent, periodic shaking.

<u>Light Dust Loadings</u>.- Tests with dust loadings in the range 0.04 to 0.1 gr/1000 cu. ft. (atmospheric dust) illustrated initial fil-

ter performance and provided basic information on cloth characteristics.*
Figure 6.44 illustrates the efficiency and pressure drop increase as new cotton bags slowly acquired a deposit of atmospheric dust. These results were obtained during a period of 484 hours of operation on atmospheric dust, but are presumed to illustrate what takes place during a few minutes when higher dust loadings are being filtered. Both efficiency and

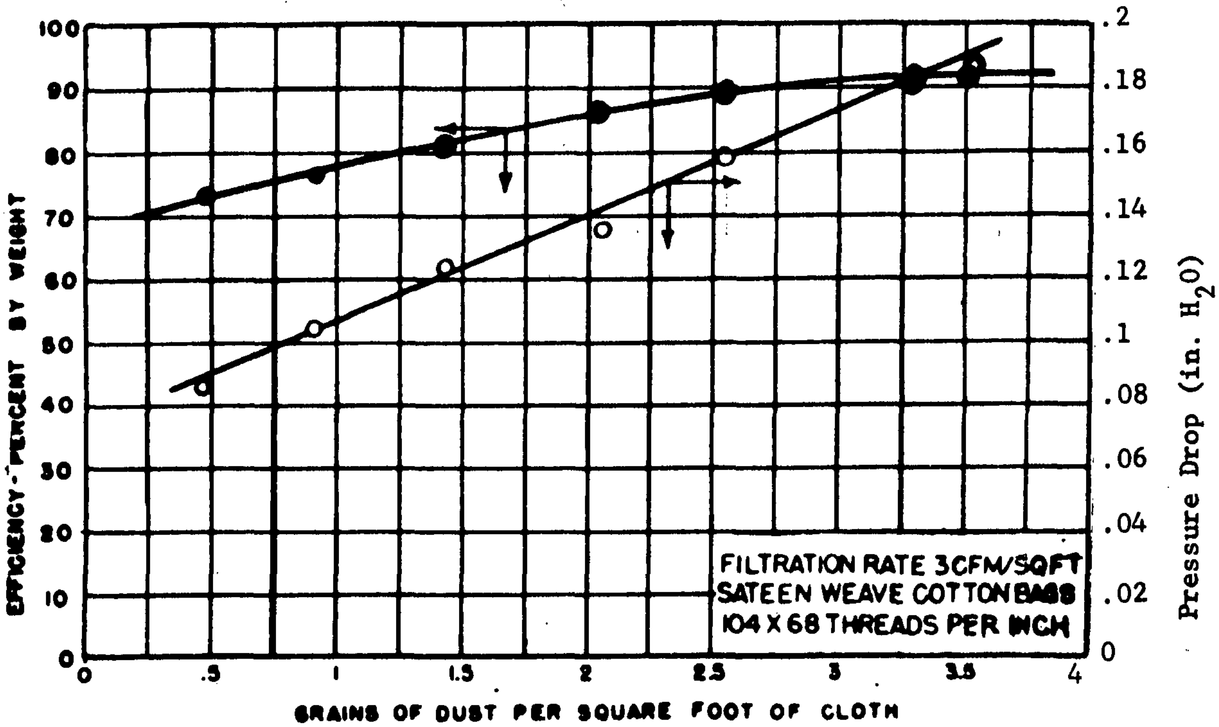


Figure 6.44. Efficiency and Pressure Drop; New Cotton Bags With Atmospheric Dust. (From Billings, et. al, Ref. 17).

pressure drop rise as a deposit forms but the rate of increase falls off after only a few grains of dust have been deposited. (From observation of industrial operations it is known that this increase would continue for several weeks with the very low dust loadings found in ambient air.) Over the period of this experiment penetration decreased 3 fold (from 27 percent to 9 percent) while pressure drop doubled (from 0.09 to 0.18 in.H_2O).

*Sateen-weave cotton bags with 104 x 68 threads per inch were used in all tests. New drag was 0.02 in.H_2O/fpm.

Filter Aid.- Figure 6.44 indicates that it takes many hours of operation (at dust loadings less than 0.1 gr/1000 cu.ft.) to increase filter efficiency to 90 percent. For recovery of atmospheric dust, and chemically toxic or radioactive dusts, a high initial efficiency is required. This can be achieved with deep beds (up to 5 feet) of fibers or granular solids, or with glass fiber paper filters which are discarded when their resistance becomes excessive. However, operations with a fabric filter on low dust concentrations can be simplified and mechanized by using a filter aid.

Asbestos floats (fibers too small for other use) were dispersed and filtered onto clean cloth of the same type as above. Table 6.9 indicates the effectiveness of this treatment in increasing the collection efficiency of oil smoke (Diol 55, mass median diameter 1.2 μm). Efficiency was measured optically.

TABLE 6.9

EFFECTIVENESS OF FILTER AIDS FOR LOW PARTICULATE LOADINGS

Quantity of Asbestos on Filter Cloth gr./sq.ft.	Pressure Drop (at 3 cfm/sq.ft.) in H_2O	Smoke Efficiency per cent
0	0.098	20.3
32	0.135	44.9
50	0.160	52.7
82	0.170	84.7
154	0.187	96.4
182	0.202	99.4
194	0.212	99.9

This shows a very substantial gain in efficiency) 20.3 to 99.9 percent) for a modest pressure drop increase (0.098 to 0.212 in. H_2O). Since bag filters are usually designed for resistances of 3 to 4 in. H_2O before shaking, flocked bags can be operated for many months on low loadings before shaking of the bags and renewal of the flock.

Table 6.10 indicates how efficiency decreased as the filter aid was removed. Some asbestos fibers were held permanently by the fabric; hence, after shaking, only a small smount of additional flock restored the high efficiency characteristics of the filter.

TABLE 6.10

REDUCTION IN EFFICIENCY OF ASBESTOS FLOCKED BAGS DURING SHAKING

Time of Bag Shaking Minutes	Pressure Drop (at 3 cfm/sq. ft) in. H_2O	Smoke Efficiency[a] percent
0[b]	0.212	99.9
0.5	0.208	97.7
1.0	0.204	97.0
2.0	0.196	96.0
3.0	0.182	94.0
5.0	0.180	93.3
7.0	0.176	90.0
10.0	-----	89.0
15.0	0.171	88.4
20.0	0.167	85.3
30.0	0.166	83.0
40.0	0.166	83.0

a. 1.2 micron droplets and optical penetrometer
b. Flocked with 194 grains of asbestos per square foot of cloth
(From Billings, et.al, Ref. 17).

Table 6.11 lists the efficiency of plain and asbestos flocked cotton bags for a variety of other aerosols and demonstrates the wide application of the technique.

The quantity of asbestos required to produce high filtration efficiency is dependent, to a large extent, on how uniformly the fibers are dispersed on the cloth. With the flocking apparatus used a resistance rise of only 0.1 to 0.2 in. H_2O was adequate.

Commercial systems for high efficiency performance with filter aids have been discussed in Chapter 3 (see Figure 3.31). Wheelabrator now uses a preliminary precoat*, prior to addition of asbestos or other

*U.S. Patent No. 3,041, 808.

TABLE 6.11

EFFICIENCY OF BAG COLLECTOR FOR VARIOUS AEROSOLS[a]

Aerosol	Loading gr./1000 ft^3.	Median Size by Count microns	Pressure Drop (at 3 cfm/sq.ft^2.) in. H_2O	Bag Treatment	Weight Efficiency per cent
Atmospheric dust	0.025	0.5	0.212	Asbestos flocked	99.0[b]
Uranium trioxide microspheres	0.0079	0.8	0.212	Asbestos flocked	99.9
Copper sulfate microspheres	0.86	0.9	0.236	Asbestos flocked	99.1
Aluminum chloride fume	166	0.6	0.244	Asbestos flocked	99.2
Ammonium bi-fluoride fume	15	0.5	0.244	Asbestos flocked	99.7
Ammonium bi-fluoride fume	15	0.5	0.11	None	74.0
Talc	0.1 - 6.0[c]	1.4	0.157 - 3.54	None	99.9+

a. Sateen weave cotton bags, filtration velocity 3 cfm/sq.ft.
b. 85 percent efficient by discoloration test, 68.2 percent efficient by particle count
c. Grains per cubic foot

(From Billings, et. al., Ref. 17).

fibrous filter aid, to promote release of the filter aid and any tarry atmospheric constituents. The specific resistance coefficient for filtration of atmospheric dust on filter aid is 16 (in. H_2O/fpm)/(lb/ft^2).

Periodic Shaking.- Figure 6.45 indicates variations in pressure drop during normal filtering and shaking operation. The cycle includes a 15 minute filtration period, 2.5 minutes for shaking, and a 2.5 minute off-period for dust settling. There are some variations in maximum and minimum pressures attained. For these thoroughly aged cotton

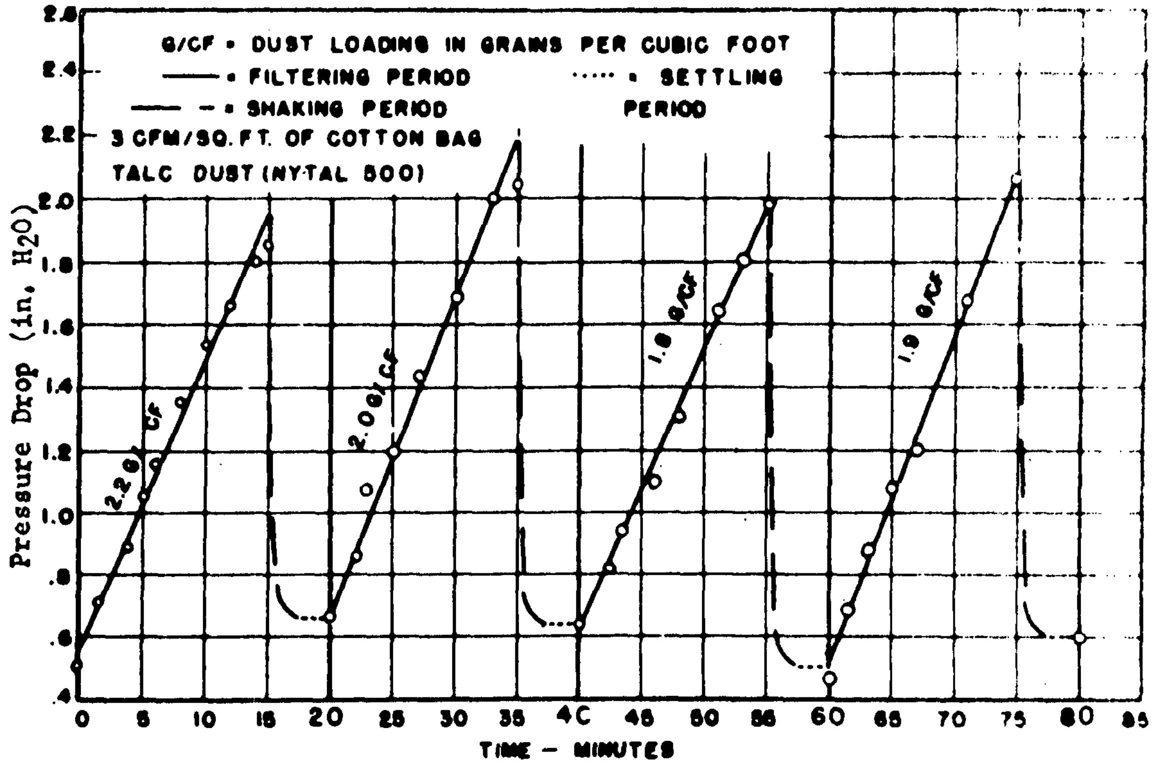


Figure 6.45. **Filter Pressure Drop During Filtering and Shaking.** (From Billings, et. al., Ref. 17).

bags, the maximum pressure drop attained after 15 minutes was about 2.0 in. H_2O. After shaking for 2.5 minutes, this reduced to approximately 0.5 to 0.7 in. H_2O(S_r = 0.2 in. H_2O/fpm).

Normal Dust Loading.- The effect of loading on pressure drop increase is shown in Figure 6.46 for loadings varying from 6 to 0.1 gr/cu.ft. of tasc. For a loading of 6 gr/cu.ft., 3.5 in. H_2O pressure drop was achieved in 19 minutes, while for a loading of 0.1 gr/cu.ft. the pressure drop was less than 2 in. H_2O after 180 minutes of operation. Residual and effective drags ($\Delta p/V$) are slightly different in each instance and may reflect changes in ambient RH on different test days. The specific resistance coefficient ($\Delta S/\Delta W$) for talc on cotton fabric averaged about 40 (in. H_2O/fpm)/(lb/ft^2).

Efficiency data on the same talc aerosol are given in Table 6.12. Pressure drop is related to the dust loading and efficiency is

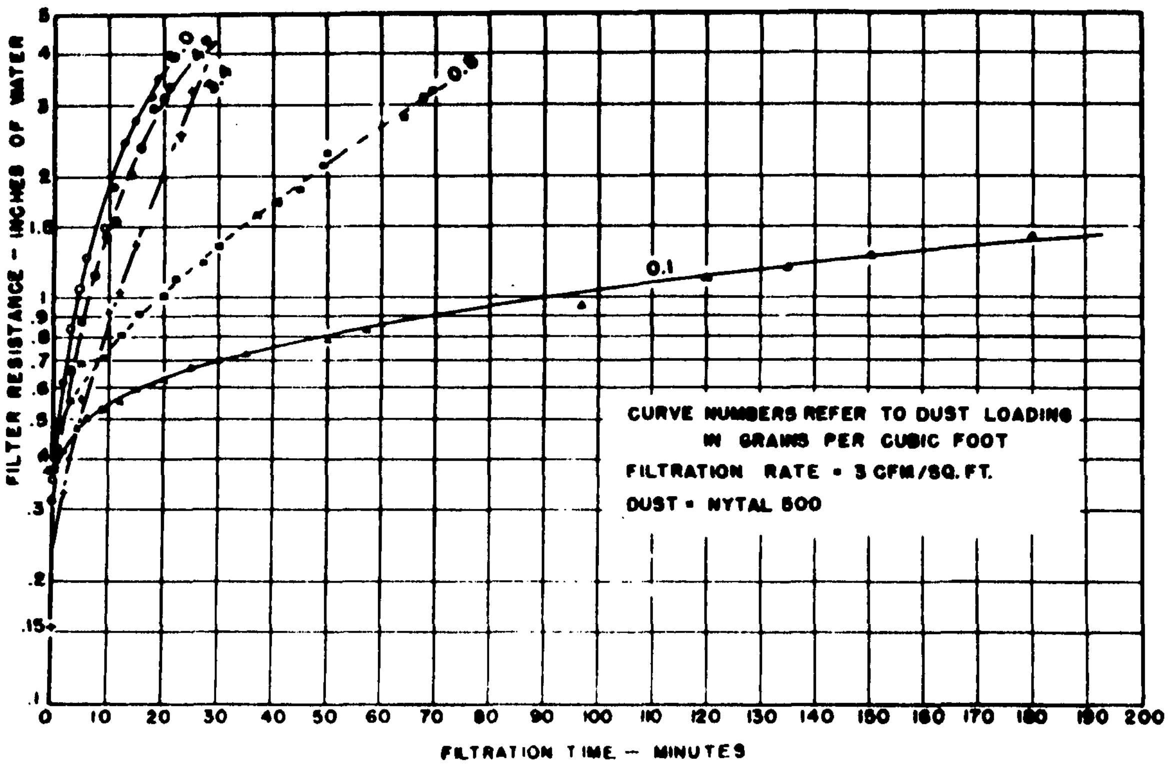


Figure 6.46. Effect of Dust Loading on Rate of Filter Pressure Drop Increase. (From Billings, et. al., Ref. 17).

greater than 99.9 percent in all cases. Pressure drop, when filtering 0.1 gr/ft^3 of talc at 3 cfm/ft^2, increased from 0.3 to 0.7 in. H_2O in 30 minutes. At 1.0 gr/ft^2, the pressure drop increased to 1.5 in H_2O at the end of 30 minutes.

The outlet dust loading increased somewhat with inlet loading, but collection efficiency remained above 99.9 percent. These data indicate that while there are some differences in specific cases, the general outlet dust concentrations from this type of collector using cotton sateen fabric will probably be less than 0.1 gr/1000 ft^3 (200 $\mu g/m^3$). Data presented earlier in Table 6.8 for cotton sateen and fly ash tend to confirm this general observation.[16] Field performance data (Table 6.23) have indicated similar outlet loadings. However, outlet loadings up to 180 gr/1000 ft^3 (0.4 gm/m^3) were observed with man-made filament yarns. Relative humidity also affects filter efficiency as discussed above.[16]

TABLE 6.12

EFFICIENCY AND PRESSURE DROP OF "DUSTUBE" FILTER AT VARIOUS LOADINGS OF "MICRONIZED" TALC[a]

Inlet Loading gr./cu.ft.	Pressure Drop in. H_2O	Outlet Loading gr./1000 ft^3.	Weight Penetration percent	Weight Efficiency percent
0.1	0.3 to 0.7	0.012	0.012	99.988
1.0	0.3 to 1.5	0.034	0.0034	99.9966
2.0	0.5 to 3.0	0.070	0.0035	99.9965

a. Mass median diameter 2.5 microns, geometric standard deviation 1.6.
b. Pressure drop increased from lower to higher value in 30 minutes.
c. Air to cloth ratio 3 cfm/$ft.^2$; sateen weave cotton bags.
(From Billings, et. al., Ref. 17).

6.2.3.2 Other Single Compartment Studies.- The data discussed below were obtained on multi-compartmented collectors operated in parallel mode, (no compartment off-line for cleaning) such that effects studied relate primarily to single compartment performance. The 3-compartment pilot fabric filter system used for most of these studies,[3,18] is shown in Figure 6.47. Each compartment contained 8 cotton sateen bags 60 in. long x 5 in. diameter.

Hopper Fallout.- Hopper fallout, γ, was defined in Equation 6.21 as the fraction of dust entering the inlet of a filter collector that does not reach the fabric. Figure 6.48 shows values of γ when filtering upward and downward, at several gas volume through-puts. Average air to cloth ratio ranged from 1.3 to 4.5 cfm/ft^2. In bottom entry, up-flow operation:

- more material was carried into the filter bags as velocity increased, and
- The fallout varied from 27% at 1.3 fpm to 8% at 4.5 fpm.

In top-entry, down-flow operation:

- the fraction falling into the hopper increased as velocity increased, and
- the fallout varied from 8% at 1.3 fpm to 30% at 4.5 fpm.

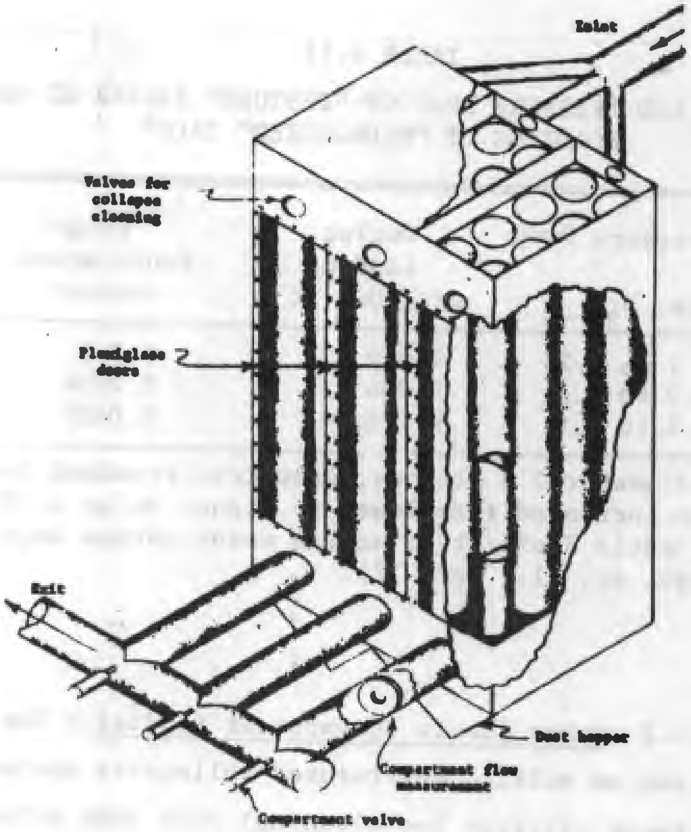


Figure 6.47. Three Compartment Baghouse (From Robinson, et. al., Ref. 18).

Lacking internal configuration dimensions, an analysis of flow velocities, particle sizes, settling velocities and stratification has not been made.

<u>Particle Size Stratification</u>.- A particle size distribution of fly-ash from hopper and filter deposits is shown in Figure 6.49 obtained from a 30,000 cfm prototype 4-compartment field unit operated on a pulverized coal-fired boiler.[18] Hopper fallout varied from 8 to 16%. Fallout sizes were considerably larger than those reaching the fabric.

<u>Deposit Consolidation</u>.- The effect of filtering velocity on the specific resistance coefficient has been reviewed above (see Figure 6.42). Further experimental data on the three compartment collector operated in parallel mode is shown in Figure 6.50. Dust was deposited at low velocity (point a), the dust feed stopped, and the air flow increased without further dust deposition. At points b and c the gas flow

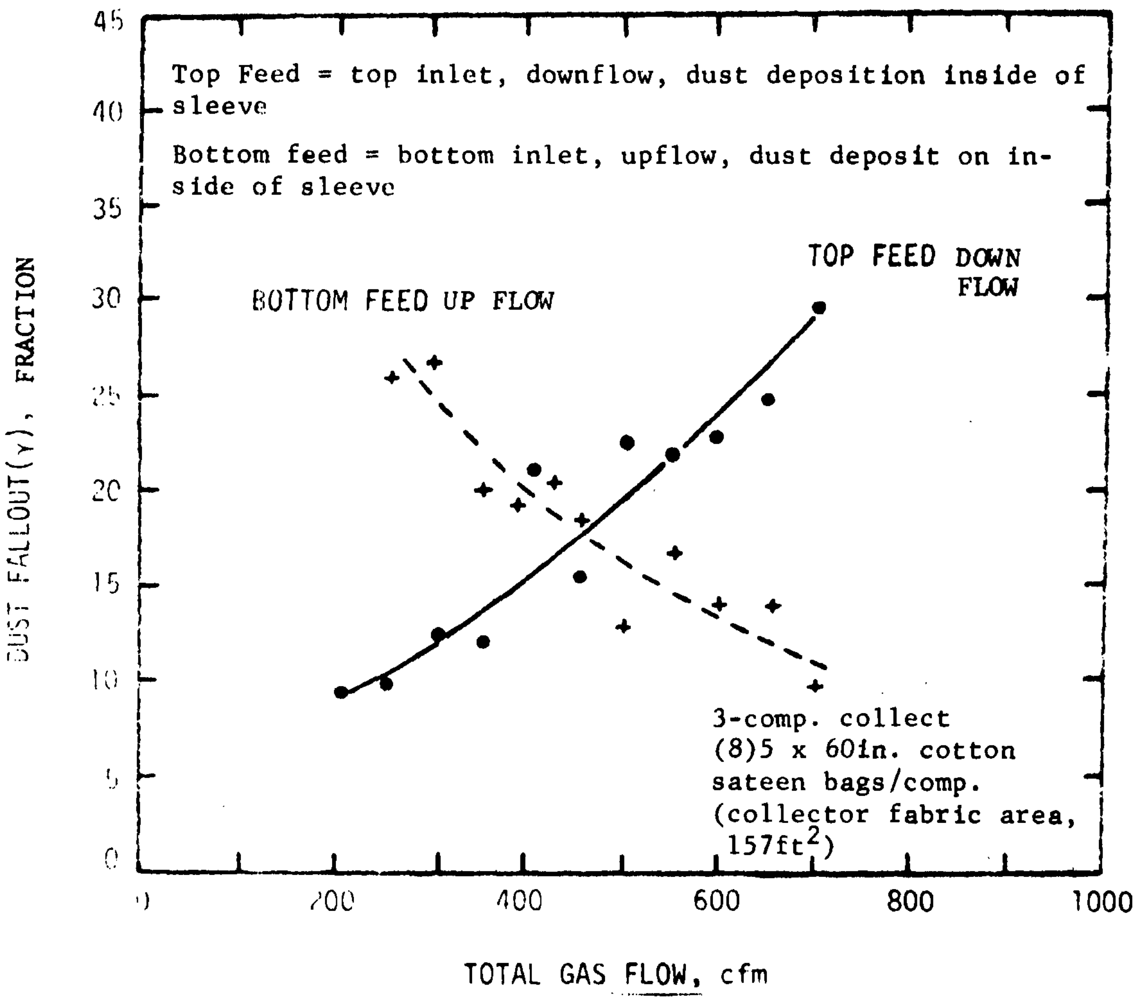


Figure 6.48. Fly Ash Fallout vs. Gas Throughput For Top and Bottom Feed (Parallel Flow, Constant Rate Filtration) (From Borgwardt and Durham, Ref. 3).

was decreased toward zero and raised again. The test shows that as flow is decreased the filter permeability remains constant, but when flow is increased the permeability decreases. The apparent compacting effect may be due to a displacement of particles from the deposit at higher gas flow and redeposition deeper in the filter matrix.

6.3 LABORATORY PERFORMANCE OF MULTICOMPARTMENT EQUIPMENT

6.3.1 Basic Pressure Drop Equations

In discussing the performance of single compartment filters, the parallel functioning of the separate filter elements was compared to

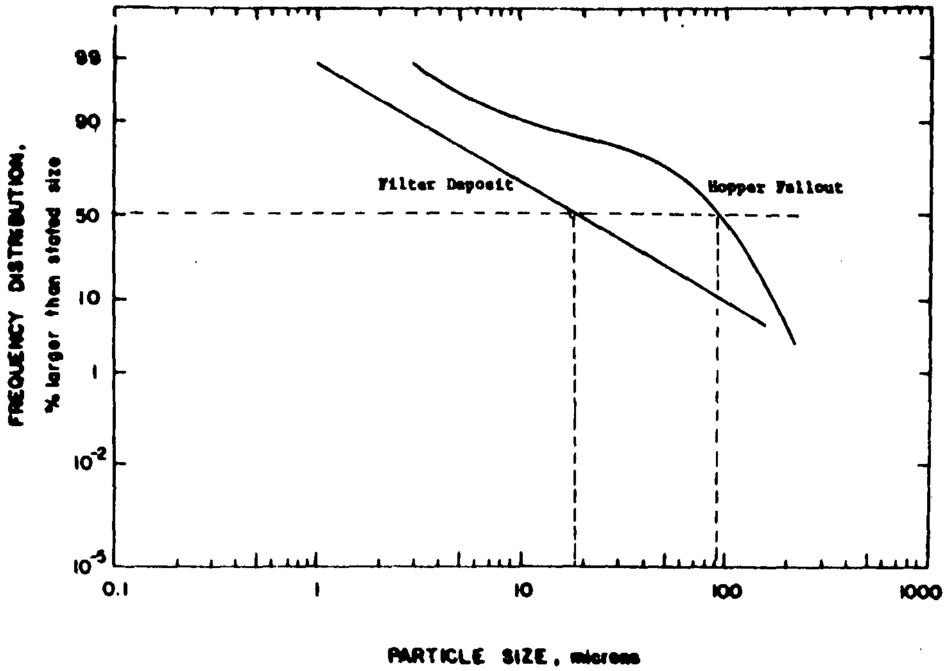


Figure 6.49. Particle Size Distribution of Fly Ash (from Robinson, et al, Ref. 18)

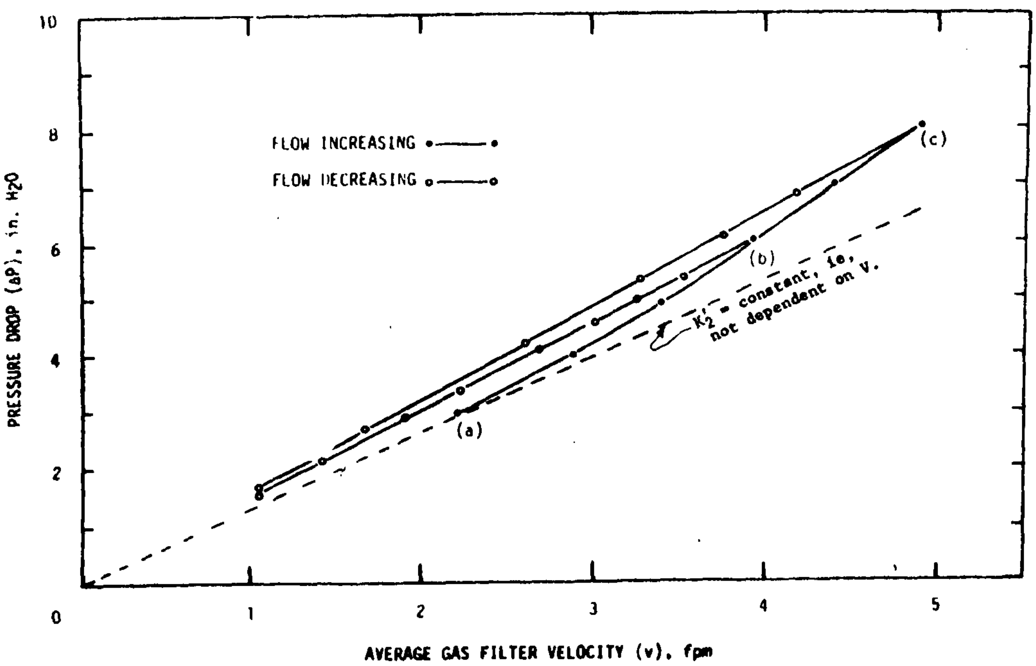


Figure 6.50. Dust Cake Compression (Pilot Baghouse, Parallel Flow Operation) (From Borgwardt and Durham, Ref. 3)

that of electrical resistances in parallel. The same analogy applies to two or more compartments operating side by side with the same differential pressure driving force. The equations are essentially unchanged if the compartments are all shut down for cleaning at the same time. If however, the compartments are taken off line one at a time for cleaning, they operate at different cycle phasings, and the equations must account for this.

When a just-cleaned compartment is returned to service, its drag will be less than that of the other compartments (Figure 6.51). Consequently the flow through the compartment will be greater (Figure 6.52). This means that the rate of deposition of dust in this compartment will be greater than in the other compartments, and the compartment drag will increase more rapidly. The compartment will rapidly approach a level of operation similar to the average of the other compartments.

The flow through the overall system, which also increases when the cleaned compartment is first returned to service, gradually decreases as the drag in the separate compartments increases. When the next compartment is removed from the system for cleaning, the overall flow will decrease again. Thus the overall flow follows a cyclic pattern.

The variation in overall flow depends on the characteristic curve of the fan driving the system and other system flow resistance characteristics. As a consequence of overall flow variation, the differential pressure across the separate compartments will also undergo at least some variation. This is indicated schematically and described in Figure 6.53.

Velocity variations may occur not only from compartment to compartment, but also from filter to filter and along the length of a filter, as discussed above in single bag performance analysis. Therefore the use of nominal velocity to describe overall filtration is arbitrary, since for a given nominal velocity many combinations of internal flow distribution may exist.

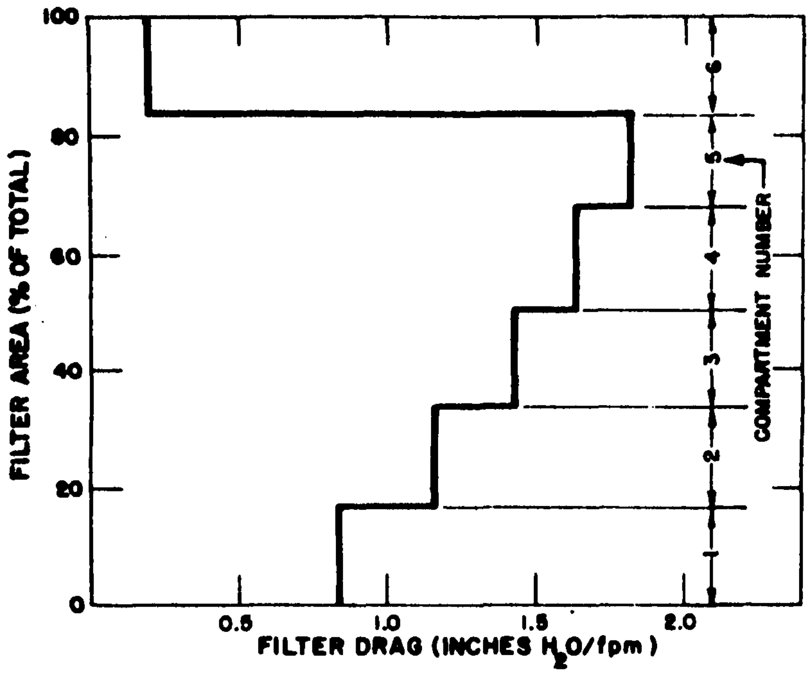


Figure 6.51. Instantaneous Filter Drag Profile for Six Compartment Baghouse. (From Walsh and Spaite, Ref. 5).

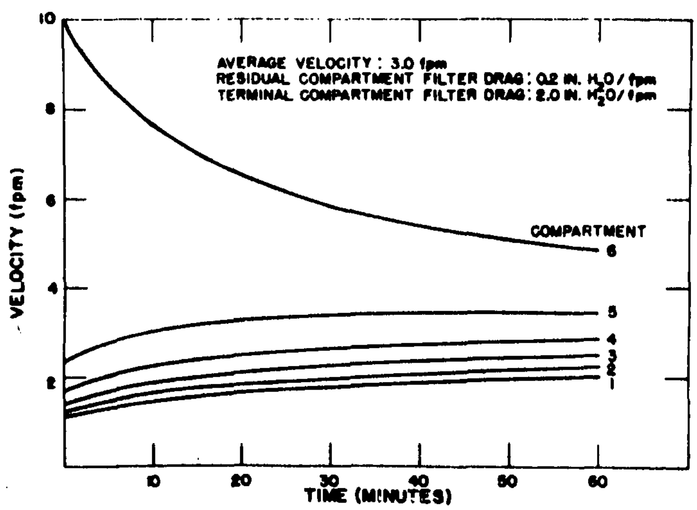


Figure 6.52. Velocity Pattern in Six Compartment Baghouse as a Function of Time (Calculated from Figure 6.51).

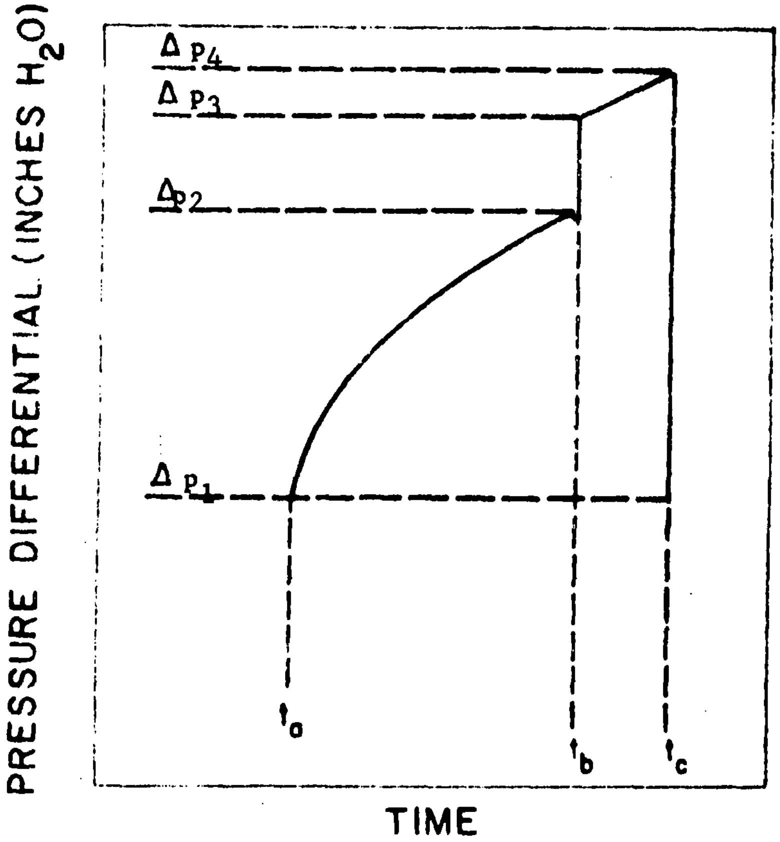


Figure 6.53. Schematic Pressure Differential Curve for Multicompartment Baghouse)(From Ref. 5).

Explanation:

Time t_a: A compartment has just returned on-line with a lowered drag; the system flow is higher than usual, and the collector pressure drop is lower than usual.

Time t_b: The next compartment has just been removed for cleaning, and total cloth area is less than usual. Thus filtering velocity is slightly increased, and pressure diff. has also increased. System flow has decreased.

Time t_c: The compartment has been cleaned, and is returned on line. The system returns to the same state as at Time t_a, and recycles.

Residual conditions are those which exist in a particular compartment as it is put on stream after cleaning, and terminal conditions are those which exist in a compartment just before it is taken out of service for cleaning. The residual drag (set by cleaning method and dust-fabric parameters) and terminal drag(set by fan and dust-fabric resistance characteristics) establish overall limits for a particular installation; therefore they are critical operating parameters. Variations in filter drag, in establishing differences in filter velocities, also influence dust penetration into the filter, filter blinding, and the structure of the dust cake. Drag itself is affected by these changes. Some of the equations describing multicompartment system dynamics are developed in Appendix 6.3, and are of a form perhaps best studied by computer techniques.

6.3.2 Performance of a Multicompartmented Collector

Billings, et al.[17] have reported a laboratory performance of a commercial multicompartment collector cleaned automatically on a time cycle.* The test unit consisted of four compartments, each containing eight bags 8 in. in diameter and 6 ft. long (100 ft^2 of cloth/compartment), as shown in Figure 6.54. Dusty air entered the bottom of each section, passing upward and through the fabric tubes. Once every 5.2 minutes each compartment was shut off from the fan by means of a damper, vented to atmosphere, and the bags cleaned. Dust removal was accomplished by lifting the whole assembly about 1-1/2" and dropping suddenly.

In addition, outside air was drawn into the compartment by the negative pressure of the hopper and inlet plenum, and passed through the bags in a reverse direction to help remove dislodged dust. Reverse air passed down the inside of the bags and through the inlet header to the other compartments. This cycle was then repeated on another section. Sateen weave cotton bags were normally used in this equipment at a filtration rate of 10 CFM/ft^2.

Performance characteristics investigated on this collector were the effects on pressure drop and efficiency of changes in reverse flow air, amount and frequency of rapping, dust loading, air velocity, and aerosol particle material. Performance of five different bag materials was also compared.

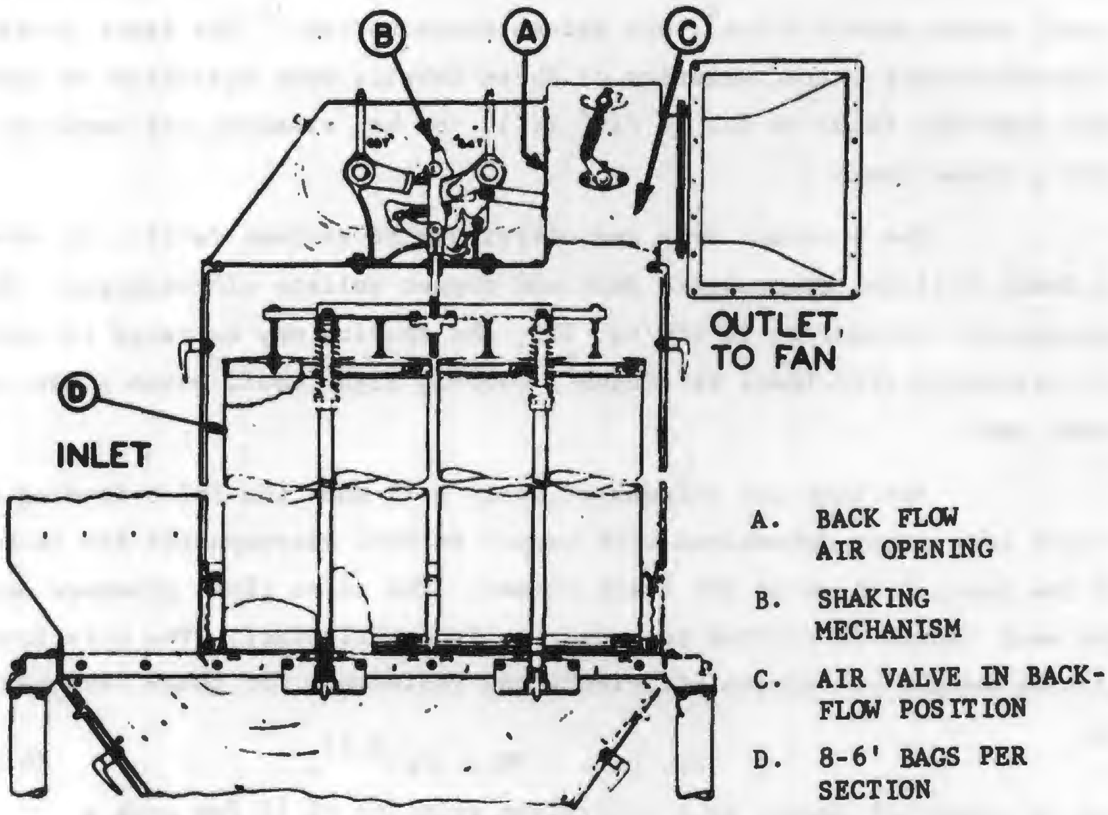


Figure 6.54. Cloth Tube Filter Cleaned by Mechanical Rapping and Back Flow Air. (From Billings, et. al., Ref. 17).

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*An adaption of the British Simon Suction Filter manufactured in the U.S. by Entolater Div., Safety Car Heating and Lighting Co., New Haven, Connecticut.

6.3.2.1 <u>Studies With Light Dust Loadings</u>

Basic Media Performance.- The combination of rapping bags, as an integral unit, to minimize distortion and the use of reverse air flow permits the choice of several bag materials other than sateen weave cotton cloth. Such fabrics are: (1) wool felt with its inherently higher efficiency but less porous structure which requires reverse air for adequate cleaning and (2) woven glass cloth capable of withstanding high temperature but having poorer flexing characteristics. Several bag materials were tested including heavy and light wool felt, woven glass cloth lubricated with a sil-

icone, woven napped Orlon^R, and sateen weave cotton.[17] The basic pressure drop-efficiency characteristics of these fabrics were evaluated on light dust loadings (0.01 to 0.1 gr./10^3 ft^3). No bag cleaning was employed during these tests.

The pressure drop and efficiency of various fabrics is shown in Table 6.13 for atmospheric dust and copper sulfate microspheres. On atmospheric aerosol at 10 cfm/sq. ft., the fabrics may be rated in order of increasing efficiency as: Orlon^R, cotton, light wool, woven glass, and heavy wool.

The last two columns of Table 6.13 show the inlet loading and weight efficiency determined with copper sulfate microspheres for each of the fabrics shown in the first column. The clean cloth pressure drop for each fabric is related to copper sulfate efficiency. The relationship between weight collection efficiency and resistance for these five fabrics is:

$$\text{Wt. eff.} = 98.5\ (\Delta p)^{0.33}, \qquad (6.20)$$

for Δp inches of water, at a filtration velocity of 10 fpm with a copper sulfate particle size of 2.7 microns (MMD). Billington and Saunders[19] report the exponent of pressure drop as 0.43 for 13 air conditioning filters, using a stain density measure of efficiency with particles in the same size range. They also mention an exponent of 0.1 found by Bigg for weight efficiency of fabric filters using particles in the range 25 to 100 microns.

Further Studies of Filter Aids. - To extend the knowledge of performance of filter aids to other fabrics and higher filtration velocities than those described in Section 6.2.2.1, Orlon^R, cotton, heavy wool felt, and woven glass were flocked with asbestos floats and tested with copper sulfate aerosols at a filtration velocity of 10 fpm. Bags were not shaken during the flocking process, nor during the testing with copper sulfate. The results of these tests are given in Table 6.14. It is possible to increase the efficiency of these materials to over 98 percent by the application of asbestos floats as a filter aid.

The use of 200 gr/ft.^{2} of asbestos floats had been suggested as an optimum amount in the study described in a previous section. To

TABLE 6.13

FABRIC COMPARISONS WITH LIGHT LOADINGS[a]

Fabric	Clean Fabric Pressure Drop in H_2O	Atmospheric Dust		Copper Sulfate	
		Inlet Loading gr./1000 cu.ft.	Weight Efficiency percent	Inlet Loading gr./1000 cu.ft.	Weight Efficiency percent
Light Wool Felt	0.07	0.184	74.8	0.89	41.1
Orlon, Napped	0.10	0.130	60.4	0.81	45.6
Cotton, Sateen Weave	0.29	0.045[b]	35.5[c]	1.02	63.7
Heavy Wool Felt	0.34	0.220	85.4	1.01	71.3
Woven Glass	0.56	0.058	81.9	0.90	81.1

[a]Filtering velocity 10 cfm/sq. ft.

[b]Believed to be experimental error.

[c]Probably nearer 60 percent.

(From Billings, et. al., Ref. 17).

TABLE 6.14

FABRIC COMPARISONS USING ASBESTOS FLOATS AS A FILTER AID[a]

Fabric	Pressure Drop[b] in H_2O		Copper Sulfate Weight Efficiency per cent	
	Initial	Final	Initial	Final
Orlon	0.16	0.95	45.6	98.56
Cotton	0.36	1.43	63.7	98.95
Dense Wool	0.36	0.90	71.3	99.28
Woven Glass	0.81	2.20	81.1	99.60

[a]200 gr./ft^2

[b]Filtering velocity - 10 fpm

(From Billings, et. al., Ref. 17).

confirm this on a different aerosol and at a different filtration rate, glass bags were flocked in small increments, and the efficiency was evaluated after each step with copper sulfate microspheres (Table 6.15). Each increment of filter aid caused an increase in pressure drop and a decrease in amount penetrating. Effluent loadings at a velocity equal to 3 fpm were not appreciably different from those at 10 fpm.

Test 7 shows the increase in penetration when the unit was shaken five times, i.e. five complete cycles or 20 strokes per compartment. About 60 percent of the original material, by weight, was recovered from the hopper at this point. The remaining asbestos on the bags then amounted to about 80 gr./ft^2. Penetration and pressure drop at this time were different than during loading due to the uneven removal of the flock and channeling of the flow through less flocked areas. Use of asbestos floats as a filter aid permits control of penetration and pressure drop. The primary aerosol particle concentration cannot be too high or frequent replacement of the filter aid will be necessary (see Figure 3.31). The use of glass bags with asbestos flock can substantially increase collection efficiency for high temperature work in such applications as the final gas cleaning stage in incineration processes. Field trials will be required to estimate service life of the combination. Present applications of filter aids (1970) also include use of granular reactants for recovery of gaseous contaminants.

6.3.2.2 Studies With Heavy Dust Loadings

Frequency and Number of Raps.- The standard cleaning cycle consisted of four raps per section, per 5.2 minutes, in conjunction with entering reverse flow air. Table 6.16 shows the variation of pressure drop and penetration as the number of raps is decreased. Efficiency increased as pressure drop increased witn decreasing number of cleaning strokes.

An investigation of the effects of the frequency of rapping was made. This was done by reducing the cycle time and the number of raps, in direct proportion, to keep the number of raps per section constant over any

TABLE 6.15

EFFECTIVENESS OF FILTER AIDS FOR LIGHT LOADINGS OF COPPER SULFATE MICROSPHERES[a]

Test No.	Filtration Velocity cfm/ft.^{2}	Cumulative Filter Aid on Fabric gr./ft.^{2}	Pressure Drop in H_2O	Copper Sulfate Loading gr./1000 ft.^{3} Inlet	Copper Sulfate Loading gr./1000 ft.^{3} Outlet	Weight Penetration percent	Weight Efficiency percent
1	10	0	0.86	0.92	0.130	18.9	81.1
2	10	25	1.56	0.79	0.024	3.1	96.9
3	10	50	1.76	0.87	0.019	2.2	97.8
4	10	100	1.80	0.88	0.012	1.4	98.6
4a	3	100	0.63	1.41	0.007	0.5	99.5
5	10	150	2.00	0.88	0.008	0.9	99.1
5a	3	150	0.66	1.68	0.008	0.5	99.5
6	10	200	2.20	0.80	0.003	0.3	99.7
6a	3	200	0.72	1.62	0.003	0.2	99.8
7	10	b	1.46	0.80	0.026	3.4	96.6

a. Woven glass bags lubricated with silicone, no fabric cleaning during tests, except prior to Test 7.

b. Recovered 60% from bags by rapping, five cycles = 20 strokes.
(From Billings, et. al., Ref. 17).

TABLE 6.16

EFFECT OF DECREASING THE NUMBER OF RAPS IN THE STANDARD CLEANING CYCLE ON PRESSURE DROP AND EFFICIENCY[a]

No. Raps/ Section in 5.2 min. cycle	Average Pressure Drop in. H_2O	Dust Loading Inlet gr./ft^3	Dust Loading Outlet gr./1000 ft^3	Weight Penetration percent	Weight Efficiency percent
4	3.2	0.85	1.68	0.20	99.80
3	3.6	0.60	0.94	0.16	99.84
2	4.5	0.60	0.63	0.10	99.90
1	5.7	0.91	0.49	0.054	99.946

a. Sateen weave cotton bags; back flow air 100 cfm; total air volume 3000 cfm; fly ash test dust.
(From Billings, et. al., Ref. 17).

long time interval. Data presented in Table 6.17 indicate that several raps followed by a long pause produced lower pressure drop than short cycling. The rapping operation appeared to be more effective in removing dust than the reverse air, the velocity of which was about 1 fpm, (see below).

Reverse Flow Air.- The amount of reverse flow air that enters a compartment to aid in cleaning is often controllable. The above equipment was modified to study the effect of reverse air volume. Results in Table 6.18 indicate a 6-fold increase in filter penetration when air volume was increased 5-fold. At the same time, pressure drop decreased about 50%.

Inlet Dust Loading - The average pressure drop increases with inlet dust loading as shown in Figure 6.55. With fly ash, the relative rate of pressure drop rise with dust loading decreases at higher loadings, regardless of filtration velocity. Talc produces relatively higher pressure drop at 2000 cfm and the rate of rise with dust load is higher than with fly ash. These curves are similar to performance data for continuously on-line cleaned reverse-jet and pulse-jet collectors.

TABLE 6.17

EFFECT OF VARIATION IN CLEANING CYCLE FREQUENCY ON PRESSURE DROP OF A MULTICOMPARTMENT COLLECTOR*

Cycle No. of Raps/Section	No. of Minutes	Average Pressure Drop in H_2O Comp. I	Comp. IV
1	1	5.8	6.0
2	2	5.4	5.8
3	3	5.0	5.5
4	4	4.8	5.4

*Sateen weave cotton bags, back flow air 100 cfm, total air volume 3000 cfm or 10 cfm/ft^2, inlet loading 0.65 gr./ft^3, fly ash test dust. (From Billings, et. al., Ref. 17).

TABLE 6.18

EFFECT OF CHANGES IN REVERSE AIR VOLUME ON PRESSURE DROP AND PENETRATION*

Amount of Reverse Air cfm	Average in H_2O	Dust Loading Inlet gr/cu.ft.	Outlet gr/1000 cu.ft.	Weight Penetration Percent	Weight Efficiency percent
51	3.1	1.10	1.3	0.12	99.88
68	2.9	1.10	---	----	-----
85	2.6	1.10	4.3	0.39	99.61
120	2.6	0.94	4.1	0.44	99.56
180	2.3	0.88	4.6	0.52	99.48
250	2.2	0.94	7.2	0.77	99.23

*Sateen weave cotton bags; air volume 2000 cfm; 4/5 cleaning cycle; fly ash aerosol; 1 fr/ft^3. (From Billings, et. al., Ref. 17).

Table 6.19 shows the penetration of fly ash as the inlet dust loading is increased from 0.40 to 13.0 gr./ft^3. Individual effluent concentrations of each compartment are given in Table 6.20. Compartment I contributed almost twice as much to the effluent as the others, probably due to uneven distribution of flow in the unit.

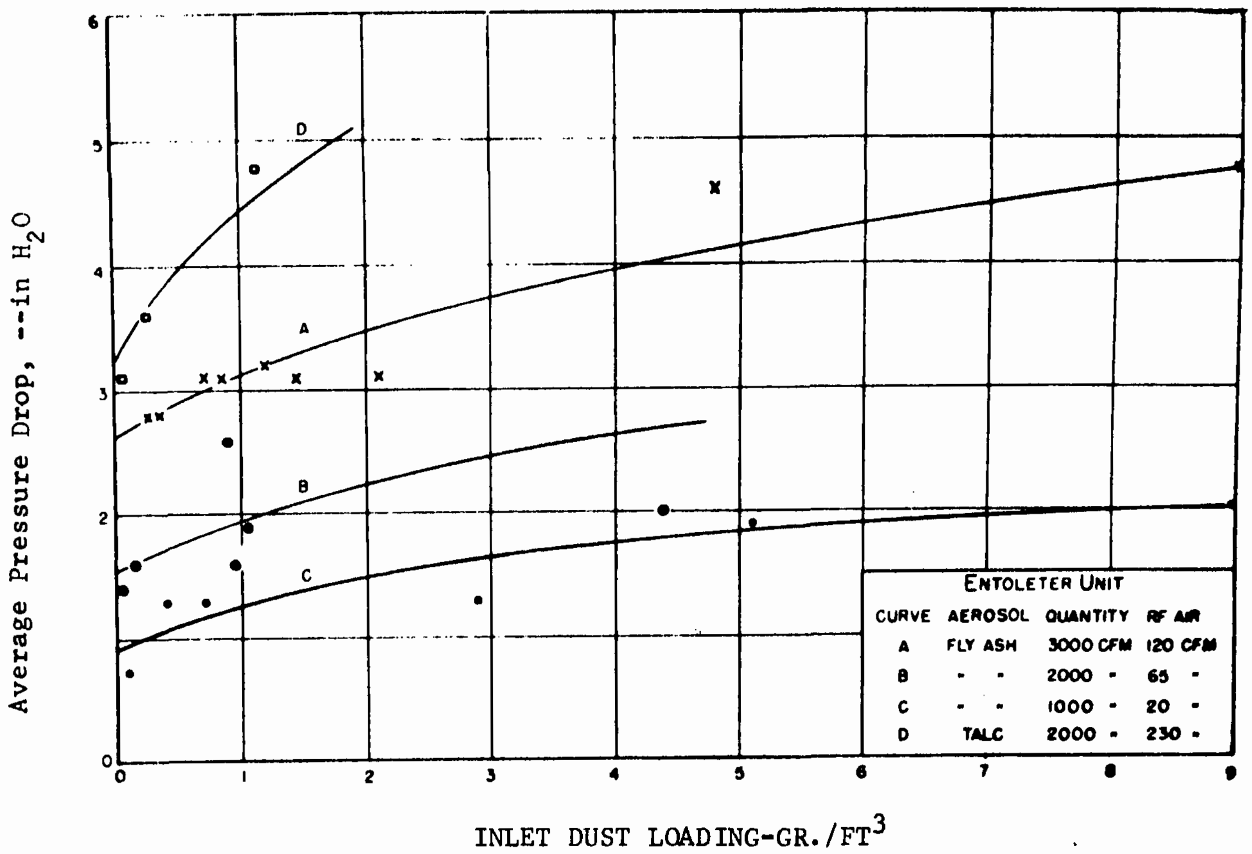

Figure 6.55. Variation of Filter with Inlet Dust Concentration (From Billings, et. al., Ref. 17).

TABLE 6.19

EFFECTS OF INLET DUST CONCENTRATION ON FLY ASH PENETRATION[a]

Dust Loading Inlet gr./cu.ft.	Dust Loading Outlet gr./10^3 ft^3.	Weight Penetration percent	Weight Efficiency percent
0.40	0.52	0.130	99.870
2.90	1.50	0.052	99.948
5.10	2.40	0.048	99.952
13.00	3.80	0.029	99.971

a. sateen weave cotton bags; back flow air 100 cfm; total air volume 1000 cfm or 3.3 cfm/sq.ft.; 4/5 cleaning cycle.

(From Billings, et. al., Ref. 17).

Comparison of five fabrics.- The basic performance of five fabrics filtering light loadings of atmospheric dust and copper sulfate has been discussed above. These fabrics were also used to filter heavy dust loadings to obtain comparative performance data. The pressure drop and penetration for each fabric, used with the standard cleaning cycle, are given in Table 6.21 for fly ash and talc dusts. Fly ash required a lower pressure drop on all fabrics. Fly ash penetration was also greater. Fabric order is similar in each series, except for Orlon^R fabric, which had the highest penetration on fly ash and near the lowest on talc. This shift in order of penetration for Orlon^R may have been caused by humidity or electrostatic charge effects.

6.4 LABORATORY PERFORMANCE OF CONTINUOUS ON-LINE CLEANED COLLECTORS

6.4.1 Reverse Jet Filter (Hersey Type)

Billings et al[17] reported on laboratory performance tests of a reverse-jet continuously on-line cleaned fabric filter (see Figure 3.3F). Pressure drop and efficiency were found to vary with inlet dust loading, filtering, velocity and cleaning ring operation parameters. Empirical pressure drop performance equations were derived for test dust simulants.

For resuspended vaporized silica (particle size, order of 1 μm), the equilibrium operating pressure drop (in. H_2O) was found to be:

$$\Delta p = \left[0.31V(M + 1.5)^{0.19} + \frac{8000 - V_{rj}}{1000} \times 0.95\right] \left(\frac{RJO}{100}\right)^{-0.18} \qquad (6.21)$$

where V = filtration velocity, 7 to 20 fpm

M = dust flux to fabric, 1 to 87 gr./ft^2 - min, ($=C_iV$)

V_{rj} = velocity of reverse-jet air, 2000 to 8000 fpm

RJO = percent of time reverse-jet operates, 6 to 100%

The pressure drop equation for resuspended fly ash ($M'_g = 16, \sigma_g > 3$) was found to be:

$$\Delta p = \left[0.047V(M + 14)^{0.35} + \frac{4200 - V_{rj}}{1000} \times 0.70\right] \left(\frac{RJO}{100}\right)^{-0.25} \qquad (6.22)$$

for $10 \leq V \leq 30$ fpm, $1 \leq M \leq 76$ fr/ft^2 -min, $2200 \leq V_{rj} \leq 4200$ fpm and $7 \leq RJO \leq 100\%$.

TABLE 6.20

INDIVIDUAL COMPARTMENT EFFLUENT CONCENTRATIONS WHEN FILTERING AN INLET DUST CONCENTRATION OF 1.1 GRAINS PER CUBIC FOOT OF FLY ASH[a]

Compartment	Dust Loading Outlet gr./10^3 ft^3.	Weight Penetration percent	Weight Efficiency percent	Pressure drop in H_2O
(I farthest from fan)	2.2	0.19	99.81	3.4
II	1.3	0.12	99.88	3.5
III	1.2	0.11	99.89	3.5
(IV nearest fan)	1.2	0.11	99.89	3.6
Overall	1.2	0.11	99.89	

a. sateen weave cotton bags; back flow air 100 cfm; total air volume 2000 cfm or 6.7 cfm/sq.ft.; 4/5 cleaning cycle.

TABLE 6.21

COMPARISON OF FIVE FABRICS FILTERING HEAVY DUST LOADINGS

Fabric	Operating Pressure Drop in H_2O	Weight Penetration gr./10^3 ft^3.	Outlet Loading gr./10^3 ft^3.
A. Talc[a]			
Cotton	5.5	0.990	99.9010
Light Wool	5.0	0.740	99.9260
Dense Wool	5.6	0.340	99.9660
Orlon	5.5	0.330	99.9670
Woven Glass	5.9	0.063	99.9937
B. Fly Ash[b]			
Orlon	2.4	5.60	99.440
Cotton	3.0	1.40	99.860
Dense Wool	2.7	0.30	99.970
Light Wool	2.6	0.26	99.974
Woven Glass	4.7	0.12	99.988

a. Mass median diameter 2.5 microns; geometric standard deviation 1.6; filtration velocity 5 cfm/sq.ft.; inlet loading 1.0 gr./ft.; 4/5 cleaning cycle, 4-Compartment Unit.

b. Mass median diameter 16 microns; geometric standard deviation >3; filtration velocity 10 cfm/sq. ft.; inlet loading 1.0 gr./ft^3., 4/5 cleaning cycle, 4-Compartment Unit.

(From Billings, et. al., Ref. 17).

Pressure drop for fine talc (M'_g = 2.5 μm, σ_g = 1.6) was found to be:

$$\Delta p = \left[0.16V(M + 1.3)^{0.30} + \frac{2000 - V_{rj}}{1000} \times 0.8\right] \left(\frac{RJO}{100}\right)^{-0.14} \qquad (6.23)$$

for $7 \leq V \leq 20$ fpm, $1 \leq M \leq 70$ gr/ft^2-min, $2000 \leq V_{rj} \leq 8000$ fpm, and $10 \leq RJO \leq 100\%$.

Average inlet and outlet dust concentration for 8 test aerosols are given in Table 6.22. Efficiency varied with amount and magnitude of cleaning.

6.4 2 Pulse Jet Collector

Dennis and Silverman[20] reported on laboratory test of a Micro-Pulsaire[R] pulsejet continuously on-line cleaned collector (See Figure 3.3H).

Equilibrium pressure drop for resuspended fly ash was given by:

$$\Delta p = 0.14 + \left[\frac{0.48\ (Ci)^{0.23}}{\left(\frac{pc}{100}\right)^2 t^{0.5}}\right] t \qquad (6.24)$$

For resuspended vaporized silica, pressure drop was found to be

$$\Delta p = 0.14 + \left[\frac{1.75\ (Ci)^{0.27}}{\left(\frac{pc}{100}\right)^2 t^{0.5}}\right] t \qquad (6.25)$$

for $0.06 \leq Ci \leq 1$ gr/ft^3, and other parameters same as above. Weight collection efficiencies were reported to be greater than 99.9% on all tests.

6.5 FIELD PERFORMANCE

Pressure drop and efficiency for several fabric filters tested in the field were reported by Dennis et al[21]. Data for intermittently cleaned tube and screen type collectors is shown in Table 6.23. Average operating efficiency was found to be greater than 99% in all tests. Field test results for reverse-jet collectors are shown in Table 6.24. Efficiency for

TABLE 6.22

AVERAGE INLET AND OUTLET DUST CONCENTRATIONS FOR A VARIETY OF AEROSOLS TESTED ON THE REVERSE-JET COLLECTOR[a]

Aerosol	Filtration Velocity ft/min	Average Dust Loading gr./cu. ft. Inlet	Outlet	Reverse-Jet Velocity fpm
Atmospheric Dust	25	3.2×10^{-5}	0.6×10^{-5}	b
" "	17	2.1×10^{-5}	0.2×10^{-5}	b
" "	8	3.3×10^{-5}	0.2×10^{-5}	b
Copper Sulfate Microspheres	25	150×10^{-5}	4.9×10^{-5}	b
" " "	17	250×10^{-5}	3.7×10^{-5}	b
" " "	8	470×10^{-5}	31×10^{-5}	b
Uranium Trioxide Microsph.	25	640×10^{-5}	27×10^{-5}	b
" " "	17	770×10^{-5}	68×10^{-5}	b
" " "	8	1800×10^{-5}	120×10^{-5}	b
Talc	8	0.14	1.2×10^{-5}	2000
"	11	0.16	1.2×10^{-5}	1620
"	8	2.0	3.9×10^{-5}	2000
"	8	8.7	6.0×10^{-5}	2000
Vaporized Silica	20	0.06	2.6×10^{-5}	2000
" "	28	0.09	4.9×10^{-5}	2000
" "	17	0.22	4.4×10^{-5}	4800
" "	22	0.87	5.8×10^{-5}	2000
" "	10	1.07	1.0×10^{-5}	4000
" "	10	1.21	41×10^{-5}	4000[c]
" "	10	1.26	1.8×10^{-5}	4000
Fly Ash	10	0.37	8.6×10^{-5}	5000[c]
" "	29	2.1	153×10^{-5}	4000
" "	20	4.0	63×10^{-5}	4000
" "	10	6.8	86×10^{-5}	4000
" "	10	11.2	44×10^{-5}	2000
" "	10	13.4	61×10^{-5}	3000
Alundum	17	2.0	13.8×10^{-5}	3000
Calcium Carbonate	25	0.0055	11.1×10^{-5}	b
" "	25	0.033	17.3×10^{-5}	b
" "	25	0.25	48×10^{-5}	1450

a. Single 18"x60" bag; American Felt Co., #51002, 19 oz./sq. yd.
b. No reverse-jet operation
c. Three 6"x60" bags; same as above.
(From Billings et al., Ref. 17).

TABLE 6.23

FIELD TEST RESULTS FOR CLOTH SCREEN(S) AND TUBE (T) COLLECTORS CLEANED BY INTERMITTENT MECHANICAL SHAKING*

Test and Unit	Operation	Material	DUST DESCRIPTION: Inlet: Loading Grains per Cu. Ft.	Inlet: Median Size Microns: Mass	Inlet: Median Size Microns: Count	Outlet: Loading Grains per Cu. Ft.	Outlet: Median Size Microns: Mass	Outlet: Median Size Microns: Count	Air Flow Rate (S.T.P.) cfm[a]	CFM per Sq. Ft. Cloth	Pressure Loss Across Collector in. Water	Collection Efficiency by Weight Per Cent	Manu-fac-turer
13(T)[b]	Founding	Iron Scale SiO_2	0.68	2.6	0.63	0.000015	-	-	7,000	2.5	1.5	99.99	American
16(T)	Founding	Bronze Scale SiO_2	0.44	-	0.82	0.000069	-	0.57	560	0.8	5.0	99.98	Wheela-brator and
16a(T)[d]	Founding	Bronze Scale SiO_2	0.595	-	-	0.000048	-	-	1,850	2.6	0.3	99.99	Equipment Corporation
17(T)	Founding	Iron Scale SiO_2	0.13	105	0.71	0.000013	-	-	2,000	2.2	2.2	99.99	
18(S)[c]	Granite chipping	Granite	0.032	3.8	0.46	0.000028	1.1	0.41	7,020	2.3	3.0	99.91	Sly Corporation
19(S)	Founding	Iron Scale	0.39	6.2	0.47	0.00063	3.4	0.37	18,200	1.5	1.9	99.65	
20(S)		SiO_2	0.19	48	0.56	0.000013	-	-	13,900	1.3	1.2	99.99	Pangborn
21(S)	Truing &	Al_2O_2	0.15	4.3	0.51	0.00011	0.87	0.43	32,000	4.1	2.9	99.93	Corporation
22(S)	shaping	SiO_2	0.10	4.4	0.57	0.000074	0.96	0.43	32,000	3.2	4.1	99.93	
23(S)	grinding		1.33	4.0	0.45	0.00003	0.59	0.38	4,520	1.4	1.7	99.99	
24(S)	wheels & sticks		0.88	3.2	0.62	0.0025	-	0.46	32,000	3.2	3.3	99.72	
25(S)	Rubber	Talc	4.3	-	1.3	0.0064	-	-	7,000	-	-	99.85	

[a] STP = 70°F and 760 mm Hg

[b] Cloth tubes

[c] Cloth envelopes over metal screens

[d] Unit 16 following replacement of worn-out bags

*(From Dennis et al., Ref. 21).

TABLE 6.24

FIELD TEST RESULTS FOR CLOTH BAG COLLECTORS CLEANED BY REVERSE-JET AIR*

Test and Unit	Operation	Material	DUST DESCRIPTION: Inlet Loading Grains per Cu. Ft	Inlet Median Size Microns Mass	Inlet Median Size Microns Count	Outlet Loading Grains per Cu. Ft.	Outlet Median Size Microns Mass	Outlet Median Size Microns Count	Air Flow Rate (S.T.P.) cfm[a]	CFM per Sq.Ft. Cloth	Pressure Loss Across Collector in Water	Collection Efficiency by Weight Per Cent
26	Truing and	Al_2O_3	0.130	18.0	0.52	0.001	0.59	0.42	18,800	17.0	4.0	99.23
27	shaping	SiC	2.260	7.2	0.70	0.0009	1.1	0.43	930	5.5	3.5	99.96
28	grinding		0.650	8.5	0.59	0.0008	0.75	0.41	1,230	7.2	3.5	99.88
29	wheels and		3.10	10.0	0.52	0.0009	0.72	0.44	9,500	32.0	3.2	99.97
30	sticks,		3.65	3.3	0.54	0.0025	2.0	0.45	8,000	26.0	2.9	99.93
31	etc.		2.44	-	-	0.0011	0.74	0.43	12,000	53.0	3.1	99.95
32		B_4C	0.075	2.3	0.48	0.0021	1.8	0.43	2,200	46.0	3.6	97.20
33	Metal	Polishing	0.0094	9.8	0.55	0.00022	1.2	0.42	6,000	32.0	6.4	97.62
34	polishing	rouge	0.0048	1.2	0.43	0.00012	0.56	0.43	5,000	27.0	3.6	97.51
35	Crushing &	BeO	0.14	-	-	0.00052	-	-	9,600	12.0	2.4	99.63
35a	grinding		0.029	-	-	0.00057	-	-	9,600	12.0	2.4	98.03
35b	Founding	$BeO;SiO_2$	0.0054	-	-	0.000022	-	-	9,600	12.0	2.4	99.59
36	Drying	Tapioca Starch	3.17	7.7	4.8	0.00054	1.1	0.43	2,130	11.3	4.4	99.99

[a] STP = 70F and 760 mm Hg

Note: All units manufactured by Turner and Haws Company ("Aeroturn").

*(From Dennis et al., Ref. 21.)

inlet dust loadings $\geq$ 0.1 gr/ft^3 was found to be 97 to 98%, with filtering velocities in the range of 25 to 45 fpm. These latter data have been attributed to poor maintenance and possible bag wear, but indicate typical field values under as-found maintenance conditions.

The literature gives pressure drop and efficiency data for a number of fabric filter installations, along with at least partial descriptions of the dust, gas, fabrics used, and operative detail. These data are summarized insofar as reported in Appendix 6.4. Due to wide variation in conditions of filtration, the data have not been analyzed. The data is indicative of fabric filter field performances, particularly those of new and unusual filter installations as these are the ones most frequently reported in the literature.

The efficiency of fabric filters in collecting particles of various sizes has not been reported. Preliminary laboratory tests on particle size efficiency using monodispersed aerosols have been discussed in Chapter 2.

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CHAPTER 7

ECONOMICS

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ECONOMICS

7.1 INTRODUCTION

Whether fabric filtration represents the optimum gas cleaning method for a given set of performance specifications depends upon a detailed cost analysis. The available data citing cost experience, however, are limited and, in many cases, oriented towards specific operations. Therefore, unless the design engineer is confronted with a very similar and proven fabric filter application, he should prepare a written specification and seek expert professional opinion. All cost factors associated with the design, fabrication and installation of the fabric filter system should be determined as accurately as possible before selecting the dust control system. In those cases where the gas treatment equipment will be of modest size or where it represents but a very small fraction of a large capital investment, one can justify a less rigorous approach.

The intent of this chapter is to provide the design engineer with practical guidelines for estimating the cost of various fabric filtration approaches. A concept underlying this chapter is that several trade-offs must be considered between size of components and operating parameters in order to optimize costs. For example, if low cost performance and high efficiency were the only criteria, one could never have too much cloth area for treatment of a fixed gas volume (Figure 7.1). There will be some point, however, when the initial costs for the larger filtration system will override the lower recurring costs of power, maintenance, etc.

The cost data assembled here have been compiled from several sources; e.g., equipment users, manufacturers of filter systems and ancillary parts, and open literature surveys by many investigating groups. Purchase costs cited for past years have been converted to their 1969 equivalents in accordance with the Marshall and Stevens Index, Table 7.1.

Several partial cost analyses have appeared in recent years, including those by Stairmand[2,3] and Stephan,[4] that relate the collection efficiency

TABLE 7.1

MARSHALL AND STEVENS INDEX FOR UPDATING EQUIPMENT COSTS*

	M&S Index	1969 Factor		M&S Index	1969 Factor
1945	106	2.64	1960	239	1.17
1950	170	1.65	1961	238	1.18
1951	181	1.61	1962	238	1.18
1952	181	1.61	1963	239	1.17
1953	183	1.53	1964	242	1.15
1954	186	1.51	1965	245	1.14
1955	192	1.46	1966	253	1.11
1956	209	1.34	1967	263	1.06
1957	226	1.24	1968	273	1.03
1958	232	1.21	1969	285	1.00
1959	236	1.19	1970	(296)	(0.95)

Example: Equipment costing $1000 in 1955 is estimated to cost $1460 in (early) 1969.

*See Ref. 1, pg. 26-8; and Chemical Engineering, recent issues, last page.

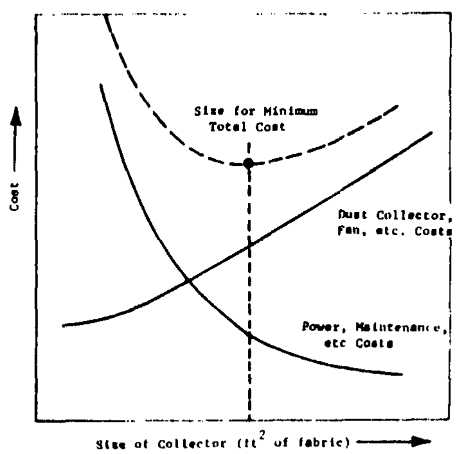


Figure 7.1. Trade-off in Costs Due to Collector Size, for Fixed Gas Flow.

of various types of particulate collectors to control costs. In Figure 7.2, for example, the efficiency is compared to control costs as a function of particle size. Although the costs quoted, which reflect British experience, are about 50 percent lower than those reported in this chapter, the relative impact of particle size upon cost is directly applicable. Stephan's data, summarized in Table 7.2, gives purchase costs and power requirements for a spectrum of particulate collectors effective on various particle sizes.

In detailed cost analyses presented in this section, several application-related variables will be shown to have an important bearing on cost. Therefore, in referring to rather generalized summations of the types shown in Figure 7.2 and Table 7.2, one must keep in mind that individual component costs, frequency of replacing parts, amount of maintenance, and cost accounting techniques may vary widely from one installation to another. A reasonable and useful cost estimate can only be prepared by examining in turn each contributing cost factor. Figure 7.3 indicates several important aspects typical of most fabric filter systems:

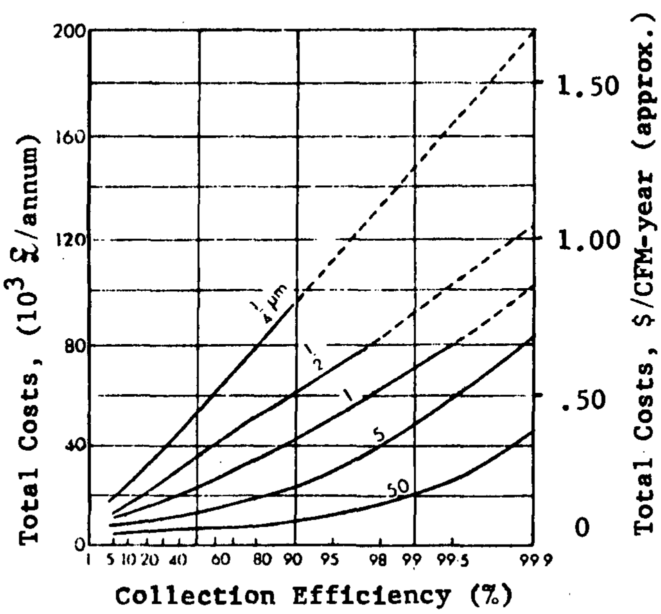


Figure 7.2. Gas Cleaning Costs for Dusts of various Particle Sizes, for 300,000 CFM and 8000 hrs/year. (From Stairmand, Ref. 2.) (1968)

TABLE 7.2

APPROXIMATE CHARACTERISTICS OF DUST AND MIST COLLECTION EQUIPMENT[1]

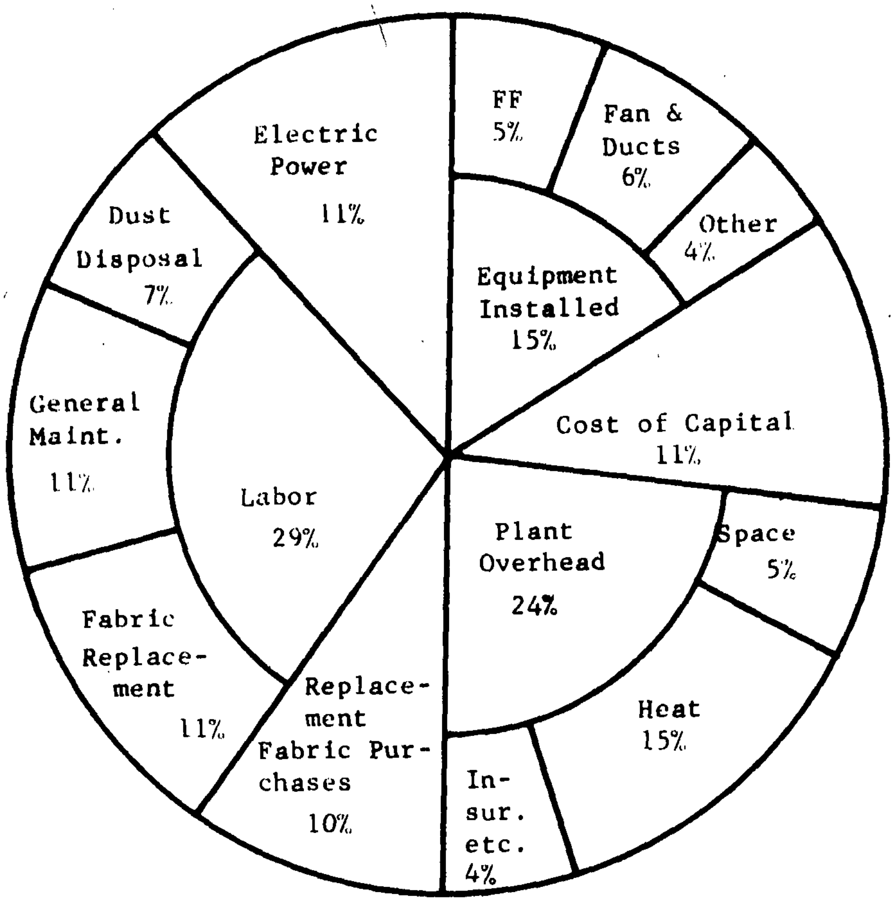
Equipment Type	Purchase Cost* ($/cfm)	Smallest Particle Collected (microns)**	Pressure Drop (in H_2O)	Power Used*** ($\frac{KW}{1000\ cfm}$)	Remarks
A. Settling Chambers					
1. Simple	0.1	40	0.1-0.5	0.1	Large, low pressure drop, precleaner
2. Multiple tray	0.2-0.7	10	0.1-0.5	0.1	Difficult to clean, warpage problem
B. Inertial Separators					
1. Baffle chamber	0.1	20	0.5-1.5	0.1-0.5	Power plants, rotary kilns, acid mist
2. Orifice impaction	0.1-0.4	2	1-3	0.2-0.6	Acid mists
3. Louver type	0.1-0.4	10	0.3-1	0.1-0.2	Fly ash, abrasion problem
4. Gas reversal	0.1	40	0.1-0.4	0.1	Precleaner
C. Cyclones					
1. Single	0.1-0.2	15	0.5-3	0.1-0.6	Simple, inexpensive, most widely used
2. Multiple	0.3-0.7	5	2-10	0.5-2	Abrasion & plugging problems
3. Mechanical	0.2-0.7	5	--	0.5-2	Compact
D. Filters					
1. Tubular	0.3-2.3	<0.1	2-6	0.5-1.5	High efficiency, temp. and humidity limits
2. Reverse jet	0.7-1.3	<0.1	2-6	0.7-1.5	More compact, constant flow
3. Envelope	0.3-2.2	<0.1	2-6	0.5-1.5	Limited capacity, constant flow possible
E. Electrical Precipitators					
1. One-stage	0.7-3.5	<0.1	0.1-0.5	0.2-0.6	High efficiency, heavy duty, expensive
2. Two-stage	0.2-0.7	<0.1	0.1-0.3	0.2-0.4	Compact, air conditioning service
F. Scrubbers					
1. Spray tower	0.1-0.2	10	0.1-0.5	0.1-0.2	Common, low water use
2. Jet	0.5-1.2	2	--	2-10	Pressure gain, high velocity liquid jet
3. Venturi	0.5-1.4	1	10-15	2-10	High velocity gas stream
4. Cyclonic	0.3-1.2	5	2-8	0.6-2	Modified dry collector
5. Inertial	0.5-1.2	2	2-15	0.8-8	Abrasion problem
6. Packed	0.3-0.7	5	0.5-10	0.6-2	Channeling problem
7. Mechanical	0.5-1.4	2	---	2-10	Abrasion problem

*Steel construction, not installed, includes necessary auxiliaries, 1969 prices.

**With ~90-95 percent efficiency by weight.

***Includes pressure loss, water pumping, electrical energy.

[1](From Stephan, Ref. 4)



Typical Installed Cost, $2.38/cfm

Typical Annual Cost, $1.05/cfm-year

Figure 7.3. Fabric Filter Annual Cost Distribution. (From GCA Survey, 1969).

- The cost of the collector is only a few percent of the total cost; therefore, the collector cost taken alone is a poor criterion to use in selecting the system.
- Fabric replacement (labor plus material) represents about 1/5 of the total annual cost; therefore more serviceable fabric may lead to substantial savings.
- Fabric replacement cost is about 4 times greater than collector cost; therefore the collector should be very carefully designed to promote fabric life.
- Labor costs are nearly 1/3 of the total annual cost, and are twice as much as the initial costs. Therefore the equipment should be designed to need a minimum of attention time.

- Direct operating costs are half the total annual cost; therefore even after the system is bought and installed, substantial savings may result from careful use.

An itemization of the principal costs associated with the installation and use of a fabric system and "typical" values for each cost are given in Table 7.3. These costs and their normal apportionment as depicted in the "pie" diagram, Figure 7.3, are discussed in detail in the following sections.

Two basic cost categories, initial and annual, must be considered. The initial cost includes the planning effort, site preparation, installation and other activities required to place the system into routine, effective operation. The annual costs include not only those for power, labor and replacement parts but also various plant overhead charges and a certain amortized fraction of the initial cost. Methods of combining these separate costs are discussed in Section 7.5.

7.2 INITIAL COSTS

The cost of purchasing, installing, and placing the fabric filter system in routine service will usually include the following items:

Cost Item	Typical Cost Range ($/CFM)	Reference Section
Basic filter assembly with filter media	0.3 - 10.+	7.2.1
Fan, blower, compressor	0.05-1.+	7.2.2
Ducting ($/ft)	2-50	7.2.3
Dust disposal equipment	--	7.2.4
Instrumentation	0.01-0.1	7.2.5
Planning and design	-0.1-	7.2.6
Foundations and installation	0.1-5.	7.2.7
Start-up, training, and shake-down period	-0.1-	7.2.8

A more detailed check list of equipment and services considered as capital cost items is given in Appendix 7.1. One should also prepare a

TABLE 7.3

TYPICAL COSTS OF FABRIC FILTRATION

I. Installed Cost - $2.38 per CFM

Planning and design	$0.10
F.O.B. baghouse	0.80
Freight	0.05
Fan and motor	0.25
Ducting	0.65
Disposal equipment	0.10
Instrumentation	0.05
Foundation and installation labor	0.28
Start-up	0.10
Total:	$2.38

II. Annual Cost - 0.77 per CFM per year

Electric power	$ 0.12	
Labor	0.30	
Plant overhead	0.25	Space: 0.055; Heat: .15; Insurance, etc.:.045
Cloth purchases	0.10	
Total:	$ 0.77	

III. Total Cost of Operation - $1.05 per CFM per year

Annual cost	$ 0.77
15 yr. amortization of the installed cost	0.16
Interest on the unamortized portion of installed cost, at 10%	0.12
Total:	$ 1.05

(see text for explanation and variations) detailed flow diagram so that no vital components will be overlooked during the costing process, Most of the items listed above represent expenditures of funds that would be charged directly to the filter system. Certain costs, however, may not be charged to the system, but incorporated in the general plant overhead.

The total initial investment is amortized over a period of time, usually 10 to 15 years, that is consistent with the expected equipment life.* Since a fixed amount of capital is tied to the filter installation, thus preventing investment elsewhere, one must charge this loss of use of the capital to the project annually as interest. Both amortization and interest distributions are discussed in Section 7.5. They are combined with the annual operating and maintenance costs to establish the effective yearly cost of owning and operating the filter system.

As a rough rule of thumb, the total initial investment cost including material and labor will average about $2.50 per CFM of gas filtering capacity, with an expected range of $1 to $7 from one installation to another depending on severity of the problems. This overall average cost is based mainly on the results of a survey of 40 fabric filter installations for which the ranges in size and cost are shown in Figure 7.4.

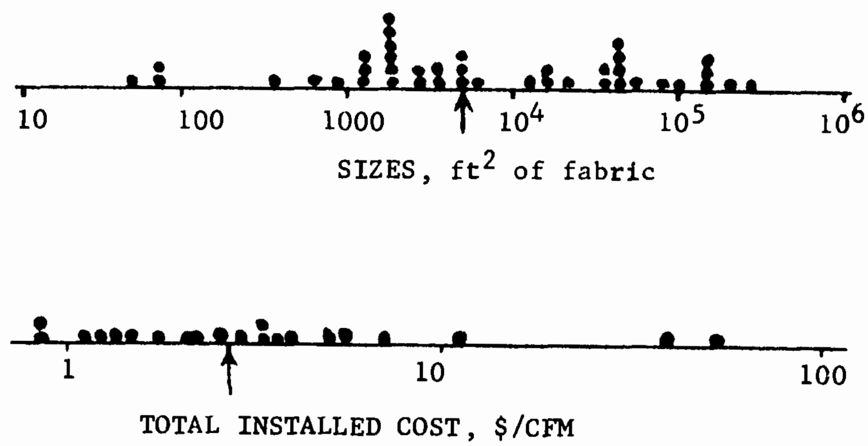


Figure 7.4. Filter Installation Cost Data. (Arrows Indicate Median Installations, ~5000 ft^2 and ~$2.40/CFM.)

*This period varies; power plants anticipate a 30 to 35 year life for most plant equipment, while 5 years may be used in corrosive chemical plants.

The breakdown of these costs, which has been given previously in Table 7.3 and Figure 7.3, is discussed in the following sections. The average figure is apportioned more or less evenly among F.O.B. basic filter cost, fan and ducting costs, and other costs associated with the purchase and installation of the system.

Initial fabric filter system costs for many diverse applications are listed in Appendix 7.1. Although these data are not always specific as to what equipment and labor costs were included, the data should enable cost estimates to within 50 percent of actual cost by the experienced designer.

While the scale factor from F.O.B. collector cost up to installed system cost is typically about three (Table 7.3), this value is obviously highly dependent on the individual system. It will be shown below that both the basic filter cost and the costs of ducting and installation can be quite different depending on the application. Examples of initial cost variations in the Iron and Steel industry provided by an experienced contractor in the air pollution control equipment field are shown in Table 7.4.

7.2.1 Initial Filter Cost

The filter assembly as shipped by the manufacturer normally includes hopper, cleaning mechanism with associated fans or motors, and one set of filter elements. The equipment may or may not be assembled, and it may not necessarily include supporting structures, paint or protective coatings, and insulation. Thus "the initial filter cost" is not entirely meaningful until all these factors are defined clearly. Since users of filtration equipment often fail to specify in their publications the above details on their initial costs, the data presented in this survey are subject to unavoidable uncertainties in some areas.

Initial costs are indicated in Figure 7.5 for four common types of fabric filter dust collectors: reverse jet, pulse jet, mechanically cleaned multi-compartment bag collectors, and single compartment,

TABLE 7.4

ESTIMATES OF CAPITAL COST BREAKDOWN*

1. Material breakdown for fabric filter systems (percent):

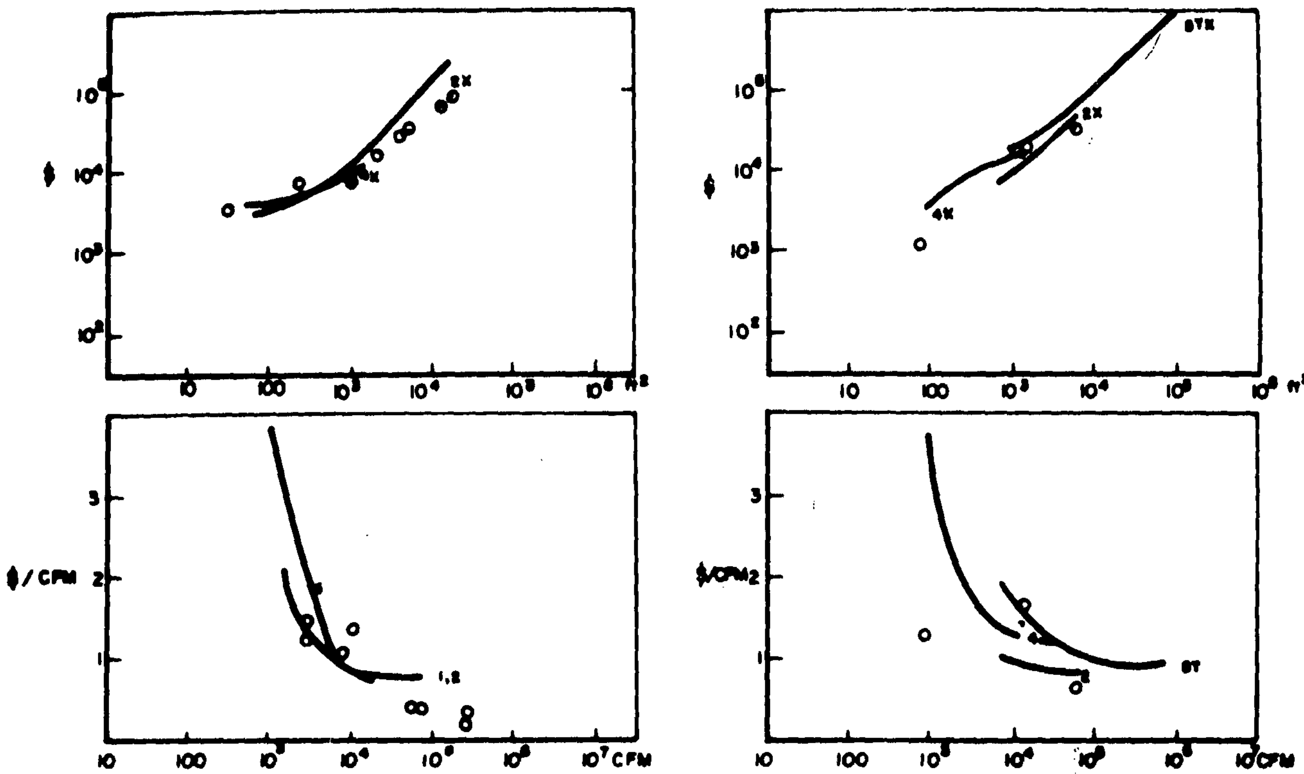
	Sinter Plant Windbox	BOF	Electric Furnace	Open Hearth	Shop Electric Furnace
Foundations	4	2	2	2	2
Ductwork and stack	4	37	35	25	37
Collector	71	32	34	42	27
Fan and motor	10	6	7	4	10
Structural	3	5	7	9	10
Electrical	5	7	9	8	7
Water treatment and piping	1	7	2	7	1
Controls	2	4	4	3	5

2. Labor/Material ratio for various components of particulate control systems (at $5/hr):

Collector	0.35
Fan, motor and starter	0.15
Stack	1.00
Ductwork	1.00
Steel	0.30
Foundations	1.30
Electrical	1.50

*From Barnes, Ref. 25.

intermittently cleaned envelope collectors. These costs are as the collector is normally shipped by the manufacturer, with freight paid to the shipping point (free on board, or F.O.B.). Costs are given both as dollars per square foot of fabric and as dollars per CFM of filtering capacity, assuming whenever necessary a typical air/cloth ratio (filtration velocity). These costs are based upon a survey of filter users, manufacturers' data, and the technical literature. Certain generalizations may be made from the information presented in Figure 7.5:



Reverse Jet Equipment (15 fpm assumed)

Pulse Cleaned Equipment (10 fpm assumed)

Note:

(a) All equipment without primary exhausters, but with secondary fans, blowers, etc. used for cleaning.

(b) Symbol (x) indicates data points estimated using the assumed air/cloth ratio.

Symbol (T) indicates high temperature equipment.

Symbol (O) indicates miscellaneous data points.

(c) Numerals indicate data source:

(1) Kane, American Air Filter Co., Ref. 26.

(2) Wright, Dracco-Fuller Co., Ref. 27.

(3) <u>Chem. Engineering</u>, (9 Feb. 1970).

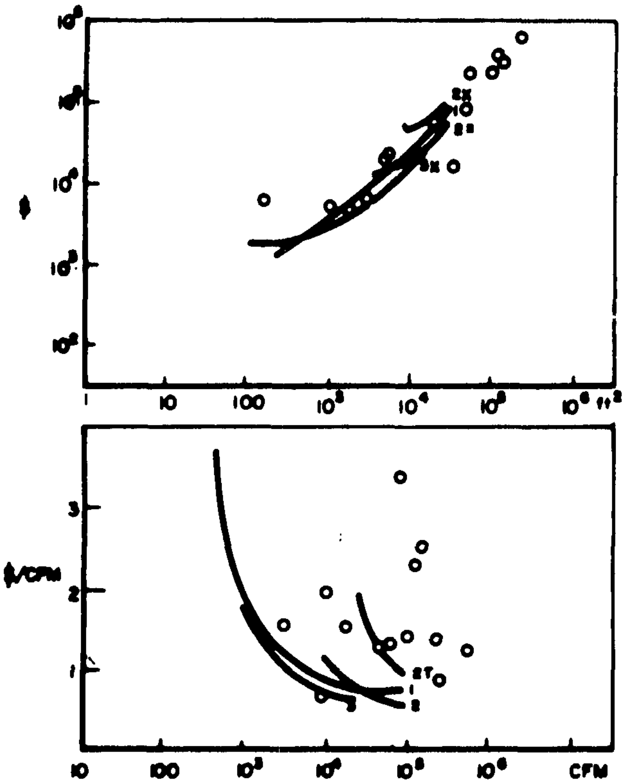
(4) Dennis, Ref. 28. Compressors and cleaning air fans included.

(5) US PHS, Ref. 29.

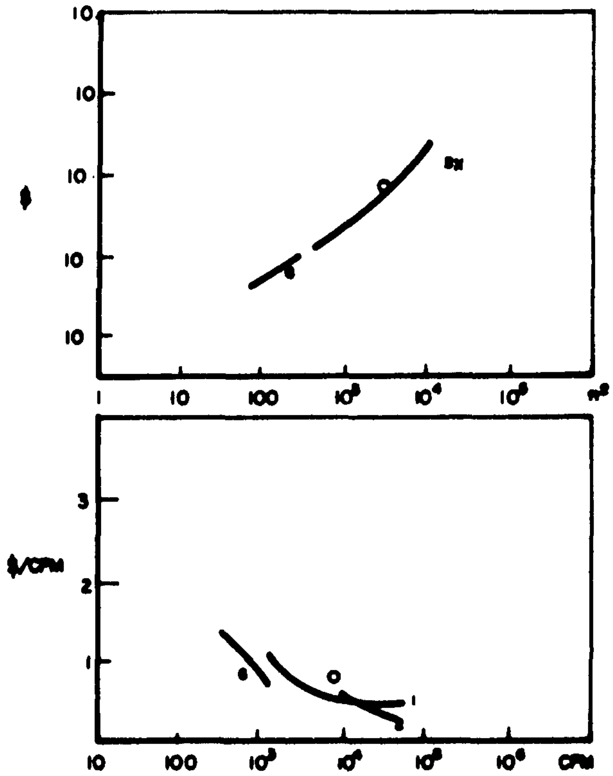
(6) A manufacturer's price list.

(d) All prices are updated, via Table 7.1, to reflect 1969 price levels.

Figure 7.5. Initial Fabric Filter Costs - 1969 Basis; F.O.B.



Compartmented Bag-Type
Equipment (3 fpm assumed)



Unit Envelope-Type Equipment
(3 fpm assumed)

Note:

(a) All equipment without primary exhausters, but with secondary fans, blowers, etc. used for cleaning.

(b) Symbol (x) indicates data points estimated using the assumed air/cloth ratio.

Symbol (T) indicates high temperature equipment.

Symbol (O) indicates miscellaneous data points.

(c) Numerals indicate data source:

(1) Kane, American Air Filter Co., Ref. 26.

(2) Wright, Dracco-Fuller Co., Ref. 27.

(3) Chem. Engineering, (9 Feb. 1970).

(4) Dennis, Ref. 28. Compressors and cleaning air fans included.

(5) US PHS, Ref. 29.

(6) A manufacturer's price list.

(d) All prices are updated, via Table 7.1, to reflect 1969 price levels.

Figure 7.5. (Continued)

1. Reverse jet and pulse jet collectors are about twice as expensive as other types in terms of fabric area, but are comparable on the basis of gas filtering capacity. Intermittently cleaned equipment is least expensive because it is designed for easier dust control applications and interruptable operations.
2. Costs per unit capacity increase sharply below about 3000 CFM, and approach levels as low as $.50 to $1.00 per CFM in large installations. For a preliminary estimate, a cost of $.80 per CFM of filtering capacity might be considered as typical, and the figure of $2. per ft^2 of fabric would represent a large number of collectors to within 50 percent of the true value.
3. Although cost data from a single source falls on one curve, costs from different sources appear to vary by as much as a factor of 3 for various reasons cited previously. This variation in cost is especially true for bag-type equipment, which is designed for a wide variety of temperature and particulate applications.

Part of the data in Figure 7.5 is shown in Figure 7.6 for better comparison. This was published about 1965 by a prominent manufacturer.[27]

The type of construction of the fabric filter assembly is particularly important for bag-type units, and for large equipment the unit cost depends more on construction features than on size. This variability factor is shown in Table 7.5 for several collector configurations designed primarily for high temperature applications. These cost estimates[30] include the baghouse, complete with the bag cleaning accessories, and materials handling equipment to accommodate dust removal from collection hoppers. They do not include the primary air moving equipment nor any costs for field installation, piping, ducting, or electrical wiring or insulation.

Except for preliminary cost estimating, prospective purchasers of filter equipment are advised to consult reputable manufacturers for accurate costs. Purchasers are advised to specify quality of material and construction, and to examine critically any bargain prices. Because the trade skills involved in producing filter equipment are fairly modest, the field is crowded. Manufacturers are often compelled to seek economies

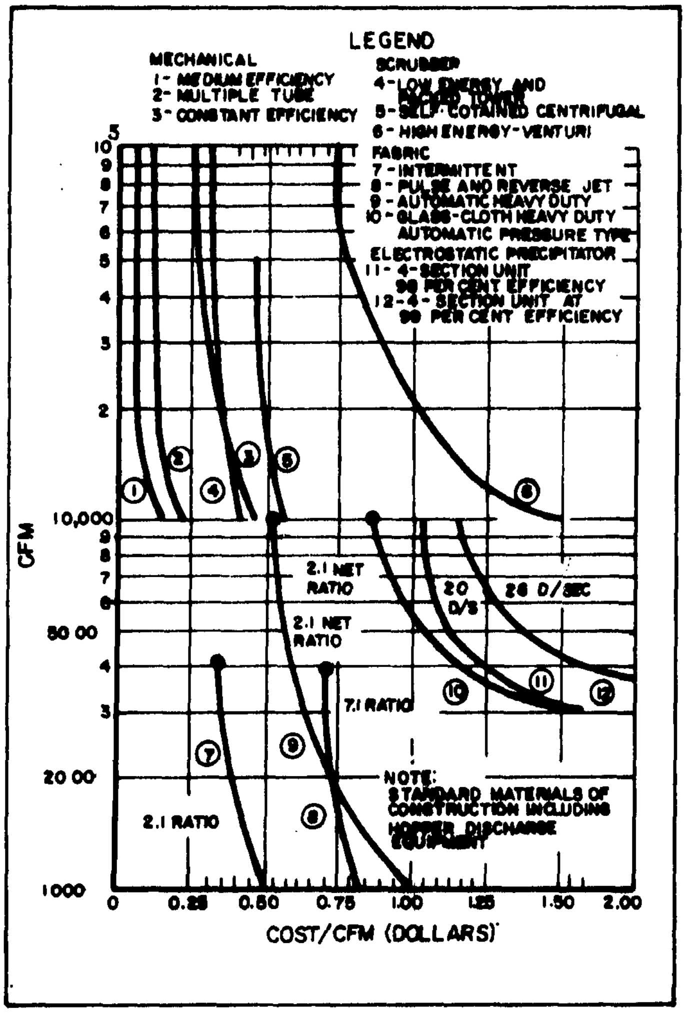


Figure 7.6. Cost Per CFM of 12 Different Dust Collector Designs Compared to the Total Volume Handled Per Minute. (To Convert to 1969 Estimated Price Levels, Multiply Scale by Marshall and Stevens Index 1.14.) (From Wright, Ref. 27).

TABLE 7.5

APPROXIMATE COST FOR BAG-HOUSES OF THE INDICATED CONSTRUCTION*

	PRICE RANGE $/SQ. FT. OF CLOTH
WITHOUT INTERNAL PARTITIONS:	
Open pressure unit	$1.20 to 1.40
Closed pressure unit	1.55 to 1.70
All welded unit	1.85 to 2.00
WITH INTERNAL PARTITIONS:	
Open pressure unit	1.35 to 1.50
Closed pressure unit	1.80 to 1.85
All welded unit	1.95 to 2.20

*Based on 11 1/2-in. diameter x 30-ft. long fiberglas filter bags and a minimum of 40,000 sq. ft. of cloth area. Cloth cleaning by repressuring. (From Adams, Ref. 30) 1969 cost basis.

that are sometimes not in the best long-term interests of the buyer. A dollar saved initially may cost several dollars in subsequent operating and maintenance costs. Furthermore, equipment that is well designed for one application may be a poor selection elsewhere. Rather than invest in cheap equipment, it is advisable to consider, if necessary, the redesign or modification of good quality standard stocked equipment. Although the purchase cost may be doubled, the long-term costs may be greatly reduced. It should be noted that about 15 percent of the operational problems encountered by fabric filter users are the result of equipment inadequacies.

7.2.2 Initial Fan, Compressor Costs

The purchase cost of fans or blowers suitable for fabric filter equipment, which includes motors, drives, and starters, varies inversely with system capacity as indicated in Figure 7.7. Purchase cost also increases with the design pressure to be delivered by the fan although this is not readily apparent in the figure because of the limited data from any one source. Cost is also determined by the style of the fan and

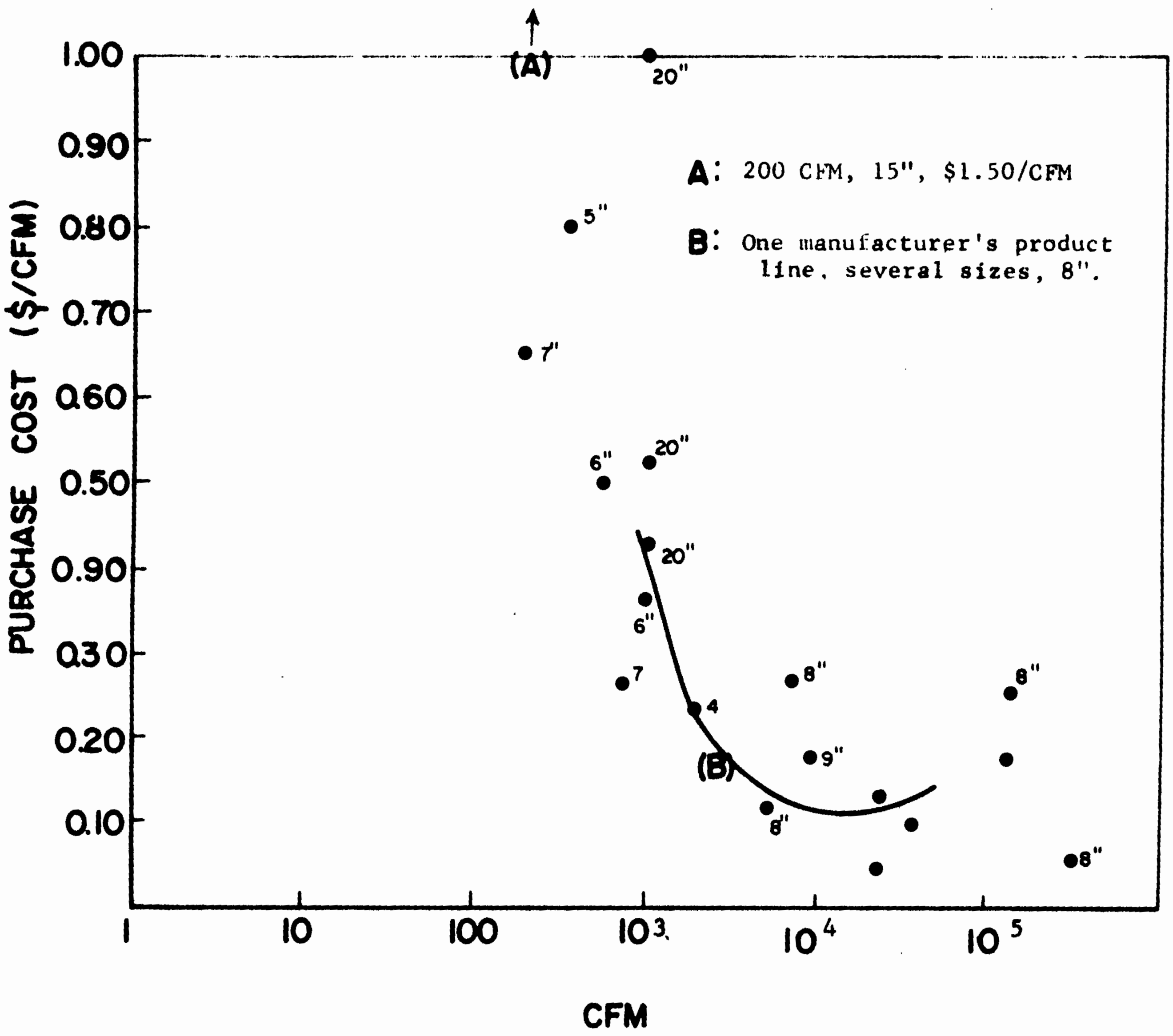


Figure 7.7. Fan and Blower Costs, Including Motor, Starter, etc. 1969 Basis. Fan Design Pressure Indicated.

its design speed. Generally, fans delivering 10,000 CFM or more will cost between \$.10 and .20 per CFM, fans delivering about 1000 CFM will cost \$.30 to .55 per CFM, and the cost of smaller fans increases sharply.

On the largest applications, the fan(s) may be custom fabricated. The gas properties and type of service affect the trade-off between initial cost and annual costs; e.g., a smaller fan running at higher speed will be slightly less efficient, and will probably require more maintenance than a larger fan operating at less than rated speed. This is especially true if the fan is located on the inlet side of the filter, where slower speeds are desirable if the dust is abrasive or gummy. Fan maintenance, which can be a big problem in some installations, may justify a larger initial size (and cost). It may be desirable to oversize the fan merely to allow for unforeseeable expansions of the collector or increased process effluents. In addition, it may be advisable to oversize the fan on collectors where the overall pressure differential fluctuates for any reason, to minimize reduction of gas flow during periods of high resistance.

Fan and motor costs are approximately equal. A starter for a 10 HP motor costs about \$75, and the drive cost should not exceed \$50. Fan-motor sets are around 60% efficient, such that one air HP, e.g. 1000 CFM capacity at 6.35 in. water represents about 1.6 electrical HP. Installation labor cost which is normally about 15% of materials cost and foundation costs is not included above.

The cost of an air compressor for pulse-cleaned equipment, pneumatically operated instrumentation, and dampers in some filter houses, is normally included with the initial fabric filter cost (see Section 7.1.1 for pulse cleaned equipment). Otherwise a separate compressor must be purchased at considerable expense, since the existing supply of shop air is often inadequate with respect to volume or pressure, or is not consistently available. For pulse cleaned collectors, the amount of compressed air varies according to the cleaning mechanism design. A typical design value is 2 SCFM per 1000 CFM of gas filtered, with delivery pressures ranging between 75 and 100 psig. The following estimates have been provided by compressor manufacturers specifically for continuous operation with dust collectors:

Pulsed Air, SCFM	Supply Pressure, psig	Motor Power, HP	Total Cost, $ F.O.B.	Approx. Initial Cost, $ per CFM filtered
135	100	25	2700	.04
100	100	25	2500	.05
10	100	3	700	.14

The cost is estimated to increase with the 0.28 power of the volume required.[31] Field installation is estimated at 0.60 times the cost of the compressor, and the ratio of installation labor to total materials cost is estimated at 0.27.

7.2.3 Duct Costs

The cost of ducting depends on the gauge and diameter as well as on the length and the material. It also depends on the complexity of the system, i.e., the number of elbows, Tees, transition sections, etc., and the amount of fitting needed to adapt the ducting to existing flanges. The ducting may require clean-out or inspection ports, dampers, or explosion panels. The cost of installing the ducting will also depend on location accessibility, as well as the method of joining and sealing the duct components.

One manufacturer of small filter units (up to 1200 ft^2) has reported his experience in installing ducting systems which for present purposes would be considered smaller than typical.[32] He indicated an average cost for installed ducting of $1.75 to 1.85 per pound of sheet metal, depending on gage and diameter. This included both fittings and straight piping on his medium and large jobs, but the cost was more for his smallest jobs. For example, a connecting duct assembly drop for a single filter unit of this size averaged about $53. (1969 cost basis). In the Chicago area one duct branch including headers cost about $250. Using the figure $1.85 per pound, Table 7.6 gives the estimated installed cost per foot for several gages and diameters: typically it is around $10 per foot. In support of this Table, a Boston sheet metal contractor independently estimated a cost of $5 per foot for a 100-foot system of 6" 18 gauge ducting including soldered joints and about 3 gates, installed.

Table 7.6 also lists the costs of typical duct fittings before installation. The cost of a fitting depends, of course, on the

TABLE 7.6

APPROXIMATE DUCT COSTS

(a) Installed Duct Systems*
($ per foot)

Metal Gage (U.S. Std.)	Thickness (inches)	Duct Diameter (inches) 6	12	24	48
6	.203	-	-	108.	216.
14	.078	-	20.75	41.50	83.
16	.062	8.25	16.50	33.00	66.
18	.050	6.60	13.20	26.40	53.
20	.0375	4.90	9.80	19.60	39.
22	.0312	4.10	8.20	16.40	31.
24	.025	3.30	6.60	13.30	-
26	.0188	2.50	5.00	10.00	-
30	.0125	1.65	3.30	-	-

(b) Duct Fitting Costs**
($ per item, not installed)

Description	Gauge	Diameter (inches) 6"	12"	24"
Straight pipe, per foot	20	2.40	3.90	6.50
	24	.56	.95	2.97
Same, with self-locking seal	24	1.50	2.80	-
	26	1.18	2.24	7.60
Reducer	20	$18.(12x6)	$36.(24x12)	
Flange	20		$23.(12")	$35(24")
Tee, 45°	20	$33(12x12x8)	$50(24x24x12)	

*1969 cost basis of $1.85 per pound for galvanized sheet steel, riveted and soldered, including a nominal number of fittings.

**1969 Boston area prices; in lots of 10 fittings each.

amount of work required to make it; typically the fitting costs 2 to 4 times as much as the same length of straight pipe.

Installation labor is estimated[31] to be 85 to 100% of material cost; that is, the cost of the installed ducting is about half material and half labor. This rule of thumb varies with material and difficulty of installation, of course.

Materials other than galvanized steel are sometimes used. Estimates for shop fabricated, field erected ducting of aluminum, galvanized steel, and stainless steel are $5.42, 8.00, and 15.12 per foot, respectively, (no sizes or gauges given).[31] These costs are further estimated to increase with the 0.55 power of the size. These estimates presumably apply to the same ducting requirement and therefore should represent thicker aluminum than steel, for structural reasons.*

There is little in the filtration literature on actual duct costs, but a survey of nine large filter installations averaging 50,000 CFM indicated the costs of the associated ducting to be $.60 per CFM (range, $.25 to $1.00). This included applications of both high and low temperature filtration, and both short and long reaches. In Iron and Steel Industry applications the system ductwork cost is estimated at around 30% of the total initial material costs.[25]

7.2.4 Dust Disposal Equipment

The purchase of dust handling and disposal equipment must be compared against doing the job manually, but even so the equipment is justified by the high cost of labor on all but the smallest dust flow rates. The disposal equipment typically includes a rotary valve and drive, one or more dust conveyors with drives, and a collection bin of some kind. This excludes the hopper, which is usually provided as part of the basic collector.

A good quality 8" dia. rotary air lock valve metering on the order of 1 CFM costs $400 to $500 including motor and drive. Motor and

*Aluminum sheet goes by Brown and Sharpe gauge numbers, while steel goes by U.S. Standard gauge numbers. For approximately the same thickness, use two B&S numbers lower than the U.S. Standard number.

drive each cost about $75 depending on size and detail. It may be possible to drive the valve from the conveyor shaft and eliminate the need of a separate motor.

The most common type of dust conveyor in use is the screw conveyor consisting of a 6" to 15" diameter covered trough, a screw of 10 to 16 gauge carbon steel, end plates, motor and motor mount, drive, and drive guard. The total cost is on the order of $40 per foot, depending on design. The trough and screw alone cost approximately $25 per foot (9" diameter, 14 gauge screw, 12 gauge trough, 2" screw shaft diameter, 30 ft. long). The cost of conveyor is about $450 including motor.

Normal power requirements are 1/15th HP per foot of conveyor, but not all dusts flow this freely. A number of dusts become sticky as the temperature drops, or pack together due to vibration or mechanical churning; consequently many problems arise with screw conveyor plugging and breakdage, and other types of dust conveying equipment are sometimes used. Table 7.7 gives cost estimates for several such conveying methods. The costs do not agree with the above estimates, and the data in Table 7.7 is suspect for other reasons, but it may be useful in making comparisons.

7.2.5 Instrumentation

The effective utilization of any fabric filter system, regardless of size, cannot be obtained unless certain basic measuring devices are incorporated. Optimum collector performance depends upon the observation or control of several major variables such as gas temperature, system pressure, fabric pressure drop, gas flow rate, humidity, particulate properties (mass concentration and size), dust levels in hoppers, etc. The above listing of variables does not necessarily represent their relative order of importance. In a system where accidental condensation of moisture could produce rapid fabric blinding the sensing of dewpoint might take priority. High temperature filtration, on the other hand, requires that the temperature not exceed levels beyond the tolerance of the fabric. In applications characterized by high and possibly variable dust loadings, the maintenance of gas handling capacity depends upon the measurement of fabric pressure loss. The number of separate sensing devices

TABLE 7.7

REPORTED ESTIMATES OF CONVEYOR COSTS*
(per foot of length)

Type, Size	Cost (1)	Size Exponent (2)	Field Installation Factor (3)	Labor/ Materials Ratio (4)
Belt 18 in. wide	460	0.65	1.69	0.33
24	550	0.65	1.69	0.33
36	640	0.65	1.64	0.28
42	720	0.65	1.64	0.28
48	770	0.65	1.64	0.28
Bucket (height)				
30 tons/hr. (8 in.x 5 in.)	225	0.65	1.84	0.44
75 tons/hr. (14 in.x 7 in.)	410	0.83	1.84	0.44
120 tons/hr. (15 in.x 8 in.)	510	0.83	1.84	0.44
Roller, 12 in. wide	7	0.90	1.69	0.33
15	8	0.90	1.69	0.33
18	9	0.90	1.65	0.29
20	10	0.90	1.65	0.29
Screw, 6 in. dia	235	0.90	1.59	0.25
12	280	0.80	1.59	0.25
14	300	0.75	1.59	0.25
16	310	0.60	1.59	0.25
Vibrating, 12 in. wide	80	0.80	1.64	0.28
18	115	0.80	1.64	0.28
24	125	0.90	1.60	0.26
36	135	0.90	1.60	0.26

*From Ref. 31.

(1) Although reported as $/ft, some of these costs appear more reasonable as total costs. 1969 basis.

(2) Cost increases with equipment length raised to this power.

(3) Installation costs include foundations, electrical, paint and field labor, and add about 65% to purchase costs.

(4) Total installation labor is about 30% of total material cost.

justified and their degree of sophistication are related to the size and/or the capital investment associated with the fabric filter system. Regardless of system size, pressure measuring devices in some form should be used and are usually supplied by the manufacturer. Simple draft gages provide a measure of fabric resistance (and magnitude of dust loading), and give the static pressures at various points within the system. These, in turn, can be related to gas flow rates and power consumption.

In a small system, observation of key pressures permits manual adjustment of gas flows and actuation of fabric cleaning equipment, either manual or motor driven. Similarly, reference to visual display of temperature indicates whether dilution air dampers or pre-cooling sprays should be adjusted. In the large fabric filter system, however, reliance upon manual control becomes highly impractical and the sensing systems are coupled directly to control locations for automatic operation. A well instrumented system not only protects the investment and decreases the chance of malfunction, but also enables the user to diagnose and rectify many of the simpler operating problems without resort to outside professional consultation. In any case, outside assistance can be employed more effectively when the operating characteristics of the system are defined and understood by the user.

Table 7.8 gives representative catalog costs of instrumentation types commonly used in fabric filter systems. Relatively more expensive equipment is recommended for long-term rugged use, high temperatures, abrasive conditions, corrosive gases, etc. The additional cost of installing and adjusting the typical instrument is estimated to be of the same order as the instrument price.

The instrument indicators can be grouped on a central control panel, the cost of the panel running $200 to $500 per foot of panel depending on the density of the instruments. This cost includes wiring and pneumatic piping but excludes instrument cost. The cost of installed instrumentation will vary from $.01 per CFM for a large baghouse to roughly $.10 for a 1000 CFM unit.

Standard instruments should be used whenever possible for reliability and ease of replacement parts. Standardization will minimize

TABLE 7.8

TYPICAL INSTRUMENTATION CATALOG COSTS - 1969

Purpose:
A: For indicating
B: For recording
C: For controlling

Variable, type	A	B	C	Catalog Cost
Temperature				
Flue gas thermometer	x			$ 45 - 70
Dial-type thermometer	x			30 - 100
Recording thermometer	x	x		25 +
Sensing switches		x	x	20
Sensor + Rustrak recorder	x	x		200
Thermocouple bridge + amplifier		x	x	200
Pressure				
Draft gauge, inclined	x			30 - 70
U-tube monometer	x			15 - 60
Sensing switches, min-max			x	30
Sensing switches, differential		x	x	40
Flow				
Hand-held tube-type kit	x			275
Low velocity mass flow, electronic	x	x		178
Time record clock	x	x		80
Motor-type valve or damper controller	x		x	125
Humidity				
In-line industrial hygrometer	x			110
Recording hygrometer (Temp,humid.)	x	x		325
Transducer, electronic		x	x	350
Dew point sensor	x			---
Mechanical Sensing				
Lever-arm, mercury switch	x	x	x	15
Particle variables				
Continuous size monitor				--
Fabric hole detector	x	x		100
Mass Concentration meter	x	x		---

maintenance costs which will be one of the factors traded off against the initial costs.

7.2.6 Planning and Design Costs

A certain amount of time goes into planning the dust collecting system, principally in the form of calculations and drafting but also as meetings, procurement, travel, etc. For the experienced user of fabric filter equipment this may not amount to much, especially if he uses so many small collectors that he keeps them in stock. For inexperienced users and those designing collection systems for new applications, the time may range from 10 to 1000 man-hours or more. Large systems justify careful planning, as do those that must perform with high reliability, and those that involve a large risk of fabric damage.

It is customary to charge small amounts of staff time to an overhead account, which means the cost will not be reckoned against the filter system. The cost of larger planning programs may or may not be added to the other costs of obtaining and installing the system. Nevertheless, the costs should be estimated and included in all comparisons of alternative dust control systems, unless the planning is to be furnished free by an equipment supplier.

Procedures for designing a filter system are discussed in Chapter 5. Engineering of this kind will cost approximately $15 per hour, including the normal overhead costs of maintaining an engineering staff. Thus a typical planning cost for a good sized system may be $1500, or on the order of $.10 per CFM of system capacity.

7.2.7 Foundation and Installation

A fabric filter system may be installed outside the main plant building when no space is available within the main structure or when a cost analysis shows that the outside location is on the whole less expensive. Although the cost of outside site preparation is discussed at length in the literature,[1,31] the basis for cost breakdown is sometimes obscure, particularly between direct and indirect costs.

Since fabric filter units weigh from 0.25 to 1 ton per 1000 CFM capacity not including fans, motors and ducting, they require substantial foundations and supporting members. These may account for 4 percent of the installation for material costs and an additional 5 percent for associated labor (Table 7.4).

Many fabric filter installations, even though themselves moderately well sealed against weather, still are best housed for easier maintenance in bad weather. A separate light weight building to house the equipment is estimated to cost $1.50 to $5 per ft^2 of floor area based on reported costs for single-story garage and maintenance shop shells. This includes foundation, structural frame, outside siding, inside partitions, and paint.[31] The filter may alternatively be located indoors, where it requires typically 1 sq. ft of floor space for each 50 CFM capacity. For this space a substantial annual charge is normally made (Section 7.2.3a). Outside or inside, the cost of installation, at about $5 per hour wages plus 50% overhead, amounts to 30 or 40% of the initial equipment cost on large equipment. It may be, however, 2 or 3 times higher in special cases. Itemized installation costs are discussed in preceding sections and shown in Table 7.4.

A frequent consideration is whether it is best to purchase the filter assembled or to assemble it on site. The net cost to the purchaser will probably be about the same; the cost of assembly at either location is estimated at around 10% of the total on-line cost. Factory assembly is usually preferred from the standpoint of job quality unless unusual skills are available at the site. Railroads, however, have size limits of approximately 9.5 x 12 (high) x 40 feet.* The cost of painting including protective coatings is estimated at 5% of the assembled cost, and the place at which the painting is done makes little difference to the purchaser.

7.2.8 Start-Up Period

Although not usually reckoned as part of the baghouse installation cost, there is in fact nearly always a period following installa-

*Freight rates for steel vary with the amount shipped. Minimum carload rate in the Boston area requires at least 40,000 lbs.

tion when personnel are becoming accustomed to the equipment and unforeseen operating problems are being corrected. This period ranges from a few hours to over a year. Start-up cost is herein treated as an initial rather than as an annual cost for convenience, even though it may extend into the useful life of the equipment.

Analysis of 78 problems reported by the users of 26 fabric filters of many types and sizes indicated that at least 20 percent of the problems were related to becoming accustomed to the equipment or to faults in the installation. Half of these start-up problems were connected with the filter itself, such as poor seals between panels, bags located too close together, or failure of the shaker mechanism due to weak design. Other start-up problems are cited in Chapter 8. Whether from inadequate design or untrained use, problems do often arise and they do cost the purchaser money. Furthermore the installation of the equipment may require a temporary plant shutdown, which may be considered a start-up cost.

It is estimated that the start-up costs may on the average add 50% to the normal maintenance cost for the first year, that is, amount to about $0.10 per CFM. Start-up cost may be much higher, or on the other hand the purchase of equipment known to be of superior quality, and the use of well trained or experienced personnel, can much reduce the learning costs.

7.3 OPERATING AND MAINTENANCE COSTS

The costs of operating the fabric filter system from day to day and keeping it in good working condition include:

Cost Item	Typical Cost Range	Section
Power		
Fan power for filtering	$ .10 - .25 per CFM-yr	7.2.1
High pressure air for cleaning	0 - .25 "	
Labor		
Fabric replacement	.02 - .20 "	7.2.2
General maintenance	.02 - .20 "	
Dust Disposal	.01 - .15 "	
Plant Overhead		
Space, heat, lights, insurance etc.	.05 - .50 "	7.2.3

Operating and maintenance costs considered to be "typical" are indicated in Table 7.3 and Figure 7.3, where together they make up $0.67 per CFM-year, or about 2/3rds of the overall yearly filter cost. In addition there are the costs of purchasing replacement fabric which are discussed separately in Section 7.3, and various incidental costs discussed in the following pages. To these are added a yearly amortized portion of the initial costs of the equipment, installation, and capitol costs (Section 7.1) as discussed in more detail in Section 7.4.

Operational and maintenance cost data were available for about 50 fabric filter installations via both the literature and the GCA Survey*. These varied in size from 330 to 820,000 CFM. The mean operating and maintenance cost as reported, including power, labor and fabric replacement but excluding overhead*, was $0.52 per CFM-year. Only 6 installations reported O&M costs in excess of $1. per CFM-year as indicated in Figure 7.8. Overhead is estimated at typically an additional $0.025 per CFM-yr., (Section 7.2.3).

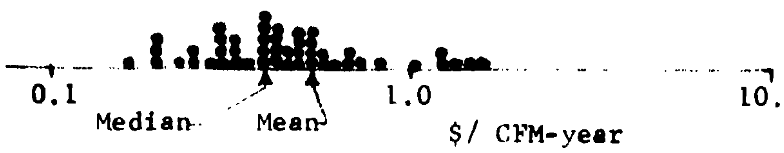


Figure 7.8. Total Operating and Maintenance Cost. (As reported, including power, labor, and fabric replacement, but excluding overhead). (From GCA Survey, 1969).

The following indicates the difference in apparent costs of two hypothetical plants, one of which meticulously includes overhead while the other uses only direct costs:

* It cannot be determined precisely what indirect costs are in the figures reported in the literature. Engineers are inclined to report only direct expenditures, while others may include the costs of plant space, employee fringe benefits, tax rebates for expendible items etc. GCA surveyed direct costs by asking for task labor requirements in hours, prices as billed, etc.

Annual O&M Costs ($/CFM-yr)

	Direct Cost Only		Including Overhead	
Power	$	.12	$	.12
Labor		.21		.38
Space		---		.05
Heat		---		.06
Other overhead		---		.04
Fabric (see Section 7.4)		.18		.09 (Tax rebate)
Total:	$	.51	$	.74

Each of these costs varies widely from installation to installation.

7.3.1 Power Costs

The cost of power for pumping the gas through the filter is perhaps the most easily determined of all the system costs; it is given simply by

$$\text{Power Cost} = CQ\bar{p}/E$$

where C = cost of electricity
Q = volume flow rate
$\bar{p}$ = average fan pressure
E = fan-motor efficiency

The cost of electric power is typically $.012 per kilowatt hour, depending on location and the type of industry. The power conversion efficiency of fan-motor units is usually taken as 60%. The average pressure at the fan is the only indeterminate factor and even this is partly determined by the filter operator's control of the fabric cleaning process. The average fan pressure is typically 5 to 10 inches of water (See Figure 7.7) and the portion contributed by the filter alone, indicated in Figure 7.9, is typically 3 to 6 inches. Power cost for fan, blower, or compressor operation may be determined using Figure 7.10, which is based on the above equation using a 60% electrical to air power conversion efficiency.

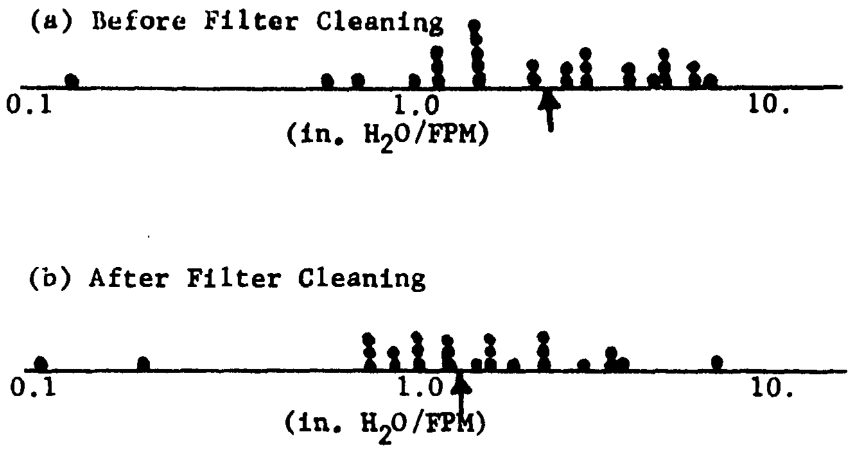


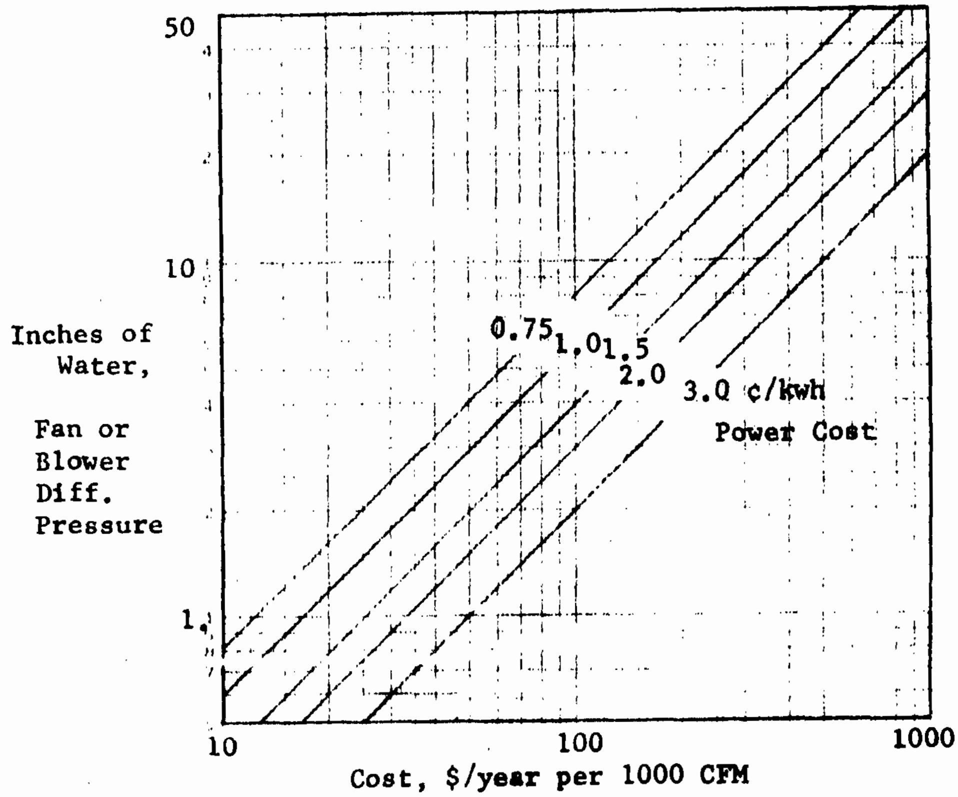
Figure 7.9. Typical Filter Pressure Drops. (Assuming an average filter velocity of 3 FPM, median pressure drops are 7.5 and 4.5 inches of water, or 6 inches average. (From GCA Survey, 1969.)

Figure 7.10 is based on full time operation; therefore, if for some reason the filter system only operates 3 hours per day the actual power cost would be one eighth as much.

7.3.2 Labor Costs

Labor skill requirements range from supervisory and instrument repair categories down to unskilled labor for such tasks as dust disposal, and these wages currently range approximately from $2.50 to around $6.00 per hour. Considering the typical labor overhead of employee benefits, medical coverage, administration etc. the net cost of average labor to the company can be estimated at almost twice the actual wage.

Among about 30 fabric filter installations reporting labor data, about .047 man-hours were required per CFM-year, equivalent to about $0.21 per CFM-year in wages. Costs for specific filter installations are listed in Appendix 7.2.1. These costs were reported to be distributed as in Table 7.9 among several tasks common to most filter installations. The task labor distributions are further shown in Figure 7.11. Fabric replacement is indicated



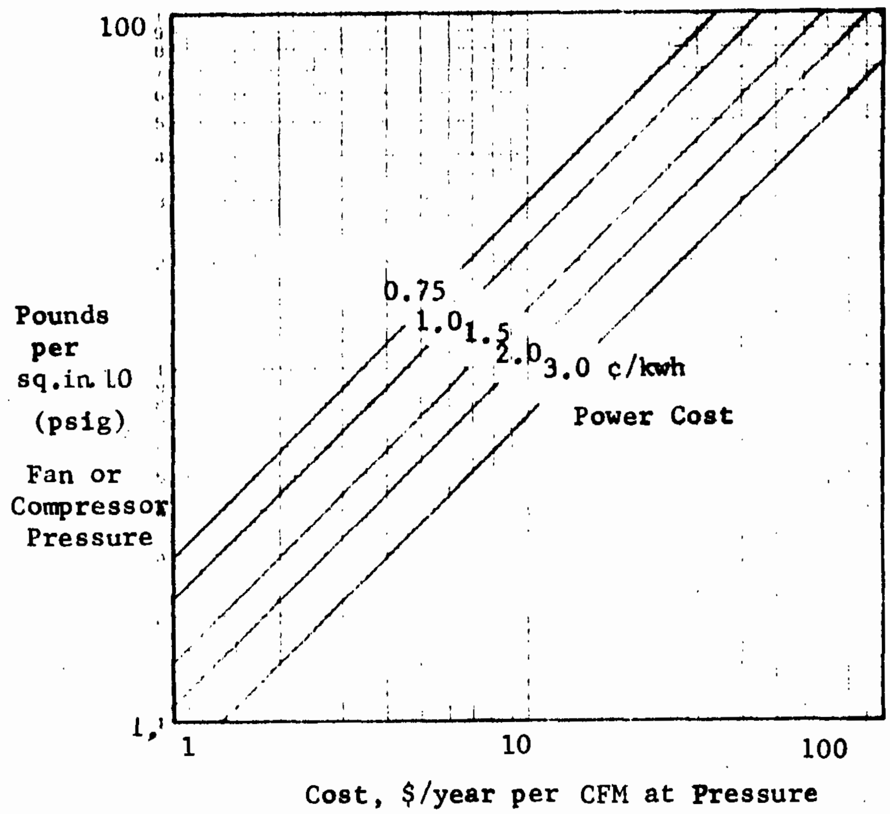


Figure 7.10. Air Power Costs. (Based on a 60% fan-motor power efficiency and full-time operation.)

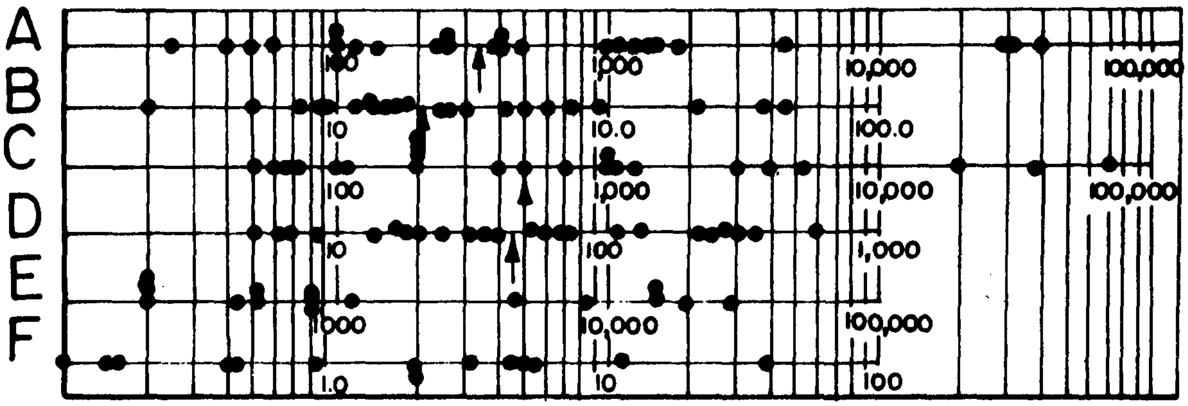
TABLE 7.9

REPORTED LABOR DISTRIBUTION COSTS*

	Bag Replacing	General Maintenance	Dust Disposal	Bag Cleaning & Repairing	Total	(Units)
%	47	39	13	1	100	%
No. Reporting:	27	26	27	27	(30)	Count
No. Practicing:	26	26	13	4	(30)	Count
Mean Practice:	.084	.083	.073	Var.	.207**	$/CFM-yr
Median Practice:	$2.00/bag	$.045/CFM-yr	$2.00/ton	---	---	---

* GCA Survey data. Reported wages, before overhead.

** The average of combined task costs was $.207/CFM-yr; the combined task average cost is $.24/CFM-yr.



A. Replacement Labor, $/year

B. Replacement Labor, $/bag

C. Other Maintenance Labor, $/year

D. Other Maintenance Labor, $/KCFM-year

E. Disposal Costs, $/year

F. Disposal Costs, $/ton

Figure 7.11. Reported Labor Costs, GCA Fabric Filter Systems Survey, 1969, (Wages, before Overhead)

to absorb almost half the labor; on the average it takes about half an hour to replace a filter element including preparation time, filter clean-out time etc. Fabric lasts about one year on the average (Section 8.3).

Fabric filters typically require about 10 hours of attention per KCFM per year for such things as inspection of the fabric, instrument adjustment, fan servicing, etc., excluding the other labor categories shown and excluding unscheduled repairs. (Unscheduled repairs are so variable that they were not made a part of the survey, but may perhaps be estimated at 1 or 2 hours per KCFM-year).

The purchase of dust handling and disposal equipment trades off against doing the job manually. Among 13 fabric filter installations reporting dust disposal costs the average direct cost was about $2. per ton with variations from $12. per ton down. These companies had already installed a reasonable amount of disposal equipment, and the $2./ton figure represents the manual balance of the task. Most of these companies did the work themselves, but about a third of them contracted the work out to a local trucking firm.

Fabric cleaning and repairing is apparently practiced by only a small percentage of filter users, usually those with expensive fabric that tends to bind or plug frequently. One installation periodically sent the bags out to be dry cleaned. Another found that ordinary cotton bags could be patched in place quickly and inexpensively. (See Chapter 8).

These reported costs could be adjusted in two ways although as given here they have not been adjusted. First, as mentioned above the cost of labor overhead could be included as a factor of from 1.5 to 2, except for labor contracted outside the company. Second, these costs could be adjusted for the fraction of the year the equipment was in actual use. For example,200 hours a year spent in replacing fabric on a filter used only 8 hours per day might be interpreted as equivalent to 600 hours a year on a full-time filter. However, there is no assurance that the fabric life would remain the same, as if the fabric were being damaged by condensation due to frequent shut-downs the fabric life might actually increase if the operation went to full-time. Lifewise most other labor requirements cannot be scaled with assurance. A scaling factor may if desired be obtained from Appendix 7.2, where approximately two-thirds of the installations operated full-time and the other third operated an average of 22% of the time, giving an average operation of 75% of the time and a scale factor of 1.33.

7.3.3 Plant Overhead Costs

Just as there is an overhead cost associated with the use of manpower, there is a cost associated with the use of the plant. This can include a variety of charges--Rentals, utilities, administration costs, taxes, etc., and the overhead cost factor depends to a large extent on the company's accounting practices. Some of these costs may go on the books against the filter system whether or not they involve actual cash expenditures, while other costs may never be compared with the filter operation even though they are directly related. The cost of space occupied by the filter is apt to be one of the latter. The following presents a brief summary of typical plant overhead costs per CFM-year:

	Direct Expense	Actual Expense
Space	$ 0	$ .055
Heat	.15	.15
Insurance, taxes	.045	.045
Other	Var.	Var.
Total:	$ .195+	$ .25+

Variances in these costs are discussed briefly below.

7.3.3.1 Space - The filter housing and its peripheral equipment should be considered as renting the plant floor space occupied, as they prevent the space being used for something more profitable. In certain circumstances the upper room space may also have value. On the other hand equipment located in unused buildings or outdoors may not incur a space cost. Plant space varies in value, but a typical rental value is $2.75 ft^2 year (1969). Rental cost may not include heat, light, water, sewer, taxes, etc.

The filter capacity packed into one square foot of housing base area depends on the filter height, the filtration velocity and the cleaning mechanism, and consequently the packing varies widely from installation to installation. Figure 7.12 shows the capacity packing for

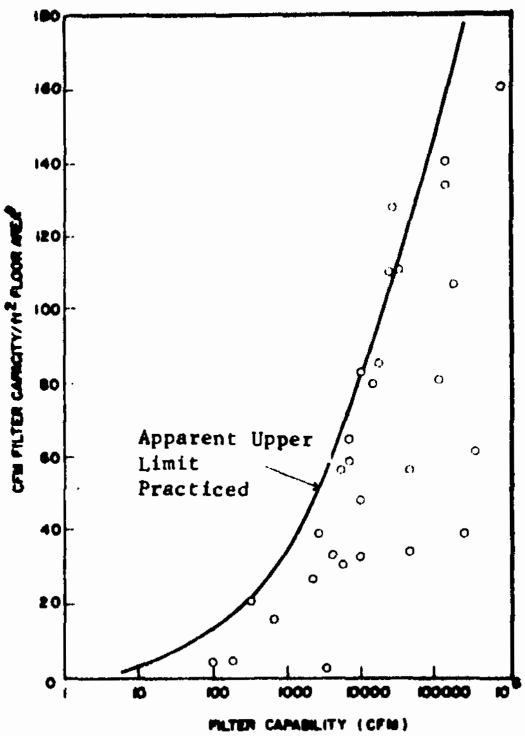


Figure 7.12. Plant Floor Area Required per Filter Capacity. (Based on Collector Dimensions plus 3 ft. Perimeter Clearance.) GCA Survey Data.

30 installations surveyed. It appears there is an upper packing limit in practice; for example, few installations of 10,000 CFM capacity would exceed 80 CFM per ft^2 although many would occupy the same amount of plant floor area and filter less air. As several maintenance problems appear when the fabric is packed too close together (Section 5.2.6) or when the air/cloth ratio is made too large (Section 4.2.2) there may be good reasons to avoid the apparent packing limit indicated in the figure.

Picking from the figure a typical capacity of 50 CFM/ft^2 of floor, and the rental cost of \$2.75/ft^2-year, one obtains a typical space cost of \$0.55 per CFM-year, which is one of the overhead costs.

7.3.3.2 Heat - Some baghouses exhaust unwanted heat to the outdoors, but others waste heat, particularly in winter months. In the northern half of the U. S., fuel usage costs approximately $.40 per CFM per year when the air is exhausted outdoors. This is an annual average based on a 154 hour week and an 8 to 9 month heating season. Over the U. S. an average heat cost may be $0.15 per CFM-year. Other cost considerations are the exhausting of air previously air conditioned, and the cost or value of providing alternative ventilation by means other than the filter system.

7.3.3.3 Insurance and Property Taxes - These combined are estimated to cost about 1.8% of the installed cost of the baghouse, or about $.045 per CFM per year.

7.3.3.4 Lights - Lighting should be installed around the baghouse, but the annual cost is probably negligible.

7.3.3.5 Supply Inventory - Normally at least one set of bags is kept on hand at all times, and spare fan parts etc. may also be stocked. Annual inventory costs amount to approximately 10% of the inventory investments.

7.3.4 Collection System Returns

Offsetting the filter system annual costs in some cases is an actual profit from operating the system. For example, particle collection may be a basic part of the manufacturing process, or the dust collected may have a high sale value as in many non-ferrous metals refining applications.

The return on investment for a fabric filter installed to control a community air pollution factor is frequently difficult to asses. Installations which eliminate dust damage claims and expensive and time-consuming complaints or litigation will represent a direct economic return to the user in terms of reduction of management problems.

Since many dust induced diseases have an etiology requiring several years exposure, and are non-specific, the utilization of fabric filtration for health protection purposes usually makes excellent economical sense. Other direct benefits from the reduction of visible but otherwise innocuous dusts include improved plant housekeeping and reduced maintenance on plant machinery, improved visibility, increased employee morale, improved product quality, etc.

7.4 CLOTH AND BAG COSTS

Bags fitted for a specific model of fabric filter are available from a number of suppliers, usually including the manufacturer of the filter. The prices depend very much on the cloth used; that is, on the kind of fiber, the weave and weight of cloth, and on specific treatments given the cloth, yarn, or fiber during manufacture to protect the fabric in use from fire, rot, mildew, abrasion and so on. Table 7.10 indicates costs for a number of fairly typical bags as purchased a set at a time. Also given for comparison are some fabric and fiber costs. A typical bag, ready to be installed by the purchaser's maintenance crew, costs $10; however, bag prices range between $1 and $100. A breakdown of the cost of a typical bag in Table 7.11 indicates that the bag cost increase accrues in making the fabric, and the rest in making the bag from the fabric.

As basic as the purchase price of the bag is, it is only one factor in the fabric-related costs of operating the filter system. Even more important is the fabric life which depends on many things as discussed in other sections of this volume. By maximizing the length of time the fabric remains useful, the fabric costs and related replacement labor costs measured in dollars per year are minimized. Figure 7.13 indicates the results of a survey of about 40 filter installations. As indicated, most fabric lasted about one year, with a resultant median cost of about $0.10 per CFM-year and a mean cost of $0.18 per CFM-year.* Cotton and glass were the most widely used fabrics reported in the survey.

Associated with the installation of every bag is a labor cost, typically between $1.50 and $2 per bag; this is discussed in Section 7.2.2.

Fourteen fibers used in fabric filtration are listed in Table 7.12 (See also Section 4.2.1). The approximate price of each fiber relative to cotton is given along with its temperature limitations. Figure 7.14 relates temperature and cost for some of the common fibers and shows why glass is a popular fiber despite its mechanical durability limitations.

TABLE 7.10

TYPICAL FILTRATION FABRIC COSTS

Basic Material	Fiber Cost/lb.	Woven Fabric Cost/Yd	Felted Fabric Cost/Yd	Selected Retail Bags* Cost	Lengths x Diameter
Cotton	.40	.41	--	13.60	21' x 9"
				1.50	5' x 5"
Wool	(Wide Var.)	1.77	--	--	--
		-~	3.97	50. F	14' x 7"
				35. F	7' x 12"
Orlon[R]	.66-.80	1.01	--	5.	9.5' x 6"
		-~		3.	13.5' x 5"
			4.82	--	--
Dacron[R]	1.40	1.04	--	30.	30' x 10"
				22.	25' x 11.5"
				13.70	22.5' x 12"
				2.80	9' x 6"
		~-	4.82	25. F	5' x 5"
Nomex[R]	2.50-6.00	--	--	50.	25' x 11.5"
				27.	20' x 8"
			11.50	--	--
Nylon	1.00	.70	--	--	--
Fiberglass	.60	.98-1.68	N.A.	27.	20' x 8"
				20.	25' x 12"
				16.50	25' x 11.5"
				10.	22.5' x 8"
				9.63	12' x 5"
				2.80	6' x 7"
Teflon[R]	--	8.00	--	75.	25' x 11.5"
		(8 oz)	36.70(23 oz)	--	--
			29.20(19 oz)	--	--
Fiberfrax[R]	20.00	38.00	--	--	--
Brunsmet[R]	~40.00	--	--	--	--

* Note: Bag costs and fabric costs are not related, as the information is from separate sources (References 9, 10,11, and GCA Survey, 1969).

(F) Felted fabrics

(R) Registered Trademark

TABLE 7.11

COSTS OF TYPICAL BAG

	Typical Bag	Range Available
Bag purchase cost:	\$ 10.	\$ 1- 100
Size:	20 ft^2	1 - 100 ft^2
Cost per ft^2:	\$ .50	\$ 0.15 - 4.00
Fabric cost:	\$ 2./yard	\$ 0.40 - 40./yard
Fabric cost per bag:	\$ 4.40	\$ 0.25 - 25.
Fiber cost:	\$ .75/lb	\$ 0.40 and up/lb
← Fiber cost per bag:	\$ 1.10	(wide variation)
Fiber-to-fabric factor:	~ 4x	-- --
Fabric-to-bag factor:	~ 2x	~0.5x - 5.0x

Types of fabric used:

Cotton	33 %
Glass	33
Polyester (e.g. DACRON[R])	15
Acrylic (e.g. ORLON[R])	5
Wool	5
Other types	9

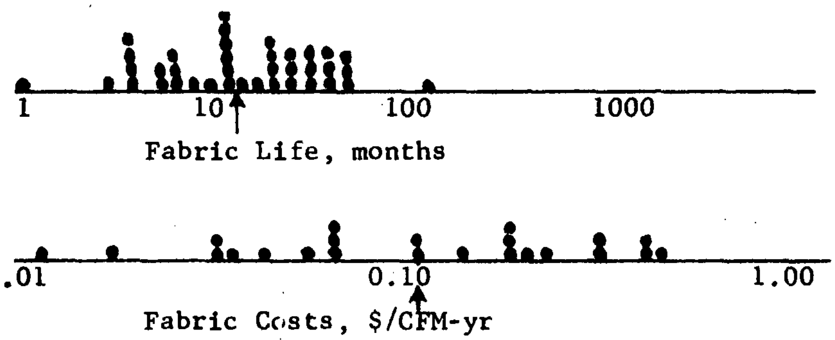


Figure 7.13. Fabric Usage Reported and Costs. (Costs as reported, before tax credit.) (From GCA Survey, 1969, and miscellaneous literature data.)

TABLE 7.12

FIBER, TEMPERATURE RANGE, AND RELATIVE COST

Type	(Typical Name)	Recommended Temp. Range: Max.	Contin.	Approximate Cost
Cotton	---	225	(160-190)	1
Rayon, acetate	---		210	1.1
Wool	---	250	(180-235)	2.75
Acrylic	(Orlon[R])	275	(200-275)	2.75
	(Dynel[R])	240	(150-180)	3.2
Vinyls	---	---	250	2.7
Polyester	(Dacron[R])	325	(250-280)	2.8
Polyethylene, polyolefin	(Polyfain[R])		200	2.
Saran			160	2.5
Polyamide	(Nylon)	250	200	2.5
- modified	(Nomex[R])	500	425	8
Polypropylene	---			1.75
Poly-TFE	(Teflon[R])	500	(225-450)	30.
Glass	---	600	(450-550)	5.5
Asbestos	---		500	3.8
Ceramic	(Fibrefrax[R])	2800	2300	~75
Metal	(Brunsmet[R])	---	---	~100

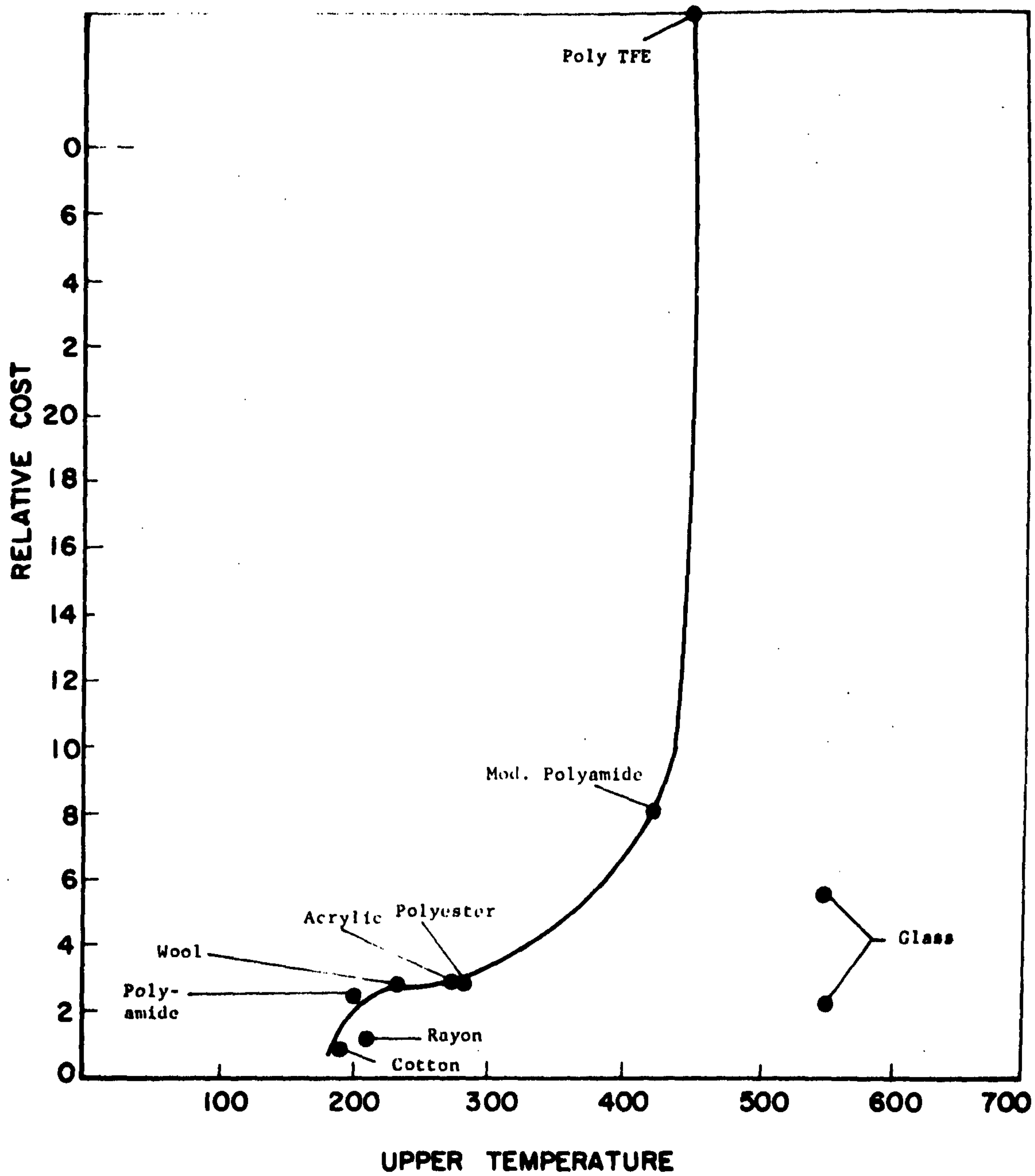


Figure 7.14. Approximate Temperature Capability/Cost Relationship for Filtration Fabric Materials. (Costs Relative to Cotton.)

7.5 ACCOUNTING COMPARISONS OF COSTS

As discussed in earlier parts of this Chapter, fabric filtration costs fall into two classes, initial or one-time costs, and periodic costs. The variations in each from installation to installation can be many-fold and each installation must be separately analyzed. Furthermore, as noted earlier, certain costs, notably overhead items but also others, may or may not appear as costs of the filter system even though they are related. In evaluating the costs of fabric filtration one should consider how the cost figures are going to be used in order to decide which of the hidden costs to include, if any.

First costs (Section 7.1) may include:

- Planning and preparation for installation
- Equipment and parts purchasing
- Installation
- Start-up and training

Periodic costs (Sections 7.2, 7.3) may include:

- Replacement fabric
- Power
- Labor and associated labor overhead
- Plant overhead, taxes
- Planned replacement parts
- Unexpected repairs
- Deductions or costs of such extenuations as
- Sale value of dust collected
- Effectiveness, reliability, convenience, etc.*
- Capital costs

First and periodic costs may be combined in either of two ways, as an annualized distribution of first costs plus the annual charges, or as a summation of future periodic costs plus the first costs. The first treatment is the simpler; it is adequate for most cost estimating, and has been implied in earlier parts of this Chapter. The second is more

*In order to compare one particulate control system with another, one should attempt to reduce all criteria of performance to the same denominator, such as dollars per CFM-year, or dollars per ton, etc. There is no completely acceptable way of doing this. One may use the data of Stairmand (e.g. Figure 7.2) to assign a dollar value to a given collection efficiency, but this must be modified in terms of the plant emission requirement.

precise; it is preferred by cost accountants because it enables a more accurate comparison of alternative proposals. Each is discussed below with examples.

7.5.1 Annual Distribution Method

To estimate the total average yearly cost of owning and using the filter system, one can simply divide the total initial cost by the expected life of the system, and add the result to the expected annual costs of operation. This is called amortizing the investment using straight-line depreciation; in this method the book value of the initial investment decreases steadily through the life of the system. Every year a fraction of the investment is written off the book value, and accepted as a filter system cost.

Since money is tied up in the investment, and since the same money could have been used elsewhere to generate profit, the investor suffers a loss of interest income as another cost. Using an interest rate of 10% and $1000 invested, the first year the interest cost is $100. The second year, since the investment has depreciated, say 1/15th in anticipation of a 15 year life, the remaining investment is $933, and the interest cost is $93.33. For the average year the equipment will be worth $500 and the interest cost will be $50; thus over the 15 year period a total of $750 will be acknowledged on the books as interest cost. This total interest cost may be annually distributed for convenience as simply $50 per year; it is equivalent to simply (Investment) x (Interest rate) ÷ (2) per year. Note that even though the interest may not be an actual cash outlay, unless the money was borrowed, it is attributable to the filter system.

Example:

Total initial investment:	$1,000 including materials, labor, freight, etc.
Cost of investment capital:	8%
Anticipated equipment life:	12 years
Anticipated yearly costs:	$325 per year including power, maintenance, fabric, plant space etc.

Straight investment depreciation:	$ 83.33	per year
Capital (interest) cost: $1000 x .08 ÷ 2 =	40.00	"
Yearly O&M costs:	325.00	"
Total estimated cost of owning and operating the fabric filter system:	$ 447.33	per year
	or $5,380 Total.	

Likewise the rate of depreciation need not be constant; other acceptable methods include faster-than-straight line depreciation and slower-than-straight line depreciation. Plant accounting policies may prefer any one of several commonly used depreciation schedules, and income tax laws accept any of several schedules. Unless the design engineer has a specific reason for using another method, the straight-line depreciation method is simplest[36].

7.5.2 Anticipated Cost Summation Method

Alternatively the anticipated future costs of using the equipment may be back-computed to the present time and summarized, in terms of present dollars.

Example based on the system just discussed:

Total initial investment:	$1,000.
Capital (interest) cost: $40./yr x 12 yrs	480.
O&M costs: $325./yr x 12 yrs	3,000.
Total cost of owning and operating the system:	$ 5,380. or $447.33 per year.

This is of course equivalent to the annual distribution method, and equally useful for estimating; but it is not as accurate as the following method.

An important principle in finance is that future expenditures are greater than their present value. For example, suppose a cost of $404 is anticipated at a time one year from now. By investing $372 at the present time at a return of 8% the cost can be met when the time comes. Thus the future expenditure is said to have a "present worth" of $372. All such anticipated future expenditures including interest costs can be summarized in present dollars. The preceding example may now be treated in the following manner:

Year	Book Value	Approx. Interest	O&M	Total Yearly Cost	Present Value of Costs at 8%
0	$ 1000	---	---	---	---
1	917	$ 77	$ 325	$ 404	$ 372
2	833	70	"	395	339
3	750	63	"	388	309
4	667	57	"	382	281
5	583	50	"	375	255
6	500	43	"	368	232
7	417	37	"	362	211
8	333	30	"	355	191
9	250	23	"	348	174
10	167	17	"	342	157
11	83	10	"	335	143
12	0	3	"	328	130
Total:	--	$ 480	$ 3900	$ 4380	$ 2794

Total initial investment:	$1,000.
Present value of future costs:	2,794.
Present value of system lifetime expenses:	$ 3,794.

According to this example, $3794 invested now would pay for the same equipment and its use as would the $5380 estimated by the previous methods. The smaller figure in this case represents more accurately the expected costs to the company, and this accounting method (or still more refined methods) should be used whenever their increased complexity is justified.

This method should be used whenever two or more systems having different initial/annual cost ratios or different lives are to be compared. Consider for example two systems, the one described above and an alternative system:

Example:

	System No. 1	System No. 2
Total initial investment:	$ 1000	$ 600
Capital (interest) cost: 8%, 12 yrs	480	288
O&M costs: (for 12 yrs)	3900	4512
Bases for comparison:		
1) Initial costs only:	1000	600
2) Annual distribution:	5380	5400
3) Present value of future costs	3794	3660

Hardly anyone comparing two different systems would look only at their initial costs. Using the method of annual distribution of initial costs as a criterion of comparison would, in the above example, lead to the wrong decision, as the more detailed present value method shows the second system will cost the company less.

7.6 ECONOMY IN FABRIC FILTER OPERATION

Chapter 5 discussed ways to minimize costs in designing fabric filter systems, and Chapter 8 will discuss guidelines for operating and maintaining the system. Operating personnel should be aware that even though they may never see the electric bill or the invoices for the replacement fabric, they can do much to affect day-to-day costs. This applies to the personnel running the dust generating process as well as those close to the filter system. Temperatures can be kept down, minimum cleaning can be exercised, minimum air can be filtered, etc. Many ways to keep costs down are discussed in other parts of this handbook.

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CHAPTER 8

OPERATION AND MAINTENANCE

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CHAPTER 8

OPERATION AND MAINTENANCE (Continued)

Chapter 8

OPERATION AND MAINTENANCE

A good fabric filter system can last 15 years and longer, providing it has the continuing interest of its personnel. Those dust control systems located in the center of plant activity, and those systems collecting a valuable dust, are the ones that usually receive the most attention and need the least supervision. On the other hand the filter house on the roof, out back, in a cold place, etc. and the filter that seems to contribute nothing but trouble will not be popular and will require extra effort.

A few principles for successful operation apply to any fabric filter system:

1. Reduce operating and maintenance costs by selecting the most suitable equipment in the first place. Study the operating, the instrumentation, and the maintenance manuals before purchasing. Get equipment of adequate quality.
2. Follow the manuals. Know what is in them, and why.
3. Know what is entering the filter system.
4. Treat the fabric with care at all times.
5. Keep the flow into the filter as low as possible, limited only by the danger of reaching the dewpoint. If there is one single way of minimizing operating and maintenance costs this is it, according to the reports of many filter users.

Complete guidelines for the operation and maintenance of specific filter models are available from most fabric filter manufacturers. This chapter discusses upkeep problems and practices common to most equipment. Because both operating and maintenance personnel are involved in system upkeep, these practices are separated in two sections, each of which may be used as a general guide. The last section discusses fabric filter equipment problems reported in a survey of about 50 different fabric filter installations. The problems are analyzed for common causes.

8.1 OPERATION OF BAGHOUSE SYSTEM

Like any new equipment, the filter system has a start-up period which can last a few minutes or many months, depending in part on how well the system was planned. Afterward the system functions with much less attention. It is important to remember, however, that any change in the input conditions will make at least some difference in the filter's operation and require a period of special attention.

8.1.1 Start-up

When the new equipment is started for the first time, the fan should be checked for correct direction of rotation and speed. The ducting, collector housing, etc. should be checked for leaks. Gas flows and pressures should be checked against the design specifications. Instruments should then be checked for correct reading and calibration adjustments made as necessary. Control mechanisms, and especially all fail-safe devices, should be checked for operability.

At the first start-up of the system, and also whenever new bags have been installed by the maintenance crew, the bags should be checked after a few hours of operation for correct tension, leaks, and expected pressure differential. Initial temperature changes or the cleaning cycle can pull loose or burst a bag. It is wise to record at least the basic instrument readings during this start-up period on new bags, for ready reference and comparison during later start-ups.

It is not always specified, but it is generally a good idea to start a new set of bags at a filter velocity lower than that to be normally used. The reason for this is that new bags have a low flow resistance, and if the fan is run at normal speed with no other flow resistance in the system, the filter velocity will at first be quite high. As a result the efficiency will tend to be low and dust particles may be driven into and plug the cloth. In contrast, a low initial velocity will allow the first dust particles to stay closer to the surface of the cloth, bridging over the pores in the cloth and leaving the rest of it much more permeable. Then the velocity can be gradually increased until, after a small percentage of the normal dust cake has formed, the normal filtering velocity can be utilized.

In addition, when removal of the dust cake must be unusually complete during every cleaning cycle, it may be worthwhile to begin filtration at a lowered velocity at every cycle. This can be done manually by gradually adjusting a blast gate, or if the procedure must be done frequently or if precise control is needed, it can be accomplished via automatic control equipment. Some filter equipment is specifically designed for this.

During any start-up, transients in the dust generating process and surges to the filter house are probable and ought to be anticipated. Unexpected temperature, pressure, or moisture has often badly damaged a new installation. In particular, running almost any indoor air or combustion gases into a cold filter can cause condensation on the walls and cloth, leading to blinding and corrosion. Condensation in the filterhouse may void the manufacturer's guarantee. It can be avoided by preheating the filter or the gas.

8.1.2 Routine Operation

Day-to-day use of a filter system requires frequent observation and occasional adjustments in order to determine and adhere to the best overall compromise between performance, bag life, power costs, etc.

8.1.2.1 Use of Instruments - A single monometer used across the filter cloth can provide a wealth or information. It indicates the permeability of the cloth, tells how heavy the dust deposit is before cleaning, how complete the cleaning is, and whether the cloth is starting to plug or blind. It tells what surges in velocity the dust deposit is undergoing, and whether there is any flow through the cloth during the cleaning cycle.

It is a good idea to post a list or a recording of the normal differential pressures through one filtration cycle, as a means to quick detection of later trouble. A high differential may mean:[1]

- an increase of air flow
- the beginning of blinding of the cloth
- hoppers so full as to block off the bags
- condensation in the cloth
- cleaning mechanism inoperative

while a low differential pressure may mean:

- the fan is slowing down, perhaps due to belt slippage or fan motor problems
- broken or unclamped bags
- plugged inlet ducting or valves closed
- leakage between sections of the filterhouse

The reading of the manometer should be easily visible from the plant operating floor, and one man should have responsibility for checking it. On an expensive system an alarm should sound if certain pressure differential tolerances are exceeded.

Other instrumentation can be nearly as valuable. If it has been installed it is probably there for a good reason and it should be used. Transients frequently occur in pressure, flow rate, temperature, and humidity. Operating personnel should know at once when an indication is excessive and what the causes may be. A trouble-shooting manual, such as shown in Appendix 8-1, should be kept handy to the filterhouse.

8.1.2.2 Flow Variations - With multiple or variable dust pick-up points there will be variations in flow rate and filtering velocity. All the branches of the inlet ducting may be open or some may be shut off, depending on plant activity. Also while one collector compartment is down for its cleaning cycle, another may be down for bag changes or still another for inspection. These system changes affect the flow through the filter. Too much flow through too few bags amounts to an overload or too high a filter velocity, leading to inefficient filtering, plugging of the cloth, loosening or bursting of the bags, or unsatisfactory building ventilation. Too low a flow is a frequent cause of condensation. When flow variations are anticipated, it is wise to have at least manual means of flow control, and automatic control equipment is often justified.

8.1.2.3 Cleaning Cycle - As the cloth ages, adjustments in the cleaning cycle may be advisable either in the amount or the intensity of cleaning or in the length of the cleaning cycle. One tries to use as little cleaning as possible so as to prolong the life of the fabric; but one has to use enough cleaning to keep the differential pressure at an economic level. There is in principle a point of optimization, although this may be difficult to locate in practice. Operating at the point of minimum cleaning is indicated by a gradual build-up of differential pressure, perhaps over a period as long as a few days. Then before the pressure gets too high, a slight increase in cleaning action (frequency or intensity or duration, as appropriate) should reverse the trend in pressure. After a few cycles or a few hours the pressure should reach a sufficiently low level to reduce the cleaning action. If this gradual fluctuation in differential pressure is not observed, it may mean that the fabric is being overcleaned, because the only way to be sure the filter operation is near the point of minimum cleaning is to continually operate around it. Changes in process or fabric condition will undoubtedly cause the cleaning requirements to shift from week to week, requiring a continual hunting for them. Normally the process will be sufficiently stable through automatic control so that day to day observation and adjustment of the cleaning cycle can be made manually by a skilled person in a few moments. This procedure of hunting for the minimum cleaning requirement is normally worthwhile on all except possibly the smallest filter systems.

8.1.2.4 Changes in Operation - The fiber is carefully designed to operate with a certain flow rate, particle size and type, etc., and any changes in these conditions, expected to exceed ten percent or so, should be analyzed for their effect on the overall filter operation. This should be an economic analysis by an engineer skilled in fabric filter systems. If large changes are indicated or a large installation investment is involved, a short pilot study using, if necessary, borrowed pilot filter equipment may be justified.

8.1.3 Shut-downs

The main precaution in shutting down the filter system is prevention of moisture in the filterhouse. Condensation can appear through the cooling of gases containing moisture, particularly combustion gases, if they are not completely purged from the filter system and replaced with drier air before the filter cools down. This can also happen with air at ambient moisture levels if the filter is in a colder location. It can happen if weather leaks into the collector particularly during extended shut-down periods. To prevent condensation some plants purge their systems carefully on shut-down and then seal the system off completely. Others continue a flow of warm air through the filter during the shutdown, which also helps prevent condensation when they start up again. A partially sealed-off filter system can be lightly pressurized with reasonably dry air to exclude seepage of damp air.

In addition to general maintenance during shutdowns, other reported practices include cleaning corners and crevices of any dust accumulations which might solidify during a prolonged shutdown; removal of any material which might catch fire on contact with air;and removal of the bags for storage under more suitable conditions.

8.1.4 Safety

The preceding portions of this chapter mention a number of precautions against system damage. There are of course any number of possible accidents. Baghouse structures and ducting are usually adequate to prevent metal fatigue or panel collapse during normal pressure excursions. It may, however, be less expensive to include explosion panels than to design the entire system to withstand a large surge of pressure. A surprisingly large number of dusts are flammable and some are spontaneously combustible. (A good test is to ignite a small conical pile of the dust and observe the rate and amount of burning.) The danger of fire in a high velocity air system containing cloth is apparent. Some plants find that their ventilating hoods collect a surprising quantity of combustible material like lunch bags and candy wrappers. Instrumentation responding quickly to sudden temperature changes, such as an automatic cooling system, may be justified in some installations.

Operating personnel should be accustomed to think "Hazard!" whenever a fabric filter is being used on abrasive dust or toxic fumes or gases. (Many dusts have some degree of abrasiveness which can make trouble in other plant equipment unless controlled.) Safety codes in such cases will not normally permit the recirculation of the filtered air to the building but if the air is recirculated, any bag failure can be serious. If the exhaust is to the outdoors then consideration has to be given to providing make-up air for ventilation to the building, as no sizable exhaust rate can be made up by leaks through doors and windows. At times the closing of windows or doors may cut down the air flow through the building so much that the dust pick-up hoods fail to ventilate adequately. In certain weather the makeup air inlet may entrain some of the outdoor exhausted gases unless precautions are taken.

The disposal of collected dust can be a problem. If the dust is poured or stirred in the open or if there are leaks in the disposal equipment some of the material will re-aerosolize; it does not take much dust escape (~0.1 percent!) to offset the remarkably high efficiency of the fabric filter. The procedures needed for disposal of radioactive dust can use up the permissible exposure quotas of many men unless carefully planned.

8.2 MAINTENANCE OF BAGHOUSE SYSTEM

There is a wide tendency to regard the dust collector as a piece of trivial equipment until something goes wrong with it, whereupon it becomes despised as a troublemaker. Planned preventive maintenance is a better policy, the amount depending on how much the plant has to lose in case of a system failure. A few companies successfully contract out the dust collector maintenance, some contracting the entire job and others only the supervisory portion, leaving the routine maintenance to in-house men.

Timing of maintenance is important. A supervisor or maintenance forman may spend two hours every day looking over a large system, because to let things go any longer than this is, in his experience, inviting trouble. For example, one leaky bag can rapidly destroy the adjacent bags unless detected. Other procedures may be best done once a month, or every six months, depending on what they are.

Maintenance procedures will be based on the operating and maintenance manuals furnished with most fabric filter equipment, and later they will be supplemented by experience. Appendix 8.1 lists examples of maintenance procedures and troubleshooting lists extracted from several such manufacturers' manuals. Records of bag changes as well as non-routine maintenance may prove invaluable later in pinpointing high-cost parts of the collector system and for projecting costs of any proposed similar equipment.

In the following paragraphs maintenance practices are suggested for the various parts of the system. While these are extracted from reports of over 100 specific installations, some comments regarding equipment apply generally. The one factor most responsible for high maintenance costs seems to be excessive filter velocities. Another factor is location; centrally located equipment receives more attention than isolated, inaccessible equipment and as a result often gives better performance. Similarly a single large system has fewer servicing points than a number of small dust collectors and will cost less to maintain, other things being equal.

The system components should all be readily accessible. Ladders, walkways, and cranes necessary for maintenance should be provided at the time of installation. Lighting outside and if possible inside the filterhouse should be installed. If the equipment is outdoors it should be especially well protected, and the hoppers, disposal equipment and fans should be enclosed to make servicing easier during bad weather. Wherever there is possibility of dust accumulation or plugging there should be access doors or cleaning ports. Doors, valves, bag clamps and tension adjustments should all be serviceable by hand with a minimum of tools, to save time.

8.2.1 Hoods and Collection Points

Check periodically for ill advised changes such as holes cut in the hoods, more hoods added, ducts blocked off, or dust intakes moved away from the dust source. Be sure any temperature sensor located in the gas stream is where it will pick up a temperature truly representative of the mixed gas.

8.2.2 Inlet Ducting

This is a moderately large problem area for several reasons:

(a) Abrasion. Flat, heavy plates installed at bends may increase elbow life. Alternatively soft, rubber-like material may out-last metal.

(b) Corrosion. Insulate to reduce condensation. Ducting made of plywood may be compatible with mildly corrosive gases. Long ducts, such as "hairpin" cooling systems, are particularly subject to corrosion unless condensation is avoided.

(c) Sticking. Some dusts may "paint out" on the inside of the ducts. If this is due to dampness or due to thermal precipitation from hot gas to cold duct, insulation should help. An increase in pressure drop from end to end is an indication of plugging. While vanes in duct turns can minimize pressure losses at the turns, they may collect material.

(d) Settling. Install clean-out doors or air lances in long horizontal runs if there is any danger of settling. Frequent plugging may require a Vee-shaped duct with a conveyor in the bottom of it, or a higher air velocity (i.e., smaller duct) at the expense of an increased pressure drop. If possible keep the bottom of the ducting straight; when tapers are necessary, put them in the sides or top.

(e) Temperature surges. Peaks in gas temperature will not be reduced or dampened appreciably by short lengths of ducting. However, the removal of duct insulation or the addition of a heat absorber like brick work or a steam boiler in the duct system will help to dampen temperature excursions. Otherwise a high-temperature by-pass of the filterhouse or some other variety of fail-safe equipment may be needed.

8.2.3 Blast Gate and Flow Control

Problems with flow control equipment are frequently reported. Any valve which may have abraded, plugged, become moved, etc. should be checked periodically. Especially the blast gate should have a positive lock against vibrational moving. It should be accessible, not in a duct high overhead, as it may have to be adjusted frequently.

Filter compartment inlet dampers are a high maintenance item and spare parts should be stocked. An indication of a bad damper seal is a differential pressure across the cloth when there is supposed to be no flow through the compartment. This is given as a common reason for short bag life in shake-type systems. The valves on the clean side of the baghouse, if any, may also malfunction if the bags have been allowed to leak extensively and the valves are fouled. Either air cylinders or motor driven actuators for dampers and valves may be used, depending partly on the required speeds of opening and closing. Motor driven actuators, although slower, may be slightly more reliable.

Being able to isolate a compartment from the rest of the system without shutting the system down can be invaluable to baghouse maintenance. However, even the best valves may not be acceptable in all cases; for example if there is danger of carbon monoxide, internal maintenance may be prohibited except during plant shutdowns.

8.2.4 Fans

Fans and blowers are reported to be a large problem area, particularly those located on the dirty side of the baghouse where material can accumulate on the vanes and throw off the balance. Corrosion and abrasion can also cause trouble. It is wise to anticipate and prepare for some fan maintenance in order to avoid long, expensive shutdowns. For example, the fan should have access doors, electric disconnects, and crane facilities for both ease and safety. Fan maintenance is reduced by installing rugged equipment, and a large slow fan will probably need less attention than higher speed equipment. If one type of fan blade does not seem to last very well, another type may be better (see Section 5.3). Having two or more fans on the system may enable maintenance of one of them without shutting down the system completely. Furthermore, seal maintenance problems on the filterhouse may be reduced by having fans both before and after the baghouse, enabling operating the house at nearly zero gauge pressure. Condensation and corrosion in the fan may be alleviated with duct and fan insulation; most fans come provided with drains in anticipation that water will sooner or later get into the fan housing.

The fan should be checked for direction of rotation periodically, as even a fan running backwards moves some air. Air flow and fan speed should be measured, not just estimated, checking belt wear and adjusting the belt tension as necessary. These checks can be combined with routine lubrication procedures.

Vibration noise probably means the rotor is out of balance, and/or the bearings are going bad. Abrasive or sticky material may easily change the fan blade weight, and the faster the fan speed, the more serious this is. Sometimes a relatively small adjustment in speed can temporarily alleviate a vibration until such time as the fan can be shut down for repair. One remedy for accumulation of material on the blades includes sand-blasting. This is a matter of hours, if the rotor has to be removed, but abrasive blasting systems have been installed in the fan housing to expedite the job.

8.2.5 Entrance Baffles

Good baffling can reduce maintenance in the filterhouse by helping to distribute the gas flow and the dust load more evenly to each compartment and to each bag. A baffle can protect the fabric nearest the compartment inlet from direct impact of abrasive particles, or it can protect the first couple of feet of each filter element from the same thing. Used skillfully, baffles can either direct the largest dust particles downward to the hopper or upward to the filter surfaces, thus in effect controlling the flow resistance of the dust deposit. For any of these purposes it might conceivably be advantageous to use baffles that are manually adjustable. On the other hand, baffles sometimes have to be removed when they contribute to maintenance problems by accumulating dust or abrading too rapidly.

8.2.6 Hoppers

Bridging and backup in hoppers should be anticipated whenever the dust is expected to have a high angle of repose (a steep angle of slide when piled), a low aggregate density, or a high particle length/diameter ratio. Steep-sided and/or wide-bottomed hoppers will presumably have already been installed. Further assistance may be obtained by antifriction coating the hopper surfaces, or by air-pulsed rubber liners in the hoppers. Vibrators are often used to loosen the flow and if used, heavy low-frequency vibration may be preferable. However, some dusts tend to lock up when vibrated, especially when the dust is already deep in the hopper. If surges in dust load are causing back-up, then over-running of the rotary valves will help. Moisture introduced through a leaking rotary valve in a suction system can cause sticking on the hopper walls. If condensation is occurring in the hopper, insulation should help.

Sledge hammering is reported to be one method of freeing a clogged hopper. A better method is the installation of poke holes in the side of the hopper; these can be designed in the original equipment if the need is anticipated. Any hopper will get better attention if it is housed against inclement weather.

8.2.7 Bag Retainment

8.2.7.1 Thimble Sheets - One fairly common complaint is that the bags are packed together so closely as to abrade against each other or against the baghouse. Close bags can neither be inspected adequately nor installed nor adjusted easily. If the bags are more than about three-deep beside the walkway, or two-deep for large bags, the man cannot reach from the walkway to do his job. Hence damage often results as he misplaces his feet. In the event of high maintenance resulting from overcrowded bags, some baghouse users take out part of the bags and block off the thimbles. Unfortunately this overloads the rest of the bags. It would be better to take out the old thimble sheet and seal in a better designed one.

The thimbles themselves are ideally seamless and blunt-lipped to minimize stress points and chafe on the cloth.

8.2.7.2 Fastening - The method of fastening and tensioning bags is one distinction between equipment by different manufacturers, and there are many variations. Generally, a minimum of tools should be needed; clamps should be both quick and finger-adjustable. By the same token, both hands should be free for the work; that is, the man should not have to hang onto a ladder or lean far over as he works on the bag. Fastenings should be secure, because as a taut bag is collapsed it becomes tighter and the fastening tends to slip. Also large changes in baghouse temperature can lead to differential thermal expansion, bag tension changes, and possible slippage. Sometimes a bag pulls completely loose from the thimble, as indicated by a dusty exhaust and an unusually low manometer pressure.

8.2.7.3 Tension - At present there is no general rule for how much tension a bag should have for best overall performance. A very slack bag can fold over at the lower cuff and bridge across or wear rapidly. Too much tightness will damage the cloth and work against the fastenings. Because of the seam, as the tube is tightened it may arc, banana-like, enough to touch the next tube. Whatever tension the bag has when it is installed will be increased by the weight of the dust cake, especially at the top of the bag. This can be an increase of several times the bag weight with some dusts. Circumferential tension as from inflation may further cause the tube to tighten lengthwise. The fabric properties may change as the bag ages, and this may also change the tension. For all these reasons the tension of the cloth needs to be checked from time to time, especially a few hours after installation of the cloth.

Correct tension is mainly a matter of filter dimensions and cleaning mechanism. Shake cleaning in particular seems to require a unique combination of tension, shake frequency, and bag properties for best results. The manufacturer's recommendation should be followed until there is more pertinent experience to go on. One rule for obtaining adequate tension is the two finger method; when two extended fingers are slipped over the uninflated, flattened tube, it is claimed that the wrist should just be able to rotate 90 degrees. This amounts to about one-half inch of slack, not a precise amount but a very ready test. Bags that clean by collapsing may be under the best tension when they take on a cloverleaf pattern as they collapse. Correct tension is reported as being from 25 to 100 pounds for glass bags of one-foot diameter, enough to keep them sufficiently open during cleaning to let the dust fall to the hopper.

8.2.8 Filter Elements

In most filter systems the biggest part of the maintenance program is related to fabric upkeep. The cloth has to be inspected regularly, and it is replaced either on a preventive basis or on short notice as trouble occurs. Some filter users are able to salvage some of the removed filter elements, while others find salvage does not pay. While other parts of the filter system may be maintained by the standard skills found in most plants, filter elements need special handling at all times. Glass fabric,for example, is especially fragile and can be ruined by kneeling on it or dragging a tool across it.

8.2.8.1 Spare Stock - At least a few replacement and usually a complete set of filter elements should be kept on hand, the quantity depending on the expected bag life, the risk, and the delivery time. The margin of safety and risk of shutdown are balanced against the costs of storage and inventory, which are annually about 10 percent of the purchase cost of the fabric stored. The spare filter elements should be labeled to indicate type and quality, clearly enough to avoid any possible confusion with other sizes, cloths, or manufacturers, and kept well separated from used filter elements. Elements are stored safely against mildew, larvae, crushing, etc. usually on a first-in, first-out inventory system.

Filter elements can be purchased either from the equipment manufacturer or from a firm that specializes in sewing various types of filter elements (Section 4.6). On the one hand, it is a good idea to avoid splitting the responsibility for filter system performance between the equipment manufacturer and a separate bag supplier. On the other hand, most filter users feel vulnerable if they are committed to getting all their stock from one source. At least one filter user solves this problem by buying cloth and sewing his own bags. Generally, the experienced firm supplies the most reliable products. Inexpensive filter elements often turn out to require a lot of maintenance and be more expensive in the long run.

8.2.8.2 Installation - In many filter houses the elements can be installed by one man, but in the interest of a short down-time a crew of two or three men usually do the job. (Not all types of equipment have to be shut down for bag replacement; see Section 5.2.) Practices differ between keeping old and new elements in separate compartments and mixing them together, which is customary when accidents happen only to a small percentage or when there is no problem about down-time. Keeping them separate is better preventive maintenance, although it is more expensive since some cloth will be discarded before its life is up. Keeping them separate is preferred when filterhouse conditions are noxious, or when entrance to the compartment takes a lot of preparation time. In either method records should be kept showing date of maintenance, a description of the cloth installed, and the location of the change by thimble number or compartment number.

8.2.8.3 Inspection - External maintenance inspection of the filter house and system is usually performed daily, while the filter elements themselves are typically inspected once a week to once a month. The appearance of the air exhausted from the filter is not always a reliable indicator of element condition; the inside of the filterhouse should also be seen.

Any dust on the floor of the clean side of the filterhouse indicates faulty operation, and the location on the floor is often a quick indication of which element has failed. More often, however, locating the hole in the fabric is a difficult, time consuming job, sometimes because the hole is hidden by other elements. Fortunately experience often shows that most of the holes occur in certain repetitive areas of the bags. Holes (or more important, thin places about to become holes) may sometimes be located by running a fluorescent light tube or flashlight through the filter element, perhaps while it is still in the filterhouse. Sometimes on squeezing the bag or tube a puff of dust will show the location of the hole.

It is important to repair holes as soon as possible after they develop, of course, especially when abrasive dust is being filtered, because a hole in one element can quickly cut a hole through the adjacent fabric. If there isn't time to repair or change the perforated bag it should be tied off until such time. The same applies to a seam failure; use whatever quick remedy will permit continuing the operation until a downtime can be scheduled.

The inspection procedure at an 80,000 CFM 500°F installation has been described in the literature and may be of interest:[2].

> "At present an inspection of the bags while the baghouse is operating requires a supervisor, the operator, and three mechanics. The operator locks out one compartment at the panel board, one mechanic closes the tipping gate valve at the bottom of the hopper, and the other two mechanics open the top and bottom inspection doors. The supervisor enters the bottom of the compartment, inspects the bags and general appearance, and any defective bags are tied off or capped at the cell plate. The procedure is reversed to put the compartment back in service, and the next compartment is inspected. All 10 compartments may be inspected and serviced in this manner in less than four hours. Inspections are made about once a month. Bags are replaced during furnace rebuilds, when the baghouse is cool."

8.2.8.4 Salvage of Filter Elements - Bags can be removed for cleaning and repair if most of the cloth is still sufficiently valuable. Patches can be sewn on, or sometimes applied with quick-setting glue without removing the bag from the baghouse. Thermosetting and pressure sensitive adhesives have been used to repair glass bags. Of course that portion of the cloth surface patched is lost for filtration, and the surrounding cloth takes a slightly higher load. Bags with holes all in one end can have a new end sewn on.

There are a number of ways of cleaning a removed bag, if this is judged to be worthwhile. Dry methods include turning it inside out and beating or brushing it, tumbling it in a drum, vacuum cleaning it, and using jets of compressed air on it. These techniques may damage the cloth, especially glass cloth. For example, cloths plugged to the point of rigidity may be actually broken by bending them. Wet cleaning methods may be more practicable when a cloth has become blinded or plugged well before its mechanical life is up. In rare cases wet cleaning of the bags inside the filterhouse may succeed. Felts have been dry cleaned successfully. Unspecified cloths were reported to withstand 6 to 8 washings before they had to be thrown away. Consulting the fabric supplier or manufacturer might well salvage a large cloth investment that has met with a partial accident.

It is good practice to install salvaged fabric in separate compartments from new fabric in order to get full service from the new compartments.

8.2.9 Collector Housing

The importance of accessibility has already been discussed: a central location, inclement weather protection, ladders, walks, and lights are all conducive to good maintenance and will reduce maintenance expenses. Also the interior of the collector should be readily accessible, if possible during operation. High temperatures or noxious dusts may make collector entrance hazardous or unpleasant and thus expensive. Respirators, coveralls, gloves, etc. if needed for entrance, should be kept close by for emergency repairs.

Faculty seals are a frequent complaint in collector housings, especially when the equipment has been assembled by an unexperienced crew. Also, seals tend to be weakened by weather, heat and age. Seals should be checked every six months to a year; one technique involves placing one man inside the compartment at night with a light and another man outside. While large leaks may be indicated by a manometer that does not zero when it is supposed to, minor leaks as along a thermocouple wire which can admit water to begin a corrosion problem are harder to find. If necessary, the filter-house panels and flange connections can be dismantled, cleaned up, and reassembled, probably using both cemented gaskets and bolts. Seals around the doors to the filterhouse must not be overlooked.

The doors should be openable by hand without need of special tools; they should be large enough for easy entrance, fabric maintenance, and periodic cleaning of the dust which inevitably penetrates the cloth to the clean side of the compartment. Glass panels in the doors may be worth-while for observing the filter elements in operation.

8.2.10 Specific Cleaning Mechanisms

Each of the standard mechanisms (see Section 3.3 and below) requires some maintenance procedures not shared by the others. Generally the more elaborate the cleaning apparatus the more maintenance of all types needed. One should use a minimum of cleaning energy; if the cloth fails to clean adequately then a small temporary increase in the cleaning process may bring the pressure drop back into line. The process of blinding tends to be an accelerating one, because as the free area of the cloth decreases the fan pulls harder in attempting to maintain the flow. This increased pressure drop in an already marginal situation must hasten the blinding process. For the maintenance man, this means being alert and ready to adjust the cleaning procedure as necessary. At the same time, however, all changes in cleaning procedure should be fully cleared before they are put into practice, because the cleaning process has far-reaching effects and a large part of the filter system expense is related to the cleaning action.

8.2.10.1 Shake - Any wear in the shaking machinery results in a lessening of the shaking action, and unless the trouble is recognized for what it is, the shaking intensity may be stepped up until the mechanism destroys itself. Regular lubrication and avoidance of gritty dust in the mechanism can best be achieved by having most of the shaker mechanism outside the filterhouse.

If the cloth is not cleaning, check the shaker rack to be sure it is moving. (For doing this while the rest of the filter system is down, a jog button located near the door of the compartment is useful.) A small adjustment of shake amplitude or frequency may markedly change the propagation of the shake wave along the cloth tube and improve the cleaning. If the cloth still won't clean sufficiently with a safe amount of shaking, it may be necessary to reduce the filtration velocity or alter the particulate characteristics for a few hours. The velocity should, of course be absolutely zero or even negative during the shake part of the cleaning cycle.

Fabric wear due to flexing may be a problem; see the comments under "Reverse Flow Plus Collapse" below.

8.2.10.2 Reverse Flow - The reverse current of air has two functions, that of pushing the dust deposit off the cloth, and usually that of flushing the dust into the hopper. The rate of flow (or the back pressure) and the timing need adjustment from time to time to keep the residual drag at an economical level.

8.2.10.3 Reverse Flow Plus Collapse - Whenever the cloth is flexed as part of the cleaning process, and wherever it flexes, there is apt to be a high rate of wear indicated by a thinning and eventual perforation of the cloth. This is especially common near the thimbles where the flexing is 3-dimensional. A decrease of air flow or an increase in cloth tension will help to reduce flexing. Frequently cloth flexure is reduced by installing rings inside the tube, sometimes sewing them into the tube. In the cases of reverse pulse and panel filters, wire grids are generally used to back up the cloth. While these do reduce flexure wear, they may also introduce frictional wear between the cloth and the ring or grid.

Note that any type of mechanical wear of the fabric--abrasion, flexure, or tensile wear--will be amplified by adverse environmental conditions. The molecular structure of both synthetic and natural fibers may be damaged by high temperatures, moisture, and/or chemical conditions, thereby weakening the fibers and making them more susceptible to mechanical wear. Thus in a particular case, lowering the filtration temperature may alleviate a flexural wear problem. The converse can also apply. For example, fibers are available for filtering at very high temperatures (nearly 2000°F) but at present there are no practicable ways of cleaning them without excessive fiber flexure. In other words, reducing the mechanical demands on a fabric may make it more tolerant of tough environmental conditions. Fabrics with different finishes, weaves, etc. may also be put on trial to circumvent a particularly troublesome mechanical or environmental problem.

8.2.10.4 Pulse - As there are almost no moving parts in the pulse cleaned apparatus, hardware maintenance is certainly reduced compared to other cleaning methods. However, the excessive use of cleaning air pressure may balloon the bags so much as to weaken them by overstretching. If the fabric is being damaged and cleaning cannot be diminished, one must try another fabric or attempt to reduce the adhesiveness of the dust (Section 2.2).

8.2.10.5 Reverse Jet - As there is a fair amount of mechanism within the clean side of the baghouse, any penetration of the bags by dust results in a wearing of the mechanism, gradual or rapid, depending on dust abrasiveness. Beyond a certain point, unless the equipment is completely overhauled the mechanism will not only destroy itself but the bags as well. Thus this method of cleaning while popular in some applications is at other times associated with fairly high maintenance.

Sometimes in reverse jet equipment a hard residue of felt fiber and dust builds up on the cleaning rings so near the bags as to begin to rub. This accretion can usually be sanded off, but may be prevented by antifriction coatings or rings made of stainless steel. The cleaning rings must stay smooth and level and at the prescribed distance from the cloth. The cloth tubes must be kept taut. Equipment operability can usually be prolonged by changing from continuous to intermittent cleaning, in which the carriage pauses for a period of time between trips. Here again is the principle of using a minimum of cleaning.

8.2.11 Rotary Valves and Conveyors

These can be high maintenance items if the dust packs together or adheres to the paddle wheel or other surfaces. The intake of moisture due to faulty seals is a frequent cause of sticking. Ordinarily a good quality valve will give long service if it gets lubrication and a check of its seals and clearances from time to time. Anti-adhesion coatings may be used to some advantage on the wheel blades. A glass window in the valve (kept clean) is a popular method of telling whether the valve is discharging normally. Kraus[3] lists a number of engineering and maintenance practices for rotary valves used in pneumatic conveying.

Smeary dust material in a screw conveyor can directly cause repeated plug-ups and breakdowns. Converting to a pneumatic conveying system is not always an improvement, depending on the dust. Possibly different conditions of dust temperature or moisture will change the properties of the dust; otherwise it may be necessary to use separate collection bins instead of conveying to a central point.

Air leaks in the rotary valve and sometimes air leaking along the conveyor from one compartment to another can re-aerosolize dust and overload the filter. Indications of this are non-zeroing manometers and unusual filter drags.

8.2.12 Instrumentation.

The operability of fail-safe mechanisms and automatic control instrumentation is very important to the safety of the filter cloth, and it is usually up to a maintenance man to be sure these are in working order. He may advise the installation of more or better instruments, since most manufacturers supply a minimum of instrumentation with their equipment in the interest of economy. Good instrumentation often pays for itself, however.

One thing to check after equipment installation is the location of all sensing instruments because a small difference in location can be serious. For example, the wrong temperature may be measured if the gases are not well mixed at the sensor location; or, a high gas velocity may give an error in the static pressure sensed at one side of a differential manometer. All instruments should be calibrated after installation, and rechecked monthly for sensor location, leaks (manometers), sticking, legibility, etc.

A central panel for most or all instrument readout,as opposed to scattered instruments,has been estimated to reduce instrument maintenance costs by as much as 50 percent, as well as making operation of the collector system more convenient. One should record instrument readings over one normal operating cycle for use in checking and troubleshooting later in the life of the equipment. The record should be posted beside each instrument.

8.3 ANALYSIS OF FABRIC FILTRATION SYSTEM OPERATION

During a 1969 survey of about 50 fabric filter installations in a variety of industries the people most familiar with the day-to-day upkeep of these filter systems were personally interviewed. These people were asked to assist with about 130 questions relating to the equipment and its performance. The questions included:

- What are your principal causes of fabric failure?
- Have you tried other fabrics, and why are you using the present one?
- Do you receive any complaints regarding the quality of your filtered effluent?
- Do you have problems associated with fabric blinding?
- What, if any, are the major difficulties with with your filter system?
- What aspects of performance or operation could be improved, based on your experience?
- What suggestions would you make for improvements in design or manufacture?
- What do you see as being the principle requirements for research or development?

From the answers to these questions, nearly 100 different suggestions for possible research and development investigation were obtained, as discussed in another volume of the contract documentation. The surveyed installations also reported a total of 112 operating problems which are summarized in this section.

As considerable care was taken to distribute the survey across a spectrum of filter applications, the operating problems reported here may with some confidence be considered typical of most filter users. The list does not include all possible problems because of the limited size of the survey. There is furthermore a wide variation in problems encountered from application to application, and from installation to installation.

Appendix 8-2 lists 43 installations which reported operational problems, together with the applications data suspected of being related to the problems. These are:

- dust source
- particle size
- air/cloth ratio
- maximum differential pressure
- temperature
- fabric material
- cleaning method
- particle abrasiveness

There are often other circumstances that also contribute to filter operating problems.

In addition to the 1969 survey of fabric filter users, the fabric filtration literature reports numerous examples of operational and maintenance problems.

8.3.1 Types and Frequency of Problems Reported

Table 8.1 lists 23 types of operational problems encountered by the installations surveyed. They are grouped into 5 causality categories as follows:

1.	Fabric-dust interactions	9 types of problems	60 problems reported
2.	Filter element difficulties	2 "	6 "
3.	Filter element-hardware interactions	5 "	12 "
4.	Collector design problems	5 "	27 "
5.	System design problems	2 "	7 "
		23 types of problems	112 problems reported

The largest category of problems reported was the first: 60 different fabric-dust related problems were reported. Of these the most frequent

TABLE 8.1

TYPES AND FREQUENCY OF PROBLEMS REPORTED

		Frequency
1. Fabric - dust deposit interactions		
a. interstitial deposit related abrasion, wear		8
b. flexure wear failure		10
c. seeping		4
d. blinding		14
e. burning, heat		6
f. holes, pinholes, shot holes		6
g. hydroscopicity		4
h. condensation		5
i. deposited dust hardens, cake tears, cracks bag		3
	Subtotal	60
2. Fabrication failures not particularly related to dust interaction, mechanical		
a. seams, sewing		2
b. tears at top		4
	Subtotal	6
3. Design or maintenance failures related to tensioning, supports, rings, collars, or cleaning device interactions		
a. chafe on housing or other bags		3
b. tensioning, bags too loose		1
c. cage, wire, ring abrasion, wear (also dust related), support mechanism interact		5

(continued)

TABLE 8.1 (Continued)

	d. cleaning carriage bag wear	1
	e. seals around cloth-metal collars	2
	Subtotal	12
4.	Collector design problems, internal, external mechanisms, incl. auxiliaries, (ex. pipes, hoods)	
	a. unable to enter collector to service or maintain during operation	4
	b. hole detection problems or performance effluent monitor	3
	c. hopper dust sticking, holdup, screw conveyors plug	6
	d. internal mechanism wear	4
	e. external mechanism wear, timer, shaker, fan, bearings, doors, seals, wall failure	10
	Subtotal	27
5.	Dust collecting system design problems, external to collector (incl. pipes, hoods)	
	a. piping, elbows, abrade	4
	b. hood inlet control poor	3
	Subtotal	7
	Total:	112

type was blinding: 14 problems of blinding of the fabric by the dust were reported, as detailed in Table 8.1. Over 25 percent of all problems reported were from blinding, flexure wear, and interstitial abrasion.

From this brief analysis one is able to anticipate that most fabric filter maintenance will center on interactions between the fabric and the dust. The dust may not collect in a convenient way on the fabric; the dust may not remove easily from the fabric; the dust may damage the fabric in some way. Being thus forewarned, maintenance labor may possibly be minimized, for example, by running pilot tests before selecting the fabric.

Appendix 8.3 compiles the data in Table 8.1 and Appendix 8.2 to indicate the kinds of application in which each problem type occurs. For example, in Appendix 8.3 one may observe that "fabric wear apparently related to interstitial abrasion" was reported in:

- 6 installations with particle sizes over 10 microns, out of 7 reporting
- 5 installations with temperatures under 200^{o}, out of 8 reporting
- 2 installations with very abrasive dust, out of 6 reporting
- 4 installations with cotton fabric, out of 8 reporting, etc.

While this breakout does not necessarily demonstrate cause-and-effect relationships, the table may be useful in troubleshooting operational problems, as it enables comparison with applications reporting similar problems.

8.3.2 Specific Applications Reporting Problem Types.

Appendix 8.2 lists the problems reported by each of the various installations surveyed. These installations are grouped by industrial category, enabling for example, the observation that all of the (four) combustion applications reported only problems related to fabric-dust interactions. Iron and steel applications also reported fabric-dust problems, notably abrasion from fabric support hardware. Again, this analysis does not necessarily demonstrate cause and effect relationships; instead, the analysis is presented for comparison with the reader's operational experience.

8.3.3 Literature Survey of Maintenance Problems

A review of about 500 documents published during the last 10 to 15 years yielded a large number of comments related to problems associated with operating and maintaining fabric filter systems. These included comments based on experience with a single filter system, as well as comments from users of many systems and from manufacturers usually with many years of experience. Much of this information has already been woven into the previous sections of this Chapter and is not repeated here. Some of the literature, however, is so valuable in amount of detail, or in description of a specific installation, or in insight and experience, that it is indexed here in Table 8.2. Most of these reports are from the Iron and Steel Industry and the Nonferrous Metals Industry.

Three cases in point are described in Appendix 8.4. These are fabric filter applications of sinter plant discharge, oil combustion, and copper smelting. The original accounts make interesting reading, as they demonstrate the range of problems associated with the development of new filter applications. These accounts are typical of the better literature describing filter system operation and maintenance.

TABLE 8.2

MAINTENANCE PROBLEMS AND PRACTICES REPORTED IN THE FABRIC FILTRATION LITERATURE

Industry*	Reference	Dust/Source	Fabric	Problem**	Remarks
1	4,5	Oil combustion	Glass	1b,3b,3c	System and procedures development for new application
5	6	Carbon Black	Glass	G,1e	General
5	2	Soap, etc.	-	Misc.	Pneumatic conveying equipment
5	7	Cleansers	Cotton	1d	Also chemical attack reported
7	8	Cement Plant	Glass	3b,1i	General
7	9	Cement	Var	G	General discussion of fabrics etc.
7	10	Cement	-	G	General
7	11	Glass Furnace	Var	1h,1i,1d	Several applications discussed
7	12	Various applics.	-	1h,1b	Panel discussion
7	13	Coal	Var	1e,1h	General
8	14	Cupola, Foundry	-	G	General manual
8	15	Cupola	-	4e	General
8	3	Open hearth	Glass	3a,3c,4c	System and procedures development
8	16	General (Steel)	-	Misc.	Misc. applications at Bethlehem Steel plants; Numerous problems
8	17	Electric Steel Furnace	-	1e	Labor and material cost analysis for one year
8	18	Sinter strand	Glass	1a,3b,1d	Discussion of system upkeep
8	19	General (Steel)	Glass	4c,4e,1h	Misc. applications at Jones & Laughlin. Fluoride attack.

TABLE 8.2 (Continued)

Industry	Reference	Dust/Source	Fabric	Problem	Remarks
9	20	Uranium plants	Wool	Misc.	Numerous problems on 18 R.jet collectors; costs
9	21	Copper Smelter	Orlon[R], Glass	1b,3a	Detailed experience with several installations
9	22,23	Secondary Cu Refining	Glass +	Misc.	General discussion of system experience
9	24	Arsenic salts	-	1b,3d	Russian plant experience
9	25	Zinc Roaster	Glass	1i,1a,1d, 2a	System and procedures development
9	26	Smelter	Terital[R]	-	Designed for low maintenance
9	27	Cu Smelting; ZnO	Orlon[R]	1-, 3-	Routine inspection described
9	28	Zinc galvanize	Cotton	1d	Occasional manual cleaning required
10	29	Air filtration	Various	-	Maintenance economics of low efficiency filter equipment
G*	30	General	-	1d	Residual cake profiles
G	31	General	-	G	General discussion by system manufacturer
G	32	General	-	G	Inspection schedule, disposal methods discussed
G	33	General	-	Misc.	Abrasion, adhesion, bridging etc. discussed
G	34	General	-	Misc.	Filter sleeve maintenance and storage
G	35	General	Felts	3d	Reverse jet equipment
G	36	General	-	G	Unit sized filters
G	1	General	(Cotton)	Misc.	General discussion by system manufacturer
G	37	General	-	-	Troubleshooting checklist, general applications

TABLE 8.2 (Continued)

Industry	Reference	Dust/Source	Fabric	Problem	Remarks
G	38	General	-	G	General upkeep of all types of collectors
G	39	General	-	-	World-wide survey of maintenance costs reported

* Industry Key:

1 - Combustion Processes
2 - Food and Feed
3 - Pulp and Paper
4 - Inorganic Chemicals
5 - Organic Chemicals
6 - Petroleum Refining
7 - Nonmetallic Minerals
8 - Iron and Steel, Foundry
9 - Non-ferrous Metals
10 - Miscellaneous
G - General discussion

** Problem 1b, 3c, etc: For explanation, see Table 8.1.

G = General discussion of system upkeep experience.

Miscellaneous = Reports of a variety of specific problems.

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