DEEP-BED SAND AND GLASS-FIBER FILTERS

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Introduction

Filters employed for removing small amounts of radioactive particles from large volumes of gas may be classified into two types, thin-bed and deep-bed filters. Thin-bed filters comprise units employing such filter media as paper (e.g., CWS, Type 6 or AEC, Type 1), wool felt (as used in the Hersey cloth collectors), and thin glass mats (e.g. AAF Type 50, Fiberglas Type AA). Deep-bed filters on the other hand, involve packings of granular (sand or coke) or fibrous materials (such as "Fiberglas") that are up to several feet deep. In this service, the total aerosol concentration is usually on the order of or less than normal atmospheric dust concentrations.

Both types of units have a so-called "life," which is reached when so," much dust has accumulated in the filter medium that the resistance of the medium to air flow is increasing rapidly. The filter medium must then be cleaned or replaced. It is in this connection that the distinction between thin-bed or "paper" filters and deep-bed filters is closely related to a philosophy of application in decontamination of radioactive aerosols. With the thin-bed filters, the intent is usually to replace or clean the filter medium periodically. The deep-bed filter, on the other hand, usually has as its objective the installation of a unit which will have a long "life," in the dust capacity sense, of say five to twenty years, corresponding to either the life of the process or the mechanical life of the system. Thus, when the resistance starts increasing rapidly, the entire filter installation will be abandoned and replaced with a new unit rather than replacing or cleaning the filter medium.

The above distinction is rather arbitrary and applies to the types of units as now used. For example, the paper filters could be installed on an abandonment basis by providing enough filter area so that the "life" would be of the same magnitude as for the deep-bed types.* On the other hand, deep-bed filters could be operated at higher capacities and the medium replaced at intervals. There would, however, be no practical objective in this, since the primary advantage of deep-bed units is that they can be made maintenance-free.

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*This is in fact, a potential unexplored manner of using paper filters. The current design velocity for many of these "high efficiency" papers, such as C.W.S. Type 6, is 5 ft./min.. At these medium velocities a "life" of on the order of 1 to 3 years is experienced. The writer feels that, by going to medium velocities in the range of 0.3 to 1 ft./min., there is a very definite potential of obtaining a more economical installation from the standpoint of total annual cost. While the first cost might be somewhat higher than in current design practice, the unit should be maintenance free. In this reduced range of velocity, the paper filters might be competitive or economically superior to deep-bed filters, which have as their only justification the fact that they are maintenance-free. Before such potentials can be evaluated, however, further data are required on the "life" characteristics of paper filters at the reduced velocities.

It is the purpose of this paper to present the various practical and economic aspects involved in the design and application of deep-bed filters for the decontamination of radioactive aerosols.

Development of Deep-Bed Filters

Deep-bed aerosol filters have been used for many years in industry in the form of so-called coke beds. These employ a packing several feet deep consisting of graded-coke ranging from 1/2-in. to 40 mesh on size. They are employed at superficial bed velocities in the range of 1 to 10 ft./min. to remove sulfuric acid mist from burner gases in contact sulfuric acid systems.

In 1948 a high activity level was detected at Hanford and traced to particulates from the chemical processing ventilation stacks. Because of the urgency of the problem, it was decided, on the basis of theoretical predictions plus the precedent of the coke filters, that a deep-bed sand filter would offer the most expedient means for eliminating this particulate contamination. While it was recognized at this time that filters employing a fibrous medium would probably have a greater merit from the standpoint of economics, it was felt that the time required for the necessary development work would be considerably in excess of that required for the sand filters. This time factor was the main basis for the selection of a sand filter for this application. It took only 3-1/2 months from start of experimental work to prove theoretical predictions of sand filter performance to the time that the first large-scale unit was in operation. All the experimental evaluations, design, procurement, and construction of the full scale unit were carried out in this period.

Since that time, further work has been carried out, especially at Hanford, to develop more complete information on the performance characteristics of deep-bed filters with emphasis on fibrous media.

Principles of Operation

When an aerosol is passed through a packing, the suspended particles are caused to deposit on the surface of the packing by one of a number of mechanisms: 1) by direct interception of the aerosol particle due to its size; 2) by interception of the particle due to its inertia; 3) by diffusional or Brownian migration; 4) by gravity settling; 5) by electrostatic attraction; and 6) by migration due to a thermal gradient. In the applications under consideration here, there is substantially no thermal gradient and, to date, there has been no positive evidence that any electrostatic effects are involved.

In sand filters which normally operate at superficial velocities of 5 to 10 ft./min. and employ granules graded from as large as 2-in. diameter down to 40 mesh, the deposition mechanisms are primarily those of diffusion and gravity settling. Collection efficiency increases appreciably as superficial velocity is reduced. With fibrous filters, on the other hand, interception, both direct and inertial, may be a controlling factor, depending on the size of the fiber relative to that of the aerosol particle. Beds of coarse fibers, larger than 100 microns in diameter, normally operate at superficial velocities in excess of 30 ft./min. and generally show improved collection efficiency as the velocity is increased. Beds of fine fibers are usually operated at velocities of 5 to 50 ft./min. and show a reduction in efficiency as velocity is increased. These effects of velocity on efficiency reflect the predominant deposition mechanism in each case.

While a detailed discussion of deposition and build-up in packed beds is beyond the scope of this paper, it should be noted that most deep-bed filters are made up of a grading of sand or fiber sizes. This is done because of structural considerations in the case of sand filters but, more importantly, for increased life in the case of both sand and fibrous filters. The aerosol will deposit throughout the depth of a given layer of the filter, but the amount deposited will be the greatest at the upstream face, becoming gradually less toward the downstream face. The greater the collection efficiency of any single layer, the greater will be the concentration of deposit on the upstream end and the shorter the filter life. A coarser layer used ahead of a fine layer will remove the coarser aerosol particles and minimize the extent of aerosol concentration at the upstream edge of the fine layer. Since accumulation of deposit in the coarser layer will have less effect on resistance than it would in the fine layer, this will serve to increase filter life. Needless to say, for every aerosol particle-size distribution there is an optimum fiber or sand-size distribution from the standpoint of filter life. At the present time, however, the fundamentals of deposition and resistance build-up are not sufficiently developed to permit direct specification of these optimum distributions. Also, in most applications, the aerosol size distribution is not known well enough to permit the use of the fundamentals if they were available.

Design of Deep-Bed Filters

The factors that must be considered in the design of a deep-bed filter are collection efficiency or penetration, pressure drop, filter size, filter life, and available packing media. Fundamentally, the most important design specification should be the maximum tolerable activity level in the exhaust gases from the filter. In practice, however, this has been a secondary consideration. In many cases, especially in new installations, neither the quantity nor the particle size of particulate activity in the gas stream is known. Even if these were known, the tolerable concentrations have not been established in most cases. Thus, in the absence of such information, what has actually taken place in practice is to provide as high a degree of clean-up as is reasonably possible. Unfortunately, in a number of cases, the degree of clean-up that has been achieved in one application has been taken as a criterion for all other similar applications without re-analysis in terms of the specific conditions involved in these applications.

Pressure drop across a filter is controlled by the design of the filter and the amount of air passed through it. The pressure drop for which a unit is designed is determined by essentially two considerations. First, the pressure drop must not exceed that which ordinary commercial fans can develop. This sets an upper limit on pressure drop of 30 to 50 in. water without getting into multi-stage fans. More important, however, are the conditions imposed by straight economic considerations. The economics of a filter installation may, according to one system of accounting, be measured by the total annual operating cost. This operating cost may be considered in three parts: 1) power costs, which are directly related to pressure drop; 2) those fixed charges, such as maintenance and earning power of the funds invested, which are directly related to the investment cost; and 3) depreciation, which is related to the investment cost and to the life of the filter. Considering a given type of filter and packing arrangement and a given air handling capacity, a high air velocity through the packing will mean a high pressure drop, a small unit, and a short filter life. The effect of air velocity on total annual operating cost and on the components thereof is shown diagrammatically in Figure 1. It is apparent that there exists an optimum velocity at which the total annual cost is a minimum. This is the velocity for which the filter should be designed. Unfortunately sufficient information is not available on the life characteristics of such filters to evaluate this optimum velocity accurately. For the conditions at which deep-bed filters have been used, this optimum velocity is probably in the range of 5 to 10 ft./min. for the sand filters and 15 to 30 ft./min. for the fibrous type. Actual designs have been based on 6 and 25 ft./min. for sand and fibrous filters, respectively, with a corresponding pressure drop in the range of 4 to 8 in. water for both types. It would probably be more economical to operate at higher velocities and pressure drops but this could not be considered until a more complete knowledge of filter life is developed. It should be noted that the optimum velocity is dependent on both the aerosol size and concentration. A finer aerosol and a higher aerosol concentration would probably call for a lower optimum velocity with a given type of packing arrangement. It should also be noted that the relatively simple economic picture given above, in which a given type of packing arrangement is considered at different velocities, becomes considerably more complicated when, in addition, an attempt is made to arrive at an optimum packing arrangement for a given application. In this connection, the actual degree of clean-up required should have little effect on the optimum design velocity although a higher degree of clean-up will increase the total annual operating cost. The higher degree of clean-up would usually be obtained by additional depths of fine sand or fiber with a corresponding increase in pressure drop.

The filter area is, of course, determined by the air handling capacity and the superficial velocity. The filter depth is usually determined by the collection efficiency required. Deep-bed filters are inherently relatively large units. Most units to date have been of the horizontal type with gas flowing up through the packing. This results in a large floor-space or area requirement. While such units could be built in other arrangements to conserve on floor space, this normally increases the initial cost.

The filter life, as mentioned previously, is determined by the aerosol concentration and the packing grading as related to the aerosol size distribution. From the standpoint of maximum filter life it would be desirable to have a continuous graded packing, with the coarsest material at the upstream end and becoming continuously finer toward the downstream end. In all cases the maximum life would correspond to the most porous packing. In the case of sand, bed porosity is essentially fixed since it can be varied over only a small range. With fibrous packings, however, porosity can be varied over as much as a ten-fold range. From the standpoint of filter depth, however, it is desirable to maintain as high a porosity as possible. With fibrous packing, therefore, the actual porosity employed in any layer should be the maximum consistent with long filter life.

While an ideal packing would be continuously graded, in practice we are limited to a relatively narrow range of available sizes and densities. In addition the fundamentals of pressure build-up in packings due to dust deposition have not been developed to a point where they may be employed quantitatively; nor are the operating data on aerosol concentration and size distribution, necessary for any such application of fundamentals, usually available. Consequently, all packing arrangements to date have been somewhat arbitrary, governed primarily by available materials. With granular materials, such as sand, the limitations are imposed by the sizes available in quantity in the specific geographic area. In the case of fibrous materials, we are limited to the range of materials currently manufactured as standard products. Any attempt at specifying special sizes or materials will usually result in a marked increase in cost. The packings have been made by using layers of successively finer material, with the coarsest at the upstream end. In the case of sand, the successive layers have differed in nominal size by a factor of approximately two. In the case of glass fiber, the successive layers also vary in nominal size by a factor of two. As an alternate to a variation in size, however, a variation in packing density by a factor of two has also been used, with the more open packing at the upstream end. In most of the units to date, the gas flow has been up through the packing because of the possible presence of condensate or entrained liquid. In this way the liquid drops will first meet and be removed by the coarsest packing at the bottom or inlet end. If down-flow were used, without other special arrangements, all the liquid would eventually reach the fine packing and cause a marked increase in resistance to air flow.

It should be apparent from the above that the overall design of a deep-bed filter involves a balance of a large number of items. Because of a lack of both fundamental and operating information and various practical limitations, it is not yet possible to provide a rigorous design for a specific application. Instead it has been necessary to resort to engineering judgement to balance the various factors and thereby to arrive at reasonable designs. The final choice of type of deep-bed filter, sand or fibrous, rests purely on economics, aside from special considerations in some applications. While this paper deals solely with the deep-bed filter, it should be noted that, in any actual design comparision, the thin-bed filter should be included. In most cases, any one of these units, a deep-bed sand filter, a deep-bed fibrous filter, or a thin-bed or paper filter, can be designed to do a given job. The one that involves the lowest total annual operating cost is the unit to use.

Cost and Performance of Deep-Bed Filters

Cost and performance data on deep-bed filters are relatively meager. In Table I are shown comparative data for both a sand filter and a glass-fiber filter designed to handle 35,000 cu. ft./min. of air. The sand filter contains 9-1/2 ft. of graded gravel and sand ranging in size from 3 in. down to 50 mesh, as indicated in detail in Table I. The successive layers of gravel and sand rest directly upon each other, all being supported by a ceramic tile air distribution system at the bottom. The fibrous filter contains a total depth of 3 ft. of graded glass-fiber layers as specified in detail in Table II. Since these layers were specified for a predetermined packing density, each layer was supported separately on a screen, with an additional screen above the layer of Type AA "Fiberglas." In both the sand and the glass-fiber filter units, the filtering medium was horizontal with the air flowing vertically up through the medium. The filter size given in Table I is for the entire unit including, besides the filter housing proper, the inlet and outlet air manifolds, but not including the space occupied by lead-in or exhaust ductwork.

The cost estimates for the sand filter are based on actual construction costs of a comparable unit corrected to the specified capacity of 35,000 cu. ft./min. The cost data for the glass-fiber unit are estimates based on a specific design for this capacity. The performance data, pressure drop and collection efficiency, for the sand filter are based on field measurements made on a unit of almost identical design operated at the same velocity in an identical service. The performance data for the glass-fiber unit are estimated from the experimental results reported by Blasewitz et al ("Filtration of Radioactive Aerosols by Glass Fibers," Parts I and II, Hanford Works Report No. 20,847, April 16, 1951, unclassified) for a substantially identical service. The magnitude of the collection efficiency has also been checked by entirely separate tests made at Ohio State University on various types and densities of "Fiberglas," using a condensed dyestuff of the same order of particle size (0.4-micron diameter) as the radioactive aerosol.

At least one sand filter of the type indicated in Table I has now been in operation for a period of over 4 years with no indications of any build-up in pressure drop due to solids accumulation. It is safe to say that this unit will have a life in excess of 5 years in this service although its life may be over 20 years. There is no sound basis on which the actual life may be estimated more accurately. As to the glass-fiber filter, there is no large scale unit that has been in service long enough to obtain any reliable life data. Based on the comparative experimental data obtained by Blasewitz et al, it is estimated that the glass-fiber filter should have a life of 2 to 3 times that of the sand filter in this service.

In Table I the cost data have been presented on the basis of $/(cu. ft./min.) of air handled for convenience of generalization. The housing cost includes excavation, concrete structure, roofing, drains, painting, duct connections, etc.. For the sand filter this cost is $3.86/(cu. ft./min.) whereas, it is only $0.94/(cu. ft./min.) for the glass-fiber filter because of its much smaller size. The graded sand and gravel for the sand filter cost $1.71/(cu. ft./min.) in place. This includes the cost of the distributor tile blocks, which constitute only a small fraction of this item. The glass-fiber filter medium cost $0.76/(cu. ft./min.). However, with the designed involved here, the aluminum screen supports cost $1.16/(cu. ft./min.) or 1-1/2 times as much as the filter medium. Thus, the total installed cost of the sand filter is $5.57/(cu. ft./min.) as compared to $2.86/(cu. ft./min.) for a glass-fiber unit of the specified design.

The cost data given in Table I for sand and fibrous filters are actually not directly comparable. They represent merely what information is currently available. For a true picture, it would be necessary to compare the cost of a sand filter having the same pressure drop, collection efficiency, and life as a fibrous unit. In the case of the glass-fiber unit for which data are given in Table I, the pressure drop is lower and both the collection efficiency and life higher than for the sand filter. To make the results comparable would mean to approximately halve the size of the glass-fiber unit and also eliminate some of the finer fibers. On this basis, the cost comparison would be considerably more favorable for the glass-fiber unit than it already is. However, because of the meager information on filter life and the fact that considerably more data are available on large sand filter installations, it would be conservative to neglect these corrections for the present when using these data for design comparisons or decisions.

If stainless steel were used in place of aluminum for the screen supports, the cost for the glass-fiber filter would be increased approximately $1/(cu. ft./min.). For many applications, it is felt that, considering the maximum quantity of acidic components that may be present in the air handled, ordinary steel would be adequate for the supports and thereby permit an appreciable reduction in cost of this item. However, noting the large cost associated with the supporting screens, it would seem logical to reconsider the design of the glass-fiber filter with the objective of eliminating this major item of expense. In the glass-fiber filter design referred to in Table I, a fixed density and a fixed depth was specified for each layer of the packing. In order to insure that the density would be maintained and not changed due to the compressive effects of the weight of fibers on top or because of the pressure drop through the unit, the intervening screen supports were required.

Both the data obtained at Hanford and those obtained at Ohio State University indicated that, for a given aerosol, a given superficial velocity, and a given fiber, the collection efficiency depends on the total weight of fiber in the packing, independent of the density of the packing. In other words, if a given filter pad is compressed, the effect on collection efficiency will be negligible in the range of densities involved in these filter units. It should be noted that, in considering this independence of collection efficiency on packing density, we are not considering the same depth of packing with different densities; we are considering the same weight of fiber at different densities, and hence a smaller depth of fiber is involved at the higher density. While collection efficiency depends only on the total weight of fiber, pressure drop will increase as the density increases. In the range of density involved, for a given weight of fiber, the pressure drop will vary approximately as the square root of bed density. Thus, compressing a given pad to half of its original thickness, will result in approximately a 40% increase in pressure drop.

In view of the above, it would seem that packing density is not a critical factor. In order to eliminate the need for the supporting screens, it is only necessary to distribute the fiber uniformly insofar as weight per unit of filter area is concerned since the actual packing density is not a critical factor. The density influences only pressure drop and is not too great a factor at that. Thus it should be possible to take layers of fiber and lay them in the filter bed, one on top of the other, covering the entire filter bed with a grid or gravel to compress the filter layers to some pre-determined average density.

In Table II are given proposed specifications for such a packing arrangement in which density of each layer is not controlled, together with a typical specification currently used at Hanford for a packing of controlled density. It will be noted that the total amount of fiber has been increased from 6.85 lb./sq. ft. of filter in the current specification to

18 lb./sq. ft. in the proposed specification, in addition to changes in the grades of fiber employed. The layers of Type 800 and 450 "Fiberglas" have been added to increase filter life. While these layers will remove only a small percentage of the total aerosol, say 10%, they will collect the coarser particles that may be present. Such large particles, if not removed, could materially reduce filter life by forming a so-called "interface block" at the upstream edge of the fine glass wool layers. It should be remembered in this connection that most of the available performance data on collection efficiency and life have come from operations at Hanford and, as such, apply only to the specific aerosol concentration and size distribution existing in the Hanford ventilation air. At another site the aerosol may be different. At the present time in the absence of actual comparative data, we can only assume that the aerosol in similar operations at other sites is of the same order of magnitude. However, a small amount of coarser aerosol particles at other sites could materially reduce the life of a filter below that experienced at Hanford.

In the proposed specification a deeper layer of Type 28 "Fiberglas" has been substituted for the current thin layer of Type AA in order to eliminate the problems of edge-sealing, puncturing of the medium, placement and chemical deterioration, associated with such a thin fragile layer of extremely fine fibers. The deep layer of Type 115K "Fiberglas" has been provided to give adequate protection to the layer of Type 28 from the standpoint of life.

While the proposed specification calls for considerably more filter medium than does the one in current use, a large portion of this is associated with the coarse layers of Types 800 and 450 for purposes of increased filter life. While the cost of the filter medium will be greater; the over-all cost of the filter should be lower because of the simpler method of installation and the fact that the screen supports will not be required.

To design a unit with the proposed specifications given in Table II, it is necessary to have available information on the corresponding properties of fibers in order to be able to estimate the filter depth and pressure drop. Blasewitz et al give such data on Type 115K "Fiberglas" but no other such data are currently available. The depths on the proposed packing specifications given in parenthesis in Table II are purely arbitrary, in order to give an order of magnitude value. They are based on an assumed density of 3 lbs./cu. ft.. Actually this density will be different for each layer, dependent on the compressive properties of each layer and on the top grid or gravel location and arrangement.

When a pad of fine glass fibers is wetted with liquid, the resistance to air flow will mount rapidly and the fibers will tend to be matted together. This, as well as the possible deterioration of fine fibers by moisture and other chemicals, has been a question of no small concern in the use of fibrous filters. Unfortunately, there has been little practical experience to date with any large glass-fiber filters., There is in existence only one large installation and this is a relatively recent one. There is, however, a fair amount of background on smaller glass-fiber filters. Numerous such units with metallic housings are located on the tank-farm vents at Hanford. In the winter difficulty was experienced with condensation, with resultant high pressure build-up, presumably in the layer of Type AA "Fiberglas." When the unit was dried out by passing air through it, the resistance returned to normal; the "Fiberglas" had not matted together and had not given any permanent increase in pressure drop. Since then, this condition has been avoided by heating the units in the winter. It should also be noted that condensation should not be a problem with large filters, especially those housed in concrete. Because of the small relative area for heat transfer and the high heat capacity of the packing itself, the amount of water vapor that is capable of condensing in such large units is negligible.

At Oak Ridge a glass-fiber filter on the dissolver off-gas vent system showed a large permanent increase in pressure drop. This unit, however, was operated at many times the gas-handling capacity for which it was originally designed. The resultant extremely high pressure drops coupled with probable large quantities of liquid or solid entrainment from the vessels preceding the filter has presumably resulted in a permanent compression of the bed. This is, however, an abnormal operating situation.

Reports eminating from Hanford indicated that, on one occasion, moisture accumulation in one of the large sand filters, due to an accidental discharge of a steam vent into the ventilation gases, had resulted in a marked increase in pressure drop. What actually happened was that some of the steam condensate had accumulated in the lines to the manometer used for measuring filter pressure drop. This caused the manometer to show a fallaciously high pressure drop. Actually the pressure drop across the sand filter had not increased as shown by the fact that the manometer reading returned to normal when the water was blown out of the lead lines.

While the above discussion had been limited primarily to sand and glass-fiber filters, the synthetic fibers (such as "Dynel," "Orlon," "Saran," etc.) offer great promise for achieving more economical installations. Temperature considerations, of course, constitute limitations on the synthetics but in atmospheric installations synthetics may be less expensive than glass fibers. In filters, the controlling item is the cost of the fiber per cu. ft. of fiber. Since the density of the synthetics is roughly one-half that of glass, the cost of the synthetic fibers on a weight basis could be as much as twice that of the corresponding glass fibers and still be competetive.

Table I--Typical Deep-Bed Filter Data

	Filter Medium	
	Sand[X]	"Fiberglas"[XX]
Air handling capacity, cu. ft./min.	35,000	35,000
Filter Size (width x length x height), ft.	85 x 85 x 14	28 x 70 x 9
Filter Medium Velocity (superficial), ft./min.	6	25
Pressure Drop, in water	8	5
Collection Efficiency, % activity	99.7	99.99
Life	>5 years	>10 years§
Installed Cost, $/(cu. ft./min.)		
Housing	$3.86	$0.94
Filter medium	1.71	
Supports		1.16§§
Fibers		0.76
Total	$5.57	$2.86

§Estimated as 2 to 3 times that of sand filter

§§For aluminum supports. This would be approximately twice as much for stainless steel.

[X]Filter medium consisted of the following approximate depths and sizes of gravel or sand. These were supported on a molded ceramic distributor tile.

Depth of Layer, in. (In order, bottom layer listed first)	Sand or Gravel Size
12	1" to 3"
12	1/2" to 2"
12	1/2" to 4 U.S. mesh
12	4 to 8 U.S. mesh
24	8 to 20 U.S. mesh
36	20 to 50 U.S. mesh
6	4 to 8 U.S. mesh

[XX]Filter medium consisted of the packing arrangement designated in Table II as "Typical Hanford Specification."

Table II--Typical Deep-Bed Glass-Fiber Packing Specifications§

"Fiberglas"[X] Number	Approx. Fiber Diameter, microns	Approx. Fiber Cost,§§ $/lb.	Typical Hanford[XX] Specification: Depth in.	Typical Hanford[XX] Specification: Density lb./cu. ft.	Typical Hanford[XX] Specification: Density lb./sq. ft.	Proposed Specification: Density lb./sq. ft.	Proposed Specification: Depth§§§ in.
800	200	0.80				3	(12)
450	110	0.80				3	(12)
115 K	30	2.00	18	1.5	2.25	6	(24)
115 K	30	2.00	6	3.0	1.5		
55 P	15	0.25	12	3.0	3.0	3	(12)
28	7	1.00				3	(12)
AA	1	4.00	1	1.2	0.1		
		Total	37		6.85	18	(72)

§Designed for an activity collection efficiency of 99.99%. Pressure drop for Hanford specification is 5 in. water; for proposed specification it should be 4 in. ± 1 in. water, depending on degree of compression.

§§Approximate purchase cost as of June 1952.

§§§Will depend on degree of compression. Values given are for a 3-lb./cu. ft. density.

[X]Fiber layers listed in order, bottom or upstream end being specified first.

[XX]Similar to that given by Blasewitz et al., "Filtration of Radioactive Aerosols by Glass Fibers," Part I, p. 121, Hanford Works Report No. 20,847, April 16, 1951, unclassified.

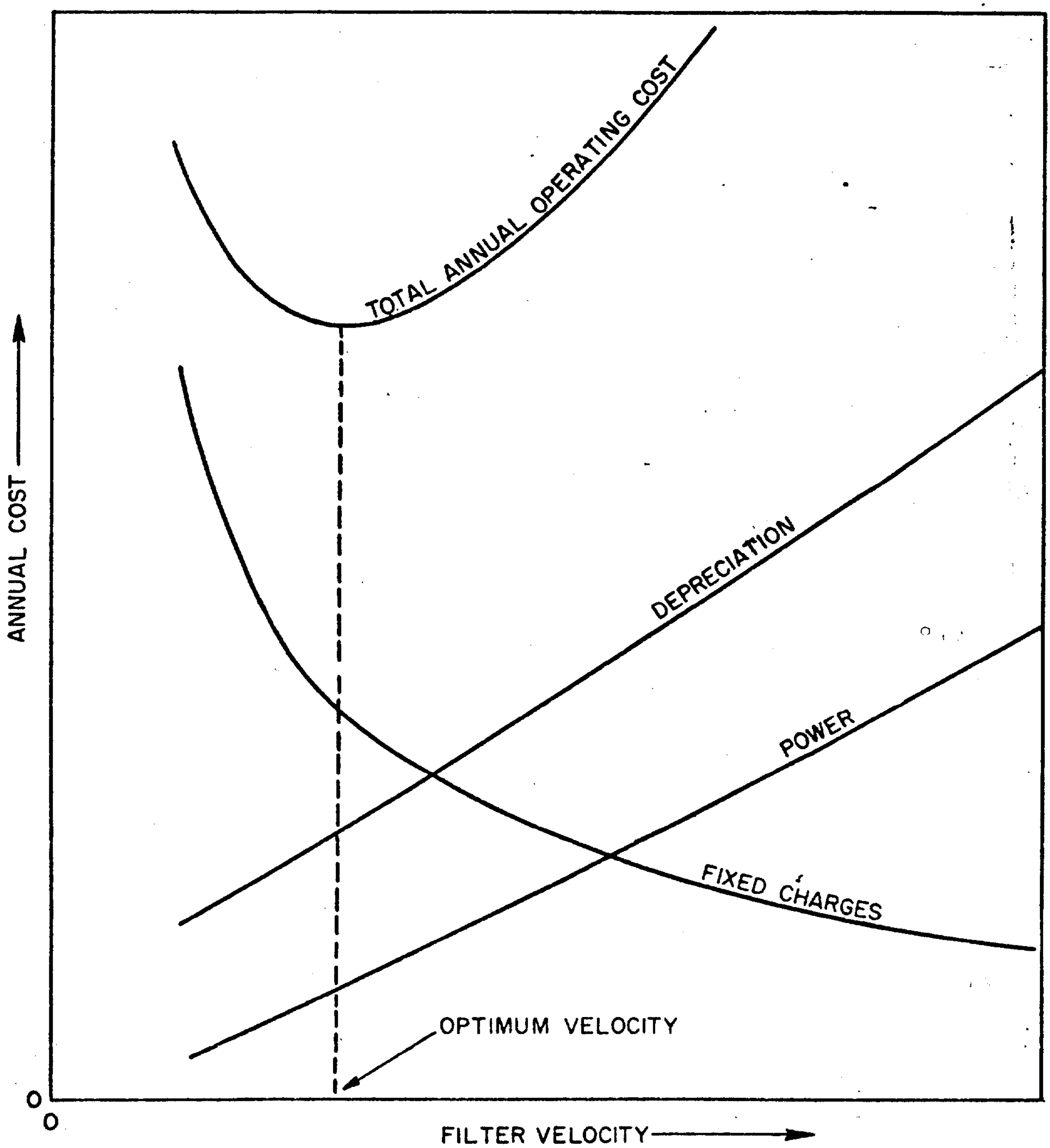

Fig. 1—Economic filter velocity.