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CHEMISTRY

FILTRATION OF RADIOACTIVE AEROSOLS BY GLASS FIBERS

PART ONE

BY

A. G. BLASEWITZ, R. V. CARLISLE, B. F. JUDSON, M. F. KATZER,
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TECHNICAL DIVISIONS

APRIL 16, 1951

HANFORD WORKS
RICHLAND, WASHINGTON

GENERAL ELECTRIC

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PART ONE

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Process Section
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April 16, 1951

HANFORD WORKS
RICHLAND, WASHINGTON

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ABSTRACT

1/ The disposal of radioactive waste gases from the plant-scale processes at the Hanford Works presents a problem that is of considerable importance in plant operation. This report is concerned with the intensive removal of the particulate matter suspended in the gas streams. In order to develop a filter unit having better performance characteristics than those of the presently employed sand filters, an extensive investigation of the filtration properties of glass fibers was undertaken. The program was divided into four portions consisting of (1) a study of the physical characteristics of glass fibers; (2) the determination of the size distribution and concentration of the particulate matter suspended in the gas streams at Hanford; (3) the correlation of pressure drop and collection efficiency under start-up conditions with superficial air velocity, the bed depth, and the packing density of the various types of glass fibers; and (4) a study of the expected service life of glass fiber filters. The results of the development program led to the design of glass fiber filters capable of operating at a higher superficial air velocity than the plant sand filters and with a greater efficiency, a lower flow resistance, and a greater life expectancy. Such filters have been constructed and are presently employed at the Hanford Works. From the operational standpoint, the performance of fixed-bed filters at this plant has been highly satisfactory. 1/2

THE FILTRATION OF RADIOACTIVE
AEROSOLS BY GLASS FIBERS

INTRODUCTION

A. The Problem of Radioactive Aerosols

The waste gases emitted from production (and laboratory) processes in the Hanford plants operated by the General Electric Company for the Atomic Energy Commission contain radioactive fission products in both gaseous and particulate forms. The potential hazard involved in the dissemination of radioactive materials over surrounding areas has been publicly recognized as necessitating the thorough decontamination of the stack gases before their discharge to the atmosphere (1), (2), (3). In accordance with the strict safety and health physics policies existing at the various AEC sites, considerable efforts have been expended to prevent any widespread contamination.

The problem of cleaning contaminated air streams is twofold, entailing the removal of radioactive gases, such as I^{131} , by one mechanism and suspended particulate matter by another. It is with the latter that this paper is concerned.

B. Design Specifications

The design specifications to be met in the filtration of radioactive aerosols are more rigorous than those of the ordinary commercial collector. Since the collection of large amounts of contaminated material in one place is inherently dangerous, the stringent requirements of AEC safety policies restrict considerably the possible methods by which the air pollution problem may be solved. A brief summary of the filter specifications is tabulated below. These are based upon the existing exhaust fan installations at the Hanford Works.

Table I - Filter Specifications

1. A collection efficiency of 99.99% for sub-micron particles present in low concentrations.
2. An initial flow resistance of less than 7 inches of water.
3. A minimum of maintenance in the continuous operation of the unit.
4. A life expectancy in terms of years.

5. No subsequent problem caused by the disposal of the collected material.

The air streams that must be cleaned contain low concentrations of particles whose sizes are predominantly in the sub-micron range. Studies on the effects of inhaling particulate materials reveal that toxic particles of all sizes should be removed as completely as possible. Since the possible toxic effects of radioactive particles in the sub-micron size range are not known, a collection efficiency of 99.99% was chosen as a feasible design figure. Ordinarily, however, the field of dust collection is primarily concerned with the elimination of process dusts, the concentration of which may be as high as several hundred grains per cubic foot. Readily available commercial equipment, such as cyclones, cloth collectors, electrical precipitators, ultrasonic precipitators, and the various types of scrubbers, separate high concentrations of particles greater than the 3-5 micron range in diameter with efficiencies varying from 50-98% (4). Their effectiveness is materially reduced with low-loading dusts in the sub-micron range. Similarly, in the treatment of atmospheric dusts where the loading is generally less than 5 grains/1000 ft.³, the ordinary air filters have a negligibly low efficiency in the removal of particles less than 1 μ in diameter.

High efficiency filtration has long been the concern of military establishments. The Chemical Warfare Service (5) and, more recently, A.D. Little, Inc. (6) have fabricated asbestos-impregnated filter papers, each layer of which has an efficiency in the order of 99.9% and a resistance of approximately one inch of water at the rated superficial velocity of 5 ft./min. The Naval Research Laboratory has recently announced (7) the development of a glass fiber filter paper which, when subjected to standard tests, indicated an efficiency of 99.999% and the normal breathing resistance of a gas mask. Although the life expectancy of filters such as these is very short, their compact, laminar construction makes them well suited to gas masks and the other military purposes for which they were designed. Large-scale, industrial filtration, however, stresses the need of a lower flow resistance and a much greater life expectancy; this is usually achieved at the expense of high filtration efficiency. The work described in this report was directed to the development of an air filter that combines the desirable properties of both military and industrial units; viz, a long life expectancy and a high collection efficiency.

The special considerations encountered in the handling of the material collected require that there be no subsequent disposal problem -- this condition makes the choice of scrubber-type collectors undesirable. Furthermore, the difficulties involved in working in zones having high radiation levels, and consequently short time limits, call for a minimum of maintenance work. The more common types of commercially available dust collectors fail to meet one or more of these specifications.

C. Sand Filters as an Expedient Solution

An expedient solution to the problem of removing radioactive aerosols from the air streams at the Hanford Works was a filter consisting of successive-ly finer gradations of sand, placed in a large underground container, and suitably equipped with air distributors, plenum chambers, and ductwork (8), (9). The characteristics of the sand filters agree well with those specified above; the pressure drop and filtering life are satisfactory; maintenance is negligible. The collection efficiency, however, is of the order of 99.7% rather than the specified 99.99%.

The need for a sand filter replacement will eventually arise. As the material accumulates within the bed, the resistance of the unit will increase and, in time, reach a point where it will prohibit any further use. Its service life ended, the "plugged" filter will remain in its place underground, and the air stream will be piped to a new unit.

It was suggested by Lapple (10) that the substitution of glass fibers for sand as the filtering media might lead to some improvements in filter design and operation. The desirability of a replacement unit capable of operating at a higher superficial velocity and having a greater life expectancy is evident. Since the results of preliminary tests were favorable, an extensive investigation of the filtration characteristics of glass fibers was initiated.

SUMMARY

The investigation of glass fibers as filtration media suitable for the intensive removal of radioactive particulate matter suspended in the gas streams at Hanford Works consisted of four parts: (1) a study of the physical characteristics of glass fibers; (2) the determination of the size distribution and the concentration of the suspended particles; (3) the correlation of pressure drop and collection efficiency under start-up conditions with superficial air velocity, the bed depth, and the packing density of the various types of glass fibers; and (4) a study of the manner in which the collection efficiency and pressure drop of glass fiber filters increase with the cumulative amount of smoke particles passing to the unit.

The first phase of the investigation was primarily concerned with the weatherability of glass fibers; i. e., the degree to which the various types of fibers can withstand the effects of water, alkali, or acid present in the gas stream passing through the filter bed. The chemical resistance of the fibers is a function of both the filament diameter and the composition of glass employed in their manufacture. The corrosive effects of water, alkalies, or acids may eventually lead to the complete destruction of the fibrous material in an operating filter. The glass specified in any filter design must, therefore, have the maximum weatherability for the particular stream conditions under which it is to be used.

The second phase of the investigation was concerned with the characteristics of the particulate matter suspended in the air streams ventilating the process cells at the Hanford Works. The particle size distribution of the heterogeneous aerosol was determined by means of the Modified Cascade Impactor and found to be predominantly in the sub-micron range. The distribution was based on radioactivity measurements rather than the more common count and weight bases and, consequently, did not involve uncontaminated particles. Other studies revealed that the dust loading of the air entering the process cells at Hanford is 0.01 - 0.02 grains/1000 ft.³, and that the loading of the effluent air is in the order of 0.2 - 0.4 grains/1000 ft.³. It was felt, therefore, that the purposes of the test program did not warrant more extensive size measurements.

The investigation of the filtration characteristics of glass fiber beds was made under fixed conditions by employing the radioactive heterogeneous aerosols emanating from the process cells. The two dependent variables, collection efficiency and pressure drop, were correlated as a function of superficial air velocity, the bed depth, and the packing density of the various types of fibers. Nomographs relating collection efficiency and pressure drop with the above parameters have been prepared for three fibers having average diameters of 1.3 microns, 14.0 microns, and 29.2 microns. The nomographs are sufficiently accurate within the indicated ranges to be of particular value in the design of fibrous filters for the removal of particles similar to those at Hanford. These charts should also be of considerable use in any application where the particle loading is low.

The final phase of the investigation was concerned with the expected service life of glass fiber filters. Tests were conducted with a methylene blue smoke having a particle size distribution similar to that of the radioactive aerosol and a dust loading 10-20 times that of the process-cell air. Studies made on several small depths of fibrous materials revealed the exponential increase in collection efficiency that occurs with the passage of smoke particles to a fixed-bed filter. During the operation of such a filter, the pressure drop also increases, eventually reaching a value that determines the service life of the unit. By including a less-efficient prefilter that effectively "protects" the more efficient material, the life expectancy of the composite filter may be extended. In a series of methylene blue tests, a comparison was made of the useful filtration life to be expected from the various types of fibrous units. At the same time, suitable prefilters were developed for the more efficient glass fibers.

The results of the development program led to the design of glass fiber filters capable of operating at a higher superficial air velocity than the plant sand filters and with a greater efficiency, a lower flow resistance, and a greater life expectancy. Such filters have been constructed and are presently employed at the Hanford Works. The first unit using glass fibers as the filtering media was placed in operation on October 26, 1950. The measured collection efficiency was greater than 99.9%, and probably near 99.99%. The initial pressure drop was 4 inches of water. These data agree very well with the design figures. The unit has operated continuously for over six months without any measurable increase in pressure drop.

From the operational standpoint, the performance of fixed-bed filters at the Hanford Works has been highly satisfactory. No maintenance has been required on the sand filters or the Fiberglas filters during their respective operating periods of 2-1/2 years and 6 months. Both the initial and operating characteristics of the filter units meet the design specifications for the intensive removal of contaminated particles from air streams which are discharged from plants processing radioactive materials on an industrial scale. The use of glass fiber filters, of course, need not be restricted to the filtration of radioactive materials. Fixed-bed filters formulated with glass fibers can be advantageously employed wherever sub-micron particles, present in air streams at low concentrations, must be removed with a very high efficiency.

GLASS FIBERS

Glass filaments, one to two hundred microns in diameters, can be produced by the extrusion of molten glass under pressure. As the photomicrographs of Figures 1, 2, 3 indicate, the individual strands are smooth surfaced and substantially cylindrical in form. Such fibers are manufactured on a large scale and are available in a wide variety of forms, characterized by the type of glass, fiber diameter, fiber length, the fiber lubricant or binder, and the manner of packing. The main producer in the field is the Owens-Corning Fiberglas Corporation of Newark, Ohio. For purposes of convenience, most of the experimental work reported in this paper was performed on Fiberglas.*

A. Nomenclature of Fiberglas Materials

The nomenclature employed by the Owens-Corning Fiberglas Corporation to designate a type of fiber is based on the average diameter expressed in inches multiplied by 100,000. Thus, No. 55 fiber has an average diameter of 0.00055 inches, while the diameter of No. 450 fiber is approximately 0.00450 inches. The smaller fibers are designated by letters rather than numbers, and the average diameters are expressed as a range; AA fiber for example, has an average diameter varying from 0.00003 inches to 0.00005 inches.

B. Weatherability of Glass Fibers

Table II lists some properties of those basic fibers studied in the investigation of glass fibers as a means of high-efficiency filtration. One of the more important properties of a fiber bed is its weatherability -- the degree to which it can withstand the effects of the conditions under which it is to be used. The large increase in surface area brought about by the formation of small filaments from a pound of solid glass results in a corresponding increase in its reactivity with acids or water. Weatherability is thus a function of fiber diameter and glass composition. Exposure of a mat of fibers to water or acid solutions results in the gradual removal of the alkalis in the glass; the rate at which this takes place is greatly accelerated by solutions

* "Fiberglas" is the trade name (Reg. U. S. Pat. Off.) of glass manufactured in any fiber or filament form by the Owens-Corning Fiberglas Corporation.

with a pH of less than 4. As the leaching reaction proceeds, the fibrous mat loses its resilience and, in the end, becomes so embrittled that the slightest force applied to it causes it to crumble to a dust. Since this could conceivably happen in a fibrous filter bed, it is imperative that the proper grade of glass be used for the specific conditions of the air stream.

The basic fibers of Owens-Corning Fiberglas Corporation are produced from four different glasses, each of which is suited to certain fields of application. Type "E" glass is employed in the production of electrical insulating materials, and fibers made of Type "T" glass are used as thermal insulation. Type "C" glass, termed "chemical glass", is recommended for acid conditions. Type "F" glass is used only in the manufacture of coarse fibers. Over the pH range of 4 to 10, the Types "C" and "E" glasses are substantially equivalent; below a pH of 4, however, the "C" material is superior to Type "E", while above a pH of 10 the reverse is true. The Type "T" material is inferior to both "E" and "C" glasses in its resistance to humidity effects and acid conditions. Since the use of the coarse fibers did not appear suitable for the air filtration problem at the Hanford Works, detailed information on the weatherability characteristics of Type "F" glass was not obtained. During long exposures to elevated temperatures, the action of the four glasses is substantially the same provided that the moisture content of the gas is very low. The service limit under these conditions is approximately 1000°F. It is advisable to consult the manufacturer concerning the weatherability of a particular type of glass prior to its use in a plant installation.

The Owens-Corning Fiberglas Corporation has subjected three of its glasses - Types "E", "C", and "T" - to a weathering test developed by the U. S. Bureau of Standards. A continuous cycle of high-humidity - high temperature, low-humidity - low temperature conditions multiplied the effect of ordinary weather changes by an estimated factor of thirty. At the end of a six month test period - the equivalent of 180 months of atmospheric weathering - the "E" and "C" glass fibers showed slight evidence of deterioration, while the deterioration of No. 55 "T" glass fibers varied from a slight to an extreme degree. A second test was conducted by continuously exposing "T" and "E" fibers to live steam (4 - 6 psig.) in an autoclave. At the end of three days the "T" glass was severely deteriorated; the "E" glass, however, showed only slight signs of deterioration after five weeks of the treatment.

Figure 1

PHOTOMICROGRAPH OF NO. 55 FIBERGLAS

Fiber magnification = 250 X
Scale magnification = 250 X
Smallest division on the scale
equals 0.01 mm. at 1X.

Figure 2

PHOTOMICROGRAPH OF NO. AA FIBERGLAS

Fiber magnification = 1000 X
Scale magnification = 50 X
Smallest division on the scale
equals 0.01 mm. at 1X.

Figure 3

PHOTOMICROGRAPH OF NO. 115 FIBER

Fiber magnification = 200 X
Scale magnification = 50 X
Smallest division on the scale
equals 0.01 mm. at 1X.

TABLE II
FIBERGLAS BASIC FIBERS

Fiber No.	Type Glass	Average Fiber Diam. (Inches)	Deviation (Inches)	Fiber Length (Inches)	Type Lubricant or Binder	Av. Packing Density (pcf) ^{7.}	Packing Form	Surface Area Per lb. Glass (Sq. Ft.)
AA	E	0.00003 - 0.00005	--	--	PFP ^{1.}	0.6	Mat	6038.
B	E	0.00010 - 0.00015	--	--	PFP	0.7	Mat	2013.
B(L and R) ^{2.}	E(L and R)	--	--	--	PFP	4.0	Mat	--
55	T	0.00055	±0.00030	6	MO ^{3.}	3.0	Bulk and Bats	537.
55P ^{4.}	T	0.00055	±0.00030	<6	PFP	1.5 to 6.0	Mat	--
115 ^{5.}	--	0.00115	--	--	PFP	--	--	263
115K ^{6.}	C	0.00115	--	--	None	1.5	Bulk	263
450	F	0.00450	±0.00050	20	PFP	3.5	Packs	68.8
600	F	0.00600	±0.00050	20	PFP	3.5	Packs	51.6
800	F	0.00800	±0.00050	20	PFP	3.5	Packs	38.7

Notes

1. PFP - indicates phenol formaldehyde polymer.
2. L and R - refers to a leaching and refiring treatment.
3. MO - indicates mineral oil.
4. P - indicates a polymer binder rather than mineral oil.
5. This sample was received from A. D. Little, Inc.
6. K - refers to crimping of the individual strands.
7. pcf - pounds per cubic foot.

An attempt to improve the acid-durability of "E" glass fibers was made by the Owens-Corning Fiberglas Corporation. A mat of the material was exposed to an acid solution and substantially leached of its alkali contents. Refiring the fibers restored their resiliency and left a mat capable of greater endurance under acid conditions. A sample mat was received and designated in this report as B(L and R) fiber. No data were given concerning any weathering tests that may have been made on the leached and refired material. A secondary effect of the treatment was a slight reduction in the size of the filaments.

C. Fiber Diameter

The fiber diameter is an important parameter in determining the collection efficiency of a Fiberglas unit. The figures given in Table II are those of the manufacturer (11) and represent average diameters, deviations from which may be 50% or more. Twenty-four random fibers were removed from a bed of No. 55 Fiberglas and their diameters measured. The average of the twenty-four measurements was 0.00053 in., but the individual values ranged from 0.00028 in. to 0.00104 in. Twenty-one AA fibers averaged 0.000091 in. with values ranging from 0.000024 in. to 0.000187 in. The average value of 20 No. 115 fibers and 20 No. 115K fibers was 0.00106 and 0.00116 in., respectively. Similarly, the values for fiber length listed in Table II are average values.

D. Fiber Lubricant

A fiber lubricant is necessary in the manufacturing process of some types of Fiberglas as, for example, No. 55. The film of mineral oil covering the individual filaments of No. 55 Fiberglas can be removed by heat or by a solvent such as carbon tetrachloride. A phenol formaldehyde polymer is often used by the manufacturer as a binder to maintain the packing density of Fiberglas mats during shipment to the customer. The resin may be removed without any effect on the fibers by slowly heating at a temperature of 800°F. or by heating for a very few minutes at 1200°F.

THE TESTING MEDIA

A. The Two Media and Their Purposes

The experimental data obtained on the filtration characteristics of Fiberglas filter beds may be divided into two categories: first, the data pertaining to the initial properties of the beds, and second, the data pertaining to the operating properties. The differentiation is due to the fact that mechanical filtration is a dynamic process. Upon its removal from the air stream, a particle is assimilated within the bed and causes an incremental change on the operating characteristics of the bed by assisting in the removal of other particles and increasing the resistance to air flow. Thus, the initial properties refer to the traits exhibited by the fibers alone and are the start-up conditions. The operating properties refer to the continually changing features of the bed, which culminate in the "plugging" of the filter.

To facilitate the assemblage of data, two testing media were employed: the process-cell air prior to its filtration in the plant sand filter and its ultimate discharge to the atmosphere, and an artificially produced methylene blue smoke. The low concentrations of radioactive and inactive particles in the former gas stream provided a convenient means of determining the initial characteristics of the filter beds, since during the length of time necessary for the tests, the effect of the filtered particles was immeasurably small. On the other hand, the particle loading of the smoke stream used to measure the operating features of the units was approximately ten to twenty times that of the process-cell air. Consequently, the life of a test filter was shortened to a suitable length of time. A further convenience in the use of an artificial smoke was the elimination of the health hazard from the test units that would have accompanied the long-term filtration of the radioactive gas stream.

B. Process-Cell Air

1. The Equipment

The supply of process-cell air used in testing the Fiberglas units was withdrawn from a 2-inch sample port located in the main ductwork immediately prior to its entry to the sand filter. Stainless steel lines (Type 347, 2-inch i. d.) were employed in transporting the gas to the test units as a preventive measure against the formation of rust particles and their possible entrainment in the air stream. After its passage through the Fiberglas bed, the air was

metered in an orifice section, decontaminated in a CWS box-type filter, and exhausted to the atmosphere through a steam-operated evacuator. The resistance to the air flow offered by the filter bed was measured in terms of pressure drop. The box filters contained fluted layers of CWS Type 6 paper and were rated for an efficiency of 99.9% at a flow rate of 30 cfm. Two types of evacuators were used - 75 gpm liquid jets and 150 cfm air jets; steam for their operation was available at pressures to 220 psig.

The collection efficiency of the Fiberglas filter in the line was measured by monitor stations located upstream and downstream of the unit. In each case, a continuous sample was withdrawn from the test stream and passed through a one-inch stainless steel line to a suitable orifice section where the flow rate was measured. The particulate matter in the samples was removed in the station and the decontaminated air was finally exhausted to the atmosphere by an evacuator. The monitor station consisted of a flanged section in the pipe-line in which the air stream was expanded to an area four inches in diameter, passed through a highly efficient filter paper, and returned to its original area. The filter employed was the Type 6 asbestos-impregnated paper (5) developed by the Chemical Warfare Service. Asbestos-type gaskets (12) were used to prevent leakage between the flange surfaces and the filter paper. A schematic drawing of the over-all testing equipment is given in Figure 4. Figure 5 contains a more detailed sketch of a monitor station.

It has been shown (13) (14) that, for the correct sampling of an air stream containing suspended particulate matter, the average velocity at the intake of the sampling tube must be substantially equal in both magnitude and direction to the local velocity of the main stream at the sampling point - the so-called "isokinetic" conditions. Should a velocity unbalancing exist, inertial effects of the particles may cause them to deviate from the flow lines into the intake tube, resulting in a coarser dust sample if the sampling velocity is too low, and a finer sample if it is too high.

Sampling of the particle content of the gas upstream and downstream of the Fiberglas units, however, was accomplished by merely drawing off a continuous aliquot at an angle of 90° to the main stream. Since the error involved in not meeting isokinetic conditions is very small for particles less than 5 microns in diameter (15), it was felt that the over-all precision of the testing equipment did not warrant a more elaborate means of sampling.

Figure 4

FLWSHEET OF THE PROCESS-CELL AIR EQUIPMENT

Figure 5 - SCHEMATIC DRAWING OF A MONITOR STATION

- Note:**
1. All material stainless steel.
 2. Bottom view identical to top view except for location of 1/8" nipples which should be in line when flanges are bolted together.
 3. Fabrication includes: (a) 4" diam. 10 gauge s.s. screen approx. 1/8" thick. (b) 4-5/8" studs 3 1/2" long. (c) 8 hex. head nuts to fit studs.
 4. All nipples welded to flanges.

2. Air Flow Measurements

Air flow measurements were made by means of orifice sections equipped with sharp-edge orifice plates and standard radius taps. The sections were individually calibrated over their rated flow range by measuring the static pressure developed by the discharged air in a plenum chamber of known characteristics. Plotting the calibration curves of pressure drop (inches of water) vs. flow rate (cfm) resulted in straight lines on log-log graph paper. Pressure drop values were read on U-tube and inclined manometers. The over-all precision of measurement was $\pm 5\%$.

3. CP Analysis

The efficiency of the Fiberglas test units was determined by measuring the amount of activity collected on the upstream and downstream filter monitors. Two means of obtaining these values were available. A field measurement was provided by the pistol-grip type of radiation survey meter, often termed the "Cutie Pie" or "CP". By means of a detachable shield, such an instrument can give an indication of the amount of β plus γ radiation, and γ radiation alone that is emanating from a source. With the shield on, and thus most of the β radiation excluded from the chamber, the instrument reads directly in terms of milliroentgens per hour; with the shield off, the scalar readings can be converted by means of a calibration chart to mrep/h⁴. * Actual values obtained are a function of the geometry of the source and the distance between the source and the CP. The source geometry of each filter was the same; namely, the area of a circle 4 inches in diameter. With the exception of a few cases involving liquid entrainment, the contamination of the filter was uniform over the exposed area. By careful manipulation of the instrument in regard to its zero point, angle of elevation, and distance from the filter, reproducible readings could be made.

4. Laboratory Analysis

The second means of calculating the efficiency of the test filter was from the results of a laboratory analysis of the monitors. The standard procedure of analysis was as follows: the complete paper was treated with hot, fuming nitric acid; the resultant solution was filtered and diluted to a known volume, from which a 10 λ aliquot was taken; the aliquot was evaporated to a -----

* mrep/hr. denotes milliroentgen-equivalent-physical per hour.

dryness on a counting disk, and the residue counted in a BGO scaler. After accounting for geometry and volume, the results were reported as microcuries of β plus γ radioactivity per filter.

The precision of the activity measurements was nominally $\pm 5\%$. However, a statistical analysis of some 200 monitoring runs made on the efficiency of a plant sand filter indicated a greater accuracy (16). These routine determinations were performed in the same manner as that outlined for the Fiberglas units and covered a period of approximately 20 months. The analysis revealed that the precision of the CP and laboratory values was $\pm 0.29\%$ and $\pm 0.27\%$, respectively. The figures included variations due to errors in sampling and random errors in activity measurements. The precision of one efficiency determination calculated from CP values was $\pm 0.14\%$ if the random errors in activity measurements were the only source of variation. A similar figure was obtained assuming the random errors in sampling were the only source of variation.

The presence of radioactive gases, such as I^{131} , in the process-cell air was a variable source of error. Data taken on the performance of a Fiberglass filter in an air stream containing relatively large quantities of I^{131} demonstrated that, due to the I^{131} , the indicated efficiency of the filter was much lower than its actual value (17). At the start of the investigation of Fiberglass filtration characteristics, the error introduced by the presence of I^{131} in the process-cell air was not too significant. Changes in plant operation with a consequent increase in the I^{131} content of the radioactive gas led to such erratic values that the installation of a reactor capable of removing I^{131} was necessary.

C. Methylene Blue Smoke

1. The Equipment

The methylene blue smoke that was used to determine the operating characteristics of fibrous filters was generated by dispersing a dilute solution of the dye into the air and evaporating the resultant droplets. The formation of the liquid aerosol was accomplished by means of four aspirators, the design of which was originally proposed by Laskin and later improved by Enquist (18). Figure 6 outlines the structure of one of the jets and the manner in which it functioned. When a jet was suspended from above the methylene blue solution so that its base was slightly immersed in the liquid, the passage of air through

the jet at a pressure of 15 psig. resulted in the liquid being aspirated into the base and ejected as a fine spray. The mist continuously formed by four aspirators was collected by an air-sweep current and passed to a cyclone separator where the larger droplets were removed. The mist-laden stream was then diluted with large volumes of clean air in a dilution chamber which served to evaporate the water and stabilize the resultant smoke. The diameter of the solid particles so formed was a function of the dye concentration in the original solution. A 2% solution resulted in smoke particles having approximately the same size distribution as those of the process-cell air.

Upon leaving the dilution chamber and before its passage to the test units, the smoke stream was sampled in the same manner as the process-cell air. A continuous aliquot was drawn off, metered in an orifice section, and filtered in a monitor station before its final exhaustion to the atmosphere. Downstream of the sample port, the main stream was divided into two parallel trunk-lines, each of which served four filter units. A second sample port was located at the extreme end of one of the trunk-lines to verify the uniform dust-loading of the gas entering the filter beds; suitable repiping also enabled the use of the second sample port as a downstream monitor in determining the efficiency changes of an operating bed. The eight parallel smoke streams passing through the Fiberglas units were individually metered in orifice sections, then collected in one header-line containing a CWS box-type filter, and exhausted to the atmosphere. The orifice sections and monitor stations were fabricated in the same manner as those in the process-cell air tests. Both U-tube and inclined manometers were employed in pressure drop measurements. A schematic drawing of the equipment is presented in Figure 7. Figures 8 through 12 contain photographs of the equipment.

2. Laboratory Analysis

Calculation of the dust-loading of the smoke, the grains of dust entering a filter bed, or the efficiency of a unit involved the measurement of the amount of dye collected on the monitor filters. Removal of the methylene blue ($C_{16}H_{18}N_3SCl \cdot 3 H_2O$) from the filter paper was accomplished by applying suction to the face of the paper and slowly backflushing with approximately 100 ml of 95% ethyl alcohol. Flushing with water was prohibited by its strong tendency to "set" the dye in the paper. After the addition of about 100 ml of water to the methylene blue solution, the alcohol was removed by distillation. The residue

was made up to a known volume and then diluted to a concentration suitable for analysis by a Beckman Spectrophotometer. Calibration of the particular instrument employed indicated that, at a wavelength of 666 millimicrons, Beer's Law of Absorption was applicable. A plot of % Transmission vs. Concentration on semi-log paper was a straight line. The nominal precision of measurement was $\pm 5\%$.

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Figure 6

DRAWING OF A METHYLENE BLUE ASPIRATOR

All material brass.

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Figure 7

FLWSHEET OF THE LIFE TEST EQUIPMENT

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Figure 8

PHOTOGRAPH OF THE LIFE TEST EQUIPMENT
SECTION I

Figure 9

PHOTOGRAPH OF THE LIFE TEST EQUIPMENT
SECTION II

Figure 10

PHOTOGRAPH OF THE LIFE TEST EQUIPMENT
SECTION. III

Figure 11 56

PHOTOGRAPH OF THE LIFE TEST EQUIPMENT
SECTION IV

Figure 12

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PHOTOGRAPH OF THE LIFE TEST EQUIPMENT
SECTION V

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CHARACTERISTICS OF THE SUSPENDED MATTER

As the section on the design specifications indicated, the choice of a dust collector to be employed in the filtration of an air stream is largely influenced by the size distribution and concentration of the suspended particulate matter. A knowledge of these characteristics is essential in determining the degree of removal to be obtained by a filter and the service life to be expected.

A. Particle Size Distribution Process-Cell Air

The particle size distribution of the process-cell air was determined by three different methods, the first two of which merely indicated the bulk of the particles to be less than a 3 to 5 micron range in diameter. The results of the third method, however, were more quantitative.

1. "Tennis Rackets"

The first exploratory attempt to characterize the particle size of the radioactive material in the process-cell air was based upon impingement of the particles on fine wires of known diameter. Due to inertial effects, the path of a particle travelling toward a cylinder placed transversely to the direction of flow deviated from the path of the air stream in which it is suspended. With increasing velocity, the difference between the flow curvatures of the air stream and the suspended particle becomes more pronounced and the chance of the particle by-passing the cylinder without a collision is decreased. Langmuir has published calculations of the trajectories of small water droplets in air moving at high velocities across a cylinder and has correlated the theoretical deposition efficiency with two dimensionless parameters (19). The equations he used to describe the motion of the particles were based on Lamb's theory of viscous fluids; their solution was made possible by means of a differential analyzer. The curves for the deposition efficiency were derived on the assumption that all particles were of uniform size -- a condition that in general is not valid. A method was devised by Langmuir, however, for taking into account certain assumed distributions of particle size.

The apparatus consisted of two monitor stations placed in the sample line and operated in series. A wire-grid was inserted in the upstream station while the downstream station contained CWS Type 6 paper. The grid was made of 3 mil, 30 mil, and 60 mil wires strung transversely to the direction of air

flow. Spacing was at 1/8-inch intervals to minimize disturbance of the flow lines around individual wires. Re-entrainment of the particles deposited on the wires was prevented by a thin film of petrolatum-petroleum oil mixture. The process-cell air flowed through the equipment at the rate of 10 cfm (848 cm/sec.).

Analysis of the individual wires, based on a comparable cross-section (referred to the activity on the 30 mil wire), indicated that the activity on the 3 mil, 30 mil, and 60 mil wires was $3.8 \times 10^{-2} \mu\text{C}$, $1.4 \times 10^{-2} \mu\text{C}$, and $0.8 \times 10^{-2} \mu\text{C}$, respectively. The data were treated as suggested in the AAF Report (20) with the further assumption that the true density of the particles was 2.8 gm/cm^3 . A value of 2.0 microns was obtained for "volume-median" diameter; theoretically, half of the particles had a larger diameter, and the other half a smaller diameter.

2. Cyclone Separator

The second means of obtaining a qualitative idea of the size characteristics of the particles in the process-cell air was a cyclone separator. The body of the cyclone consisted of a piece of pipe, 12 inches long and 2 inches in diameter. Air entered through a 1/4-inch i. d. tube welded tangentially to the pipe at a point 1/2 inch from the top. The exit was a length of 1-inch i. d. pipe centered on the top of the 2-inch pipe and extending a distance of one inch into the main body. A sketch of the apparatus is presented in Figure 13. The flow rate of the process-cell air through the equipment was one cfm. The collection efficiency of the cyclone was determined in the same manner as that outlined in the section on Testing Media.

From the performance of a cyclone separator some knowledge of the size characteristics of the entering particles may be obtained. The expression for the diameter of the smallest particle completely removed by the cyclone is given by Anderson (21) as:

$$D_{\min} = \sqrt{\frac{9\mu b}{\pi NV(\rho_s - \rho)}}$$

where: $D_{\min}$ = minimum diameter, ft., of particles completely separated.

b = inlet width, ft.

- N = number of turns made by the gas stream in the cyclone, dimensionless.
- V = inlet velocity, ft. /sec.
- μ = viscosity of air; lb. /ft. sec.
- ρ_s = true density of particle, lb. /ft. ³.
- ρ = gas density, lb. /ft. ³.

Anderson also indicates that a fractional separation, X, should be theoretically obtained on particles smaller than D_{min} , when,

$$D_X = D_{min} \sqrt{X (2-X)^{0.5}}$$

where:

- X = fractional separation, dimensionless.
- D_x = diameter ft. of particles smaller than D_{min} that are removed to a degree X.

Figure 13

SCHEMATIC DRAWING OF CYCLONE SEPARATOR

Assuming the true density of the particles to be 2.8 gm/cm^3 and employing an average value of $N=5$, as suggested by Lapple*, substitution in the above expression resulted in the following:

At X = 1.00,	$D_{\min}$	= 1.2 microns
At X = 0.50,	D_x	= 1.0 microns
At X = 0.25,	D_x	= 0.7 microns
At X = 0.10,	D_x	= 0.5 microns

Theoretically, the test cyclone should thus separate completely all particles greater than 1.2 microns in diameter and remove a measurable amount of particles in the 0.5 to 1.0 micron range. The collection efficiency of the experimental unit, however, was less than 5%, indicating the preponderance of the particles to be less than 0.5 micron in size.

3. Modified Cascade Impactor

The third and more quantitative method of measuring the particle size distribution made use of the Modified Cascade Impactor. Originally devised in Great Britain (22), the instrument was revamped by Laskin et al (23) to increase the precision with which it might be constructed and to adapt its use to large-scale routine analyses. The main features of the impactor are outlined in the schematic drawing of Figure 14**. It consists essentially of a system of four jets and sampling slides, termed "stages", operating in series. The course of the air passing through the instrument is deflected by an angle of 90° at the exit of each jet. The orifices of the jets are progressively smaller so that the magnitude of the velocity vector is successively increased immediately prior to its abrupt change in direction. The inertial effects of the particles tend to separate them from the air stream in which they are suspended and causes their impingement on the stage. Since the efficiency with which the particles are collected increases with increasing velocity, the median size of

* Lapple, C. E., Private Communication, January, 1950.

** Assembly drawings have been published by the AEC in MDDC-1500, entitled "The Modified Cascade Impactor". The document is available from the Office of Technical Service, Department of Commerce, Washington, D. C.

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Figure 14

SCHEMATIC DRAWING OF MODIFIED CASCADE IMPACTOR

the material removed by each slide progressively decreases. Thus, the total distribution is continuously broken into four overlapping distributions, one on each stage.

May (22) applied dimensional analysis to a system made up of a jet of air issuing from a slit and impacting on a plane surface, and found that for geometrically similar conditions the condition for equal impaction efficiency is:

$$\rho_s \frac{VD_n^2}{\mu L} = I_n$$

where ρ_s = the true particle density (gm/cm³)(assumed large with respect to air).

V = the velocity of gas issuing from the slit, (cm/sec).

L = a characteristic length of the system taken as the slit width (cm).

μ = the viscosity of the gas (poises).

D_n = the diameter (cm) of the particle at the impaction efficiency, n.

I_n = a constant at the impaction efficiency n (dimensionless).

The limitation of geometric similarity implies that the slit length and the ratio of the slit width to the clearances between the slit and the plane surface must remain constant. The four stages of the Modified Cascade Impactor comply with this requirement; in each case, the slit length is 1.40 cm, and the slit width to clearance space ratio is 1.0. The impaction efficiency, n, is defined as the percentage ratio of the number of particles hitting the collecting plate to the number of particles entering the jet, and assumes all particles hitting the stage are retained. In his derivation, May further assumed the flow to be streamline and neglected the effect of gas density. Applying experimental results to the above relationship, May found that the values of I_n for a given n were relatively constant; the variation was 15% over a 12-fold range of D_n , and indicates the theoretical expression to be valid. The variance of the I_n values was attributed to the fact that the geometry of the first two stages of the British Impactor was not strictly similar to the third and fourth stages.

Since the instrument has been standardized by Laskin, it is convenient to rearrange the equal-impaction-efficiency formula so that the calibration constants, once they are determined, can be applied to the sampling of a material of any density at any velocity. Thus:

$$\rho_s V D_n^2 = I_n \mu L = \text{constant}$$

Working with uranium dusts, Laskin (23) experimentally determined the calibration constants of the four stages in the Impactor itself and, also, that of the so-called fifth stage which is a high-efficiency filter paper located downstream of the unit. The last stage served to collect those particles that were small enough to penetrate the instrument proper. The particle distribution on the last stage was calculated from theory as the most probable value.

In order to use the Modified Cascade Impactor in a study of the process-cell air, the figures obtained by Laskin were converted to the following values, assuming $\rho_s = 2.8 \text{ gm/cm}^3$:

Stage No.	Stage Median, D_n , (microns) for the following sample flow rates (cfm)		
	<u>0.5</u>	<u>1.0</u>	<u>2.5</u>
I.	7.72	5.48	3.46
II.	3.24	2.30	1.45
III.	1.71	1.21	0.77
IV.	1.14	0.81	0.51
V.	0.68	0.48	0.31

Since it was realized that the bulk of the radioactive particulate matter was less than 5μ in size, no attempt was made to sample the process-cell air under isokinetic conditions. The gas was drawn from the mainstream, metered in an orifice section, passed through the Impactor and its fifth stage, and then ejected to the atmosphere. Re-entrainment of the particles was prevented by coating the slides with a thin film of adhesive. Figure 15 contains electron-microscope photographs of some of the slides.*

The amount of activity collected on the stages was measured in terms of disintegrations per minute by means of a BGO counter. The activity on the downstream filter was determined by the standard analysis outlined in the

* The photographs were prepared by E. H. Kalmus of the Los Alamos Scientific Laboratory, Los Alamos, N. M.

Figure 15

TWO ELECTRON PHOTOMICROGRAPHS
OF PROCESS - CELL AIR PARTICLES

1μ

Magnification 7,500 X

1μ

Magnification 6,200 X

section on Testing Media. From these figures the cumulative per cent of activity less than the stage median value was calculated and plotted vs. the stage median diameter, D_n , on a logarithmic probability grid (24). A sample calculation is given in Appendix A as Figure A-1.

The Codex No. 3228 paper used consists of a system of coordinates based on a scale derived from the probability integral. A straight line represents the following theoretical probability equation for the asymmetrical size-frequency distribution (25):

$$F(d) = \frac{\sum n}{\text{Log } \sigma_g \sqrt{2\pi}} \left[\frac{(\log d - \log dg)^2}{2 \log^2 \sigma_g} \right]$$

where: $F(d)$ = frequency of observations of the diameter D .

$\sum n$ = total number of observations.

dg = geometric mean.

σ_g = geometric standard deviation.

The constants dg and σ_g completely define the frequency distribution. The former is obtained from the expression:

$$\log dg = \frac{\sum (n \log d)}{\sum n}$$

and is the 50% or median intercept on the curve. The latter is obtained from the equation:

$$\log \sigma_g = \sqrt{\frac{\sum n (\log d - \log dg)^2}{\sum n}}$$

and can be calculated from the curve by the relation:

$$\sigma_g = \frac{84.13\% \text{ size}}{50\% \text{ size}} = \frac{50\% \text{ size}}{15.87\% \text{ size}}$$

The size distribution curves of the more common dusts, when plotted on arithmetic paper, are skewed with respect to a vertical axis and must be normalized by the use of logarithms as above. However, dusts of uniform

particle size distribution, such as those formed by condensation methods, follow the normal probability curve, and their sizes need not be expressed as logarithms.

Figures A-2 through A-7 contain six logarithmic-probability plots of the particle size distribution in the process-cell air. Best-fitting straight lines were drawn through the experimental points, with the emphasis placed on the three middle values. The existence of some divergency at the extremes is not uncommon on this type of curve (23). Figure A-8 is a plot of Figure A-2 on an arithmetic-probability grid. The extreme curvature of the line indicates that the size distribution must be normalized by the use of logarithms. The data indicate that the sizes of the particulate matter in the process-cell air are predominantly in the sub-micron range. Experimental values of dg and σ_g are tabulated below:

<u>Date</u>	<u>Flow Rate (cfm)</u>	<u>dg (microns)</u>	<u>σ_g</u>
1-10-50	0.5	0.66	2.0
1-16-50	1.0	0.31	2.0
4-11-50	1.0	0.33	2.2
4-12-50	1.0	0.33	2.1
8-8-50	2.5	0.25	2.2
8-8-50	2.65	0.19	2.3

The observed values appear to have some correlation with the flow rate of the sample gas stream. Theoretically, however, this should not be the case. The mean particle diameter should be relatively independent of the sample flow rate and should experience only those variations caused by the continually changing conditions in the process operation. An investigation of this apparent discrepancy was not undertaken.

The size distribution curves of the particles in the process-cell air were based on activity measurements, rather than the usual count or weight frequency measurements. The air stream, however, contains both contaminated and uncontaminated particles, the relative amounts of which have not been determined. As a result, the distribution curves represent only an approximation of the total size distribution. It is felt that this approximation is of the correct order of magnitude and sufficiently accurate to meet the needs of the investigation.

B. Particle Size Distribution Methylene Blue Smoke

The particle size distribution of the methylene blue smoke was measured by means of the Modified Cascade Impactor. The curves were based on analytical determinations of the amount of dye on the four slides and the downstream filter paper. The stage constants were obtained from Laskin's figures by applying a suitable density correction. The true (not apparent bulk) density of methylene blue is 1.29 gm/cm^3 , so that the D_n values became:

<u>Stage No.</u>	<u>Stage Median, D_n, (microns) for the following sample flow rates (cfm)</u>	
	<u>1.7</u>	<u>2.5</u>
I.	6.18	5.10
II.	2.59	2.14
III.	1.36	1.12
IV.	0.91	0.75
V.	0.55	0.45

Figures A-9 and A-10 contain logarithmic-probability plots of the size-weight distribution of the smoke particles. Figure A-11 is a plot of Figure A-9 on an arithmetic-probability grid. The extreme curvature of the line indicates that the distribution does not follow the normal probability curve, but is skewed with respect to a vertical axis. The geometric mean diameter of the smoke particles was in the same order of magnitude as that of the process-cell air. Experimental values of dg and σ_g are tabulated below:

<u>Date</u>	<u>Flow Rate (cfm)</u>	<u>dg (microns)</u>	<u>σ_g</u>
5-31-50	2.5	0.56	2.4
7-28-50	1.7	0.57	2.4

C. Dust Loading - Process-Cell Air

A second factor which influences the choice of a dust collector suitable for the filtration of a particular air stream is that of particle concentration. The radioactivity of the particulate matter suspended in the process-cell air, however, prevented the direct determination of the dust loading by the common method of filtering a known volume of the gas stream and weighing the amount of material removed. As a result, an indirect method was employed

which involved the direct measurement of the dust loading in the air stream entering the process-cell area and the comparison of the "plugging rates" of the air streams entering and leaving the process-cell area.

The process cells are ventilated by a continuous current of air which originates outside the process building. Atmospheric air is drawn into each building through a number of individual conditioner units, is then passed through the various cells, and finally collected in a header prior to filtration by the plant sand filter and discharge from a stack. The conditioners are Carrier units located some 60 feet above ground level and rated at 4500 cfm each. Since the process building is kept under a slight vacuum, appreciable quantities of unconditioned air enter the system through doorways and other openings.

Direct determinations of the dust loading in the air streams to the process area were made at two points in the above system: (1) outside the process building at one of the inlet ducts, and (2) downstream of the particular Carrier unit that conditioned the above air stream. Simultaneous test measurements were made in which 1.1 cfm sample aliquots were continuously drawn through CWS Type 6 filter paper at a superficial velocity of 50 fpm. The period of testing was such that the gradual accumulation of the deposited material brought about at least 8-inch increase in the pressure drop across the filter. Before the start of the test and at its completion, the CWS papers were stored in a constant-humidity, constant-temperature room for a week, and then weighed. From the weight difference of the paper and the total number of cubic feet of air that passed through the filter, an estimate was made of the dust loading expressed in terms of grains/1000 ft.³.

The results of the test indicated that the dust loading of the atmospheric air outside the process building was 0.02 grains/1000 ft.³. This figure is much lower than the range of 0.2 - 0.4 grains/1000 ft.³ given by Lapple as an estimate of the atmospheric dust concentrations to be found in rural and suburban localities (4). The corresponding figure for the same air stream downstream of the conditioner unit was 0.008 grains/1000 ft.³, indicating that the collection efficiency of the Carrier unit was 66%. The efficiency of such a filter depends upon the amount of material that has accumulated within the bed and, consequently varies with the operating history of the unit. The various conditioners in the building have not been operated over the same periods of time and, therefore, do not have the same collection efficiency. Furthermore, the leakage of unfiltered

air into the building is appreciable enough to lower the over-all efficiency with which the air is cleaned. In view of these considerations, a conservative estimate of the dust loading in the feed stream entering the process area would be closer to that of the raw air than the filtered air.

A second direct measurement of the atmospheric dust loading was made employing Whatman No. 41 filter paper instead of CWS Type 6. The procedure was much the same as in the previous test except that, prior to weighing, the paper was reduced to its bone-dry weight by heating it in an oven at 212°F. for one hour. The resultant estimate of the loading of the atmospheric air was 0.01 grains/1000 ft.³. Although the figure differs from that of the previous test by a factor of two, it is in the same order of magnitude and indicates that the particle loading in the atmosphere surrounding the Hanford Works is one tenth that of the more common estimates.

The basic assumption made in the estimation of the dust loading in the air stream leaving the process cells was that the changes in the air resistance of the filter paper caused by the deposition of the radioactive particles were essentially the same as those caused by the uncontaminated particles. Since the exact manner in which the various parameters, such as particle size, shape, structure, and composition, affect the "plugging" of a filter is unknown, the assumption is, at best, an approximation. If this is assumed to be the case, air streams having the same dust content should bring about the same pressure drop increase across a CWS Type 6 filter paper after the passage of equal volumes of gases at a specific superficial velocity.

On this basis, eight test runs were made in which a 1.1 cfm aliquot of the process-cell air was continuously drawn through a CWS Type 6 filter paper at a superficial velocity of 50 fpm until the pressure drop across the filter gained eight inches of water. The average volume of air required to bring about the specified resistance increase was 9500 cubic feet with an average deviation of $\pm 32\%$. On the other hand, the passage of 208,000 cubic feet of atmospheric air under the same conditions was required to bring about an 8.65-inch increase. Thus, the dust loading of the process air, prior to its entry into the plant sand filter, is approximately twenty times that of the atmospheric air outside the process building, or in the order of 0.2 - 0.4 grains/1000 ft.³. The figures indicate that the preponderance of both the contaminated and uncontaminated

particles in the process-cell air originate in the process-cell area. Despite the large increase in dust loading caused by the particles emanating from the process area, the loading of the air stream is still sufficiently low to make filtration by a fixed bed practical in terms of expected filter life.

D. Dust Loading Methylene Blue Smoke

The dust loadings of the artificial methylene blue smoke generated for use in the life-test studies were determined directly from the sample monitor stations located in the system. By maintaining the flow through the CWS Type 6 paper at a constant level throughout the monitoring period and then analyzing for the amount of methylene blue deposited, the loading could be calculated in terms of grains/1000 ft.³. Throughout the series of tests, the particle concentrations in the gas streams varied between the extremes of 2 to 20 grains/1000 ft.³, but, for the most part, remained in the range of 2 to 8 grains/1000 ft.³.

It cannot be assumed that the operating characteristics of Fiberglas filters, as determined by methylene blue smoke, apply directly to a Fiberglas bed filtering process-cell air. Physical and chemical properties of the particles, such as size distribution, molecular structure, surface area, and any tendency toward agglomeration, affect the manner in which the resistance of a unit increases. Although the particle size of the methylene blue smoke approximated that of the process-cell air, it was not possible to control the other characteristics.

THE MECHANISM OF AEROSOL FILTRATION

The literature of mechanical filtration contains various mathematical expressions that theoretically describe the mechanisms by which a fibrous bed removes suspended particulate matter from an air stream. Since filtration is a dynamic process, these expressions can apply only to the initial characteristics of the bed. The assimilation of collected material continually changes the operating features of the bed in a manner dependent upon the size distribution, concentration, and structure of the particles. Although the collection efficiency and resistance of the unit are constantly undergoing changes, the actual mechanism by which an individual particle is removed remains essentially the same whether the collecting agent is a glass fiber or another particle.

A. The Basic Assumption

The basic assumption underlying the theory of mechanical filtration is that once a particle comes into contact with a fiber, or any object, it will adhere. The force of adhesion is of the van der Waals' type and, therefore, operative over only a very short distance. Since the immediate area of contact between the particle and the surface does not necessarily increase with increasing particle size, the retarding force is not a critical function of the particle diameter. On the other hand, the forces that tend to dislodge the particle do depend on the particle dimensions. The viscous drag exerted by the gas increases with the square of the particle diameter, and the weight of the particle itself is proportional to the cube of the diameter. Thus, a particle much larger than a few microns may be dislodged from the first fiber it strikes, but small particles almost always adhere.

B. Direct Interception

There are three mechanisms by which dispersed particles may come into contact with the fibers in a filter bed. The first of these is "Grundabscheidung", or direct interception. For small particles, which are not subjected to Brownian motion and which are suspended in a gas moving at a low velocity, the path travelled by the center of a particle does not deviate from the flow line of the air as it moves around a fiber. The condition for contact is that the flow line pass within the distance $D/2$ of a fiber where D = particle diameter. Thus, the efficiency of removal by direct interception increases

with increasing particle size. So long as the inertial effects of the particle are negligible, the degree of removal is independent of the velocity, since the shape of the streamlines does not change in laminar flow.

C. Impingement

As the particle size and gas velocity increase, the particle path and the flow line do not coincide during their passage around an individual fiber. Inertial effects cause the particulate matter to deviate from the streamline and travel nearer the fiber, thereby increasing its chances of impingement. Since the inertia of a given particle is a function of its velocity, the degree of removal attained by this mechanism is greater at higher velocities. A comparative sketch of direct interception and impingement is presented in Figure 16.

As the discussion on "tennis rackets" indicated, Langmuir (19) has correlated deposition efficiency with particle size, fiber diameter, and gas velocity. When applied to the impingement of sub-micron particles on Fiberglass, his equations indicate that the collection efficiency of the larger fibers is not appreciable because of impingement until higher velocities are reached. With smaller fiber diameters, however, the deposition efficiency may be appreciable. The values obtained for fiber Numbers AA, B, 55, 450, 115, 600, and 800 are tabulated below. These calculations refer to individual fibers only and assume the flow lines around the filaments to be undisturbed. In an actual filter bed, however, the proximity of the neighboring strands affects the flow patterns so that the calculated results tend to be conservative. Throughout Table III the particle diameter was taken as 0.5μ and the density as 2.8 gm/cm^3 .

Table IV correlates the impingement efficiency on individual strands of Fiberglass with particle and fiber diameters. The calculations were made at a superficial velocity of 100 feet per minute and particle density equal to 2.8 gm/cm^3 . The figures indicate that for a particular fiber diameter and gas velocity there is a minimum particle size below which no deposition occurs. This minimum size increases with the larger filaments. Similarly, the size of the particles removed at a given efficiency decreases with decreasing fiber diameter. Thus, high efficiency filtration by impingement alone is feasible only with higher air velocities and large dust particles.

Figure 16

COMPARATIVE SKETCH OF FILTRATION
BY DIRECT INTERCEPTION AND IMPINGEMENT

DIRECT INTERCEPTION - PATH OF PARTICLE CENTER
COINCIDENT WITH PATH OF AIRSTREAM

IMPINGEMENT - PATH OF PARTICLE CENTER NOT COINCIDENT
WITH PATH OF AIRSTREAM

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TABLE III

IMPINGEMENT EFFICIENCY ON INDIVIDUAL STRANDS OF
FIBERGLAS AS A FUNCTION OF VELOCITY

Fiberglas No. Fiber Diameter, μ Velocity fpm	AA 1.28 Efficiency %	B 2.54 Efficiency %	55 14.0 Efficiency %	115 29.2 Efficiency %	450 114. Efficiency %	600 153. Efficiency %	800 203. Efficiency %
10	1.2	0					
25	14.8	2.6					
50	34.5	17.0					
75	45.0	26.4	0				
100	52.2	34.4	0.8				
150	62.0	45.0	3.5	0			
200	67.2	52.4	7.5	0.7			
250	73.0	57.8	12.6	1.8			
300	76.4	62.2	21.2	3.0	0	0	0

NB All calculations assume particle diameter = 0.5μ and particle density = 2.8 gm/cm^3 .

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TABLE IV

IMPINGEMENT EFFICIENCY ON INDIVIDUAL STRANDS OF FIBERGLAS
AS A FUNCTION OF PARTICLE DIAMETER

Fiberglas No. Fiber Diameter, μ Efficiency %	AA 1.28 Diameter μ	B 2.54 Diameter μ	55 14.0 Diameter μ	115 29.2 Diameter μ	450 114. Diameter μ	600 153. Diameter μ	800 203. Diameter μ
90	1.14	1.62	3.80	5.47	10.8	12.5	14.5
75	0.62	0.87	2.02	2.96	5.84	6.77	7.78
50	0.48	0.68	1.58	2.29	4.53	5.23	6.03
25	0.30	0.42	1.00	1.43	2.84	3.29	3.79
10	0.28	0.40	0.95	1.36	2.70	3.13	3.61
0	0.14	0.19	0.45	0.65	1.28	1.47	1.71

NB All calculations assume superficial velocity = 100 fpm and particle density = 2.8 gm/cm^3 .

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D. Diffusion

The third mechanism by which air-borne particles may come into contact with a surface enables the mechanical filtration of very fine dusts. Due to the effects of Brownian motion, the paths travelled by very small particles are not consistently coincident with the flow lines of the gas stream. This random motion increases the chance of contact between the particles and the fiber surfaces. Once contact is made, a concentration gradient is established which serves as the driving force for the continuous diffusion of the particles toward the fiber. A second parameter upon which the rate of diffusion depends is that of particle size; the smaller the particle the greater the diffusion constant. The degree of removal is further increased by lowering the speed at which the air streams pass the fiber. Such action lengthens the time spent by the particles in the neighborhood of the collecting surfaces and, consequently, increases the likelihood of contact.

Numerous attempts have been made to correlate the three filtration mechanisms described above and express the characteristics of a filter bed in mathematical form (26). The most recent of these is that of Langmuir (27), who directed his efforts toward the combined mechanisms of direct and Brownian interception alone. His omission of the effect of impingement was based on the fact that the fibrous filters in which he was interested showed a decrease in efficiency when the velocity was increased. This indicated a masking of inertial deposition by the other filtration mechanisms. That such is not always the case has been shown by Davies (26), and also by the experimental results of this paper.

E. Filtration Formula

A general expression may be derived for the initial filtration characteristics of a laminar type filter operating at only its rated superficial velocity. Assuming the aerosol to be homogeneous and that each filter layer removes the same average fraction of particles, the rate of deposition is:

$$-\frac{dW}{dN} = MW$$

where: W = weight rate of flow of particulate matter

N = number of filter layers (comparable to transfer units).

M = a constant = the average collection efficiency per layer.

α = the over-all collection efficiency.

Subscripts "i" and "o" = inlet and outlet conditions.

Rearranging and then integrating the relation over the total filter results in:

$$\int_{W_i}^{W_o} \frac{dW}{W} = -M \int_0^{N_o} dN$$

$$\ln \frac{W_o}{W_i} = -MN_o$$

$$\frac{W_o}{W_i} = e^{-MN_o}$$

since, by definition:

$$\alpha = \frac{W_i - W_o}{W_i} = 1 - \frac{W_o}{W_i}$$

$$\alpha = 1 - e^{-MN_o}$$

Such an expression applies only to laminar type filters in which the physical characteristics of each layer are the same; for example, a unit made up of a number of CWS filter papers. Fiberglas beds, however, involve other parameters, such as bed depth and packing density.

It has been found convenient to express the collection efficiency in terms of a dimensionless "decontamination factor" involving common logarithms rather than natural logarithms. Thus:

$$\alpha = 1 - 10^{-DF}$$

For each type of Fiberglas investigated, the decontamination factor was empirically determined as a function of bed depth, packing density, and superficial air velocity. In mathematical form:

$$DF = -\log(1 - \alpha) = \frac{CL^a \rho_p^b}{V^c}$$

where:

L	=	bed depth, inches
ρ_p	=	packing density, lbs. /ft. ³
V	=	superficial velocity, ft. /min.
C	=	a constant, the dimensions of which are such that the decontamination factor is dimensionless.
a, b, c	=	empirically determined exponents.

The resistance to air flow offered by each type of Fiberglas was expressed in terms of L, V, and ρ_p by the relation:

$$\Delta p = KL^x V^y \rho_p^z$$

where:

Δp	=	pressure drop, inches of water
K	=	a constant
x, y, z	=	empirical exponents.

INITIAL CHARACTERISTICS OF FIBROUS BEDS

In order to fabricate a Fiberglas filter having a high collection efficiency under the conditions of optimum velocity and most economical bed depth, the empirical constants in the design equations mentioned above must be known. The investigation of these characteristics was accomplished by a series of test runs made under controlled conditions and may be divided into two phases: (1) a study of the resistance offered by the filter beds to the flow of air, and (2) an examination of the efficiency of filtration.

A. The Testing Units

A typical unit in which the Fiberglas was tested consisted of a piece of large-diameter (between 4 and 10 inches) stainless steel pipe flanged at both ends. Taps were placed near the top and bottom of the pipe to provide pressure drop measurements. Above the bottom pressure tap, a screen was welded inside the main body to serve as a support for the filter bed. The Fiberglas was then packed to the desired depth. Since the height of the individual pipe section was standardized at 8 inches, bed depths greater than 8 inches were obtained by bolting together the necessary number of spools. The inlet and outlet spools were provided with special flange sections that adapted the air flow area to the inlet and outlet pipes. Figure 17 contains a sketch of a testing unit.

The desired packing density of those fibers that were received in mat form was obtained by measuring the received bulk density and then compressing the pads to the extent necessary. To preserve their shape the pads were placed between two circular screens. The bottom screen was welded to the walls of the unit, while the top one was welded to a steel ring that served as a spacer. The ring determined the depth of the filter pad and also kept the packing density constant. The thin space between the ring and the wall surface was sealed with an adhesive to prevent by-passing of the air stream around the bed.

The packing density of the bulk Fiberglas was regulated by weighing the amount of material calculated to fill a specific volume at the desired density. The filter was then packed as uniformly as possible and a slightly oversize screen was wedged into the filter so that it rested on top of the packing. The force necessary to compress large amounts of Fiberglas may be considerable and, consequently, influence the structure of plant-scale containers. The resilience of the material requires that these forces be continually maintained.

Figure 17

SCHEMATIC DRAWING OF A FIBERGLAS TESTING UNIT

Figure 17

SCHEMATIC DRAWING OF A FIBERGLAS TESTING UNIT

Figure 18

PLOT OF COMPRESSIVE FORCE
VS. PACKING DENSITY

No. 115 K Fiberglas

The necessary compressive force to restrain No. 115K Fiberglas to a given density is shown in Figure 18, a plot of force (lbs./ft.²) vs. density (lb./ft.³). The received bulk density of 115K is 1.5 lbs./ft.³.

B. Permeability Tests

The resistance offered by Fiberglas beds to the air streams passing through them was measured in a series of permeability tests in which atmospheric air was used rather than the contaminated gas. The various parameters that were correlated as a function of pressure drop included superficial velocity, bed depth, and packing density for each type of Fiberglas. Pressure drop vs. velocity measurements were made on a suitable number of filter beds, each of which had a different bed depth and packing density. Cross-plotting the data resulted in a general expression for the pressure drop of each type of Fiberglas.

1. No. 55 Fiber

The velocities at which the resistance of No. 55 Fiberglas was measured range from 5 to 100 fpm. When Δp vs. V values are plotted on arithmetic or logarithmic paper, keeping the other two parameters fixed, the results are essentially straight lines with an average slope of 1.0. This linearity indicates the flow to be laminar. Figures B-1, B-2, and B-3 in Appendix B contain such plots for beds at 3.0, 6.0 and 9.0 pcf. The linearity is not exact, however, especially for the lower densities. The plots for the 3.0 pcf beds develop a slight curvature in the lines at approximately 10 fpm and again at 50 fpm, and similarly for the 6.0 pcf beds at about 50 fpm. These regular deviations are attributed to the gradual compression of the beds by the larger air flow rates. Excessive gas velocities may result in compression to the extent that the bed pulls away from the inlet screen, or, in the case of smaller beds without a downstream screen, the bed may actually move along the container.

In the early phase of the program, some difficulty was experienced in obtaining reproducible results with beds packed at 3.0 pcf. No. 55 Fiberglas is shipped by the manufacturer in the form of large bats, approximately 96" x 24" x 3/4". The average bulk density of this material is in the neighborhood of 3.0 pcf. It was found that shredding the bats into small pieces and placing at random the required weight of the fibers into the container tended to produce a non-uniform bed. More consistent results were obtained later by cutting out large portions of the fibrous material and carefully placing them in the unit.

To prevent by-passing of the packing, the individual sections were made slightly larger in diameter than the container.

The data mentioned previously have been cross-plotted to give the graphs of Figures B-4 and B-5. The resistance to flow of No. 55 Fiberglas is a linear function of bed depth and varies with packing density raised to the 1.6 power. Removal of the mineral oil lubricant by soaking in carbon tetrachloride and drying the fibers produced no change in the permeability characteristics of the material. A nomograph of the equation

$$\Delta p = K_{55} L V \rho_p^{1.6}$$

is presented in Figure D-1 of Appendix D.

2. No. 55P Fiber

No. 55P Fiberglas is No. 55 produced by Owens-Corning as a pre-formed mat and having a phenol-formaldehyde polymer as a binder. The process of forming the pads increases the resistance of the fibers by a factor of over two, possibly due to the use of shorter fiber lengths; for example, the pressure drop per inch of bed depth at 25 fpm is 0.19 inches of water for No. 55 at 6.0 pcf, while for No. 55P at 6.0 pcf it is 0.41 inches. Furthermore, removing the binder resulted in a slight increase in flow resistance, an effect that actually may have been the result of experimental error. A plot of Δp vs. V for No. 55P Fiberglas is presented in Figure B-6.

3. "AA" Fiber

No. "AA" Fiberglas is manufactured in mat form with a phenol-formaldehyde polymer coating the fibers as a binder. The mats are 0.5-inch thick and have an average bulk density of about 0.6 pcf. Since compression takes place at about 10 fpm, most of the experimental work was performed on beds packed at 1.2 pcf. The resistance of "AA" Fiberglas, while not excessive, is much higher than that of the other fibers; at 25 fpm, for example, the pressure drop per inch of bed depth is 0.026 inches of water for No. 55 at 1.5 pcf, but it is 2.7 inches for "AA" at 1.2 pcf. Plots of the permeability data, given in Figures B-7 through B-11, indicate the flow resistance of "AA" Fiberglas to be an essentially linear function of superficial velocity and of bed depth over a velocity range of 2-100 fpm. The exponent on the packing density is 1.5. Removing the binder by heating at 450°C. had no effect on the pressure drop

characteristics of the "AA" Fiberglas. A nomograph of the equation

$$\Delta p = K_{AA} L V \rho_p^{1.5}$$

is presented in Figure D-2.

Besides the restraining screens, large-scale use of the pads require that an adhesive be applied to the edges of the pads to prevent by-passing of the gas. An effective seal between the glass fibers and stainless steel was obtained with sodium silicate supplied by the Philadelphia Quartz Company. Such an agent increases the resistance of pads having a small area; however, the effect becomes negligible as the ratio of area to perimeter increases.

4. "B" and "B(L and R)" Fibers

Fibers "B" and "B(L and R)" are also manufactured in mat form. Since the filament diameter of "B" Fiberglas is approximately twice that of "AA", the resistance is considerably less. The pressure drop per unit of depth at 25 ft. /min. is 0.33 inches of water for "B" Fiberglas at 1.4 pcf as compared to 2.6 inches for "AA" at 1.2 pcf. The leaching and refiring process slightly increases the resistance of "B" material. At 25 fpm the $\Delta p/L$ value for "B(L and R)" Fiberglas packed at 3.5 pcf is 1.85 inches of water; assuming that ρ_p exponent is 1.5 (which has not been experimentally verified), this value corresponds to 0.38 inches of water at 1.2 pcf. Figures B-12 and B-13 contain graphs of the Δp vs. V data obtained on the "B" and "B(L and R)" Fiberglas.

5. Nos. 450, 600, and 800 Fibers

The resistance per inch of bed depth offered by the coarse fibers is negligibly small at the lower velocities. The data for Fiber Nos. 450, 600, and 800 are given in Figures B-14, B-15, and B-16. These large fibers are coated with a phenol-formaldehyde polymer and are very brittle. The manufacturer ships this Fiberglas in the form of packs about 0.5 in. thick. The average length of the fibers is much greater than that of the "AA" or "B" Fiberglas and the mats are consequently much more loosely knit. The shipping density is approximately 3.5 pcf. Compressing and packing the coarse pads tends to fracture the fibers, resulting in tiny splinters of glass. Once lodged in the skin, the splinters can be very irritating, so that adequate clothing protection must be provided for personnel handling these coarser fibers.

6. No. 115 Fiber

The test sample of No. 115 was not an Owens-Corning product but was received from A. D. Little, Inc. The fibers were covered with a resin binder and arranged in loosely knit packs. Handling the material presented difficulties similar to those experienced with the coarser fibers. No attempt was made to remove the binder. The permeability data are plotted in Figure B-17.

7. No. 115K Fiber

Owens-Corning's No. 115K Fiberglas, often termed "curly wool", is shipped in bulk form and without a binder. The letter "K" designates that these fibers have been individually crimped; i. e., the strands are not essentially straight, but have regular undulations. The shape of the fibers is illustrated in the photograph of Figure 19. The material is easily handled and offers no difficulty in the preparation of a uniform filter bed. Closely reproducible results were obtained with such low packing densities as 1.5 and 3.0 pcf. The resistance of the fibers is slightly higher than that of No. 115, possibly due to the crimping process or a difference in fiber diameter. The pressure drop per inch of bed depth is 0.038 inch of water for No. 115 at 3.75 pcf and 25 fpm; the corresponding figure for No. 115K Fiberglas is 0.043 inch. Permeability tests indicate the resistance to be directly proportional to superficial velocity and bed depth; the exponent on the packing density is 1.5. Figures B-18 through B-21 contain the experimental data and the cross-plots obtained with the "curly wool". The equation

$$\Delta p = K_{115K} L V \rho_p^{1.5}$$

is presented in nomographic form in Figure D-3 of Appendix D.

The three alignment charts included in Appendix D are a convenient means of summarizing the permeability characteristics of the various fibers. They have been experimentally shown to be valid over the indicated ranges of L , V , and ρ_p ; extrapolated values, however, should be employed with caution. The equations are based on averaged curves and do not take into account the effects of bed compression and non-uniform packing. For design purposes the nomographs are sufficiently accurate to be of considerable value.

Figure 19

PHOTOGRAPH OF NO. 115K FIBERGLAS

C. Filtration Characteristics

The bed depth at which a particular packing was tested was chosen on the basis of the efficiency values that the bed might have over a velocity range of 2 to 100 fpm. An attempt was made to bracket these values between 10% and 99%, corresponding to decontamination factors of 0.046 and 2.00 (for convenience, a graph of collection efficiency vs. decontamination factor is included in Appendix C as Figure C-1). It was felt that the actual determination of collection efficiencies in the order of 99% or greater was subject to larger errors than those involved in extrapolating the empirical curves. Furthermore, although the ultimate purpose of the investigation was a filter having an over-all decontamination factor of at least 4, the individual sections making up such a filter would not have such a high degree of removal. The validity of such an experimental procedure was verified by formulating and testing composite filters designed to have an over-all collection efficiency of 99.99%. Efficiency values in this range were measured by continuously sampling the gas upstream and downstream of the test units at different flow rates, and were found to be in excellent agreement with the calculated figures.

1. No. 55 Fiber

No. 55 Fiberglass was tested at four different packing densities, 3.0, 4.5, 6.0, and 9.0 pcf. Figure C-2 contains the experimentally determined DF values for 12 and 24 inches of 3.0 pcf fibers plotted on log-log paper against the superficial velocity. Figures C-3, C-4, and C-5 contain similar graphs for densities of 4.5, 6.0 and 9.0 pcf, respectively. Each of the curves indicates that, up to a velocity range of approximately 50 to 75 fpm, the collection efficiency decreases as the velocity is increased. Thus, the possible removal of particles by impingement is masked by the more predominant diffusion of the particles to the fibers. Beyond 75 fpm, however, the degree of removal gradually increases. This characteristic may be attributed to the combined effects of particle impingement and bed compression. No attempt was made to correlate the various parameters causing this phenomenon, since practical considerations for the filter beds at the Hanford Works limit the velocities that can be used to values considerably less than 75 fpm. The slopes of the best-fitting straight-lines drawn through the experimental points in the velocity range of 2 to 50 fpm averaged -0.4.

A cross-plot of the data, presented in the DF vs. L curves of Figure C-6, indicates the exponent for the bed depth to be +0.9. The fact that the bed depth exponent is 0.9 rather than 1.0 demonstrates the effect that particle size distribution has on collection efficiency. During the passage of a gas stream through a fibrous filter, the size distribution of the suspended particulate matter continually undergoes incremental changes brought about by particle deposition. Since the collection efficiency of an incremental layer of the filter is a function of the size of the particles passing through it, the median particle diameter continually shifts toward the particular size that most readily penetrates the filter. The net result is that the filter increment required to achieve a given collection efficiency increases in depth as the particle size distribution changes, or, in mathematical terms, the bed depth exponent for a given heterogeneous aerosol is less than one.

The average slope of the DF vs. ρ_p curves given in Figure C-7 is +1.1. The empirical values varied from 1.0 to 1.2. A nomograph of the equation

$$DF = \frac{C_{55} L^{0.9} \rho_p^{1.1}}{V^{0.4}}$$

is presented in Figure D-4 of Appendix D. The chart is valid only over the ranges of 2 to 50 fpm, 1.5 to 9.0 pcf, and 3 to 24 inches.

2. No. 55P Fiber

Since the flow resistance of No. 55P Fiberglas is greater than that of No. 55, it readily follows that the filtration efficiency of the former material is higher than that of the latter. Under the conditions where $\rho_p = 3.0$ pcf, $L = 6''$, and $V = 25$ fpm, the efficiency of the 55P unit was 79%, as compared to 58% for the No. 55 filter. The investigation of No. 55P characteristics was not extensive. The data are given in Figure C-8 as a plot of DF vs. V.

3. "AA" Fiber

The degree of removal attained by "AA" Fiberglas is much higher than that of other fibers operating under similar conditions of packing density, bed depth, and superficial air velocity. The experimental curves of DF vs. V, presented in Figures C-9 and C-10, show a breaking point at approximately 50 to 75 fpm beyond which the collection efficiency increases with increasing velocity. The negative slope of the 2 to 50 fpm region is evidence of the masking

of any particle removal by impingement. The theoretical calculations of Table IV, however, demonstrate that the effects of particle impingement should be appreciably greater with "AA" fibers than with No. 55. Since the two mechanisms are influenced in opposite directions by an increase in velocity, the over-all effect should be a flattening of the low-velocity portion of the DF vs. V curves. This corresponds to a decrease in the velocity exponent from the value given by the No. 55 data. Such was the case; the average slope of the curves in Figures C-9 and C-10 is 0.2, as compared with 0.4 for the No. 55 Fiberglas.

Cross-plotting the data results in a value of +0.8 for the bed depth exponent of the "AA" Fiberglas, as compared to the corresponding figure of +0.9 for the No. 55 Fiberglas. The difference between the two exponents might possibly be attributed to limitations of the experimental measurements. The tests were performed under the varying field conditions at the Hanford Works, and, consequently, there were some uncontrolled factors, such as the size distribution, shape, etc., of the suspended particulate matter. The variance of these parameters may have been greater than was anticipated, and thereby influenced the test results. A second factor influencing the measurement of the exponent is the precision of the efficiency tests. In the preceding section, for example, the slope of the DF vs. ρ_p curve for No. 55 Fiberglas varied in one instance from +1.0 to +1.1 when the measured efficiency varied from 83% to 85%. Thus, while the data demonstrate quite conclusively that the bed depth exponent is less than one, it is conceivable that the actual value may be closer to +0.9 than to +0.8. To make a more rigorous determination of the exponent under Hanford field conditions would require a sufficiently large number of tests to permit a statistical average. It is felt, however, that for design purposes such a determination is unnecessary. The use of +0.8 as the bed depth exponent merely provides an additional safety factor in the filter calculations.

From a hypothetical standpoint, the difference between the +0.8 exponent of the "AA" Fiberglas and the +0.9 exponent of No. 55 Fiberglas may be significant. If the assumption is made that the characteristics of the air streams employed in the testing of both fibers were virtually the same, the difference may conceivably be attributed to the relatively higher efficiency of the "AA" Fiberglas. During the passage of the gas stream through the filter, the rate at which the particle size distribution is changed by incremental layers of the bed is more rapid and the effect on the collection efficiency may, there-

fore, be more pronounced. Visualizing the filtration process in this manner leads to the conclusions that (1) the bed depth exponent for all fibers employed in a homogeneous smoke stream is probably one, and (2) the exponent in a heterogeneous smoke stream is less than one, the exact value being a function of the efficiency of the particular fiber and the size distribution of the suspended particulate matter.

The experimental data indicate the packing density exponent to be +1.0. The graphs for "AA" are given in Figures C-11 and C-12. The equation

$$DF = \frac{C_{AA} L^{0.8} \rho_p^{1.0}}{V^{0.2}}$$

is represented by the nomographic chart of Figure D-5. The equation has been experimentally verified over the ranges of 2 to 50 fpm, 0.6 to 1.8 pcf, and 0.25 to 1.50 inches.

The high efficiency of "AA" Fiberglas suggests its use as a final clean-up layer in a composite filter. The cost in terms of resistance to flow is not prohibitive for the velocities commonly employed in aerosol removal at Hanford Works. Although the pressure per inch of bed depth at 25 fpm is 2.7 inches of water for "AA" fiber at 1.2 pcf, the collection efficiency is 99.8%. On the other hand, one inch of No. 55 Fiberglas at 1.5 pcf and 25 fpm has a resistance of 0.03 inches of water, but its efficiency is less than 5%. The investigation of the operating characteristics, which are discussed later, revealed that the life expectancy of "AA" fiber is comparatively low. Because of this, a "AA" clean-up layer must be suitably protected by less-efficient, but longer-lived, filter strata.

4. "B" and "B(L and R)" Fiber

Because of the effects of particle impingement, the low velocity portions of the DF vs. V curves for "B(L and R)" Fiberglas are less steep than the corresponding plots of the No. 55 data. The average slope, however, is greater in the case of the B(L and R) fiber than the "AA", the values being 0.25 and 0.20, respectively. In a qualitative manner this is in accordance with the theoretical calculations of Table IV which show that inertial deposition is less on B(L and R) fibers than on "AA". A graph of decontamination factor versus velocity for B(L and R) Fiberglas as 4.0 pcf is presented in Figure C-13. The runs made on "B" fiber are summarized in the DF vs. V graph of Figure C-14. Evidence

of the presence of I^{131} in the process-cell air (the test stream) is indicated by the scattering of the data. Since the number of tests was insufficient to characterize the relation completely, the curve is not quantitative, but merely gives the order of magnitude.

5. Nos. 450, 600, and 800 Fibers

The filtration characteristics of the coarse fibers were not extensively examined, since it was felt that the problem of handling these fibers would materially hinder their use in a plant-scale filter. No attempt was made to correlate bed depth and packing density with collection efficiency. However, for each of the three types of fibers, Nos. 450, 600, and 800, the efficiency was studied as a function of superficial velocity at particular values of L and ρ_p . The data are presented in graphical form as Figures C-15, C-16, and C-17. The degree of removal attained by the three grades of Fiberglas was low and decreased with increasing diameter. For example, at 25 fpm the efficiency of No. 450 at $L = 8''$ and $\rho_p = 5.7$ pcf is approximately 18%; for No. 600 at $L = 7''$ and $\rho_p = 5.1$ pcf, it is 8.5%; and for No. 800 at $L = 8''$ and $\rho_p = 6.6$ pcf, it is 10%. On the assumption that both the bed depth and packing density exponents are one (neither assumption has been experimentally verified), the three values calculated for the condition of $V = 25$ fpm, $L = 8''$, and $\rho_p = 5.7$ pcf are 18.3%, 10.6%, and 9.0% for the 450, 600, and 800 fibers, respectively. The curves from which the above figures were taken are dotted to indicate that they are not too reliable. The collection efficiencies of the three units were low enough to decrease the accuracy of the tests. Furthermore, the increasing amount of I^{131} present in the process-cell air, when these measurements were made, resulted in a considerable variance in the test results. It is felt, however, that the straight lines drawn are of the correct order of magnitude. As was the case with the other types of Fiberglas mentioned earlier, the DF vs. V curves for Nos. 450, 600, and 800 fibers break in the region of 50-100 fpm and the slope changes from negative to positive. Furthermore, the slopes of the lines characterizing the low velocity range are steeper than the corresponding curves for "AA" and "B" Fiberglas. While no quantitative conclusions can be drawn from these observations, they are in general agreement with the results of Table IV, which indicates the impingement of sub-micron particles on the coarse fibers to be considerably less than on the fine fibers.

6. No. 115 Fiber

Since the problem of handling No. 115 fiber is as difficult as that of Nos. 450, 600, and 800, the investigation of its filtration characteristics was neither extensive nor complete, but was carried out for purposes of comparison with the over-all picture of Fiberglas filtration and, more specifically, with 115K Fiberglas. Efficiency values were determined over the velocity range of 1.8 to 100 fpm on two beds, 10 and 20 inches deep, packed at 3.8 pcf. Figure C-18 contains the data in graphical form plotted as decontamination factor vs. superficial velocity. Cross-plots of the DF as a function of bed depth are given in Figure C-19. The degree of removal attained by a bed of No. 115 fiber falls in between that of Nos. 55 and 450 Fiberglas beds operating under the same conditions. Thus, when $L = 10''$, $\rho_p = 3.8$ pcf, and $V = 10$ fpm, the collection efficiency of No. 115 fiber is 75%, as compared to 92% with a No. 55 bed and 18% with a No. 450 bed. The last figure was calculated from the experimental results of an 8-inch bed packed at 5.7 pcf by assuming the exponents to be one. While this assumption may not be rigorous, it is felt that the figure is of the correct order of magnitude. For the same operating conditions, the No. 115K Fiberglas has a collection efficiency of 73%. The velocity exponent of the 115 fiber is approximately 0.4 as determined by the slope of the DF vs. V curves over the velocity range of 1.8 to 50 fpm. Cross-plotting the data obtained from two bed depths of No. 115 fiber indicates the bed depth exponent to be in the order of 0.5. This value is considerably lower than that obtained from the more extensive investigation of the No. 115K Fiberglas.

7. No. 115K Fiber

The results of the initial tests, the ease with which the material could be handled and particularly its chemical resistance, warranted a complete survey of the filtration properties of No. 115K Fiberglas. Filter units were tested at four packing densities - 1.5, 3.0, 6.0, and 9.0 pcf - and most of these at three bed depths - 6, 12, and 18 inches. Efficiency values were determined over the velocity range of 1.8 to 100 fpm; emphasis was placed on the lower superficial velocities up to 75 fpm. The original data are presented in Figures C-20 through C-23 by means of graphical representations of DF values vs. superficial air velocity. The general shape of the curves resembles the results obtained with the other fibers. In the operating range of 2 to 50 fpm, the slope of the DF vs. V curves averaged -0.4, which is the same as that of the No. 115

fiber. Cross-plots of DF vs. L, however, indicate that the bed depth exponent is +0.9 for No. 115K Fiberglas, as compared with +0.5 for No. 115 fiber. Since the large diameter material is less efficient than either "AA" or No. 55 Fiberglass, a bed depth exponent of 0.9 is much more readily visualized from the theoretical standpoint than 0.5. Furthermore, the investigation of No. 115K Fiberglass was more extensive than the study of No. 115 fiber and the data are probably more reliable. Cross-plotting DF vs. ρ_p results in a packing density exponent of + 0.9. The corresponding exponents are +1.1 for No. 55 Fiberglass and +1.0 for AA Fiberglass. An explanation for the differences between the figures and the significance of a value less than one is not apparent. The cross-plots are presented in Figures C-24 and C-25. The equation

$$DF = \frac{C_{115K} L^{0.9} \rho_p^{0.9}}{V^{0.4}}$$

is represented by the nomograph of Figure D-6. The operating ranges over which the chart has been experimentally verified are 2 to 50 fpm, 1.5 to 9.0 pcf, and 6 to 18 inches.

The efficiency characteristics of the three principal fibers are conveniently summarized by the nomographs of Appendix D. As was the case with the permeability nomographs, caution should be employed with values extrapolated beyond the indicated ranges of V, L, and ρ_p . The equations are based on averaged curves and do not take into account the effects of bed compression and non-uniform packing. The charts are sufficiently accurate to be of considerable value in the design of Fiberglass filters for the treatment of aerosols comparable in size distribution to the process-cell air at Hanford Works.

A second possible means of summarizing the efficiency characteristics of the various fibers is that of correlating the parameters involved with fiber diameter. The correlation, however, was not accomplished during this investigation. The collection efficiency per inch of bed depth for those fibers that were extensively studied varied over too wide a range to permit a correlation with fiber diameter.

OPERATING CHARACTERISTICS OF FILTER BEDS

The proper design of a highly efficient Fiberglas filter involves not only an adequate knowledge of the characteristics outlined in the preceding section, but also sufficient information regarding the on-stream properties to insure a maximum life expectancy. The investigation of the latter aspect of Fiberglas filtration was made by means of the methylene blue apparatus described previously and was divided into two phases: (1) a study of the manner in which the collection efficiency of a filter bed increases with the amount of smoke particles passing to it, and (2) a comparison of the useful filtration life to be expected from the various types of filter units.

A. Collection Efficiency Increases

The concept of mechanical filtration as a dynamic process was demonstrated by measuring the average collection efficiency during the passage of an incremental amount of smoke to a test filter. The cumulative grains of dust passed to the unit were then plotted against the values of efficiency. The upstream monitor used in the test was the CWS Filter Station located between the dilution chamber and the tee dividing the main stream into two parallel trunk lines (cf. Figure 7). In order to obtain a downstream sample, the monitor station that was ordinarily located at the extreme end of one of the trunk lines was repiped so that the entire smoke stream passing through the test filter was exhausted through the new station rather than to the header-line. With such an arrangement, the efficiency changes of an individual bed could be measured without disturbing the life tests being conducted on the seven remaining units. Four filter beds were examined: (1) 2" of No. 55 Fiberglas at 6.0 pcf, (2) 4" of No. 55 Fiberglas at 3.0 pcf, (3) 2" of No. 115K Fiberglas at 6.0 pcf, and (4) 6" of No. 115K Fiberglas at 6.0 pcf. In each case the superficial velocity was 25 fpm. From the nomographs of Figures D-4 and D-6, the initial collection efficiencies are found to be 50%, 46%, 26%, and 55%, respectively. The corresponding initial pressure drops predicted by the nomographs of Figures D-1 and D-3 agreed well with the experimental values. The data are presented in Tables V through VIII. Figures E-1, E-2, E-3, and E-4 in Appendix E contain graphs of collection efficiency and pressure drop plotted versus Σ values; Σ is defined as the cumulative grains of methylene blue passing to the

unit per square foot of filter area. It should be stressed that the abscissa is grains/ft.² passing to the unit and does not represent the amount of material collected within the filter bed. Furthermore, Σ was chosen as the independent function rather than the more common concept of time to avoid the introduction of another variable, that of dust loading. Although the practical life of a filter is expressed in terms of time, a graphical representation of the pressure drop history would not be a smooth curve unless the dust concentration remained relatively constant.

After an initial steep rise, the efficiency curves level off to approach the 100% value asymptotically. As plotted, the curves are merely a qualitative indication of the manner in which the collection efficiency changes. The shape of a more accurate curve would have a steeper slope. The reason for this is that the experimental efficiencies are plotted as point values, whereas they are actually average values over increments of the abscissa. Just where in the increments the average efficiencies are valid varies in an unknown manner, since the efficiency changes exponentially during each increment. The magnitude of the error involved depends upon the size of the increment and the portion of the curve in which it is taken.

On the other hand, the curves expressing the change in resistance to flow with grains/ft.² passing to the unit do not include such an error because pressure-drop readings were made each time the filter monitors were removed from the stream. The early portion of the pressure-drop curves is relatively flat, while the corresponding efficiency values increase rapidly. As the slope of the collection efficiency curve flattens, the pressure-drop curve becomes progressively steeper. Thus, the shape of two graphs can be interpreted in terms of one another. During the initial rapid rise of the collection efficiency, the amount of material assimilated within the bed is not sufficient to bring about an immediate increase in flow resistance. Upon reaching high efficiency values, however, virtually all of the material approaching the unit remains within the bed and, consequently, builds up the pressure drop at a more rapid rate.

During the steep portion of the pressure-drop curve, the filter resistance experienced sudden decreases which required the passage of varying amounts of material to the unit before the original resistance was regained. The occurrence of these phenomena was unpredictable - some took place when the flow of smoke through the unit was stopped, and other during the operation of the apparatus. The

Table V

**INCREASE OF FLOW RESISTANCE AND COLLECTION EFFICIENCY
WITH PASSAGE OF METHYLENE BLUE SMOKE TO THE UNIT**

No. 55 Fiberglas, L = 2", $\rho_p = 6.0$ pcf, V = 25 fpm

Dust Loading Grains/1000 ft. ³	Σ - values* Grains/ft. ²		Pressure Drop Inches of Water	Efficiency %
	Increment	Total		
			0.38	(50.0)**
4.3	11.7	11.7	0.39	69.6
5.0	11.2	22.9	0.42	72.7
6.2	22.5	45.4	0.48	83.7
6.5	20.2	65.6	0.51	89.7
6.5	15.5	81.1	0.55	89.9
7.1	16.2	97.3	0.59	92.1
8.3	16.7	114.0	0.63	93.4
9.6	11.5	125.5	0.63	94.3
8.6	20.7	146.2	0.74	95.3
10.3	29.0	175.2	1.01	97.4
10.3	22.5	197.7	1.8 - 1.55	98.7
9.9	24.8	222.5	2.7 - 2.25	98.9
12.0	30.0	252.5	3.1	98.6
17.0	25.6	278.1	3.13 - 1.58	98.3
10.3	22.0	300.1	3.75	98.4
10.8	39.0	339.1	5.5	99.4

* Σ - defined as the cumulative grains of methylene blue smoke passing to the unit per square foot of filter area.

** Initial collection efficiency as determined from the nomographs.

Table VI

INCREASE OF FLOW RESISTANCE AND COLLECTION EFFICIENCY
WITH PASSAGE OF METHYLENE BLUE SMOKE TO THE UNIT

No. 55 Fiberglas, L = 4", $\rho_p = 3.0$ pcf, V = 25 fpm

<u>Dust Loading</u> <u>Grains/1000 ft. ³</u>	<u>Σ - values</u> <u>Grains/ft. ²</u>		<u>Pressure Drop</u> <u>Inches of Water</u>	<u>Efficiency</u> <u>%</u>
	<u>Increment</u>	<u>Total</u>		
			0.27	(46%)*
6.9	5.2	5.2	0.27	43.1
9.3	3.5	8.7	0.28	52.9
7.3	17.2	25.9	0.29	63.3
5.1	5.0	30.9	0.30	53.1
8.3	8.3	39.2	9.31	72.8
6.5	9.0	48.2	0.32	75.0
17.1	42.6	90.8	0.38	79.4
14.7	78.7	169.5	0.50	90.4
13.2	72.7	242.2	0.70	95.1
17.6	90.0	332.2	1.56 - 1.34	98.6
20.0	22.5	354.7	1.85	99.1

* Initial collection efficiency as determined from the nomographs.

Table VII

INCREASE OF FLOW RESISTANCE AND COLLECTION EFFICIENCY
WITH PASSAGE OF METHYLENE BLUE SMOKE TO THE UNIT

No. 115K Fiberglas, L = 2", $\rho_p = 6.0$ pcf, V = 25 fpm

<u>Dust Loading</u> <u>Grains/1000 Ft. ³</u>	<u>Σ - values</u> <u>Grains/Ft. ²</u>		<u>Pressure Drop</u> <u>Inches of Water</u>	<u>Efficiency</u> <u>%</u>
	<u>Increment</u>	<u>Total</u>		
			0.15	(26%)*
2.9	1.0	1.0	0.15	42.5
2.4	1.3	2.3	0.15	37.1
3.1	3.1	5.4	0.16	35.4
2.8	3.9	9.3	0.16	46.9
2.2	3.7	13.0	0.16	42.8
--	8.6	21.6	--	50.4
--	9.6	31.2	--	52.1
--	9.1	40.3	--	50.6
--	7.5	47.8	--	55.2
--	22.9	70.7	--	58.7
--	12.3	83.0	--	76.7
8.9	10.0	93.0	--	65.2
7.8	9.8	102.8	--	66.4
7.5	10.0	112.8	0.28	68.0
8.6	16.2	129.0	0.30	76.1
4.8	13.9	142.9	0.33	77.3
6.3	15.8	158.7	--	81.9
6.9	12.4	171.1	0.43	82.8
6.5	10.6	181.7	0.47	--
7.6	12.2	193.9	0.47	85.7
7.8	17.5	211.4	0.59	89.1
5.8	21.5	232.9	0.92	90.8
5.9	6.3	239.2	1.17	95.7
2.9	13.5	252.7	2.5	96.2
5.5	13.3	266.0	5.5	99.0

* Initial collection efficiency as determined from the nomographs.

Table VIII

INCREASE OF FLOW RESISTANCE AND COLLECTION EFFICIENCY
WITH PASSAGE OF METHYLENE BLUE SMOKE TO THE UNIT

No. 115K Fiberglas, L = 6", $\rho_p = 6.0$ pcf, V = 25 fpm

<u>Dust Loading</u> <u>Grains/1000 ft. ³</u>	<u>Σ- values</u> <u>Grains/ft. ²</u>		<u>Pressure Drop</u> <u>Inches of Water</u>	<u>Efficiency</u> <u>%</u>
	<u>Increment</u>	<u>Total</u>		
			0.50	(55%)*
4.4	1.1	1.1	0.50	41
4.6	1.5	2.6	0.50	48
4.3	3.5	6.1	0.50	74.5
4.4	5.4	11.5	0.50	76.4
3.7	2.2	13.7	0.48	86.6
5.0	5.7	19.4	0.50	86.0
4.3	6.7	26.1	0.50	85.9
4.2	6.4	32.5	0.50	84.7
4.4	5.4	37.9	0.51	85.2
4.8	6.6	44.5	0.52	83.7
4.6	5.2	49.7	0.55	85.5
4.5	6.8	56.5	0.54	87.4
4.4	5.6	62.1	0.55	86.4
5.7	8.5	70.6	0.58	88.1
4.9	6.1	76.7	0.58	88.4
5.3	5.9	82.6	0.58	83.4
4.6	5.8	88.4	0.59	89.6
5.4	5.6	94.0	0.60	91.5
4.8	8.8	102.8	0.62	90.1
4.8	3.3	106.1	0.64	91.2
4.9	8.7	114.8	0.64	92.5
5.2	15.8	130.6	0.70	94.2

Table VIII - Continued

4.7	8.2	138.8	0.68	92.6
5.9	8.1	146.9	0.74	94.0
2.0	10.2	157.1	0.80	95.1
3.0	10.8	167.9	0.84	96.2
5.1	8.8	176.7	0.92	97.0
5.0	8.9	185.6	1.00	97.2
4.7	6.9	192.5	1.25	98.3
5.6	15.1	207.6	1.83	98.7
5.8	18.1	225.7	3.50	99.5
5.7	20.5	246.2	8.2	99.9

* Initial collection efficiency as determined from the nomographs.

decreases are attributed to the actual movement of the material collected within the bed. On the basis of the data presented in the next section, it is felt that the increase in the over-all collection efficiency and pressure drop of the filter unit is due to the build-up of particulate matter in a small layer of Fiberglass at the face of the bed. Thus, while the initial efficiency is the result of particle removal throughout the bed, the fact that the assimilated particles serve to assist in the collection of other particles tends to increase the efficiency of the first layers at the face of the filter at a more rapid rate and eventually restricts the filtering action of the whole unit to that of the first section. The large number of particles contained in the high-efficiency portion of the bed form agglomerates and "bridges" between the Fiberglass filaments. Since the van der Waals forces that cause the adhesion of the particles to the glass or to other particles are not a critical function of particle diameter, and since the size of the particle aggregates continually increases, it would appear that at some point the viscous drag exerted by the gas stream is sufficient to overcome the force of adhesion. Dislodging the agglomerates results in a redistribution of the particles throughout a wider layer of Fiberglass and a consequent drop in the flow resistance. Data illustrating this effect are presented in the next section. On such a basis, it is conceivable that there would be a concurrent drop in the collection efficiency of the unit (cf. Figure E-1). The extent to which the efficiency and pressure drop values decrease is dependent upon the amount of material dislodged and the width of the layer of Fiberglass through which it is redistributed.

B. Comparative Life Expectancy

In order to obtain data on the comparative life expectancies of the various Fiberglass filter beds, the methylene blue apparatus was arranged in the same manner as that outlined in the sketch of Figure 7. Except for the instances described in the immediately preceding section, there were no downstream filter monitors. Instead, the two CWS filter stations served to verify the uniform dust-loading of the smoke entering the eight parallel test units and substantiate the original supposition that the smoke particles would not deposit appreciably along the intervening lengths of pipe. Calculations made from 109 test runs during which the two monitor stations were operated simultaneously indicate that the deviation between the two loading values averaged $\pm 7.3\%$.

Sample data for the first fifteen runs are given in Table IX. On the basis of this figure and the sand filter data presented below, the nominal precision of the life expectancy tests may be set at $\pm 10\%$, as compared to $\pm 5\%$ for the efficiency tests conducted with the process-cell air. While such a precision includes variations due to errors in sampling, filter analysis, and non-uniform loading in the trunk-line, it is felt that the dominant error was that of flow control. The life expectancy of the highly efficient CWS Type 6 paper used to determine methylene blue loading is relatively short. As a result, the large concentration of particles in the smoke stream causes the resistance of the paper to increase rapidly and a consequent drop in the flow rate. This necessitated continual attention to maintain constant flow rates through the sample monitors.

1. Test Sand Filter

One of the primary objectives in the study of air filtration by Fiberglas was the development of a highly efficient filter capable of operating for a much longer period of time than the current sand filters without any appreciable increase in pressure drop. In view of this, the basis of comparison chosen for the life expectancy tests was a model of one of the sand filters currently in use at the Hanford Works. The fine sand in the large-scale plant filter is supported by layers of successively coarser aggregate and, on the bottom, by a series of cement distribution blocks. The blocks and the section of the coarsest rocks were omitted from the life-test replicas. The specifications of the aggregate layers used in the small-scale test units are presented in Table X. The first model consisted of a 4.5-inch steel unit in which a No. 10 mesh screen supported 2" of Type IV sand, 12" of Type V, and 3" of Type VI. The smoke stream flowed upward through the filter at a superficial velocity of 10 fpm. Fluidization of the Type VI sand occurs at 17 fpm. Pressure taps were located in the plenum chambers above and below the filter, and also, at the interfaces between the three layers. Permeability tests made on different packings of the same unit did not result in reproducible pressure-drop readings. This was attributed to a combination of two factors: (1) The layers were placed in the unit by merely pouring in the particular type sand until the specified bed depth was reached, and, consequently, some variation in packing density might be expected; and (2) intermixing of the sands occurred at the interfaces which

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Table IX

COMPARISON OF THE DUST LOADING AS DETERMINED
BY TWO FILTER MONITORS

Total Time Min.	First Monitor Station			Second Monitor Station			Per Cent Deviation
	Av. Flow Cfm.	Grains Deposited	Loading Gr. /1000 ft. ³	Av. Flow Cfm.	Grains Deposited	Loading Gr. /1000 ft. ³	
455	1.0	1.49	3.3	1.0	1.39	3.1	6.1
145	1.0	0.81	5.6	1.0	0.88	6.1	8.2
189	1.0	1.14	6.0	1.0	1.16	6.1	1.6
240	1.0	1.49	6.2	1.0	1.48	6.2	0.0
36	1.1	0.29	7.3	1.1	0.25	6.3	13.7
38	1.1	0.30	7.2	1.1	0.28	6.7	6.9
372	1.0	2.60	7.0	1.0	2.54	6.8	2.9
107	1.0	1.02	9.5	1.0	0.92	8.6	9.5
320	1.0	2.85	8.9	1.0	3.13	9.8	9.2
465	1.0	5.73	12.3	1.0	4.44	9.5	22.8
440	1.0	3.42	7.8	1.0	3.23	7.3	6.4
355	1.0	3.60	10.2	1.0	2.83	8.0	21.6
95	1.0	0.65	6.8	1.0	0.65	6.8	0.0
85	1.0	0.66	7.8	1.0	0.60	7.1	9.0
330	1.0	2.22	6.7	1.0	2.15	6.5	3.0

Average deviation of first 15 runs - 8.1%.

Average deviation of 109 runs - 7.3%.

Table X

SPECIFICATIONS OF AGGREGATE LAYERS IN THE TEST SAND FILTERS

<u>Type Sand</u>	<u>Nominal Size</u>	<u>Tolerances</u>
II	1 3/4" - 5/8"	< 5% over 1 3/4" < 5% under 5/8"
III	3/4" - 4 mesh	< 5% over 3/4" < 5% through 4 U. S. mesh
IV	4-8 mesh	< 1% on 3 U. S. mesh < 40% on 4 U. S. mesh < 7% through 8 U. S. mesh
V	8-20 mesh	< 5% on 8 U. S. mesh < 5% through 20 U. S. mesh
VI	20-40 mesh	< 2% on 20 U. S. mesh 30-50% between 20 and 30 U. S. mesh < 3% through 50 U. S. mesh

NB All grades were reasonably free of silt, clay, and organic matter.

influenced the readings given by the pressure taps considerably. The initial pressure drop and the Σ values corresponding to pressure drop increases of 1, 2, 3, 4, and 5 inches are presented in Table XI.

The pressure drop history of the unit is represented graphically in Figure E-5 of Appendix E, which contains a plot of Δp vs. cumulative grains/ft.² for the individual layers and the total filter. As the curves indicate, the presence of the coarse sands afforded considerable "protection" to the Type VI aggregate. The importance of the role played by the Type IV material in the life of the filter had not been anticipated in the design of the test unit. Since the major portion of the larger supporting sands of the plant-scale filter were not represented in the test model, the results of Figure E-5 and the data for the first unit in Table XI had no quantitative meaning as a basis of comparison, but demonstrated the need for a more exact replica.

The second unit consisted of 12" Type II, 12" Type III, 6" Type IV, 12" Type V, and 3" Type VI material packed in a Lucite tube. Although the large rocks that constitute the Type I aggregate in the plant filter were omitted and a much smaller layer of Type VI sand was used, the model proved to be a sufficiently accurate replica of the large-scale unit. The omission of part of the fine sand was warranted by the evidence of the first test which indicated the life of the whole filter to be determined by the coarser material. The test was conducted at approximately the same superficial velocity at which the plant unit operates, viz 5 fpm. Pressure taps were located at each of the interfaces between the layers. Difficulties were again experienced in obtaining reproducible pressure drop readings when the unit was repacked. The data are given in Table XI. Figure E-6 contains the pressure-drop history of the unit plotted in terms of the cumulative grains of methylene blue passing to the unit per square foot of filter area. Inspection of the curves reveals that the resistance of the highly efficient Type VI sand increased from the initial 1.25" of water to 1.50" during the passage of the first 80 to 90 grains/ft.² to the unit. Beyond that point, the protection afforded by the coarse material was sufficient to prevent any further increase. Both the Type IV and V layers underwent a significant increase in pressure drop corresponding to an increase in collection efficiency. The pressure-drop data indicate the life of the total filter to be restricted primarily by that of the Type IV layer. Visual inspection of the sand, however,

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Table XI

DATA ON THE LIFE EXPECTANCY OF THE TEST SAND FILTERS

Type Sand	Layer Depth Inches	Sup. Vel. Fpm.	Initial Pres. Drop In. Water	Σ Values (grains/ft ²)* for the following pressure drop increases (inches of water)					Shutdown Values	
				Pressure Drop	Σ Grains/ft ²					
12										
2										
3										
4										
5										
FIRST TEST UNIT										
IV	2		0.07	85.5	89.1	-	-	-	2.4	
V	12		1.30	70.9	83.6	89.1	-	-	4.40	
VI	3		1.80	-	-	-	-	-	2.00	
Entire Filter		10	3.17	58.2	78.2	84.5	88.2	89.1	8.80	90.0
SECOND TEST UNIT										
II	12		-	-	-	-	-	-	-	
III	12		0.02	-	-	-	-	-	-	
IV	6		0.06	109.5	112.5	116.4	121.7	125.9	5.0-4.95(V)**	
V	12		0.55	-	-	-	-	-	1.35-1.25(V)	
VI	3		1.25	-	-	-	-	-	1.58-1.45(V)	
Entire Filter		5	1.88	96.0	108.6	114.4	118.8	122.5	7.83	131.
THIRD TEST UNIT										
II	11		-	-	-	-	-	-	-	
II-III	2		< .01	-	-	-	-	-	.01	
III	10		0.015	-	-	-	-	-	0.01	

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Table XI (Cont.)

<u>THIRD TEST UNIT (Cont.)</u>									
III-IV	2	0.01	-	-	-	-	-	-	0.02
IV	4	0.025	-	-	-	-	-	-	0.045
IV-V	2	0.06	97.5	103.0	106.8	109.3	111.7	6.05	
V	10	0.37	-	-	-	-	-	0.55	
V-VI	2	0.30	-	-	-	-	-	0.48	
VI	2	0.51	-	-	-	-	-	0.62	
Entire Filter	5	1.29	90.4	101.5	105.6	108.1	110.3	7.65	114.5

* Σ defined as the cumulative grains of methylene blue smoke passing to the unit per square foot of filter area.

** (V) - signifies oscillation of the pressure drop.

revealed a heavier concentration of methylene blue in the interface between the Types IV and V sands as compared to that of either adjacent layer. Since some intermixing of the sands took place at the interface, the location of the pressure tap at that point prevented any rigorous determination of whether the predominant pressure-drop increase occurred in the Type IV or V layers or in the interface itself.

The possible significance of the interfacial layer was considered because of a phenomenon that took place after the passage of 126. grains/ft.² to the unit. The indicated resistance of the Type IV layer decreased from 5.00 inches of water to 0.85 inch, and that of Type V simultaneously increased from 1.25 inches to 2.60 inches. Since the total of the other layers remained constant at 1.60 inches, the net result was a decrease in the over-all pressure drop from 7.85 inches to 5.05 inches of water. A suitable hypothesis by which the phenomenon might be explained is that outlined in the preceding section in regard to the resistance decreases of the Fiberglas' filters; i. e., the accumulation of the filtered material in a small bed depth, the dislodgement of some of the agglomerated particles, and their redistribution in the adjacent section of the filter. If this were the case, the segment of the bed which determined the life of the filter was located immediately below the pressure tap where the Types IV and V intermixed. The observed changes in flow resistance would then indicate a movement of the collected material beyond the pressure tap, and since the over-all pressure drop decreased, a possible redistribution from the intermixed layer into the Type V sand.

In an attempt to confirm the above hypothesis, the methylene blue distribution throughout the filter was determined. Incremental layers of sand were removed from the "plugged" unit and treated with ethyl alcohol in a Soxhlet extractor. The resultant solution was then diluted with water, the alcohol distilled off, and the concentration of methylene blue found by means of a Beckmann Spectrophotometer. A schematic drawing of the test sand filter is presented in Figure 20, indicating the pressure tap locations and the incremental layers analyzed for methylene blue. The large size of the aggregate in the bottom layer (Type II) did not permit treatment of the material in a Soxhlet

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Figure 20

SCHEMATIC DRAWING OF THE SECOND SAND FILTER TEST UNIT
INDICATING PRESSURE TAP LOCATIONS AND THE INCREMENTAL LAYERS
ANALYZED FOR METHYLENE BLUE

extractor. The results of the analysis are represented by the bar graph of Figure 21. Unfortunately, the extraction procedure did not effect a complete separation of the methylene blue from the sand particles. Visual observation of the treated layers indicated that the degree of removal obtained varied with the type of sand. Furthermore, the total amount of methylene blue found in the sand filter by the analysis was only 21% of the amount calculated to have passed to the unit. As a result, the bar graph of Figure 21 is merely a qualitative representation of the methylene blue distribution throughout the sand filter. Despite the inefficiency of the analytical method, however, the data demonstrate conclusively that the preponderance of the material removed from the air stream was collected in the interfacial layer between the Types IV and V sand strata and that the consequent increase in the resistance of this portion of the bed determined the life of the total filter.

To provide a further confirmation of the above hypothesis, a third test unit was fabricated from Lucite tubing. The sand packing duplicated that of the second model, but the location of the pressure taps was rearranged to yield more definitive data as to which layer determines the life of the filter. Figure 22 contains a schematic diagram showing the positions of the various taps. Photographs of the equipment are included in Figures 23 through 26. The nominal "pressure drop across the interface" actually was the resistance across a 2-inch layer, extending one inch above and one inch below the line of demarcation between the strata. The layers of sand were thus subdivided into interface sections and the remaining unmixed sections.

Table XI contains the data obtained during the "plugging" of this unit. A graphical representation of the flow resistance as a function of Σ is presented in Figure E-7. The data demonstrate conclusively that the life of the sand filter is determined by the 2-inch IV-V interface and confirms the hypothesis mentioned above.

In the light of the above information, data were obtained on the distribution of radioactivity throughout one of the plant sand filters. The traverse was accomplished by lowering an ionization chamber into a vertical monitoring tube that was included in the original design. The probe was encased in a lead shield, 3/4" thick, and provided with a 1/4" circumferential slit. The encasing

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Figure 21

BARGRAPH OF METHYLENE
BLUE DISTRIBUTION
THROUGHOUT SECOND
SAND FILTER TEST UNIT

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Figure 22

SCHEMATIC DRAWING OF THE THIRD SAND FILTER TEST UNIT
INDICATING PRESSURE TAP LOCATIONS

Figure 23

PHOTOGRAPH OF THE THIRD SAND FILTER TEST UNIT
SECTION I

Figure 24

PHOTOGRAPH OF THE LIFE TEST EQUIPMENT
SECTION II

Figure 25

PHOTOGRAPH OF THE THIRD SAND FILTER TEST UNIT
SECTION III

Figure 26

PHOTOGRAPH OF THE THIRD SAND FILTER TEST UNIT
SECTION IV

served to restrict the readings to the geometry of a small layer of the filter and minimize the radiation from sources above and below the instrument. The relative level of activity was measured in terms of micro-micro-amperes by means of an ammeter attached to the probe by an extension cord. The distributions at the north and south edges of the filter are presented in Figure E-8. Both curves have two maxima, one within 2 inches of the IV-V interface, and the other within 2 inches of the V-VI interface. The location of the strata interfaces was calculated from the original specifications for the filter. It is possible that the calculations may not represent the actual location, since both sides of the unit slope towards the center. Consequently, it is not known definitely whether the peaks occur at the interfaces or within the Type V sand, although it is believed that the maxima probably occur at the interfaces.

In each case the activity level is greater at approximately the V-VI interface than at the IV-V interface. Presuming that the particulate matter in the process-cell air acts in the same manner as the methylene blue smoke, it would then appear that the plant sand filter is at an early phase of its expected "life". Inspection of Figure E-7 reveals that during the passage of the first 50 grains/ft.² of methylene blue, the pressure drop across the IV-V and V-VI interfaces rose from 0.06 and 0.30 to 0.12 and 0.47, respectively. Beyond that point, however, the IV-V interface rose rapidly to become the major contributor to the filter resistance while V-VI interface remained essentially constant. If the pressure-drop build-up in the large-scale filter follows the same course of action, the V-VI interface should eventually have a lower level of radioactivity than the IV-V interface.

To establish a basis of comparison for the Fiberglas life-expectancy tests, the "life" of a unit was arbitrarily defined as the number of grains passed to the unit per square foot of filter area during a pressure-drop increase of 5 inches. Thus, from Table XI, the "lives" of the second and third models were 122.5 and 110.3 grains/ft.², respectively. These figures differ by 10% but are felt to be sufficiently precise for the purposes of the investigation.

2. Fiberglas Filters

Simultaneously during the operation of the sand filter experiments,

the methylene blue smoke stream was used to conduct a series of comparative life tests on glass fiber beds. The units were fabricated for the most part from Lucite tubing (4-5 inches i. d.) and were packed in the same manner as the process-cell air test filters. The beds, however, were not uniform in the sense that they consisted of only one type of Fiberglas packed at one density; they were actually made of composite layers having different fibers at different packing densities. The arrangement of the individual sections in the test units was such that two purposes were accomplished: (1) the "life" of the bottom layer was determined, and (2) some knowledge was gained of the "protection" offered by the bottom layer to the succeeding section or sections. The term "protection" refers to the extension of the filter life resulting from the inclusion of a prefilter in the unit.

The first series of test runs were conducted at a superficial velocity of 50 fpm. The material having the shortest life expectancy proved to be that having the greatest collection efficiency, viz the "AA" Fiberglas. At a linear velocity of 50 fpm, the passage of 28.5 grains of methylene blue per square foot of filter area to a unit consisting of 1/4 inch of "AA" at 1.2 pcf increased the pressure drop from 1.62 inches of water to 9.90 inches. From the nomograph of Figure D-5, it can be seen that the initial collection efficiency of the pad was 82%. Thus, while a highly efficient filter could be fabricated entirely from "AA" Fiberglas, its service life would be relatively short due to the rapid rise in its resistance to air flow. With the inclusion of a suitable prefilter, however, the life expectancy of the over-all filter is materially increased. The protection offered to an "AA" pad by 5 inches of No. 55 Fiberglas at 9.0 pcf is illustrated by the Δp vs. Σ plot in Figure E-9. The pressure drop across the "AA" rose from 1.40 to 1.60 inches during the passage of 34.7 grains/ft.² and then remained constant. The resistance of the No. 55 material increased at an increasingly rapid rate and eventually gained 5 inches in pressure drop at Σ equal to 112.2 grains/ft.². The life of the whole unit was thus determined by the No. 55 layer rather than the shorter lived "AA". The data are presented in Table XII.

Greater protection of the "AA" pad was provided by 11 inches of No. 55

packed at 6.0 pcf. A Δp vs. Σ plot (Figure E-10) again indicates an initial rise in the "AA" resistance and a subsequent leveling off so that the over-all filter life was determined by the No. 55 layer. Furthermore, the life of the 6.0 pcf material was 228.5 grains/ft.² as compared to 112.2 grains/ft.² for the previous 9.0 pcf Fiberglas. This trend was observed throughout the tests - the less efficient the material, the greater the life-expectancy; or, in more practical terms, decreasing the packing density or increasing the fiber diameter increases the possible service life of a filter unit. The life of the forefilter is independent of its depth since "plugging" occurs in a relatively small layer near the upstream surface. The depth of the forefilter, however, must be sufficient to protect the more efficient material in the succeeding layers.

The pressure-drop history of a unit composed of 5 inches of No. 55 Fiberglas at 3.0 pcf protecting 11 inches of No. 55 at 6.0 pcf is pictured graphically in Figure E-11. The initial efficiencies of the two layers calculated by means of the alignment chart were 42% and 91%, respectively. From the shape of the curves, it is evident that the initial efficiency of the 3.0 pcf layer was sufficient to protect the 6.0 pcf layer and extend the life of the total filter by a factor of over two. The 3.0 pcf layer experienced a pressure-drop increase of two inches after the passage of 544.7 grains/ft.² to the unit; the unprotected 6.0 pcf material, however, required only 199.9 grains/ft.² to undergo the same increase in resistance.

An attempt to protect the 3.0 pcf layer of No. 55 by 12 inches of No. 450 Fiberglas at 5.7 pcf proved unsuccessful. The data on the initial characteristics of No. 450 fiber were not extensive enough to determine accurately the initial efficiency of the prefilter, but merely indicated it to be less than 20%. As the curves of Figure E-12 demonstrate, the amount of material that passed through the prefilter during the build-up of its collection efficiency was sufficient to increase the resistance of the No. 55 layer markedly. Thus, at a Σ value of 534.0 grains/ft.², the pressure drop across the No. 450 material was 0.18 inch as compared to its initial 0.11 inch; on the other hand, the resistance of the No. 55 Fiberglas was 3.45 inch versus its initial 0.62 inch. An increase in

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Table XII

DATA ON THE COMPARATIVE LIFE EXPECTANCIES OF GLASS FIBER FILTERS

Fiber No.	Bed Depth In.	Packing Density Pcf.	Linear Velocity Fpm.	Initial* Efficiency %	Initial Δp In. of Water	Σ Values for the following Pressure-Drop Increases					Shutdown Values	
						1	2	3	4	5	Δp	Σ
55	5	9.0	50	83	4.15	69.4	88.7	100.0	107.1	112.2	14.0	126.0
AA	1/4	1.2		83	1.40	-	-	-	-	-	1.50	
55	11	6.0	50	91	4.49	163.2	199.9	213.2	221.3	228.5	16.8	244.3
AA	1/4	1.2		83	1.50	-	-	-	-	-	1.75	
55	5	3.0	50	42	0.49	414.1	544.7	-	-	-	2.90	549.3
55	11	6.0		91	4.32	-	-	-	-	-	4.75	
450	12	5.7	50	<20	0.11	-	-	-	-	-	0.18	534.0
55	5	3.0		42	0.62	369.2	485.5	-	-	-	3.45	
600	12	6.8	50	<20	0.11	900.7	-	-	-	-	1.20	918.0
450	12	5.7		<20	0.13	-	-	-	-	-	0.25	
800	12	6.6	50	<20	0.06	-	-	-	-	-	0.21	904.3
600	12	6.8		<20	0.10	-	-	-	-	-	0.21	

* As determined from the nomographs of Appendix D.

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either the bed depth or the packing density of the No. 450 Fiberglas would be required to protect the succeeding layer.

Tests conducted at 50 fpm on Nos. 600 and 800 material indicated the life expectancy of these coarse fibers to be relatively large. One unit consisted of 12 inches of No. 600 Fiberglas at 6.8 pcf protecting 12 inches of No. 450 at 5.7 pcf, the other was composed of 12 inches of No. 800 at 6.6 pcf protecting 12 inches of No. 600 at 6.8 pcf. The initial efficiency of each layer was estimated at less than 20%. The curves of pressure drop vs. Σ values are presented in Figures E-13 and E-14. The life of the No. 800 material was greater, requiring 904.3 grains/ft.² to increase the resistance from 0.06 to 0.21 inch, while the No. 600 layer at the same Σ value reached 1.13 inches from its initial 0.11 inch. When these figures are compared to the "AA" values, the desirability of including less efficient forefilters becomes evident.

Table XIII contains the results of a second series of tests conducted at a superficial velocity of 25 fpm. Since Table XIII and Figures E-15 through E-24 are largely self-explanatory, detailed descriptions of the individual tests will not be given. In general, the forefilter in each unit successfully protected the succeeding layer. The same pattern was observed as in the first group of tests; namely materials of lower packing density and larger fiber diameter were capable of assimilating larger amounts of particles during a given pressure drop increase. Under conditions of equal gas volumes, the effect of the lower superficial velocity was to increase slightly the life-expectancy of the No. 55 Fiberglas; no definite correlation was noted.

The phenomenon of sudden pressure-drop decreases described in the previous sections occurred during the operation of the long-lived units; viz the coarse fibers and the low density (1.5 pcf) No. 55 material. Since the effect is caused by the dislodgment of accumulated particles and their redistribution in the bed, the continual re-occurrence of the redistribution should result in a material extension of the filter life. This proved to be the case: A 2-inch pressure-drop increase across 14 inches of No. 55 at 1.5 pcf (Figure E-19) corresponded to a Σ value of 2040 grains/ft.², as compared to 111.2 and 270.3 grains/ft.² for 6.0 pcf. (Figure E-15) and 3.0 pcf (Figure E-16) beds, respectively. The action of the pressure-drop, once it began to fluctuate, was unpredictable and apparently random. During the early portion of the filter life tests the pressure-drop history of two 1.5 pcf beds of No. 55 Fiber-

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Table XIII

DATA ON THE COMPARATIVE LIFE EXPECTANCIES OF GLASS FIBER FILTERS

Fiber No.	Bed Depth In.	Packing Density Pcf.	Linear Velocity Fpm.	Initial* Efficiency %	Initial Δp In. of Water	Σ Values for the following Pressure-Drop Increases					Shutdown Values	
						1	2	3	4	5	Δp	Σ
55	8	6.0	25	92	1.58	100.9	111.2	117.3	121.4	-	6.00	122.7
AA	1/4	1.2		91	0.8	-	-	-	-	-	0.93	
55	5	3.0	25	52	0.33	223.4	270.3	-	-	-	1.95 ^{(V)**}	284.2
55	8	6.0		92	1.63	-	-	-	-	-	1.75	
115	5	3.8	25	45	0.18	392.7	481.4	520.2	539.6	-	4.70 ^(V)	574.1
55	5	3.0		52	0.30	-	-	-	-	-	0.38	
450	12	10.0	25	(?)	0.18	556.9	652.7	698.7	740.5	767.0	6.95 ^(V)	830.2
115	5	3.8		45	0.18	-	-	-	-	-	0.50	
55	14	1.5	25	58	0.27	637.5	2040.0	2805.0	2917.0	2958.0	5.38 ^(V)	2994.0
55	5	3.0		46	0.29	-	-	-	-	-	0.37	
450	12	10.0	25	(?)	0.18	805.8	897.6	969.0	989.4	-	4.9 ^(V)	1063.0
55	14	1.5		58	0.34	-	-	-	-	-	0.53	
450	25	5.0	25	(?)	0.10	1260.0	1452.0	1542.0	1591.0	1612.0	8.27 ^(V)	1716.0
55	14	1.5		58	0.27	-	-	-	-	-	0.76 ^(V)	

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Table XIII (Continued)

55	10	1.5	25	48	0.17	621.0	3710.0	-	-	-	1.80(V)** 4563.0
55	5	3.0		52	0.34	2270.0	2410.0	-	-	-	2.40(V)
450	24	2.0	25	(?)	0.04	2778.0	3111.0	3400.0	-	-	2.85(V) 3903.0
55	14	1.5		58	0.25	750.0	-	-	-	-	0.90(V)
800	24	5.0	25	(?)	0.04	3813.0	-	-	-	-	1.30(V) 3952.0
55	14	1.5		58	0.30	492.0	-	-	-	-	1.05(V)

* As determined from the nomographs of Appendix D.

** (V) - signifies oscillation of the pressure drop.

glas agreed within the over-all precision of the tests; however, during the random action of the flow resistance, the units diverged considerably. Thus, at a pressure-drop increase of one inch the Σ values for the 14-inch and 10-inch 1.5 pcf layers were 637.5 and 621.0 grains/ft.², respectively, or a variance of 2.6%; on the other hand, at a resistance increase of two inches, the values were 2040. and 3710 grains/ft.², or a variance of 45.0%. In each of the two units the layer succeeding the 1.5 pcf stratum consisted of 5 inches of No. 55 Fiberglas packed at 3.0 pcf. Inspection of Figure E-19 reveals that 14-inches of No. 55 fiber at 1.5 pcf successfully protected the 3.0 pcf section during the passage of 2994. grains/ft.² to the unit. The curve depicting the action of the pressure drop across the 1.5 pcf layer rose smoothly from its initial value of 0.27 inch to 1.08 inches (corresponding to 537.8 grains/ft.²), at which point it began to oscillate at random, approaching a final value of 5.38 inches. The resistance of the 3.0 pcf layer gained 0.04 inch at the outset of the test and then remained relatively constant. At a Σ value of 1934. grains/ft.² the pressure drop began to oscillate very slightly and gradually increased so that at the end of test the pressure drop of the section had gained 0.08 inches. On the other hand, it can be seen from Figure E-22 that 10-inches of No. 55 Fiberglas at 1.5 pcf did not protect from the succeeding 3.0 pcf section entirely -- toward the completion of the test, the 3.0 pcf layer experienced a considerable increase in pressure drop. The resistance of the 1.5 pcf layer rose along a relatively smooth curve from its initial value of 0.17 inch to approximately 1.11 inches (corresponding to a Σ value of 595.1 grains/ft.²) and then began to oscillate in a random fashion. The range over which the pressure drop varied remained substantially constant throughout the test, although it exhibited a slight increase toward the end. The final pressure drop across the 1.5 pcf layer was 1.80 inches after the passage of 4563 grains/ft.² to the unit. After experiencing a slight increase during the early portion of the test, the resistance of the 3.0 pcf section remained at a relatively constant level until a Σ value of approximately 1500 grains/ft.². The pressure drop then increased along a smooth curve from 0.51 inch at 1492. grains/ft.² to 2.00-inches at 2322. grains/ft.², at which point it began to vary in a random manner. The final resistance of the 3.0 pcf was 2.40-inches at the Σ

value of 4563. grains/ft.², or a total increase of 2.06-inches, as compared to a total increase of 1.63-inches across the 1.5 pcf layer.

Since the resistance of the 3.0 pcf layer began to increase long after the 1.5 pcf layer had experienced its initial oscillations, it is conceivable that the low density section reached a "saturation point" at Σ equal to 1492. grains/ft.². Thus, if the 1.5 pcf bed were "saturated" with methylene blue, the passage of more smoke to the unit should cause some of the accumulated material to be dislodged from the 1.5 pcf layer and redeposited in the 3.0 pcf layer, resulting in an increase in the resistance of the latter section. Presuming this to be the case and comparing Figure E-22 with Figure E-16 in which 5-inches of No. 55 Fiberglas at 3.0 pcf was employed as a forefilter for 8 inches of No. 55 fiber at 6.0 pcf, it can be seen that the slope of the 3.0 pcf curve in Figure E-16 is much steeper than that in Figure E-22. Thus, the amount of material collected by the 1.5 pcf layer was greater than that lost by subsequent re-entrainment. The resistance of the 3.0 pcf layer in Figure E-22 began to oscillate somewhere between 2.00 and 2.45 inches of water; this is in fair agreement with the unprotected layer of Figure E-16, which began to vary in a random manner at 2.78 inches.

The divergence between the actions of the two units depicted in Figures E-19 and E-22 may be reasonably attributed to bed "saturation" and the consequent re-entrainment of the collected material. From the fact that the forefilter in the first case contained 14-inches of No. 55 Fiberglas at 1.5 pcf as compared to 10-inches in the second case, it follows that the unit of Figure E-19 should have offered more protection to the 3.0 pcf layer, since more material was required to "saturate" the low density layer. However, an explanation of the behavior of the 3.0 pcf layer in Figure E-19 beyond the Σ value of 1934 grains/ft.² is not readily available.

Besides the redistribution of the accumulated smoke particles, a second factor entered into the random action of the flow resistance which occurred in the units made up of Nos. 55 and 55P fibers. The bottom section of the 1.5 pcf layer was compressed by varying amounts, presumably because of the increase in resistance brought on by the material collected. The resulting changes in

bed depth and packing density affected the pressure drop and perhaps the location of the assimilated particles. This phenomenon was not observed in units made up of 115, 450, 600, and 800 fibers, all of which experienced intervals of pressure drop fluctuation.

At the end of the tests two of the long-lived units were disassembled and the collection efficiencies of the individual beds were measured. The first unit was composed of 24-inches of No. 450 Fiberglas at 2.0 pcf, protecting 14-inches of No. 55 at 1.5 pcf. A total of 3903 grains of methylene blue passed to the unit per square foot of filter area and caused a pressure-drop increase of 2.81-inches across the No. 450 layer and 0.65-inch across the No. 55 layer. The corresponding collection efficiencies rose from a low, undetermined value (less than 10%) to 97.0% for the No. 450 fiber, and from an estimated 58% to 96.1% for the No. 55 fiber. Similarly, the second unit which consisted of 24-inches No. 800 fiber at 5.0 pcf, protecting 14-inches No. 55 at 1.5 pcf, received a total of 3952 grains/ft.². The increases in resistance were 1.26-inches and 0.75-inch, respectively, while the efficiencies rose from a low, undetermined value (less than 10%) to 98.7% and from 58% to 92.4%. The detailed results of the efficiency tests are tabulated below in Table XIV.

Two composite filters made up of various layers of No. 55 Fiberglas at different densities and a clean-up layer of "AA" were operated at 50 and 25 fpm. The pressure-drop histories of the two units, presented in Table XV and Figures E-25 and E-26, illustrate the advantage gained by including less efficient material as a pre-filter in a bed having a high over-all efficiency. The unit that was tested at a linear velocity of 50 fpm consisted of 16-inches of No. 55 at 1.5 pcf, 6-inches of No. 55 at 3.0 pcf, 8-inches of No. 55 at 6.0 pcf, and 1-inch of "AA" at 1.2 pcf. The individual layer efficiencies, as calculated from the alignment charts, were 52%, 49%, 82%, and 99.7%, respectively; so that the filter as a whole had an initial collection efficiency of 99.99%. Because of the high superficial velocity, the original pressure drop of 9.87-inches of water exceeded the maximum resistance specified for process-cell air filtration. A significant increase in the resistance of the 3.0 pcf layer occurred during the latter half of the test. The shape of the curve in Figure E-25 is much the same as in Figure E-22, and indicates that the forefilter reached its saturation point during

Table XIV

**MEASURED EFFICIENCY VALUES OF TWO FIBERGLAS UNITS
AFTER THE COMPLETION OF THEIR LIFE EXPECTANCY TESTS**

<u>Fiber No.</u>	<u>Bed Depth Inches</u>	<u>Packing Density Pcf.</u>	<u>Estimated Initial Eff. %</u>	<u>Final Σ Value Grains/ft. ²</u>	<u>Final Pressure Drop Increase Inches of Water</u>	<u>Final Efficiency Values %</u>
450	24	2.0	(<10)	3903	2.81	95.5 96.9 97.9 97.8 Average 97.0
55	14	1.5	58	3903	0.65	95.8 95.9 96.7 Average 96.1
Total Filter			(>58)	3903	3.46	99.9 99.9 >99.8 Average 99.9
800	24	5.0	(<10)	3952	1.26	98.6 98.7 Average 98.7
55	14	1.5	58	3952	0.75	92.8 92.0 Average 92.4
Total Filter			(>58)	3952	2.01	99.97

Table XV

DATA ON THE COMPARATIVE LIFE EXPECTANCIES OF GLASS FIBER FILTERS

Fiber No.	Bed Depth In.	Packing Density Pcf.	Linear Velocity Fpm.	Initial* Efficiency %	Initial Δp In. of Water	Σ Values for the following Pressure-Drop Increases					Shutdown Values	
						1	2	3	4	5	Δp	Σ
55	16	1.5		52	0.70	276.3	376.2	2636.0	3454.0	3727.0	8.10 ^{(V)**}	
55	6	3.0		49	0.79	2629.0	2960.0	3150.0	3625.0	-	4.75 ^(V)	
55	8	6.0		82	3.10	-	-	-	-	-	3.30 ^(V)	
AA	1	1.2		99.7	5.28	-	-	-	-	-	5.90	
Entire Filter			50	99.99	9.87	215.0	340.0	1370.0	2680.0	2927.0	22.05 ^(V)	4417.0
55	1st In.	1.5		--	0.02	(1)	-	-	-	-	-	
55	2nd and 3rd In.	1.5		-	0.04	(2)	-	-	-	-	0.02 ^{(V)**}	
55	14	1.5		58	0.30	583.1	3921.0	-	-	-	1.75 ^(V)	
55	1st In.	3.0		-	0.04	2745.0	(3)	-	-	-	-	
55	6	3.0		58	0.33	2734.0	2982.0	3330.0	-	-	3.20 ^(V)	
55	8	6.0		92	1.50	-	-	-	-	-	1.35 ^(V)	
AA	3/4	1.2		99.5	1.93	-	-	-	-	-	1.80?	
Entire Filter			25	99.99	4.16	227.3	595.1	2709.0	2777.0	3797.0	8.10 ^(V)	4563.0

* As determined from the nomographs of Appendix D.

**^(V) Signifies oscillation of the pressure drop.

- (1) The pressure drop increased to 0.61 inch at $\Sigma = 407.7$ grains/ft.² and then decreased to a negligible value following the compression of the bottom portion of the bed.
- (2) The pressure drop increased to 0.74 inch at $\Sigma = 621.0$ and then gradually decreased to 0.02 inch following the compression of the bottom portion of the bed.
- (3) The pressure drop increased to 1.58 inches at $\Sigma = 2812$ grains/ft.² and then decreased to a negligible value following the compression of the bottom portion of the layer.

the test and permitted the re-entrainment of some of the collected material. Despite the bed saturation, however, the life of the filter was determined by the 1.5 pcf layer -- a pressure-drop increase of 5-inches across the total unit corresponded to a Σ value of 2927 grains/ft.². For the case in which the flow rate of the aerosol streams is the same, the figure indicates the life expectancy of the composite filter to be 2.7 times that of the sand filter.

The second composite unit consisted of 14-inches of No. 55 at 1.5 pcf, 6-inches of No. 55 at 3.0 pcf, 8-inches of No. 55 at 6 pcf, and 3/4-inch of "AA" at 1.2 pcf. The calculated layer efficiencies were 58%, 58%, 92%, and 99.8%, resulting in an over-all efficiency of 99.99%. At the operating velocity of 25 fpm, the original pressure drop was 4.16 inches of water, which was well within the resistance limit specified for process-cell air filtration. Extra pressure taps enabled the measurement of the pressure drop across the first inch of the bottom 1.5 pcf layer, the second and third inches of the same layer, and the first inch of the 3.0 pcf section. A comparison of Figures E-26A and E-26B reveals that, during the initial rise of the pressure drop across the 14-inches of 1.5 pcf Fiberglas, the major portion of the resistance was in the first inch of the layer. The second and third inches experienced a significant increase in pressure drop which accelerated rapidly beyond 407.7 grains/ft.² due to both particle deposition and compression of the bottom portion of the bed. Furthermore, beyond a Σ value of 621.0 grains/ft.², bed compression took place to such an extent that the Fiberglas moved past the extra pressure taps and the pressure drop across the first three inches of the 12-inch layer gradually decreased to a final value of 0.02-inch of water.

The 1.5 pcf layer of Fiberglas did not protect the succeeding layers throughout the entire test, with the result that the life of the unit was ultimately determined by the resistance of the 3.0 pcf section. As Figure E-26B indicates, the 1.5 pcf layer reached its "saturation point" somewhere between 1500 and 2000 grains/ft.². The subsequent redistribution of the collected material brought about a substantial increase in the pressure drop across the 3.0 pcf stratum, the major portion of which occurred in the first inch of the layer. Beyond a Σ value of 2812 grains/ft.², the bottom part of the bed compressed, moving past the pressure tap and causing the resistance of the nominal first

inch to decrease to a negligible value (Figure E-26A). The history of the filter during the passage of the first 3000 grains/ft.² to the unit is not directly comparable to the test filter of Figure E-22 -- the latter did not experience a marked increase in the resistance of the 3.0 pcf layer. An explanation of this apparent discrepancy is not readily available.

Despite the fact that the resistance of the 3.0 pcf section determined the life of the unit, the presence of the forefilter resulted in a considerable extension of the filter life expectancy. Thus, from Table XIII, a 2-inch pressure-drop increase across an unprotected 5-inch layer of No. 55 Fiberglas at 3.0 pcf corresponded to a Σ value of 270.3 grains/ft.², while the protected 6-inch layer of Figure E-26B required the passage of 2982. grains/ft.² before increasing 2-inches in pressure drop. Furthermore, from Table XI, it can be seen that under the conditions of equal flow rates and similar aerosol streams the life of this composite filter was 6.9 times that of the test sand filter.

Tests were conducted at 25 fpm on the life expectancy of No. 55P Fiberglas packed at 1.5, 3.0, and 6.0 pcf. The data are given in Table XVI and Figures E-27 through E-29. Because the material is more efficient than No. 55, the service life of No. 55P fiber is shorter than that of No. 55; for example, 18-inches of No. 55P at 1.5 pcf experienced a 2-inch pressure-drop increase at Σ equal to 725.4 grains/ft.², while 14-inches of No. 55 at 1.5 pcf and the same linear velocity experience a 2-inch increase at 2040. gains/ft.².

The operating characteristics of No. 115K Fiberglas were studied in two series of tests conducted at 50 and 25 fpm. The experimental procedure was the same as in the preceding life tests, so that a detailed description is unnecessary. The data are given in Tables XVII and XVIII and Figures E-30 through E-40. Among the first groups of runs operating at 50 fpm, the unit consisting of 6-inches of No. 115K at 6 pcf and 8-inches of No. 115K at 9.0 pcf had an additional pressure tap to measure the resistance of the first inch of the 6.0 pcf layer. From the curves of Figure E-31, it can be seen that the life of the filter was determined by the 6.0 pcf bed, and, in turn, the life of the 6.0 pcf layer was determined by the resistance of the first inch.

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Table XVI

DATA ON THE COMPARATIVE LIFE EXPECTANCIES OF GLASS FIBER FILTERS

Fiber No.	Bed Depth In.	Packing Density Pcf.	Linear Velocity Fpm.	Initial* Efficiency %	Initial Δp In. of Water	Σ Values for the following Pressure-Drop Increases					Shutdown Values	
						1	2	3	4	5	Δp	Σ
55P	8	6.0	25	N99	3.0	76.2	89.1	95.0	98.4	101.0	9.85	105.9
AA	3/4	1.2		99.4	1.87	-	-	-	-	-	1.95	
55P	6	3.0	25	79	0.77	132.3	143.6	150.0	154.0	157.0	8.9	164.4
55P	8	6.0		N99	3.00	-	-	-	-	-	3.1	
AA	1/2	1.2		97	-	-	-	-	-	-	-	
55P	18	1.5	25	N90	0.63	539.9	725.4	742.2	754.0	-	4.75(V)**	1023.0
55P	8	3.0		N88	1.08	-	-	-	-	-	1.10	

Table XVII

DATA ON THE COMPARATIVE LIFE EXPECTANCIES OF GLASS FIBER FILTERS

115K	8	9.0	50	68	2.70	145.4	159.1	166.3	169.1	171.8	9.1	173.3
AA	3/4	1.2		98.5	4.45	-	-	-	-	-	4.9	
115K	1st In.	6.0	50	11	0.11	215.4	233.6	242.7	249.1	253.6	8.05	260.9
115K	6	6.0		47	1.05	204.6	233.6	242.7	248.2	253.6	9.15	
115K	8	9.0		68	2.5	-	-	-	-	-	2.70	
115K	6	3.0	50	29	0.37	286.3	306.3	315.4	322.7	330.0	6.65	338.6
115K	8	6.0		55	1.35	-	-	-	-	-	1.55	
115K	12	1.5	50	29	0.27	524.5	558.1	584.7	602.7	618.1	9.70	667.2
115K	6	3.0		29	0.38	-	-	-	-	-	0.50	

* As determined from the nomographs

**(V) Signifies oscillation of the pressure drop.

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Table XVIII

DATA ON THE COMPARATIVE LIFE EXPECTANCIES OF GLASS FIBER FILTERS

Fiber No.	Bed Depth In.	Packing Density Pcf.	Linear Velocity Fpm.	Initial* Efficiency %	Initial Δp In. of Water	Σ Values for the following Pressure-Drop Increases					Shutdown Values	
						1	2	3	4	5	Δp	Σ
115K	8	9.0	25	78	1.20	111.4	121.4	126.4	129.1	131.0	8.65	134.8
AA	3/4	1.2		99.4	2.10	-	-	-	-	-	2.60	
115K	6	6.0	25	55	0.54	203.2	215.4	222.0	224.1	228.2	8.00	239.9
115K	8	9.0		78	1.55	-	-	-	-	-	1.60	
AA	1/2	1.2		97	-	-	-	-	-	-	-	
115K	6	6.0	25	55	0.50	199.1	216.2	224.5	227.6	228.1	8.2	246.2
115K	6	3.0	25	37	0.20	307.2	321.8	331.8	340.0	348.1	6.40	360.1
115K	8	6.0		62	0.70	-	-	-	-	-	0.77	
115K	6	3.0	25	37	0.18	314.5	336.3	345.4	354.5	361.8	9.15	400.9
115K	8	6.0		62	0.65	-	-	-	-	-	0.72	
115K	3	3.0	15	25	0.06	341.1	354.5	361.8	372.7	381.8	7.05	435.2
115K	6	6.0		62	0.32	-	-	-	-	-	0.52	
115K	1st In.	1.5	25	-	<0.01	827.2	954.5	1045.0	1300.0	1391.0	4.1(V)**	1724
115K	12	1.5		37	0.13	845.4	92.7	1027.0	1310.0	1400.0	6.3(V)	
115K	6	3.0		37	0.18	-	-	-	-	-	0.31	

* As determined from the nomographs.

** (V) Signifies oscillation of the pressure drop.

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A comparison of the test results of Nos. 55 and 115K Fiberglas at 50 fpm reveals that the life expectancy of the latter material is greater than that of the former at high packing densities, but the reverse is true at low densities. Thus, taking a 2-inch pressure-drop increase as a basis, the Σ value for No. 55 fiber at 9.0 pcf is 88.7 grains/ft.², while for No. 115K it is 159.1 grains/ft.²; at 6.0 pcf Σ for No. 55 was 199.9 grains/ft.², and for No. 115K Σ was 233.6 grains/ft.². At 3.0 pcf, however, the value for No. 55 fiber is 544.7 grains/ft.², as compared to 306.3 for No. 115K; similarly, at 1.5 pcf, the figures are 376.2 for No. 55 and 558.1 for No. 115K at a resistance increase of two inches, but at a 3-inch increase the Σ value for No. 55 is 2636. grains/ft.² versus 584.7 for No. 115K. The reversal in the life expectancies of the 115K and 55 Fiberglas at 1.5 pcf may be presumed to be caused by the random fluctuation of the pressure drop across the No. 55 layer and the concurrent redistributions of the collected material. However, in the case of the 3.0 pcf material, the pressure-drop curves of both No. 55 and No. 115K fibers were smooth and no explanation can be given for the apparent discrepancy.

When the results of the second group of tests, which were conducted at 25 fpm, are compared to the No. 55 Fiberglas data, the above discrepancy does not arise. On the basis of a 2-inch pressure-drop increase, the Σ values for the 6.0 pcf layers were 111.2 grains/ft.² for No. 55 fiber and 215.4 grains/ft.² for No. 115K. At a packing density of 3.0 pcf, the figures were 270.3 and 321.8 grains/ft.² for the No. 55 and No. 115K, respectively. In the case of 1.5 pcf materials, the random fluctuation of the pressure drop again produced a reversal; thus, at a resistance increase of one inch, the Σ values were 637.5 and 827.2 grains/ft.² for No. 55 and No. 115K, respectively, but at a 2-inch increase, the figures were 2040. and 954.5 grains/ft.². Under the conditions of equal gas volumes and similar aerosol streams, the effect of the lower superficial velocity was to increase the life expectancy of the No. 115K Fiberglas by a factor of two to four; no definite correlation, however, was noted.

Two re-runs were made, one on 6-inches of No. 115K at 6.0 pcf, and another on 6-inches of No. 115K at 3.0 pcf. The Σ values corresponding to

a pressure-drop increase of five inches across the 6.0 pcf layers were 228.2 and 228.1 grains/ft.², indicating excellent agreement. For the 3.0 pcf strata, the values for this resistance increase were 348.1 and 361.8 grains/ft.², or a difference of 3.8%, which is well within the nominal precision of the tests.

THE DESIGN OF FIBERGLAS FILTERS

A convenient method of co-ordinating and summarizing the material presented in the previous sections is to give illustrative examples of filter formulations designed to remove suspended particulate matter in the sub-micron size range with an efficiency of 99.99% or greater. The design of two Hanford plant units will be discussed: first, the off-gases from an individual process operation which are vented in a separate system; and second, process-cell air comparable to that with which the efficiency studies were made. In both instances the rigorous design specifications for the filtration of radioactive aerosols had to be met.

The main differences between the two air streams are flow rate, and the acid and moisture contents. The quantities of off-gases that are emitted are much smaller than those of the process-cell air and tend to fluctuate considerably. The flow rate of the former stream varies between 20 and 170 scfm, as compared with 20,000 scfm for the process-cell air. Since the highest concentration of radioactive particles in the off-gas stream occurs during the periods of high flow rate, proper filter design must be based upon the most severe flow conditions. A second factor influencing filter formulation is the acid and water content of the air streams. The off-gases contain acid vapors in varying amounts that often reach a volume concentration as high as 50 - 60%. The particle loading in both gas streams is relatively low and the size distribution of the particles is predominantly in the sub-micron range.

The filter formulation developed for the decontamination of the off-gases at Hanford is presented in Table XIX. The area is defined so that at maximum flow rate the superficial velocity is approximately 20 fpm. The over-all bed depth is 43-inches and consists of 12-inches of No. 115K at 1.5 pcf, 10-inches of No. 115K at 3.0 pcf, 20-inches of No. 115K at 6.0 pcf, and 1-inch of "AA" at 1.2 pcf. The choice of No. 115K Fiberglas instead of No. 55 was influenced primarily by its greater weatherability under acid conditions, and also by the ease with which the material is handled. The initial efficiencies

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Table XIXFILTER FORMULATION FOR AN ACID-CARRYING AIR-STREAM

Approximate superficial velocity - 20 fpm.

The gas stream contains varying amounts of sub-micron particles and acid vapors; the latter often reach a volume concentration as high as 50%.

<u>Layer</u>	<u>Type Fiberglas</u>	<u>Packing Density Pcf.</u>	<u>Bed Depth Inches</u>	<u>Initial Efficiency %</u>	<u>Initial Pressure Drop Inches of Water</u>	<u>Life Expectancy* Σ - grains/ft.²</u>
Bottom	115K	1.5	12	39	0.10	> 1400
Second	115K	3.0	10	53	0.24	> 362
Third	115K	6.0	20	93	1.34	> 228
Clean-up	AA	1.2	1	99.9	2.20	> 28
TOTAL			43	99.99	4.0	> 1400

* Σ is defined as the cumulative grains of methylene blue passing to the filter layer per square foot of filter area.

of the respective layers are 39, 53, 93, and 99.9% to give an over-all efficiency of 99.99%. The pressure drop across the filter at a linear velocity of 20 fpm is 4.0 inches of water. The depths and efficiencies of the individual layers are sufficient to protect the succeeding layer or layers so that the life expectancy of the unit is determined by the 1.5 pcf bed. Since the life tests were conducted at 25 fpm, the service life in terms of cumulative grains of methylene blue passing to the unit per square foot of filter area can only be estimated at $> 1400 \text{ grains/ft.}^2$.

From the viewpoint of filtration performance the above formulation might readily be applied to the process-cell air provided the area were enlarged to maintain the same linear velocity for a flow of 20,000 scfm rather than 170 scfm. Certain considerations, however, make it advantageous to redesign the unit. The operating and design philosophies of the two installations are quite different. The off-gas filter is a relatively small and easily replaceable package unit. The process-cell air filter, on the other hand, is a large, fixed-bed unit, the construction of which represents an important capital investment. Furthermore, the replacement of a fixed-bed filter at the end of its service life involves the fabrication of additional ductwork necessary to redirect the air stream through a new unit. Consequently every effort should be made to minimize the construction and replacement costs.

The most important factor in the cost of filtration by a fixed-bed is the expected service life. Extending the life expectancy of a unit by including suitable forefilters postpones the need for a replacement and, therefore, decreases the filtration expenses proportionately. In the case of the small, off-gas filters, the depth of the filtration bed was limited to 43-inches by the space available for the installation. Consequently, the use of forefilters was restricted by this limitation and the necessity of maintaining the specified over-all collection efficiency. The absence of such a restriction in the case of the process-cell air filter enables the use of a deeper bed and a resultant extension in the life expectancy. The additional bed depth must include a less efficient forefilter to protect the 1.5 pcf layer of No. 115K Fiberglas. The forefilter selected was a layer of No. 115K Fiberglas packed at a nominal

density of 0.75 pcf. Since No. 115K Fiberglas is shipped in bulk form at 1.5 pcf, packing the material at the lower density requires it to be shredded and, consequently, results in a non-uniform bed. Because of this, no attempt has been made to determine either the initial or the operating characteristics of such beds. The function of the recommended layer is to extend the life expectancy of the unit. The extent of increase of life expectancy, however, has not been evaluated.

Two secondary savings may be realized in the construction costs of a large, fixed-bed filter. First, the use of a deeper bed permits an increase in the superficial velocity of the air stream without decreasing the specified collection efficiency. The limiting factors are the expected service life and, primarily, the maximum flow resistance that the fan installations can handle. By increasing the superficial velocity, the filter area requirement and, consequently, the filter housing costs are decreased. Secondly, the resilience of No. 115K Fiberglas packed at 6.0 pcf requires a force of 60 lbs./ft.² (from Figure 18) to retain the shape and packing density of the layer. This force would influence considerably the structure of the filter container. Since the process-cell air has a low moisture and acid content, the 115K Fiberglas at 6.0 pcf can be replaced with a preformed (fibrous) mat having less weatherability. In this manner, the difficulties involved in the use of No. 115K fiber at high packing densities in large filters can be avoided. Owens-Corning Fiberglas Corp. has suggested No. 55P Fiberglas manufactured as a preformed mat and having as a binder their normal phenol-formaldehyde polymer with a silicone additive. The addition of silicones to the binder is intended to increase the weatherability of the material without affecting the efficiency or permeability characteristics. (Tests have not as yet been made to confirm the last statement.) Besides the savings in installation costs of the extra materials of construction, a further economy is realized in the use of this Fiberglas (designated as No. 55Ps); viz the cost per pound is much less than that of No. 115K.

On the basis of the above considerations, a design formulation is given in Table XX for a composite, fixed-bed filter capable of removing low concentrations of sub-micron particles. The unit is designed to operate at a superficial air velocity of 25 fpm. The over-all depth is 55-inches and

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Table XX

FILTER FORMULATION FOR A NON-ACID-CARRYING AIR-STREAM

Approximate superficial velocity - 25 fpm.

The gas stream contains varying amounts of sub-micron particles and has a low acid content.

<u>Layer</u>	<u>Type Fiberglas</u>	<u>Packing Density Pcf.</u>	<u>Bed Depth Inches</u>	<u>Initial Efficiency %</u>	<u>Initial Pressure Drop Inches of Water</u>	<u>Life Expectancy* Σ - grains/ft.²</u>
Bottom	115K	0.75**	12	< 37	< 0.12	> 1400
Second	115K	1.5	18	50	0.18	1400
Third	115K	3.0	12	56	0.34	362
Fourth	55Ps***	3.0	12	94	1.7	157
Clean-up	AA	1.2	1	99.8	2.70	28
TOTAL			55	99.999	5.0	> 1400

* Σ is defined as the cumulative grains of methylene blue passing to the filter layer per square foot of filter area.

** The shipping density of No. 115K is 1.5 pcf so that the figure 0.75 pcf is merely nominal and indicates the material is shredded to less than 1.5 pcf. The filtration characteristics of such a layer will vary in an unknown manner since the packing density is not uniform.

*** No. 55 Ps designates No. 55P Fiberglas manufactured as a preformed mat and having as a binder the normal phenol-formaldehyde polymer with a silicone additive. The silicone addition is intended to increase the weatherability of the material without affecting the efficiency or permeability characteristics. As yet no tests have been made; the data given are based on No. 55P experiments.

may be broken down into layers consisting of 12-inches of No. 115K Fiberglas at 0.75 pcf, 18-inches of No. 115K at 1.5 pcf, 12-inches of No. 115K at 3.0 pcf, 12-inches of No. 55Ps at 3.0 pcf, and 1-inch of "AA" at 1.2 pcf. Since the characteristics of 0.75 pcf material are unknown, the efficiency-resistance values are merely given as less than the corresponding figures for a 1.5 pcf layer. At a linear velocity of 25 fpm, the calculated efficiency of the entire unit is 99.999% and the pressure drop is 5 inches of water. The plant sand filters, which service the process-cell air at the Hanford Works, have been operating for over 2-1/2 years without any appreciable increase in pressure drop and have an expected service life of at least 6-8 years. The life expectancy of the composite Fiberglas unit formulated above should be at least twice as great as that of the sand filter, or in the order of 15 years. These design figures meet the specifications required in the problem of radioactive particle filtration.

The first plant-scale unit employing glass fibers as filtration media was placed in operation at the Hanford Works on October 26, 1950. The filter was installed in the vent line for one of the process vessels. The operating conditions were those previously described in this section for the off-gas filter and the formulation was that of Table XX. The installation was provided with complete sampling facilities, by means of which aliquots of the gas stream could be drawn from plenum chambers upstream and downstream to the filter bed. The measured collection efficiency was definitely greater than 99.9%, and probably near 99.99%. The initial pressure drop across the filter was 4 inches of water. These data are in excellent agreement with the design figures. The unit has been in operation for over six months without any measurable increase in pressure drop. Details of the filter evaluation tests are given in the document, "Decontamination of the Dissolver Vent Gases at Hanford", by A. G. Blasewitz et al (28).

From the operational standpoint the performance of fixed-bed filters at Hanford Works has been highly satisfactory. No maintenance has been required on the sand filters or the off-gas Fiberglas filters during their respective operating periods of 2-1/2 years and 6 months. Both the initial and operating

characteristics of the filter units meet the design specifications for the intensive removal of contaminated particles from air streams which are discharged from plants processing radioactive materials on an industrial scale. The use of glass fiber filters, of course, need not be restricted to the filtration of radioactive materials. Fixed-bed filters formulated with glass fibers can be advantageously employed whenever sub-micron particles, present in air streams at low concentrations, must be removed with a very high efficiency.

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AGB, RVC, BFJ, MFK, EFK, WCS, BW/lb-dt

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