Bulletin of the University of Minnesota

ENGINEERING EXPERIMENT STATION

FRANK B. ROWLEY, Director

BULLETIN NO. 16

FACTORS AFFECTING THE PERFORMANCE AND RATING OF AIR FILTERS

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Vol. XLII No. 58 November 27 1939

MINNEAPOLIS

Entered at the post office in Minneapolis as second-class matter, Minneapolis, Minnesota. Accepted for mailing at special rate of postage provided for in section 1103, Act of October 3, 1917, authorized July 12, 1918.

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PREFACE

The material contained in this bulletin is the result of researches in the Engineering Experiment Station concerning the problems caused by atmospheric dust. Parts of the work have been in progress for several years and have included methods of measuring dust in the air, methods of cleaning the dust out of the air, and the rating of air cleaning devices. The work reported in this bulletin has particularly to do with the operating characteristics of air filtering devices and methods of rating them. The first direct work with air filter performance was in connection with the development of a standard code for rating air filters which was adopted by the American Society of Heating and Ventilating Engineers in 1933. In the summer of 1937 an extensive investigation was made of the performance characteristics of air filters used in railroad air conditioning work. This was made in co-operation with the Research Committee of the Association of American Railroads and various filter manufacturers. Since 1937 the investigations have been continued, a part of them in co-operation with the Research Committee of the American Society of Heating and Ventilating Engineers, and a part supported by funds from the Graduate School, University of Minnesota. A part of the results and some of the cuts have been taken from the following publications:

"Report on Relative Performance of Air Filters." Mechanical Division of Association of American Railroads. January 15, 1938.

"A.S.H.V.E. Research Report No. 1094, Air Filter Performance As Affected by Kind of Dust, Rate of Dust Feed and Air Velocity through Filter," by F. B. Rowley and R. C. Jordan. (*A.S.H.V.E. Transactions,* 44:415. 1938.)

"Air Filter Performance As Affected by Low Rate of Dust Feed, Various Types of Carbon, and Dust Particle Size and Density," by F. B. Rowley and R. C. Jordan. (Published in *A.S.H.V.E. Journal Section, Heating, Piping and Air Conditioning.* June, 1939.)

"A Standard Air Filter Test Dust," by F. B. Rowley and R. C. Jordan. (Published in *A.S.H.V.E. Journal Section, Heating, Piping and Air Conditioning.* October, 1939.)

In addition to the support given this work by the American Society of Heating and Ventilating Engineers and the Graduate School, University of Minnesota, the authors wish to acknowledge the co-operation of the several filter manufacturers who have been generous in furnishing filters for the investigation, and also the assistance of Axel B. Algren, assistant director, Engineering Experiment Station, Harold E. Ostdahl, research assistant, and Roy G. Knutson, student assistant, in carrying through the research program.

Factors Affecting the Performance and Rating of Air Filters

INTRODUCTION

The problems created by dust in air are becoming increasingly important from both the economic and health standpoints. Dust may be an economic consideration in some manufacturing process; it may be a hazard to health; or it may be an ordinary nuisance. In each case there are at least two distinct factors; first, that of measuring the amount of dust in the air, and second, that of removing it from the air. Both of these are often complicated and troublesome for the air conditioning engineer.

Several methods have been proposed, and some of them successfully used, for measuring the amount of dust in the air, but thus far no single method has proven to be sufficiently simple and universally adaptable to be accepted as a standard. This has complicated the problem and to a great extent hampered the development in this branch of air conditioning. In most cases the removal of dust from the air and the rating of devices for this work present complications which are at least equal to those of measuring the amount of dust in the air. The general purpose of this research has been to study the characteristics of certain types of air cleaning devices and to investigate standards for testing and rating air filters.

It is difficult to set up a laboratory test procedure which will measure the characteristics of an air filter and give reliable data by which its true performance in practice can be predicted. This is due partly to the questions involved in the selection of a rational basis for the rating of filters, and partly to the difficulty of simulating the actual conditions under which the filter must operate in practice.

Three methods by which the efficiency or arrestance of an air filter may be determined are in use at the present time. It may be based upon, first, the reduction in weight of dust in the air, second, the reduction in dust particle count, and third, the decrease in the "soiling power" of the air-dust mixture in passing through the filter. Test methods may be identical in all respects with the exception of the arrestance measuring method, and yet may yield three entirely different filter ratings.

The weight method of determining filter arrestance, in which the weight of dust in the air before and after passing through the filter is measured, is the method specified by the American Society of Heating and Ventilating Engineers Code for Testing and Rating Air Cleaning Devices, and is probably the best measure of filter performance from a nuisance standpoint. This is the method used throughout the researches presented in this bulletin, and since the average comfort air conditioning installation is usually concerned more with dust from the nuisance than from the health standpoint, the method appears to be satisfactory in so far as filter ratings are concerned, providing a proper synthetic dust is used and the filters are tested under laboratory conditions which will simulate operating conditions.

There is much evidence to support the theory that the number and size of dust particles in a given volume of air is an excellent indication of the effect which certain types of dust will have on health. The particle count method of determining the arrestance of a filter, in which counts are made of the dust particles in the air-dust mixture from both sides of the filter, is therefore a measure of the filter performance in so far as health is concerned. However, it seems unlikely that it would give as satisfactory an indication of the removal of nuisance dust as would either of the other test methods. At the present time this method is limited because of the time required to make the large number of dust counts necessary to give a single accurate average of the dust particle concentration, and because of the lack of an accepted method for making the dust counts.

Unless all particles of the test dust were of approximately the same size, there would not be a close correlation between the arrestances as determined by the weight and count methods. For instance, a filter which might show an arrestance of 80 per cent by the weight method might drop as low as 20 per cent by the dust count method. This is due to the fact that a small percentage of large dust particles which are easily removed by the average filter may constitute the greatest percentage of the actual weight of the dust. The dust count method does, however, present good possibilities as a method of measuring the dust in the air, and it appears also that it may be adaptable as a field method of testing air filters, which may be correlated with the laboratory method of test. A practical field test method is one of the big problems in air cleaning at the present time.

The rating of air filters by the relative "soiling power" of the air-dust mixture before and after passing the filter appears to have possibilities of practical application in both the laboratory and the field. This has been developed by passing equal quantities of the air-dust mixture, sampled from either side of the filter, simultaneously through filter papers of identical physical properties and determining the relative opacity to light of these filter papers by means of a photoelectric cell. This method has the advantage of requiring only a short time for an arrestance determination, and it appears probable that for the same kind of dust the results may be correlated with other methods. It is evident that light- and dark-colored dust would have entirely different effects on the amount of light that would pass through the filter paper, and, therefore, the type of dust to be handled by the filter would be an important factor in using the "soiling power" method.

The method used in determining the arrestance of of an air filter may be largely responsible for the arrestance value obtained, and it is possible that more than one test procedure should be standardized in order to determine the arrestance of a filter for the particular field in which it is to be used. A standard test method should be one which can be applied both in the laboratory and in the field, or else separate methods should be devised for each and carefully correlated so that the practical performance of a filter in the field may be checked with its laboratory test values.

In general, the objects of these filter researches were:

1. To study the apparatus and test method as specified in the American Society of Heating and Ventilating Engineers Code for Testing and Rating Air Cleaning Devices used in general ventilation work for the purpose of determining what refinements or fundamental changes would be desirable.

2. To produce a dust mixture which would simulate average air-borne dust and which could be duplicated for test purposes.

3. To investigate some of the factors which affect air filter performance and to determine the effects of these factors on different types of filters.

Some of the specific problems investigated were:

1. Suitable elements for a synthetic test dust.

2. The effect on filter performance of such factors as the rate of dust feed to the filter, air velocity through the filter, dust particle size, dust density, and the different types of dust.

3. The problem of dust standardization and duplication of dust for filter tests.

4. The effect of lint on the performance characteristics of filters.

5. Single and tandem operation of filters.

TEST APPARATUS AND PROCEDURE

With the exception of the dust feeding device the assembled test apparatus shown in the photograph of Figure 1 and the detail drawing of Figure 3 is the same as that specified in the A.S.H. and V.E. Standard Code for Testing and Rating Air Cleaning Devices. The main test duct is 20 inches square and 9 feet long, connected by a reducing section 3 feet long and a 12-inch-diameter section 5 feet long to an exhaust fan. The test filter is placed in the 20-inch square duct with the exhaust face about 8 inches from the reducing section. A direct current drive variable speed fan is used to draw the air through the filter, the volume being measured by a standard rounded orifice and the pressure drop across the filter being measured by a standard inclined water gage.

The dust feeding apparatus is shown at the left of Figure 1 and in the detail drawing of Figure 4. It consists of a revolving disc upon which the dust sample has been evenly distributed in a ring of uniform thickness. The disc containing the dust sample is placed on a rotating plate and a continuous uniform ribbon of dust is shaved from the outside edge of the dust ring by a specially designed knife edge fastened to the end of an air tube. Air is drawn through this tube by a low pressure air line and Venturi tube. The velocity of the entering air picks the ribbon of dust from the rotating plate and carries it through a tube to the distributing nozzle at the entrance of the filter test ap-

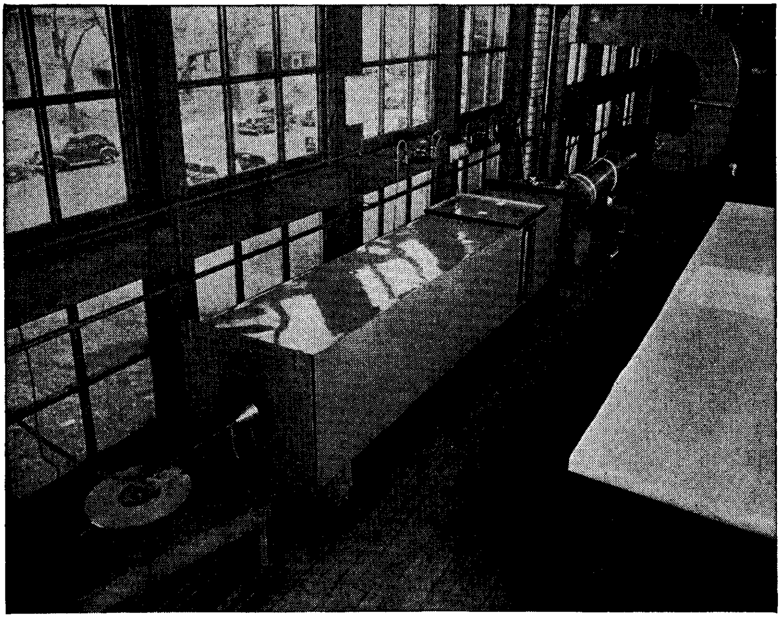

FIGURE 1. ASSEMBLED VIEW OF TEST APPARATUS

paratus. The circular plate carrying the disc is rotated by a friction wheel in contact with the disc directly under the dust pick-up tube. The rotating plate is moved forward by a screw mechanism which is operated at a constant relative speed to the rotating plate. Thus the ring of dust moves toward the cutting knife at a constant speed, and since the tangential velocity of the disc is maintained constant by the friction wheel underneath it, the dust ribbon is of uniform cross section and there is a constant rate of dust feed to the filter.

The apparatus used to distribute the dust sample on the aluminum disc is shown in Figure 2. In this device the disc is clamped to a surface plate by an inner and outer clamping ring as shown. The required weight of dust is placed between the rings and leveled off to a uniform thickness by a rotating scraper or leveling device. With thin layers of dust it is necessary to use a vibrating apparatus in order to distribute the dust evenly over the plate without carrying it around with the scraper, but with thicker samples of dust it is possible to omit this vibrating apparatus and still get uniform dust distribution over the plate.

In making a test the correct weight of dust mixture for a one-hour test period is distributed evenly on the aluminum disc by the distributing apparatus. This disc is then placed in the dust feeding device and

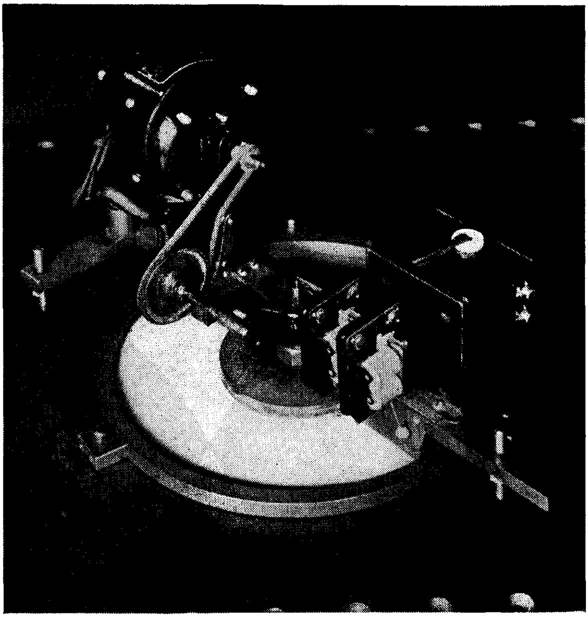

FIGURE 2. APPARATUS FOR DISTRIBUTION OF DUST SAMPLE ON PLATE

the rate of dust feed is controlled by the rotating speed of the disc. The volume of air passing through the filter is regulated as required for the particular test either by controlling the speed of the fan or by adjusting the fan discharge outlet. The volume of air passing through the filter is determined from the area and the pressure drop across the standard orifice. The pressure drop across the air filter is measured by a standard water gage. The amount of dust in the air leaving the filter is measured by drawing a certain percentage of this air through a fine grain alundum crucible for the continuous periods of the tests and noting the gain in weight of the crucible due to the dust separated from the air. The arrestance calculations are based on the results of a one-hour test. The volume of air going through the filter is obtained by means of the formula:

$$\text{C.F.M.} = 1096.5A\sqrt{\frac{\text{V.P.}}{d}}$$

where A = area of orifice in square feet.
V.P. = velocity pressure in inches of water.
d = air density in pounds per cubic foot.

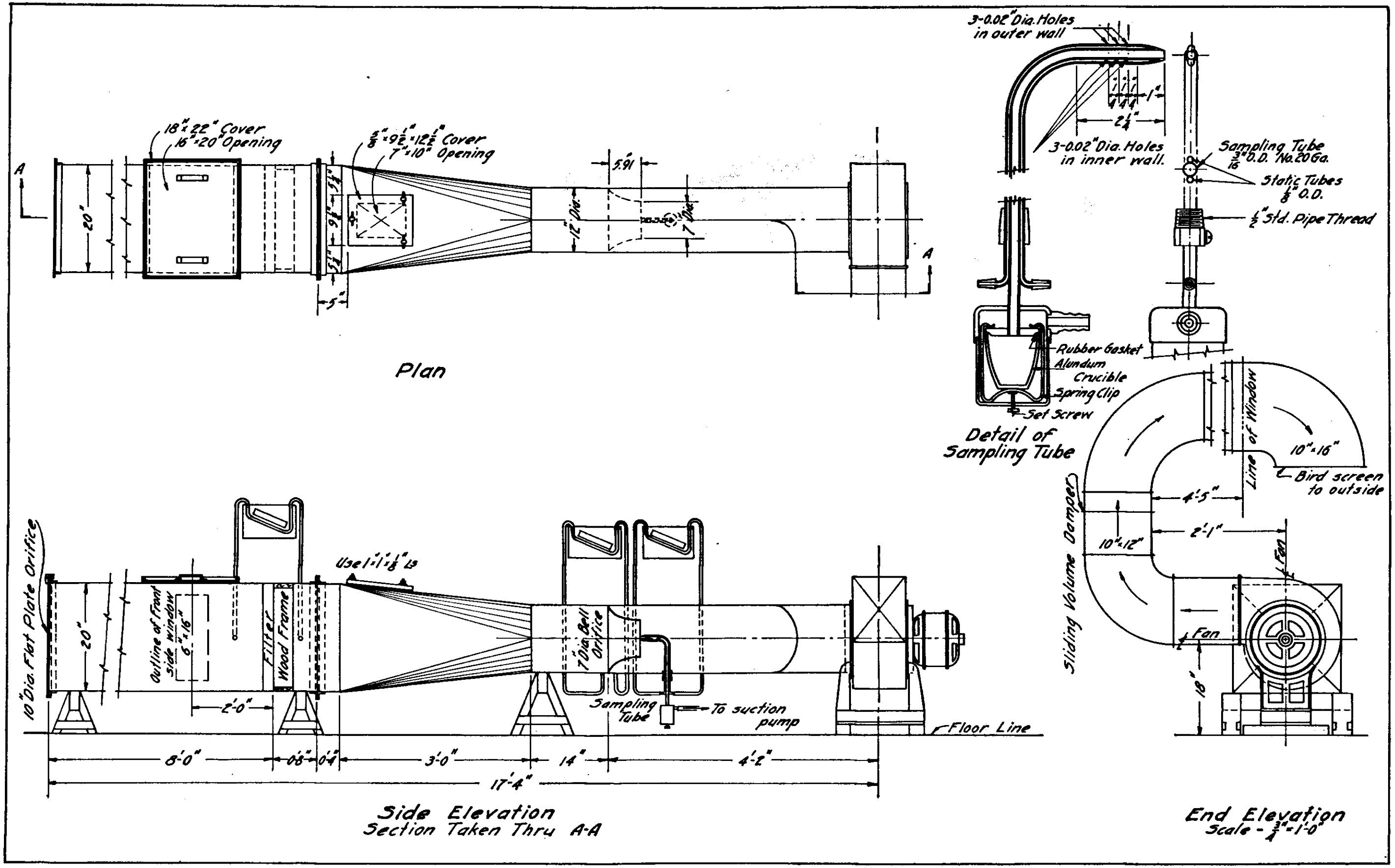

FIGURE 3. DETAIL DRAWING OF AIR FILTER TEST APPARATUS

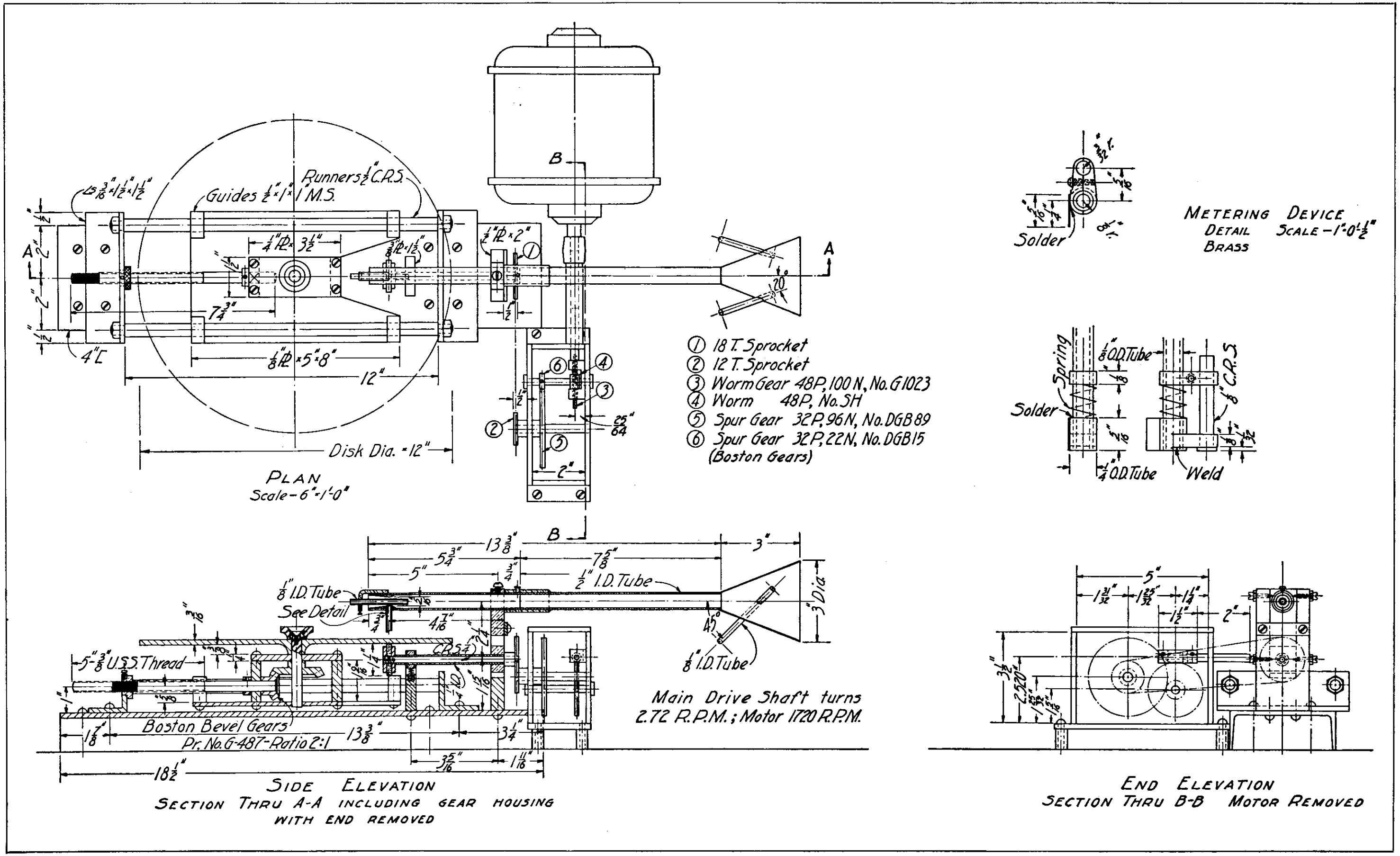

FIGURE 4. DETAIL DRAWING OF DUST FEEDER

That portion of the filtered air which is carried through the alundum crucible is taken out of the air stream by the sampling tube shown as a detail in Figure 3. An equal velocity of air is maintained on the inside and outside of the sampling tube by two static pressure tubes, one with openings to the outside, and the other with openings to the inside of the sampling tube. Theoretically, when these two static pressures are balanced, the air velocities are equal on the inside and outside of the tube. There was, however, some discrepancy in these readings and it was necessary to calibrate the sampling tube for accurate results.

The alundum crucible is weighed before and after each hour of the test run on an analytical balance which is accurate to .0001 gram. The increase in weight of the crucible multiplied by the ratio of the area of the sampling tube and the orifice gives the total amount of dust passing the filter. Knowing the amount of dust fed into the air stream on the upstream side of the filter and the amount in the air passing through a filter for a given period of time, one can calculate by means of the formula:

Arrestance $= 1 - G/G_o$, where G = weight of dust per unit time on downstream side of filter.
G_o = weight of dust per unit time on upstream side of filter.

The accuracy with which the amount of dust in the air leaving the filter could be measured by use of the alundum crucible was checked periodically by running the test apparatus with no filter in the air stream. In these tests the amount of dust as measured by the crucible method showed a maximum variation of approximately 5 per cent from that actually fed into the filter, and the average variation for several tests was 1.6 per cent. For a filter having 90 per cent arrestance a variation of 5 per cent in the weight of dust leaving the filter would give a maximum possible error of .5 per cent in arrestance of the filter.

AIR FILTERS

Air filters may be classified according to the principle of air cleaning employed, or according to their application. The four general types are: A, viscous air filters; B, dry air filters; C, air washers; D, electric precipitators. The work reported in this bulletin includes both the viscous and dry filters, and those filters used may be classified further as the permanent or cleanable type and the throw-away type of filter.

The viscous type of filter usually consists of a fibrous or cellular material coated with some adhesive substance. The filter pack is usually graded as to density, fiber size, adhesive coating, or some combination of the three for the purpose of progressively cleaning the air as it passes through the filter and for distributing the load throughout the filter. This design has a tendency to increase the life and dust holding capacity of the filter, while a filter which is not so packed and designed may have a tendency to collect the greater part of the dust at the entering face and thus build up excessive air resistance through the filter. The principle of air cleaning in this type of filter is that of adhesive impingement. The dust particles in the air coming in contact with the adhesive material on the filter pack adhere to this material, and the air is gradually cleaned in passing through. Efficiency is obtained by subdividing the air stream to increase the possibility that all of the dust particles may come in contact with adhesive material and yet not to such an extent as to increase unduly the resistance of the air passing through the filter. The success of this type of filter depends not only upon the type of pack used but also upon the type of adhesive coating employed. A good adhesive should thoroly cover the surface of the material, retain a uniform viscosity through a wide range of temperatures, have high dust penetrating ability, be nonevaporative, odorless, fire resisting, and have germicidal properties. The selection of a good viscous material has been one of the major problems in this type of air filter.

The dry filter works on a different principle from the viscous type. It usually consists of some finely woven or packed material with the filter interstices much smaller than those of the viscous type. In some of the dry filters the air passages are so fine as to take out a part of the dust by a screening action. However, it appears that in most cases the major part of the dust is removed as in the viscous filters by impingement and centrifuging. The calculated power consumption for a filter with openings small enough to eliminate all of the dust by screening is unreasonably high. The dry as well as the viscous filter may be made either as cleanable or noncleanable types.

The choice of filters for these tests was based on a wide variation in basic filter design. No attempt was made to choose filters with the best performance characteristics in any class. When interpreting the test results it should be remembered that only one design of each type of filter was selected, and that the filters were not all of the same thickness or necessarily of the best design of a particular manufacturer. The purpose of the tests was not to rate or compare different filters, but rather to study the characteristics of certain types of filters and the effects on test results of different kinds of dust and methods of test procedure.

Figure 5 shows the filters used in this series of tests. They may be described briefly as follows:

A. A permanent type of cleanable oil filter, 4 inches thick with 24 layers of expanded metal and wire screen graded from coarse mesh to fine mesh at leaving side.

B. A viscous coated throw-away type filter, 2 inches thick. The fibrous media were graded in fiber size, density, and oiling from entering to leaving side. This filter also appears designated as B-1 and B-2 due to the fact that three different lots of filters were used, each with slight variations in construction. Filters B

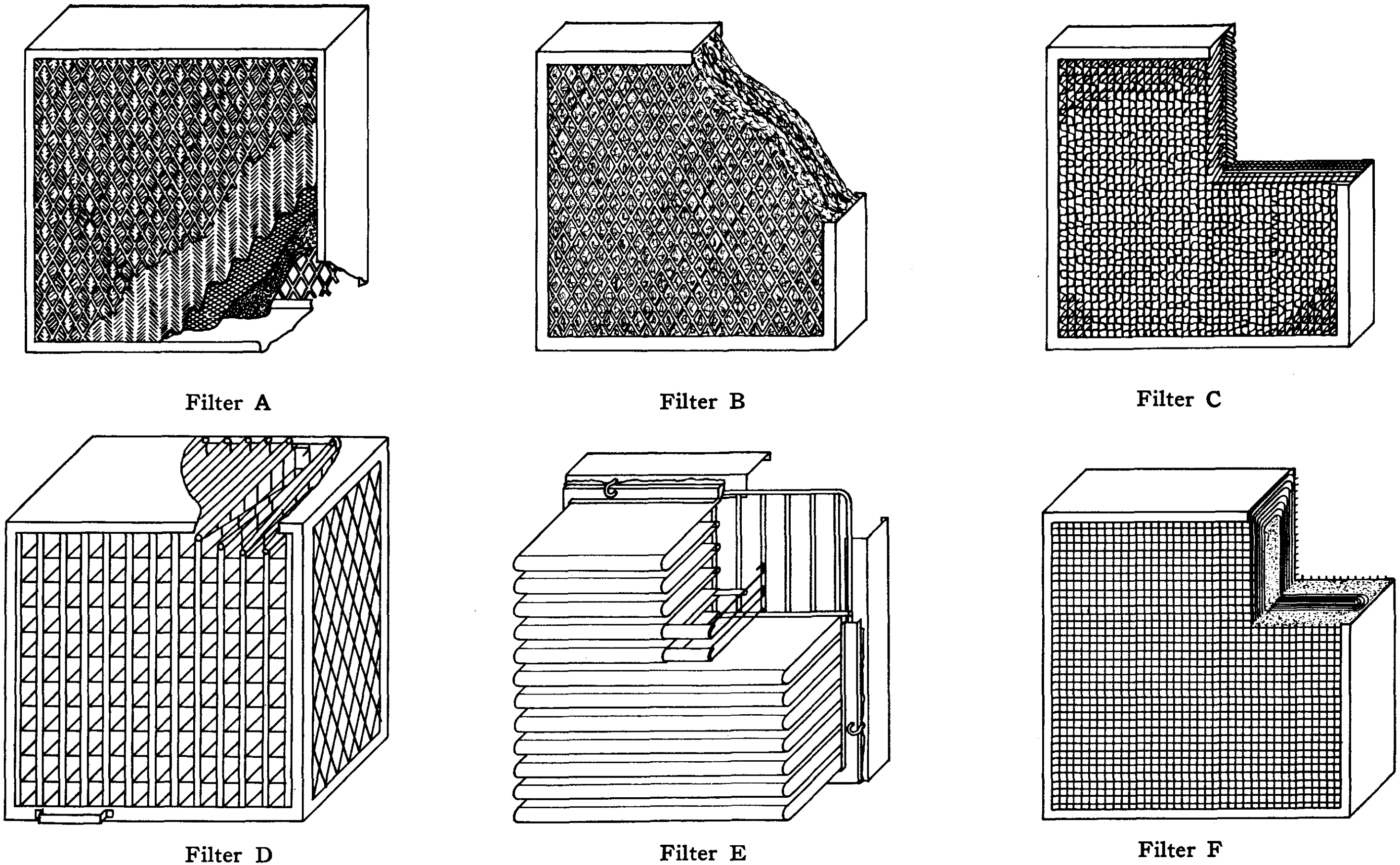

FIGURE 5. SECTIONAL VIEWS OF AIR FILTERS TESTED

and B-1 were practically the same, and did not give any appreciable test result differences. Filter B-2 was higher in initial resistance and arrestance and, therefore, shorter in life and dust holding capacity.

C. A cellular type of filter, 2 inches thick. This filter was built in two sections each with the axis of cells set at 45 degrees to the center line of duct and at 90 degrees to each other. The cells on the entering side were of larger dimensions than those on the leaving side of the filter.

D. A filter of cotton media of coarse material on the entering side and glazed on the leaving side. The filter media were accordian plaited in frame to give an area of approximately 12 times the cross-sectional area of air stream.

E. A filter of wool media fitted over a metallic frame. The filter media was accordian plaited to give an area of approximately 9.8 times the cross-sectional area of air stream.

F. A dry type filter, 4 inches thick of metal wool filtering media. The inner pack was of horizontal fiber direction while the two outer packs, on either side of inner pack, were of vertical fiber direction.

SYNTHETIC TEST DUST

There are many varieties of dust in the air. The density, particle shape and size, as well as other characteristics, vary through wide ranges. Experience has shown that the type of dust passed through a filter may have a marked effect on the filter arrestance, and that a given dust may not have a like effect on the performance of two different types of filters. These facts present one of the big problems in setting up a laboratory test procedure which will show the true qualities of a filter when applied to an air conditioning installation. It is important that the dust used for the laboratory test be of a type which will have the same effect on filter performance as will the dust in the air which the filter must handle in practice.

The standard synthetic dust selected for the A.S.H. and V.E. Air Filter Code consists of 50 per cent by weight of powdered lampblack, containing a minimum of 97.5 per cent free carbon, and having a minimum bulking value of 3.5 pounds per cubic foot, mixed with 50 per cent by weight of Pocahontas bituminous coal ash screened to pass a 200-mesh screen. Experience has shown several defects in this mixture. In the first place many varieties of lampblack will satisfy the code requirements and yet have widely different properties in so far as a filter test is concerned. Even the variations in lampblack of the same trade name may be such as to invalidate entirely any results for comparative purposes. In the second place 50 per cent of lampblack by weight is a very much higher percentage of carbon than that to be found in the dust of average air, and some filters show efficiencies as low as 20 per cent for this type of material. Obviously filters rated by the dust mixture specified by the Air. Filter Code may show wide variations from the results expected in practice, and the ratings may be unfair to many of the filters.

In the spring of 1937 the Research Committee of the Association of American Railroads decided on a series of tests to be conducted at the University of Minnesota to determine the characteristics of those filters in common use for air conditioning installations in railroad cars. Preparatory to these tests representatives of all filter manufacturers interested in railroad air filters were invited to a conference for the purpose of discussing the test procedure to be used in making the tests. As the result of this conference, and an investigation of several samples of dust collected from railway air conditioning systems, a new dust mixture was selected. This mixture consisted of 50 per cent by weight of Pocahontas ash screened through a 200-mesh screen, 20 per cent by weight of Illinois fly ash screened through a 200-mesh screen, 20 per cent by weight of lampblack meeting the Air Filter Code specifications and screened through a 100-mesh screen, and 10 per cent by weight of fuller's earth. The correct percentages of the four kinds of dusts were mixed together and screened through a 100-mesh screen to insure a uniform mixture. The physical properties of the component dusts used in this mixture are shown in Table I.

TABLE I

PROPERTIES OF DUSTS USED IN TESTS

Dust	Density, Grams per C.C.		Screen Analysis Per Cent by Weight		Moisture Loss, Per Cent, Heated to 175° F. for Eighteen Hours
	Loose	Jolted to Max. Density	Between 200 and 325 Mesh	Passed 325 Mesh	
Fuller's earth, Passed 100 mesh	0.412	0.600	....	....	5.10
Fly ash from Illinois coal Passed 200 mesh	0.488	0.740	Approx. 23	Approx. 77	0.20
Pocahontas ash, Passed 200 mesh	0.455	0.766	Approx. 19	Approx. 81	0.15
Cottrell ash, Passed 100 mesh	0.888	1.285	....	....	0.98
Lampblack Passed 100 mesh	0.128	0.156	....	....	1.18
50 per cent Pocahontas ash 50 per cent lampblack	0.215	0.316	....	....	....
50 per cent Pocahontas ash 20 per cent Illinois fly ash 20 per cent lampblack 10 per cent fuller's earth	0.317	0.480	....	....	....

In the railroad air filter tests a mixture of dust containing some lint was also devised to simulate the lint conditions encountered in railroad Pullman cars and elsewhere. This mixture consisted of 90 per cent by weight of the 50-20-20-10 mixture previously described, and 10 per cent by weight of short wool fibers known as "Naperflox," which were cut in lengths of 3/16 inch and less. The dust and lint were fed into the air stream separately, other test data being taken as specified in the

Air Filter Code. While this test procedure gave the relative merits of the various filters when lint was present, it was recognized that the lint was not in every way comparable to that found in average air.

The investigations reported in this bulletin include many tests in which different dust mixtures and the individual components of the mixtures have been used to determine the influence of the component parts of a dust on the performance of a filter. In addition to the standard dusts specified, many other kinds of dust have been used. The object has been to get a dust which would simulate the dust found in practical installations and which could be duplicated with reasonable accuracy for test purposes. The results of these various tests, together with recommendations, will be discussed under the heading, Dust Standardization.

RATE OF DUST FEED AND FILTER PERFORMANCE

The A.S.H. and V.E. Standard Air Filter Code specified 0.35 gram of the dust mixture per 1,000 cubic feet of air passing through the filter. This represents a much greater weight of dust per unit volume of air than would be found under ordinary conditions. It is necessary, however, to increase the weight in order to shorten the time of a filter test, and also to have a dust concentration in the air leaving the filters such that the dust can be separated out of the air and weighed by practical methods. The criticism of this part of the Air Filter Code has been due to the uncertainty as to the dust arrestance of some types of filters when subjected to heavy concentrations of dust as compared with the arrestance of these filters under normal operating conditions with very much lighter dust concentrations.

It has been contended that when heavy dust concentrations are used, the viscous fluid on certain types of filters will not penetrate the initial layers of dust rapidly enough to make them efficient in catching the succeeding dust particles. Under ordinary operating conditions, however, more time is available for the dust particles to be penetrated by the viscous fluid, and thus a continuously active dust catching surface is provided.

In order to settle the question of a practical rate of feed which would give representative test results, a series of tests were run on Filters A, B, C, and D at different dust concentrations. The dust mixture consisted of 50 per cent by weight of Pocahontas ash screened through a 200-mesh screen, 20 per cent by weight of Illinois fly ash screened through a 200-mesh screen, 20 per cent by weight of lampblack (Germantown Eaglebrand) screened through a 100-mesh screen, and 10 per cent by weight of fuller's earth, all thoroly mixed and screened through a 100-mesh screen. A face air velocity of 300 feet per minute was selected, and the dust mixture was fed into the air stream at the rates of 10, 20, 30, 40, 60, and 100 grams of dust per hour. This gave dust concentrations of 0.2, 0.4, 0.6, 0.8, 1.2, and 2.0 grams per 1,000 cubic feet of air, respectively. For those filters in which it was evident from preliminary test data that small variations in the dust concentration would have no great effect on the filter arrestance, a part of the specified tests was omitted. In all of the tests the required amount of dust was fed into the air stream leading to the filter at a constant uniform rate, and the arrestances were calculated at the end of each one-hour period. Each test was continued until the air pressure drop across the filter reached 0.4 inch of water. The results of these tests are shown in Table II.

TABLE II

TEST RESULTS* ON FILTERS A, B, C, AND D FOR DIFFERENT DUST CONCENTRATIONS

(Face air velocity 300 feet per minute. Dust mixture, 50, 20, 20, 10)

Filter	No. Test	Rate of Dust Feed, Grams/Hr.	Initial Filter Resist., Inches Water	Length of Test, Hours	Total Dust Fed, Grams	Average Arrestance, Per Cent	Dust Holding Capacity, Grams
A	16	20	0.225	32.8	656	77.2	503.8
	134	40	0.229	14.5	580	77.5	449.0
	111	40	0.220	15.1	604	80.3	483.6
	112	60	0.220	11.0	657	76.9	504.8
	144	100	0.230	5.2	520	79.7	411.9
B	106	10	0.146	24.8	248	80.0	199.8
	12	20	0.153	15.8	316	78.8	249.2
	102	30	0.150	9.6	288	81.3	233.6
	104	40	0.148	8.0	320	81.0	259.2
	103	40	0.152	7.3	292	81.9	237.5
	101	40	0.150	8.7	347	81.7	282.4
	107	60	0.157	5.4	324	82.0	264.6
	143	100	0.147	3.9	390	82.8	322.8
C	145	10	0.142	29.0	290	72.3	210.7
	11	20	0.148	15.6	312	72.0	221.0
	105	40	0.142	9.0	358	69.9	250.3
	127	60	0.156	6.0	360	71.4	256.0
	142	100	0.147	4.6	460	68.2	313.9
D	110	10	0.086	20.7	207	89.8	186.2
	31	20	0.088	10.8	216	92.0	198.5
	113	20	0.091	11.4	228	92.5	208.8
	108	40	0.095	6.3	252	93.5	233.5
	109	60	0.090	4.1	246	94.6	231.1
	149	100	0.087	2.4	240	92.4	222.5

* Based on a final resistance of 0.4 inch of water across the filter.

The curves of Figure 6 show the test results for Filter B and are typical for all tests. In order that the curves might be on a comparable basis, the air resistances across the filter and arrestance values were plotted against weight of dust fed to the filter in grams. For the 10-gram rate of feed the points only are shown. The irregularity in these points was due to the difficulty of determining the small increase in crucible weight necessarily accompanying the low rate of feed.

From the performance data for Filter A, Table II, it will be noted that the variations in arrestance are not great, and that there is no general trend to show an advantage for either the low or high rate of dust feed. The highest arrestance value was at 40 grams of dust per hour, altho this was substantially the same as that for the 100-gram rate. The

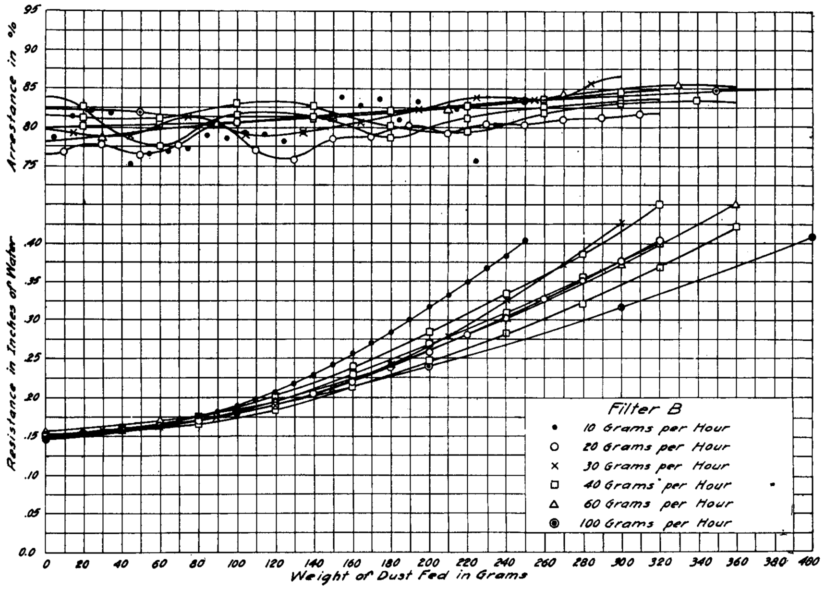

FIGURE 6. ARRESTANCE AND RESISTANCE CURVES AT VARIOUS RATES OF DUST FEED FOR FILTER B

highest dust holding capacities were at 20 and 60 grams per hour, and there was a definite dropping off at 100 grams per hour, indicating that the filter was becoming overloaded at this rate of dust feed. In general it may be stated that the performance characteristics of Filter A were equally satisfactory for any rate of dust feed from 20 to 60 grams per hour, and that the arrestance values were substantially the same up to 100 grams of dust per hour. The dust catching surfaces of the filter were well graded and there was a reasonably uniform distribution of dust throughout the filter up to the 60-gram rate.

From the test results for Filter B there appeared to be an improvement in the performance characteristics as the rate of dust feed was increased. However, there was a variation in the test results for different filters under the same test conditions as noted from the dust holding capacities, for tests Nos. 104, 103, and 101, all of which were run at a rate of 40 grams of dust per hour. With filters having substantially the same initial resistances, the filter performance characteristics were reasonably uniform between dust feed rates of 20 and 60 grams per hour.

The low dust holding capacity at 10 grams per hour as compared with the high dust holding capacity at 100 grams per hour indicates that there was a better distribution of dust throughout the filter at the higher rates of feed than at the lower rates of feed.

The test results for Filter C show slightly higher arrestance values at the 10- and 20-gram rates of dust feed, but show increasingly better dust holding capacities from 10 to 100 grams of dust per hour. As in Filter B it is probable that at the higher rate of dust feed more of the dust was carried into the filter, giving a higher dust holding capacity, but allowing some of the dust to pass on through, and, therefore, giving a slightly lower arrestance.

For Filter D the dust holding capacity increased as the rate of dust feed increased from 10 to 40 grams, remained approximately the same at 60, and decreased slightly at 100 grams of dust per hour. Both the arrestance and dust holding capacity were lower for the 10-gram rate than for the higher rates of dust feed. The arrestance values were substantially the same from 20 to 100 grams of dust per hour, with the highest at the 60-gram rate.

There was not an excessive change in the dust holding capacity for any of the filters due to varying the rate of dust feed from 20 to 60 grams per hour. For Filters B and C there was a marked increase in dust holding capacities for a dust rate of 100 grams per hour. For Filters B, C, and D, the only ones tested at the 10-gram rate, there was a decrease in dust holding capacities for this rate. For Filters B and C the dust holding capacity at the 100-gram rate was approximately 50 per cent greater than the capacity at the 10-gram rate of dust feed. For Filter A the dust holding capacity at 100 grams of dust per hour was considerably lower than that for any rate of dust feed between 20 and 60 grams per hour. The increase in dust holding capacity for Filters B and C at the 100-gram rate indicates that at this rate of feed a lesser amount of dust was retained on the entering surface of the filter, and therefore more of the dust was carried back into the filter to give a more uniform distribution throughout the filter volume. This makes it possible for the filters to retain more dust without building up an excessive air resistance across the filter.

In order to compare filter performance at rates of dust feed varying from 10 to 100 grams per hour, which are practical for laboratory tests, with rates of dust feed which might be expected in practice, an additional series of tests was run at a dust feed rate of 2 grams per hour. Since it was impractical to run the tests to completion at the 2-gram rate of dust feed, they were continued only long enough to give accurate determinations of arrestance values. In order to correct for the dust in the laboratory air, which was a factor at the low rate of dust feed, the apparatus was operated in the laboratory without a filter in place, and the increase in crucible weight was recorded for four 5-hour periods.

The recorded increases were .0014, .0013, .0017, and .0015, giving an average of .0015 gram for the five-hour period. As a check on this procedure a filter, which from previous tests was estimated to have an arrestance value of 80 per cent, was placed in the test apparatus and a test was made without the addition of the dust mixture to the air stream. The rate of gain in crucible weight was found to be 20 per cent of that for the test without the filter, indicating that the calibration tests were correct and that the average weight of dust in the laboratory air used for the filter tests increased the dust feed to the filter by approximately .248 gram per hour. A correction was accordingly made by adding this weight to the 2-gram rate of feed. It should be noted that the rate of 2 grams per hour corresponds to .617 gram per 1,000 cubic feet, which is comparable to the dust concentration in the air of industrial districts. This rate of feed is only 8 times the normal dust concentration in the laboratory air, whereas the feed of 40 grams per hour is 160 times normal. The corrected arrestance values for the 2-gram rate of dust feed are shown in Table III, together with the values for rates of 10 to 100 grams taken from Table II. The test values for the 2-gram rate are substantially the same as those for the higher rates of feed which are more practical for laboratory test purposes.

TABLE III

AVERAGE DUST ARRESTANCES FOR FILTERS A, B, C, AND D FOR DIFFERENT RATES OF DUST FEED

(Face air velocity 300 feet per minute. Dust mixture 50, 20, 20, 10)

Filter	Rate of Dust Feed, Grams per Hour							
	2		10	20	30	40	60	100
	Test Value	Corrected Value	Test Value	Test Value	Test Value	Test Value	Test Value	Test Value
A	77.5	80.1	....	77.2	....	77.5 80.3 81.0	76.9	79.7
B	82.1	84.3	80.0	78.8	81.3	81.9 81.7	82.0	82.8
C	71.6	75.2	72.3	72.0 92.0	....	69.9	71.4	68.2
D	88.4	90.7	89.8	92.5	....	93.5	94.6	92.4

From the results of these tests the following conclusions may be drawn.

1. The arrestance, the dust holding capacity, and the life of the four types of filters tested are substantially the same for the rates of dust feed from 20 to 60 grams per hour and do not show any great variations for rates of 10 and 100 grams per hour.

2. Tests on the four types of filters at a dust feed rate of 2 grams per hour show substantially the same arrestance values as those obtained at rates from 10 to 100 grams per hour.

3. Since it is not practical to make laboratory tests at the very low rates of dust feed to determine dust holding capacity and life of a filter, and since the arrestance values at these low rates are substantially the same as the arrestance values at the higher rates, it is reasonable to set the rate of dust feed for laboratory tests at a point that will expedite the test work. Rates beween 20 and 60 grams per hour appear to be satisfactory. The higher rates simplify the test procedure and shorten the time required to obtain complete data on a filter.

AIR VELOCITY THROUGH FILTER AND FILTER PERFORMANCE

Since the air capacity of a filter is in direct proportion to the velocity of air through the filter, it is desirable to use air velocities which are as high as are consistent with efficient filter performance. There are many instances in the design of air conditioning equipment in which the available space is limited, and, for that reason as well as for the economic problems involved, there is a tendency to reduce the number of filters and increase the air velocity to a maximum. Excessive air velocities through filters result in excessive pressure drops across the filters and, therefore, high power consumption in operation. The cleaning efficiency of a filter is also governed partially by the air velocity, and excessive velocities have a tendency to carry the dust through the filter. While there is a reasonable range in the optimum air velocity for different filters, most of them are designed to operate between 200- and 400-feet-per-minute, face velocity. The actual air velocity through the filter media will be much less than this for the cloth filter which consists of a series of accordian plaits as shown for Filters D and E, Figure 5.

In making this series of tests, Filters A, B, C, and D were used. A dust mixture consisting of 50-20-20-10 percentages by weight of the various components as in the previous test was fed into the air stream at the rate of 20 grams per hour. Each filter was tested at air velocities

TABLE IV

DUST ARRESTANCE AND INITIAL FILTER RESISTANCE AT DIFFERENT AIR VELOCITIES

(Dust mixture 50, 20, 20, 10. Dust feed 20 grams per hour)

Velocity Air in Feet per Minute	Filter A		Filter B		Filter C		Filter D	
	Arrestance, Per Cent	Initial Resistance, Inches Water	Arrestance, Per Cent	Initial Resistance, Inches Water	Arrestance, Per Cent	Initial Resistance, Inches Water	Arrestance, Per Cent	Initial Resistance, Inches Water
200	74.4	.105	77.4	.070	65.7	.068	89.1	.043
300	76.1	.220	77.0	.153	65.0	.145	86.9 87.8	.088
400	77.6	.372	78.7	.231	66.2	.237	92.6	.149

of 200, 300, and 400 feet per minute. Since the tests were for the purpose of determining the arrestance values only, all tests were stopped at the end of the three-hour period, the arrestance and air resistance being determined for each hour of the test. A summary of the test results is shown in Table IV. For all of the filters the arrestance values are slightly greater at the 400-foot air velocity than for the lower velocity. For Filter A the arrestance is lower for the 200- than for the 300-foot velocity, and for Filter D it is higher. These variations are not great, and it is possible that the dust concentration may have had some effect on the filters. Since the rate of dust feed was maintained uniform at 20 grams per hour for all of the tests, the actual dust concentration in the air would be decreased as the air velocity was increased. On the theory that the major portion of the dust is centrifuged out of the air by changes of flow direction in passing through the filter, the higher arrestance values at the higher velocities may be explained on the basis of greater inertia of the dust particles.

From this series of tests it may be concluded that the variations in filter arrestance are not great between the velocities of 200 and 400 feet per minute. It should be noted, however, that filter resistance varies as some power of the air face velocity. Thus, if the life of a filter is to be limited by a final resistance of .4 to .5 inch of water, it can be seen by reference to Table IV that the choice of a 400-feet-per-minute face velocity may reduce the life to a fraction of that for a 200-feet-per-minute velocity.

DUST PARTICLE SIZE AND FILTER PERFORMANCE

The object of this part of the program was to determine the particle size distribution for different kinds of dusts screened to different sizes, and to find the effect of particle size on the performance of different types of filters. The analysis for particle size was made for all dusts used except fuller's earth, but the effect of particle size on filter performance was determined only for Illinois fly ash and Pocahontas ash for two different ranges of screenings.

The results of the dust particle size analysis are shown in Table V. Where one figure is given in the column headed "Screen Mesh," it indicates that all dust particles pass a screen of that mesh. When two figures are given it indicates that all dust particles passed the larger screen and were retained on the finer screen. In making the analysis of particle size from the screened samples, a small portion of the dust was placed on a glass slide and covered by a drop of turpentine. The slide was then tapped until the dust particles had distributed themselves in the turpentine, after which the turpentine was evaporated, leaving the dust particles exposed on the glass surface. Microphotographs were then made of these samples and used for measuring the dust particle sizes. Results given in the table are the averages of from three to five hundred particles for each sample of dust. Since the arrestance of a filter is based on the percentage by weight of dust removed, it would appear that the figures in the column headed "Approximate Diameter of Particle with Average Volume" are better measures of the qualities of dust as a filter test material than are the figures giving the approximate average diameter of particles. The volume increases as the cube of the diameter increases, and the weights of the dust particles are in direct relation to their volumes.

TABLE V

PARTICLE SIZE DISTRIBUTION IN DIFFERENT KINDS OF DUSTS

Type of Dust: Material	Type of Dust: Screen Mesh	Approx. Ave. Diam. of Particle	Approx. Diam. of Particle with Ave. Volume	Distribution: Per Cent Less Than 5 Microns	Distribution: Per Cent Less Than 15 Microns	Distribution: Per Cent Less Than 25 Microns	Per Cent Vol. with Diam. More Than 25 Microns
Carbon black	100	3.7	7.0	84.0	98.8	100.0	0.0
Lampblack	100	4.6	7.2	71.9	96.8	100.0	0.0
Bone black	100	3.7	5.9	80.3	98.9	100.0	0.0
Cottrell ash	200	2.8	6.0	96.7	99.6	100.0	0.0
Illinois fly ash	200 to 325	5.4	20.1	79.6	93.5	96.0	95.3
Illinois fly ash	325	4.4	9.7	80.9	94.9	98.3	57.5
Pocahontas ash	200 to 325	8.9	22.3	60.4	84.4	91.9	89.0
Pocahontas ash	325	3.9	10.3	84.6	96.9	98.9	43.8

Referring to the distribution of particle sizes in the various samples, it is interesting to note that for the carbon black, lampblack, bone black, and Cottrell ash all of the particles are below 25 microns in diameter, even tho the 100-mesh screen used for the first three samples would pass 147 microns diameter particles, and the 200-mesh screen used for the Cottrell ash would pass 74 microns diameter particles. It should be noted, however, that carbon black and lampblack have a tendency to agglomerate, and it is very difficult to pass them through a screen finer than 100 mesh, even tho the individual particles should all pass a 325-mesh screen. All the Cottrell dust could have been screened through a 325-mesh screen as it does not agglomerate. In the case of the Illinois fly ash and Pocahontas ash, two different ranges of particle sizes were screened. The figures giving particle size distribution show that a large number of the fine particles were retained on the 325-mesh screen. As a matter of fact the greater number of particles of Illinois fly ash and Pocahontas ash which were retained on the 325-mesh screen should have passed this screen. The retention was caused probably by many of the small particles adhering to the larger ones and thus being prevented from passing the screen.

An interesting point to consider is the large percentage in total weight of dust sample accounted for by the very small percentage of particles over 25 microns in diameter. This is shown very clearly for the Illinois fly ash screened between 200 and 325 mesh, and to a slightly lesser extent for the Pocahontas ash screened to the same size. This is a very important point to consider when selecting a dust to be used for testing a filter on the weight basis. A small percentage of large-sized particles may have an undue influence on the filter arrestance. While a large percentage of the weight of the coarsely screened coal ash dusts is made up of particles above 25 microns in diameter, all of the particles of these samples were of the type which float readily in the air.

An attempt was made to use the dust from Illinois fly ash and Pocahontas ash screened between 100 and 200 mesh, but many of these particles were so heavy that they settled out of the air very rapidly and were impractical for filter tests. The particle sizes which should pass the different screens are as follows:

Screen Size	Dust Particle Size, Microns
100	147
150	104
200	74
325	43
400	38

From the results shown in Table V it would appear that carbon black, lampblack, and bone black might be screened through a 100-mesh screen; Cottrell ash either 200- or 325-mesh screen; and Illinois fly ash and Pocahontas ash should be screened through a 325-mesh screen. From the table of screen sizes it is evident that nothing would be gained by screening finer than 325 mesh.

Table VI shows the performance characteristics for Filters A, B-1, C, and D when using the fine and coarse screened Pocahontas and Illinois fly ashes. The Illinois fly ash was not used for Filter A. This was due to the time required and to the probability that nothing new would be gained over the results for the other tests.

An analysis of the test data in Table VI indicates that the performance characteristics for Filters A, B-1, and C are slightly better when using the coarse ash, the greatest difference in arrestance being for Filter C. For Filter D, however, the results are reversed. When the Illinois fly ash was used on Filter D, it was found that the coarse ash had a tendency to drop off the face of the filter, making it impossible to complete the test without giving misleading results. That this was not true of the fine-mesh dust was shown by weighing the cotton filtering pad before and after the test. Approximately 95 per cent of the weight of dust taken out of the air by the filter was accounted for in this manner. A part of the 5 per cent loss probably resulted from the falling of the dust from the filter media during removal from the frame.

The Pocahontas ash which passed a 325-mesh screen was graded

TABLE VI

COMPARISON OF FILTER PERFORMANCE ON DIFFERENT DUST PARTICLE SIZES

(Dust feed 40 grams per hour. Air face velocity 300 feet per minute)

Type of Dust	Approx. Diam. of Particle with Ave. Volume	Filter A			Filter B-1			Filter C			Filter D		
		Arres. Per Cent	Life Hrs.	D.H.C. Grs.	Arres. Per Cent	Life Hrs.	D.H.C. Grs.	Arres. Per Cent	Life Hrs.	D.H.C. Grs.	Arres. Per Cent	Life Hrs.	D.H.C. Grs.
Pocahontas ash	10.3	91.4	16.0	585.6	93.2	6.7	249.8	77.7	10.3	325.5	94.5	13.5	511.0
Pocahontas ash	22.3	94.4	16.0	604.1	93.5	7.4	277.4	84.9	12.9	441.8	91.8	12.7	464.0
Illinois fly ash	9.7	....	....	....	96.3	10.8	415.9	81.6	13.9	457.7	94.6	30.4	1152.8
Illinois fly ash	20.1	....	....	....	96.2	15.3	588.9	83.3	15.0	497.0	90.6	....	....

NOTE.—Results based on a resistance rise of .15 inch of water across the filter.

further into five smaller particle size ranges by means of a Federal Laboratory Air Classifying Unit. These dusts were than analyzed at 500 diameters under the microscope and tested on Filters B-2, C, and D. The results of these tests are shown in Figure 7. The arrestance for Filters B-2 and C showed a marked decrease with decreasing particle size, whereas those for Filter D remained reasonably constant throughout the range of dusts tested. This is true probably because Filters B-2 and C utilize the impingement principle of dust elimination to a greater extent than does Filter D. The decreased mass of small particles results in lower inertia and allows them to flow with the air stream regardless of direction changes. Smoke particles are practically impossible to eliminate from the air by ordinary filtration methods because of their extremely small particle size.

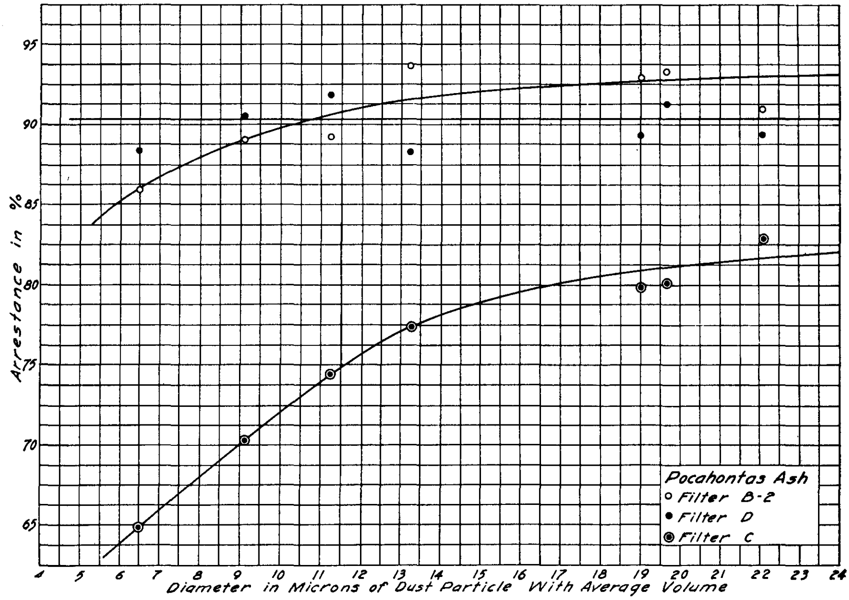

FIGURE 7. EFFECT OF DUST PARTICLE SIZE ON ARRESTANCE FOR FILTERS B-2, C, AND D

The optical system used in measuring the particle sizes for the dusts used in the tests of Figure 7 was not the same as that used for the dusts of Table VI, and therefore the two are not strictly comparable. Higher magnifications increase the resolving power and thereby tend to reduce the "diameter of particle with average volume." Thus, for the tests shown in Figure 7 the smallest diameter particle tested was 6.5 microns, whereas it would have been approximately 3 to 4 microns had the optical system been the same as that used for the dust measurements of Table VI. The dust particles of Figure 7 which were above 19.5 microns in diameter were screened and not air separated.

This investigation shows that within the range of dusts obtainable by screening, the 200-mesh sieve is the most practical for ash dusts and the 100-mesh sieve for carbon dusts. Coarser screens give particles which cannot be classed as "air floated." Screens finer than 325 mesh show very little reduction in particle size, and the 200- and 325-mesh dusts give practically the same results on filter tests. Dusts that are finer than those obtained by screening show marked reductions in filter arrestance. However, such dusts are too difficult to obtain in sufficient quantities for extended filter tests.

THE EFFECT OF DIFFERENT DUSTS ON FILTER PERFORMANCE

The kind of dust used for a filter test may have a decided influence on some of the performance characteristics of the filter. The relative effect of a given type of dust may be different for different types of filters. Thus, for instance, some brands of carbon black will give a very low arrestance for one type of filter and a high arrestance for another type, even tho these filters may show substantially the same arrestance values when tested with Pocahontas ash or some similar type of dust. Likewise a given dust when used in a dust mixture may have a dominating influence on the test results as obtained by that mixture. It is thus important in selecting any dust or mixtures of dusts to know the effect of each type of dust on the various performance characteristics of the different filters to be tested, and also the influence of each type of dust on the dust mixture relative to these performance characteristics. In order to obtain this information several different types of dusts were selected and the performance characteristics of the various filters were determined, first, with these dusts used individually and, second, with various dust mixtures considered practical in previous test series.

The results from this series of tests are shown in the graphs of Figures 8, 9, and 10, and in Tables VII and VIII. Lampblack, carbon black, bone black, Cottrell ash, Pocahontas ash, and Illinois fly ash were all used individually and in various combinations. The Pocahontas ash and Illinois fly ash were screened to different sizes as indicated. (The physical properties of the dusts are shown in Tables I and V.) Filters A, B-1, C, and D were used and in many cases all of these filters were used on each single dust or dust mixture. The filters were all 2 inches in thickness except Filter A which was 4 inches in thickness. All of the tests were run at a face air velocity through the filter of 300 feet per minute and with 40 grams of dust per hour. The length of each test was based on .15 inch of water pressure rise across the filter. It was recognized that a resistance rise of .15 inch of water was less than that specified in the Air Filter Code or than would be expected in practical operation of the filter. The low limit was selected because of the excessive time that would have been required to run all tests to a final resistance of .4 or .5 inch of water, and only relative values were required and not the maximum life or dust holding capacity of any of the filters. The initial resistances of the filters in inches of water at a 300-feet-per-minute face velocity were as follows:

A, .23 inch; B-1, .145 inch; C, .149 inch; D, .101 inch.

The arrestance values of Figure 8 for the various filters, when tested with different types of dusts, show a wider spread when using lampblack and carbon black than when using bone black or any of the other dusts. In general, lampblack and carbon black are finer dusts, tend to agglomerate, and are not of the same granular structure as the other types of dust. All of the filters show satisfactory arrestance values for the different types of coal ashes. No single filter is superior for all of the different types of dusts used.

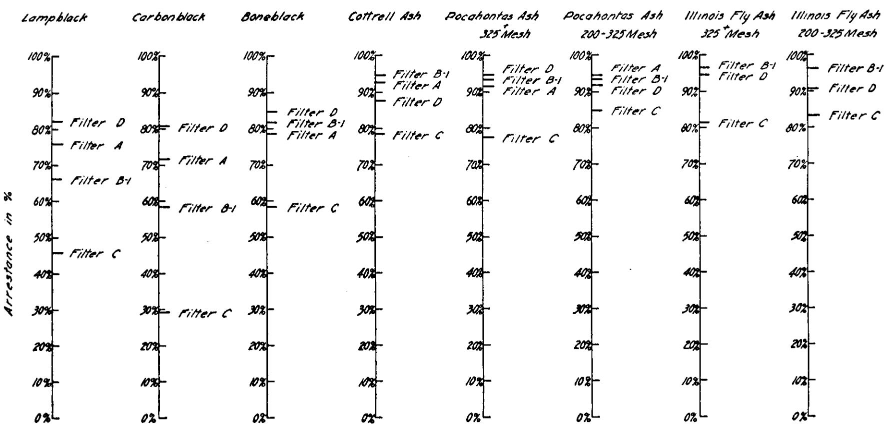

FIGURE 8. COMPARATIVE FILTER ARRESTANCE FOR DIFFERENT DUSTS. DUST FEED, 40 GRAMS PER HOUR

The comparative values for life of the different filters when using each type of dust are shown in Figure 9. In general, it may be said that the length of life is proportional to the density of the dust and that the filters may be expected to show more nearly equal performance in this respect for the different kinds of dust if the length of life is based on the volume rather than the weight of dust taken out of the air by the filters. As in the case of filter arrestances, no single filter showed the longest life for all dusts.

The relative values for dust holding capacity in grams, as shown in Figure 10, follow substantially the same order as those for comparative life, as shown in Figure 9. The reason for any differences in the orders is that arrestance values are not the same for all of the filters when using a particular dust.

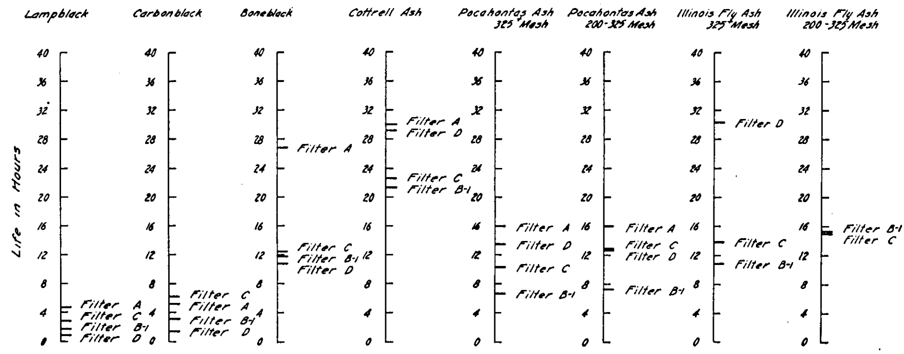

FIGURE 9. COMPARATIVE FILTER LIFE FOR DIFFERENT DUSTS. DUST FEED, 40 GRAMS PER HOUR

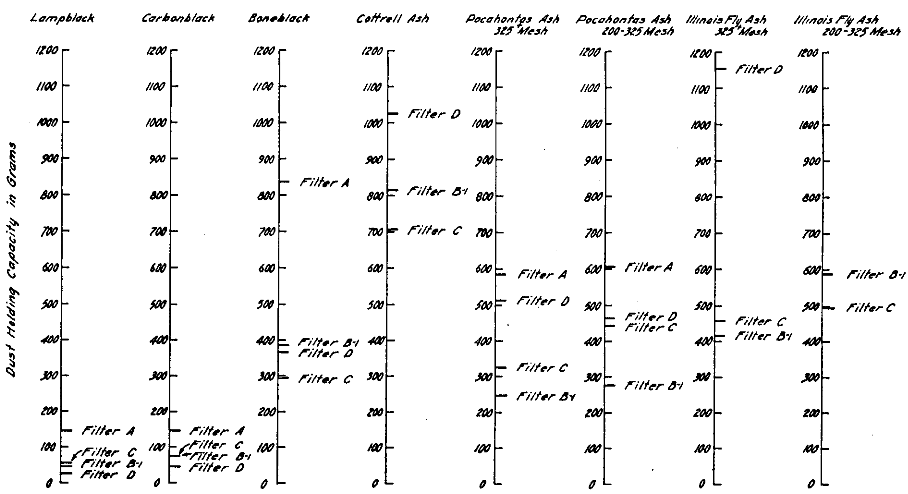

FIGURE 10. COMPARATIVE FILTER DUST HOLDING CAPACITY FOR DIFFERENT DUSTS. DUST FEED, 40 GRAMS PER HOUR

In order to determine the relative effect of each individual type of dust on the different performance characteristics of a filter as compared with its effect on the same filter when used in a mixture with other dusts, a series of tests were made in which each filter was tested by using a dust mixture and then by using each element in the mixture. The arrestance values for the individual dusts were used to calculate a weighted

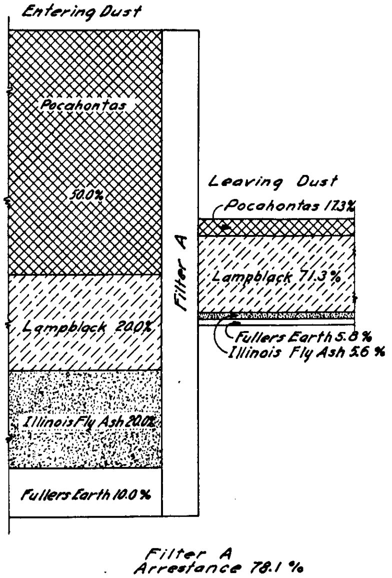

FIGURE 11. RELATIVE WEIGHTS OF MIXED DUST ENTERING AND LEAVING FILTER A

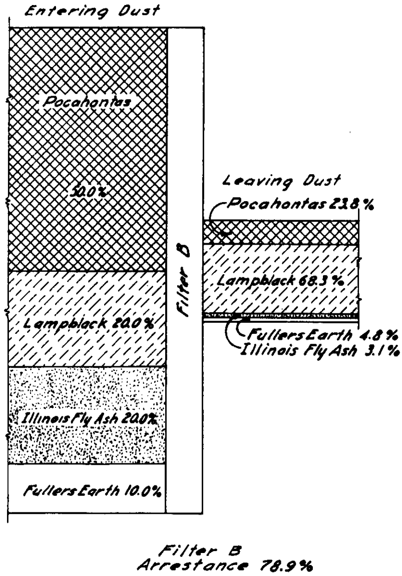

FIGURE 12. RELATIVE WEIGHTS OF MIXED DUST ENTERING AND LEAVING FILTER B

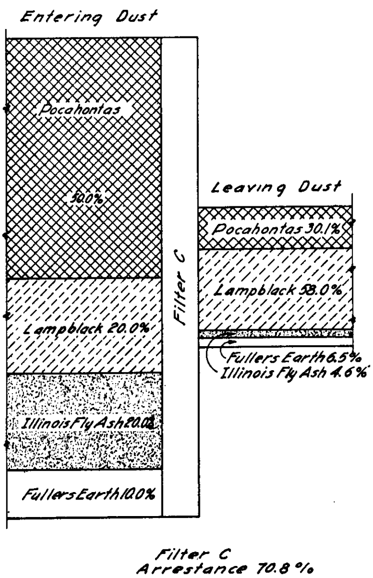

FIGURE 13. RELATIVE WEIGHTS OF MIXED DUST ENTERING AND LEAVING FILTER C

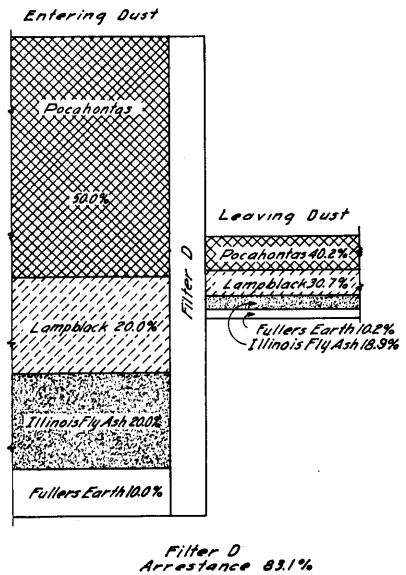

FIGURE 14. RELATIVE WEIGHTS OF MIXED DUST ENTERING AND LEAVING FILTER D

arrestance value for the given mixture and this calculated value was compared with the actual test value of the given mixture. The results of these tests and the calculated weighted values are shown in Table VII. From the figures of this table it will be noted that there is a rather close correlation between the calculated weighted values and the test values, the maximum variation being 5.8 per cent for Filter C when using the 50-20-20-10 mixture, and the minimum variation 1.2 per cent for Filter D on the 50-50 dust mixture.

TABLE VII

COMPARISONS OF ARRESTANCE VALUES AS DETERMINED BY TESTS WITH DUST MIXTURES AND BY WEIGHTED VALUES FROM TESTS ON INDIVIDUAL DUSTS

(Air velocity 300 feet per minute. 20 grams dust per hour)

Type of Filter	50% Pocahontas, 20% Ill., 20% Lampblack, 10% Fuller's Earth		50% Pocahontas, 50% Lampblack		Per Cent Difference	
	Straight Mix Test	Weighted Values	Straight Mix Test	Weighted Values	50-20-20-10	50-50
A	76.1	78.1	54.6	57.0	+2.0	+2.4
B	77.0	78.9	56.2	58.9	+1.9	+2.7
C	65.0	70.8	46.5	48.9	+5.8	+2.4
D	87.7	83.1	81.5	80.3	—4.6	—1.2
	86.9				—3.8	

The graphical representations of a second series of tests on four different filters, A, B, C, and D, made to determine their arrestance values on the individual types of dust are shown in Figures 11, 12, 13, and 14. In these graphs the arrestance values for the individual dusts have been used to calculate the weighted arrestance values for each filter when using the dust mixtures shown. In this series of tests a different lot of lampblack was used than for those shown in Figures 8, 9, and 10, and it is interesting to note that, with the exception of Filter D, the filters were very inefficient in removing this lampblack. A wide variation has been found in the lampblack and carbon black arrestance values even with materials purchased under the same trade name. It was these variations that caused this material to be questioned as an appropriate element to be used in a synthetic dust.

The figures of Table VIII show the comparison between the actual lives of three different types of filters when tested with the dust mixture indicated and the weighted life of each filter as calculated from test values obtained by using each element of the dust mixture. These are the same filters and component dusts as were used for the tests shown in Table VII. In all cases the calculated weighted life of the filter is much higher than the actual life by test, and the correlation between calculated and test life is very low.

TABLE VIII

COMPARISON OF ACTUAL LIFE OF FILTER WITH WEIGHTED LIFE FOR 50-50 MIXTURE

Filter	Actual Life,* Hours	Weighted Life, Hours	Per Cent Actual Life of Weighted Life
B-1	3.4	4.6	73.9
C	3.9	6.8	57.3
D	2.2	8.1	27.2

* Based on final resistance of .30 inch of water across the filter.

The following conclusions may be drawn from this investigation:

1. Lampblack and carbon black are difficult dusts to remove from the air and, if mixed in a test dust in large quantities, they will unduly handicap the performance of most filters, either by reducing the dust arrestance or by increasing the rate of resistance rise and thus shortening the life of the filter.

2. The arrestance of a filter on a given dust mixture may be predicted if the arrestances for this filter on the individual components of the mixture are known. This is not true for the life and dust holding capacity of the filter.

3. The performance of a filter varies greatly with the mixture of dust used. By proper choice of a test dust, one type of filter may be shown to have better performance characteristics than the majority of the other filters, whereas another dust mixture may reverse the relative merits.

DUST DENSITY AND FILTER PERFORMANCE

In making this series of tests a dust feed of 40 grams per hour was used with a filter face velocity of 300 feet per minute. The life in hours and the dust holding capacity in grams were both determined on a basis of .15 inch of water increase in the resistance across the filter. Nine different types of dust were used, as shown in Table IX. This table also gives the physical characteristics of the dusts and a summary of test results, including life in hours, dust holding capacity in grams, and arrestance values for the various filters, using each of these dusts. From the table it will be noted that soot, the lightest dust, has a density of about one tenth that of Cottrell ash, the heaviest dust, and that the lampblack and carbon black used are of approximately the same density, and about one sixth that of Cottrell ash. The finely screened Pocahontas ash was slightly denser than the coarsely screened Pocahontas ash, but the reverse was true for the Illinois fly ash. In all cases the Illinois fly ash had a slightly higher density than the Pocahontas ash, and the Cottrell ash was 50 per cent denser than either the Pocahontas ash or the Illinois fly ash.

In all cases the life and dust holding capacity increased with increased density. This was to be expected since each filter had a definite volumetric dust holding capacity, and for the heavier dusts the volumetric feed was in inverse relation to the density. The graphical relationship between filter life and dust density is shown in Figure 15, and

TABLE IX

RELATION BETWEEN DUST DENSITY AND FILTER PERFORMANCE*

(Dust feed 40 grams per hour. Face air velocity 300 feet per minute)

Type of Dust	Dust Density		Diameter Particle, Microns, with Ave. Vol.	Life, Hours				Dust Holding Capacity, Grams				Arrestance, Per Cent			
	Grams/ C.C.	Lbs./ Cu. Ft.		A	B-1	C	D	A	B-1	C	D	A	B-1	C	D
Soot	.135	8.5	......	......	......	......	......	......	......	......	......	......	58.9	29.7	66.9
Lampblack	.203	12.7	7.2	4.8	1.8	2.8	0.9	146.6	45.2	50.8	29.5	75.9	66.0	45.4	82.0
Carbon black	.210	13.2	7.0	5.1	3.1	6.2	1.5	145.8	71.0	72.4	48.5	71.4	58.2	29.4	80.9
Pocahontas, 200-325 mesh	.686	42.8	22.3	16.0	7.4	12.9	12.7	604.1	277.4	441.8	464.0	94.4	93.5	84.9	91.8
Pocahontas, 325+ mesh	.718	44.8	10.3	16.0	6.7	10.3	13.5	585.6	249.8	325.5	511.0	91.4	93.2	77.7	94.5
Bone black	.741	46.3	5.9	26.9	11.8	12.5	10.8	838.4	386.0	292.4	365.4	78.7	81.8	58.2	84.7
Illinois fly ash, 325+ mesh	.795	49.7	9.7	......	10.8	13.9	30.4	......	415.9	457.7	1152.8	......	96.3	81.6	94.6
Illinois fly ash, 200-325 mesh	.857	53.5	20.1	......	15.3	15.0	......	......	588.9	497.0	......	......	96.2	83.3	90.6
Cottrell ash	1.285	80.4	6.0	43†	21.4	22.6	29.2	1590†	815.1	709.4	1021.6	92.3	94.7	78.4	87.7

* All values based on a resistance rise of .15 inch of water across filter.

† Estimated value.

is similar to that for dust holding capacity and dust density. For Filters A, B-1, and C the arrestance values were considerably lower when using soot, lampblack, and carbon black than when using the other dusts. For Filter D the arrestance for soot was rather low, but those for lampblack and carbon black were only moderately below those for the other types of dusts. In general it may be said that, with the exception of the very light carbon dusts, the arrestance values did not

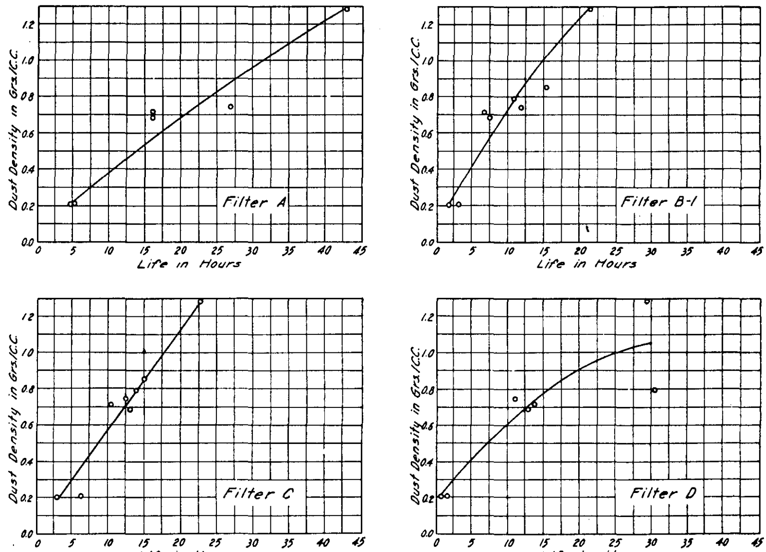

FIGURE 15. EFFECT OF DUST DENSITY ON FILTER LIFE.
DUST FEED, 40 GRAMS PER HOUR

show the same direct relation to the density of the dust as did the life and dust holding capacity values. There are apparently other factors than dust density which affect the arrestance values.

While, with a constant weight of dust feed, both the lives and dust holding capacities of all filters showed a decided increase as the density of the dust was increased, these results would have been different if the dust holding capacity had been based on the volume of dust feed instead of on the weight. The relative dust holding capacities based on volume for the different filters are shown in Table X. While in this table lampblack and carbon black show the lowest dust holding capacities for all of the dusts, this reduction in value is not as pronounced as it was when based on weight, and for Filter A the percentage reduction is very small.

In rating a filter for life and dust holding capacity in the laboratory, it is evident that a dust should be selected which has not only the proper particle size, but also a density corresponding reasonably well with the

TABLE X

DUST HOLDING CAPACITIES* IN CUBIC CENTIMETERS

Type of Dust	Density (Jolted) Grams/C.C.	Rate of Feed† in C.C./Hour	Dust Holding Capacity in C.C.			
			Filter A	Filter B-1	Filter C	Filter D
Lampblack	.203	199	722	222	251	146
Carbon black	.210	190	693	338	345	231
Pocahontas ash, 200-325 mesh	.686	58	881	404	644	677
Pocahontas ash, 325+ mesh	.718	56	816	348	453	711
Bone black	.741	54	1,130	522	395	492
Illinois fly ash, 325+ mesh	.795	50	....	522	575	1,450
Illinois fly ash, 200-325 mesh	.857	47	....	688	580	....
Cottrell ash	1.285	31	....	635	552	795

* Based on a resistance rise of .15 inch water across filter.
† Based on a weight of 40 grams per hour.

density of the dust to be found in the air. Of the coal ashes used, Pocahontas should have the highest rating and Cottrell the lowest rating as to this quality. From the standpoint of practical application it is evident that if a filter is called upon to remove a low density dust from the air, the life and dust holding capacity will be much lower than for a high density nonflocculating dust. Thus, the performance of a filter in smoky areas might not be as satisfactory as would the performance of the same filter in nonsmoky districts.

DUST STANDARDIZATION

During the early part of the filter research program it was discovered that rather wide variations might be encountered in the results for tests performed on identical filters using dust mixtures of the same specifications. Apparently some of these variations were caused by slight differences in the construction of the filters, but the major variations appeared to be caused by some differences in the components of the dust mixtures. In order to eliminate the effects of variations in the dust constituents throughout any series of tests a sufficient amount of each type of dust was obtained at the beginning of the series to last throughout all of the tests involved. Therefore the test values for each series are comparable within themselves, but the results for different series may not be strictly comparable, even tho the same specifications were followed in making up the dust mixtures. In an attempt to discover and control the factors which were causing the variations in test results an extended investigation was made into the properties of the carbon and ash which were used in making up the synthetic test dusts.

CARBON

The A.S.H. and V.E. Air Filter Code states that the standard dust shall include 50 per cent by weight of powdered lampblack containing 97.5 per cent of free carbon minimum and having a bulking value of 3.5 pounds per cubic foot minimum. There are many different types of carbon that will fulfill these requirements, and even tho the specification is limited to lampblack, there is still a wide latitude in the properties of the lampblacks which could be selected to meet the specifications. The variations in these properties may have a marked effect on the performance of the filter.

In order to find out more about the different kinds of carbons and their effects on filter performance, four materials were selected and a study made of the effects of these materials on the performance characteristics of Filters A, B-1, C, and D. The carbons selected were as follows: lampblack, Germantown Eaglebrand, manufactured by L. Martin and Company; carbon black, No. 5 grade, manufactured by Binney and Smith Company, New York; bone black No. 7 "Cosmic Black" manufactured by the Agricultural Chemical Company, Detroit, Michigan; and soot, removed from the flues of an oil burning installation in which there was incomplete combustion. The materials were all screened through a 100-mesh screen and the analysis is shown in Table V. It will be noted that all of the dusts are made up of very fine particles, the largest majority in each case being less than 5 microns in diameter. The densities, however, as shown in Table XI are very different, soot being about two thirds the density of either lampblack or carbon black, and bone black being more than three times the density of either of these materials. The bone black was more granular and did not tend to agglomerate as did the other carbon dusts.

The results for the tests of Filters A, B-1, C, and D when using each of the carbon dusts are given in Table XI and are shown graphically for Filter C in the curve of Figure 16, which is typical of the curves for the other three filters. In the case of soot, tests were made for short periods on Filters B-1, C, and D. Soot showed the lowest density for all of the dusts, but for Filters B-1 and C the arrestance values were substantially the same as those for carbon black and were the lowest of all test values. Filter D showed better arrestance values for all of the dusts than did the other three, altho soot gave a comparatively low value even on this filter. Bone black showed the highest arrestance values and was the heaviest dust. In each case the lives and dust holding capacities when using bone black were decidedly longer than for the other types of dusts. Carbon black gave somewhat longer life and dust holding capacity than lampblack, and it is probable that soot would have given the shortest life and dust holding capacity if the tests on it had been carried to completion. Different relative results probably would have been obtained from these tests if different brands of carbon black

TABLE XI

COMPARISON OF FILTER PERFORMANCE* ON DIFFERENT CARBONS

(Dust feed 40 grams per hour. Face air velocity 300 feet per minute)

Type of Dust	Dust Density (Jolted)		Filter A			Filter B-1			Filter C			Filter D		
	Gr./ C.C.	Lbs./ C. Ft.	Arrestance, Per Cent	Life, Hrs.	D.H.C., Grs.	Arrestance, Per Cent	Life, Hrs.	D.H.C., Grs.	Arrestance, Per Cent	Life, Hrs.	D.H.C., Grs.	Arrestance, Per Cent	Life, Hrs.	D.H.C., Grs.
Lampblack	.203	12.7	75.9	4.8	146.6	66.0	1.8	45.2	45.4	2.8	50.8	82.0	0.9	29.5
Carbon black...	.210	13.2	71.4	5.1	145.8	58.2	3.1	71.0	29.4	6.2	72.4	80.9	1.5	48.5
Bone black	.741	46.3	78.7	26.9	838.4	81.8	11.8	386.0	58.2	12.5	292.4	84.7	10.8	365.4
Soot	.135	8.5	....	....	....	58.9	....	....	29.7	....	....	66.9	....	....

* All values based on a resistance rise of .15 inch of water across filter.

or lampblack had been used. However, from the general characteristics of the dusts it appeared that either lampblack or carbon black would make a satisfactory carbon ingredient for a standard test dust if it could be duplicated.

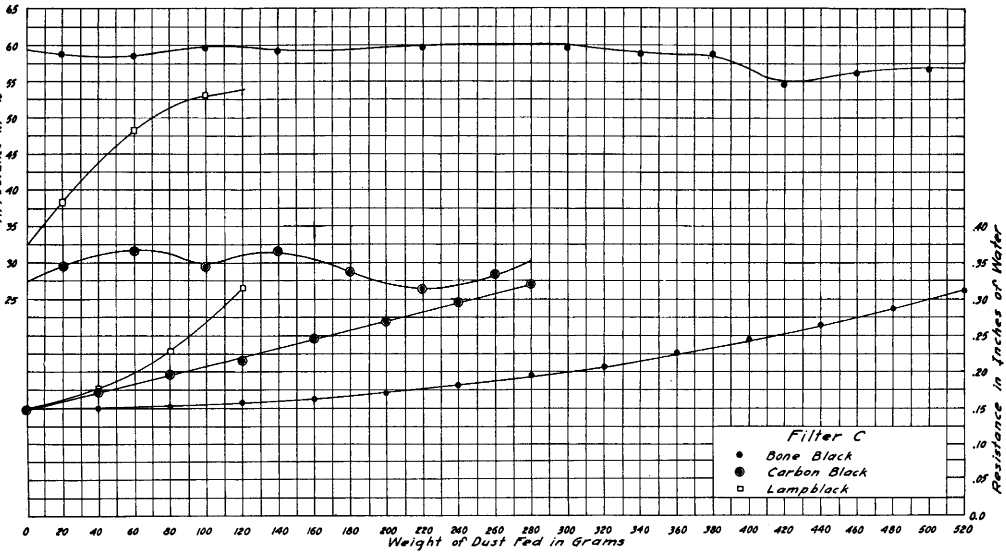

FIGURE 16. EFFECT OF DIFFERENT CARBONS ON PERFORMANCE OF FILTER C. DUST FEED, 40 GRAMS PER HOUR

In order to determine the variations in test results which might be expected from various carbon materials which would come within the Air Filter Code specifications, samples were selected of both lampblack[1] and carbon black. All of the samples of each of these materials were of the same brand, but selected from different lots and from material manufactured at different dates.

The test results from the different samples of lampblack are shown in Table XII. In this series of tests the face air velocity was maintained at 300 feet per minute with a dust feed of 40 grams per hour. The same type of filters, B-1, were used in all tests. As will be noted from the test results, there was a spread in arrestance values from 28.1 to 82.4. The lowest arrestance values were from lot A, and the 28 per cent arrestance was obtained on one of the earlier samples selected. There was a spread in the arrestance values for the samples of lot B from 56.8 to 82.4, and a spread in the values for life of filter from 1.5 to 4.5 hours. The significant point in these tests results is the wide spread obtained in arrestance values and the uncertainty of consistent

[1] The distinction between the two types of materials is that lampblack is formed by the burning of oil, and carbon black by the burning of gas.

results from different samples of this material. It would be impractical to use a material giving such a wide range of test results as a basis for a synthetic test dust.

TABLE XII

COMPARISON OF LAMPBLACK* ON FILTER B-1

(Dust feed 40 grams per hour. Face air velocity 300 feet per minute)

Source	Dust Sample	Dust Density	Ave. Resis.‡ Rise per Hour	Life† in Hours	Ave. Arres. for Two Hours
A	1	.156	.024	Approx. 4.5	28.1
	2	.238	.066	2.3	46.7
B	1	.183	.088	1.8	78.8
	2	.213	.089	1.8	74.0
	3	.203	.084	1.9	78.4
	4	.206	.063	2.3	75.6
	5	Approx. same as 1, 2.	.087	1.9	82.4
	6	Approx. same as 1, 2.	.084	1.9	64.4
	7	Approx. same as 1, 2.	......	......	56.8
	8	Approx. same as 1, 2.	.098	1.8	66.2
C	1	.209	.074	2.1	71.1
D	1	.265	.049	1.5	58.4

* All lampblacks same brand and same manufacturer but from different supply houses.
† Based on final resistance of .30 inch of water across filter.
‡ Based on two-hour average.

In making the tests on carbon black, two different brands of material were selected. These were known as Double Bolted Carbon Dust and Super-spectra Carbon Black, both obtained from Binney and Smith Company, New York City. Seven samples were selected from the first material and three from the second, all taken from different shipments manufactured at different times. In making these tests Filter B-2 was used, the face velocity was maintained at 300 feet per minute and the dust feed at 20 grams per hour. The rate of dust feed was set at 20 grams as against 40 grams for the lampblack because of the lower density of the carbon black. The test results on both brands of carbon black as given in Table XIII, show a much higher degree of uniformity than those for lampblack. In the case of Super-spectra Carbon Black there was a marked drop in arrestance after the second hour of the test, which was probably caused by the inability of the oil to absorb the dust as rapidly as it was fed. Even tho the rate was only 20 grams per hour the extremely low density of this dust resulted in a high volumetric rate of feed. Of the various carbon dusts tested the Double Bolted Carbon Dust appears to have the best properties for a dust to be selected as a standard to fulfill the carbon requirements in the Air Filter Code.

TABLE XIII

COMPARISON OF FILTER B-2 PERFORMANCE CHARACTERISTICS ON TWO TYPES OF CARBON BLACK

(Dust feed 20 grams per hour. Face air velocity 300 feet per minute)

Sample No.	Density in Gr. per C.C. (Jolted)	Resistance Rise in 3 Hrs., In. Water	Average Arrestance, Per Cent
	Double Bolted Carbon Dust		
1	.154	.118	52.5
2	.148	.125	53.5
3	.162	.130	59.6
4	.155	.135	51.0
5	.171	.123	54.7
6	.159	.126	53.1
7	.177	.143	59.2
	Super-spectra Carbon Black		
1	.066	.152	64.5
2	.068	.129	68.0
3	.068	.131	67.7

It should be noted that the requirements of a carbon dust for filter testing are very exacting and may be entirely different from the requirements of the dust when used for commercial purposes.

ASH

There is a wide variation possible in the chemical and physical properties of coal ash, even tho the coal has the same commercial designation. These differences may be inherent in the original coal or may be due to some element in the combustion process by which the ash is formed. In order to investigate the effect of some of these variations on filter performance, samples of coal from five different West Virginia Pocahontas fields and five different Illinois coal fields were selected. All of these coals were burned at uniform rates of combustion, and one of the Pocahontas samples was also burned at different rates of combustion. The resulting ashes were used for tests on two different types of filters.

In making these tests the jolted density of the resulting ash was determined, but no microscopic examination was made to determine the distribution of particle size in a given sample. The source of the sample and densities of the resulting ash when burned at a uniform moderate rate are shown in Table XIV. The densities of the ash for slow burning as compared with fast burning are shown for Sample C in Table XIX. The moderate rate of combustion was estimated as that corresponding to the average hand-fired domestic furnace rather than the average stoker-fired furnace.

The various test dusts as shown in Tables XIV and XIX were used for testing both Filters B-2 and C. In these tests the face air velocity was maintained at 300 feet per minute, and the ash was fed to the filter

TABLE XIV

SOURCE OF SAMPLE AND DENSITY OF TEST ASHES

(Coal burned at uniform rate)

District	Coal Sample	Dust Density in Grams/ C.C. (Jolted)	Source
West Virginia	A	0.737	Sewell Seam, Fayette County
	B	0.761	Dorothy Seam, Crown City
	C	0.790	No. 3 Seam, McDowell County
	D	0.818	No. 3 Seam, McDowell County
	E	1.028	Beckley Seam, Raleigh County
Illinois	F	0.661	Herrin No. 6 Seam, Perry County
	G	0.667	Herrin No. 6 Seam, Franklin County
	H	0.722	Harrisburg No. 5 Seam, Saline County
	I	0.740	Belleville No. 6 Seam, Macoupin County
	J	0.852	Springfield No. 5 Seam, Fulton County

at the rate of 40 grams per hour. Each test was continued until the pressure drop across the filter had risen .15 inch of water. The results of these tests are shown in Tables XV and XIX. The complete graphical test results for Filter B-2 on the Illinois coal ashes at a moderate rate of combustion are shown in Figure 17. These curves are typical for all of the tests.

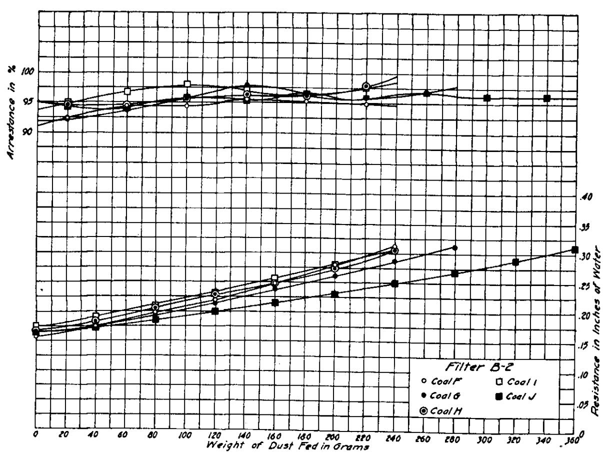

FIGURE 17. EFFECT OF FIVE DIFFERENT ILLINOIS COAL ASHES ON PERFORMANCE OF FILTER B-2

The test results of Table XV indicate that for Filter B-2 the arrestance values are in close agreement for the different densities of each coal with the exception of the Pocahontas coal, E, which has a very high density and shows a somewhat lower arrestance value for this filter. For Filter C the arrestance values are not as consistent on either type

TABLE XV

FILTER PERFOMANCE* FOR WEST VIRGINIA POCAHONTAS AND ILLINOIS COAL ASHES ON FILTERS B-2 AND C

(Dust feed 40 grams per hour. Face air velocity 300 feet per minute)

Source	Coal Sample	Jolted Density Gr./C.C.	Filter B-2			Filter C		
			Arrestance, Per Cent	Life, Hours	Dust Holding Capacity, Grams	Arrestance, Per Cent	Life, Hours	Dust Holding Capacity, Grams
West Virginia	A	0.737	94.8	6.8	258.0	82.4	9.5	313.1
	B	0.761	93.2	6.2	233.3	78.3	8.4	262.5
	C	0.790	94.8	7.8	295.3	83.7	9.0	301.2
	D	0.818	94.2	7.3	275.1	85.5	9.0	307.7
	E	1.028	90.8	11.0	400.1	....	....	....
Illinois	F	0.661	94.4	5.9	222.7	83.4	8.8	293.6
	G	0.667	95.6	7.1	271.0	84.6	8.7	294.9
	H	0.722	96.0	6.3	241.9	....	....	....
	I	0.740	96.6	6.6	255.4	86.7	11.3	394.9
	J	0.852	95.4	9.3	355.4	82.9	10.9	362.0

* Based on resistance rise of .15 inch of water across filter.

of ash, altho the variations are not serious. No doubt there is some difference in the particle size for the different ash samples as well as a difference in density which will affect the arrestance values. There is a rather definite linear relationship between dust density and filter life for both the Pocahontas and Illinois coal ashes for both filters, as indicated in the curves of Figure 18.

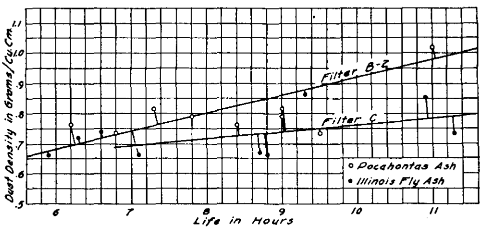

FIGURE 18. EFFECT OF ASH DUST DENSITY ON FILTER LIFE. DUST FEED, 40 GRAMS PER HOUR

Since different filters were used with the different samples of ash, it is likely that there would be some variation in the characteristics of the filters even tho they were of the same make. In order to determine the effect of this variation, tests were made on five different filters of each type using Pocahontas ash from the same lot. The results for these tests as shown in Table XVI indicate a moderate variation between the different filters of the same type.

TABLE XVI

FILTER PERFORMANCE* VARIATION FOR FILTERS B-2 AND C WITH SAME LOT OF POCAHONTAS ASH

(Dust feed 40 grams per hour. Face air velocity 300 feet per minute)

Filter	Test No.	Performance Characteristics: Arrestance, Per Cent	Life, Hours	Dust Holding Capacity, Grams
B-2	1	93.2	7.0	261.2
	2	93.7	6.7	251.3
	3	94.8	7.8	295.3
	4	93.2	6.5	242.1
	5	93.2	7.0	261.2
C	1	82.1	9.7	319.6
	2	83.6	8.9	298.5
	3	83.7	9.0	301.2
	4	83.7	9.1	305.4
	5	81.7	9.2	299.6

* Based on resistance rise of .15 inch of water across filter.

The figures of Table XVII give the variations in performance characteristics for Filters B-2 and C for ash densities between .65 and .85 gram per cubic centimeter. As will be noted, the range in arrestance values is very small. For Filter B-2 the percentage variations from the average for arrestance, life, and dust holding capacity are substantially the same when considering either the Pocahontas ashes or the Illinois ashes as a group, or the single Pocahontas ash. For Filter C the variations are greater for the group than for the single ash.

TABLE XVII

FILTER PERFORMANCE* VARIATION WITH DIFFERENT ASHES

(Ash density 0.65 to 0.85 gram/c.c.)

Filter	Performance Characteristics	Range for Various Pocahontas		Range for Various Illinois Ash		Range for One Pocahontas	
		Range in Performance Units	Range / Ave. in Per Cent	Range in Performance Units	Range / Ave. in Per Cent	Range in Performance Units	Range / Ave. in Per Cent
B-2	Arrestance	1.6 per cent	1.7	2.0 per cent	2.1	1.6 per cent	1.7
	Life	1.6 hours	22.9	1.2 hours	18.5	1.3 hours	18.6
	Dust holding capacity	69.5 grams	26.0	48.3 grams	19.5	53.2 grams	20.5
C	Arrestance	7.2 per cent	8.8	3.3 per cent	3.9	2.0 per cent	2.4
	Life	1.1 hours	12.3	2.6 hours	27.1	0.8 hour	8.7
	Dust holding capacity	50.6 grams	17.1	101.3 grams	30.9	21.1 grams	6.9

* Based on .15 inch resistance rise; face air velocity 300 feet per minute; dust feed 40 grams per hour.

An indication of the effect of ash variation alone on filter performance is given in Table XVIII. The values shown in this table were obtained from those in Table XVII by subtracting the range in performance units for one ash from the range in performance units for various ashes and correcting the percentages accordingly. The results of this table are not strictly valid as the ranges of percentages of Table XVII are not all based on the same number of tests. The negative values may be considered within the range of experimental error.

TABLE XVIII

FILTER PERFORMANCE* VARIATION WITH DIFFERENT ASHES CORRECTED FOR FILTER VARIATION

(Ash density .65 to .85 gram/c.c.)

Filter	Performance Characteristics	Range for Various Pocahontas Ashes: Range in Performance Units	Range for Various Pocahontas Ashes: Range/Ave. in Per Cent	Range for Various Illinois Ashes: Range in Performance Units	Range for Various Illinois Ashes: Range/Ave. in Per Cent
B-2	Arrestance	0.0 per cent	0.0	0.4 per cent	0.4
	Life	0.3 hour	4.3	—0.1 hour	—1.5
	Dust holding capacity	16.3 grams	6.1	—4.9 grams	—1.9
C	Arrestance	5.2 per cent	6.4	1.3 per cent	1.5
	Life	0.3 hour	3.4	1.8 hours	18.8
	Dust holding capacity	29.5 grams	10.0	80.2 grams	24.4

* Based on .15 inch of water resistance rise; face air velocity 300 feet per minute; dust feed 40 grams per hour.

The values in Tables XVII and XVIII give an indication of the magnitude of the error which is likely to be introduced by the use of various ashes. They do not indicate true ranges of percentages as they are not based upon a sufficient number of tests for statistical accuracy. The running of a sufficient number of tests to accomplish this would have involved too much time and expense and probably would have added little to the results. The tabulations in Table XVIII indicate that the greatest variations in performance characteristics are for Filter C. This probably is due to the fact that variations in the average dust particle size have more effect on Filter C than on any of the other filters tested.

The test results for Filters B-2 and C on the ashes from one Pocahontas coal burned at two different combustion rates are shown in Table XIX. The slow rate of combustion was comparable with that of a well-banked domestic fire, while the fast rate of combustion was somewhat in excess of that ordinarily encountered in domestic installations. The ash from the fast burned coal had the highest density and, on both filters, resulted in higher arrestance, longer life, and greater dust holding capacity than the slow burned ash. In the fast burned coal the lighter fractions of the ash probably were carried off with the flue gases, thus giving a denser ash of greater particle size. The greater average particle size would explain the higher arrestance, and the higher density, the increased life and dust holding capacity. These tests indicate that any standards set up for the ash constituent of a dust mixture should include a limiting maximum combustion rate.

TABLE XIX

EFFECT OF ASH BURNING RATE ON PERFORMANCE OF FILTERS B-2 AND C

(Face air velocity 300 feet per minute. Dust feed 40 grams per hour)

Filter	Ash	Density (Jolted) in Gr./C.C.	Arrestance, Per Cent	Life, Hours	Dust Holding Capacity, Grams
B-2	No. 3. McDowell County Pocahontas (Fast burned)	.860	94.3	7.5	282.8
B-2	No. 3. McDowell County Pocahontas (Slow burned)	.765	90.2	5.5	198.2
C	No. 3. McDowell County Pocahontas (Fast burned)	.860	85.2	10.7	365.0
C	No. 3. McDowell County Pocahontas (Slow burned)	.765	78.9	7.9	249.5

* Based on .15 inch water resistance rise; face air velocity 300 feet per minute; dust feed 40 grams per hour.

OTHER DUST MATERIALS

The extended investigation of various types of carbon and coal ash as desirable constituents for a synthetic dust were not made without considering many other types of dust which have been suggested and

TABLE XX

MATERIALS INVESTIGATED FOR ARTIFICIAL TEST DUSTS

Type of Dust	Reasons for Discarding from Consideration
Fuller's earth	Absorptive when used in large percentages
Air floated silica (325 mesh)	High density—physiological hazard
Borax	Tendency to agglomerate and fall to bottom of test duct
Rosin dust	Too sticky
Chalk dust	High density
Alum	High density
Ground English walnut shells (parting dust)	Apparently too absorptive—filter arrestance dropped off rapidly in test
TiO_2	Plugged feeder—tendency to agglomerate and fall to bottom of test duct
Talc and soapstone parting dust	High density
Lycopodium	Average particle size too large
Al_2O_3	High density
Pumice	High density
Wood ash	Too difficult to obtain in quantities

used to some extent for filter test work. Some of the dusts investigated, together with the reasons for not accepting them as satisfactory, are shown in Table XX. While all of the test dusts as listed in Table XX were unsatisfactory for the reasons given, it is possible that further investigations may produce a material which will have all of the requirements and be more satisfactory than any combination of carbon and ash dusts which may now be recommended.

CONCLUSIONS AS TO ELEMENTS OF SYNTHETIC DUST

As previously stated, there are two fundamental requirements of any dust that is to be used for filter test work. First, it must simulate air-borne dust in all of its properties which may affect filter performance. Second, it must be possible and practical to obtain the dust in sufficient quantities for test purposes and with reasonable certainty that all of the properties can be duplicated.

The properties of a test dust which must be comparable to those of air-borne dust may be summed up as follows:

A. It must be similar in density and air flotation characteristics.

B. It must have reasonable likeness in range and distribution of dust particle size.

C. It must not have a tendency to agglomerate and thus change the physical characteristics of the dust.

D. It must not create any physiological or other hazard.

From a study of dust samples taken from the air the average dust in so far as its effect on filter performance is concerned may be divided into two general classes: first, carbon as a light, flocculent dust formed by incomplete combustion: second, a light weight, somewhat granular dust similar to light coal ash which does not readily settle out of the air. These two types of dust are mixed in various proportions in the air and often contain more or less fibrous material or lint. From an analysis of the dust found in the air the two materials which suggest themselves as likely elements of a synthetic dust are either carbon black or lampblack, formed from incomplete combustion, and a fine, light weight ash formed from the combustion of coal or some other material.

From the investigation made of different types of materials, namely carbon and ash, which seem to be suited to the requirements of a synthetic dust, there are at least four general factors which must be controlled: first, the source of the new materials; second, the method of manufacture; third, the range in particle size, and fourth, the density of the final sample.

With specific reference to carbon, greater uniformity of test results was obtained from carbon black manufactured from gas than from lampblack manufactured from oil. It should be noted, however, that the requirements for a filter test dust may have no relation to the requirements of the carbon dust used for other industrial purposes. The particle size of all carbon dust was found to be comparatively fine. However, there was a tendency in some cases for the dust particles to aggregate and stick together. In no case was it practical to screen the carbon dust below the 100-mesh screen because of this tendency. The density of the various samples of Double Bolted Carbon Dust were rather uniform, averaging .16 gram per cubic centimeter, or 10.0 pounds per cubic foot, thus coming well within the Air Filter Code requirements. The test results using different samples of this dust on the same types of filters were uniform, indicating that it would be possible to duplicate the dust samples, a factor which is very important in any element selected for a synthetic dust.

With reference to the results obtained from the study of various ashes, it appears that the raw material might well be limited to Pocahontas coal. Altho the coal might be limited to a specific field, test results are reasonably uniform as long as there is not too wide a spread in density of the resulting ash. The ash should be formed by a slow rate of combustion in order not to overheat and incinerate the ash, or to carry the fine particles away with the products of combustion. For all of the tests made, Pocahontas coal giving densities between .65 and .85 at low rates of combustion gave satisfactory results. Little was gained by screening the sample below 200 mesh and, since this is a costly operation, it is not recommended.

DUST MIXTURES

From an analysis of dust samples taken from the air it appears that there are two main types of dust, and from a study of many types of artificial dusts it appears that these two natural dusts in the air may be simulated with carbon black and Pocahontas ash, each prepared by a definite process. Tests have shown the performance characteristics of the various filters to be quite different when using the two different types of dust. Thus, it appears that it is not necessary to use more than two different types of dust in a test mixture, but that it is important that these dusts be mixed in substantially the same proportions as they will be in the air which must be handled by the filter.

Most of the test dust mixtures used at the present time are proportioned on a weight basis. Since there is a wide variation in the densities of the individual dust, there will be large differences in the ratio of the components when calculated on a volume basis. The figures in Table XXI show the analysis of six different test dusts both on the weight and volumetric basis. The figures in the second column show the wide variation in densities of the different mixtures, and the figures for the percentages by weight and volume of the different dusts in the mixture show the wide variation in the components on the weight and volume basis. The sample, made up of 50 per cent Pocahontas ash and 50 per cent lampblack as specified by the Air Filter Code, shows only 17 per cent of Pocahontas ash by volume and 83 per cent of lampblack. The density of the combined sample is less than one third that of Cottrell ash, which is sometimes used as a test dust.

TABLE XXI

VOLUMETRIC ANAYLSIS OF DUST MIXED ACCORDING TO WEIGHT

Dust Mixture Per Cents by Weight	Vol. in C.C. of 40 Gr. of Mix.	Vol. Per Cent Lampblack	Vol. Per Cent Carbon Dust	Vol. Per Cent Pocahontas Ash	Vol. Per Cent Illinois Ash	Vol. Per Cent Fuller's Earth	Vol. Per Cent Cottrell Ash
50 Pocahontas ash 20 Illinois ash 20 Lampblack 10 Fuller's earth	95.0	54.0		27.5	11.3	7.2	
50 Pocahontas ash 50 Lampblack	154.3	83.0		17.0			
90 Pocahontas ash 10 Carbon dust	72.2		35.0	65.0			
80 Pocahontas ash 20 Carbon dust	92.4		54.8	45.2			
70 Pocahontas ash 30 Carbon dust	112.5		67.5	32.5			
100 Cottrell ash	31.1						100.0

Altho air-borne dust varies greatly in composition, depending upon such factors as locality, weather, time of year, etc., it seems improbable that it would consist ordinarily of more than 50 per cent by volume of carbon. This fact was recognized by manufacturers and users of filters when a mixture of 50 per cent Pocahontas ash, 20 per cent Illinois fly ash, 20 per cent lampblack, and 10 per cent fuller's earth was selected as a basis for railroad air filter tests made at the University of Minnesota in 1937. Usually lampblack or carbon black is a very difficult dust to separate out of the air, and most filters which will successfully separate it show short life and low dust holding capacity. If a test dust mixture is to contain 83 per cent by volume of a dust which has very decisive effects on filter performance and which is found in much lower percentages in average air, it is evident that the rating of the filter will be misleading.

It might be advisable to formulate more than one standard dust mixture for the purpose of rating filters to meet the requirements of the dust load which they must handle. Dust filters to be operated in smoky areas would be tested with a dust mixture incorporating a higher percentage of carbon than filters to be operated in areas relatively free from smoke. For the determination of the general performance of filters it would appear advisable to have a basic standard mixture, the alternate mixtures to be used only in case the manufacturer or purchaser desires ratings for specific purposes. The base mixture should be as representative as possible of average air-borne dust and result in a reasonable range in performance characteristics for the different filters. A dust mixture which shows a high arrestance on the average filter shows little range between the arrestance values for different filters. The opposite is true of a dust resulting in a comparatively low arrestance on average filters. Furthermore, for the same weight of dust feed per hour, a low density dust will result in short filter life and low dust holding capacity, while a higher density dust will show the other extreme. A basic standard dust mixture should show none of these extremes.

TABLE XXII

COMPARISON OF FILTER B-2 PERFORMANCE CHARACTERISTICS* ON THREE POCAHONTAS ASH-CARBON DUST MIXTURES

(Face air velocity 300 feet per minute. Rate of dust feed 40 grams per hour)

Per Cent Mixture	Average Arrestance, Per Cent	Life, Hours	Dust Holding Capacity, Grams
70 Pocahontas ash 30 Carbon dust	84.4	3.5	117.4
80 Pocahontas ash 20 Carbon dust	87.8	4.0	140.7
90 Pocahontas ash 10 Carbon dust	90.9	5.0	182.0

* Based on .30 inch of water final resistance across filter.

As previously explained, the investigations made on the various types of dust indicate that the required elements of a dust mixture will be supplied by the two dusts, Pocahontas ash and carbon black. These two types of dust were thus selected and mixed in different ratios in order to find a suitable mixture as a basic test dust. The dusts were mixed in percentages by weight of 70-30, 80-20, 90-10 of Pocahontas ash and carbon dust, respectively. These dust mixtures were used with Filter B-2 at a face velocity of 300 feet per minute and a rate of dust feed of 40 grams per hour. From the results of these tests shown in Table XXII it was decided that the 80-20 ratio, giving approximately 50 per cent by volume of each type of dust, was the most representative of the three mixtures for a base test dust.

The 80-20 dust mixture was used for testing Filters A, B-2, C, and D, and the resulting characteristics compared with test results for the 50-50, 50-20-20-10, and the 100 per cent Cottrell ash tests. The results of these tests are shown in Table XXIII. A typical set of performance curves for the 50-50, and 50-20-20-10 mixtures are shown in Figure 19 for Filter A, and the performance characteristics of the 80-20 mixture for Filters A, B-2, C, and D are shown in Figure 20. The 50-50 mix-

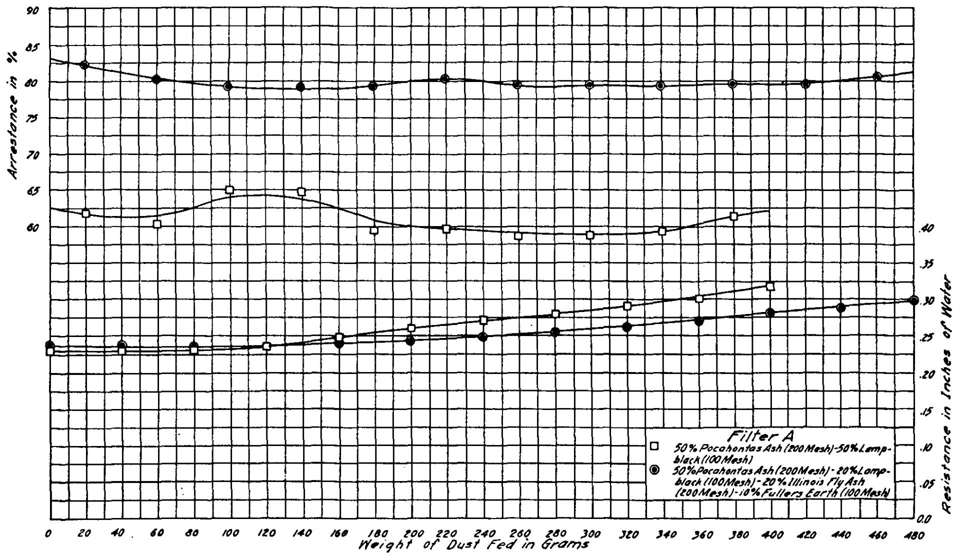

FIGURE 19. PERFORMANCE CURVES FOR FILTER A ON TWO DUST MIXTURES. DUST FEED, 40 GRAMS PER HOUR

ture resulted in the lowest arrestance, shortest life, and lowest dust holding capacity, while the Cottrell ash showed the other extremes. The 50-20-20-10 mixture gave approximately the same results as the 80-20 mixture, probably because each contained 20 per cent by weight of carbon, and because fuller's earth and Pocahontas ash both have about the same effect on filter performance. The test values on these two mixtures lay between those for the 50-50 and the Cottrell test dusts.

A test dust such as Cottrell ash results in performance characteristics which are probably better than those actually obtained in practice, whereas a dust such as the 50-50 mixture probably penalizes the filter unduly. The 80-20 and the 50-20-20-10 mixtures give approximately the same results, but the former is easier to prepare because it has only two components.

The results of this investigation on test dust standardization may be stated briefly as follows:

There are two general classes of dusts in so far as their effects on the rating of air filters on a weight basis are concerned; first, the light flocculent dusts represented by lampblack and carbon black; and second, the more granular dusts represented by the coal ashes. These dusts vary in density and particle size and it is necessary to control these variations within reasonable limits if the effects of the

TABLE XXIII

COMPARISON OF FILTER PERFORMANCE* ON FOUR TEST DUSTS

(Face air velocity 300 feet per minute. Dust feed 40 grams per hour)

Type Filter	50-50 Mixture			50-20-20-10 Mixture			80-20 Mixture			Cottrell		
	Arrestance, Per Cent	Life, Hours	D.H.C., Grams	Arrestance, Per Cent	Life, Hours	D.H.C., Grams	Arrestance, Per Cent	Life, Hours	D.H.C., Grams	Arrestance, Per Cent	Life, Hours	D.H.C., Grams
A	60.9	9.0	219.1	79.9	12.0	383.2	79.1	10.0	316.3	92.3	36.0	1329.0
B-2				84.7	3.0	101.7	87.8	4.0	140.7			
C	59.0	3.9	91.45	73.6	6.0	175.0	70.1	6.8	191.0	78.4	22.8	715.0
D	92.7	2.2	81.6	96.2	4.9	188.7	94.4	6.9	260.5	88.1	34.0	1198.0

* Based on .30 inch of water final resistance across filter.

dusts on filter performance are to be capable of duplication. Numerous tests conducted with various ashes and carbons indicate that carbon black and Pocahontas ash satisfy the requirements of a standard test dust if controlled within reasonable limits as to density and rate of burning. Changes in manufacturing processes may affect the standardization of the carbon black, but for any given set of manufacturing conditions there was less variation in the carbon blacks than the lampblacks tested. The 50 per cent by weight of lampblack as specified in the American Society of Heating and Ventilating Engineers Air Filter Test Code results in 83 per cent by volume of lampblack. This is apparently in excess of the amount of carbon ordinarily found in the air, and 20 per cent by weight of carbon appears to be a more reasonable specification. For these reasons the mixture of 80 per cent by weight of Pocahontas ash screened through a 200-mesh sieve and having a jolted density between .65 and .85 grams per cubic centimeter mixed with 20 per cent by weight of Double Bolted Carbon Dust screened through a 100-mesh screen and having a jolted density between .145 and .180 grams per cubic centimeter is recommended as a standard test dust to be used for the general rating of air filters on a weight basis in the laboratory.

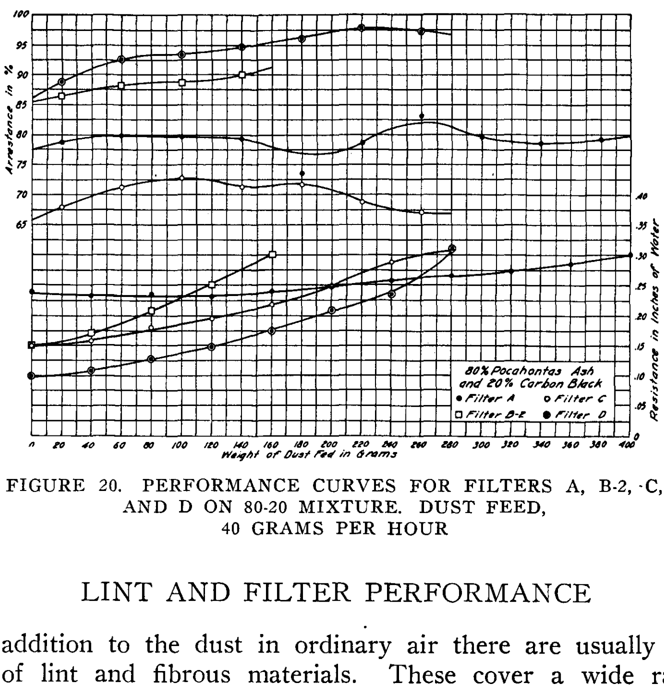

FIGURE 20. PERFORMANCE CURVES FOR FILTERS A, B-2, C, AND D ON 80-20 MIXTURE. DUST FEED, 40 GRAMS PER HOUR

LINT AND FILTER PERFORMANCE

In addition to the dust in ordinary air there are usually various forms of lint and fibrous materials. These cover a wide range of diameters and lengths of fibers, but the very fine, short fibers usually dominate in the lint samples collected from air filters. The relative weight of lint and dust also varies through wide ranges for different samples of air. The selection of an appropriate sample of lint and the proportioning of this sample to the dust in a test mixture is somewhat of an arbitary procedure. The solution for this part of the test problem, therefore, seems to be to select a type of lint which can be duplicated and which will simulate as nearly as possible that found in the average air, and then to select a proportion between the lint and dust which will represent average conditions under which a filter must operate. When tested on a lint-dust mixture of this type, all filters should have a correct relative rating.

In the work done on railroad air filters mentioned previously, the lint problem was recognized. As explained under the heading, Synthetic Test Dust (page 11), a short wool fiber lint was prepared and mixed with the 50-20-20-10 dust mixture in the ratio of one part of wool lint to nine parts of dust mixture by weight. This lint was composed of fibers which were probably somewhat longer and of larger diameter than those of average lint found in the air, but the test results gave relative performance values for the various filters when lint was present.

TABLE XXIV

FILTER PERFORMANCE ON DUST AND DUST-LINT MIXTURES*

(Dust feed 20 grams per hour. Air face velocity 300 feet per minute)

Filter	Type of Test	Initial Resistance Inches Water	Life, Hours	Average Arrestance, Per Cent	Dust Holding Capacity, Grams	Per Cent Lint Test Life of Dust Test Life
A	Dust	.225	33.5	78.6	526.7	
	Lint	.222	8.0	80.1	116.8	23.9
B	Dust	.153	15.8	78.9	249.2	
	Lint	.151	3.9	82.8	58.0	24.7
C (2 two-pass in tandem)	Dust	.295	10.2	77.8	159.9	
C (1 four-pass filter)	Lint	.285	5.6	77.0	77.2	54.8
E	Dust	.188	5.5	90.0	98.7	
	Lint	.226	3.4	91.0	55.3	61.8
F	Dust	.178	22.7	80.4	364.3	
	Lint	.176	7.6	81.0	111.0	33.4

* Dust mixture, 50-20-20-10. Dust-lint mixture, 90 per cent of 50-20-20-10 and 10 per cent of wool lint.

In the lint tests the dust was fed by the standard method at the rate of 18 grams per hour, and the lint was fed into the air stream by a special lint feeding device which consisted of a rotating wire screen cage against which an air jet at approximately 100 pounds gage pressure was directed. The air jet separated the lint fibers and carried them through the screen into the air stream. The total amount of lint fed was distributed as uniformly as possible throughout the period by dividing the lint into two equal parts and feeding one part at 15 minutes and the other at 45 minutes after the start of each test. The actual time required to feed each sample of lint was from two to three minutes. Tests were run on Filters A, B, C, E, and F. The performance characteristics of these filters when lint was present as compared with the same filters without lint are shown in Table XXIV. The curves of Figure 21 show graphically the test results for Filter B with and without lint and are typical of the graphical results for the other filters. The

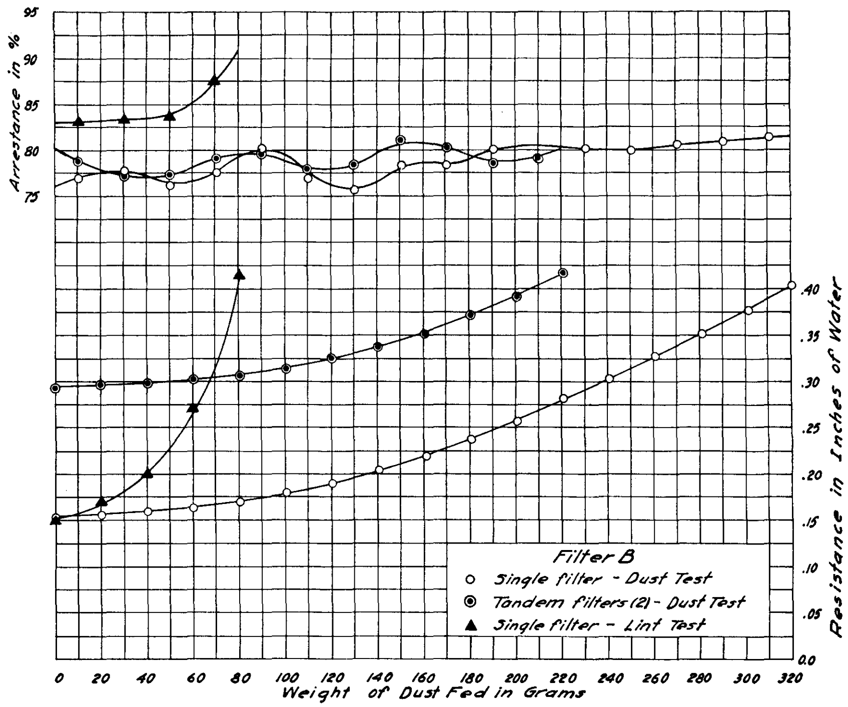

FIGURE 21. PERFORMANCE CURVES FOR FILTER B FOR SINGLE AND TANDEM OPERATION DUST TESTS, AND SINGLE OPERATION LINT TEST

figures for Filter C are not strictly comparable since the dust tests were made on two filters in tandem and the lint test was made on one four-pass filter which was of the same total thickness as the two filters but of slightly different design. In each case the addition of 10 per cent lint to the dust mixture greatly reduced the life and dust holding capacity. This was caused by the collection of lint across the face of the filter which built up a high air resistance and resulted in a rapid increase in pressure drop across the filter. For Filters A, B, and F the addition of lint reduced the life to less than one third of that without the lint. For Filter C the life was reduced to 54.8 per cent, and for Filter E, 61.8 per cent. In Filter C there were very wide openings at the entrance side of the filter which apparently served to catch the lint without causing as rapid a build up of resistance across the filter as for those filters with smaller entrance openings. In the case of Filter E there was no appreciable media depth and the life of the filter was short for both tests.

For Filters A, B, C, and F the arrestance was slightly higher when using the lint than when using the dust alone. In these filters the lint was collected in a layer near the front of the filter and gave additional dust eliminating media in this plane. In the case of Filter F the media were loosely packed and without a viscous coating. With this filter the arrestance values increased rapidly during the first part of each test, but the rate of increase was more rapid when lint was used. Thus while the average arrestance values for the tests do not show any appreciable increase for lint, there was actually an increase when compared with the first part of the test without lint.

These tests indicate that in general the addition of lint to the dust to be removed from the air greatly reduces the life and dust holding capacity of a filter, whereas the arrestance is increased slightly. It is recognized that the lint used in these tests was not entirely representative of that found in ordinary air, and the questions of lint reproduction and the methods of lint elimination are under further study.

THICKNESS OF FILTER MEDIA

The most effective thickness of filter media depends upon many factors. If the material is well graded from very coarse openings at the entrance to very fine openings at the downstream side of the filter, it may be possible to use a thick filter mat and still distribute the dust load throughout the filter. If, on the other hand, the media are closely packed on the entrance side, it may be that the greater part of the dust is removed at the entrance side of the filter, and the remaining portions only serve to build up the air pressure drop across the filter. It has sometimes been the practice to use two filters in tandem or to use thicker filter media in order to get a higher cleaning efficiency from a given type of material. While the tests reported here on single and tandem operation of filters and also on filters of different thicknesses cannot be considered as conclusive for all types of filters, they do show a condition which often prevails when filters are thus installed.

The results in Table XXV were taken from tests on Filters B and C for both single and tandem operation. In each test the life and the dust holding capacity were based on final resistance of .4 inch of water across the filter. In both cases the lives and dust holding capacities were reduced in tandem as compared with single operation because of the higher initial resistances for tandem operation. The average arrestances were substantially the same for Filter B, but for Filter C tandem operation showed 5.3 percentage units higher than for single operation. The test results of Table XXVI are values obtained for 1- and 2-inch media thicknesses of Filter B-2. In these tests the life was somewhat reduced and the arrestance value was slightly higher for the 2-inch than for the 1-inch filter.

The resistance curves for tandem operation paralleled those for single operation but started at higher initial resistances. The same condition existed for the 2-inch as compared with the 1-inch thickness of Filter B-2.

TABLE XXV

TEST RESULTS FOR FILTERS B AND C, SINGLE AND IN TANDEM

(Face air velocity 300 feet per minute. Dust mixture 50-20-20-10. Rate of dust feed 20 grams per hour)

Filter	Method of Installation	Initial Resistance, In. Water	Life,* Hours	Average Arrestance, Per Cent	Dust Holding Capacity,* Grams
B	Single	.15	15.7	78.9	249.2
B	Tandem	.29	10.3	79.0	161.3
C	Single	.15	15.9	72.5	225.7
C	Tandem	.30	10.3	77.8	159.9

* Based on final resistance of .40 inch of water.

TABLE XXVI

TEST RESULTS FOR FILTER B-2 FOR TWO THICKNESSES OF MEDIA

(Face air velocity 300 feet per minute. Dust mixture 50-20-20-10. Rate of dust feed 40 grams per hour)

Media Thickness	Initial Resistance, In. Water	Life,* Hours	Average Arrestance, Per Cent	Dust Holding Capacity,* Grams
1 inch	.11	5.7	83.2	187.5
2 inches	.17	4.5	86.6	155.4

* Based on final resistance of .40 inch of water.

In general, it may be concluded that tandem operation of identical filters results in only a small gain in arrestance which is more than offset by a shorter useful life and greater average power requirements.