# NATIONAL BUREAU OF STANDARDS REPORT

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# PROGRESS REPORT FOR CALENDAR YEAR, 1956
on
AIR FILTER SYSTEMS FOR ARMY AIRCRAFT

by

C. W. Coblentz
W. F. Goddard

Report to
Engineering and Development Branch
Office of the Chief of Transportation
Department of the Army
Washington, D. C.

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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# AIR FILTER SYSTEMS FOR ARMY AIRCRAFT

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C. W. Coblentz
W. F. Goddard
Air Conditioning, Heating, and
Refrigeration Section
Building Technology Division

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## Abstract

A new method for conducting gravimetric performance tests on air cleaners is described and examples of the precision and consistency of the method are reported. The development and laboratory tests of a deflecting-vane type prefilter for the L-19 aircraft are described and its performance evaluated. Development of a modified oil-bath air cleaner was undertaken during the year and comparisons between a proprietary model and an experimental modification are made. Various cloths and a few foam rubber materials were investigated as dry filter media. A summary of the performance of all proprietary and experimental air cleaners investigated since the inception of this project is reported. The results of measurements of dust concentration around a hovering helicopter are reported and the size analysis of dust samples collected during these tests at Fort Eustis is tabulated. Recommendations are made as to the types of filters most suited to the conditions encountered on improved airfields, whereas different types are recommended for use in dusty areas.

## I. DEVELOPMENT AND EVALUATION OF A NEW AIR CLEANER TEST METHOD

The commonly used method for determining the efficiency of induction air cleaners for internal combustion engines is described in U. S. Army Specification #90.21. This method uses, as an absolute filter, two layers of heavy cotton flannel downstream from the air cleaner under test to arrest all the dust that has passed the air cleaner. The weight increase of the absolute filters is determined by weighing them before and after the test with a drying period of six hours at about 230 F preceding each weighing. The size of the filter used is related to the air flow rate at which the air cleaner is being tested, and for air flow rates in the range from 250 cfm to 500 cfm, a 30-inch diameter is required.

An alternate to this method was sought because the necessity for drying the flannel filter material extended a single test to more than one working day and because the absolute filters required for specimens with air flow rates in excess of 500 cfm were large and cumbersome.

An investigation of materials that could be used as absolute filters led to a glass fiber paper, produced at the National Bureau of Standards, which is practically non-hygroscopic and which has fibers as small as 0.3 micron in diameter. This material had been tested by the Atomic Energy Commission and found to retain more than 99.99 percent of all solid particles of 0.3 micron size and larger. This glass fiber paper has an air flow resistance of about 14 in. W.G. at 41 feet per minute face velocity, and it breaks easily when bent. Since it was not adaptable for use as a full flow filter for flow rates applicable to aircraft or automotive engines, a method was developed in which this paper was utilized as an absolute filter for small samples of air drawn simultaneously from upstream and downstream of the air cleaner under test.

Isokinetic sampling is regarded as desirable for the air flow rates and dust particle sizes encountered in this field of application. Isokinetic sampling consists of drawing samples

from a stream of air such that the velocities inside and outside the sampling nozzle are equal at or near the tip. The intent is to avoid error due to inertia, particularly critical for the larger particles. For this work, sampling rates in the range from 0.5 to 1.5 cubic feet per minute were used. Sampling nozzles of four different sizes were provided and the center of the test duct was used as the sampling station.

It was found that a three-inch disc of the glass fiber paper could withstand the pressure of an air flow rate of two cfm without rupture with a moderate dust accumulation on its surface. These three-inch discs are clamped into aluminum frames and are weighed on a laboratory balance before and after each test with an accuracy of ±0.1 mg. After passing through the glass fiber papers, the air samples from upstream and downstream of the air cleaner are measured with two identical orifice flow meters. The manometers for these flow meters are mounted on opposite sides of a graduated scale to facilitate the adjustment for equal air flow rates. By maintaining a fixed and equal vacuum on the downstream side of both orifices, the flow meters could be calibrated in terms of standard air flow rates with a gas meter, independent of the flow resistances of the samplers and the air pressures at the nozzles inlets.

The filtering efficiency is determined with the formula:

$$E = \frac{U - D}{U} \times 100$$

where $E$ = efficiency of air cleaner, percent
$U$ = weight increase of upstream sampler
$D$ = weight increase of downstream sampler

Using this method, good reproducibility in test results was obtained with a variety of air cleaners. It will be noted that an error of ±10 percent in the determination of either the upstream or downstream sampler gain will produce an error in the efficiency of only ±0.5 percent for a filter with an efficiency of 95 percent.

The validity of the observed weight increases of the samplers can easily be ascertained by operating the complete apparatus without any air cleaner mounted in the test position. The dust collected by both samplers, then, should be the same and equal to the weight of the dust introduced into the duct multiplied by the ratio of the sampling air flow rate to the total air flow rate.

## The Dust Injection Apparatus

In order to obtain efficiency values of adequate accuracy, a dust injection apparatus was designed and constructed that provided the following features:

1. Infinite adjustment of the dust feed rate, to furnish the desired dust concentration at any air flow rate;

2. Constant dust feed rate for the duration of each test;

3. Uniform injection of the dust during the entire test period without separating the fine and coarse particles;

4. Dispersion of dust agglomerations.

Variable dust feed rate was attained by mounting a turntable on a variable speed transmission, whose speed ratio could be infinitely varied to provide turntable speeds from zero to nine rpm. The turntable was provided with a concentric groove into which the dust was supplied from a small hopper, filling the groove to a constant, predetermined level. A high pressure aspirator removed the dust from the groove and injected it as a high velocity air stream into the test duct. This air stream impinged against a baffle in the center of the test duct to break up any dust agglomerations that may have passed the aspirator and to promote thorough mixing of the dust and air.

## Performance on Four Different Types of Air Cleaners

### a. Observations with a Paper Air Cleaner

Filtering efficiencies determined with this new test method on four specimens of a paper filter, using successively classified air cleaner test dust "fine" and a mixture of 50 percent each "fine" and "coarse," are shown in Table 1.

TABLE 1

Filtering Efficiency of Paper Air Cleaners

| Filter No. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Fine dust | 98.4 | -- | 98.4 | -- |
| Mixed dust | 97.8 | 97.6 | -- | 99.1 |

The tests with "fine" dust were made with specimens #1 and #3 new and showed perfect agreement. The test results in specimens 1, 2, and 4 with "mixed" dust are not in as good agreement with each other. Examination of the filters after the tests revealed that the rim of specimen 2 was damaged and the seal of specimen 1 was probably damaged by rapping the element to remove the "fine" dust accumulated during the first test with this specimen. Specimen 4 showed a slightly higher efficiency with "mixed" dust than either specimens 1 or 3 with "fine" dust. Presumably the damage to filters 1 and 2 accounted for the lower efficiency with mixed than with fine dust in specimens 1 and 3. Usually, higher efficiencies are observed with mixed dust than with fine dust on this type filter

b. Observations with a Block-Type Aircraft Air Cleaner

Consistent test results were obtained with a block-type aircraft air cleaner using both "fine" and "coarse" dust and also a mixture of 50 percent of each. Two runs were made with the same type of dust and then the filter was cleaned and oiled for the next run with the next coarser grade of dust. Table 2 shows how the efficiency of the filter increased with the use of coarser dust and it also shows the increase of efficiency of each second run caused by the accumulated dust loads.

TABLE 2

Efficiency of a Block-Type Aircraft Air Cleaner
percent

| Test Dust | 1. Run | 2. Run |
|---|---|---|
| Fine | 96.7 | 97.4 |
| Mixed | 97.8 | 98.1 |
| Coarse | 98.6 | 98.7 |

### c. Observations with a Cyclone-Type Air Cleaner

As part of the performance test of a cyclone, self-cleaning air cleaner, the effect of a variation of the bleed-off rate on the cleaning efficiency was determined. The following Table 3 shows the values obtained.

TABLE 3

Effect of Bleed-Off Rate on the Efficiency of a Self-Cleaning Cyclone Cleaner

| Bleed-Off Rate, % | Efficiency, % |
|---|---|
| 5 | 88.9 |
| 7.5 | 90.8 |
| 10 | 91.0 |
| 15 | 91.5 |
| 20 | 93.0 |

It will be noted that a change of bleed-off rate between 7.5 percent and 15 percent produced a change in the efficiency of only 0.7 percent. However, deviations beyond this range of bleed-off rates in both directions caused appreciable changes in the cleaning efficiency. The bleed-off rate recommended by the manufacturer was 10 percent.

### d. Observations with an Oil-Bath Air Cleaner

The results of 40 consecutive test runs with an oil bath air cleaner are shown graphically in Fig. 1. During each test run 50 grams of dust were introduced into the air stream and the air flow rate and dust concentration were maintained constant. The dust was alternated between fine, half and half, and coarse during successive tests. The curves of least mean distances show some increase in filtering efficiency with increasing dust load. The average deviation of the points of observation from the lines of least mean distances corresponds to 0.25 percent efficiency and there is one point out of the forty which deviates more than 1.0 percent.

## Comparison of the Absolute Filter Cloth and the Sampling Methods

The performances of the absolute filter described in U. S. Army Specification #90.21 and the glass fiber paper developed at the National Bureau of Standards were compared by conducting tests with both in the test duct, simultaneously.

The absolute filter consisted of two layers of ten-ounce Canton flannel installed in a circular frame and backed up by a 16-mesh wire screen. The free inside diameter of the filter was 16 inches, and the air flow rate used was 200 cfm, well within the 50 to 250 cfm limit called for in the U. S. Army specification for this size absolute filter. An insulated box, electrically heated to 230 F ±1/4 F, was used to dry the filter material. The filter cloths were suspended on wires passing freely through the top of the box to a balance and thus could be weighed after drying without opening the box. The weight of the cloths was determined to the nearest 0.01 g.

The results of two series of three tests each made with this arrangement are shown in Table 4. A different specimen air cleaner of the same type was used for each series of three tests, and 20 g of the same classified test dust was introduced into the test apparatus during each test run. It will be noted that new absolute filters were used for the first three tests whereas the cloths used for the second three runs had been used previously and cleaned by simply shaking out the dust. The pressure drops of the absolute filters with new cloths averaged 15.7 cm W.G. initially and 29.1 finally; for those with used cloths the corresponding pressure drops were 18.6 and 34.8 cm W.G. The final dust load on the absolute filters was about 1.2 g/sq ft, at which load the absolute filter pressure drop taxed the suction pressure capacity of the exhaust blower at 200 cfm. The total weight of the two layers of ten-ounce cloth was about 105 g and it was determined that a new cloth lost approximately 0.10 g when dried a second time without being exposed to any more dust. This is about 6 percent of its practical dust holding capacity.

## TABLE 4

### Comparative Performance of Two Absolute Filters

| Test | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Air Cleaner Ident. | | 1 | 1 | 1 | 2 | 2 | 2 |
| Cond. of Abs. Filter Element | | new | | | used second time | | |
| Dust Concentration | mg/cu ft | 13.3 | 12.3 | 14.6 | 14.9 | 15.9 | 16.2 |
| Pressure Drop, Air Cleaner, Start | cm W.G. | 1.8 | 2.6 | 3.5 | 1.6 | 2.2 | 3.4 |
| Pressure Drop, Air Cleaner, End | cm W.G. | 2.7 | 3.5 | 6.5 | 2.4 | 3.6 | 7.6 |
| Pressure Drop, Abs. Filter, Start | cm W.G. | 15.3 | 16.2 | 15.5 | 18.4 | 18.8 | 18.6 |
| Pressure Drop, Abs. Filter, End | cm. W.G. | 29.7 | 29.8 | 27.8 | 34.4 | 36.4 | 33.7 |
| Sampler Gain, Upstream | mg | 78.4 | 78.4 | 80.3 | 76.4 | 72.6 | 72.0 |
| Sampler Gain, Downstream | mg | 6.1 | 8.1 | 9.1 | 7.9 | 8.1 | 6.9 |
| Abs. Filter Gain | g | 1.41 | 1.44 | 1.75 | 1.91 | 1.99 | 1.87 |
| Efficiency $E_{sampler}$ | % | 92.2 | 89.7 | 88.7 | 89.7 | 88.8 | 90.4 |
| Efficiency $E_{abs.filter}$ | % | 93.0 | 92.8 | 91.3 | 90.5 | 90.0 | 90.7 |
| $E_a - E_s$ | % | 0.8 | 3.1 | 2.6 | 0.8 | 1.2 | 0.3 |

The dust retaining efficiency of the flannel filter cloth itself was determined by installing glass fiber samplers on its upstream and downstream sides and introducing the dust into an air cleaner of the same type used for the other tests. Seven test runs were made in which the filter paper on the upstream of the absolute filter and downstream of the air cleaner was changed each time, whereas that in the sampler downstream of the absolute filter was used during all seven runs. The downstream sampler showed a total weight gain of 2.6 mg, and the total weight gain of the seven upstream samplers was 43.9 mg, which indicated an efficiency of the filter cloth of

$$(1 - \frac{2.6}{43.9}) \times 100 = 94.0\%$$

This appears reasonable considering that the dust particles which passed the air cleaner were of a very much smaller mean size than those introduced into it.

The average efficiency determined with the absolute filter method for the six tests in Table 4 is 91.4 percent. The total dust introduced was 120 g, and the total weight gain of the absolute filters was 10.37 g for these six runs. Assuming that 94.0 percent was the true efficiency of the filter cloth, the actual amount of dust which would have been retained if the cloth had been an absolute filter is then

$$\frac{10.37}{0.940} = 11.03 \text{ g}$$

This would reduce the efficiency determined with the absolute filter method from 91.4 percent to 90.8 percent. Upon applying a correction for the small amount of dust drawn by the samplers from the test duct upstream of the absolute filter (0.4 percent of that fed), the average absolute filter method efficiency is reduced to 90.4 percent. This value is still 0.5 percent higher than the average efficiency of 89.9 percent determined by sampling method and the glass fiber paper for the same tests.

There was some inconsistency in the efficiency values obtained by both methods as shown in Table 4. The efficiency values observed by the sampling method ranged from 0.3 to 3.1 percent lower than those observed with the absolute filter cloth indicating that the glass fiber paper arrested more of the fine dust particles passing through the test filter than did the flannel cloth filter. Less time was required to make an efficiency determination by the sampling method, and the test results observed with four types of air cleaners were quite consistent, as shown earlier in this report.

## II. DEVELOPMENT AND TEST RESULTS OF A PREFILTER FOR THE L-19 AIRCRAFT

Prefilters used for engine air cleaners are usually of either the cyclone or the deflection type. The first type separates the heavier dust particles from the air stream by drawing the dust-laden air through a "turbulator" which imparts a spinning motion to the air. The deflector-type abruptly changes the direction of the air flow by means of a series of baffles. Both utilize the inertial forces to separate the larger dust particles from the air stream. It is believed that these prefilters break up a portion of the large particles by impact on the walls with a resulting increase of small particles that may reduce the efficiency of the air cleaner.

Earlier investigations at other laboratories indicated that although the service interval of some air cleaners can be lengthened by using a prefilter, the filtering efficiency is decreased. For example, unpublished reports of laboratory tests made at the Cadillac Motor Car Division of the General Motors Corporation showed that an oil bath air cleaner, with an efficiency of 99.5 percent when used alone, was able to arrest only 98.8 percent of the dust in conjunction with a precleaner. The efficiency of the precleaner alone was 67 percent and, consequently, the service period of the oil bath air cleaner could presumably be lengthened three times. Since lengthening of the service period appeared very desirable for military aircraft induction air cleaners, it was decided that prefilters would be investigated even though their use might decrease the filtering efficiency of the combination.

Conversations with service supervisors and representatives of the engine manufacturers have confirmed the opinion expressed in the report on the performance test of the Air-Maze aircraft filter (NBS Report 4569) that the light weight of that filter combined with its small size, reasonable pressure loss and good filtering efficiency make this type extremely attractive for use in small aircraft; since there is practically no correlation between the operating time of the aircraft and the service interval of the filter, the establishment of an effective service regulation appeared extremely difficult. Under favorable conditions, the filter may not be loaded with dust in 100 hours flight time, whereas it may be loaded to capacity in only 20 minutes when operating in a very heavy dust concentration.

Preliminary tests showed that the pressure drop of the Air-Maze filter increased in proportion to the weight of the accumulated dust load regardless of the particle size, whereas paper filter elements showed that the larger dust particles affected the pressure drop much less than small particles. For example, a Fram paper filter could be loaded with seven times as much coarse dust gathered at Fort Eustis, than with A.C. Spark Plug test dust "fine" for the same pressure drop. The Air-Maze filter also showed little difference in efficiency when operated with coarse and fine dusts.

An experimental prefilter was designed for use on the L-19 aircraft in which the ram effect of the air stream produced by the propeller or the movement of the aircraft would deflect the major portion of the dust from the air cleaners. The pitch of the deflecting vanes of this experimental model could be changed to determine the angle at which prefilter pressure drop and efficiency were optimal. The ram air pressure obtainable with the laboratory blowers was less than 0.5 in. W.G., equivalent to the velocity pressure of a 32 miles per hour wind, whereas the velocity of air just behind the propeller would be on the order of 200 miles per hour producing a ram pressure of about 19 in. W.G. Although the effectiveness of the prefilter increases with the ram air pressure, it was found that even with this low ram pressure, the amount of dust that could be introduced was quadrupled with the addition of the prefilter

to the Air-Maze air cleaner for the same pressure drop. The effect of the prefilter is shown in Figure 2 where the left curve presents the pressure drop without a prefilter and the right one with a prefilter. It will be noted that the pressure drop of the new air cleaner was 0.7 in. W.G. less without a prefilter than with a prefilter but that with a dust load of 20 g the pressure drops became equal. At higher dust loads, the pressure drop of the air cleaner increased at a much higher rate when the precleaner was not used.

A series of tests was made with an Air-Maze filter in which it was loaded alternately with and without a prefilter with increments of 20 g of dust. Table 5 shows the results of this series. It indicates that the increase in pressure drop during each run made with the prefilter installed was lower than that of the preceding run without a prefilter, although the overall pressure loss increased with the accumulated dust load.

TABLE 5

Comparison of the Incremental Loading Rate and Pressure Drop of an Air-Maze Filter with and without a Prefilter

| Test No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Prefilter Used | no | yes | no | yes | no | yes | no |
| Cumulative Dust Load, g | 20 | 40 | 60 | 80 | 100 | 120 | 140 |
| Pressure Drop, Start, in.W.G. | 2.09 | 3.15 | 2.83 | 4.80 | 5.31 | 7.44 | 9.50 |
| Increase of Pressure Drop, in. W.G. | 1.11 | 0.67 | 1.46 | 1.14 | 2.60 | 2.32 | 6.06 |
| Weight Increase of Filter, g | 18.3 | 9.0 | 17.7 | 8.5 | 17.3 | 7.2 | 18.0 |
| Filtering Efficiency, % | 96.0 | 96.6 | 97.2 | 97.7 | 98.0 | 98.7 | 99.2 |

The filtering efficiency increased steadily with dust load regardless of whether or not a prefilter was used

As stated above, it can be assumed that the effectiveness of the precleaner increases with the ram air velocity and, also, if coarser dust is involved, as will be the case when ground sand is thrown up into the air induction system by the propeller. Under laboratory conditions it was found that the air cleaner and precleaner combined could accommodate 168 grams of dust for a pressure drop of 10 in. W.G., whereas the air filter alone could accommodate only 50 grams of dust for the same pressure drop. This shows a ratio of about 3.4 to 1 in dust handling capacity in favor of the precleaner.

After consultation with representatives of the Office of the Chief of Transportation, five prototype prefilters were built of light weight metal for flight test on the L-19. Figures 3 and 4 show photographs of these prefilters which weigh 17 oz each and can be attached to the clevis pins which hold the Air-Maze air cleaner without any modification or special tools.

These prefilters were supplied to the sponsor in June, 1956, for flight tests.

## III. PERFORMANCE OF SOME EXPERIMENTAL OIL BATH AIR CLEANERS

The Donaldson oil bath air cleaner had been tested previously and the findings were reported to the Office of the Chief of Transportation in NBS Report 4620. The specimen was later disassembled and it was found that oily dust deposits had clogged considerable portions of several screens. This observation led to the assumption that the scrubbing effect of the oil had not adequately reached those parts on which dust had accumulated. The beneficial effect of the screens and the inverted cone over the oil sump was considered doubtful, so it was decided to remove all these parts and to operate the air cleaner without them.

The air cleaner was then tested at an air flow rate of 315 cfm, the same as that used for the former tests. Fig. 1 shows the efficiencies obtained when the modified filter was loaded with dust using different particle sizes for alternate tests. These three curves are also shown as the dotted lines in the lower family of curves in Fig. 5, with the individual points of observation omitted. The three solid lines in the lower part of Fig. 5 were taken from NBS Report 4620, Fig. 1, to show how the filtering efficiency was affected by the removal of certain components from the filter. For all three dust size ranges the efficiency of the modified filter was about 1% lower than the original at the beginning of the test; but the efficiency of the modified filter increased steadily with the dust load whereas the efficiency of the original filter decreased with increasing dust load.

More important than the effect on the efficiency was the effect of the modification on the pressure drop and dust holding capacity. The pressure drop of the filter with clean oil decreased from 7.87 in. W.G. to 4.38 in. W.G. as a result of the modification.

The pressure drop of the original filter went up to 9.45 in. W.G. with a dust load of 1380 grams, whereas, after the modification, a dust load of 2000 grams produced a pressure drop of only 5.90 in. W.G. The upper pair of curves in Fig. 5 show the increase of pressure drop in the two tests. These findings indicated that it should be possible to develop an oil bath air cleaner for small aircraft with satisfactory weight and filtering efficiency which would have a sufficient dust holding capacity to permit service intervals of more than one hundred hours.

An experimental oil bath air cleaner was designed and built and operated with various modifications. It has been found that a filtering efficiency of about 97% can be reached with a mixture of 50% each A.C. Spark Plug dust "coarse" and "fine" at a pressure drop of less than 4 in. W.G. Several media, like steel wool and wood excelsior, have been found to be nearly equally effective as oil separators and present investigations are concerned with the determination of the oil supply rate which will allow the maximum air flow rate without

an oil pull-over and which will not reduce the filtering efficiency. Tests are also being conducted with knitted wire mesh as an oil separator. Fig. 6 is a photograph of an experimental oil bath air cleaner made of transparent material to permit observation of the flow of oil during operation.

Synthetic felts and fabrics were found not to be feasible as an oil separating medium because the wick effect of these materials did not let the oil drain back into the sump. Several of these materials with different thicknesses and density have been investigated for their usefulness as filter media for oiled impingement filters. Although the filtering efficiency of most of these materials was found to be excellent when saturated with oil, it was observed that the dust did not penetrate into the material but accumulated on the surface only. This so reduced the dust holding capacity of the materials that they were not considered useful as filter media for oil bath cleaners.

## IV. PERFORMANCE OF CLOTH AS A DRY FILTER MEDIUM

Investigations were made of various cloths as dry filter media for air cleaners. Preliminary tests showed that the filtering efficiency was satisfactory with almost all tightly woven materials. However, unless there was a heavy nap on the inlet side of the cloth it was found that the dust particles would build up a thin and dense layer on the surface of the filter which caused the pressure drop to increase very fast with a relatively small dust load. From these findings it was deducted that an acceptable filter cloth should have a heavy napping on one side and a dense woven body.

Table 6 represents a summary of the performance tests made on nine knitted or woven fabrics. Four of these materials were commercial cloths and the others were made especially for these tests by the North Carolina School of Textiles.

The highest filtering efficiency observed was 98 percent with "Skinner Sunback" which is a light fleeced material with a tightly woven silk backing. The pressure drop, however, increased beyond an acceptable value with a small dust load which is believed due to the light fleece and the dense backing.

## TABLE 6

### Performance of Cloth as a Filter Medium

| Material | Weight oz/sq yd | Face Vel. ft/min. | Test* Dust | Pressure Drop in. W.G. |  | Dust Load g/sq ft | Efficiency % |
|---|---|---|---|---|---|---|---|
|  |  |  |  | Clean | Loaded |  |  |
| Cotton Flannel | 9.0 | 59 | 50/50 | 0.63 | 5.24 | 13 | 89 |
|  |  | 116 | 50/50 | 1.06 | 5.84 | 15 | 84 |
| Knitted Dynell Cotton Napped | 8.2 | 50 | Fine | 0.24 | 1.45 | 27 | 88 |
|  |  | 67 | 50/50 | 0.39 | 2.01 | 27 | 88 |
|  |  | 100 | 50/50 | 0.63 | 2.44 | 27 | 82 |
|  |  | 133 | 50/50 | 0.67 | 3.00 | 27 | 51 |
| Orlon Fleece | 6.9 | 75 | Fine | 0.24 | 0.78 | 20 | 84 |
|  |  | 75 | Fine |  | 1.90 | 40 | 86 |
|  |  | 100 | Fine | 0.29 | 0.87 | 20 | 82 |
|  |  | 100 | Fine |  | 2.36 | 40 | 85 |
|  |  | 150 | Fine | 0.56 | 1.11 | 20 | 75 |
|  |  | 150 | Fine |  | 3.74 | 80 | 91 |
|  |  | 200 | Fine | 0.75 | 1.08 | 20 | 54 |
|  |  | 200 | Fine |  | 3.40 | 80 | 82 |
| Skinner Sunback | 10.8 | 100 | Fine | 1.42 | 14.16 | 15 | 98 |
| Sweat Pants | 8.1 | 50 | Fine | 0.12 | 2.48 | 33 | 94 |
|  |  | 100 | Fine | 0.49 | 0.95 | 17 | 78 |
|  |  | 100 | 50/50 | 0.49 | 1.42 | 67 | 66 |
| Cotton Knit, 12 gage barked & napped | 13.0 | 100 | 50/50 | 0.67 | 7.86 | 120 | 98 |
|  |  | 150 | 50/50 | 0.79 | 10.16 | 120 | 97 |
|  |  | 200 | 50/50 | 1.26 | 7.28 | 120 | 76 |
| 8/2 Cotton ground 8/2 Dacron-Vicara 50/50 backing napped | 13.0 | 100 | 50/50 | 0.59 | 4.33 | 120 | 96 |
|  |  | 150 | 50/50 | 0.87 | 4.76 | 120 | 89 |

(Continued)

## TABLE 6 (Continued)

| Material | Weight oz/sq yd | Face Vel. ft/min | Test*D Dust | Pressure Drop in. W.G. Clean | Pressure Drop in. W.G. Loaded | Dust Load g/sq ft | Efficiency % |
|---|---|---|---|---|---|---|---|
| 8/2 Cotton ground 8/2 Dynell backing | 13.0 | 100 | 50/50 | 0.79 | 7.28 | 120 | 97 |
| | | 150 | 50/50 | 1.10 | 8.86 | 120 | 94 |
| 8/2-16/2 Cotton, 12 gage Jersey napped | 12.8 | 100 | 50/50 | 0.71 | 7.67 | 120 | 90 |

*50/50 Mixture of 50% each "Fine" and "Coarse" A. C. Spark Plug Co. Test Dust

The orlon fleece, on the other hand, had a rather loose backing which reduced the efficiency but the long fleece increased the dust holding capacity considerably. It will be noted that the pressure drop of the clean material increased almost linearly with the air flow rate whereas the efficiency for the first 20-gram dust load decreased with increasing air flow rate. The filtering efficiency increased with accumulated dust load. At 200 ft/min face velocity the efficiency for the first 20-gram dust load was only 54 percent but the average efficiency for an 80-gram dust load was 82 percent and equalled that determined for the first 20-gram dust load at 100 ft/min face velocity.

The performance of a knitted dynell cloth with a cotton nap which was the first sample made by the Textile School was similar to that of the orlon fleece. A 9 oz/sq yd cotton flannel showed about the same efficiency but its pressure drop increased much more rapidly due to lack of sufficient napping. The loose knitted cotton fabric used for sweat pants had a filtering efficiency of 94 percent at 50 ft/min face velocity, but the efficiency decreased considerably at higher air flow rates.

Based upon this information four more napped fabrics were procured from the North Carolina School for Textiles which weighed close to 13 oz/sq yd. Preliminary results showed that these materials could be loaded with 120 grams of dust per square foot and permitted face velocities of 150 ft/in. without sacrificing filtering efficiency.

Further tests are scheduled to determine whether any one of these cloths can be recommended for actual use in an aircraft air cleaner. Also the mode of arranging the cloth in the air cleaner to obtain the minimum of weight and space requirement and the simplest accessibility for cleaning needs further study. Present data indicate that a dry cloth air cleaner for the H-13 aircraft will need about 2 sq ft of cloth and would have a dust holding capacity of 240 grams, compared to 45 grams to 60 grams observed for the Air-Maze aircraft filter.

## V. SUMMARY OF PERFORMANCE TESTS ON SEVERAL TYPES OF AIR CLEANERS

A summary of the performance of the principal air cleaner types and materials tested is contained in Table 7. Some of these air cleaners such as the Fram paper filter, the Air-Maze P-1 aircraft type, the Farr Rotonamic, and the Donaldson oil bath air cleaner, have been described in detail in previous reports.

The Purolator #51845 paper filter with a design air flow rate of 300 cfm was tested with the corresponding Fram Model AX-13638. Both filters had the same dimensions and their performance was found to be almost identical. The dust holding capacity of 45 g was about equal to that of the Air-Maze filter, whereas their filtering efficiency was slightly lower. All these filters are satisfactory if they are serviced properly, but their low dust holding capacity reduces their value considerably when operated in very dusty surroundings.

### Rotating Air Cleaners

The experiments with rotating air cleaners as previously reported have been expanded and the effect of air flow rate, dust concentration and particle size range was further investigated. Efficiencies up to 92 percent were attained with A.C. "coarse" dust.

A modification of this type of cleaner was designed and built that did not require an aspirator to produce the air bleed-off. This was accomplished by mounting two blower wheels on one axis and operating one wheel as a blower and the other one as the dust separator. Fig. 7 is a photograph of this apparatus which was driven by a variable speed motor. The scrolls or housings around the two wheels expand in opposite directions such that the air pressure from the blower is used to push the air through the dust-separating wheel and remove the dust from the bleed-off slot. The funnel attached on the bleed-off slot is on the lower part of the right housing and the bleed-off air flow produced by an outside blower was adjusted

## TABLE 7

### Peformance of Air Cleaners and Filter Media

| Mfr. Model | Type | Air Flow Rate, cfm | Weight g | Load Capacity g | Pressure Drop in. W.G. Initial | Pressure Drop in. W.G. Final | Avg. Eff. % | Remarks |
|---|---|---|---|---|---|---|---|---|
| Fram CA-100 PL | Paper | 120 | 170 | 24 | 1.5 | 7.0 | 98.9 | Weight without enclosure |
| Fram AX-13638 | Paper | 300 | 349 | 45 | 1.7 | 12.0 | 97.0 | Weight without enclosure |
| Purolator 51845 | Paper | 300 | 342 | 45 | 2.3 | 10.8 | 97.0 | Weight without enclosure |
| Air-Maze P-1 | Flocked Screen | 305 | 220 | 45 | 2.3 | 9.6 | 98.3 | Old type, 2 flocked screens |
| Air-Maze P-1 | Flocked Screen | 305 | 242 | 60 | 1.6 | 7.4 | 93.4 | New type, 1 flocked screen |
| Donaldson A-10574 | Oil bath | 315 | 12,200 | 1,590 | 7.9 | 8.6 | 97.2 | |
| Farr Rotonamic | Cyclone | 200 | 3,700 | self-cleaning | 8.4 | 8.4 | 92.6 | Weight without aspirator |
| Thermix Corp. Experimental | Cyclone | 250 | 5,900 | self-cleaning | 7.6 | 7.6 | 89.5 | Weight without aspirator |
| NBS Experimental | Rotating | 150 | 8,000 | self-cleaning | 1.2 | 1.2 | 83.2 | |
| Winslow Corp. Helicopter | Cloth | 600 | 5,000 | - | 1.8 | 1.0 | 72.0 | |
| Natural Latex Foam 3/8 in. thick | | 300 | 160 | 174 | 4.2 | 9.3 | 98.9 | |
| Plastic Felt, Dycon 1" | Oiled | 300 | 20 | 25 | 2.8 | 10.0 | 98.6 | |
| B.F.Goodrich Felt | Neoprene-coated | 300 | 57 | 112 | 2.6 | 11.0 | 97.4 | |
| Cotton Cloth Experimental | Flat | 150 | 37 | 120 | 0.8 | 10.2 | 97.1 | Weight without frame |

so that the pressure in the funnel was equal to atmospheric pressure, simulating a free bleed-off air flow from the dust separator. The bleed-off air was drawn through a filter bag in the square can, and the efficiency of the apparatus was determined from the weight increase of the filter bag and the weight of the total dust introduced. An exhaust blower was used downstream of the air cleaner to overcome the pressure drop of the orifice flow meter used for measuring the air flow rate. The pressure at the outlet flange of the dust separator was maintained at between ±1 in. W.G. Table 8 below shows the performance of this apparatus operating at speeds from 1200 rpm to 2800 rpm and air flow rates of 100 cfm and 150 cfm for both A.C. test dust "coarse" and "fine."

TABLE 8

Efficiency of Rotating Air Cleaner
Air Flow Rate, cfm

| Speed of Separator | 100 | | 150 | |
|---|---|---|---|---|
| rpm | Fine | Coarse | Fine | Coarse |
| 1200 | 57.9 | -- | 69.6 | 85.2 |
| 1600 | 68.2 | 89.1 | 71.7 | 86.1 |
| 1800 | -- | 89.3 | 68.4 | 88.2 |
| 2000 | 64.9 | 86.6 | 70.1 | 82.7 |
| 2400 | 57.5 | 89.3 | 67.7 | 90.7 |
| 2800 | 67.4 | 88.0 | 75.8 | 88.3 |

It will be noted that peak efficiency of 90.7 percent was observed with "coarse" dust at 2400 rpm and 150 cfm air flow rate. The efficiency with "fine dust increased from 57.9 percent at 100 cfm and 1200 rpm to 75.8 percent at 150 cfm air flow rate and 2800 rpm blower speed. Although the efficiency of this air cleaner was found to increase about three percent when a 32-mesh wire screen was installed inside the separating wheel, further work on this type of device was discontinued. The development of special separator blades to obtain a higher efficiency would have required considerable expense which appeared unwarranted at this time.

The power requirement of a rotating air cleaner is estimated at 0.1 hp per 100 cfm air flow rate. Future development of such air cleaners, possibly driven by an engine exhaust turbine,

appears promising since they would produce a better volumetric efficiency of the aircraft engine because the full ram pressure of the air could be utilized without any loss in the air cleaner.

## Winslow Air Cleaner

A special purpose aircraft air cleaner manufactured by the Winslow Engineering Company of Oakland, California, which consisted of several knitted socks, was tested. The socks were spread open by helical springs and the air flowed from the outside to the inside. The socks were oiled but the material was so light that the small amount of oil that adhered to the fibers did not cause a build-up of accumulated dust. This appeared to be the reason for an observed decrease of the efficiency from 87 percent with a clean sock to 57 percent after 120 g dust had been introduced into one of the four socks of the test specimen.

Based on the experience obtained in testing different cloth filters it now appears that the efficiency of the Winslow type could be considerably improved by using a much heavier material. The dimensions of the filter tested were about 30x24x7 inches and its weight 10 pounds. It was not considered feasible for use in military aircraft in its present form.

## Cyclonic Air Cleaners

The use of self-cleaning cyclone-type air cleaners appeared as a solution to the service problem and two cyclonic models were tested. The Farr Rotonamic showed an efficiency of 92.6 percent with a pressure drop of 8.4 in. W.G. and an experimental model built by the Thermix Corporation of Greenwich, Connecticut, had an efficiency of 83.2 percent and a pressure drop of 7.6 in. W.G.

Tests were also made with an experimental cyclone built in this laboratory but they were discontinued after it appeared impossible to obtain an efficiency of 95 percent with a mixture of 50 percent each "fine" and "coarse" dust with a pressure drop of less than 10 in. W.G.

It is probable that the combination of weight and pressure drop of the cyclonic air cleaner would result in a loss in useful power of an aircraft engine on the order of 3 percent. However, this penalty might be justified in very dusty atmosphere to prevent premature destruction of engines from cylinder wear.

## Foam Rubber Air Cleaners and Miscellaneous Materials

Latex foam, 3/8 inch thick, showed initially an excellent filtering efficiency and dust holding capacity. However, after operating this filter for about one hour, cracks appeared in the material which reduced the filtering efficiency considerably. It was learned, thereafter, that these cracks were the result of ozone in the air and that latex foam would be destroyed by the effect of ozone.

Subsequently, all known manufacturers were asked to supply samples of their synthetic foam which were known not to be affected by ozone. A considerable number of samples was received and tested, but none had an air flow resistance that was low enough to be considered as a suitable material for air cleaners.

In the course of these investigations the B. F. Goodrich Corporation supplied several samples of a neoprene coated felt of wool and horsehair. When oiled, this material showed about the same air flow resistance and efficiency as the Air-Maze air cleaner but almost 2 1/2 times as much dust holding capacity. This very promising result was obtained with one out of a group of eight samples. When additional quantities of this particular construction were requested, the manufacturer was unable to furnish any of a quality equal to the one with which the good results were obtained. Therefore, further tests on this material were abandoned.

Test with a white plastic felt showed a very low filtering efficiency when used dry, but when oiled, it could be operated at a face velocity of 1000 ft/min , about equal to the Air-Maze filter. It had a good efficiency, but the dust holding capacity was little better than half of that of the Air-Maze filter at equal pressure loss. This material did not appear promising for use in air cleaners.

## VI. OBSERVATIONS MADE IN FIELD TESTS AT FORT EUSTIS, VIRGINIA

An examination was made of a sample of dust taken from the paper air cleaner on a H-13 helicopter which had been operated in the Fort Eustis area. Four micro-photographs were taken of this

dust and are shown in Fig. 8 to Fig. 11. Each division of the scale in the center of the photographs represents a distance of 16 2/3 microns (0.00066 inch). The particles range in size from the limit of resolution of the microscope to few in excess of 150 micron size. It appears that the large dark area on the upper left side of Fig. 8 is an agglomeration of smaller particles and that the light and transparent particles consist of quartz sand whereas the dark particles are composed of some decrepitated material, most likely to be clay. The broad dark line in the center of Fig. 9 as well as the curved line near the center of Fig. 10 are organic fibers of different origin Fig. 11 shows numerous quartz particles in the 20 to 50-micron size range to which some clay is bonded; there also is a clay particle with a small chip of quartz adhering to it, about 1 inch below the center and 1/4 inch left.

A microscopic count was made of the dust particles in seven particle size ranges, the percentage weight of each size was determined and summarized in Table 9 below.

TABLE 9

Size Range Distribution of Dust Collected in an Air Cleaner of an H-13 Helicopter in Fort Eustis

| Size Range, microns | Percent, weight |
|---|---|
| 0-5 | 1.2 |
| 5-10 | 1.2 |
| 10-20 | 5.4 |
| 20-40 | 4.2 |
| 40-80 | 19.6 |
| 80-200 | 34.6 |
| 200+ | 32.8 |

The grain size distribution of the dust by weight was computed from the counting of particles of each size range per unit area. Random samples of the dust were spread on micoscopic slides with an adhesive made of Canadian balsam and Castor oil. These slides were then mounted on a "micro viewer" which was divided into 150 equal squares. Three different magnifications were used to count the different particle sizes.

The size of one square on the viewer corresponded to 22 microns for counting the 5 to 10- and 10 to 20-micron particles, a smaller magnification that produced 100-micron length of each side of the square was used for the 20 to 40- and 40 to 80-micron particle range and a still smaller magnification for the dust particle range of 80 to 200 microns and larger than 200 microns had a 220-micron length of each side of the square.

The number of particles of each of the six size ranges was counted on at least three complete fields on the viewer. If less than 20 particles of any size range had been counted in three fields further fields were counted until 20 particles of that size range were found, but not more than ten fields were examined for any one particle size range.

If the number of particles for one size range thus counted was A, the number of total squares examined was B and the length of the side of each square on the viewer corresponded to C microns, then the number N of particles of that size range determined per unit is

$$N = \frac{A}{B \times C^2}$$

No counting of the particles in the 0 to 5-micron size range was made as the percentage weight of this range was expected to be small and a reasonably accurate count would have been extremely difficult. The assumption was made that the weight in this size range was approximately equal to that of the 5 to 10-micron size range.

The mean particle size for each of the six size ranges was assumed to be the arithmetic mean of the smallest and largest particles, i.e., the mean particle in the 40 to 80-micron size range was considered to be 60 microns and that of the particles larger than 200 microns was estimated at 250 microns. By multiplying the number of particles determined for each size range per unit with the cube of the mean size, the ratio of weight of the particles in each size range was determined. Assuming that the weight of the 0 to 5-micron particles equals that of the 5 to 10-micron particles, the percentage weight for each particle size range could then be calculated.

Several tests were made to obtain information regarding the dust concentration on or near a helicopter hovering low above ground. These data cannot be considered comprehensive, but are indicative of the conditions at a certain time at Fort Eustis.

The dust concentrations determined at three-feet and six-feet elevation at different distances downstream from the helicopter with a wind of approximately ten mph are shown in Table 10 below.

TABLE 10

Dust Concentration near a Helicopter

| Distance from Rotor Axis, ft | Dust Concentration, mg/cu ft<br>Elevation, 3 ft | <br>Elevation, 6 ft |
|---|---|---|
| 20 | - | 8.0 |
| 30 | 12.3 | 6.0 |
| 40 | 14.0 | 3.3 |
| 70 | 17.1 | - |

It appears that the concentration at the six-foot elevation decreased within a short distance, whereas at three feet above ground the dust concentration increased as far as 70 feet away from the rotor axis.

The range of visibility depends not only on the dust concentration but also to a large degree on the particle size. A wide scattering of the observed data from different tests was, therefore, expected. It is believed that the most indicative observations of the visibility were obtained behind an L-19 aircraft, about three feet above the ground. In these tests, the visibility decreased from 600 feet at a 15.0 mg/cu ft dust concentration to 25 feet at a 51.7 mg/cu ft concentration.

An attempt was made to determine the air flow pattern around a landing helicopter by putting a strip of flour two feet wide and 30 feet long on the ground. Two tests were made with layers

of flour of different thickness, but both times the flour was blown away when the helicopter was still too high above ground and no distinct flow pattern could be noticed. The determination of the air flow pattern underneath the moving rotors was tried when the helicopter was idling on the ground by blowing flour through a 20-foot long, 5/16-inch diameter pipe to a place near the rotor. It was found that the air velocity produced by the rotor was too high and the flour was diffused at such a rate that it was not at all visible.

## CONCLUSIONS

This study of the performance characteristics of various proprietary and experimental air cleaners suggests that their application to small aircraft and helicopters should be divided into two categories; namely, those for aircraft operating from relatively dust free landing fields only, and those which operate under any possible conditions. It also appears to be desirable that the dust holding capacity of the air cleaner be such that its service period can coincide with the major service period of the aircraft itself.

For aircraft that operate only on improved landing fields with rather low dust concentrations, air filters such as the Air-Maze, Fram, and Purolator units described in this report provide a high cleaning efficiency with a simple, lightweight, and inexpensive device. Because the accumulation of dust on the filter in such areas would be slow, their relatively low dust-holding capacity would not be a serious disadvantage. If necessary, the deflecting-vane type of prefilter described in this report could be used with the Air-Maze filter to increase the service interval three to four times. The addition of a prefilter would probably avoid the occasional need of by-passing the Air-Maze filter because of excessive dust load and high pressure drop. The deflecting-vane type prefilter removes only the larger particles and therefore would not appreciably extend the service interval of paper-type filters because their pressure drop is affected principally by small particles only.

On aircraft operating on unimproved airfields or in dusty areas, air filters such as the Air-Maze, Fram, and Purolator types could accumulate enough dust in a few minutes to raise their pressure drop to ten in. W.G. or more and require by-passing of the filter to maintain the combustion air supply to the engine. Even a prefilter on the Air-Maze type would not extend the cleaning interval to more than about an hour under such conditions. Consequently, for dusty areas, it appears logical to equip the aircraft with a device having a greater

dust-holding capacity even at the expense of a few pounds additional weight. The most promising air cleaners for dusty areas appear to be the cyclonic self-cleaning type, and the oil bath filter type described in this report. While these devices have a higher pressure drop than the initial values for the Air-Maze, Fram, and Purolator units, it is comparable in magnitude or a little lower than that attained by these three filters after a few minutes operation in dusty atmospheres.

The Farr cyclonic self-cleaning air cleaner can function indefinitely with an efficiency of about 92 percent and a pressure drop of approximately 8.5 in. W.G. The Donaldson oil bath filter with some modifications can operate with an efficiency above 95 percent for mixed coarse and fine dust for periods approaching 100 hours flight time under severe dust conditions without exceeding a pressure drop of six in. W.G. The use of one of these types of air cleaner would probably preclude the necessity for by-passing the air cleaner even under severe dust conditions. Both of these proprietary air cleaners could be reduced in weight by the choice of other metals and the use of lighter gage material.

The exhaust gas venturi required to provide continuous scavenging or bleed-off from the Farr device would be simple in principle and would not increase the back pressure on the engine objectionably. Neither would it add excessively to the weight of the air cleaning system.

By establishing two classes of air cleaners, the choice of which would depend on the dustiness of the flying conditions in the area of use, the advantages of simplicity and light weight would be gained for aircraft using improved landing fields and the advantages of adequate dust-holding capacity and continuous protection to the engines would be secured for aircraft in dusty areas.

The development of a dry cloth filter to be used on both the H-13 and L-19 has led to a group of knitted and napped fabrics which show good filtering efficiency and a dust-holding capacity that corresponds to about five times that of the air cleaners presently used. Another advantage of the dry cloth filter as compared to the Air-Maze would be the ease of cleaning, and it would be superior to the paper filters as it does not need frequent replacement.

The development of an oil bath air cleaner for the H-13 is progressing and it is planned to provide this air cleaner with a dust-holding capacity sufficient to last 100 hours flight time under the most severe dust conditions. It is estimated that an experimental model of an oil bath air cleaner for the model H-13 helicopter can be completed for flight testing during 1957.

The investigations on dry cloth filters made thus far were restricted to single layer fabrics. Preliminary studies, however, seem to indicate that higher filtering efficiencies can be obtained even with increased air velocity by using double layers of cloth. Future tests are, therefore, scheduled to determine combinations of fabrics which will produce the best performance in an air cleaner.

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

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