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**A STUDY OF THE FILTRATION AND
PERMEABILITY CHARACTERISTICS OF
IPC 1478 FILTER PAPER**

Project 1983

Contract No. DA-29-O44-XZ-549

Final Report

to

U. S. Department of Defense
DEFENSE ATOMIC SUPPORT AGENCY

February 13, 1960

Incl 1

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THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

A STUDY OF THE FILTRATION AND PERMEABILITY CHARACTERISTICS
OF IPC 1478 FILTER PAPER

Project 1983

Contract No. DA-29-044-XZ-549

FINAL
REPORT

to

U.S. Department of Defense
DEFENSE ATOMIC SUPPORT AGENCY

February 13, 1960

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A STUDY OF THE FILTRATION AND PERMEABILITY CHARACTERISTICS
OF IPC 1478 FILTER PAPER

SUMMARY

This work was conducted to study the filtration and pressure drop-flow rate characteristics of IPC 1478 filter paper over wide ranges in pressure and temperature (simulating conditions for altitudes up to about 70,000 ft.). The project was done in two phases: In the first, a wind tunnel was designed and constructed for operation at a pressure of 1/20 atm., a temperature of 7°F. (simulating a stagnation temperature) and a flow rate of 5000 ft./min. at 1/20 atm. The aerosol was monodisperse spherical particles of SiO_2 whose size distribution function (mass basis) was narrow, peaking at about 0.02 micron. The retention of IPC 1478 paper for these particles was found to be essentially 100%. The study revealed an apparently anomalously high diffusion of these particles (and also of a boron oxide aerosol) in air. In the second phase, the wind tunnel was modified for operation at temperatures down to -40°F., a generator for the production of very small (about 40 A.) particles of aluminum oxide was developed, and a General Electric Continuous Condensation Nuclei Detector was employed for particle counting and retention determination. Retention (generally in the range, 30-75%) for the aluminum oxide particles and pressure drop were determined over wide ranges in pressure, temperature, and flow rate. Data reduction theory was developed, and applied to the pressure drop-flow rate observations. Modern kinetic theory was applied to the diffusion of very small particles in a gas, and the theory of diffusion of particles from a streaming gas to the tube wall was evolved and applied to the estimation of particle size.

INTRODUCTION

The development of a filter paper having good retention for small air-borne particles, high air permeability, minimum ash content and low radio-activity was undertaken in 1947. The filter paper known as "IPC 1478" evolved from this work in 1949. The paper was made from second-cut cotton linters, Grade 46, obtained from the Hercules Powder Company. The fibers were lightly beaten and the sheets were formed on large, specially made, handsheet molds. Cotton scrim was used as a backing material to add strength to the sheet. The sheets were impregnated with "Kronisol" (di-butoxyethyl phthalate) for the purpose of improving the retention. Tests performed at atmospheric pressure with a 2000-ft./min. air velocity, at room temperature and -40°F., employing a carbonyl-iron aerosol, showed that the retention was improved markedly after impregnation with the "Kronisol". The retention, for the conditions of testing, was essentially 100% at both room temperature and -40°F. The filter paper was produced on the handsheet molds until 1956, when paper machine production was initiated.

This report presents the results of a study of the filtration characteristics of IPC 1478 paper under conditions simulating high-altitude sampling of atmospheric particulate matter.

OBJECTIVES

PHASE 1

In September, 1956 a contract was entered into between The Institute of Paper Chemistry and the Armed Forces Special Weapons Project (AFSWP) for the purpose of studying the retention characteristics of IPC 1478 filter paper for spherical particles of 0.02 to 1.0 micron diameter and of density about 2.5 g./cc. Silicon dioxide and calcium carbonate were given as examples of suitable materials. The conditions of testing were: pressure, 1/20 atmosphere; air velocity, 5000 ft./min. downstream from the test filter; temperature, about 7°F. (corresponding approximately to the stagnation point temperature for an ambient temperature of -68°F.).

The presumption was that the retention of particles in the neighborhood of 0.02 micron would be very low for the conditions specified. Accordingly, the development of a filter paper superior to IPC 1478 was made part of the contract.

PHASE 2

The first phase of the study revealed the excellent retention properties of IPC 1478 for the silicon dioxide particles of about 0.02 micron diameter. At this time greater interest was expressed in the retention properties of IPC 1478 for particles smaller than 0.02 micron, and the contract was modified as follows:

The retention properties of IPC 1478 for particles smaller than 0.02 micron were to be studied. The absolute pressure range, 1/20 to 1/5

atmosphere, and the downstream velocity range, 1000 to 5000 ft./min., were specified. Pressure drop-flow rate data were to be obtained over these ranges of pressures and velocities at temperatures of -40° , 0° , and 70°F .

APPARATUS

WIND TUNNEL, CHOICE OF DESIGN

The closed-system, recirculating wind tunnel was given first consideration. Calculation showed that an unusually powerful turbine-type compressor would be required for the range of pressure differentials when operating at an air density of only 5% of normal. On turning to positive-displacement compressors and vacuum pumps it was found that a two-stage Nash "Hytor" vacuum pump would meet the requirements. Calculations and reference to the characteristics of this pump showed that it could be used on an open-ended wind tunnel. Several advantages then became apparent in favor of this type of wind tunnel. Probably the greatest advantage is that particles which pass through the test filter are simply discharged, and no special means for their removal is necessary as in the operation of a recirculating tunnel.

WIND TUNNEL, CONSTRUCTION DETAILS^a

The open-ended wind tunnel constructed for this work consists of a linear array of components, shown in Fig. 1, which are connected with 2-inch copper tubing of suitable wall thickness. The air from the room enters the tunnel through a filter, consisting of 3 plies of IPC 1478 paper, which removes

^aThis tunnel was used in Phase 1 of the project; it was modified (see section on Modified Wind Tunnel) for the work of Phase 2.

Figure 1. Schematic Diagram of First Wind Tunnel

most of the particulate matter from the air stream. (The area of the filter is about 20 times that of the test specimen.) The air then passes through an orifice-type flowmeter, calibrated to give the mass rate of flow in the tunnel. To substantiate the accuracy of the orifice design and calculations, volumetric checks of the two orifices used in the study were made. The air next moves through a heat exchanger which reduces the temperature to about -30°F.; most of the atmospheric moisture is removed at this point. The cross-sectional area of the heat exchanger is so large that the air at essentially atmospheric pressure moves through it at very low velocity.

A 2-inch Saunders valve located at the outlet of the heat exchanger together with a second valve at the vacuum pump serve to regulate the flow rate and pressure in the tunnel. A portion of the air is by-passed around the Saunders valve through the aerosol generating chamber. Two 1-inch Saunders valves located up and downstream from the aerosol chamber serve to regulate the absolute pressure and air flow in the chamber. An orifice flowmeter located upstream from the chamber indicates the mass rate of flow of air through the chamber. A mercury manometer serves to indicate the absolute pressure in the chamber.

A metal bellows located just downstream from the 2-inch Saunders valve permits the axial movement of the tunnel needed for insertion or removal of a filter specimen. Provision for mounting the specimen was made by inserting a flange connection in the line of 2-inch tubing. The flange surfaces were machined to provide an airtight seal when the specimen was clamped between them. The specimen was supported by an 8 x 8-mesh screen made of 0.018-inch

diameter wire. At the high rates of flow, correction was made for the small pressure drop across this screen.

Freon-12 was circulated through copper tubing wrapped around the 2-inch tunnel to cool the air to about 7°F. The tunnel was insulated with fiberglass and was vapor sealed with a polyethylene film. The temperature of the air stream at the specimen was measured with a thermocouple consisting of 0.004-inch Chromel, Alumel wires. The junction was located centrally in the 2-inch tunnel about 1/4 inch upstream from the filter specimen. The small diameter wire minimizes the effects of radiation and conduction, thus providing a true measure of air temperature. The thermocouple was calibrated through the temperature range of interest using a brine solution and several mercury thermometers.

Two openings in the form of 2-inch tees, one located about 3 feet upstream and the other about 2 feet downstream from the filter specimen, permit aerosol sampling for the purpose of determining the particle dimension. An optical aerosol density meter was located upstream from each of the sampling ports. These unusually sensitive meters were originally intended to measure the aerosol density up and downstream from the specimen; however, as the emphasis during the course of work shifted to smaller and smaller particles, these meters became useless because of insensitivity to extremely small particles.

A 3-inch Saunders valve (see earlier reference to the 2-inch valve) was located at the downstream end of the tunnel. A second metal bellows was located immediately in front of the vacuum pump to prevent the moderate pump vibration from being transmitted to the tunnel.

VACUUM PUMP

The 2-stage Nash "Hytor" vacuum pump (shown in Fig. 2) driven at 1100 r.p.m. by a 15-horsepower electric motor moves the required volume of air at 3.8 cm. Hg absolute pressure in the tunnel. The volume rate of flow corresponding to a velocity of 5000 ft./min. in the 2-inch tunnel is 109 c.f.m.

This type of pump requires a sealing fluid which must be circulated continuously through the vane system when it is in operation. The capacity of the pump at low pressures is a function of the vapor pressure of the sealing fluid and for this pump to meet the required air flow at the desired wind tunnel pressure the water temperature must be about 58°F. or lower. Water from the city mains was employed during the winter and deep well water was used during the summer.

A feature of the Nash "Hytor" pump that is of considerable importance in this project is the production of essentially nonpulsating flow. Also, these pumps are ruggedly built and will maintain their rated pumping capacity for many years of continuous duty without servicing other than oiling the bearings and checking the packing glands occasionally.

A ball-check valve was located at the entrance to the vacuum pump to prevent the water from flooding the tunnel in case of power failure. The pressure drop across this valve was negligible for the rates of air flow used in this work.

Figure 2. Two-stage Nash Hytor Vacuum Pump and 15-H.P.
Electric Motor Drive

100 22

AEROSOL GENERATOR^a

The aerosol generator consists of a 4-inch diameter cylinder about 20 inches long, standing in an upright position, with an oxyhydrogen torch located at the bottom. The chamber is connected to the tunnel, as stated earlier, so that a portion of the air stream is drawn from the tunnel and then is returned to the tunnel after admixture with the particles from the flame. The air enters the bottom of the cylinder and rises past the torch. The torch barrel is insulated from the cold air so that vapors carried through the barrel will not condense on the inner surface of the latter. The oxygen and hydrogen supply lines are equipped with regulators, rotameters, and needle valves to permit control of the flow rates. A small portion of the hydrogen bubbles through an organic liquid (ethyl orthosilicate) containing silicon atoms (1). The vapor from the ethyl orthosilicate is carried to the oxyhydrogen flame, where the reactions result in the production of silicon dioxide. Particles generated in this manner are carried up through the chamber and into the tunnel where the stream is mixed with and carried down the tunnel by the main air stream.

OPTICAL AEROSOL DETECTORS

In earlier work, employing an aerosol of carbonyl iron, the use of optical detectors for determining the aerosol concentration was successful. Each detector designed for the present work consists of a cubical aluminum block with a 2-inch hole bored through the center (which was made an integral part of the tunnel). Two holes bored at right angles to the tunnel and at

^aThis was the first generator developed; later work required the development of a different type of generator.

right angles to each other serve as illuminating and viewing ports. The illumination, furnished by a mercury arc lamp, has high energy at short wavelengths to enhance Raleigh scattering. A compensating system employing two S-4 response phototubes serves as the detector. One phototube views the scattered light from the particles and the other views the lamp directly; its output is used to balance the signal caused by scattered light from the lenses and apertures.

The output from the mercury arc lamp pulsates at 120 cycles/sec. in synchronism with the 60-cycle/sec. power source, which permits the use of an alternating current amplifier. The difference in phototube output is fed to a Densichron (2) through a preamplifier. Measurements showed that the aerosol concentration (silicon dioxide) was about one milligram per cubic meter of air for the successful operation of this detecting system. Electron micrographs (Fig. 3) taken of the aerosol at this concentration showed evidence of agglomeration which influenced the response of the detectors. When particle agglomeration was eliminated, the sensitivity was inadequate and this system of detection was abandoned, in so far as work with ultra small particles was concerned.

Figure 3. Electron Micrograph of Silicon Dioxide Aerosol at a
Concentration of About 1 Milligram per Cubic Meter
of Air - Magnification 50,000X

AEROSOL SAMPLING AND ELECTRON MICROSCOPY

ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators were employed in attempts to capture particles on grids for viewing with the electron microscope, simultaneously with the use of the optical detectors. The precipitator shown in Fig. 4, consists of a 1-inch diameter copper tube about 3 inches long with a 1/8-inch polished brass rod located centrally in the tube. The supporting 3/8-inch diameter copper rod and the 1/8-inch brass rod project through a 1/2-inch thick by 3-inch square piece of Glyptal-painted transite which forms the seal over the 2-inch opening in the aerosol sampling port. The electron microscope grids are placed in slight recesses on a thin, flat brass plate which was positioned on the inside of the 1-inch diameter copper tube. The recesses are just slightly deeper than the thickness of the grid so that the top surfaces of the grids are essentially on the same plane as the surrounding surface.

The grids consist of 1/8-inch diameter 200-mesh screens which are the basic support for a very thin film of collodion which, in turn, supports the collected particles. In the interest of good resolution it is important that the collodion film be thin and that the surface be as smooth as possible. An improvement in the technique of applying the collodion film to the grids was made. The usual procedure is to place one drop of an amyl acetate solution of collodion on the surface of clean water, permitting the drop to spread out in a thin film. The solvent evaporates and the collodion film sets up. The grid is ordinarily placed on the collodion film, and the film and grid removed together. It has been noted that, after placing the drop of solution on the water surface,

Figure 4. Schematic Diagram of Electrostatic Precipitator

considerable shrinkage took place when the collodion film started to solidify. This shrinkage was eliminated by (a) placing an aluminum tube beneath the surface of the water, (b) lowering the water level just before the collodion film started to set up and shrink until the collodion film rested lightly on the edge of the aluminum tube. This kept the collodion film from shrinking and thereby provided a smoother, thinner film. The grids were located on a coarse screen just below the level of the edge of the aluminum tube so that by dropping the water level a little further the collodion film was deposited on the grids. The coarse screen with the grids was then removed and placed in a sealed container, where they were dried and stored for later use.

One electrostatic precipitator was placed upstream and another downstream from the filter specimen; thus, the retention of the specimen could be determined by counting the particles collected on the grids in the two precipitators. It was necessary to warm the precipitators to approximately room temperature before removing them from the cold tunnel to avoid condensation of moisture on the grids. This was done by placing a soldering iron (tip removed) over the 3/8-inch copper rod supporting the precipitator for several minutes before removing the precipitator.

Positive and negative potentials from 800 to 2000 volts were applied to the cylinders of the precipitators, and positive and negative potentials of 7000 volts were applied to the torch flame. At times the electrostatic field seemed to influence the collection efficiency but, after performing many experiments, the conclusion was that the electrostatic field had very little influence on the collection efficiency for the very small particles involved in the study.

Whatever the mechanism of collection, very satisfactory samples were obtained for electron microscope examination.

Electron micrographs permitted determination of the dimensions and shape of the particles. The earliest tests showed serious agglomeration. Through reduction of aerosol concentration, which was made possible after improvement in techniques, the agglomerates were eliminated and the particles produced were spherical and of uniform dimension. Figure 5 shows the particle size distribution on a mass basis before eliminating the agglomerates. Figure 6 shows the particle size distribution after eliminating the agglomeration. The concentration of aerosol at which the data for Fig. 5 were collected was about 0.1 milligram of silicon dioxide per cubic meter of air and for Fig. 6 the concentration was 10 to 20 micrograms of silicon dioxide per cubic meter. This concentration was determined by analyzing the filter specimen spectrographically for silicon after passing a known volume of aerosol-laden air through the filter. Calibration curves for spectrographic analysis were prepared using filter specimens containing known added amounts of silicon. The quantity of silicon contained in the original filter paper was accounted for in the calibration.

There was evidence that, at the higher concentrations, the retention measurements were influenced by the fact that agglomerates were being formed in the filter; in some cases, the micrographs taken downstream from the filter showed several large agglomerates--but no particles in that size range were present in the micrographs taken upstream. This problem was eliminated at the lower concentrations.

Figure 5. Particle Size Distribution for Silicon Dioxide Aerosol Before Eliminating Agglomeration

Figure 6. Particle Size Distribution for Silicon Dioxide Aerosol
After Eliminating Agglomeration

RETENTION MEASUREMENTS EMPLOYING SILICON DIOXIDE AEROSOL

WIND TUNNEL CONDITIONS FOR RETENTION TESTS

Numerous retention tests were made with IPC 1478 paper employing the silicon dioxide aerosol. Tests were also made with a 0.003-inch thick perforated brass plate (in place of the filter specimen) which had a sufficient number of 1-millimeter holes to give a pressure drop very nearly equal to that for the filter paper for the same flow conditions. The micrographs taken up and downstream at the velocity and pressure of interest indicated that the number of particles collected downstream was very nearly equal to the number collected upstream. This was done to assure that the collection efficiencies of the grids in the up and downstream positions were very nearly equal for the conditions of the test. It was presumed that very few particles would be stopped by the perforated brass sheet.

The conditions for three illustrative determinations for IPC 1478 paper, with reproductions of the electron micrographs, are presented in Fig. 7-9; in each case, (a) and (b) designate, respectively, up and downstream positions.

During the experimental phases of this work, more than four hundred grids were exposed, "shadowed" and examined with the electron microscope. After perfecting all the techniques involved, sixteen determinations were very carefully conducted; excluding runs in which agglomeration was obviously a factor (higher concentrations), retentions of essentially 100% were found for the IPC 1478 paper. Figures 10, 11, and 12 show the particle size distribution of the silicon dioxide aerosol, on a mass basis, for each of the upstream grids.

7b

Electron Micrograph of Silicon
Dioxide Aerosol Collected
Downstream from IPC 1478 Filter
Specimen - Magnification 50,000X

7a

Electron Micrograph of Silicon Dioxide
Aerosol Collected Upstream from IPC
1478 Filter Specimen - Magnification
50,000X

Upstream grid	287-1
Downstream grid	288-1
Magnification (this reproduction)	50,000 X
Downstream velocity	4000 ft./min.
Downstream absolute pressure	4.7 cm. Hg
Absolute pressure in torch chamber	28.8 cm. Hg
Voltage on electrostatic precipitator cylinder (-)	1000 volts
Collection time	24 min.
Voltage on torch (+)	7000 volts
Pressure drop across filter specimen	9.8 inches H ₂ O
Air temperature at filter specimen	0°F.
Filter specimen	IPC 1478
Retention, mass basis	98%

8b

Electron Micrograph of Silicon
Dioxide Aerosol Collected
Downstream from IPC 1478 Filter
Specimen - Magnification 50,000X

8a

Electron Micrograph of Silicon Dioxide
Aerosol Collected Upstream from IPC
1478 Filter Specimen - Magnification
50,000X

Upstream grid
Downstream grid
Magnification (this reproduction)
Downstream velocity
Downstream absolute pressure
Torch chamber absolute pressure
Voltage on electrostatic precipitator cylinder (-)
Collection time
Voltage on torch (+)
Pressure drop across filter specimen
Air temperature at filter specimen
Filter specimen
Retention, mass basis

223-1
224-1
50,000 X
5000 ft./min.
3.9 cm. Hg
31.4 cm. Hg
1000 volts
6 min.
7000 volts
12 inches H₂O
11°F.
IPC 1478
100%

9b

Electron Micrograph of Silicon
Dioxide Aerosol Collected Downstream
from IPC 1478 Filter Specimen
Magnification 50,000X

9a

Electron Micrograph of Silicon
Dioxide Aerosol Collected Upstream
from IPC 1478 Filter Specimen
Magnification 50,000X

Upstream grid	217-2
Downstream grid	218-2
Magnification (this reproduction)	50,000 X
Downstream velocity	5000 ft./min.
Downstream pressure	3.8 cm. Hg
Torch chamber absolute pressure	32.2 cm. Hg
Voltage on electrostatic precipitator cylinder (-)	1000 volts
Collection time	12 min.
Voltage on torch (+)	7000 volts
Pressure drop across filter specimen	11.6 inches H ₂ O
Air temperature at filter specimen	3°F.
Filter specimen	IPC 1478
Retention, mass basis	100%

Figure 10. Particle Size Distribution for Silicon Dioxide Aerosol
Shown in Figure 7a

Figure 11. Particle Size Distribution for Silicon Dioxide Aerosol
Shown in Figure 8a

Figure 12. Particle Size Distribution for Silicon Dioxide Aerosol
Shown in Figure 9a

The magnification for the micrographs employed in the retention studies was 100,000X but for the purposes of this report the micrographs shown in Fig. 7-9 are magnified 50,000X.

CONTINUOUS CONDENSATION NUCLEI DETECTOR

In view of the lengthy procedure involved in sampling the aerosol for viewing with the electron microscope, and the difficulties in maintaining the necessary resolving power of the microscope, other means of detecting the aerosol were sought. At the suggestion of the Project Officer, the Continuous Condensation Nuclei Detector (CN Meter) (3) was investigated, and arrangements for obtaining the CN Meter were made. A photograph of this piece of equipment with the associated sampling device is shown in Fig. 13.

OPERATION OF THE CONTINUOUS CONDENSATION NUCLEI DETECTOR AND SAMPLER

The CN Meter was received from the General Electric Company early in July, 1958. This device provides a very sensitive^a means for counting extremely small particles. The air sample input to the CN Meter should be essentially at atmospheric pressure and, hence, it was necessary for the General Electric Company to design and build a sampling device which would remove air from the wind tunnel at 3.8 cm. Hg and pressurize it to atmospheric pressure before introduction to the CN Meter. The sampling device consists of two hemispheres bolted together, with a flexible diaphragm separating the two halves. A rotating valve and two solenoid valves control the cycling of the system. The diaphragm is moved pneumatically. The cycling proceeds in the

^aAn illustrative range of operation: 1×10^{-10} to 30×10^{-10} gram per cubic meter of air for 40-angstrom particles having a density of 4.0 g./cc.

Figure 13. Continuous Condensation Nuclei Detector (CN Meter) and Sampling Device

following manner: Starting with the diaphragm in the most downward position, the rotating valve opens the lower chamber to the tunnel and at very nearly the same time a cam-actuated microswitch operates a solenoid valve which opens the upper chamber to a vacuum line. The diaphragm rises and the air enters from the tunnel to the lower chamber. After the diaphragm has reached the uppermost position, the rotating valve closes the connection between the bottom chamber and the tunnel, and the solenoid valve closes the upper chamber from the vacuum pump. Then the rotating valve connects the lower chamber to the atmosphere and clean air is drawn in through suitable filters until the lower chamber reaches atmospheric pressure. The rotating valve then closes the connection of the lower chamber to the atmosphere and connects the lower chamber to a bladder arrangement which feeds directly to the CN Meter. At about the same time, the remaining cam-actuated solenoid valve opens the upper chamber to a source of low pressure air which forces the diaphragm down and causes the air in the lower chamber to move into the bladder. This completes the cycle. The air removed from the tunnel is diluted with clean air in the ratio of the pressures involved, but the particle count per unit volume remains the same in the CN Meter as in the tunnel except for losses on the walls of the tubing and the sampling device which connect the CN Meter to the tunnel.

SPECIAL TESTS WITH THE CONTINUOUS CONDENSATION NUCLEI DETECTOR

The first tests with the CN Meter were misleading in that apparently the CN Meter showed good sensitivity for the small particles of silicon dioxide. Further tests showed that the sensitivity was very erratic; it was discovered that the electrode for igniting the flame was sufficiently close to the latter

that it became sufficiently heated to emit particles when the introduction of ethyl-orthosilicate increased the size and emissivity of the flame. When the flame was operated with the same flow of hydrogen and oxygen, but without the ethyl-orthosilicate vapor, the CN Meter indicated clean air. The electrode was moved farther from the flame and the apparent sensitivity for the silicon dioxide particles disappeared.

Several experiments employing the electron microscope grids were performed in an attempt to learn the reason for the low sensitivity of the CN Meter for the small silicon dioxide particles. One experiment consisted of placing the electron microscope grids in the tubing leading to the CN Meter. The fact that no particles were collected on the grids indicated that the particles were not reaching the CN Meter.

It was suspected that the behavior of these particles could be accounted for on the basis of an electrostatic charge, but calculation and experiment ruled this out.

Another experiment consisted of placing a bundle of seven plastic tubes of 11/64-inch diameter and one foot length in the tunnel. An electron microscope grid had been placed in each end of each tube. The air velocity through the tunnel was 5000 ft./min. at 3.8 cm. Hg. The velocity through the plastic tubes was estimated to be about 10 ft./sec. Electron micrographs showed that the grids located at the upstream end of the tubes collected a large number of particles, whereas the downstream grids collected none, indicating that the particles were diffusing to the walls of the tubing in a distance of travel less than one foot. The average velocity of the air through

the sampling tubes to the CN Meter is less than 10 ft./sec. Figures 14a and 14b are electron micrographs showing the concentrations of particles on grids located at the up and downstream ends of the plastic tubes.

The same type of experiment was performed with a 4-inch length of square brass tubing. The results of this and other experiments are discussed in the section on diffusion loss (Appendix III). The diffusion theory relating to this work is presented in Appendix III.

The high rate of diffusion loss to the walls of the tubing which transports the aerosol laden air from the tunnel to the CN Meter caused all of the particles to be removed from the air stream before reaching the latter. The CN Meter indicated clean air when in reality the concentration of particles in the tunnel was about one million per cubic centimeter (an aspect of the extreme smallness of the particles). This count was based on the mass of silicon dioxide collected by a filter for a known volume of air passing through the filter and on the particle dimension determined with the electron microscope (mass concentration of about 10 micrograms per cubic meter).

A different organic liquid, tri-n-propyl borate, was used in place of the ethyl-orthosilicate with the hope that the particles of boron oxide would not diffuse out of the air stream as rapidly. The electron micrographs taken of grids placed in the square tube show that the boron oxide aerosol behaves similarly to the silicon dioxide.

Another attempt was made with an organic liquid, trimethyl aluminum, but the test was inconclusive, as no particles were visible on the grids, indicating that either the particles were not generated in the same manner as

14a

Electron Micrograph Showing Concentration of
Particles Collected at Upstream End of a 1-foot
Piece of 3/16-inch Diameter Plastic Tube -
Magnification 50,000X

14b

Electron Micrograph Showing Concentration of
Particles Collected at Downstream End of a
1-foot Piece of 3/16-inch Diameter Plastic
Tube - Magnification 50,000X

for the silicon dioxide or that the collection efficiency of the grids was different for the aluminum oxide.

These experiments showed that, to employ the CN Meter, it would be necessary to develop another aerosol. Also, at this time the contract was modified with respect to the low-temperature requirement, range of pressures, and aerosol particle dimension (see section on Objectives, Phase 2).

MODIFIED WIND TUNNEL

Modification was made in that portion of the wind tunnel between the heat exchanger and the Nash "Hytor" vacuum pump. Photographs of the modified tunnel and a schematic diagram are presented in Fig. 15 and 16. A Cambridge "Absolute Filter" was installed in the exit line from the heat exchanger to remove any particles from the air stream; a very low "clean air" or aerosol-free count was desired in the work with the CN Meter. A moisture trap consisting of a large "U" tube immersed in a bath of alcohol and "dry ice" was installed just downstream from the Cambridge filter. The heat exchanger drops the air temperature to about -30°F . and removes most of the moisture. The "dry ice" bath further reduces the air temperature to about -50°F . and removes more moisture so that the relative humidity of the air at -40°F . is well below saturation. The 2-inch Saunders valve was replaced with a 2-inch gate valve as the rubber diaphragm in the former failed to function at the lower temperatures. A 6-foot section of the 2-inch tunnel (upstream from the filter specimen) was enclosed in a 3-inch copper tube. Freon-22 was circulated in the annular space between the two tubes by a 3-horsepower refrigeration unit. An 18-inch section of the 2-inch tunnel (downstream from the filter specimen) was similarly enclosed within a 3-inch copper tube with Freon-22 circulated in the annular space between

Figure 15. View of the Modified Wind Tunnel

Figure 16. Schematic Diagram of the Modified Wind Tunnel

the two tubes by a 1/2-horsepower refrigeration unit. The temperature is manually controlled. A calibrated thermocouple consisting of Chromel, Alumel wires of 0.004-inch diameter connected to a sensitive galvanometer indicates the temperature of the air stream at a point about 1/4 inch upstream from the specimen.

The aerosol sampling ports consist of 2-inch tees which project through and are welded to the 3-inch tube. These openings located up and downstream from the filter specimen permit sampling the aerosol with either the CN Meter or the electron microscope grids. The filter specimen is clamped between two machined flanges which form an air-tight seal against the atmosphere.

The aerosol generator was modified in that the volume of the torch chamber was reduced and a second and new chamber was added which permitted the introduction of an aerosol generated by means of a high-voltage, low-current spark employing electrodes of elements of interest.

It will be recalled that the requirements of the modified contract were to determine the pressure drop-flow rate and retention characteristics of IPC 1478 paper for a range of pressures downstream from the filter from 1/20 to 1/5 atmosphere, for velocities from 1000 to 5000 ft./min. downstream from the filter, and for temperatures of -40°, 0°, and 70°F. The aerosol dimension was to be from 0.02 micron diameter down to the smallest dimension which the equipment could detect.

The tunnel was insulated by placing a fine mesh, copper screen trough around the tunnel and filling the trough with a granular, mineral-base

insulating material^a. The thickness of insulation was about 3 to 4 inches on all sides of the tunnel. No vapor seal was employed as it was found that the moisture which collected during a day's run would evaporate when the equipment was shut down at night. The insulating material and screen were removed for the photograph shown in Fig. 15.

RETENTION TESTS WITH VARIOUS AEROSOLS

AEROSOL FROM ELECTRICALLY HEATED NICHROME WIRE

In view of the anomalous behavior of the silicon dioxide and the boron oxide which made it impractical to employ the CN Meter, a new aerosol was sought. Electrically heated nichrome wire was tried and appeared to be a good source of particles which could be transported through appreciable lengths of tubing. However, the composition of the aerosol was unknown (it could consist, for example, of chromium, nickel, or mixed oxides). Retention measurements were performed with the aerosol generated from an electrically heated nichrome wire using the CN Meter. The results and conditions of test were as follows:

Temperature at the test filter	-40°F.
Absolute pressure downstream from the test filter	3.8 cm. Hg
Air velocity downstream from the test filter	5000 ft./min.
Test filter	IPC 1478
Retention (several tests)	61 to 75%

OIL "FOG"

The vacuum pump connected to the CN Meter discharges a very fine oil fog while operating. The outlet from this pump was connected to the tunnel

^a"UniFil" was used, although other commercial, mineral-base loose-fill insulating materials could be employed. When it became necessary to remove the insulation, a "tank-type" vacuum cleaner was used. The convenience of this method of insulating cold experimental equipment cannot be overemphasized.

and the concentration of particles adjusted by blending oil-laden air with clean air. This was a stable source and a retention test was performed. No attempt was made to determine the particle size but it could be presumed that these particles were relatively large as they were visible in high concentration under strong light. The results and conditions of test are as follows:

Temperature at the test filter	-40 °F.
Absolute pressure downstream from test filter	3.8 cm. Hg
Air velocity downstream from the test filter	5000 ft./min.
Test filter	IPC 1478
Retention	94%

ALUMINUM OXIDE AEROSOL

Electrically heated aluminum wire was tried and found to be unstable; hence, no retention tests were made using it as a source of aerosol.

An electric spark, employing aluminum wire electrodes, was set up with a 15,000-volt, 60-cycle transformer. A 10.5-megohm resistor connected in series with the spark limited the current through the spark to 1.4 ma. The number of particles generated per unit time could be controlled by adjusting the current-limiting resistor. The diameter of the wire electrodes was about 2 mm. and the spark gap was set to about 1.5 mm. After a short "conditioning period" the rate of generation of particles became fairly constant. The particles generated in this manner undoubtedly consist of aluminum oxide with a density of 3.5 to 4.0. These particles could be transported through the sampling device to the CN Meter in sufficient numbers to permit making a reliable retention measurement.

Attempts were made to determine the particle size and shape through use of the electron microscope, but without success. Apparently the particles

were either too small to be visible or they were not being deposited on the grids. The collection time for these experiments was lengthened to several hours with no evidence of the particles showing on the grids.

The dimension of the particles was determined by measuring the rate of diffusion loss upon passing through tubing of known dimension and at a known air velocity. This determination led to an estimate of 40 angstroms. The results of this study are discussed in the section on diffusion loss (Appendix III).

RESPONSE OF THE CN METER

The response of the CN Meter, with respect to particle count at various pressures and velocities in the wind tunnel, employing the aluminum oxide aerosol, was determined. Curves were established by holding the pressure constant (at the levels of interest) in the tunnel and varying the velocity, and then holding the velocity constant (at levels of interest) and varying the pressure. The tests were performed at 70° and -40°F. The constancy of the aerosol generator during the tests was checked by referring back to a standard pressure and velocity set at the beginning of the tests. The response curves for constant pressure (average level) and changing velocity are shown in Fig. 17, and those for constant velocity (average level) and changing pressure are shown in Fig. 18^a.

^aThese plots at average levels of pressure and velocity were justified by the finding that the slopes in each family of curves were nearly uniform.

Figure 17. Response Curves for the Continuous Condensation Nuclei Detector (CN Meter) with Constant Pressure and Varying Velocity in the Tunnel

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Figure 18. Response Curves for the Continuous Condensation Nuclei Detector (CN Meter) with Constant Velocity and Varying Pressure in the Tunnel

RETENTION TESTS PERFORMED WITH THE ALUMINUM OXIDE AEROSOL

The sampling device for the CN Meter is connected to the tunnel at points up and downstream from the filter specimen with 1/2-inch copper tubing. A single tube connects the sampling device to a tee with one branch connected to the upstream port through a manually operated valve, and the other branch connected to the downstream port through a similar valve. The two branches were of identical length, diameter, and shape. The retention data were obtained by (a) closing the downstream valve and opening the upstream valve so that the sampler removes the aerosol-laden air from the upstream port. The number of particles per cubic centimeter of air is counted and then (b) the upstream valve is closed and the downstream valve opened so that the number of particles per cubic centimeter of air downstream from the specimen is counted. These counts are based on the calibration by the General Electric Company. The absolute count need not be accurate in this method, so no attempt was made to check the accuracy of the CN Meter on an absolute basis. After counting the number of particles up and downstream from the test filter, and knowing the effects of pressure and velocity on the count, it is possible to calculate retention in the following manner:

Particle count per cc. of air, upstream	C_1
Particle count per cc. of air, downstream	C_2
Slope of the log particle count <u>vs.</u> log pressure curve (Fig. 18)	S_p
Slope of the log particle count <u>vs.</u> log velocity curve (Fig. 17)	S_v
Absolute pressure upstream, cm. Hg	P_1
Absolute pressure downstream, cm. Hg	P_2

Velocity, ft./min., upstream	V_1
Velocity, ft./min., downstream	V_2
Factor relating particle count upstream and downstream for the same pressure and velocity at the two sampling ports (no filter)	k

$$\text{Retention, \%} = 100 \left\{ 1 - C_2 / [kC_1(p_2/p_1)S_p + S_v] \right\}$$

The aerosol concentration for the retention tests employing the aluminum oxide aerosol ranged from a minimum of about 1×10^{-10} gram per cubic meter of air to a maximum of about 30×10^{-10} gram per cubic meter of air. These concentrations are based on a particle density of 4.0 and an average particle diameter of 40 angstroms. This estimate of concentration in the wind tunnel does not consider the loss of particles in the sampling device. It is essential that the concentration of aerosol be sufficiently low that retention measurements will not be influenced by particle agglomeration or by loading of the filter.

Three samples of IPC 1478 paper (machine-made) marked high, low, and average weight, and several samples identified by individual sheet numbers, were received from the Project Officer for testing. In addition, a number of samples of IPC 1478 paper (machine-made) which had been studied on a project with the Research Laboratories Division of the Bendix Aviation Corporation were included to increase the ranges of sampling and pressure. A number of handsheets were tested for comparison purposes. The machine-made filter papers are identified by a letter H, L, or A, and B indicating the particular sample from which the specimen was taken. The individual specimens of handsheets are identified by number only.

Pressure drop-flow rate and retention data for IPC 1478 paper were obtained at the following absolute downstream pressures, downstream velocities, and temperatures: 1/20, 1/10, and 1/5 atmosphere; 1000, 2000, 3000, 4000, and 5000 ft./min.; -40°, 0°, and 70°F. Fifteen specimens of the machine-made paper (five for each designated sample), and ten specimens of the handsheets were used for each set of conditions. Several samples of machine-made IPC 1478 paper were used to obtain pressure drop-flow rate data at intermediate pressures and at pressures above 1/5 atmosphere. (These are the samples studied on the project with Bendix; for these, retention data were not obtained.) All the foregoing data are presented in Table I (Appendix I). The column headings of Table I are explained on the first page of the Appendix. It is to be noted that the mean of the up- and downstream velocities is the "harmonic mean," that is, $\bar{V} = 2V_1V_2/V_1 + V_2$). With reference to Column six, labeled "Retention," it will be recalled that these data are for the aluminum oxide aerosol of particle size estimated at about 40 angstroms. Of interest are the data given on the last page of Table I, which presents pressure drop-flow rate and retention data for one, two, and three plies of IPC 1478 paper. Also of interest are data presented on the second and third pages from the end of Table I for unimpregnated handsheets. With regard to the retention of aluminum oxide particles in unimpregnated handsheets, one must recall the heavy dependence of the retention of carbonyl iron particles--and presumably other particles--on the presence of "Kronisol."

The retention data for the IPC 1478 paper are presented in Fig. 19-35, and Fig. 36 gives the results for one, two, and three plies. These figures will be found in Appendix II.

The "Kronisol" content of each of the machine-made samples was determined (by extraction with carbon tetrachloride); the results are given in Table II (Appendix I).

PRESSURE DROP-FLOW RATE RELATIONSHIP

The pressure drop-flow rate data presented in Table I have been reduced by means of the theory presented in Appendix IV. On the basis of the theory (and the stated assumptions), a relationship should exist between $\bar{p}\Delta p/\mu^2$ and $\bar{p}\bar{V}/\mu$ over wide ranges of temperature and pressure, where $\bar{p}$ is the arithmetic mean of the upstream and downstream densities of the air, Δp is the pressure drop across the filter, μ is the viscosity of the air, and $\bar{V}$ is the harmonic mean of the upstream and downstream velocities, i.e., $\bar{V} = 2V_1V_2/(V_1 + V_2)$, in which V_1 and V_2 are, respectively, the up- and downstream velocities. In the interest of maintaining consistency with past work in the presentation of variables, reduced quantities, $\bar{\sigma}\Delta p/\omega^2$ and $\bar{\sigma}\bar{V}/\omega$, have been employed; these are analogous, but not equal, to Reid's reduced pressure drop, $\sigma\Delta p/\omega^2$, and "pseudo Reynolds' number," $\sigma V/\omega$ (5,6). In these numbers, $\sigma = \rho/\rho_0$ and $\omega = \mu/\mu_0$, where the subscript zero refers to a reference condition of temperature and pressure (59°F., 2116.2 lb./sq. ft.--the NACA standard atmosphere at sea level). In the present work, $\bar{\sigma}$ is calculated as of the temperature of the air stream and the arithmetic mean of the up- and downstream pressures, whereas in Reid's work the calculation is made for a point immediately upstream from the filter.

The reduced pressure drop and Reynolds' number given in columns four and five were calculated on the Institute's IBM 610 computer. The 1450 data points so computed are presented on a log-log plot in Fig. 45. Three separate

least-squares fits to polynomials, for the machine-made papers, were also computed on the IBM 610: The polynomials were quadratic, cubic, and quartic. From the limited point of view of minimization of the sums of squares of the deviations, the fit to the quartic was, of course, the best. However, certain important principles were used as guides in the selection of the best fit. These are (a) the relationship (when plotted on a log-log basis) should asymptotically approach a straight line of unit slope as the reduced Reynolds' number approaches zero, (b) the combined effects of increasing turbulence and of increasing mechanical compaction of the filter under the action of the pressure drop with increasing Reynolds' number should be to cause the relationship gradually to curve upward with a smoothly increasing slope. Now, by a statistical accident, the only sample (B) for which data were obtained in the highest range of Reynolds' number has a flow resistance significantly lower than that of the average of all the remaining samples (the sprinkling of points which fall generally below the relationship are those for Sample B). Because of this circumstance, the least-squares fits to the cubic and quartic displayed slight undulations which were judged to be in violation of the above-stated principles, and were clearly attributable to the statistical consideration just mentioned. Accordingly, the quadratic function was selected. This relationship, with $x = \bar{\sigma} \bar{V}/\omega$, and $y = \bar{\sigma} \Delta p / \omega^2$, is:

$$\log y = -0.0388 + 1.0717 \log x + 0.1577 (\log x)^2.$$

The machine computation indicated a standard deviation in $\log y$ of 0.0254, which corresponds approximately to 6% in y (for the machine-made papers).

The IBM 610 was programmed to yield the percentage deviations of y from the foregoing relationship. The resulting error distribution curves for the machine-made papers and handsheets are given in Fig. 46.

DISCUSSION

APPARATUS

Both the original and the modified wind tunnel systems met the respective contract specifications on pressure, flow rate, and temperature; the systems operated in a smooth, easily controllable manner, and such auxiliary equipment as flowmeters, manometers, etc., functioned with good accuracy.

An early decision in the work was that the aerosol should be continuously generated in the system, in such manner that the time between the point of generation and arrival at the filter should be very short. The first experiments with silicon dioxide particles revealed (through electron microscope examination) that agglomeration of the particles occurred. This, obviously, would result in spuriously high retention data. Also, if the concentration of the particles were too high, the filter specimen could become "loaded", and this would cause the pressure drop-flow rate and retention data to be erroneous. Simulation of field use dictates that filter clogging should be avoided and that particle concentration should be so low that the observations are independent of concentration. Generation of the particles in the system (as opposed to dispersion of previously prepared particles) at low concentration produced an almost completely monodisperse aerosol, and filter clogging was undetectable in the time intervals required to perform the tests. Later, as the techniques

were improved, long-term runs became possible, and still later, when the General Electric Continuous Condensation Nuclei Detector (CN Meter) was added to the system, runs of many hours could have been conducted without detection of clogging (had such runs been necessary).

Where it can be used, as in the first phase of this project, the electron microscope technique for measuring retention has the great advantage that one can determine retention as a function of particle size, as well as to see generally the condition and shape of the particles. During the course of the project the resolution of the electron microscope was substantially enhanced and improvement of related techniques made it possible to detect and measure particles of size down to roughly 50 A.; the resolution of the instrument was better than this figure, but the structure of the supporting film usually made it impossible to distinguish particles from the background when the former were as small as 50 A.

It was originally hoped that the electron microscope and the CN Meter could be used jointly until the latter could be calibrated. However, no aerosol could be found which could be simultaneously detected by both systems. This led to a series of diffusion experiments, the theory and results of which are discussed in Appendix III. The most interesting result of this phase of the study is that particles of silicon dioxide and boron oxide exhibit an anomalous diffusion rate that is far in excess of that which is calculated on the basis of diffusion theory for particles of the observed diameters.

The combination (in the second phase of the program) of the CN Meter and the low-current high-voltage spark generator of the aluminum oxide ("low-current spark generator") functioned with remarkable stability. The CN Meter

proved to be extremely sensitive and trouble-free in its operation. In view of the substantial loss of particles in the special sampling device (not ordinarily a part of the CN Meter), it would seem to be desirable to make CN Meter units integral parts of a tunnel system. This might make it possible to employ the CN Meter in studies involving aerosols having the peculiar behavior of silicon dioxide; a system of this sort would have the further advantage of permitting work with particles even smaller than those used in the last phase of the present work.

RETENTION OF SILICON DIOXIDE AEROSOL BY IPC 1478 PAPER

The retention of the IPC 1478 filter paper for silicon dioxide particles of all sizes examined was essentially 100%. This is an extraordinary result, especially when account is taken of the fact that the observed particle size ranged down to about 50 A. (0.005 micron). The later discovery of the anomalous diffusion of silicon dioxide particles raises an interesting question: Is the high retention of silicon dioxide directly attributable to anomalous diffusion? Explanations based on electrical effects, such as "image forces" resulting from charges on the particles equivalent to one or two electrons, were ruled out on the basis of calculations.

RETENTION OF ALUMINUM OXIDE AEROSOL

Inspection of Fig. 19-35 (Appendix II) shows that the retention of the aluminum oxide aerosol depends upon the conditions, but is generally in the range, 30-75%. It should be recalled that these particles, too small to be seen on the electron micrographs (if, indeed, a sufficient number were collected on the grids for observation), were estimated to be extremely small (about 40 A.).

The dependence of retention on velocity and pressure appears to be in good accord with filtration theory. The dependence upon pressure is not so obvious as that on velocity, if diffusion is considered to be the principal mechanism of collection. At a pressure as low as 3.8 cm. Hg, the mean free path of air molecules is of the order of 20,000 A.; in comparison with a particle radius of 20 A., it is seen that the ratio of the mean free path to particle radius is 1000. Thus, one is clearly concerned with "molecular flow" or "slip" of the air in connection with any relative motion between a particle and the surrounding air; although the viscosity of air per se is almost independent of pressure in the range 3.8 to 15.2 cm. Hg, the "slip" effect would change by approximately fourfold in this range. This would be reflected in both diffusion and impaction (to the extent that the latter may be significant).

The very large slip (characterized by the ratio of the mean free path of the air molecules to the particle radius), particularly at the lower pressures, should have two effects: First, the mobility of the particles should be increased as the pressure is reduced, and this would be observed in increased diffusion coefficient and filter retention. Second, however, increasing slip resulting from decreasing pressure should cause a greater tendency for particles to be caught by inertial impaction. Both of these effects should result in greater retention at lower pressure. An examination of the data (Fig. 33-35) shows that there is a pronounced effect of pressure on retention, in this sense. All the particles employed in this work were so small that one would expect the mechanism of inertial impaction to be less important than that of diffusion. Of course, one learns the relative importance of the two mechanisms through study of the dependence of retention on stream velocity; if the retention

increases with decreasing velocity (increasing time for diffusion to filamentous particles of the filter), the controlling mechanism is diffusion; however, as is well known, if impaction is the controlling mechanism, the retention is observed to increase with increasing velocity. With the exception of the anomaly presented by the data in Fig. 31 (discussed below), the data of Fig. 19-32 indicate that, for the ranges in pressure and velocity involved in this work, diffusion is the dominant mechanism of particle capture.

The retention data presented in Fig. 31, for handsheets at 70°F., do not conform with those for the same paper at lower temperatures or with those for machine-made paper at 70°F. This is not a spurious outcome of using too few specimens, as ten specimens were employed and the standard errors were similar to those of other runs. This series of determinations, conducted early in the second phase of the project, was the only one in which the heat exchanger was at room temperature. Although the air leaving the exchanger was probably very humid, the stream approaching the filter was undoubtedly quite dry because of the substantial expansion of the air-water vapor mixture on passing from essentially atmospheric pressure to 1/5 atm. or lower. Thus, the effect cannot be attributed to humidification of the main air stream. However, another possible effect could operate. The pressure in the low-current spark generator was about 60 cm. Hg and, accordingly, the air at this point could have been quite humid. There would seem to be at least two possibilities: (a) In the high-velocity stream issuing from the resistance orifice at the top of the spark chamber there should be essentially isentropic cooling of the air, probably resulting in a short-lived fog. However, the fog might well cause agglomeration of the particles which, having formed, would persist after the water evaporated. If such agglomeration occurred, the retention characteristics would, of course,

be different. (b) The nature and size of the particles may be influenced at the point of generation by the presence of water vapor.

All of the other data were obtained with the heat exchanger in operation at about -30°F. , so that the air in the spark chamber was very dry.

COMMENT ON RETENTION OF PARTICLES GENERALLY

During the course of this work, retention measurements were made for silicon dioxide, aluminum oxide, particles from electrically heated nichrome wire, and fine oil mist. For this very limited list of particle types, the retention varied from roughly 50 to 100%, when the pressure was 3.8 cm. Hg and the downstream velocity 5000 ft./min.; the retention ranged down to lower values if a higher pressure was employed. Accordingly, it must be assumed that, in the field, the retention for particles generally covers an appreciable range, the size of the range depending, apparently, on the absolute pressure, the velocity of air through the filter, the nature, size and shape of the particles, etc. With regard to this conclusion, there is the evidence found by Dr. Sidney C. Stern and his associates at General Mills Company that, where two IPC 1478 filters were used in combination in balloon flight testing of the atmosphere, essentially all the radioactivity was collected by the first filter (4). In the work referred to, the typical rate of flow was relatively low, which would favor high retention if the particles collected were very small.

It is suggested that wider use be made of two-ply filters. The total volume of air sampled, for given conditions of pressure, pressure drop and temperature, would be reduced, but the advantages might well outweigh this disadvantage. For example, where the retention (for a given particle type and size) for a single filter is 90%, the retention of a two-ply filter should be

about 99%; in another example, where the single-filter retention is 60%, that of a two-ply filter would be 84%. Errors in collection resulting from uncertainty in retention would be reduced. Measured collections (from the field) on the two members of a two-ply combination would yield interesting information; for example, in parallel collections in the field, in which one system employed a single filter and the other a two-ply combination, consideration of flow rates and measurements of radioactivity of the single and of the two members of the two-ply filter would lead to a calculation of the effective retention for the actual particles of interest.

PRESSURE DROP-FLOW RATE DATA

Elsewhere in this report the reader will find the detailed theory of the data reduction method employed in this work (Appendix IV) and the presentation of the pressure drop-flow rate data and relationship (earlier section, "Pressure Drop-Flow Rate Relationship"). Attention is now directed to Fig. 45 and 46. The fit of the quadratic relationship, given by the solid line in Fig. 45, is seen to be quite good. The quality of fit can perhaps be best assessed through inspection of Fig. 46, which gives the distribution functions for the deviations for both the machine-made papers and the handsheets involved in this work. It is to be noted that the deviations are the combined effects of all sources: sample variability, experimental error, imperfectness of fit of the quadratic function (see earlier discussion of choice of this function), and imperfectness of the assumption that the effect of compaction resulting from the compressive stress induced by the pressure drop is negligible (see Appendix IV).

Figure 46 shows that the machine-made paper is not significantly unlike the handsheets in permeability. It is of interest to consider the

deviations of individual data points in a little more detail. First, it should be said that not all the 1450 points on Fig. 45 could be made to show, because of coincidences: 188 points are actually twins, 72 are triplets, 32 are quadruplets, one is an octet (shown), and one is nonary (shown). Of all the points, 91% lie between $\pm 12.5\%$ of the relationship; of the machine-made paper specimens alone, 94% lie within these limits; of the handsheets alone, 84% lie within the limits. The over-all experimental error (at maximum) is estimated to be 5%, so that deviations substantially greater than this figure are believed to be due to sample variability. Finally, it will be recalled (from an earlier section) that the standard deviation from the relationship shown in Fig. 45 is, for the machine-made papers, 0.0254 (in the logarithm), which corresponds roughly to 6% in $\bar{\sigma}\Delta p/\omega^2$. The error distribution curve for the machine-made papers is seen to be approximately normal: the standard deviation corresponding to the observation that 94% of the data points lie between $\pm 12.5\%$ is 6.6%.

In the opinion of the writers, some of the scatter of the data points on Fig. 45 is attributable to the effect of compaction (due to the pressure drop) on the flow resistance. At a given level of the reduced pressure drop ($\bar{\sigma}\Delta p/\omega^2$), the actual pressure drops corresponding to a number of points vary through a large range; accordingly, the compaction effects (which are demonstrable) cover a wide range from negligible to significant levels. The effect is generally most important at the higher levels of reduced pressure drop and Reynold's number, and it is felt that not all of increasing curvature of the line of best fit (Fig. 45) at higher Reynolds' number is due to turbulence but that some of the curvature is attributable to the compaction effect. Another interesting aspect of this is the creep that occurs in the compressive deformation of a filter; as a result of creep, the exact value observed for the pressure drop

is a function of the past history of the material with respect to the schedule of temperature, pressure, and flow rate. Until the various users of IPC 1478 paper wish to make allowance for the effects of compaction and of creep of compaction, there would seem to be no point in analyzing the matter further.

The present work has not included a study of the effect of "slip" in the flow of air through IPC 1478 paper. This effect is quite significant in ordinary papers, even at pressures above one atmosphere, because the pore size is of the same order as the mean free path of the gas molecules (roughly 10^{-5} cm.). At a pressure of $1/20$ atmosphere, the mean free path is twenty times greater and, hence, one would expect an appreciable slip effect, except that the pore size in the filter paper is much larger than that in ordinary paper. It can only be said that some of the scatter of the data points (Fig. 45 and 46) is theoretically attributable to the slip phenomenon.

CONCLUSIONS

1. The continuous-flow wind tunnel system is satisfactory for studying filter efficiency over wide ranges in temperature, pressure and flow rate.
2. The retention of monodisperse spherical particles of silicon dioxide of diameter ranging from about 0.005 to 0.03 micron in IPC 1478 filter paper is essentially 100% for the conditions: pressure, $1/20$ atm.; temperature (simulated stagnation), 7°F. ; air velocity (downstream), 5000 ft./min.
3. The techniques developed for use of the electron microscope in the sampling of the air stream, study of the silicon dioxide particles,

and measurement of the retention of these particles in the filter paper are satisfactory. The electron microscope method has the advantage of revealing the state of agglomeration or dispersion of the particles.

4. The rate of loss of silicon dioxide and boron oxide particles from a stream of air during laminar flow in a small tube is high, and this is believed to be due to an anomalously high diffusion coefficient for such particles in air. It is believed that the high collection efficiency for particles of silicon dioxide is attributable to this hypothesized abnormally high diffusion rate.

5. The General Electric Continuous Condensation Nuclei Detector (CN Meter) and its associated sampling device for withdrawing air samples from the main stream are satisfactory for the measurement of particle count at very low concentration levels (e.g., 1×10^{-10} to 30×10^{-10} gram per cubic meter), where the rate of loss of the particles from the air stream to the tube wall is not abnormally high.

6. The aluminum oxide aerosol generator, developed in this study to meet the need for retention measurements for extremely small particles, functions in a stable manner and produces particles of size estimated to be about 0.004 micron (40 A.) in diameter.

7. The retention of the extremely small aluminum oxide particles in IPC 1478 paper, determined with the CN Meter, is primarily a function of absolute pressure and the flow rate; it increases with diminishing pressure and velocity and, the actual value depending on the exact conditions, is generally between about 30-75%.

8. The dependence of the retention of the aluminum oxide particles in IPC 1478 paper on pressure and velocity indicates that the controlling mechanism of capture is that of diffusion.

9. The presence of "Kronisol" (di-butoxyethyl phthalate) in IPC 1478 paper is regarded as important. The retentions observed in the present study for silicon dioxide and aluminum oxide particles were essentially the same for impregnated and unimpregnated filters. However, in earlier work with carbonyl iron particles, the retention was found to be very strongly dependent upon the presence or absence of the "Kronisol." It is concluded that, for some materials in particulate form, the probability of sticking fast to a fiber or fibril of the filter is greatly increased by the "Kronisol"; accordingly, for general use of IPC 1478 paper, the presence of "Kronisol" is considered necessary.

10. It has been possible to evolve a data reduction theory, the use of which leads to a unique relationship between a "reduced pressure drop" and a "reduced Reynolds' number" (see text). The standard deviation of the individual data points from the relationship determined by least-squares fitting is of the order of 6% (resulting from sample variability, experimental error, and all other sources of variance).

11. Some of the variance in pressure drop-flow rate data is due to failure in the field and in the laboratory to take into account the effect of compaction of a filter caused by the pressure drop (and creep in this compaction). Some of the variance is probably due to "slip" in the flow of air through a filter, particularly at the lowest absolute pressures.

12. Although (for a given pressure drop) the total rate of collection of particulate matter in the field would be lessened somewhat by the use of two-ply filters, the uncertainty in the retention would be reduced and, to the extent that the error in field sampling is related to this uncertainty, the accuracy of field work would be improved through the use of two-ply filters.

SUGGESTIONS FOR FUTURE RESEARCH

A study should be made of the apparently anomalous diffusion of particles of silicon dioxide and boron oxide, for it seems highly probable that the mechanism of the very high diffusion rate in tubing is also active in a filter medium. It is suspected that the particles of a number of substances display substantially higher diffusion coefficients than can be accounted for on the basis of modern diffusion theory and, hence, a more general theoretical and experimental study should be made of the phenomena underlying the diffusion of particles of various classes of substances. This study should include an examination of the commonly held idea that, when a very small particle makes contact with a solid surface, the probability of remaining on the surface is essentially unity.

It was not possible in the present study to examine the size and shape of the aluminum oxide particles through the use of the electron microscope (an old RCA Type EMB whose resolution had been greatly improved). At the time of writing, a new electron microscope (RCA Type EMU-3f) has been installed with funds kindly granted by The Louis Calder Foundation. The resolution of the new instrument is better than 15 A. (often about 10 A. according to informal reports), and the contrast of electron micrographs obtained with the new microscope is superior to that of the older models. Accordingly, it is

suggested that an examination of the aluminum oxide particles be made with the new equipment; this study would probably include efforts to reduce the structural imperfections of the supporting film on a grid and to improve the probability of capture of particles by a grid.

The mechanical compaction of IPC 1478 paper (and the creep in this compaction) under the compressive action of the pressure drop, is, in the opinion of the writers, a significant effect in the pressure drop-flow rate relationship. It is suggested that any future project on the properties of IPC 1478 paper include a careful investigation of this phenomenon. Some attention should also be devoted to the role of "slip" in the flow of air through the filter paper, particularly at the lowest pressures of interest, where the slip effect may be significant.

ACKNOWLEDGMENTS

The application of modern diffusion theory to the diffusion of very small particles, and the theory of diffusion of particles out of a stream of gas in a tube, presented in Appendix III, is the work of Dr. Richard W. Nelson of the Physics Group. Dr. Nelson also programmed the Institute's IBM 610 computer for many of the calculations needed during the course of the work. Other members of the Physics Group who assisted valuably were Irwin W. Beckwith, who conducted much of the experimental development work and made many of the observations, and Robert J. Gertz, who, in addition to assisting in the taking of observations, performed the extremely tedious and exacting task of measuring and counting hundreds of thousands of aerosol particles on the electron micrographs. Grateful acknowledgement is also made of the

very effective aid, rendered during constructional phases of the project, given by members of the instrument and millwright shops. The inclusion of pressure drop-flow rate data for the machine-made samples of IPC 1478 paper, designated as "B" was kindly permitted by the Research Laboratory Division of the Bendix Aviation Corporation.

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APPENDIX I

TABLE I

PRESSURE DROP-FLOW RATE AND RETENTION DATA FOR IPC 1478 SAMPLES

Definitions of column-head symbols:

p , Downstream pressure, absolute, lb./sq. ft.

Δp , Pressure drop across filter, lb./sq. ft.

$\bar{V}$, Harmonic mean of the upstream and downstream velocities,
 $\bar{V} = 2V_1V_2/(V_1 + V_2)$, where V_1 and V_2 are, respectively, the
up- and downstream velocities; ft./sec.

$\bar{\sigma} \Delta p / \omega^2$, "Reduced" pressure drop, lb./sq. ft. See Appendix IV.

$\bar{\sigma} \bar{V} / \omega$, "Reduced" Reynolds' number, ft./sec. See Appendix IV.

The last column gives the retention of aluminum oxide particles, per cent.

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention,
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	%

Machine-Made Specimen A-1, Basis Weight 33.12 lb./1000 sq. ft. -40°F.

105.8	12.53	15.9	1.16	1.24	60
105.8	26.73	29.7	2.63	2.46	64
105.8	42.32	41.7	4.43	3.67	55
105.8	56.53	52.0	6.25	4.84	59
105.8	67.38	63.2	7.75	6.12	49
211.6	14.20	16.0	2.56	2.43	61
211.6	31.74	31.3	5.96	4.94	47
211.6	52.91	44.7	10.39	7.38	49
211.6	73.23	58.0	14.99	9.99	41
211.6	95.23	69.2	20.36	12.45	44
423.2	16.15	15.5	5.74	4.64	60
423.2	44.00	31.8	16.16	9.82	48
423.2	73.23	46.8	27.77	14.93	37
423.2	104.14	59.3	40.82	19.55	36
423.2	144.52	70.8	59.06	24.34	34

Machine-Made Specimen A-2, Basis Weight 32.80 lb./1000 sq. ft. -40°F.

105.8	12.53	15.6	1.16	1.21	73
105.8	25.06	29.0	2.45	2.38	69
105.8	38.70	42.3	4.00	3.67	63
105.8	53.46	53.2	5.84	4.89	56
105.8	67.66	62.8	7.79	6.08	50
211.6	15.59	15.8	2.82	2.41	46
211.6	32.30	31.3	6.07	4.95	58
211.6	50.68	44.7	9.90	7.35	48
211.6	73.23	58.0	14.99	9.99	47
211.6	96.90	68.5	20.78	12.36	46
423.2	17.82	16.2	6.35	4.86	46
423.2	41.77	31.0	15.30	9.55	50
423.2	76.85	46.7	29.26	14.96	42
423.2	105.81	59.0	41.55	19.49	36
423.2	146.46	71.0	59.97	24.46	36

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$P,$ lb./sq. ft.	$\Delta P,$ lb./sq. ft.	$\bar{V},$ ft./sec.	$\bar{\sigma} \Delta P / \omega^2,$ lb./sq. ft.	$\bar{\sigma} \bar{V} / \omega,$ ft./sec.	Retention, %
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Machine-Made Specimen A-3, Basis Weight 32.53 lb./1000 sq. ft. -40°F.

105.8	11.97	15.6	1.10	1.21	77
105.8	26.17	29.7	2.57	2.45	70
105.8	40.38	42.8	4.20	3.74	65
105.8	53.46	53.2	5.84	4.89	62
105.8	67.94	63.0	7.83	6.11	53
211.6	15.59	16.4	2.82	2.50	59
211.6	32.86	31.8	6.18	5.03	50
211.6	53.46	45.8	10.51	7.57	46
211.6	74.90	58.0	15.39	10.02	50
211.6	96.90	68.5	20.78	12.36	49
423.2	15.59	15.9	5.54	4.75	54
423.2	42.32	31.7	15.51	9.77	48
423.2	72.68	46.2	27.55	14.73	42
423.2	105.81	59.2	41.55	19.56	46
423.2	146.46	71.0	59.97	24.46	46

Machine-Made Specimen A-4, Basis Weight 32.83 lb./1000 sq. ft. -40°F.

105.8	12.53	15.6	1.16	1.21	63
105.8	25.62	29.8	2.51	2.45	69
105.8	40.93	42.2	4.26	3.70	71
105.8	51.79	53.5	5.63	4.89	63
105.8	67.11	63.0	7.71	6.09	56
211.6	15.04	16.2	2.72	2.46	53
211.6	30.91	30.8	5.79	4.85	54
211.6	52.35	46.0	10.27	7.59	51
211.6	73.79	57.0	15.12	9.83	48
211.6	97.46	68.0	20.93	12.28	34
423.2	15.59	15.4	5.54	4.61	53
423.2	41.77	32.0	15.30	9.86	39
423.2	73.79	46.0	28.00	14.68	36
423.2	104.70	59.3	41.07	19.57	35
423.2	141.45	71.3	57.63	24.43	29

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	

Machine-Made Specimen A-5, Basis Weight 32.15 lb./1000 sq. ft. -40°F.

105.8	11.42	15.6	1.05	1.21	69
105.8	26.73	29.8	2.63	2.46	64
105.8	40.38	42.7	4.20	3.73	56
105.8	54.02	52.5	5.92	4.84	61
105.8	66.55	63.3	7.63	6.11	57
211.6	14.76	16.0	2.67	2.43	70
211.6	30.91	30.8	5.79	4.85	49
211.6	55.41	46.5	10.94	7.72	45
211.6	70.73	57.8	14.41	9.90	52
211.6	97.46	68.3	20.93	12.34	23
423.2	17.82	17.2	6.35	5.16	46
423.2	40.93	31.8	14.98	9.79	38
423.2	73.79	46.8	28.00	14.94	54
423.2	102.19	59.2	39.98	19.48	47
423.2	141.73	71.3	57.76	24.44	36

Machine-Made Specimen A-6, Basis Weight 32.48 lb./1000 sq. ft. -40°F.

105.8	11.97	16.2	.87	1.06	75
105.8	25.62	29.7	1.97	2.07	62
105.8	38.15	42.3	3.08	3.10	63
105.8	54.02	53.2	4.65	4.15	53
105.8	65.44	63.7	5.87	5.18	44
211.6	14.76	16.0	2.09	2.06	64
211.6	33.41	32.2	4.94	4.32	47
211.6	48.17	44.8	7.35	6.20	38
211.6	72.12	58.2	11.56	8.47	45
211.6	91.61	67.7	15.27	10.24	42
423.2	19.77	17.7	5.54	4.50	38
423.2	39.82	31.8	11.42	8.28	43
423.2	67.38	45.5	19.93	12.21	47
423.2	102.47	59.5	31.48	16.58	42
423.2	133.10	72.0	42.21	20.71	31

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen A-7, Basis Weight 32.80 lb./1000 sq. ft. 0°F.					
105.8	13.09	16.3	.95	1.08	67
105.8	25.62	29.0	1.97	2.02	65
105.8	37.59	42.5	3.03	3.11	61
105.8	53.46	53.2	4.59	4.14	42
105.8	65.44	63.0	5.87	5.13	43
211.6	14.20	15.8	2.01	2.03	65
211.6	32.30	31.0	4.76	4.15	49
211.6	51.79	46.8	7.96	6.53	46
211.6	72.68	57.7	11.67	8.40	46
211.6	91.61	68.5	15.27	10.36	48
423.2	16.15	15.9	4.51	4.03	46
423.2	39.82	31.0	11.42	8.07	50
423.2	67.66	46.8	20.02	12.56	36
423.2	96.34	59.8	29.41	16.56	41
423.2	137.55	71.7	43.82	20.72	28
Machine-Made Specimen A-8, Basis Weight 32.99 lb./1000 sq. ft. 0°F.					
105.8	12.53	16.2	.91	1.07	74
105.8	27.85	29.5	2.16	2.07	67
105.8	40.93	41.8	3.35	3.10	58
105.8	56.53	53.7	4.91	4.23	59
105.8	67.66	63.2	6.12	5.18	53
211.6	14.76	16.1	2.09	2.07	38
211.6	33.69	31.7	4.98	4.25	57
211.6	54.02	45.2	8.35	6.34	48
211.6	71.84	57.0	11.51	8.29	44
211.6	97.46	69.2	16.43	10.58	32
423.2	20.33	17.8	5.70	4.53	55
423.2	41.77	32.0	12.01	8.35	48
423.2	72.68	46.0	21.62	12.42	43
423.2	107.76	59.2	33.29	16.59	35
423.2	138.11	71.7	44.02	20.73	30

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen A-9, Basis Weight 33.28 lb./1000 sq. ft. 0°F.					
105.8	13.09	16.5	.95	1.09	72
105.8	28.40	29.7	2.21	2.09	62
105.8	41.77	41.5	3.43	3.09	61
105.8	57.08	52.5	4.97	4.14	55
105.8	68.50	63.0	6.21	5.18	50
211.6	16.15	16.4	2.30	2.12	69
211.6	35.92	32.3	5.34	4.36	60
211.6	54.58	45.2	8.44	6.34	57
211.6	74.90	56.0	12.08	8.19	53
211.6	99.41	69.3	16.82	10.64	47
423.2	19.77	17.5	5.54	4.45	48
423.2	44.00	31.7	12.68	8.29	47
423.2	74.35	46.2	22.16	12.49	33
423.2	104.70	59.3	32.24	16.56	18
423.2	143.96	71.2	46.16	20.71	21
Machine-Made Specimen A-10, Basis Weight 32.87 lb./sq. ft. 0°F.					
105.8	12.53	15.9	.91	1.05	74
105.8	26.17	30.3	2.01	2.12	61
105.8	40.38	41.5	3.29	3.07	46
105.8	52.91	53.3	4.53	4.14	56
105.8	64.88	63.8	5.81	5.18	54
211.6	15.31	16.4	2.17	2.11	71
211.6	32.58	31.8	4.81	4.26	54
211.6	52.35	44.8	8.06	6.26	37
211.6	74.90	57.8	12.08	8.46	26
211.6	95.23	69.3	15.98	10.55	46
423.2	18.38	16.8	5.15	4.27	53
423.2	41.49	32.5	11.93	8.48	39
423.2	69.61	46.2	20.64	12.43	34
423.2	99.41	59.7	30.44	16.58	25
423.2	133.10	71.3	42.21	20.51	32

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen A-11, Basis Weight 33.27 lb./1000 sq. ft. 70°F.					
105.8	13.64	15.5	.69	.79	72
105.8	26.17	29.7	1.39	1.61	66
105.8	40.93	41.2	2.31	2.37	59
105.8	55.41	52.2	3.31	3.17	59
105.8	69.61	62.7	4.38	4.01	44
211.6	15.59	15.8	1.53	1.58	71
211.6	34.25	31.5	3.50	3.28	58
211.6	54.02	45.2	5.77	4.91	39
211.6	73.23	56.8	8.13	6.41	40
211.6	93.84	68.2	10.85	8.02	37
423.2	18.93	17.5	3.66	3.44	42
423.2	41.49	31.8	8.24	6.42	45
423.2	66.55	45.5	13.59	9.45	40
423.2	96.34	58.7	20.32	12.59	31
423.2	129.20	72.3	28.19	16.04	30
Machine-Made Specimen A-12, Basis Weight 33.14 lb./1000 sq. ft. 70°F.					
105.8	13.64	15.5	.69	.79	70
105.8	27.85	29.5	1.49	1.61	72
105.8	41.49	41.8	2.35	2.41	62
105.8	54.58	51.7	3.25	3.13	61
105.8	68.50	63.0	4.29	4.01	59
211.6	15.59	16.1	1.53	1.61	65
211.6	33.69	32.2	3.44	3.35	60
211.6	50.68	45.3	5.37	4.88	43
211.6	70.73	57.8	7.81	6.49	45
211.6	93.28	69.7	10.78	8.19	50
423.2	16.71	16.2	3.23	3.18	54
423.2	39.82	32.0	7.89	6.45	39
423.2	65.44	46.3	13.35	9.60	41
423.2	94.12	59.3	19.80	12.68	38
423.2	125.02	72.3	27.17	15.97	25

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	

Machine-Made Specimen A-13, Basis Weight 32.66 lb./1000 sq. ft. 70°F.

105.8	13.09	15.5	.66	.79	74
105.8	28.68	30.3	1.54	1.66	60
105.8	40.38	41.3	2.28	2.37	56
105.8	54.58	52.0	3.25	3.15	61
105.8	67.94	63.0	4.25	4.01	67
211.6	16.15	16.7	1.59	1.67	66
211.6	32.30	30.7	3.29	3.18	54
211.6	51.79	45.5	5.50	4.92	49
211.6	70.17	57.2	7.74	6.42	52
211.6	92.17	68.5	10.62	8.03	49
423.2	17.82	16.5	3.44	3.24	51
423.2	41.49	32.5	8.24	6.56	48
423.2	67.38	46.3	13.77	9.62	43
423.2	94.12	59.2	19.80	12.66	36
423.2	127.25	72.5	27.71	16.05	30

Machine-Made Specimen A-14, Basis Weight 33.01 lb./1000 sq. ft. 70°F.

105.8	13.64	15.5	.69	.79	71
105.8	27.29	29.0	1.46	1.58	63
105.8	40.38	40.7	2.28	2.33	66
105.8	54.85	51.7	3.27	3.13	64
105.8	68.50	63.0	4.29	4.01	61
211.6	15.59	16.1	1.53	1.61	67
211.6	33.97	31.8	3.47	3.31	58
211.6	48.73	43.7	5.14	4.69	56
211.6	71.84	57.3	7.95	6.45	49
211.6	89.94	67.3	10.32	7.85	48
423.2	19.77	17.7	3.83	3.49	60
423.2	38.70	31.0	7.66	6.24	47
423.2	65.99	46.3	13.47	9.61	35
423.2	94.12	58.5	19.80	12.51	38
423.2	127.25	72.5	27.71	16.05	37

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen A-15, Basis Weight 33.17 lb./1000 sq. ft. 70°F.					
105.8	13.64	15.5	.69	.79	70
105.8	27.29	29.5	1.46	1.60	66
105.8	41.77	42.0	2.37	2.42	62
105.8	54.02	52.0	3.21	3.14	67
105.8	67.94	63.0	4.25	4.01	64
211.6	16.15	16.2	1.59	1.62	69
211.6	33.69	30.8	3.44	3.20	60
211.6	52.35	45.3	5.57	4.90	53
211.6	70.73	57.2	7.81	6.43	38
211.6	90.50	68.2	10.40	7.97	53
423.2	17.26	16.2	3.34	3.18	58
423.2	41.49	32.3	8.24	6.52	61
423.2	67.94	46.3	13.90	9.63	53
423.2	95.79	59.0	20.19	12.64	35
423.2	128.37	72.3	27.99	16.03	27

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen L-1, Basis Weight 34.94 lb./1000 sq. ft.			-40°F.		
105.8	12.53	15.9	1.16	1.24	65
105.8	28.40	30.1	2.81	2.51	61
105.8	43.44	42.3	4.57	3.74	57
105.8	54.85	52.9	6.03	4.89	59
105.8	70.73	62.2	8.23	6.09	52
211.6	15.59	16.4	2.82	2.50	62
211.6	33.97	30.7	6.40	4.87	56
211.6	55.97	45.6	11.06	7.58	51
211.6	80.19	57.2	16.65	9.99	53
211.6	100.52	67.0	21.71	12.17	55
423.2	19.77	16.6	7.06	4.99	49
423.2	45.67	32.3	16.80	10.00	48
423.2	81.59	46.3	31.22	14.91	25
423.2	111.94	58.9	44.24	19.58	20
423.2	154.54	70.4	63.79	24.45	36
Machine-Made Specimen L-2, Basis Weight 34.64 lb./1000 sq. ft.			-40°F.		
105.8	12.53	15.6	1.16	1.21	70
105.8	27.29	29.7	2.69	2.46	62
105.8	40.93	42.7	4.26	3.74	61
105.8	54.58	52.7	5.99	4.87	59
105.8	69.06	62.8	7.99	6.11	47
211.6	15.59	16.2	2.82	2.47	61
211.6	31.74	30.8	5.96	4.86	52
211.6	51.23	44.9	10.02	7.39	40
211.6	76.02	57.3	15.65	9.92	35
211.6	94.67	67.4	20.22	12.11	34
423.2	16.15	15.7	5.74	4.70	58
423.2	40.38	31.3	14.77	9.63	44
423.2	75.46	46.6	28.69	14.90	47
423.2	109.43	59.0	43.14	19.56	40
423.2	142.29	71.3	58.02	24.46	41

$P,$ lb./sq. ft.	$\Delta P,$ lb./sq. ft.	$\bar{V},$ ft./sec.	$\bar{\sigma} \Delta P / \omega^2,$ lb./sq. ft.	$\bar{\sigma} \bar{V} / \omega,$ ft./sec.	Retention, %
Machine-Made Specimen L-3, Basis Weight 34.93 lb./1000 sq. ft. -40°F.					
105.8	12.53	15.6	1.16	1.21	70
105.8	28.40	29.1	2.81	2.42	61
105.8	42.88	41.8	4.50	3.69	57
105.8	56.53	52.6	6.25	4.89	54
105.8	71.28	62.3	8.32	6.11	52
211.6	15.59	16.1	2.82	2.45	60
211.6	32.30	29.7	6.07	4.69	57
211.6	50.68	43.2	9.90	7.10	51
211.6	76.02	55.9	15.65	9.68	48
211.6	103.58	67.2	22.50	12.28	46
423.2	17.82	16.6	6.35	4.98	58
423.2	44.55	31.8	16.37	9.83	39
423.2	80.75	46.6	30.88	14.99	40
423.2	114.72	58.7	45.47	19.57	29
423.2	150.64	70.8	61.94	24.49	40
Machine-Made Specimen L-4, Basis Weight 34.42 lb./1000 sq. ft. -40°F.					
105.8	13.09	15.5	1.21	1.21	64
105.8	27.85	29.2	2.75	2.43	56
105.8	45.11	41.9	4.78	3.73	59
105.8	56.53	52.3	6.25	4.86	57
105.8	70.17	62.6	8.15	6.12	45
211.6	16.15	16.2	2.93	2.47	72
211.6	34.53	31.6	6.52	5.02	44
211.6	57.08	46.1	11.31	7.68	47
211.6	76.30	57.2	15.72	9.91	39
211.6	100.52	67.3	21.71	12.23	38
423.2	20.88	18.2	7.47	5.48	57
423.2	44.00	31.8	16.16	9.82	48
423.2	77.97	46.1	29.72	14.78	34
423.2	113.05	58.8	44.73	19.57	27
423.2	154.82	70.4	63.93	24.45	34

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen L-5, Basis Weight 34.23 lb./1000 sq. ft. -40°F.					
105.8	12.53	15.7	1.16	1.22	66
105.8	26.73	29.6	2.63	2.45	57
105.8	42.88	42.3	4.50	3.73	53
105.8	57.64	52.9	6.40	4.94	47
105.8	67.66	62.6	7.79	6.06	46
211.6	15.31	16.1	2.77	2.45	54
211.6	33.69	30.9	6.35	4.90	53
211.6	53.46	45.1	10.51	7.46	48
211.6	75.46	56.5	15.52	9.77	48
211.6	100.52	67.3	21.71	12.23	39
423.2	16.15	15.7	5.74	4.70	52
423.2	45.11	32.3	16.58	9.99	46
423.2	77.41	46.7	29.49	14.97	37
423.2	111.94	58.6	44.24	19.48	51
423.2	146.19	70.7	59.84	24.34	46
Machine-Made Specimen L-6, Basis Weight 34.10 lb./1000 sq. ft. 0°F.					
105.8	13.64	15.9	.99	1.05	70
105.8	28.40	29.4	2.21	2.07	66
105.8	40.93	42.0	3.35	3.12	63
105.8	57.08	52.4	4.97	4.14	51
105.8	67.11	62.2	6.05	5.09	45
211.6	16.15	16.4	2.30	2.12	63
211.6	37.31	30.6	5.56	4.14	52
211.6	61.82	45.1	9.71	6.42	54
211.6	82.70	56.0	13.54	8.32	41
211.6	104.70	67.9	17.89	10.53	40
423.2	22.00	17.5	6.18	4.46	59
423.2	44.55	32.0	12.85	8.37	47
423.2	77.97	46.7	23.33	12.68	49
423.2	108.87	59.0	33.67	16.55	34
423.2	148.14	70.6	47.70	20.62	30

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen L-7, Basis Weight 33.83 lb./1000 sq. ft.				0°F.	
105.8	13.09	15.8	.95	1.04	71
105.8	28.40	29.4	2.21	2.07	63
105.8	45.11	41.9	3.75	3.16	55
105.8	57.08	52.4	4.97	4.14	54
105.8	74.90	61.5	6.95	5.17	57
211.6	16.15	16.0	2.30	2.06	68
211.6	35.92	30.7	5.34	4.14	58
211.6	54.58	43.1	8.44	6.05	61
211.6	78.52	57.9	12.75	8.53	61
211.6	98.85	67.5	16.71	10.35	44
423.2	18.38	16.8	5.15	4.27	49
423.2	40.38	32.0	11.59	8.33	46
423.2	72.68	46.0	21.62	12.42	44
423.2	110.82	58.6	34.34	16.47	32
423.2	145.07	71.1	46.57	20.70	40
Machine-Made Specimen L-8, Basis Weight 34.58 lb./1000 sq. ft.				0°F.	
105.8	13.09	15.8	.95	1.04	68
105.8	26.73	28.8	2.06	2.02	61
105.8	44.00	41.9	3.64	3.15	65
105.8	57.64	52.3	5.02	4.14	61
105.8	69.06	62.8	6.27	5.18	49
211.6	17.26	16.5	2.46	2.13	66
211.6	35.08	30.5	5.21	4.11	54
211.6	55.41	44.2	8.59	6.21	33
211.6	78.52	55.9	12.75	8.24	41
211.6	99.96	67.1	16.93	10.31	35
423.2	19.77	17.9	5.54	4.55	54
423.2	44.55	31.8	12.85	8.32	53
423.2	76.30	46.2	22.79	12.52	35
423.2	109.99	59.0	34.06	16.57	46
423.2	138.67	71.6	44.22	20.72	17

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen L-9, Basis Weight 33.74 lb./1000 sq. ft. 0°F.					
105.8	13.64	15.8	.99	1.05	69
105.8	28.68	29.4	2.23	2.07	61
105.8	41.21	41.4	3.37	3.07	59
105.8	56.53	52.4	4.91	4.13	53
105.8	69.61	62.4	6.34	5.15	56
211.6	16.15	16.0	2.30	2.06	53
211.6	34.25	31.5	5.07	4.23	50
211.6	52.35	43.6	8.06	6.09	42
211.6	78.52	56.2	12.75	8.28	49
211.6	101.08	67.2	17.16	10.35	52
423.2	20.33	17.9	5.70	4.56	46
423.2	41.77	31.8	12.01	8.30	34
423.2	73.79	45.5	21.98	12.30	42
423.2	106.92	59.2	33.00	16.58	39
423.2	139.23	71.3	44.43	20.64	39
Machine-Made Specimen L-10, Basis Weight 33.60 lb./1000 sq. ft. 0°F.					
105.8	12.53	15.9	.91	1.05	61
105.8	26.73	28.9	2.06	2.02	61
105.8	41.77	42.0	3.43	3.13	63
105.8	51.23	53.7	4.36	4.15	53
105.8	67.94	62.8	6.15	5.16	46
211.6	15.31	15.6	2.17	2.01	61
211.6	32.86	30.9	4.85	4.14	39
211.6	50.68	42.9	7.77	5.97	44
211.6	72.12	55.6	11.56	8.09	50
211.6	98.85	67.7	16.71	10.38	30
423.2	17.82	16.3	4.99	4.14	47
423.2	41.49	31.8	11.93	8.29	44
423.2	72.68	46.0	21.62	12.42	34
423.2	108.87	59.1	33.67	16.58	26
423.2	140.34	71.5	44.83	20.72	35

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen L-11, Basis Weight 33.64 lb./1000 sq. ft. 70°F.					
105.8	13.64	15.5	.69	.79	72
105.8	27.85	30.0	1.49	1.63	64
105.8	41.49	41.7	2.35	2.40	67
105.8	55.97	52.4	3.35	3.19	66
105.8	70.73	61.8	4.47	3.97	64
211.6	16.15	16.2	1.59	1.62	78
211.6	32.30	30.3	3.29	3.14	68
211.6	54.58	46.9	5.83	5.10	55
211.6	74.35	58.4	8.27	6.61	50
211.6	95.79	68.2	11.12	8.05	41
423.2	17.82	16.6	3.44	3.26	58
423.2	40.38	31.8	8.01	6.41	54
423.2	68.50	45.9	14.02	9.55	29
423.2	98.01	58.7	20.71	12.61	35
423.2	134.49	71.9	29.51	16.04	31
Machine-Made Specimen L-12, Basis Weight 33.35 lb./1000 sq. ft. 70°F.					
105.8	12.53	15.6	.63	.80	69
105.8	27.29	29.5	1.46	1.60	67
105.8	41.49	41.1	2.35	2.37	61
105.8	55.41	52.1	3.31	3.16	62
105.8	70.17	62.4	4.42	4.00	56
211.6	15.59	16.1	1.53	1.61	66
211.6	34.81	31.4	3.57	3.27	57
211.6	53.46	44.7	5.70	4.85	51
211.6	76.85	57.8	8.60	6.57	38
211.6	98.01	69.3	11.43	8.21	46
423.2	20.33	17.9	3.94	3.53	58
423.2	44.00	33.1	8.76	6.70	43
423.2	71.28	46.1	14.63	9.62	35
423.2	99.96	58.4	21.16	12.57	37
423.2	135.61	71.8	29.79	16.04	35

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen L-13, Basis Weight 33.52 lb./1000 sq. ft. 70°F.					
105.8	12.53	15.6	.63	.80	74
105.8	26.73	29.6	1.43	1.60	67
105.8	41.49	41.8	2.35	2.41	66
105.8	52.91	52.0	3.13	3.13	65
105.8	68.50	62.9	4.29	4.01	65
211.6	15.59	16.1	1.53	1.61	77
211.6	33.69	31.8	3.44	3.30	61
211.6	50.12	44.7	5.31	4.81	54
211.6	71.28	58.5	7.88	6.58	46
211.6	89.94	68.1	10.32	7.95	48
423.2	17.82	17.1	3.44	3.36	62
423.2	39.26	31.8	7.78	6.41	46
423.2	65.99	46.1	13.47	9.57	46
423.2	92.72	58.3	19.48	12.45	36
423.2	130.31	72.2	28.47	16.04	41
Machine-Made Specimen L-14, Basis Weight 33.76 lb./1000 sq. ft. 70°F.					
105.8	13.09	15.5	.66	.79	77
105.8	26.73	29.6	1.43	1.60	69
105.8	41.77	41.8	2.37	2.41	69
105.8	55.41	52.1	3.31	3.16	62
105.8	71.28	62.3	4.51	4.01	62
211.6	16.15	16.1	1.59	1.61	76
211.6	34.25	31.5	3.50	3.28	66
211.6	52.35	44.5	5.57	4.81	60
211.6	74.35	57.2	8.27	6.47	52
211.6	95.79	68.0	11.12	8.03	53
423.2	18.38	16.6	3.55	3.26	67
423.2	42.88	32.5	8.53	6.57	51
423.2	71.28	46.1	14.63	9.62	52
423.2	100.24	58.9	21.23	12.68	45
423.2	135.05	71.8	29.65	16.03	44

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen L-15, Basis Weight 33.69 lb./1000 sq. ft. 70°F.					
105.8	13.64	15.5	.69	.79	73
105.8	28.40	29.4	1.52	1.60	71
105.8	41.49	41.2	2.35	2.37	69
105.8	54.85	52.1	3.27	3.16	63
105.8	69.61	62.2	4.38	3.98	59
211.6	16.71	16.0	1.64	1.60	65
211.6	34.53	31.9	3.54	3.32	62
211.6	49.29	43.6	5.21	4.69	50
211.6	70.73	57.1	7.81	6.41	62
211.6	96.34	68.2	11.20	8.06	60
423.2	17.82	16.5	3.44	3.24	63
423.2	39.26	31.0	7.78	6.24	52
423.2	67.66	45.5	13.83	9.46	40
423.2	97.46	58.9	20.58	12.64	29
423.2	131.43	72.1	28.75	16.03	27

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen H-1, Basis Weight 36.84 lb./1000 sq. ft. -40°F.					
105.8	13.09	15.5	1.21	1.21	75
105.8	28.68	29.0	2.84	2.42	71
105.8	44.00	41.4	4.64	3.67	69
105.8	58.75	52.1	6.55	4.89	55
105.8	71.28	62.3	8.32	6.11	69
211.6	16.15	15.8	2.93	2.41	70
211.6	33.41	30.1	6.29	4.77	60
211.6	55.41	45.1	10.94	7.49	63
211.6	79.08	56.2	16.38	9.79	44
211.6	103.58	66.9	22.50	12.23	52
423.2	18.93	16.6	6.76	4.98	39
423.2	45.11	31.3	16.58	9.68	43
423.2	81.03	45.8	30.99	14.74	34
423.2	115.56	58.3	45.84	19.46	37
423.2	153.43	70.5	63.26	24.45	28
Machine-Made Specimen H-2, Basis Weight 36.47 lb./1000 sq. ft. -40°F.					
105.8	13.37	15.5	1.24	1.21	69
105.8	28.68	28.6	2.84	2.38	72
105.8	44.00	41.7	4.64	3.70	64
105.8	61.82	49.0	6.97	4.65	61
105.8	72.12	62.1	8.44	6.11	53
211.6	16.71	15.7	3.03	2.40	57
211.6	31.74	29.6	5.96	4.67	46
211.6	54.02	44.3	10.63	7.33	48
211.6	81.59	57.0	16.98	9.98	46
211.6	107.20	66.4	23.45	12.22	52
423.2	17.26	15.5	6.15	4.64	52
423.2	43.44	30.9	15.94	9.54	51
423.2	80.75	45.9	30.88	14.76	32
423.2	114.16	58.7	45.23	19.56	39
423.2	153.43	70.5	63.26	24.45	10

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	

Machine-Made Specimen H-3, Basis Weight 36.00 lb./1000 sq. ft. -40°F.

105.8	13.09	15.8	1.21	1.23	77
105.8	27.29	29.2	2.69	2.42	67
105.8	44.55	41.8	4.71	3.71	67
105.8	59.03	52.6	6.59	4.94	66
105.8	71.84	62.2	8.40	6.12	64
211.6	15.59	15.7	2.82	2.39	65
211.6	32.86	30.0	6.18	4.75	54
211.6	54.58	44.3	10.75	7.34	58
211.6	81.03	56.2	16.85	9.83	45
211.6	101.08	66.7	21.85	12.13	51
423.2	19.49	17.4	6.96	5.23	52
423.2	47.06	32.2	17.34	9.98	52
423.2	80.75	46.9	30.88	15.09	39
423.2	114.16	58.7	45.23	19.56	42
423.2	159.27	70.6	66.06	24.63	31

Machine-Made Specimen H-4, Basis Weight 35.66 lb./1000 sq. ft. -40°F.

105.8	12.53	15.5	1.16	1.21	72
105.8	27.29	29.7	2.69	2.46	68
105.8	44.00	42.4	4.64	3.76	59
105.8	56.53	51.8	6.25	4.82	73
105.8	69.61	62.7	8.07	6.12	61
211.6	16.15	16.2	2.93	2.47	71
211.6	32.86	30.9	6.18	4.89	45
211.6	55.41	45.4	10.94	7.54	43
211.6	79.64	57.2	16.51	9.98	44
211.6	101.08	68.3	21.85	12.42	35
423.2	19.49	16.9	6.96	5.08	59
423.2	45.11	31.6	16.58	9.77	35
423.2	77.97	46.1	29.7	14.78	33
423.2	110.54	58.9	43.63	19.55	35
423.2	150.64	70.7	61.94	24.45	21

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention,
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	%

Machine-Made Specimen H-5, Basis Weight 36.28 lb./1000 sq. ft. -40°F.

105.8	12.53	15.2	1.16	1.18	71
105.8	28.40	29.8	2.81	2.48	67
105.8	44.55	42.7	4.71	3.79	54
105.8	59.59	52.0	6.66	4.89	60
105.8	71.28	62.1	8.32	6.09	60
211.6	16.15	16.4	2.93	2.50	64
211.6	33.69	30.8	6.35	4.88	50
211.6	58.20	45.4	11.55	7.58	54
211.6	74.90	55.7	15.39	9.62	49
211.6	103.03	66.2	22.36	12.09	27
423.2	16.71	15.5	5.95	4.64	57
423.2	45.94	31.4	16.91	9.72	57
423.2	77.41	46.1	29.49	14.77	43
423.2	116.67	58.6	46.34	19.58	36
423.2	155.93	70.4	64.46	24.48	31

Machine-Made Specimen H-6, Basis Weight 36.49 lb./1000 sq. ft. 0°F.

105.8	14.20	16.1	1.04	1.07	75
105.8	28.40	29.5	2.21	2.08	60
105.8	45.11	41.2	3.75	3.11	60
105.8	60.70	51.8	5.35	4.14	54
105.8	71.84	62.2	6.59	5.18	56
211.6	16.71	16.0	2.38	2.07	64
211.6	35.36	30.4	5.25	4.09	66
211.6	54.02	42.6	8.35	5.97	47
211.6	78.52	56.2	12.75	8.28	46
211.6	102.19	67.9	17.38	10.48	37
423.2	18.93	16.6	5.30	4.22	51
423.2	44.55	31.7	12.85	8.30	39
423.2	75.46	45.9	22.52	12.43	25
423.2	111.94	58.9	34.73	16.58	50
423.2	148.69	70.9	47.90	20.72	33

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P_s	ΔP_s	$\bar{V}_s$	$\bar{\sigma} \Delta P_s / \omega^2$	$\bar{\sigma} \bar{V}_s / \omega$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen H-7, Basis Weight 36.49 lb./1000 sq. ft. 0°F.					
105.8	13.09	16.1	.95	1.06	69
105.8	28.68	30.1	2.23	2.12	69
105.8	44.55	41.3	3.69	3.11	69
105.8	58.75	52.1	5.14	4.14	57
105.8	70.17	60.2	6.40	4.98	54
211.6	17.26	16.2	2.46	2.10	69
211.6	35.08	30.5	5.21	4.11	45
211.6	58.20	45.4	9.07	6.42	48
211.6	81.03	56.6	13.23	8.38	47
211.6	100.52	67.3	17.04	10.35	43
423.2	18.93	16.1	5.30	4.09	50
423.2	45.11	31.6	13.02	8.27	47
423.2	76.85	44.6	22.97	12.09	34
423.2	108.87	59.0	33.67	16.55	33
423.2	149.25	70.8	48.11	20.70	35
Machine-Made Specimen H-8, Basis Weight 35.31 lb./1000 sq. ft. 0°F.					
105.8	14.20	16.5	1.04	1.09	72
105.8	28.40	28.9	2.21	2.04	64
105.8	39.82	40.9	3.24	3.02	63
105.8	57.64	52.1	5.02	4.12	49
105.8	70.73	61.8	6.46	5.12	55
211.6	16.15	16.1	2.30	2.08	66
211.6	31.74	29.8	4.68	3.98	47
211.6	57.64	45.4	8.97	6.41	50
211.6	76.02	56.2	12.29	8.24	59
211.6	101.63	68.5	17.27	10.56	44
423.2	13.09	15.6	3.64	3.94	59
423.2	42.88	31.7	12.35	8.28	55
423.2	75.46	45.9	22.52	12.43	36
423.2	107.20	59.1	33.10	16.55	37
423.2	145.63	71.1	46.77	20.72	43

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen H-9, Basis Weight 35.55 lb./1000 sq. ft. 0°F.					
105.8	13.09	16.1	.95	1.06	72
105.8	28.68	30.3	2.23	2.14	60
105.8	41.21	41.6	3.37	3.09	53
105.8	54.85	52.9	4.73	4.14	51
105.8	71.28	62.3	6.53	5.18	53
211.6	16.15	16.4	2.30	2.12	62
211.6	34.53	32.3	5.12	4.34	48
211.6	52.91	44.6	8.15	6.24	41
211.6	76.02	56.5	12.29	8.28	45
211.6	102.47	68.2	17.44	10.53	42
423.2	16.71	15.8	4.67	4.01	58
423.2	42.88	31.7	12.35	8.28	48
423.2	70.73	46.3	21.00	12.47	37
423.2	106.92	59.5	33.00	16.66	32
423.2	145.63	71.1	43.77	20.72	33
Machine-Made Specimen H-10, Basis Weight 35.03 lb./1000 sq. ft. 0°F.					
105.8	13.09	15.8	.95	1.04	69
105.8	26.17	32.3	2.01	2.26	59
105.8	40.93	41.1	3.35	3.05	60
105.8	57.64	53.2	5.02	4.21	53
105.8	70.17	62.6	6.40	5.18	55
211.6	15.59	15.9	2.22	2.05	63
211.6	34.53	31.6	5.12	4.25	47
211.6	55.97	46.3	8.68	6.52	45
211.6	74.90	57.2	12.00	8.37	49
211.6	96.90	69.2	16.32	10.57	39
423.2	20.33	17.6	5.70	4.48	49
423.2	39.82	31.8	11.42	8.28	48
423.2	72.68	46.0	21.62	12.42	35
423.2	104.70	59.3	32.24	16.56	25
423.2	135.05	71.8	42.91	20.70	42

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	

Machine-Made Specimen H-11, Basis Weight 35.23 lb./1000 sq. ft. 70°F.

105.8	14.76	15.9	.75	.82	69
105.8	27.29	29.1	1.46	1.58	59
105.8	43.44	44.2	2.48	2.56	58
105.8	55.41	52.1	3.31	3.16	44
105.8	66.55	62.7	4.14	3.97	51
211.6	16.15	15.9	1.59	1.59	68
211.6	44.55	29.8	4.66	3.17	57
211.6	57.08	45.2	6.13	4.94	37
211.6	74.90	56.9	8.35	6.45	22
211.6	98.85	68.2	11.54	8.10	29
423.2	18.93	16.6	3.66	3.27	56
423.2	43.44	32.0	8.65	6.48	37
423.2	71.84	46.1	14.76	9.63	42
423.2	101.63	58.7	21.55	12.66	38
423.2	134.49	71.2	29.51	15.88	21

Machine-Made Specimen H-12, Basis Weight 35.17 lb./1000 sq. ft. 70°F.

105.8	13.09	16.0	.66	.82	68
105.8	26.17	29.1	1.39	1.57	62
105.8	39.82	42.0	2.24	2.40	59
105.8	52.91	52.5	3.13	3.16	53
105.8	67.38	62.7	4.20	3.98	53
211.6	15.31	15.9	1.50	1.59	64
211.6	32.02	30.8	3.26	3.19	61
211.6	50.96	44.6	5.40	4.81	50
211.6	70.73	57.1	7.81	6.41	35
211.6	92.72	68.3	10.70	8.01	40
423.2	18.93	17.4	3.66	3.42	52
423.2	51.23	32.2	10.29	6.57	47
423.2	67.94	46.6	13.90	9.69	45
423.2	95.79	59.3	20.19	12.71	38
423.2	128.09	72.4	27.92	16.05	26

P_1	ΔP_1	$\bar{V}_1$	$\bar{\sigma} \Delta P / \omega^2$	$\bar{\sigma} \bar{V} / \omega$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen H-13, Basis Weight 36.27 lb./1000 sq. ft. 70°F.					
105.8	13.64	15.5	.69	.79	68
105.8	29.24	30.0	1.58	1.64	55
105.8	44.00	41.5	2.52	2.41	52
105.8	57.08	51.9	3.43	3.17	39
105.8	71.28	61.6	4.51	3.96	50
211.6	17.26	16.6	1.70	1.66	67
211.6	34.53	31.1	3.54	3.24	58
211.6	55.97	44.9	6.00	4.89	55
211.6	74.90	57.2	8.35	6.48	48
211.6	100.52	69.2	11.78	8.24	27
423.2	22.00	18.3	4.27	3.61	53
423.2	43.44	32.3	8.65	6.54	44
423.2	73.79	46.0	15.19	9.63	41
423.2	102.19	58.0	21.68	12.51	36
423.2	139.78	71.5	30.83	16.04	33
Machine-Made Specimen H-14, Basis Weight 35.93 lb./1000 sq. ft. 70°F.					
105.8	13.64	15.5	.69	.79	64
105.8	28.40	29.5	1.52	1.61	63
105.8	42.88	41.6	2.44	2.41	52
105.8	54.85	51.8	3.27	3.14	52
105.8	69.06	62.8	4.34	4.01	48
211.6	16.71	16.4	1.64	1.64	56
211.6	33.69	31.0	3.44	3.22	47
211.6	51.79	43.8	5.50	4.73	49
211.6	73.79	56.7	8.20	6.41	32
211.6	96.34	68.6	11.20	8.11	23
423.2	18.93	16.6	3.66	3.27	49
423.2	45.11	32.7	9.00	6.63	36
423.2	70.73	45.9	14.51	9.57	31
423.2	99.96	58.1	21.16	12.51	28
423.2	136.16	71.8	29.93	16.05	31

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen H-15, Basis Weight 35.85 lb./1000 sq. ft. 70°F.					
105.8	14.20	15.4	.72	.79	69
105.8	27.85	29.4	1.49	1.60	67
105.8	41.49	41.1	2.35	2.37	48
105.8	55.41	51.5	3.31	3.13	50
105.8	70.17	61.9	4.42	3.97	53
211.6	16.15	16.2	1.59	1.62	72
211.6	33.97	31.3	3.47	3.25	58
211.6	53.46	45.9	5.70	4.98	57
211.6	74.90	58.0	8.35	6.57	53
211.6	96.34	68.6	11.20	8.11	34
423.2	19.49	17.4	3.78	3.43	58
423.2	40.38	31.6	8.01	6.37	43
423.2	67.94	46.3	13.90	9.63	42
423.2	96.90	59.1	20.45	12.68	36
423.2	133.10	72.3	29.16	16.11	15

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen FD 067a, Basis Weight 31.01 lb./1000 sq. ft. -40°F.					
105.8	13.09	15.7	1.21	1.22	75
105.8	26.17	29.7	2.57	2.45	69
105.8	38.70	42.5	4.00	3.69	57
105.8	54.58	53.0	5.99	4.89	68
105.8	67.66	62.5	7.79	6.05	64
211.6	15.31	16.6	2.77	2.53	46
211.6	31.46	30.5	5.90	4.81	47
211.6	49.84	44.5	9.72	7.30	41
211.6	74.90	57.3	15.39	9.90	52
211.6	95.23	67.3	20.36	12.10	36
423.2	17.82	17.3	6.35	5.19	56
423.2	39.82	30.5	14.55	9.38	39
423.2	72.68	46.3	27.55	14.76	37
423.2	106.92	59.2	42.04	19.58	19
423.2	145.07	71.2	59.32	24.49	31
Machine-Made Specimen FD 067b, Basis Weight 31.83 lb./1000 sq. ft. -40°F.					
105.8	12.53	15.6	1.16	1.21	77
105.8	25.62	30.5	2.51	2.51	64
105.8	38.15	42.7	3.93	3.70	66
105.8	52.91	53.0	5.77	4.86	66
105.8	67.11	63.0	7.71	6.09	68
211.6	15.31	16.4	2.77	2.49	64
211.6	32.30	31.7	6.07	5.01	63
211.6	50.12	45.0	9.78	7.39	48
211.6	70.73	57.3	14.41	9.82	53
211.6	94.12	68.2	20.08	12.24	24
423.2	15.59	15.6	5.54	4.67	60
423.2	40.38	31.3	14.77	9.63	35
423.2	71.28	46.5	26.98	14.80	36
423.2	103.58	59.2	40.58	19.51	30
423.2	152.31	70.3	62.73	24.36	44

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention,
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	%

Machine-Made Specimen FD 068b, Basis Weight 31.11 lb./1000 sq. ft. -40°F.

105.8	11.97	15.6	1.10	1.21	70
105.8	27.29	29.8	2.69	2.47	61
105.8	39.82	43.3	4.13	3.78	46
105.8	55.41	52.0	6.10	4.82	65
105.8	69.61	61.7	8.07	6.02	73
211.6	15.59	15.9	2.82	2.42	51
211.6	33.41	31.5	6.29	4.99	54
211.6	54.02	45.0	10.63	7.45	53
211.6	74.35	56.8	15.26	9.80	54
211.6	97.46	67.2	20.93	12.14	35
423.2	16.15	15.5	5.74	4.64	48
423.2	42.88	31.7	15.73	9.78	44
423.2	73.79	46.0	28.00	14.68	27
423.2	103.87	58.8	42.89	19.49	25
423.2	147.58	71.0	60.50	24.48	37

Machine-Made Specimen FD 069a, Basis Weight 30.83 lb./1000 sq. ft. -40°F.

105.8	12.53	15.3	1.16	1.19	72
105.8	27.29	29.7	2.69	2.46	64
105.8	40.38	42.7	4.20	3.73	58
105.8	53.46	53.2	5.84	4.89	61
105.8	65.99	63.5	7.55	6.12	59
211.6	14.76	16.3	2.67	2.48	62
211.6	32.30	31.0	6.07	4.90	57
211.6	50.12	44.7	9.78	7.34	48
211.6	76.02	58.0	15.65	10.04	47
211.6	98.29	68.3	21.14	12.36	43
423.2	16.71	16.2	5.95	4.85	55
423.2	43.44	32.3	15.94	9.97	34
423.2	74.35	46.7	28.23	14.92	39
423.2	107.76	59.0	42.40	19.53	26
423.2	147.02	71.0	60.23	24.47	25

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen FD 069b, Basis Weight 32.16 lb./1000 sq. ft. -40°F.					
105.8	12.53	15.9	1.16	1.24	68
105.8	26.17	30.3	2.57	2.50	62
105.8	40.93	42.5	4.26	3.72	57
105.8	56.53	52.0	6.25	4.84	67
105.8	66.55	63.2	7.63	6.10	63
211.6	15.59	16.2	2.82	2.47	62
211.6	33.69	31.2	6.35	4.95	48
211.6	52.91	45.7	10.39	7.55	51
211.6	76.85	57.8	15.85	10.03	52
211.6	98.01	67.7	21.07	12.24	37
423.2	17.26	16.5	6.15	4.94	52
423.2	42.88	32.0	15.73	9.87	43
423.2	76.02	46.7	28.92	14.94	32
423.2	107.76	59.2	42.40	19.60	48
423.2	147.02	71.0	60.23	24.47	44
Machine-Made Specimen FD 070a, Basis Weight 31.35 lb./1000 sq. ft. -40°F.					
105.8	12.53	15.9	1.16	1.24	69
105.8	25.62	28.8	2.51	2.37	58
105.8	39.82	42.3	4.13	3.69	49
105.8	54.58	52.7	5.99	4.87	48
105.8	66.55	63.2	7.63	6.10	50
211.6	14.76	16.0	2.67	2.43	67
211.6	31.74	31.3	5.96	4.94	58
211.6	47.61	44.0	9.25	7.19	59
211.6	73.23	57.2	14.99	9.85	43
211.6	93.84	67.2	20.01	12.05	44
423.2	16.71	16.2	5.95	4.85	51
423.2	40.93	32.0	14.98	9.85	35
423.2	72.12	46.3	27.32	14.75	41
423.2	105.81	59.3	41.55	19.59	42
423.2	145.63	71.2	59.58	24.50	36

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention,
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	%

Machine-Made Specimen FD 070b, Basis Weight 32.27 lb./1000 sq. ft. -40°F.

105.8	14.20	15.8	1.32	1.24	71
105.8	28.12	29.7	2.78	2.47	59
105.8	42.88	41.5	4.50	3.66	60
105.8	60.70	51.8	6.82	4.89	58
105.8	71.84	62.0	8.40	6.10	54
211.6	15.59	15.9	2.82	2.42	60
211.6	33.41	30.7	6.29	4.86	48
211.6	57.08	45.5	11.31	7.58	49
211.6	79.08	56.8	16.38	9.90	48
211.6	102.47	67.2	22.21	12.25	25
423.2	16.71	15.7	5.95	4.70	56
423.2	44.55	32.2	16.37	9.95	46
423.2	76.02	45.8	28.92	14.66	36
423.2	111.38	58.8	43.99	19.54	36
423.2	150.64	70.7	61.94	24.45	36

Machine-Made Specimen FD 071a, Basis Weight 31.87 lb./1000 sq. ft. -40°F.

105.8	13.09	15.5	1.21	1.21	69
105.8	29.24	30.0	2.90	2.51	67
105.8	45.11	41.8	4.78	3.72	53
105.8	57.08	52.2	6.32	4.87	57
105.8	70.17	62.5	8.15	6.11	53
211.6	16.15	16.5	2.93	2.51	56
211.6	36.48	31.3	6.92	4.99	70
211.6	51.79	43.5	10.15	7.17	63
211.6	74.90	56.0	15.39	9.68	34
211.6	102.47	67.8	22.21	12.36	47
423.2	17.26	15.5	6.15	4.64	47
423.2	45.11	32.3	16.58	9.99	44
423.2	77.41	46.7	29.49	14.97	35
423.2	111.94	58.7	44.24	19.52	19
423.2	149.81	70.8	61.55	24.47	25

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P_s	ΔP_s	$\bar{V}_s$	$\bar{\sigma} \Delta P_s / \omega_s^2$	$\bar{\sigma} \bar{V}_s / \omega_s$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	

Machine-Made Specimen FD 071b, Basis Weight 32.08 lb./1000 sq. ft. -40°F.

105.8	12.53	15.6	1.16	1.21	66
105.8	27.29	29.5	2.69	2.44	59
105.8	40.38	42.3	4.20	3.70	53
105.8	55.41	53.2	6.10	4.93	50
105.8	67.66	62.8	7.79	6.08	48
211.6	15.59	15.9	2.82	2.42	54
211.6	32.86	31.5	6.18	4.98	50
211.6	54.58	45.8	10.75	7.59	37
211.6	74.90	57.3	15.39	9.90	38
211.6	102.47	67.3	22.21	12.27	34
423.2	18.38	16.6	6.55	4.98	29
423.2	42.88	31.3	15.73	9.66	37
423.2	76.85	46.2	29.26	14.80	15
423.2	108.32	58.5	42.65	19.38	29
423.2	148.69	70.8	61.02	24.44	24

Machine-Made Specimen FD 072a, Basis Weight 32.37 lb./1000 sq. ft. -40°F.

105.8	12.53	15.6	1.16	1.21	64
105.8	26.17	30.3	2.57	2.50	59
105.8	43.44	42.7	4.57	3.78	53
105.8	52.91	53.3	5.77	4.89	49
105.8	66.55	63.3	7.63	6.11	44
211.6	15.04	15.9	2.72	2.42	57
211.6	30.63	30.0	5.73	4.72	55
211.6	49.29	44.0	9.60	7.21	45
211.6	73.79	57.5	15.12	9.91	39
423.2	15.31	15.9	5.44	4.75	52
423.2	42.88	31.7	15.73	9.78	41
423.2	72.12	46.8	27.32	14.91	42
423.2	107.20	59.2	42.16	19.58	36
423.2	138.11	71.7	56.08	24.49	34

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen FD 072b, Basis Weight 31.68 lb./1000 sq. ft. -40°F.					
105.8	13.09	15.5	1.21	1.21	62
105.8	27.29	29.8	2.69	2.47	60
105.8	42.88	42.3	4.50	3.73	47
105.8	55.41	52.8	6.10	4.89	44
105.8	71.84	62.2	8.40	6.12	52
211.6	16.15	15.9	2.93	2.42	61
211.6	33.69	31.3	6.35	4.96	50
211.6	52.35	43.8	10.27	7.23	31
211.6	74.62	56.7	15.32	9.79	30
211.6	98.85	67.5	21.28	12.22	33
423.2	18.38	16.6	6.55	4.98	49
423.2	45.67	32.0	16.80	9.90	49
423.2	74.35	46.0	28.23	14.69	42
423.2	113.05	58.8	44.73	19.57	38
423.2	150.64	71.3	61.94	24.66	38
Machine-Made Specimen WP 772, Basis Weight 31.31 lb./1000 sq. ft. -40°F.					
105.8	12.53	15.6	1.16	1.21	64
105.8	26.17	30.0	2.57	2.47	59
105.8	40.93	42.7	4.26	3.74	52
105.8	50.12	53.8	5.41	4.88	46
105.8	65.44	63.5	7.48	6.10	51
211.6	14.20	16.1	2.56	2.44	66
211.6	32.86	31.3	6.18	4.95	56
211.6	51.79	46.7	10.15	7.70	47
211.6	74.90	58.3	15.39	10.07	39
211.6	95.23	69.3	20.36	12.46	37
423.2	17.26	17.0	6.15	5.09	45
423.2	41.77	31.8	15.30	9.80	36
423.2	72.68	46.7	27.55	14.89	40
423.2	100.52	59.7	39.25	19.61	42
423.2	137.28	71.7	55.69	24.47	30

P_s	ΔP_s	$\bar{V}_s$	$\bar{\sigma} \Delta P_s / \omega^2$	$\bar{\sigma} \bar{V}_s / \omega$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen WP 771, Basis Weight 30.52 lb./1000 sq. ft. -40°F.					
105.8	11.97	15.9	1.10	1.23	61
105.8	23.39	29.7	2.27	2.42	53
105.8	38.70	42.5	4.00	3.69	55
105.8	50.12	52.8	5.41	4.79	46
105.8	65.99	63.2	7.55	6.09	34
211.6	14.48	16.3	2.61	2.47	59
211.6	30.63	31.7	5.73	4.99	43
211.6	49.84	46.2	9.72	7.58	47
211.6	70.17	57.2	14.28	9.79	34
211.6	90.50	68.6	19.17	12.23	31
423.2	17.26	17.6	6.15	5.27	55
423.2	39.26	31.8	14.34	9.77	52
423.2	71.84	46.8	27.20	14.91	45
423.2	100.52	59.6	39.25	19.58	32
423.2	137.55	71.9	55.82	24.54	21
Machine-Made Specimen WP 770, Basis Weight 30.85 lb./1000 sq. ft. -40°F.					
105.8	11.42	15.9	1.05	1.23	68
105.8	23.95	29.4	2.33	2.40	57
105.8	37.03	43.1	3.80	3.72	53
105.8	49.84	53.9	5.37	4.89	40
105.8	62.37	63.5	7.05	6.04	31
211.6	13.64	16.4	2.46	2.49	45
211.6	27.29	29.2	5.07	4.56	45
211.6	49.29	45.5	9.60	7.46	38
211.6	68.50	57.9	13.89	9.88	25
211.6	92.17	70.0	19.59	12.52	4
423.2	16.71	17.0	5.95	5.09	40
423.2	38.70	32.8	14.13	10.07	27
423.2	67.11	46.9	25.28	14.86	44
423.2	93.84	59.6	36.39	19.44	17
423.2	130.31	71.7	52.49	24.29	25

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine-Made Specimen WP 769, Basis Weight 30.34 lb./1000 sq. ft. -40°F.					
105.8	11.42	16.0	1.05	1.24	73
105.8	26.17	28.9	2.57	2.38	69
105.8	39.26	43.2	4.06	3.76	61
105.8	50.68	53.0	5.48	4.82	63
105.8	64.88	63.7	7.40	6.11	59
211.6	15.31	15.7	2.77	2.39	71
211.6	30.91	31.0	5.79	4.88	62
211.6	49.84	43.2	9.72	7.09	58
211.6	69.06	57.0	14.02	9.73	41
211.6	94.12	68.4	20.08	12.28	42
423.2	16.71	16.5	5.95	4.94	64
423.2	42.32	32.5	15.51	10.02	45
423.2	71.28	46.3	26.98	14.74	37
423.2	101.63	59.5	39.74	19.57	36
423.2	141.73	71.2	57.76	24.41	48

$P,$ lb./sq. ft.	$\Delta P,$ lb./sq. ft.	$\bar{V},$ ft./sec.	$\bar{\sigma} \Delta P / \omega^2,$ lb./sq. ft.	$\bar{\sigma} \bar{V} / \omega,$ ft./sec.
Machine-Made Specimen B-8		61°F.		
93.6	14.98	15.2	0.71	0.72
93.6	28.51	28.5	1.43	1.44
93.6	41.93	40.3	2.23	2.16
93.6	56.02	50.6	3.17	2.88
93.6	70.99	59.6	4.27	3.60
150.9	16.99	15.6	1.26	1.16
150.9	33.98	29.5	2.66	2.32
150.9	52.99	41.9	4.38	3.48
159.9	70.42	53.3	6.10	4.64
242.3	58.90	44.0	7.45	5.59
242.3	68.69	57.6	8.85	7.46
242.3	91.01	69.2	12.20	9.32
972.3	20.59	16.2	9.42	7.43
972.3	52.56	31.8	24.44	14.86
972.3	103.39	48.7	49.29	23.37
1455.2	70.42	33.5	48.87	23.39
1455.2	131.62	49.1	94.26	34.97
1455.2	201.60	64.1	146.05	46.67
1760.4	28.80	17.0	23.80	14.15
1760.4	80.21	33.6	67.24	28.30
Machine-Made Specimen B-7		61°F.		
242.3	18.72	15.8	2.19	1.86
242.3	38.16	30.5	4.64	3.73
391.8	16.13	16.1	3.00	3.01
391.8	36.29	31.4	6.93	6.03
391.8	61.06	45.7	12.01	9.04
391.8	88.27	59.1	17.92	12.06
391.8	118.22	71.4	24.82	15.07
628.5	18.14	16.1	5.38	4.81
628.5	42.91	31.6	12.99	9.61
628.5	75.89	46.2	23.55	14.42
628.5	110.30	60.1	35.11	19.22
972.3	156.24	63.4	76.41	31.18
972.3	215.71	77.1	108.48	39.00

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.
Machine-Made Specimen B-13		-40°F.		
93.6	8.64	15.9	0.70	1.08
93.6	18.43	30.3	1.56	2.17
93.6	29.66	43.2	2.65	3.25
93.6	41.04	54.7	3.87	4.33
93.6	51.26	65.4	5.04	5.42
150.9	10.80	16.1	1.39	1.75
150.9	23.04	31.0	3.09	3.49
150.9	36.00	44.7	5.02	5.24
242.3	88.85	70.4	21.03	14.02
628.5	15.70	16.5	8.25	7.27
628.5	39.60	32.3	21.19	14.55
628.5	70.13	47.4	38.41	21.82
972.3	105.55	49.8	89.30	35.44
Machine-Made Specimen B-14		-40°F.		
242.3	12.10	16.3	2.48	2.80
242.3	26.35	31.6	5.56	5.61
242.3	44.50	45.8	9.72	8.41
242.3	65.81	58.7	14.95	11.22
391.8	13.54	16.4	4.45	4.53
391.8	32.98	32.0	11.11	9.07
391.8	56.59	46.6	19.62	13.60
391.8	83.52	60.2	29.89	18.13
Machine-Made Specimen B-17		-40°F.		
1455.2	24.91	17.4	30.17	17.68
1455.2	72.58	34.2	89.35	35.36
1760.4	27.07	17.4	39.63	21.39

$P,$ lb./sq. ft.	$\Delta P,$ lb./sq. ft.	$\bar{V},$ ft./sec.	$\bar{\sigma} \Delta P / \omega^2,$ lb./sq. ft.	$\bar{\sigma} \bar{V} / \omega,$ ft./sec.
Machine-Made Specimen B-11		0°F.		
93.6	10.51	15.8	0.67	0.92
93.6	21.02	30.0	1.42	1.83
93.6	32.83	42.5	2.34	2.75
93.6	42.77	54.3	3.19	3.67
93.6	54.29	64.6	4.25	4.58
150.9	11.95	16.0	1.21	1.48
150.9	24.77	30.8	2.62	2.96
150.9	38.88	44.3	4.29	4.43
242.3	13.10	16.2	2.11	2.37
242.3	28.51	31.5	4.74	4.75
242.3	46.22	45.6	7.95	7.12
242.3	67.97	58.5	12.17	9.49
242.3	89.71	70.3	16.69	11.87
391.8	14.26	16.4	3.69	3.84
391.8	34.85	31.9	9.24	7.68
391.8	58.03	46.6	15.82	11.51
391.8	85.68	60.1	24.13	15.35
391.8	113.33	72.8	32.93	19.19
628.5	16.13	16.5	6.65	6.16
628.5	40.90	32.3	17.20	12.31
628.5	70.13	47.4	30.15	18.47
972.3	239.04	77.9	169.09	50.00
Machine-Made Specimen B-12		0°F.		
972.3	19.58	16.5	12.46	9.52
972.3	53.57	34.1	34.67	20.00
972.3	110.02	49.7	73.22	30.00
972.3	169.06	64.4	115.75	40.00
1455.2	74.59	34.1	72.13	29.93
1455.2	136.80	50.1	135.03	44.90
1455.2	227.52	64.9	231.28	59.87
1760.4	30.24	17.4	34.78	18.11
1760.4	84.82	34.2	99.07	36.22

$P,$ lb./sq. ft.	$\Delta P,$ lb./sq. ft.	$\bar{V},$ ft./sec.	$\bar{\sigma} \Delta P / \omega^2,$ lb./sq. ft.	$\bar{\sigma} \bar{V} / \omega,$ ft./sec.	Retention, %
Handsheet Specimen 1		-40°F.			
105.8	14.76	15.6	1.38	1.23	64
105.8	25.06	29.8	2.45	2.45	59
105.8	38.70	42.3	4.00	3.67	45
105.8	53.46	53.2	5.84	4.89	53
105.8	67.11	63.3	7.71	6.12	60
211.6	13.64	16.2	2.46	2.46	54
211.6	31.46	31.0	5.90	4.89	52
211.6	53.46	44.3	10.51	7.33	27
211.6	70.17	57.2	14.28	9.79	26
211.6	125.58	64.3	28.42	12.24	27
423.2	17.82	16.3	6.35	4.89	60
423.2	41.77	31.8	15.30	9.80	44
423.2	70.73	46.2	26.75	14.70	44
423.2	107.76	59.2	42.40	19.60	20
423.2	138.11	71.7	56.08	24.49	33
Handsheet Specimen 2		-40°F.			
105.8	12.53	15.7	1.16	1.22	72
105.8	23.95	30.0	2.33	2.45	53
105.8	38.70	42.3	4.00	3.67	49
105.8	50.12	53.8	5.41	4.88	42
105.8	64.88	63.8	7.40	6.12	42
211.6	14.76	16.1	2.67	2.45	63
211.6	32.02	31.0	6.01	4.90	39
211.6	49.29	44.8	9.60	7.34	48
211.6	67.94	57.5	13.76	9.80	30
211.6	117.23	65.3	26.13	12.24	18
423.2	15.59	16.4	5.54	4.90	47
423.2	37.59	31.8	13.70	9.75	33
423.2	67.11	46.3	25.28	14.67	38
423.2	98.29	59.7	38.29	19.57	27
423.2	131.99	72.2	53.25	24.51	35

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 3		-40°F.			
105.8	14.76	15.6	1.38	1.23	73
105.8	26.17	29.7	2.57	2.45	66
105.8	38.70	42.3	4.00	3.67	56
105.8	53.46	53.2	5.84	4.89	51
105.8	65.99	63.5	7.55	6.12	64
211.6	13.64	16.2	2.46	2.46	60
211.6	32.58	31.0	6.12	4.90	45
211.6	52.91	44.5	10.39	7.35	57
211.6	74.35	56.7	15.26	9.79	47
211.6	121.40	64.8	27.27	12.24	29
423.2	17.82	16.3	6.35	4.89	36
423.2	41.77	31.8	15.30	9.80	51
423.2	73.23	46.0	27.77	14.68	44
423.2	104.70	59.3	41.07	19.57	43
423.2	148.69	70.8	61.02	24.44	35
Handsheet Specimen 4		-40°F.			
105.8	13.64	15.6	1.27	1.22	69
105.8	23.95	30.0	2.33	2.45	66
105.8	36.76	42.7	3.76	3.68	56
105.8	51.23	53.7	5.55	4.90	48
105.8	63.77	64.0	7.24	6.11	54
211.6	13.64	16.2	2.46	2.46	66
211.6	32.58	31.0	6.12	4.90	54
211.6	47.06	45.0	9.13	7.34	55
211.6	65.99	57.7	13.31	9.79	44
211.6	91.05	68.5	19.31	12.22	44
423.2	17.82	16.3	6.35	4.89	56
423.2	38.70	31.8	14.13	9.76	48
423.2	67.11	46.3	25.28	14.67	49
423.2	103.03	59.5	40.34	19.60	43
423.2	133.10	72.0	53.77	24.47	38

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 5		-40°F.			
105.8	15.59	17.3	1.46	1.36	66
105.8	27.29	29.2	2.69	2.42	64
105.8	40.93	40.5	4.26	3.55	55
105.8	56.53	52.7	6.25	4.90	52
105.8	69.06	61.5	7.99	5.99	49
211.6	16.15	15.7	2.93	2.39	66
211.6	33.69	30.3	6.35	4.80	52
211.6	55.97	44.2	11.06	7.35	50
211.6	79.64	56.2	16.51	9.80	42
211.6	101.08	66.0	21.85	12.00	37
423.2	18.38	15.8	6.55	4.74	57
423.2	45.67	31.3	16.80	9.69	49
423.2	76.30	45.3	29.03	14.50	48
423.2	121.96	58.3	48.71	19.59	33
423.2	158.16	70.0	65.52	24.39	13
Handsheet Specimen 6		-40°F.			
105.8	14.76	17.2	1.38	1.35	67
105.8	27.29	31.0	2.69	2.57	58
105.8	37.59	41.0	3.86	3.54	53
105.8	52.35	53.5	5.70	4.90	54
105.8	62.93	63.0	7.12	6.00	48
211.6	15.31	16.4	2.77	2.49	63
211.6	31.19	29.5	5.84	4.65	49
211.6	51.23	43.8	10.02	7.21	49
211.6	73.79	56.8	15.12	9.79	35
211.6	98.29	67.7	21.14	12.25	36
423.2	26.73	17.0	9.63	5.15	32
423.2	46.50	31.7	17.12	9.82	36
423.2	73.23	45.3	27.77	14.45	38
423.2	109.43	59.2	43.14	19.63	26
423.2	143.96	71.0	58.80	24.39	36

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention,
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	$\frac{1}{2}$
Handsheet Specimen 7		-40°F.			
105.8	11.42	16.1	1.05	1.25	61
105.8	23.67	30.5	2.30	2.49	55
105.8	33.97	41.7	3.44	3.55	56
105.8	47.06	53.5	5.02	4.80	46
105.8	72.12	62.2	8.44	6.12	38
211.6	13.64	16.5	2.46	2.50	50
211.6	29.24	31.0	5.46	4.87	48
211.6	45.94	44.3	8.89	7.21	42
211.6	69.06	57.0	14.02	9.73	37
211.6	91.05	68.3	19.31	12.18	36
423.2	17.26	17.3	6.15	5.18	47
423.2	38.15	31.5	13.92	9.67	39
423.2	65.99	45.7	24.83	14.47	34
423.2	100.52	59.7	39.25	19.61	37
423.2	139.23	70.8	56.59	24.21	27
Handsheet Specimen 8		-40°F.			
105.8	12.53	16.0	1.16	1.24	69
105.8	26.17	30.3	2.57	2.50	61
105.8	37.59	41.3	3.86	3.57	61
105.8	52.35	52.3	5.70	4.79	53
105.8	64.32	63.8	7.32	6.11	48
211.6	14.76	16.0	2.67	2.43	64
211.6	31.46	30.3	5.90	4.78	50
211.6	52.35	43.8	10.27	7.23	53
211.6	75.46	56.3	15.52	9.74	44
211.6	99.41	67.5	21.42	12.24	42
423.2	17.26	15.8	6.15	4.73	51
423.2	44.00	32.3	16.16	9.98	44
423.2	74.35	45.2	28.23	14.44	45
423.2	112.49	58.5	44.49	19.46	36
423.2	150.64	70.2	61.94	24.28	27

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 9		-40°F.			
105.8	15.31	15.8	1.43	1.24	67
105.8	30.35	29.5	3.03	2.48	61
105.8	45.67	41.2	4.84	3.68	59
105.8	58.20	51.0	6.48	4.77	62
105.8	73.23	62.2	8.60	6.15	48
211.6	16.71	15.6	3.03	2.38	63
211.6	37.31	30.7	7.09	4.90	58
211.6	60.70	44.2	12.11	7.42	44
211.6	86.88	55.3	18.28	9.79	44
211.6	109.99	65.2	24.18	12.06	54
423.2	20.33	16.4	7.27	4.93	53
423.2	49.29	31.3	18.21	9.73	49
423.2	84.93	45.3	32.62	14.64	37
423.2	125.58	57.8	50.34	19.49	31
423.2	168.46	69.5	70.51	24.47	43
Handsheet Specimen 10		-40°F.			
105.8	10.58	16.0	.97	1.23	68
105.8	22.55	29.0	2.18	2.36	60
105.8	34.53	41.5	3.50	3.54	57
105.8	47.06	53.5	5.02	4.80	59
105.8	69.61	62.7	8.07	6.12	60
211.6	13.64	16.3	2.46	2.47	57
211.6	30.35	32.0	5.68	5.04	53
211.6	47.06	44.7	9.13	7.29	48
211.6	72.12	58.3	14.73	10.02	40
211.6	91.05	68.5	19.31	12.22	43
423.2	17.82	17.0	6.35	5.10	48
423.2	38.70	31.8	14.13	9.76	44
423.2	69.06	46.0	26.07	14.61	39
423.2	100.52	59.2	39.25	19.45	38
423.2	138.11	71.5	55.08	24.42	12

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention,
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	$\frac{1}{\phi}$
Handsheet Specimen 11		-40°F.			
105.8	13.09	15.5	1.21	1.21	74
105.8	27.85	29.8	2.75	2.48	63
105.8	41.77	41.8	4.36	3.67	54
105.8	53.46	51.2	5.84	4.71	61
211.6	15.31	16.2	2.77	2.46	66
211.6	33.41	30.7	6.29	4.86	62
211.6	57.64	44.5	11.43	7.42	48
211.6	77.97	56.3	16.11	9.79	45
211.6	103.03	66.7	22.36	12.18	48
423.2	18.93	16.5	6.76	4.95	53
423.2	47.06	31.8	17.34	9.86	45
423.2	78.52	45.3	29.95	14.54	32
423.2	115.28	58.2	45.72	19.42	41
423.2	152.87	67.8	63.00	23.50	40

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 1		0°F.			
105.8	13.09	16.9	.95	1.12	72
105.8	24.50	29.3	1.87	2.03	64
105.8	36.20	41.7	2.90	3.03	61
105.8	50.12	55.5	4.25	4.27	57
105.8	68.50	62.9	6.21	5.17	64
211.6	13.64	15.3	1.93	1.96	58
211.6	29.52	31.3	4.33	4.16	52
211.6	45.67	42.9	6.93	5.91	56
211.6	69.06	57.9	11.01	8.37	47
211.6	90.50	68.6	15.05	10.35	34
423.2	16.15	16.2	4.51	4.10	60
423.2	39.26	32.2	11.26	8.38	53
423.2	67.66	46.6	20.02	12.51	37
423.2	99.41	59.6	30.44	16.56	20
423.2	128.09	71.6	40.41	20.49	30
Handsheet Specimen 2		0°F.			
105.8	14.20	16.4	1.04	1.09	72
105.8	27.29	30.1	2.11	2.11	61
105.8	40.38	41.1	3.29	3.04	47
105.8	57.08	55.1	4.97	4.35	61
105.8	72.12	61.8	6.62	5.15	71
211.6	15.59	15.7	2.22	2.02	68
211.6	33.97	31.8	5.03	4.27	58
211.6	50.12	42.8	7.68	5.95	43
211.6	74.35	56.0	11.98	8.18	56
211.6	99.96	69.0	16.93	10.60	54
423.2	17.26	15.8	4.83	4.01	60
423.2	42.88	31.7	12.35	8.28	47
423.2	71.28	45.8	21.18	12.34	50
423.2	104.70	58.1	32.24	16.23	45
423.2	141.45	71.4	45.24	20.72	29

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 3		0°F.			
105.8	13.09	16.1	.95	1.06	73
105.8	27.29	30.1	2.11	2.11	61
105.8	40.38	41.5	3.29	3.07	57
105.8	50.68	52.8	4.30	4.07	46
105.8	63.21	63.7	5.62	5.14	62
211.6	15.31	16.5	2.17	2.13	66
211.6	31.74	30.1	4.68	4.02	56
211.6	51.23	42.8	7.87	5.96	45
211.6	76.85	57.1	12.44	8.39	44
211.6	98.01	67.4	16.54	10.32	49
423.2	17.82	16.5	4.99	4.19	56
423.2	41.49	31.6	11.93	8.24	46
423.2	71.28	45.3	21.18	12.21	54
423.2	105.25	58.5	32.43	16.35	53
423.2	138.67	70.3	44.22	20.34	52
Handsheet Specimen 4		0°F.			
105.8	12.53	15.9	.91	1.05	69
105.8	25.06	30.4	1.92	2.11	65
105.8	37.59	41.0	3.03	3.00	53
105.8	53.46	54.4	4.59	4.23	49
105.8	69.06	62.8	6.27	5.18	67
211.6	32.30	31.7	4.76	4.24	48
211.6	49.56	45.3	7.59	6.29	47
211.6	66.83	56.1	10.60	8.07	49
211.6	94.12	70.2	15.76	10.67	40
423.2	17.26	16.8	4.83	4.26	39
423.2	40.38	31.5	11.59	8.20	41
423.2	69.06	46.2	20.47	12.42	28
423.2	101.63	58.7	31.19	16.34	45
423.2	133.10	71.3	42.21	20.51	28

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention,
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	%

Handsheet Specimen 5 0°F.

105.8	14.20	15.7	1.04	1.04	76
105.8	27.85	29.2	2.16	2.05	65
105.8	42.32	41.7	3.48	3.11	67
105.8	54.02	51.6	4.65	4.03	58
105.8	75.46	61.4	7.01	5.18	71
211.6	16.15	16.2	2.30	2.09	68
211.6	33.97	31.2	5.03	4.19	62
211.6	55.41	44.2	8.59	6.21	37
211.6	73.23	54.5	11.77	7.95	45
211.6	100.52	67.6	17.04	10.40	40
423.2	16.71	15.5	4.67	3.93	52
423.2	45.11	32.1	13.02	8.41	22
423.2	77.97	46.7	23.33	12.68	32
423.2	109.99	58.7	34.06	16.49	49
423.2	143.96	70.5	46.16	20.51	44

Handsheet Specimen 6 0°F.

105.8	13.64	16.3	.99	1.08	71
105.8	28.40	29.5	2.21	2.08	60
105.8	42.32	42.3	3.48	3.15	62
105.8	53.46	49.2	4.59	3.83	59
105.8	71.84	62.2	6.59	5.18	61
211.6	16.15	16.0	2.30	2.06	56
211.6	33.97	30.7	5.03	4.12	49
211.6	55.97	44.7	8.68	6.29	45
211.6	79.64	56.5	12.96	8.34	39
211.6	101.63	67.2	17.27	10.36	41
423.2	16.71	15.5	4.67	3.93	56
423.2	42.88	31.1	12.35	8.12	39
423.2	80.47	45.9	24.15	12.50	33
423.2	111.94	58.1	34.73	16.35	36
423.2	146.46	70.3	47.08	20.50	43

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 7		0°F.			
105.8	13.64	15.8	.99	1.05	74
105.8	28.40	28.9	2.21	2.04	53
105.8	41.77	42.0	3.43	3.13	36
105.8	55.97	52.0	4.85	4.09	21
105.8	64.88	63.3	5.81	5.14	63
211.6	16.15	16.0	2.30	2.06	61
211.6	33.97	30.4	5.03	4.08	41
211.6	54.85	43.2	8.49	6.07	54
211.6	80.75	56.0	13.17	8.29	42
211.6	106.37	67.9	18.24	10.56	22
423.2	17.26	15.5	4.83	3.93	49
423.2	42.88	31.4	12.35	8.20	41
423.2	76.85	45.8	22.97	12.42	26
423.2	112.49	58.1	34.92	16.36	24
423.2	150.64	69.6	48.63	20.38	21
Handsheet Specimen 8		0°F.			
105.8	13.64	16.1	.99	1.07	73
105.8	27.29	30.8	2.11	2.16	59
105.8	42.32	42.9	3.48	3.20	67
105.8	54.85	52.2	4.73	4.09	61
105.8	72.68	61.3	6.69	5.12	64
211.6	14.76	15.8	2.09	2.03	61
211.6	32.86	30.0	4.85	4.02	50
211.6	51.23	43.1	7.87	6.01	50
211.6	74.90	55.2	12.08	8.08	35
211.6	103.58	68.9	17.67	10.66	50
423.2	17.82	16.2	4.99	4.11	49
423.2	41.49	31.0	11.93	8.08	38
423.2	76.02	46.2	22.70	12.52	31
423.2	104.70	58.1	32.24	16.23	37
423.2	151.76	70.6	49.04	20.70	36

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 9		0°F.			
105.8	12.53	16.3	.91	1.07	70
105.8	25.06	30.2	1.92	2.10	63
105.8	40.38	42.5	3.29	3.15	62
105.8	51.23	51.6	4.36	3.98	63
105.8	64.32	64.5	5.75	5.23	61
211.6	15.31	15.6	2.17	2.01	66
211.6	32.86	30.9	4.85	4.14	48
211.6	52.35	44.5	8.06	6.22	44
211.6	69.61	55.8	11.11	8.08	52
211.6	91.05	68.5	15.16	10.35	43
423.2	18.38	16.6	5.15	4.22	57
423.2	40.38	31.0	11.59	8.07	38
423.2	70.17	46.2	20.82	12.44	30
423.2	103.58	58.6	31.86	16.35	38
423.2	133.93	70.8	42.51	20.39	36
Handsheet Specimen 10		0°F.			
105.8	13.64	15.8	.99	1.05	74
105.8	26.17	28.9	2.01	2.02	76
105.8	41.77	41.7	3.43	3.10	67
105.8	54.58	52.5	4.70	4.10	61
105.8	65.99	62.1	5.93	5.06	61
211.6	14.76	15.8	2.09	2.03	58
211.6	33.41	30.6	4.94	4.10	53
211.6	54.85	45.7	8.49	6.42	46
211.6	73.23	56.8	11.77	8.28	43
211.6	99.96	68.7	16.93	10.56	29
423.2	16.71	15.8	4.67	4.01	49
423.2	41.49	31.0	11.93	8.08	43
423.2	104.70	58.6	32.24	16.37	41
423.2	138.11	71.1	44.02	20.56	33

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 1		70°F.			
105.8	13.64	15.3	.69	.78	67
105.8	27.85	32.7	1.49	1.78	65
105.8	41.49	42.3	2.35	2.43	69
105.8	54.30	55.1	3.23	3.33	74
105.8	67.38	63.2	4.20	4.01	71
211.6	16.71	16.7	1.64	1.67	13
211.6	35.36	32.0	3.63	3.34	35
211.6	57.08	48.0	6.13	5.24	36
211.6	73.23	57.5	8.13	6.49	34
211.6	97.46	72.2	11.35	8.55	56
423.2	19.49	16.9	3.78	3.33	18
423.2	43.44	33.4	8.65	6.76	7
423.2	70.73	47.4	14.51	9.89	26
423.2	102.47	60.9	21.75	13.14	34
423.2	137.55	73.4	30.27	16.43	50
Handsheet Specimen 2		70°F.			
105.8	17.26	15.1	.88	.79	64
105.8	34.53	28.8	1.90	1.61	61
105.8	52.35	41.0	3.09	2.46	66
105.8	69.06	52.1	4.34	3.33	71
105.8	85.21	60.0	5.66	4.05	78
211.6	15.59	16.2	1.53	1.62	37
211.6	33.41	32.1	3.41	3.33	37
211.6	54.02	47.7	5.77	5.18	57
211.6	71.28	59.2	7.88	6.66	47
211.6	95.23	70.8	11.04	8.35	50
423.2	19.77	17.3	3.83	3.41	32
423.2	42.32	33.6	8.41	6.79	33
423.2	67.94	47.0	13.90	9.77	36
423.2	100.52	62.2	21.29	13.40	28
423.2	130.87	73.8	28.61	16.40	38

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 3		70°F.			
105.8	16.15	15.2	.82	.79	75
105.8	32.58	29.6	1.78	1.64	69
105.8	48.17	41.4	2.80	2.45	70
105.8	65.99	53.9	4.10	3.40	74
105.8	75.46	62.0	4.85	4.05	63
211.6	20.88	16.2	2.07	1.64	52
211.6	41.77	30.8	4.34	3.26	46
211.6	69.06	46.4	7.60	5.19	44
211.6	92.72	57.4	10.70	6.74	46
211.6	117.23	67.2	14.17	8.26	52
423.2	22.00	16.2	4.27	3.20	28
423.2	52.35	32.2	10.52	6.58	25
423.2	89.10	46.7	18.65	9.94	17
423.2	125.58	58.8	27.30	13.00	26
423.2	167.63	71.2	38.02	16.42	37
Handsheet Specimen 4		70°F.			
105.8	13.64	15.3	.69	.78	77
105.8	26.73	29.3	1.43	1.59	69
105.8	40.93	41.8	2.31	2.40	65
105.8	54.58	54.6	3.25	3.31	82
105.8	66.55	63.3	4.14	4.00	78
211.6	18.38	16.4	1.82	1.65	59
211.6	36.76	31.6	3.78	3.31	47
211.6	58.75	46.1	6.33	5.05	46
211.6	79.64	58.2	8.96	6.66	48
211.6	103.03	68.6	12.13	8.21	55
423.2	19.49	16.3	3.78	3.21	45
423.2	44.55	32.3	8.88	6.55	40
423.2	75.46	47.1	15.56	9.88	36
423.2	109.99	60.5	23.53	13.16	27
423.2	145.63	72.6	32.31	16.38	46

$P,$ lb./sq. ft.	$\Delta P,$ lb./sq. ft.	$\bar{V},$ ft./sec.	$\bar{\sigma} \Delta P / \omega^2,$ lb./sq. ft.	$\bar{\sigma} \bar{V} / \omega,$ ft./sec.	Retention, %
Handsheet Specimen 5		70°F.			
105.8	15.31	15.2	.78	.78	79
105.8	32.02	30.4	1.74	1.68	85
105.8	45.67	41.1	2.63	2.40	85
105.8	62.93	53.2	3.86	3.32	84
105.8	75.18	62.1	4.82	4.05	85
211.6	20.88	16.3	2.07	1.65	35
211.6	43.44	32.3	4.53	3.43	35
211.6	67.11	46.0	7.36	5.13	38
211.6	91.05	57.0	10.47	6.67	48
211.6	117.23	67.8	14.17	8.33	52
423.2	20.88	16.2	4.05	3.20	37
423.2	52.35	32.6	10.52	6.66	27
423.2	85.76	46.6	17.88	9.88	23
423.2	125.58	60.3	27.30	13.33	26
423.2	164.29	71.2	37.14	16.37	33
Handsheet Specimen 6		70°F.			
105.8	15.31	15.2	.78	.78	76
105.8	28.40	29.1	1.52	1.59	79
105.8	45.67	42.8	2.63	2.50	85
105.8	58.75	53.4	3.55	3.28	77
105.8	72.12	63.3	4.58	4.08	76
211.6	17.82	16.5	1.76	1.66	33
211.6	36.20	31.8	3.72	3.32	41
211.6	58.75	47.1	6.33	5.16	40
211.6	76.30	57.7	8.52	6.55	48
211.6	102.47	69.8	12.05	8.34	49
423.2	19.49	16.8	3.78	3.31	35
423.2	47.06	33.3	9.40	6.77	24
423.2	74.35	47.2	15.31	9.88	25
423.2	109.99	62.1	23.53	13.51	40
423.2	141.17	73.1	31.19	16.42	31

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 7		70°F.			
105.8	15.31	15.2	.78	.78	74
105.8	30.35	29.8	1.64	1.64	79
105.8	45.11	42.3	2.59	2.47	71
105.8	59.03	53.3	3.57	3.28	75
105.8	73.23	62.8	4.67	4.07	72
211.6	19.77	16.7	1.96	1.68	63
211.6	40.10	32.0	4.16	3.37	51
211.6	60.70	45.9	6.57	5.05	56
211.6	83.81	57.7	9.51	6.65	55
211.6	108.87	68.8	12.96	8.33	52
423.2	20.88	16.7	4.05	3.29	56
423.2	50.12	33.5	10.05	6.83	50
423.2	81.03	46.8	16.81	9.87	49
423.2	118.90	60.8	25.67	13.35	33
423.2	151.76	71.6	33.88	16.25	44
Handsheet Specimen 8		70°F.			
105.8	14.20	15.3	.72	.79	62
105.8	29.24	30.3	1.58	1.66	77
105.8	42.32	42.5	2.40	2.45	79
105.8	54.85	53.7	3.27	3.25	81
105.8	69.06	64.1	4.34	4.09	78
211.6	16.15	16.2	1.59	1.62	49
211.6	37.03	31.7	3.81	3.32	54
211.6	56.25	45.0	6.03	4.91	33
211.6	79.64	57.2	8.96	6.54	48
211.6	105.81	68.7	12.52	8.27	37
423.2	17.82	15.7	3.44	3.09	53
423.2	45.67	31.9	9.11	6.47	24
423.2	79.64	46.9	16.50	9.88	32
423.2	115.28	59.5	24.80	13.01	32
423.2	148.14	71.1	32.95	16.08	15

$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet Specimen 9		70°F.			
105.8	15.31	15.7	.78	.81	69
105.8	29.79	30.3	1.61	1.66	69
105.8	45.67	41.9	2.63	2.45	75
105.8	60.15	51.9	3.66	3.21	71
105.8	75.46	62.0	4.85	4.05	70
211.6	17.82	16.5	1.76	1.66	49
211.6	37.03	31.4	3.81	3.29	53
211.6	57.92	45.7	6.23	5.00	37
211.6	78.80	58.1	8.85	6.63	28
211.6	100.52	68.6	11.78	8.17	44
423.2	20.88	16.9	4.05	3.33	53
423.2	45.94	32.9	9.17	6.68	45
423.2	76.02	46.5	15.68	9.76	52
423.2	109.43	60.0	23.40	13.04	23
423.2	143.96	71.9	31.89	16.19	39
Handsheet Specimen 10		70°F.			
105.8	14.76	15.7	.75	.81	69
105.8	30.35	29.4	1.64	1.62	70
105.8	45.94	41.7	2.65	2.44	82
105.8	59.59	52.0	3.61	3.21	77
105.8	78.52	62.0	5.10	4.09	67
211.6	18.10	16.0	1.79	1.61	60
211.6	39.26	31.1	4.06	3.27	56
211.6	59.59	43.8	6.43	4.81	45
211.6	85.76	56.4	9.76	6.53	42
211.6	112.49	67.1	13.48	8.18	51
423.2	20.33	15.9	3.94	3.13	46
423.2	49.84	33.0	9.99	6.73	58
423.2	84.93	46.2	17.69	9.79	14
423.2	123.63	58.9	26.82	12.99	18
423.2	135.61	70.4	29.79	15.72	43

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P_s	ΔP_s	$\bar{V}_s$	$\bar{\sigma} \Delta P_s / \omega_s^2$	$\bar{\sigma} \bar{V}_s / \omega_s$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet (Unimpregnated) Specimen 1		-40°F.			
105.8	12.53	15.6	1.16	1.21	67
105.8	28.68	29.0	2.84	2.42	59
105.8	42.88	41.5	4.50	3.66	54
105.8	56.53	52.7	6.25	4.90	50
105.8	70.17	62.5	8.15	6.11	57
211.6	16.15	16.5	2.93	2.51	60
211.6	34.53	30.7	6.52	4.87	47
211.6	54.85	44.0	10.81	7.30	47
211.6	81.03	56.2	16.85	9.83	50
211.6	100.52	66.7	21.71	12.12	46
423.2	21.44	15.8	7.67	4.76	50
423.2	44.00	31.7	16.16	9.79	43
423.2	76.85	45.8	29.26	14.67	42
423.2	111.10	59.0	43.87	19.60	43
423.2	150.36	70.5	61.81	24.38	33
Handsheet (Unimpregnated) Specimen 2		-40°F.			
105.8	13.64	15.8	1.27	1.23	69
105.8	28.12	29.5	2.78	2.45	62
105.8	41.77	41.8	4.36	3.67	56
105.8	54.58	53.0	5.99	4.89	51
105.8	67.66	63.0	7.79	6.10	47
211.6	16.15	16.0	2.93	2.44	63
211.6	33.41	30.8	6.29	4.88	58
211.6	51.23	44.7	10.02	7.36	37
211.6	72.68	56.8	14.86	9.77	52
211.6	98.01	67.7	21.07	12.24	42
423.2	17.26	16.5	6.15	4.94	55
423.2	41.77	31.8	15.30	9.80	47
423.2	72.68	46.3	27.55	14.76	39
423.2	107.20	59.2	42.16	19.58	29
423.2	143.96	71.2	58.80	24.46	43

P_1	ΔP_1	$\bar{V}_1$	$\bar{\sigma} \Delta P_1 / \omega^2$	$\bar{\sigma} \bar{V}_1 / \omega$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Handsheet (Unimpregnated) Specimen 3			-40°F.		
105.8	13.09	15.8	1.21	1.23	77
105.8	28.68	29.5	2.84	2.46	64
105.8	44.00	41.7	4.64	3.70	63
105.8	57.03	52.2	6.32	4.87	56
105.8	67.94	62.0	7.83	6.01	61
211.6	16.71	16.4	3.03	2.50	65
211.6	33.69	30.8	6.35	4.88	52
211.6	54.02	44.3	10.63	7.33	50
211.6	76.02	56.0	15.65	9.70	52
211.6	100.52	67.3	21.71	12.23	48
423.2	18.93	17.0	6.76	5.10	53
423.2	44.00	31.7	16.16	9.79	40
423.2	74.90	46.0	28.46	14.70	41
423.2	109.99	59.0	43.38	19.58	38
423.2	151.76	70.7	62.47	24.48	37

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$P,$	$\Delta P,$	$\bar{V},$	$\bar{\sigma} \Delta P / \omega^2,$	$\bar{\sigma} \bar{V} / \omega,$	Retention, %
lb./sq. ft.	lb./sq. ft.	ft./sec.	lb./sq. ft.	ft./sec.	
Machine Made 1, 2, and 3 Ply Filters 70°F. Velocity Downstream From Test Filter, 4000 ft./min.					
A (1 Ply)					
423.2	95.23	59.1	20.07	12.66	40
A (2 Ply)					
423.2	183.78	54.2	42.37	12.72	58
A (3 Ply)					
423.2	260.63	50.5	64.58	12.72	71
L (1 Ply)					
423.2	98.57	59.4	20.84	12.76	36
L (2 Ply)					
423.2	187.12	54.2	43.28	12.76	54
L (3 Ply)					
423.2	262.45	50.0	66.68	12.68	59
H (1 Ply)					
423.2	100.52	58.7	21.30	12.65	31
H (2 Ply)					
423.2	192.13	53.7	44.66	12.69	57
H (3 Ply)					
423.2	277.34	50.0	69.76	12.79	69

TABLE II

"KRONISOL" CONTENT OF MACHINE-MADE IPC 1478 PAPER

Sample	"Kronisol" Content ^a , %
IPC 1478 "A" Series	18.0
IPC 1478 "L" Series	24.5
IPC 1478 "H" Series	24.9

^aBased on the weight of the extracted paper.

APPENDIX II

FIGURES SHOWING RETENTION OF ALUMINUM OXIDE AEROSOL BY SAMPLES OF IPC 1478 PAPER

Figures 19-35, showing the retention by samples of IPC 1478 paper of aluminum oxide aerosol at pressures of 3.8, 7.6, and 15.2 cm. Hg, velocities of 1000, 2000, 3000, 4000, and 5000 ft./min., and temperatures of -40°, 0°, and 70°F.

The standard errors, based on five determinations for the machine-made paper and ten determinations for the handsheets, are shown in Fig. 19-32.

Figure 36 shows the retention for aluminum oxide aerosol by one, two and three plies of IPC 1478 paper at an absolute pressure of 15.2 cm. Hg and a velocity of 4000 ft./min.

Figure 19

109 120

Figure 20

Figure 21

Figure 22

Figure 23

100 124

Figure 24

Figure 25

100 126

Figure 26

Figure 27

Figure 28

100 120

Figure 29

100 100

Figure 30

Figure 31

Figure 32

Figure 33

Figure 34

Figure 35

Figure 36. Retention for One, Two, and Three Plies of IPC 1478 Paper

APPENDIX III

DIFFUSION THEORY AND APPLICATION TO THE ESTIMATION OF THE
SIZE OF THE ALUMINUM OXIDE PARTICLES

DIFFUSION THEORY AND APPLICATION TO THE ESTIMATION OF THE
SIZE OF THE ALUMINUM OXIDE PARTICLES

THE REMOVAL OF SMALL PARTICLES BY DIFFUSION

In many cases, though not all, the device which detects and counts the particles must be located at a distance (usually of the order of several inches to several feet) from the rest of the apparatus, to which it must be connected by means of tubing. During passage through the tubing, some particles will be lost due to coagulation if the concentration is sufficiently high, and in any case some will reach the wall as a result of diffusion or turbulence or both. Of these, at least a part will adhere to the wall. Moreover, passage through the tubing is likely to have a selective effect if the particles are of more than one kind or size, since the particles will then have different diffusion coefficients. Thus, it is desirable to have reliable estimates and, if possible, an exact theory of the removal of particles in simple and experimentally convenient cases. We have obtained such a theory for the following conditions: (a) the tube is a cylinder of circular cross section; (b) the flow of the suspending medium through the tube is steady and the velocity distribution is parabolic; (c) the concentration is low enough so that coagulation may be neglected; (d) the particles are small enough to make sedimentation unimportant.

As is usual in theories of this kind, we have assumed that every particle which reaches the wall will adhere to it. In the absence of systematic experimental tests of the results of the theory, this can best be justified by its successful use in calculations dealing with the removal of particles from motionless media. At pressures of the order of magnitude of

one atmosphere, the velocity of the suspending medium at the wall will indeed be negligible, and the same assumption should be correct. The calculation begins with the equation for diffusion with convection, in which it is tacitly assumed that the mean free path of molecules of the suspending medium is always very small compared to the radius of the tube.

It is found that the removal of monodisperse particles during passage through a tube under the conditions described can be represented by an exponential decrease in the density of particles, after an equilibrium radial distribution of particle density has become established. The density, at any given distance from the axis, becomes proportional to $e^{-\alpha z}$, where z is the distance along the axis and α is an attenuation factor which depends on the diffusion coefficient of the particles, D , on the radius of the tube, a , and on the velocity of the suspending medium at points on the axis, u_0 . The results are presented in terms of dimensionless parameters $a\alpha$ and $\xi = D/(au_0)$.

In a limiting case which is often encountered in practice, the parameter ξ is positive but small ($0 < \xi \ll 1$) and, to a good approximation, $a\alpha \approx 7.314\xi$. In another limiting case (obtained, for example, when the medium is nearly motionless) ξ is positive and large ($1 \ll \xi$); here $a\alpha \approx 2.405$. For other values of ξ , the corresponding value of $a\alpha$ may be obtained from graphs or tables.

The distance along the tube, within which the equilibrium radial distribution will be established, may be estimated from the following rules: (a) when ξ is positive but small the calculated density will be correct within 1% if $\xi \Delta z/a > 0.123$; (b) when ξ is positive and large the calculated density will be correct within 1% if $\Delta z/a > 1.48$; in which Δz is the required

distance. The formulas above are applicable after this point has been reached.

The selective effect of passage through the tube results from the dependence of the diffusion coefficient D on the nature and size of the particles. For small particles which differ only in radius, it is found that the diffusion coefficient is proportional to $1/y^2$, where y is the radius, when y is small compared to the mean free path of the molecules of the suspending medium. Thus, when ξ is positive but small, the smallest particles are removed more rapidly. When ξ is positive and large, there is virtually no selective effect. Solutions have also been obtained for negative values of u_0 , representing diffusion against a current, and here it is found that α is a decreasing function of $|\xi|$; such a device functions as a filter which attenuates the larger particles more rapidly than the small (the attenuation is high in all cases, however).

It should be possible to obtain distribution functions for particles of a given kind which occur with a range of radii, by experiments in which the length of tubing between source and detector is varied. Thus, if $E(y)$ is the efficiency of the detector, $P(y)$ is the distribution in effect at a given point along the tube, and z is the length of tube between this point and the detector, the density of particles measured will be

$$N(z) = \int_0^{\infty} E(y) P(y) e^{-\alpha(y) z} dy$$

Solution of this integral equation then furnishes the distribution function $P(y)$.

It was also desired to obtain, from attenuation measurements, as accurate an estimate as possible of the size of particles, which would be especially useful in the range where measurements could not be made with the electron microscope locally available. Such estimates have been made, based on the theory of binary diffusion in gases, and are presented in the following section. An effort was made to find a plausible explanation for observations indicating an anomalously large diffusion rate for particles of silicon dioxide; it is suggested that a sufficiently thick coating of adsorbed gas molecules on such particles should cause a substantial increase in the diffusion coefficient for particles of a given radius (amounting approximately to a factor of two). An assumption as to the presence (and thickness) of such a film is the only adjustable element in the calculation. It has not been possible up to this time to measure diffusion loss and hence to infer the diffusion coefficient of particles, and also to obtain direct measurements of particle diameter. Thus, it is only possible to indicate a range of possible diameters corresponding to a given diffusion coefficient, when the chemical nature of the particle is supposed to be known.

DISCUSSION OF TWO EXPERIMENTS

In the first of these, particles of aluminum oxide, generated by a spark gap having aluminum electrodes, were passed at rather low velocities through various lengths of Tygon tubing, of 1/4-inch inside diameter. Irregularities in the flow were eliminated by use of a reservoir having flexible walls, preceded by a restriction, between the tubing and the detector. The other experimental conditions were as follows: temperature, 20°C.; pressure in the tubing, 60.1 cm. Hg; the suspending medium was air; the velocity at the

axis was 77 cm./sec.; the pressure drop along the tubing was negligible. It is believed that conditions at the generator, including the flow rate, were unchanged during each run. The diagrams presented in Fig. 37 show the results for two runs.

It will be observed that the points fall on or near straight lines, having the same slope, in these semilogarithmic diagrams. In terms of the theory we are proposing, this indicates a homogeneous population. If there were a mixture of sizes present, the smaller particles would be removed first and the resulting curves would be concave upward, having a steeper slope at the left.

The attenuation factor obtained from the diagrams is $\alpha = 0.00635$ cm.⁻¹, from which it is found that $\xi = 0.000276$ and $D = 0.00674$ cm.²/sec., according to the theory.

The predicted diameter, calculated as described above, is 38 A. if the particles are not covered by adsorbed air, or 54 A. if the coverage is complete.

We will now describe a second experiment, to which, it is clear, the theory is not applicable. A square brass tube, 4 inches long, having a 3/16-inch square opening, was provided with shallow recesses along one wall, in which were placed a number of electron microscope grids (coated with collodion). This tube was placed in the wind tunnel and exposed to the current of air and particles for a time, following which electron microscope photographs were made of the collected particles (silicon dioxide, in this case). The number of particles per unit area was found for each grid, and particle size distribution curves were obtained. The latter show a sharp maximum at approximately 110 A.

RETENTION, PER CENT

Figure 37. Aluminum Oxide Particle Count (Determined with General Electric CN Meter) as a Function of Distance Along 1/4-inch Tygon Tubing. Axial Velocity, 77 cm./sec.; Temperature, 20°C.; Pressure, 60.1 cm. Hg

130

144

Figures 38 and 39 show the number of particles per unit area as a function of grid position, for two runs, and state the experimental conditions. The second run differs from the first only in that the velocity in the tube was reduced by use of a restriction at the exit end.

According to the calculations, particles of 50 A. radius should have a diffusion coefficient of the order of $2 \times 10^{-3} \text{ cm.}^2/\text{sec.}$, and the attenuation factor for the first run should be about $3 \times 10^{-4} \text{ cm.}^{-1}$, assuming an "equivalent radius" of 0.25 cm. and a velocity $u_0 = 914 \text{ cm./sec.}$ In the second run, the attenuation factor for particles of this size should be about $1.5 \times 10^{-3} \text{ cm.}^{-1}$, assuming a velocity $u_0 = 168 \text{ cm./sec.}$ From the experimental points, it is found that the observed attenuation factor in the first run was $\alpha = 0.154 \text{ cm.}^{-1}$, and in the second $\alpha = 1.01 \text{ cm.}^{-1}$.

The discrepancy, amounting to three orders of magnitude, cannot be dismissed by noting that the experimental conditions do not altogether agree with the assumptions made in the theory. Thus, the velocity distribution in the tube does not immediately become parabolic and the flow, although it soon becomes steady, will be turbulent near the entrance of the tube; moreover, an equilibrium radial distribution of particles probably is not obtained. These differences appear worth mentioning but inadequate as an explanation.

Similarly, the difference in pressure (1/20 atmosphere in the experiment being discussed) should not be important. The velocity is larger by an order of magnitude in the first run, compared to the experiment described previously. There is, finally, the completely different method of collecting and counting particles.

Figure 38. Apparent Diffusion Loss for Silicon Dioxide Aerosol During Flow in 3/16-inch Square Tube at Velocity of 1800 Ft./Min.

Figure 39. Apparent Diffusion Loss for Silicon Dioxide Aerosol During Flow in 3/16-inch Square Tube at Velocity of 330 Ft./Min.

One might guess that effects due to centrifugal separation could play a part near the entrance of the tube, but it is found that the time required for particles of the given size to follow changes in the velocity of the suspending medium under the conditions of the experiment is of the order of 10^{-11} sec.

If the aerodynamic conditions in the tube are not too unlike the conditions assumed in the theory, it would seem that some different hypothesis as to the collection efficiency of the wall may be required under the conditions of the experiment.

These findings confirm an earlier observation, made during the course of this project, that the diffusion of the particles of silicon dioxide (Fig. 38 and 39) and of boron oxide appeared to be anomalously high; this was based on the Einstein diffusion equation, modified by the slip correction. In that observation the diffusion seemed to be too high by one or two orders of magnitude.

THEORY OF THE REMOVAL OF SMALL PARTICLES BY DIFFUSION

In the following sections, the details of the theory of diffusion loss and of the calculation of the diffusion coefficient are given.

DIFFUSION IN A MOVING FLUID

It will be supposed that the concentration C of identical particles in a moving medium is a solution of the equation

$$\nabla \cdot (D \nabla C) - \nabla \cdot (C \vec{u}) = \frac{\partial C}{\partial t}, \quad (1)$$

which satisfies certain boundary conditions; D is the diffusion coefficient, t is the time and $\vec{u}$ is the velocity of the medium. This description will be correct when the concentration is small enough (so that coagulation may be neglected) provided that, except for diffusional displacements, the particles move with the velocity of the medium (thus, such processes as sedimentation and differential acceleration are not contemplated). If it is assumed, further, that the diffusion coefficient does not depend on the concentration and that the medium is an incompressible, homogeneous fluid, the equation takes the form

$$D \nabla^2 C - (\nabla C) \cdot \vec{u} = \frac{\partial C}{\partial t} \quad (2)$$

When the fluid is air, incompressibility is an approximation which, though a bit rough, simplifies the calculations. For the same reason, it will be assumed that the temperature is constant.

COLLECTION OF PARTICLES DURING STEADY FLOW THROUGH A CYLINDER

Let the fluid and suspended particles flow through a cylinder of radius a , the axis of which is to be the z axis of a cylindrical co-ordinate system, in such a way that the only nonzero component of the fluid velocity is $u_z = u_0(1 - r^2/a^2)$, where r is the distance from the axis and u_0 is a constant. With the simplifying assumptions stated above, the concentration in a steady state is a solution of the equation

$$D \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 C}{\partial \phi^2} + \frac{\partial^2 C}{\partial z^2} \right] - \frac{\partial C}{\partial z} u_z = 0, \quad (3)$$

where ϕ is the angular co-ordinate. It will now be assumed that the concentration does not depend on ϕ . Moreover, it will be supposed that the

particles are suspended in a gas, and that particles which reach the wall adhere to it. Thus, a boundary condition is that $C = 0$ whenever $r = a$.

This equation has a solution of the form $f(r)e^{-\alpha z}$, where $f(r)$ is defined by

$$\frac{d^2 f}{dr^2} + \frac{1}{r} \frac{df}{dr} + \left[\alpha^2 + \frac{\alpha}{D} u_0 \left(1 - \frac{r^2}{a^2} \right) \right] f = 0, \quad (4)$$

with the boundary condition $f(a) = 0$. The possible values of the attenuation factor α will depend on the quantities D , a and u_0 . Equation (4) is of the Sturm-Liouville type when rewritten as

$$\rho \frac{d^2 F}{d\rho^2} + \frac{dF}{d\rho} - \rho^3 F + \alpha \left[\sqrt{\frac{\alpha u_0}{D}} + \alpha^2 \sqrt{\frac{D}{\alpha u_0}} \right] \rho F = 0, \quad (5)$$

where $\rho = r/n$, $F(\rho) = f(n\rho)$ and $n = (Da^2/\alpha u_0)^{1/4}$. The boundary conditions are of the usual form that $\rho^F F'$ have the value zero when $\rho = 0$ and when $\rho = a/n$. Thus, the eigenfunctions of Equation (4) provide an orthogonal and complete set, in terms of which the values of C obtaining at points on a transverse plane $z = z_0$ may be expanded:

$$C(r, z_0) = \sum_i A_i f_i(r). \quad (6)$$

A solution of Equation (3) which has these values on the plane $z = z_0$ and for which $C = 0$ when $r = a$ and $z \geq z_0$ is given by

$$C_A(r, z) = \sum_i A_i f_i(r) e^{-\alpha_i(z - z_0)}. \quad (7)$$

Let the eigenfunctions be labelled in such an order that α_i increases as the index i increases. As z increases, the "higher modes" are attenuated more rapidly, and at a sufficient distance to the right of z_0 only the first term in the sum will be important. The expansion coefficients are given by

$$A_i = \left[\int_0^a C(r, z_0) f_i(r) r dr \right] / \left[\int_0^a [f_i(r)]^2 r dr \right]. \quad (8)$$

It is convenient to rewrite Equation (4) in the form

$$\frac{d^2 w}{dx^2} + \frac{1}{x} \frac{dw}{dx} + \left[a^2 \alpha^2 + \frac{a \alpha}{\xi} (1 - x^2) \right] w = 0, \quad (9)$$

where $x = r/a$, $w(x) = f(ax)$ and $\xi = D/(au_0)$. Numerical integration of this equation yields the possible values of the product $a\alpha$ as functions of the dimensionless parameter ξ . The boundary conditions are $w(1) = 0$ together with $w(0) = 1$ and $w'(0) = 0$, the latter being chosen in conformity with the definition of the function J_0 . In the limit that ξ is large, Equation (9) becomes equivalent to Bessel's equation and has the solutions $J_0(a\alpha x)$. In physical terms, this limit corresponds to one or a combination of the following conditions: low velocity, small radius or large diffusion coefficient.

The velocity u_0 may be positive or negative. The former represents the usual case of particles carried by the gas through the cylinder, with some loss due to collection at the wall; it will be referred to as "downstream diffusion." The latter represents the case of diffusion of particles against a current of particle-free gas; this will be referred to as "upstream diffusion."

An important special case results when ξ is positive but very small. This corresponds, for example, to a large and positive velocity u_0 . The permissible values of $a\alpha$ in this case are proportional to ξ , and the first five of them are given in the table below, together with the corresponding values for the limiting case which results when ξ is very large. For each case, the values of the expansion coefficients for a uniform initial distribution $C(r, z_0) = 1$ are also given.

	$0 < \xi \ll 1$			$1 \ll \xi$		
i	$a\alpha_i$	A_i		$a\alpha_i$	A_i	
1	7.3136ξ	$+ 1.6749$		2.4048	$+ 1.6021$	
2	44.61ξ	$- 1.5212$		5.5201	$- 1.0647$	
3	113.8ξ	$+ 1.465$		8.6537	$+ 0.8513$	
4	214.9ξ	$- 1.440$		11.7915	$- 0.7295$	
5	348.4ξ	$+ 1.421$		14.9309	$+ 0.6487$	

The values of $a\alpha$ belonging to the first eigenfunction are shown as functions of ξ in Fig. 40 and 41. As might be expected, the attenuation factor for "upstream diffusion" is larger than that for "downstream diffusion," especially when ξ is small in absolute value, but the two approach equality when ξ is large in absolute value (as would be true, for example, if the gas were nearly motionless).

Figure 40a. Parameter α as a Function of ξ , for Downstream Diffusion

Figure 40b

Figure 41a. Parameter α as a Function of ξ , for Upstream Diffusion

Figure 41b

THE CONNECTION BETWEEN PARTICLE RADIUS AND THE DIFFUSION COEFFICIENT

The following discussion will be restricted to the diffusion coefficients of monodisperse particles suspended in a gas. It is necessary to distinguish between particles which are small compared to the mean free path Λ of the gas molecules and particles which are large compared to this length (the value of which, for air at 0°C. and 760 mm. Hg pressure is about 6.7×10^{-6} cm.). For small particles, in this sense, the diffusion coefficient is proportional to $1/y^2$, where y is the particle radius, provided that y is somewhat larger than the dimensions of a gas molecule; the diffusion coefficient is inversely proportional to the pressure and varies approximately as $T^{3/2}$, where T is the temperature on the absolute scale. For large particles, the diffusion coefficient is proportional to $1/y$; it is independent of the pressure (provided the pressure is not reduced to a point where Λ approaches the particle radius) and, for particles in air, it varies with the temperature as $T^{0.232}$.

For particles of intermediate size, a formula devised by Knudsen provides a suitable interpolation. It reduces to Einstein's value, $D = kT/(6\pi\eta y)$, in the large-particle case and to the kinetic theory result at the other extreme. The formula is

$$D = \frac{kt}{6\pi\eta y} \left[1 + (C_1 + C_2 e^{-C_3 y/\Lambda}) \frac{\Lambda}{y} \right] \quad (10)$$

Typical values, for particles in air, are said to be $C_1 = 1.25$, $C_2 = 0.44$, $C_3 = 1.09$. The viscosity η is 1.72×10^{-4} poise for air at 0°C., and $k = 1.38 \times 10^{-16}$ ergs/degree K. Since the temperature dependence of D is different in the two limiting cases, it must be supposed that $C_1 + C_2$ depends on the temperature.

The kinetic theory result for the coefficient of binary diffusion (in the first approximation, which is sufficient for dilute suspensions) may be written as the product of three factors, $D = D^{(1)} D^{(2)} D^{(3)}$, where

$$D^{(1)} = \frac{0.002628}{p \sqrt{2M_1}} = 3.4214 \times 10^{-4} \times p^{-1} \quad (11a)$$

$$D^{(2)} = \frac{\sqrt{1 + M_1 \times 1.66 / (4\pi y^3 q/3)}}{\left[(y_1 + y)/2 \right]^2} \quad (11b)$$

$$D^{(3)} = T^{3/2} / \Omega \quad (11c)$$

in which p is the pressure in atmospheres, $M_1 = 29$ is the molecular weight of an "air molecule," $y_1 = 3.6$ is the radius of an "air molecule" in A., y is the radius of the particle in A., q is the density of the particle in g./cm.³, T is the temperature in °K and Ω is a function of the temperature which also depends on the intermolecular potential function characteristic of the material of the particle. D is then given in cm.²/sec.

Figure 42 shows the variation in $D^{(2)}$ with particle radius for the density $q = 2$ g./cm.³. The straight lines (broken) represent the approximation $4/y^2$ which becomes accurate for larger particles in this region. Other values of the density result in curves which differ appreciably from that shown only for radii in the 3 to 6 A. region. The calculated values appear in Table III.

Figure 42. The Factor $D^{(2)}$ as a Function of Particle Radius

TABLE III

VALUES OF $D^{(2)}$ AS A FUNCTION OF PARTICLE RADIUS AND DENSITY

Density, g./cm. ³	Radius, A.	$D^{(2)}$
1.0	1	0.6681
	2	0.1991
	3	0.1096
	4	0.07521
	5	0.05651
	6	0.04454
	7	0.03619
	8	0.03006
	9	0.02539
	10	0.02175
	15	0.01158
	20	0.007187
	25	0.004892
	30	0.003544
	40	0.002104
	50	0.001392
	60	0.0009889
	70	0.0007384
	80	0.0005723
2.0	90	0.0004566
	100	0.0003727
	1	0.4910
	2	0.1672
	3	0.1011
	4	0.07229
	5	0.05531
	6	0.04398
	7	0.03590
	8	0.02989
3.0	9	0.02529
	10	0.02169
	1	0.4155
	2	0.1551
	3	0.09813
	4	0.07129
	5	0.05491
	6	0.04379
	7	0.03580
	8	0.02984
4.0	9	0.02526
	10	0.02167
	1	0.3720
	2	0.1487
	3	0.09659
	4	0.07079
	5	0.05470

The factor $D^{(3)}$ is shown as a function of temperature in Fig. 43 on several different hypotheses as to the nature of the particle. The upper curve is correct for a material having an intermolecular potential minimum of the same depth as that found for two "air molecules." The lower curves represent material having stronger attractive forces; for example, the curve marked $\epsilon/k = 500^\circ\text{K}$ would be appropriate for a material having a melting point around 1450°K . In the opinion of the writer, it is likely that particles of nearly any kind will quickly become covered with adsorbed air molecules and the resulting behavior with respect to diffusion will be very nearly that of the upper curve. To the extent that this is true, all or nearly all materials will have the same diffusion coefficients for a given particle radius (neglecting the density effect) if the particle radius is understood to include the thickness of the film of air.

The calculated values appear in Table IV.

The values of D which result on combining the three factors are shown for two cases in Fig. 44. It is assumed that the air is at n.t.p., and that the density of the particle is $q = 2 \text{ g./cm.}^3$; the values of the parameter ϵ/k are 100°K (broken line) and 500°K (dotted line). For comparison, there also appear (solid lines) values computed from Knudsen's formula using values of the constants given earlier in this section; these values are said to describe experimental results for "average" particles (data taken from a diagram prepared by T. A. Rich, dated August 20, 1957). If the latter is correct in the large-particle region, changes in the values of the constants in Knudsen's formula would be required to secure agreement with the present calculations in the small-particle region; for example, one might increase $C_1 + C_2$ by a factor of approximately five.

Figure 43. The Factor $D^{(3)}$ as a Function of Temperature, for Various Levels of ϵ/k

TABLE IV
VALUES OF $D^{(3)}$ AS A FUNCTION OF ϵ/k AND TEMPERATURE

$\epsilon/k, ^\circ K$	Temperature, $^\circ K$	$D^{(3)}$
100	40	109.1
	60	247.6
	80	443.9
	100	694.9
	120	995.9
	140	1343
	160	1734
	180	2164
	200	2631
	220	3135
	240	3674
	260	4244
	280	4844
	300	5475
	320	6137
	340	6825
	360	7541
	380	8284
	400	9054
	450	11,090
250	500	13,280
	1000	42,560
	75	244.0
	100	431.4
	125	676.4
	150	978.8
	175	1339
	200	1755
	225	2225
	250	2747
	275	3317
	300	3936
	325	4603
	350	5311
	375	6062
	400	6855
	425	7686
	450	8554
	475	9463
	500	10,400
	1000	35,790

TABLE IV (Continued)

ϵ/k , °K	Temperature, °K	$D^{(3)}$
500	150	690.1
	175	935.0
	200	1220
	225	1545
	250	1913
	275	2320
	300	2768
	325	3259
	350	3787
	375	4356
	400	4963
	425	5609
	450	6293
	475	7014
	500	7770
	1000	29,420
1000	300	1952
	350	2645
	400	3451
	450	4371
	500	5412
	1000	21,980

Figure 44a. The Kinetic Theory Diffusion Coefficient $D = D^{(1)}D^{(2)}D^{(3)}$ as a Function of Particle Radius. $q = 2 \text{ g./cm.}^3$; $T = 273^{\circ}\text{K}$; $p = 1 \text{ Atm.}$; $D^{(1)}D^{(3)} = 1.583$

Broken Line Shows Values When $\epsilon/k = 100 \text{ }^{\circ}\text{K}$
Dotted Line Shows Values When $\epsilon/k = 500 \text{ }^{\circ}\text{K}$
Solid Line Represents Knudsen's Formula

Figure 44b

Figure 44c

APPENDIX IV

DATA REDUCTION THEORY FOR THE PRESSURE
DROP-FLOW RATE RELATIONSHIP

DATA REDUCTION THEORY
FOR THE PRESSURE DROP-FLOW RATE RELATIONSHIP

When a filter is employed under widely different conditions covering substantial ranges in temperature, absolute pressure, flow rate, and pressure drop, it is, of course, desirable to have a general relationship between the frictional pressure drop across the filter and the flow rate. Reid (5, 6) saw the need for this and in 1949 carried out an analysis for the reduction of data. His theory is based on the analogy between the pressure loss coefficient of a duct obstruction and the drag coefficient of a solid body (6). Accordingly, the velocity term appearing in Reid's theory was taken by him to be the velocity of the air at a point immediately upstream from the filter; consistent with this, the density and viscosity of the air were taken to be these quantities at an upstream point.

When the data presented in this report are handled by means of Reid's theory, some of the data points are observed to deviate substantially from a common relationship; the largest deviations are noted where the absolute pressure is low and the pressure drop and flow rate are high. According to the theory presented in this portion of the Appendix, these deviations stem from the choice of upstream velocity, density and viscosity; in the following paragraphs it is shown that the velocity term appearing in the theory should be the harmonic mean of the fore and aft velocities; the density should be that corresponding to the arithmetic mean of the fore and aft absolute pressures; and the viscosity of air, depending only on the temperature, is essentially unchanged by the passage through the filter. (The flow of air through a filter is isenthalpic and, for all the pressures

encountered in the field as well as in the laboratory testing of the filters, the flow through the filter should be almost exactly isothermal.)

To avoid confusion, Reid's symbols will be employed; these will be defined, along with several quantities introduced by the present theory, when encountered.

The theoretical considerations rest on several assumptions:

1. The filters are homogeneous and of uniform thickness. Actually, the filters are neither homogeneous nor uniform in thickness; this assumption, like those below, is made in the interest of developing a useful data reduction theory.

2. The filters are incompressible. Actually, the frictional pressure drop in the filter produces a variable compressive stress (zero at the upstream face of the filter, maximum at the downstream face) which compacts the material and thus increases the flow resistance (the void volume ϵ of the Kozeny-Carman theory is reduced). In the opinion of the writers, some of the curvature of the relationship presented in Fig. 45 is attributable to compaction of the filter under the pressure drop. Although it is felt that the effect of compressibility can be included in a theoretical treatment, it is believed that inclusion of this factor is not vital to the development of a useful data reduction theory. The point is mainly of theoretical interest: for example, the theory cautions one against assuming that all of the curvature of the relationship given in Fig. 45 is due to the increase in turbulent portion of the flow with increase in the Reynolds' number.

3. The effect of "slip" (or "molecular flow") is negligible.

Without doubt, the contribution of slip to the flow of air through a filter is measurable, particularly at $1/20$ atmosphere, where the mean free path of the air molecules is twenty times that at standard atmospheric pressure. However, this assumption, like that of incompressibility, is mentioned as being mainly of theoretical interest; a useful data reduction theory can be developed without inclusion of the slip effect. Before passing to the next assumption it should be stated that, very probably, some of the deviations of data points from the common relationship could be reduced through measurements of basis weight, compressibility, and pore size distribution (and allowing for these factors in the theory); these factors are not all evaluated for each filter at the present time, and such evaluation is not recommended unless it is desired to reduce the standard deviation.

4. The frictional pressure drop developed within the filter is the same as the observed difference in pressures at points in the free stream just upstream and downstream from the filter faces. In principle, there should be a small pressure drop across the upstream face of the filter, and a small pressure rise across the downstream face. (This follows from the fact that the velocity of the air increases, then decreases, when the air passes the upstream and downstream faces, respectively. The pressure head differences occurring across the filter faces are approximately equal and opposite to the velocity head changes.) This assumption amounts to the statement that the difference between the magnitudes of the pressure across the two faces is negligible. Numerical estimates indicate that, for the extreme cases, this difference is less than 1% of the observed pressure drop.

APPLICATION OF REYNOLDS' THEORY

The total pressure drop developed in the filter is designated $(\Delta p)_f$, where the subscript means "in the filter." The contribution to this of the pressure drop across a lamina of thickness dz is designated $d(\Delta p)_f$. Equation (1) is obtained by applying a familiar form of Reynolds' equation to a lamina:

$$d(\Delta p)_f = k \rho^{n-1} \mu^{2-n} r^{n-3} V_f^n dz, \quad (1)$$

in which k is a pure-number coefficient; ρ and μ are the density and viscosity of the air, respectively, in the lamina under consideration, at distance z from the downstream face of the filter; r is an appropriate linear dimension of the pores in the filter; V_f is the local mean velocity of the air through the lamina; and n is an exponent which, in usual practice, is empirically determined to fit data in a limited regime of flow. When one collects the terms raised to the power n , the familiar Reynolds' number, $(V_f \rho r / \mu)$, is obtained. The factor of dz is then seen to be $k(\mu^2 / \rho r^3) (V_f \rho r / \mu)^n$. The most general form for the factor would involve an infinite number of values of n ; or, using the functional representation, one may write

$$d(\Delta p)_f = k(\mu^2 / \rho r^3) \phi(V_f \rho r / \mu) dz \quad (2)$$

for the differential equation which should be applicable to all regimes of flow.

The equation of continuity demands that $V_f \rho$ remain constant throughout the filter. Since, for a given set of conditions, μ and r are also constant, the Reynolds' number and the function of the Reynolds' number $\phi(V_f \rho r / \mu)$ are invariant throughout the filter. From the gas law, $\rho = (M/RT)p$, in which M is the equivalent molecular weight of air, R is the gas

constant, T is the absolute temperature and p is the local absolute pressure. Noting that $p = p_{2f} + (\Delta p)_f$, where p_{2f} is the pressure in the filter at $z = 0$ and $(\Delta p)_f$ is the frictional pressure drop existing between the plane at z and the downstream face, Equation (2) may be written as

$$[p_{2f} + (\Delta p)_f] d(\Delta p)_f = k(RT/M)(\mu^2/r^3) \phi(v_f \rho r/\mu) dz. \quad (3)$$

This integrates to

$$p_{2f}(\Delta p)_f + (1/2)(\Delta p)_f^2 = k(RT/M)(\mu^2/r^3) \phi(v_f \rho r/\mu) z; \quad (4)$$

noting that $p_{2f} + (1/2)(\Delta p)_f$ is the arithmetic mean pressure in the filter, and substituting mean density for mean pressure, one has

$$(\Delta p)_f = k(\mu^2/\bar{\rho} r^3) \phi(v_f \rho r/\mu) z. \quad (5)$$

The equation of continuity leads, as shown earlier, to invariance of the Reynolds' number throughout the filter; it also leads to the result that the fore and aft Reynolds' numbers in the free stream are equal, although of more importance at the moment is the result,

$$\rho_1 V_1 = \rho V_f \eta = \rho_2 V_2, \quad (6)$$

which states that the mass rate of flow is the same at points upstream (subscript 1), in the filter, and downstream (subscript 2), during steady flow. The air velocity in the filter is, of course, substantially higher than a corresponding free stream speed, because the structural elements of the filter and the interfiber void configuration result in an equivalent area available for flow which is only a fraction η of the apparent face area of the filter. One may now define a mean corresponding free stream velocity $\bar{V}$:

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air velocity, density, and viscosity are those of the air at a point immediately upstream from the filter. One of his data reduction plots involves the numbers $\sigma \Delta p / \omega^2$ and $\sigma V / \omega$, in which, for the purpose of referring flow rate to a standard condition of pressure and temperature, Reid employs reduced density and viscosity, i.e., $\sigma = \rho / \rho_0$ and $\omega = \mu / \mu_0$, where ρ_0 and μ_0 are, respectively, the density and viscosity of air under the reference conditions. It will readily be seen that Reid's numbers are similar to those obtained from Equation (9); in an effort to utilize Reid's concept of reduced density and viscosity, the quantities $\bar{\rho} \Delta p / \omega^2$ and $\bar{\rho} \bar{V} / \mu$ have been converted to $\bar{\sigma} \Delta p / \omega^2$ and $\bar{\sigma} \bar{V} / \omega$, respectively. These are the numbers plotted from the data in Fig. 45. The reduced density $\bar{\sigma}$ is based on the arithmetic mean of the of the fore and aft densities (or computed from the arithmetic mean of the fore and aft pressures); $\bar{V}$, as stated earlier, is the harmonic mean of the fore and aft air velocities; and ω is based on the viscosity, which is constant for all points upstream from the filter, in the filter, and downstream from the filter. In calculating $\bar{\sigma} \bar{V} / \omega$ it should be noted that $\sigma_1 \bar{V}_1 / \omega = \bar{\sigma} \bar{V} / \omega = \sigma_2 V_2 / \omega$, and, hence, this number is most simply and directly computed from the data obtained in the present study from the downstream pressure, temperature, and velocity. In calculating $\bar{\sigma} \Delta p / \omega^2$, the most simple and direct computation of the reduced arithmetic mean density is based on $p_2 + (\Delta p / 2)$ and the temperature.

Figure 45

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Figure 46. Distribution Functions for the Deviations of the 1450 Points on the Plot of Figure 45 from the Least-Squares Polynomial Fit. Machine-Made Specimens, Open Circles; Handsheet Specimens, Solid Points