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(Final Report)

IMPROVEMENT OF LAMINAR-FLOW EQUIPMENT  
FOR MICROELECTRONIC APPLICATION

National Aeronautics and  
Space Administration  
Cambridge, Massachusetts

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IMPROVEMENT OF LAMINAR-FLOW EQUIPMENT  
FOR MICROELECTRONIC APPLICATION

June 1, 1967 through May 31, 1968

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IMPROVEMENT OF LAMINAR-FLOW EQUIPMENT  
FOR MICROELECTRONIC APPLICATION

FOREWARD

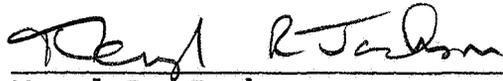
This is the final report on the project entitled "Improvement of Laminar Flow Equipment for Microelectronic Application." This project was sponsored by the Electronics Research Center of the National Aeronautics and Space Administration during the period June 1, 1967 through May 31, 1968 under Contract No. NAS12-552.

Part I of this report is concerned with the evaluation and improvement of laminar flow equipment for microelectronic applications. Part II is a survey document intended to describe available equipment and present and potential application to the medical profession.

Respectfully submitted,  
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IMPROVEMENT OF LAMINAR-FLOW EQUIPMENT  
FOR MICROELECTRONIC APPLICATION

ABSTRACT

This program was undertaken to improve laminar flow equipment for microelectronics applications and to study the application of laminar flow equipment to the medical profession.

There are only two possible approaches to improving laminar flow benches for control of particulate contamination in laminar flow benches. Either filtration efficiency can be improved or air flow patterns can be modified. The first method was chosen and a laminar flow bench with an improved filter was constructed and delivered to NASA for evaluation. Theoretical calculations were also made in order to evaluate the conditions under which contaminated room air can penetrate into the clean area of an open laminar flow bench. It was concluded that movements of personnel or objects near the open face of a bench can propel dirty air into the bench.

The study of medical applications indicated that laminar flow equipment is of potentially great benefit in the treatment of burn and cancer chemotherapy patients. The use of laminar techniques in operating rooms in efforts to reduce post-operative infections has not been wide enough to demonstrate a statistically significant effect.

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# IMPROVEMENT OF LAMINAR-FLOW EQUIPMENT FOR MICROELECTRONIC APPLICATION

## I. INTRODUCTION

This program had two major objectives. The first of these objectives was to improve laminar flow equipment for microelectronic application. The second objective was to write a preliminary survey document for the technical utilization of laminar flow equipment by the medical profession. This report is therefore logically organized in two parts. The first part is concerned with microelectronic applications while the second part is devoted to medical applications.

The first part of this report is limited in scope to laminar flow benches or hoods, since these are in predominant use in the microelectronics industry. Clean rooms are not discussed as such; although much of the material is directly applicable to clean rooms.

## II. PRESENT "STATE-OF-THE-ART"

### A. The Laminar Flow Concept

The laminar flow concept was developed to meet the need for ultra-clean areas for use in operations where air borne particles create serious contamination problems. The creation and maintenance of a relatively particle-free atmosphere is possible only by removing particles from the atmosphere. Since it is difficult if not impossible to reduce the rate of particle generation to acceptable standards of cleanliness in areas where people must work, it is necessary to continually remove

the generated particles from the atmosphere. In the laminar flow concept this is done by maintaining a continuous unidirectional flow of filtered air through the entire clean volume. The air velocity is generally 100 feet per minute.

#### B. Basic Types of Laminar Flow Benches

Laminar flow benches are produced by many different manufacturers. Although each manufacturers' product differs in design details, only a few basically different types are available. The principle design features are:

1. Horizontal Flow
2. Vertical Flow
3. Horizontal Radial Flow
4. Vented Fume Hoods
5. High-Velocity Perimeter Air Flow

In the horizontal flow bench the filters are mounted in a vertical plane at the back of the bench and the air flow is in a horizontal direction toward the front of the bench. A worker at the bench thus faces directly into the barely perceptible air stream.

The vertical flow bench has the filter mounted in a horizontal plane above the working surface. In this bench the air flows from the filters downward and through the perforated working surface.

The fume hoods are vertical flow hoods which inspire a small amount of air from the room into the working area in order to prevent diffusion of noxious gases into the room. All or part of the air stream is then vented to the outside of the building.

The radial flow bench has a circular filter. The air flow is horizontally and radially from the filter to the periphery of the bench. With this type of bench it is possible to station several workers around the bench.

Some manufacturers provide a narrow stream of relatively high velocity air at the perimeter of the opening to the working area of the bench. This feature represents an attempt to reduce the diffusion of dirty air from the room into the clean area.

### C. Filters for Laminar Flow Benches

The HEPA filters used in most laminar flow equipment were not developed specifically for use in laminar flow equipment. These filters were used because they were judged to be the best available. This judgment was made, however, with only meager information about the requirements of the various operations performed in the clean areas. The possibility exists therefore that the choice was only the best choice from an inadequate group. This question cannot be answered definitely without good information, based on experimental evidence, on the effect of particle contamination on microelectronics.

The filtering element in the HEPA filters is a mat of fine glass fibers. The filtering element is pleated to provide a large filtering area within a relatively small face area. The pleated element is sealed to a frame with an adhesive. Particles are removed from the air stream by the filtering element by two primary mechanisms. Large particles, larger than the

interstices of the filtering medium, are trapped on the surface of the filter. Smaller particles are able to penetrate into the filtering element where they are collected by impingement on the fibers due to inertial and diffusional forces. The two filtration mechanisms result in a condition where large particles are completely removed, very small particles are very efficiently removed because of their high diffusivity, while particles in a size order of  $0.1 \mu$  are removed with the lowest efficiency.

Although the HEPA filters are very efficient in removing particles they are not perfect even for particles considerably larger than the average interstice of the filtering element. Some penetration of relatively large particles is possible because of imperfect gasketing, imperfections in the filtering element, and inadequate sealing of the element to the frame. The highest quality HEPA filter presently available, has an efficiency of 99.99% for  $0.3 \mu$  DOP particles. The improved efficiency over 99.97% for the more commonly used HEPA filter is due largely to improved gasketing and sealing techniques. This improved filter can provide a significant reduction in particle count in the clean areas. The expected reduction in particle count would be a factor of three. Whether this improvement in the quality of the filtered air would be significant in its effect on microelectronics work remains to be established. Of more importance might be an improved distribution of air velocity from the filter face.

The glass fibers in the HEPA filters are resistant to corrosion by all common chemicals other than hydrogen flouride

and caustics. However other parts of the filter are subject to chemical attack and solvents may attack the adhesive used to seal the media to the frame.

### III. CONTAMINATION IN LAMINAR FLOW BENCHES

Although laminar flow benches are very effective in reducing air borne particulate contamination, complete removal of air borne particulates from the clean area is an unrealistic goal. Particulate matter in the clean area of the bench may result from:

1. Particles passed through the HEPA filter,
2. Particles brought into the clean area on dirty objects or generated within the clean area,
3. Convection of dirty room air into the clean area.

The HEPA filters generally used in laminar flow benches use fine glass fiber mats as the filtering medium. These filters are 99.97% efficient in the removal of 0.3  $\mu$  diameter dioctyl phthalate particles.

Particles brought into the clean area or generated within the area are beyond the control of any laminar flow device. This source of contamination can only be controlled by using adequate cleaning procedures.

#### A. Convection of Dirty Air by Turbulent Wakes

Contaminants can enter the clean area in turbulent wakes of objects moved into the laminar flow bench. Any object moving in air generally produces a turbulent wake, even at low velocities. This turbulent wake can trap dirty air from the room and introduce contaminants into the clean area. Some of these contaminants

will be swept out by the filtered laminar air stream; however, contamination from this source can occur. For example, a worker stationed before a laminar flow bench moving a hand into the clean area could carry dirt-laden air from the room into the clean area in the turbulent wake produced by the motion of the hand.

Little can be done in the design of laminar flow benches to eliminate contamination from this source. Contamination from this source is related to the concentration of contaminants in the ambient air and the physical activity near the clean bench. The amount of contaminants introduced into the clean area can be reduced by awareness of the problem and avoidance of rapid movements of large objects into the clean area.

#### B. Propulsion of Air Parcels Into the Clean Area

Another mechanism by which dirt-laden air from the room can enter the clean area is propulsive in nature. That is, an object moving toward the clean area can propel a parcel of air toward the clean area. Given sufficient momentum the dirty air parcel can penetrate to considerable distances even against the flow of filtered air. The motion of the object supplying the propulsive force need not be directly toward the clean area, just as a fan blade propels air in a direction perpendicular to its plane of motion. In order to establish the magnitude of this effect some calculations were made of the penetration of air parcels into the face of a laminar flow stream.

If we consider a parcel of air, spherical in shape, with a radius of  $r_0$ , and an initial velocity of  $U_0$ , then the momentum

of the parcel is:

$$\rho \frac{4}{3} \pi r_o^3 U_o \quad (1)$$

where  $\rho$  is the density of air.

We assume that as the parcel of air moves through the still air the parcel grows due to the incorporation of the still air which the parcel intercepts. Since momentum is conserved:

$$\rho \frac{4}{3} \pi r_o^3 U_o = \rho \frac{4}{3} \pi r^3 \frac{dx}{dt} \quad (2)$$

where,

$x$  is the distance in the direction of the initial velocity,

$t$  is the time,

$r$  is the radius of the parcel,

The differential change in the mass of the parcel,  $dM$ , is then:

$$dM = \pi r^2 \rho dx = 4 \pi r^2 dr \quad (3)$$

and

$$dx = 4 dr \quad (4)$$

integrating

$$\int_0^x dx = \int_{r_o}^r 4 dr \quad (5)$$

$$x = 4r - 4r_o$$

$$r = \frac{x + 4r_o}{4} \quad (6)$$

substituting (6) into (2)

$$\frac{dx}{dt} = \frac{U_o r_o^3}{\frac{x + 4r_o}{4}} \quad (7)$$

and integrating

$$\int_0^x (x + 4r_o)^3 dx = \int_0^t 64 U_o r_o^3 dt \quad (8)$$

$$\int_0^x (x^3 + 12r_o x^2 + 48r_o^2 x + 64r_o^3) dx = \int_0^t 64 U_o r_o^3 dt$$

$$\frac{x^4}{4} + 4r_o x^3 + 24r_o^2 x^2 + 64r_o^3 x = 64 U_o r_o^3 t \quad (9)$$

From Equation 9, the penetration,  $x$ , of a parcel of air radius,  $r_o$ , and initial velocity,  $U_o$ , can be calculated as a function of time. If the parcel of air is propelled into the face of a moving stream of velocity,  $V$ , the penetration,  $X$ , is:

$$X = x - Vt \quad (10)$$

and the velocity relative to a stationary point,  $U$ , is:

$$U = U_o - V.$$

These calculations were made for the typical case where air parcels are propelled into the face of a laminar stream of

100 fpm, using initial velocity,  $U$ , and parcel radius,  $r_0$ , as parameters to calculate penetration,  $X$ . The results of these calculations are presented in Figure 1.

The curves in Figure 1 can be used to estimate the penetration of parcels of dirty air into the clean area of a laminar flow bench. For example, a worker stationed at a laminar flow bench could move a hand toward the clean area at a velocity of 20 fps. This movement could be expected to create a moving parcel with dimensions approximately the dimensions of the propelling object, in this case,  $r_0$ , would be approximately 1/4 ft. and  $U$  equal to 20 fps. From Figure 1, a penetration of approximately 0.8 ft. would be expected.

#### C. Flow Separation Due to Divergent Flow Channel

Dirty air can also enter the clean area because of a phenomenon commonly termed flow separation. A fluid flowing in a channel of increasing cross-sectional area must decrease in velocity otherwise the flow cannot fill the entire channel. If the angle of divergence of the channel walls is small, the fluid will decrease in velocity and the flow will be in the same direction throughout the channel. If, however, the angle of divergence is too great, flow separation occurs at the channel walls, that is an eddy current forms and the flow is in the reverse direction at the channel walls. This type of flow is shown in Figure 2. This phenomenon is of interest here since a flow reversal in a laminar flow bench could introduce dirty room air into the clean area. The geometrical conditions which lead

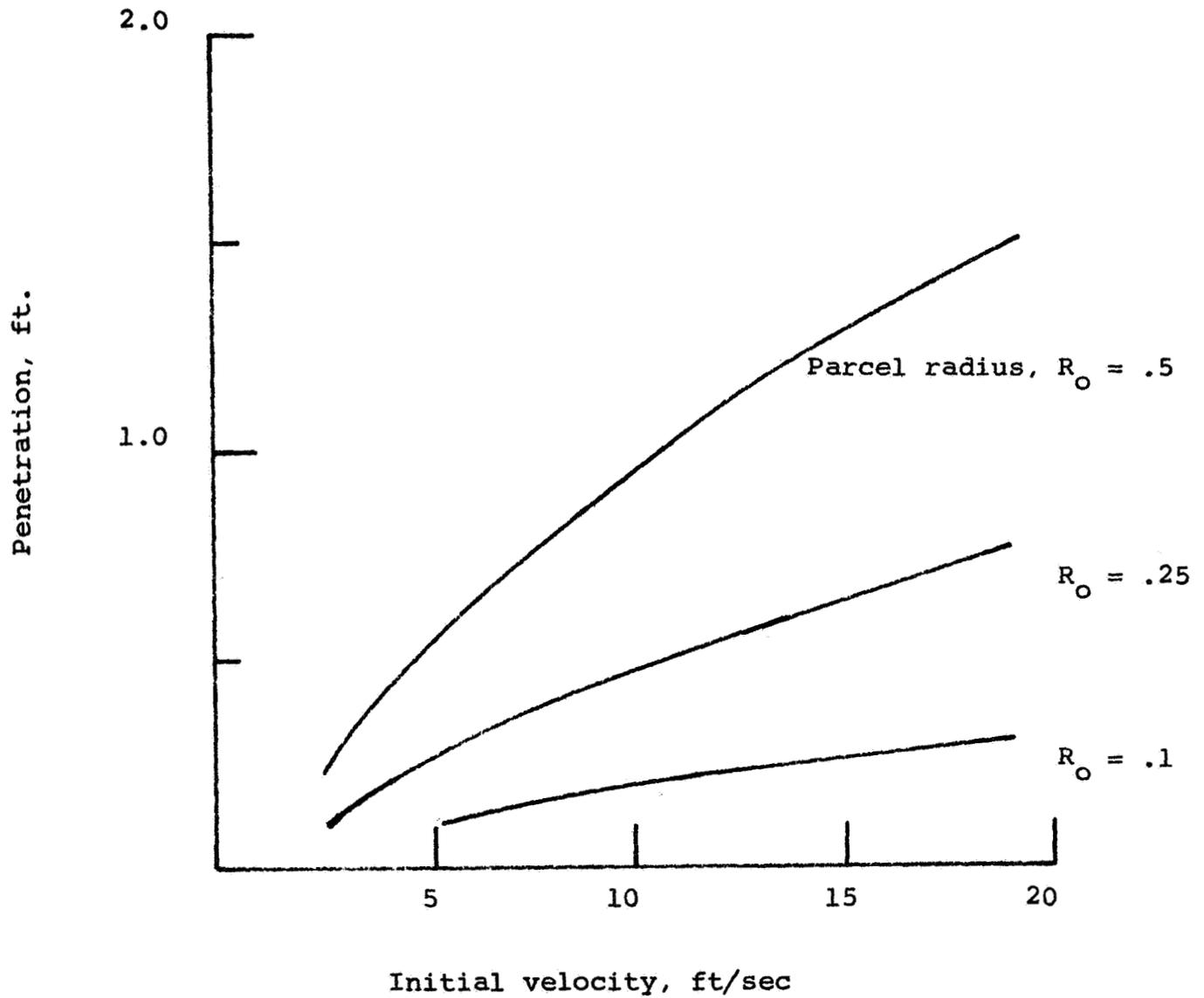


FIGURE 1

Penetration of Spherical Air Parcels  
into an Air Stream, 100 FPM

to flow separation in air streams are known.<sup>1</sup> Flow reversal will take place at a distance,  $b$ , from the beginning of the divergent section when:

$$\frac{b}{a} \tan \alpha = 0.213$$

where the symbols refer to Figure 2. Thus for a bench with diverging walls 4 ft. wide and 2 ft. deep, flow reversal would take place if the angle of divergence were greater than 12°.

Another type of laminar flow bench which is presently marketed has a radial flow pattern. In this case, however, no flow reversal could take place since there are no walls present to provide the resistance.

#### D. Laminar Fume Hoods

Another aspect of contamination due to introduction of room air into the clean area is concerned with the use of vented laminar flow fume hoods. In this type of hood some room air is necessarily drawn into the hood from the room in order to prevent noxious fumes from escaping into the room from the hood. A typical such hood is illustrated in Figure 3. In Figure 3 the greater portion of the air passing through the HEPA filters at the top is recirculated. A fraction of the air is discharged out of the building and makeup air is drawn into the system both at the opening to the hood and through a pre-filter. A hood of this type must be very carefully adjusted since improper

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<sup>1</sup>Corcoran, W.H., Opfel, J.B., and Sage, B.H., "Momentum Transfer in Fluids," Academic Press, Inc. 265, New York, 1956.

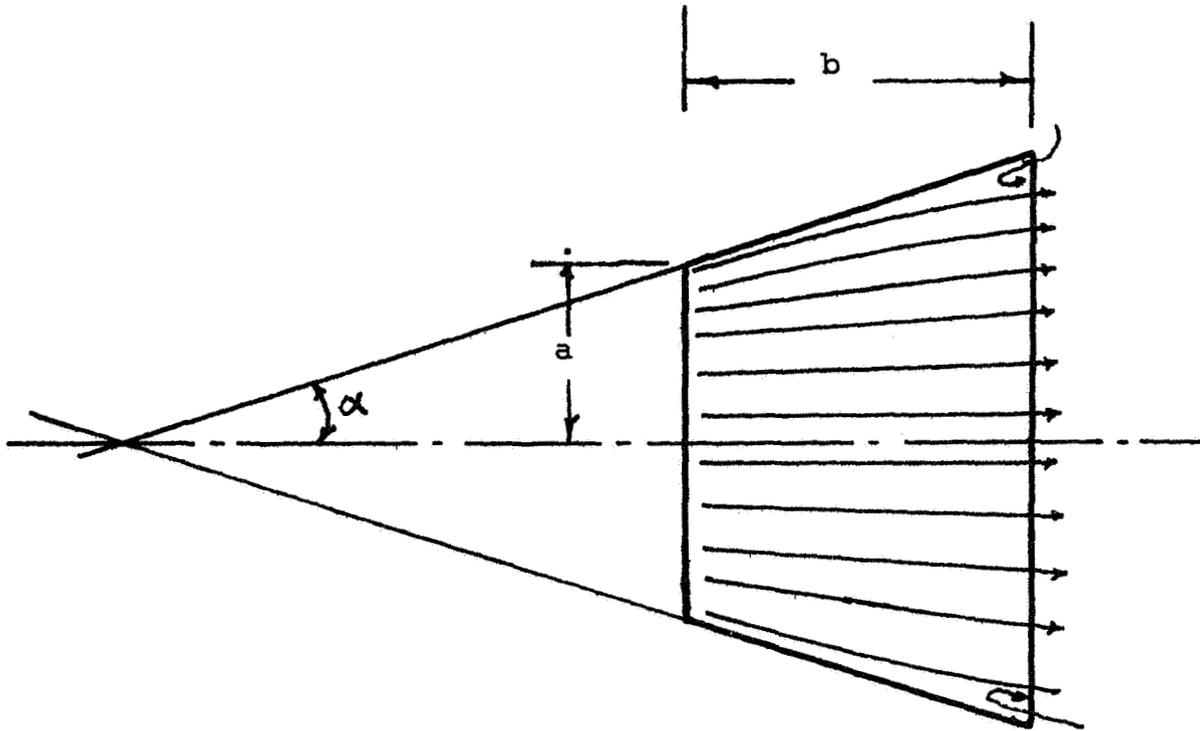


FIGURE 2

Flow Separation in a Divergent Channel

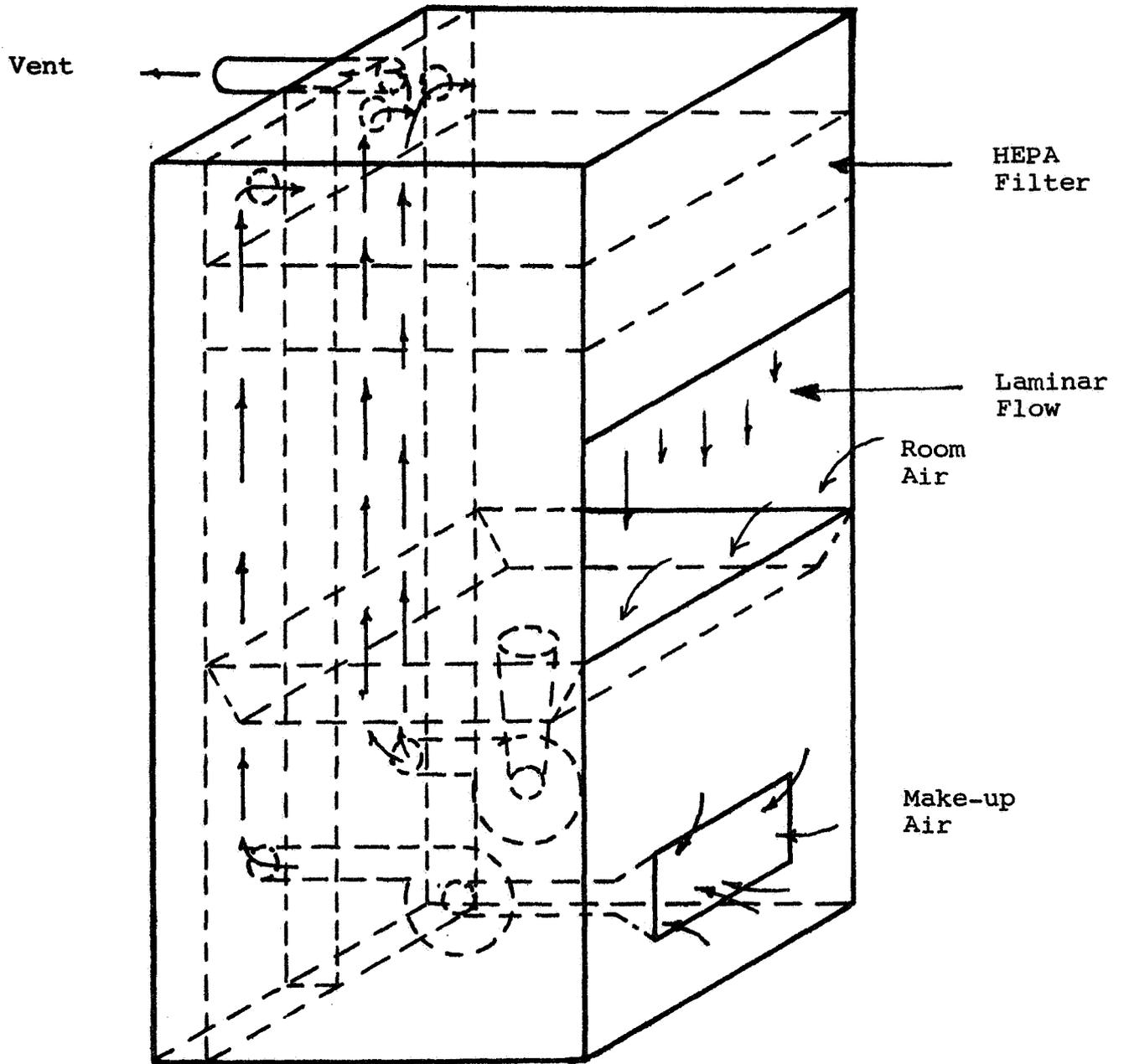


FIGURE 3

Vented Laminar Flow Hood

adjustment can allow either noxious fumes to discharge into the room or allow too great a flow into the hood from the room, introducing contaminants into the clean area. Also, since some of the air is recirculated in the hood, the concentration of noxious fumes in the hood will be considerably higher than if all the air were discharged. This buildup in concentration can be readily calculated. If  $X$  is the rate of gaseous contaminants emitted in the hood,  $Q_1$  is the air circulation rate in the hood.  $Q_2$  is the rate of discharge through the vent, and  $C$  is the concentration of contaminant in the hood, then  $C = X/Q_2$ . If the ratio of  $Q_2$  to  $Q_1$  is  $F$ , then  $C = FQ_1$ . If all the air moving through the hood were discharged, the concentration of fume would be at a minimum,  $C_{\min} = X/Q_1$ , at some finite ratio of vented air to circulated air, the fume concentration would be:

$$C = C_{\min}/F.$$

Thus, if only one-third of the air were vented the concentration would be higher than the minimum by a factor of 3. Also, since the air is circulated in the hood, the noxious fumes can mix readily with the circulating air. Thus, the entire volume of the hood is exposed to the fume. This fact should not normally cause difficulty. However, materials which could be adversely affected by fumes emitted from some process in the hood should not be kept in the same hood. Measurement of the contaminant gas concentration in this type of hood will, in most

cases, be unwarranted, since the process being carried out in the hood will, in general, require the presence of the particular fume or gas in much higher concentrations than that present in the circulating air stream. Processes or materials which could be adversely affected by the gas in the hood must be performed at another station.

The foregoing analysis indicates that contaminated air from the room can enter the clean area of a laminar flow bench by several mechanisms. Thus, improvement of the filtration efficiency of the equipment can reach a point where further improvement produces an insignificant change in the particle concentration in the clean area. For this reason a clean bench in a dirty room may not provide as clean an environment as a clean room. Also, a clean bench in a clean room could be expected to provide the most particulate free environment within the present state of laminar flow technology.

#### IV. TESTING OF LAMINAR FLOW EQUIPMENT

##### A. Particle Detection and Measurement

Of the several techniques that can be used to measure particle loading in air, only two appear to be practical for application to the low-particle-concentration environment of a clean hood. These are microscopic counting and light scattering. Other methods, such as collecting samples on filters and weighing the filters or measuring their optical density, are grossly inaccurate at the low concentrations prevailing in clean hoods. Methods based on changes in dielectric constants

or sonic characteristics have been suggested for measuring particles in air, and some development along these lines have been tried, but at the present time no usable instrumentation is available.

Methods based on microscopic counting achieve reasonable accuracy only when very large numbers of particles are counted. For example, counting 500 particles from a population in which all particles have diameters between 1 and 10  $\mu$  can lead to a 50% error in the value of the mass mean diameter.<sup>2</sup> To reduce the error to 10% would require counting 10,000 particles. Therefore, a light-scattering particle counter is the only reasonable choice for the particular application discussed. Commercially available light-scattering particle counters are of two basic types.

The first type, of which the IITRI and Royco Instruments are examples, is a single-particle counter. The sample is drawn through a small, defined viewing volume of such dimensions that it is statistically improbable that more than one particle is in the volume at one time. Light scattered from individual particles passing through the viewing volume is detected as a light pulse by a photomultiplier tube. The signals from the photomultiplier are amplified, discriminated for amplitude, and read out either as numbers of particles or concentration.

The second type uses a large viewing volume in which many particles can be present simultaneously. The light scattered

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<sup>2</sup>Jackson, M. R., Iglarsh, H., and Salkowski, M.J., "Sample Size Induced Errors In The Transformation of Particle Size Distributions" ASTM-IITRI International Conference on Powder Technology, May, 1968.

from all the particles in the viewing volume is sensed by a photomultiplier and, after amplification, yields an integrated readout. No estimate of the size of particles is possible; only the total light scattered, which is a function of the total volume or the mass of particles in the viewing volume, is possible.

Measurements made in a clean room with the two types of light-scattering instruments closely agree with each other. The single-particle counter, however, has the advantage of yielding particle-size information, while the large-viewing-volume instruments have the advantage of sampling larger volumes, a characteristic that in turn affords statistical advantages when "clean" air is sampled.

The use of light-scattering instruments to monitor laminar-flow areas is subject to errors; some errors are inherent in the design of the instrument and others can be minimized by the proper technique.

One inherent error is due to the fact that the fraction of light scattered by a particle at any given angle is a function of the index of refraction, the size, and the shape of the particles. The size data obtained from sampling air containing non-spherical particles and particles composed of many different materials are necessarily subject to some error. This error, however, is generally small as compared to errors introduced by sampling under anisokinetic condition or by deposition in the sampling lines.

A representative sample of an aerosol can be obtained only when the sampling tube or probe faces into the stream and when the velocity in the sampling probe is nearly the same as the velocity of the aerosol stream. The need for matching sampling and stream velocities is apparent when the results of non-matching velocities are considered. If the velocity in the sampling probe is lower than the stream velocity, the large particles having a high inertia enter the probe and some of the accompanying air is deflected around the probe. The result is a high apparent particle concentration and a shift of the particle-size distribution to the high side. Conversely, if the velocity of the sampling probe is higher than the stream velocity, more fluid than high-inertia particles is pulled into the probe. The result is a low apparent particle count and a shift of the particle-size distribution to the low side.

An estimate of the error due to anisokinetic sampling can be made from the following correlation.<sup>3</sup>

$$\frac{C}{C_0} = \frac{U_0}{U} \left\{ 1 + f(p) \left[ \left( \frac{U}{U_0} \right)^{\frac{1}{2}} - 1 \right] \right\}^2$$

where

C is the apparent concentration of the particles  
 $C_0$  is the true concentration of the particles

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<sup>3</sup>Watson, H. H., "Errors Due to Anisokinetic Sampling of Aerosols", Am. Ind. Hyg. Assoc. Quart., Vol. 15, pp. 21-25, 1954.

$U_0$  is the stream velocity (cm/sec)  
 $U$  is the sampling velocity (cm/sec)  
 $p$  is  $\frac{d^2 \pi U_0}{18 \mu D}$   
 $d$  is the particle diameter ( $\mu$ )  
 $\pi$  is the particle density (g/cc)  
 $\mu$  is the fluid viscosity (poise)  
 $D$  is the sampling-probe diameter (cm).

Figure 4 presents the function  $f(p)$  plotted against  $p$ , and Figure 5 presents a series of curves calculated from the above correlation. In Figure 5 the stream velocity was taken as 100 ft/min, a typical value in laminar-flow equipment. The diameter of the sampling nozzle was taken as  $\frac{1}{4}$  in., and the particle density was taken as 1.0 g/cc. From Figure 5 it is apparent that errors due to anisokinetic sampling are very small for particles less than 10  $\mu$  in diameter.

An aerosol passing through a tube is subject to deposition of particles on the interior walls of the tube. The mechanism of deposition changes markedly as the flow changes from laminar to turbulent.

In laminar flow, particles can travel to the walls and deposit only under the effect of Brownian diffusion, gravitational settling, or electrostatic forces. The Brownian forces are very small and generally do not produce significant deposition unless very long sampling lines are used. Gravitational settling of particles in the sampling line can introduce serious errors if the particles are large and if long horizontal sections of tubing are used. Deposition due to electrostatic forces is a complex

phenomenon and is not discussed in detail in this report. However, it is generally possible to reduce electrostatic deposition to acceptable levels by using grounded metal tubing for the sampling lines, humidifying the air, or introducing ionizing radiation to neutralize any charges on the particles.

In turbulent flow, a fluid in a tube has velocity components in the radial direction as well as in the longitudinal direction. Mixing of the fluid takes place, and deposition of particles from the fluid onto the wall occurs more readily. A theoretical model for defining the rate of deposition was developed by Friedlander and Johnstone<sup>4</sup> and verified more recently by Schwendiman and Postma<sup>5</sup>. The amount of deposition is estimated from a turbulent-diffusion coefficient,  $k$ , which can be correlated to the function:

$$D^{0.84} \left[ \frac{\rho_p \rho_g d^2 f V^2}{\mu^2 \left( 1 + \frac{13.5 \rho_p d^2}{\mu} \right)} \right]$$

where

- $D$  is the tube diameter (cm)
- $\rho_p$  is the particle density (g/cc)
- $\rho_g$  is the gas density (g/cc)
- $f$  is the Fanning friction factor
- $V$  is the fluid velocity (cm/sec)
- $\mu$  is the fluid viscosity (poise)
- $d$  is the particle diameter (cm).

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<sup>4</sup>Friedlander, S. K. and Johnstone, H. F., "Deposition of Suspended Particles from Turbulent Gas Streams," Ind.Eng.Chem., Vol. 49, Part 2, p. 1151.

<sup>5</sup>Schwendiman, L.C. and Postma, A.K., "Turbulent Deposition in Sampling Lines," Seventh AEC Air Cleaning Conference, TID-7627, Office of Technical Services, Dept. of Commerce, Washington, 25, D. C., pp. 127-136, 1961.

For air and particles having a density of 1.0 g/cc and for values of  $k/V$  less than  $1 \times 10^{-3}$ , the correlation can be reduced to:

$$k = 29.42 D^{1.79} d^{4.26} f^{2.13} (1 + 7.34 \times 10^4 d^2)^{-2.13} V^{5.26}$$

The ratio of the exit concentration to the entrance concentration can then be calculated from:

$$\frac{C}{C_0} = \exp - \frac{4kL}{VD}$$

where

$L$  is the length of tubing.

Turbulence occurs in tubes when the Reynolds number exceeds 2100. The Reynolds number,  $DV\rho/\mu$ , is a dimensionless quantity.

The solid lines in Figure 6 give the relationship between velocity in a tube and the diameter of the tube for flow rates of 0.1, 0.5, and 1.0 cfm. The dashed line in Figure 6 gives the critical velocity, so all points above the dashed line represent conditions of turbulent flow.

To illustrate the amount of deposition that can take place, a series of calculations was made for the case of a  $\frac{1}{2}$ -in. tube, a flow rate of 1.0 cfm, and a particle density of 1.0 g/cc<sup>3</sup>. The results of these calculations are presented in Figure 7, which graphically indicates the futility of attempting to detect particles larger than 10  $\mu$  in diameter with accuracy while using long lengths of sampling tubing under turbulent-flow conditions.

The foregoing discussion leads to the following conclusions related to particle counting with laminar-flow equipment.

1. Light-scattering particle counters are best suited for this application.
2. The inlet nozzle should be sized to approximately match the nozzle velocity and the stream velocity.
3. The nozzle should point directly "upwind".
4. Tubing from the instrument to the nozzle should be short and large enough in diameter to avoid turbulent flow in it.

#### B. Air Velocity Checks

Users of clean benches are increasingly aware that the benches as purchased do not function as purported. They usually let dirty air leak into the work environment and often do not meet the air velocity limits established. During use, leaks develop and the air velocity changes. Therefore, each bench must undergo both acceptance and routine checks so that defects can be located and corrected. Suggested testing positions for horizontal and vertical laminar-flow work benches are shown in Figures 8 and 9.

Air-velocity measurement is the first test to be performed on a new clean bench. When a hot-wire anemometer (Alnor Instrument Co., Division of Illinois Testing Laboratories, Inc., 420 N. LaSalle, Chicago, Illinois; Hastings-Raydist, Hampton, Virginia; Flow Corporation, 217 Coolidge Hill Road, Watertown, Mass., 02172; Thermo-Systems, Inc., 2418 E. Hennepin Avenue, Minneapolis, Minn.; Aero Research Instrument Company, 315 N. Aberdeen, Chicago, Illinois, 60607) is used, the test is fast, simple and accurate. The sensing element is held, by a ringstand and clamp, 6 to 8 in.

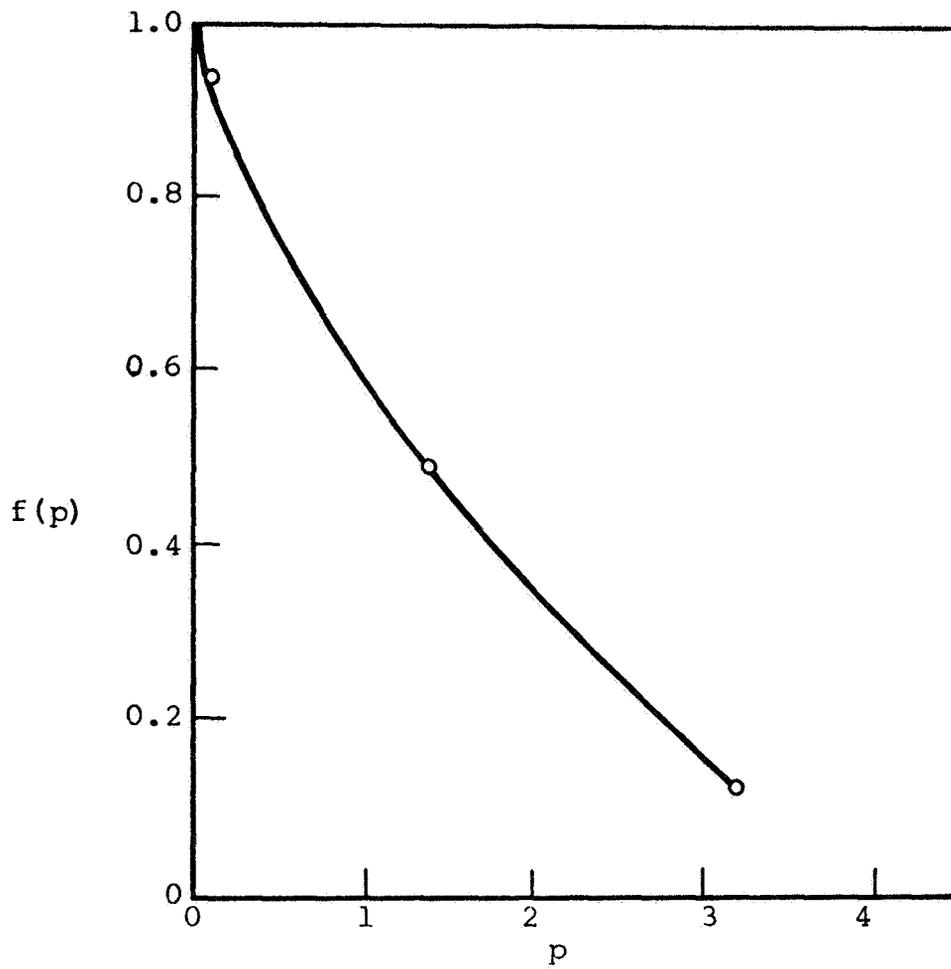


Figure 4

RELATIONSHIP BETWEEN  $f(p)$  AND  $p$   
(Data from ref. 3)

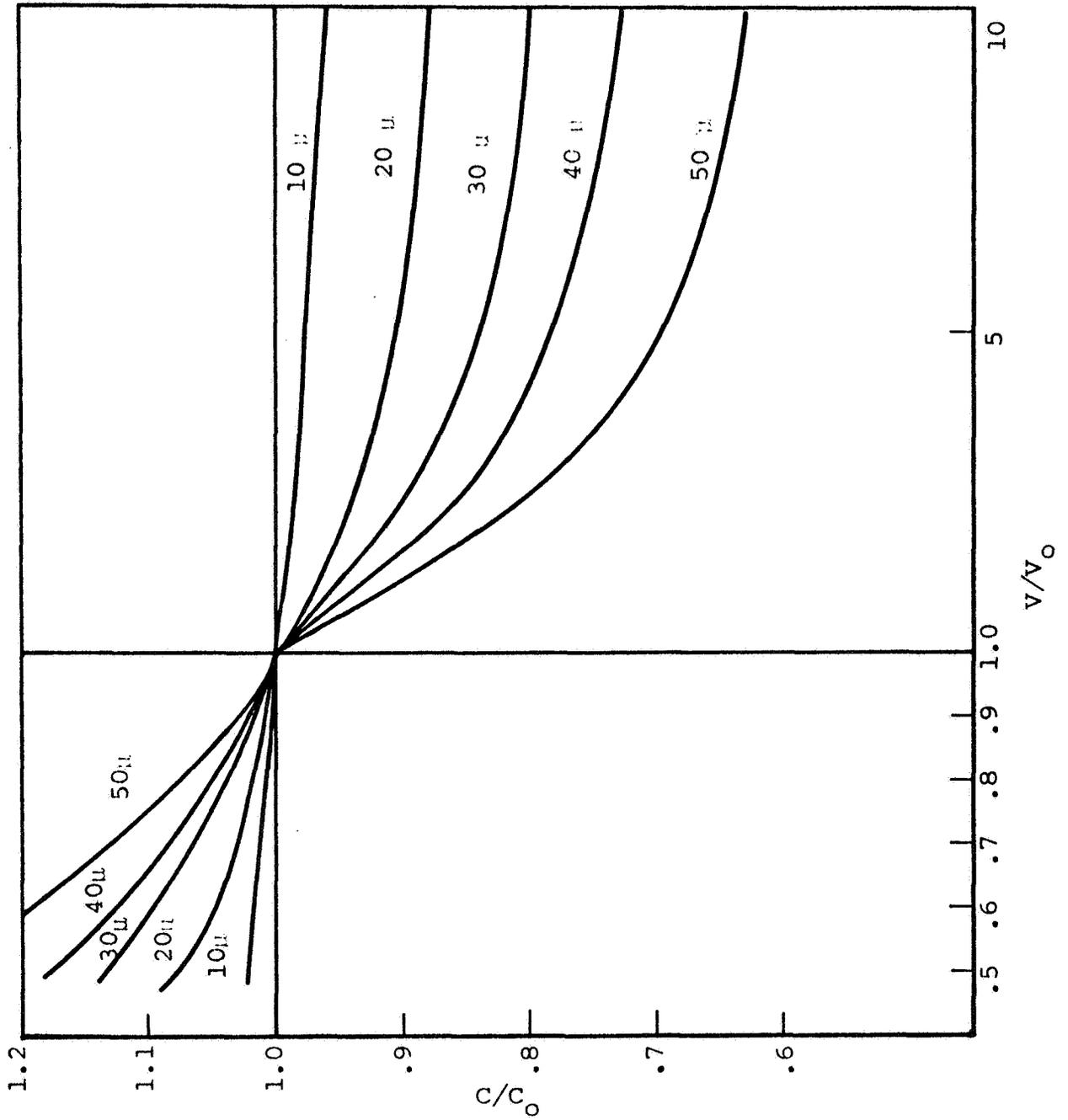


Figure 5

EFFECT OF MISMATCHING SAMPLING VELOCITY TO STREAM VELOCITY

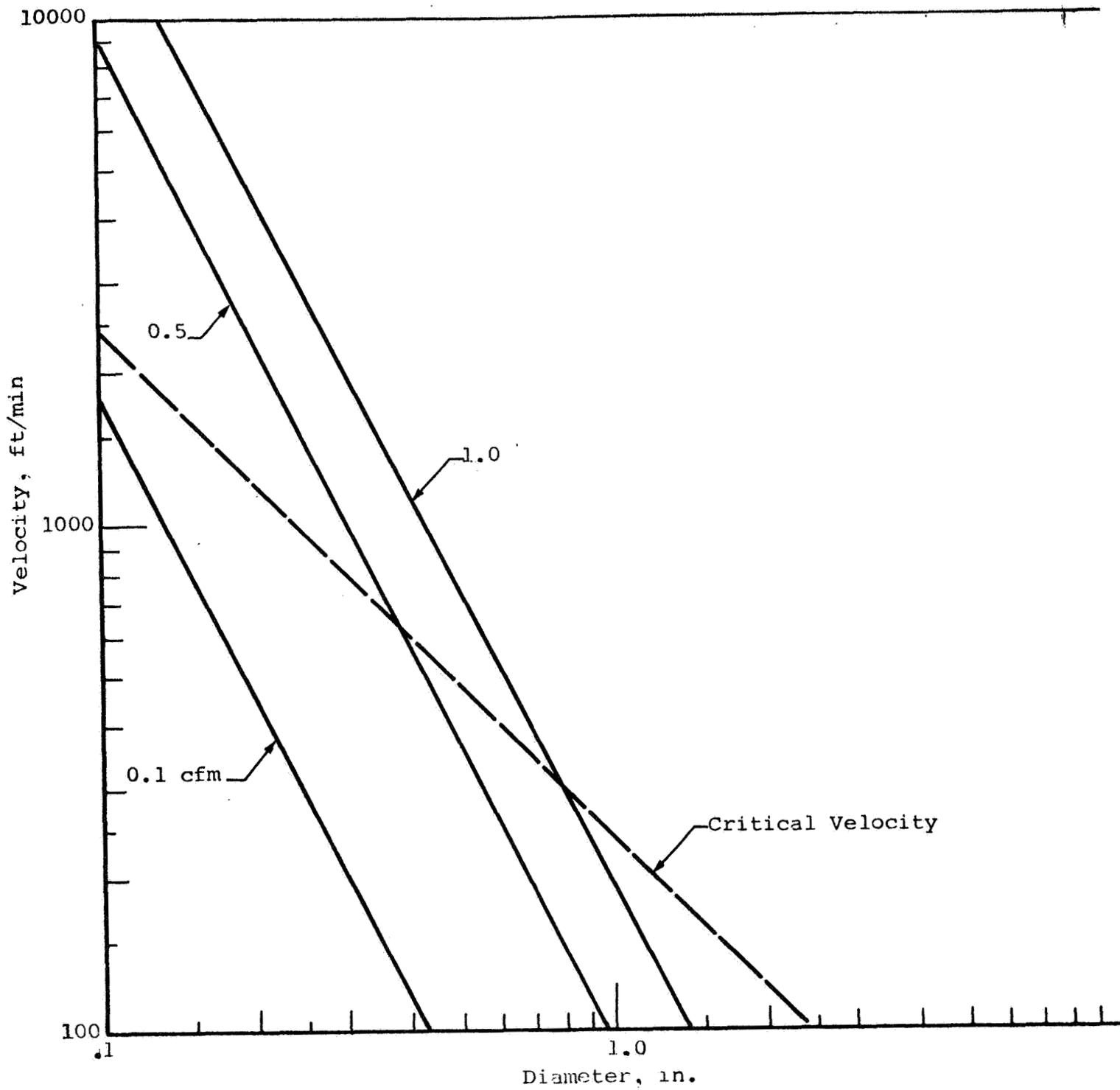


Figure 6

VELOCITY IN TUBES

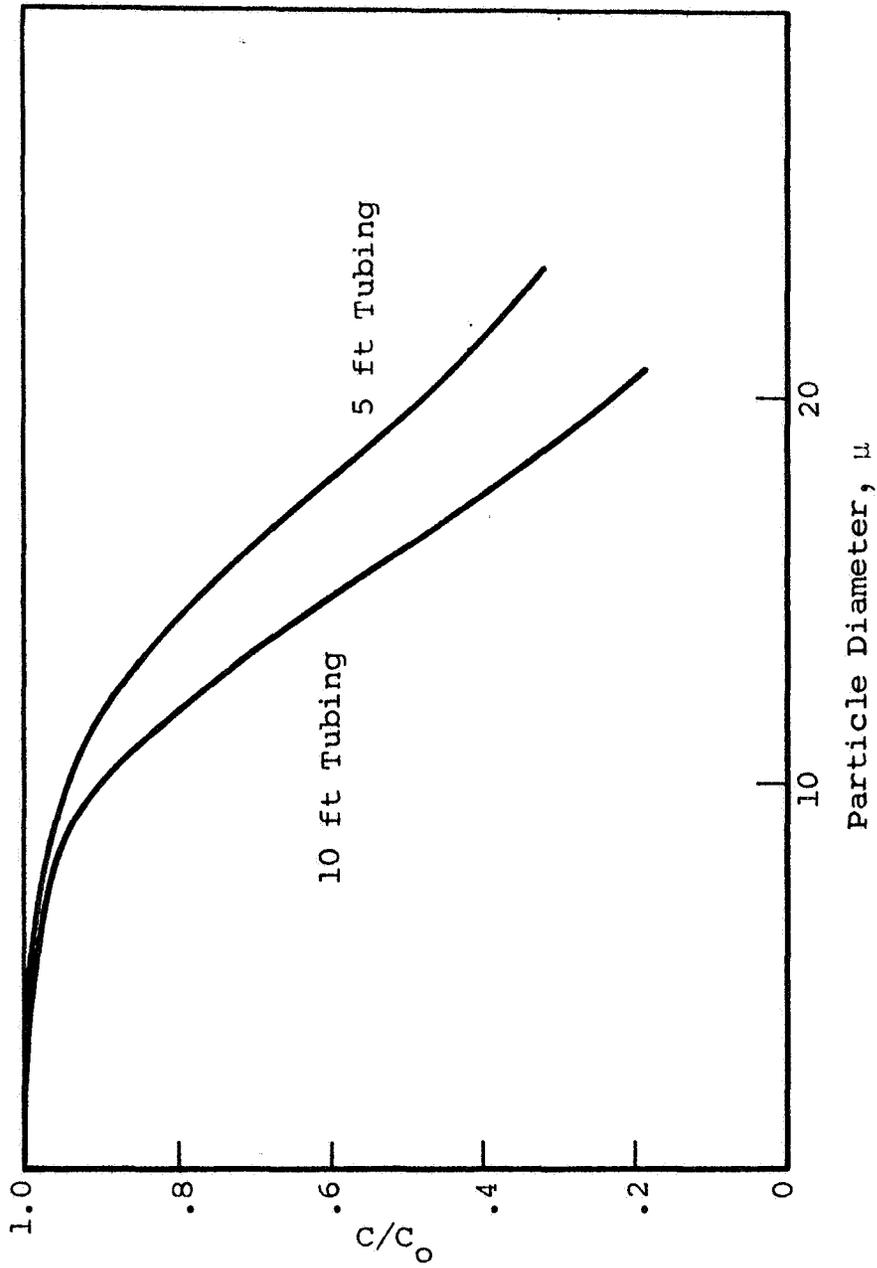


Figure 7

EFFECT OF TURBULENT DEPOSITION IN SAMPLING LINE

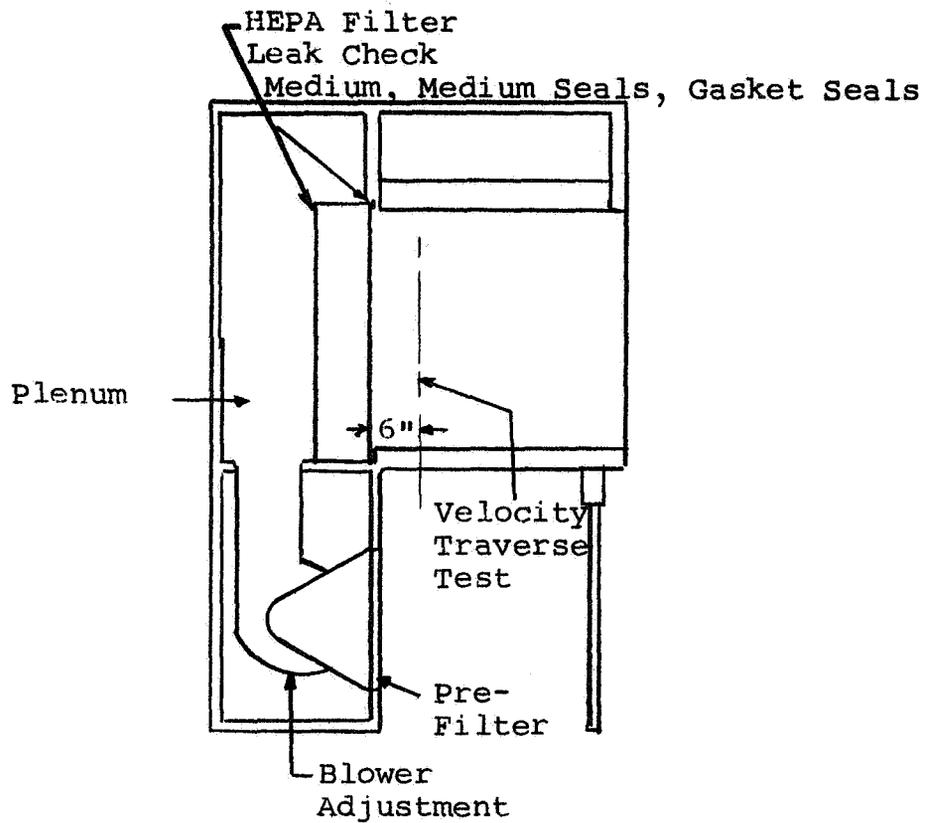


Figure 8

TESTING POSITIONS FOR HORIZONTAL  
LAMINAR-FLOW WORK BENCH

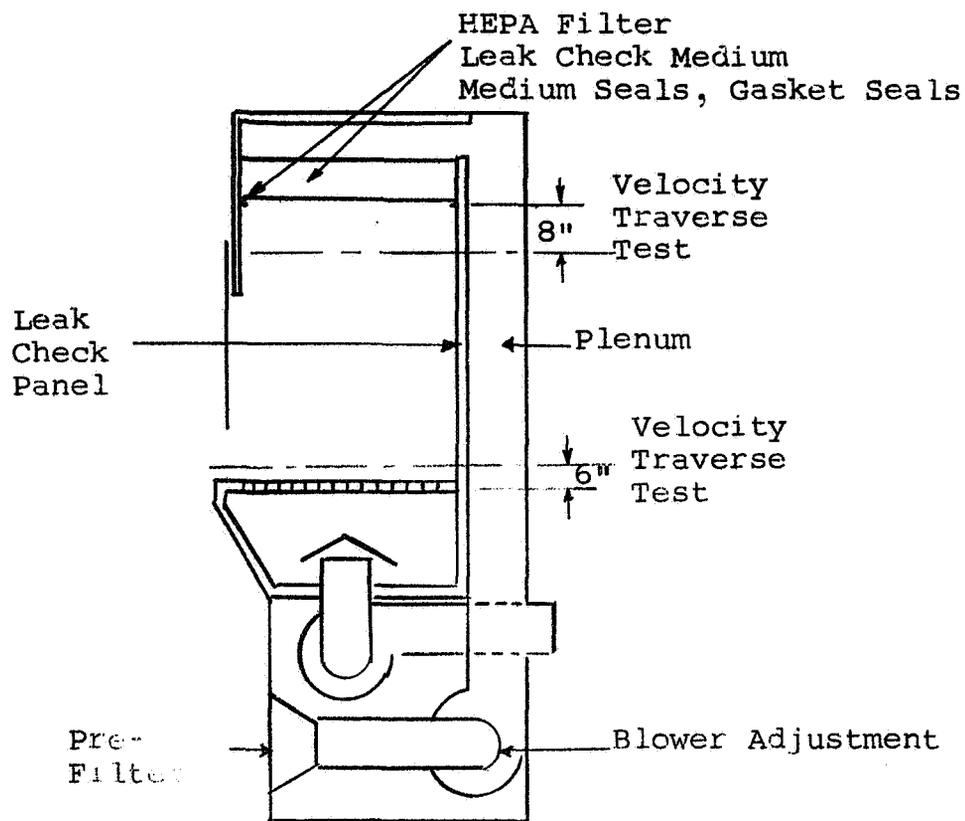


Figure 9

TESTING POSITIONS FOR VERTICAL  
LAMINAR-FLOW WORK BENCH

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from the filter face in the unobstructed bench. The meter is read directly in feet per minute. The sensing element is delicate, and care must be exercised during use to prevent damage.

In horizontal flow benches Western Electric Company<sup>6</sup> measures velocity at 18 locations and records the data on the report form shown in Figure 10. In vertical flow benches, additional readings are taken 3 in. above the work surface. The velocity readings are averaged and compared with specifications for average-velocity levels and uniformity. Section 40.3.6 of Federal Standard 209 suggests an average minimum level of 90 ft/min. The test is made with the volume control of the bench near its midpoint to permit adjustment of the velocity as the filters load up with dust. After the clean bench passes the velocity test, it must be leak-tested before acceptance.

Each bench should be scheduled for a periodic velocity recheck. The prefilter should be cleaned or replaced, and the blower control should be adjusted to bring the velocity back to the prescribed limits. When it is no longer possible to make the adjustment, the HEPA filters must be replaced. The periodicity of recheck is determined from experience; a quarterly recheck is suggested at the inception of the maintenance program. If the air velocity is satisfactory at quarterly rechecks, the period between testing can be extended. On the other hand, if most benches need quarterly adjustments, the period between testing should be reduced.

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<sup>6</sup>Pink, W. V., Contamination Control, Vol. 10, p. 10, 1967.

**CLEAN WORK STATION "MAINTENANCE AND PROVE-IN" REPORT**

ESE \_\_\_\_\_  
 AREA \_\_\_\_\_ OPEN AREA   
 BLDG. \_\_\_\_\_ COL. \_\_\_\_\_ CLOSED ROOM

INITIAL TEST DATE 1-10-66 TYPE  HORIZ.  
 PROCESS SLICE CLEANING  VERT.  
 VELOCITY PROFILE PATTERN:  EXHAUST

VELOCITY READINGS — SEE TABULATED CHART  
 GRAND TOTAL — " "  
 AVER VELOCITY — " "  
 DEV. FROM AVER — " "

REMARKS 1-10-66, GASKET LEAKS; TIGHTENING CLAMPS DOES NOT CORRECT, REFERRED UNIT TO FACTORY PLANNING.  
1-17-66, LEAKS CORRECTED BY SUPPLIER - RECHECK OK - VELOCITY OK.  
4-12-66, PINHOLE LEAKS IN MEDIA SEALED WITH SILASTIC.  
7-10-66, GASKET LEAKS CORRECTED BY TIGHTENING CLAMPS. ADJUSTED FAN SPEED TO 3/4 (LOW VELOCITY OF 80 FPM AT FIRST CHECK).  
1-8-67, VELOCITY APPROACHING LOW LIMIT - REQUIRES NEW HEPA FILTER. TIGHTENED CLAMPS AND SEALED PINHOLE LEAKS.  
1-20-67, REPLACED HEPA FILTER; CAULKED CONSTRUCTION JOINT IN PLENUM.  
3-15-67, RECALL CHECK DUE TO HIGH COUNTS DETECTED DURING MONITORING. FOUND MEDIA AND GASKET LEAK ALONG BOTTOM EDGE. SEALED MEDIA AND TIGHTENED CLAMPS. VELOCITY OK.

COPY TO:  
 OPERATING DEPT. \_\_\_\_\_  
 FUNCT. PROD. ENGR. \_\_\_\_\_  
 FACTORY PLANNING \_\_\_\_\_

**AND PROVE-IN" REPORT**

PROVE-IN RECHECK

DATE	1-10-66	1-17-66	4-12-66	7-10-66
SAMPLE POSITION	AIR VELOCITY			
	6"	6"	6"	6"
	FROM FILTER FPM			
1	100		95	105
2	105		100	110
3	100		100	110
4	100		95	100
5	105		105	115
6	105		100	115
7	120		110	120
8	120		110	120
9	120		105	120
10	115		105	120
11	110		100	115
12	120		105	115
13	110		100	120
14	95		90	100
15	95		90	100
16	100		95	105
17	120		110	120
18	100		100	110
TOTAL	1940		1815	2020
AVERAGE VELOCITY	108		101	112
DEVIATION FROM AVER.	+12		+4	+8
BLOWER SETTING	1/2	1/2	1/2	3/4
EXHAUST BALANCED	/	/	/	/
PHI FILTER CLEAN/D	YES	/	YES	YES
TEST INSTRUMENT	R220	R220	R220	R220
MEDIA LEAKS	NO	NO	YES	NO
GASKET LEAKS	YES	NO	NO	YES
LEAKS CORRECTED	NO	/	YES	YES
HEPA REPLACED	/	/	/	/
BENCH DEFECTIVE	YES	NO	NO	NO
INVESTIGATOR				
APPROVED, DEPT.				

REPAIR RECALL

DATE	10-4-66	1-8-67	1-20-67	3-15-67
SAMPLE POSITION	AIR VELOCITY			
	6"	6"	6"	6"
	FROM FILTER FPM			
1	100	90	105	100
2	105	90	115	110
3	95	75	110	100
4	95	75	110	100
5	100	85	120	110
6	100	85	120	110
7	105	95	125	115
8	105	95	125	115
9	105	95	120	115
10	100	90	105	100
11	95	80	105	100
12	105	90	100	95
13	100	85	110	105
14	90	70	110	105
15	90	70	105	100
16	90	70	115	105
17	105	90	120	110
18	90	80	120	110
TOTAL	1775	1510	2040	1905
AVERAGE VELOCITY	98.5	89	113	106
DEVIATION FROM AVER.	+6.3	+6	+2	+9
BLOWER SETTING	FULL	FULL	1/2	1/2
EXHAUST BALANCED	/	/	/	/
PRE FILTER CLEAN/D	YES	YES	YES	YES
TEST INSTRUMENT	R220	R220	R220	R220
MEDIA LEAKS	NO	YES	NO	YES
GASKET LEAKS	NO	YES	YES	YES
LEAKS CORRECTED	/	YES	YES	YES
HEPA REPLACED	/	/	YES	/
BENCH DEFECTIVE	NO	NO	NO	NO
INVESTIGATOR				
APPROVED, DEPT.				

Figure 10

CLEAN BENCH ACCEPTANCE AND MAINTENANCE REPORT

### C. Leak Testing

The HEPA filters provided in clean benches are certified by the manufacturer to provide a specified overall minimum filtration efficiency, usually 99.97%. The certification procedure does not guarantee that the filters do not have leaks and certainly does not certify that they have been installed correctly in the clean bench. Filters leak through pinholes and tears in the medium and through breaks in the bond sealing the medium to the filter frame. Leaks in a new bench are almost certain to be found at the gasket seal between the filter frame and the bench frame. Leaks result from rough handling of the filters during shipment, storage, and installation; damaged gaskets or inadequate gasket clamping pressures; warped or rough gasket sealing surfaces; and dust, dirt, and other artifacts wedged between the gasket and the sealing surface. Installation and handling tips for HEPA filters can be found in the literature (7,8). Since the Electronics Research Center will be required to change HEPA filters in the future, copies of these documents should be obtained.

No standard procedure for leak testing clean rooms or benches exists. Section 50.1 of Federal Standards 209 offers some basic recommendations. Briefly, the procedure consists of injecting an

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<sup>7</sup>Little, J. C., Heating, Piping, Air Conditioning, Vol. 37, p. 142, 1965.

<sup>8</sup>Schneider, R. W., TID-7627, Office of Technical Services, U. S. Department of Commerce, Washington, D. C.

aerosol of di-octyphthalate (DOP) smoke into the plenum chamber upstream of the filter, and, with a probe connected to a light-scattering aerosol photometer, scanning the downstream face of the filter medium, the bond between the medium and the filter frame, the filter gasket seal, and the interior joints of the bench for escaping aerosol.

The essential items of equipment are a smoke generator and an aerosol photometer. A generator can be purchased from Royco Instrument Company, Menlo Park, California; T. D. Associates, Baltimore, Maryland; Testing Machine, Inc., Mineola, New York; and C. F. Taylor, Ltd., Camberly, England. Aerosol photometers are available from the first two sources above and from the Phoenix Precision Instrument Co., Philadelphia, Pa. The DOP smoke generator should produce a polydispersed aerosol with a light-scattering mean particle diameter of about  $0.7 \mu$ . During certification testing by the manufacturer, a homogeneous  $0.3\text{-}\mu$ -DOP smoke is used. The equipment required for certification is complex, expensive, and not necessary for leak testing, because a polydispersed smoke is acceptable and even preferred, since large particles pass through holes with ease, but not through the medium.

Either thermally or pneumatically operated generators are acceptable. Thermal generators should be equipped with a provision for quenching the aerosol. When no such provision is made, the generator must be used upstream of the filter bank at a distance sufficient to prevent vapors of DOP from reaching

the filter. That is, the aerosol must be cooled enough to condense the DOP from the vapor state to liquid droplets. The generator must be capable of providing a mass concentration of DOP of 10 to 100  $\mu\text{g}/\text{liter}$  upstream of the filters.

The aerosol photometer should have an undiluted flow rate of 1 cfm and should provide a perceptible scale deflection at aerosol concentrations equal to 0.01% of the upstream aerosol concentration. Federal Standard 209 defines a significant leak as an aerosol photometer reading equivalent to 0.01% of the upstream aerosol concentration; leaks of this magnitude should be sealed. The photometer should also have internal calibration features to compensate for changes in amplification of the photomultiplier output, light aging, drift, etc.

When the bench is ready for leak testing, the DOP aerosol is injected at some reasonable location upstream of the filters, where thorough mixing of the aerosol can be obtained. Points of high turbulence, such as fan discharges, should be used to advantage. The generator output is adjusted to produce an aerosol mass concentration of 10 to 100  $\mu\text{g}/\text{liter}$  upstream of the filter. Preliminary adjustments can be made from a knowledge of the generator output and the airflow of the system to be checked. Final adjustments of the concentration should be based on a membrane filter sample. Since most generators have an adjustable output control, they can be easily calibrated for use in different clean benches. Once the proper output is obtained, the photometer is adjusted to give a full-scale reading at this

concentration. Knuth<sup>9</sup> found that three generators gave a full-scale deflection on his meter at an aerosol concentration of 40  $\mu\text{g}/\text{liter}$ . It is important that the aerosol concentration does not "overload" the meter. Knuth found that a concentration of 200  $\mu\text{g}/\text{liter}$  overloaded his meter.

Once the aerosol concentration and the meter have been properly adjusted, the meter is moved to the downstream side of the filter and, a probe is connected with a minimum length of flexible tubing. Since a leak is a photometer reading equal to or greater than 0.01% of the challenge aerosol, the photometer sensitivity is adjusted to give a significant scale deflection at aerosol concentrations exceeding 0.01% of the upstream concentration. The entire downstream face of the filter, the sealing surfaces, and the enclosure are scanned with a slow, steady horizontal motion. Successive traverses should overlay in a vertical direction. The probe should be held 1 in. from the filter face during scanning.

The area of the filter face scanned is established by the detector flow rate and the face velocity of the filter. The area of the minimum size leak detectable is a function of the area scanned, because a leak essentially permits passage of the upstream aerosol concentration, while an area free of leaks lets essentially nothing pass. Because a leak is 0.01% of the upstream concentration, the smallest leak detectable has an area 0.01% of

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<sup>9</sup>Knuth, R. H., "An Evaluation of Two Portable Thermal Aerosol Generators for In-Peace Filter Testing," 9th AEC Air Cleaning Conference, Boston, Mass., Sept., 1966.

the area being scanned. (This conclusion is not precisely true, because the air flowing through a leak is proportional to the square root of the pressure drop, while that flowing through the medium is directly proportional to the pressure drop. Equating the flows, however, is convenient.) The scan speed is related to the linear dimension of the scanned area parallel to the direction of the scan and the response of the detector. The size of the probe is relatively unimportant. It need not be sized for isokinetic sampling, because the aerosol of interest is in the submicron size range. If the probe velocity is higher than the filter-face velocity, the area scanned is greater than the area of the probe, a result that may facilitate overlapping of successive scans, since the operators best reference for judging overlap is probably the probe size (Figure 11). Square probes 1 to 2 in. on a side are recommended. Velocities for probes of different sizes at a detector flow rate of 1 cfm are shown below.

<u>Probe Size,</u> <u>in.</u>	<u>Probe Velocity,</u> <u>fpm</u>
1 x 1	144
1.25 x 1.25	92
1.50 x 1.50	64
2 x 2	36

Since the detector flow rate is 1 cfm, the area scanned and the area of the minimum leak detectable can be determined for various filter-face velocities. If the detector has a 1-sec. response time, the scan time can be established. Calculations for four face velocities are shown in Table 1. These data show that

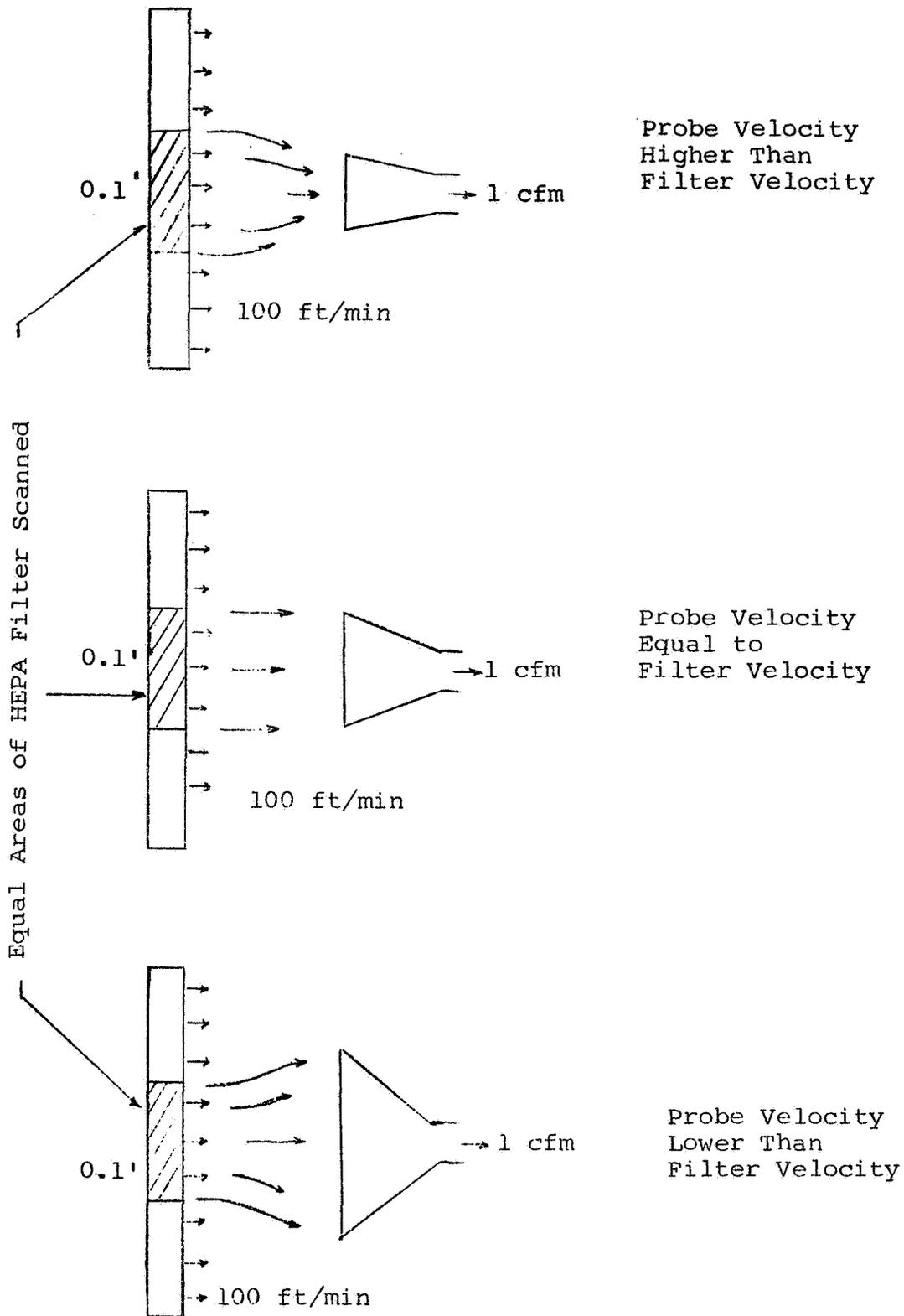


Figure 11

RELATIONSHIP BETWEEN DETECTOR FLOW VOLUME,  
 PROBE SIZE, FILTER VELOCITY, AND FILTER AREA SCANNED

the scan rate should be about 1.2 in/sec and that the area of the minimum leak detectable at normally encountered face velocities is about  $0.1 \text{ mm}^2$ , or  $300 \mu^2$ , on a side. If the leak were long and narrow, say 3 mm by  $30 \mu$ , the scan rate would not be appreciably slower; rectangular leaks of such dimensions would most likely be found at the gasket seal.

Points of leakage should be marked for correction. Silicone sealant can be used to repair minor breaks in the filter medium. Leaks through the gaskets can usually be stopped by adjusting the clamping mechanism. After repairs are made, the system should be rechecked. Filters that cannot be made leak tight should be rejected, and if gasket leaks cannot be stopped, the clean bench should not be accepted.

Replacement filters must be leak checked before being inserted into a clean bench. Leak checking is best accomplished by fabricating a single filter holder that permits easy access to the upstream side of the filter so that repairs can be readily made. In fact, it is advantageous to test all filters in this holder and then to check for perimeter leaks at the gasket seals once the filter is installed in a clean bench.

As for the velocity test, each bench should be rechecked for leaks both on a routine basis and whenever difficulties are encountered with high particle counts or unassignable causes of failure of a device worked on in the clean bench.

Table 1

AREA SCANNED, AREA OF MINIMUM LEAK, AND SCAN RATE  
AS A FUNCTION OF FILTER-FACE VELOCITY<sup>a</sup>

Filter-Face Velocity, ft/min	Filter-Face Area Scanned, in. <sup>2</sup>	Dimensions of Area Scanned, in.	Dimensions <sup>b</sup> of Minimum Leak Detectable, mm	Scan Rate, in/sec
120	1.20	1.1 x 1.1	0.28 x 0.28	1.1
100	1.44	1.2 x 1.2	0.31 x 0.31	1.2
80	1.80	1.34 x 1.34	0.34 x 0.34	1.3
20	7.20	2.68 x 2.68	0.68 x 0.68	2.7

<sup>a</sup>Detector flow rate of 1 cfm and response time of 1 sec assumed.

<sup>b</sup>Assumes a square configuration for the leak.

## V. IMPROVEMENT OF LAMINAR FLOW BENCHES FOR MICROELECTRONIC APPLICATION

The deposition of foreign particles on microelectronic devices during certain stages of production can lead to failure of the devices. Some of the possible failure modes and the necessary particle characteristics to produce failure can be considered. The production of a microelectronic device in simplest terms involves diffusing trace amounts of materials into a silicon wafer. The amount of donor or acceptor material is in the order of parts per hundred million. A foreign particle  $0.1 \mu$  in diameter is diffused into the silicon wafer could "poison" an area more than 0.002 inches in diameter to a level of one part per hundred million. Since critical dimensions are often considerably less than 0.002 in. there is no doubt that particles less than  $0.1 \mu$  in diameter could seriously effect the performance of some microelectronic devices. In this failure, mode small particles may create more harm than larger particles since a larger particle ( $10 \mu$ ) could be more easily washed off in the cleaning steps than a small particle ( $0.1 \mu$ ). Also, a hydrophobic particle, one not readily wet by water, may be exceptionally difficult to wash off.

Foreign particles deposited on the silicon wafer either before or during the application of the photo-resist could also create problems. In this case, however, a small particle in the order of  $0.1 \mu$  would probably not affect the process. The thickness of the photo-resist coating is many times the diameter of the particle

so that the particle would in effect be surrounded by the coating. A particle of this size could not act as a light mask since, being of a size comparable to the wavelength of the light, it would not block the light except under very improbable conditions. Again, however, the surface characteristics of the particle could be important. A particle which is not wetted by the photo-resist could prevent coverage in the area of the particle. This is considered unlikely because the photo-resist solutions are formulated with wetting agents to insure good wetting. Thus, in order to produce harmful effects during the formation of the photo-resist coating a particle would probably have to be somewhat larger than  $0.1 \mu$ , perhaps in the order of 1 to  $10 \mu$ .

Another possible failure mode could result from a relatively hard, abrasive particle. This failure mode would be purely mechanical, that is, a scratch during some part of the manufacturing process which cuts through a critical area. This type of failure could result only for a relatively large particle, probably greater than  $10 \mu$  in diameter.

The above consideration of possible failure modes, although not complete, indicates that particles smaller than  $1 \mu$  in diameter could create problems only if diffused into the wafer. Thus, it may be possible that a filter or air cleaning system that is more efficient on particles larger than  $1.0 \mu$  even though less efficient on smaller particles may yield better overall results. A possible way to make such a filter is by using a

filtering element which is more amenable to sealing and gasketing, such as the plastic membrane filters.

Improvement of the quality of the air passing through the filters of a laminar flow enclosure can be expected to reach a point of diminishing return unless steps are taken to reduce the amount of contamination from other sources. Movement of object into and out of the clean area can create turbulence which introduces unfiltered air from the room into the laminar flow enclosure. Particles can also be generated by objects inside the enclosure either by abrasion or by dislodgment of dirt from the objects. Turbulent eddies within the enclosure can effectively trap particles for relatively long periods of time largely negating the effectiveness of the laminar flow principle.

Two general approaches which may lead to substantial improvement are considered. One approach is to decrease the amount of contaminated air which can enter the clean area of the bench. This could possibly be done by increasing the flow velocity of the laminar stream. The second approach is considered to be more desirable for the following reasons:

1. With a laminar flow bench having an improved filter it will be possible to demonstrate whether presently used HEPA filters are adequate or if improved filtration efficiency does provide benefits.
2. Development of an improved filter will make available a higher efficiency filter system should such a need arise not only for microelectronic applications but also in other areas of technology.

3. Increased flow velocity may increase turbulence in the laminar stream to the point where poorer performance may result.

The high efficiency glass fiber filters presently used in HEPA filters are generally 99.97% efficient in removal of 0.3  $\mu$  diameter DOP droplets. Other filter materials are available, however, it has been reported that porous cellulose ester membrane filters of 0.8  $\mu$  average pore size are more than 99.99997% efficient on potassium permanganate aerosols of 0.026  $\mu$  mean diameter and tungsten particles of 0.01  $\mu$  mean diameter<sup>10</sup>. It is also reported that filters of this type are 99.9995% efficient on 0.3  $\mu$  DOP smoke<sup>11</sup>. Thus, it is reasonable to expect that a laminar flow hood equipped with a membrane filter could reduce particle levels in the hood by approximately two orders of magnitude.

It is appreciated that improving the filtration efficiency in laminar flow hoods for microelectronic work must reach a point of diminishing returns. That is, the amount of contaminants passing through the filter may be insignificant compared to the amount carried into the clean area by turbulence caused by activity in and near the hood. However, construction and evaluation of such a filtering system would be useful in determining if this point has already been reached or if improvement in filtering efficiency can still produce additional improvement in microelectronic work.

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<sup>10</sup>Megaw, W. J., and Wiffer, R. D., Eighth AEC Air Cleaning Conference, TID 7677, pp. 401-417, 1963.

<sup>11</sup>Personal communication from R. Keefer, Gelman Instrument Co., 600 S. Wagner Road, Ann Arbor, Michigan.

During this program a filter was constructed measuring 2 feet by 2 feet using Gelman Acropore 800 filter media. This filter was incorporated in a laminar flow bench manufactured by Mathews Research.

The filter media was sealed to the plywood frame with Dow Corning Silicone Cement. The system was checked for leaks with the IITRI particle counter, and no particle penetration could be detected using dirty room air as the test aerosol. This unit was sent to NASA, Cambridge, for use in a planned evaluation program.

#### VI. CONCLUSIONS AND RECOMMENDATIONS

1. The laminar flow bench containing the more efficient membrane filter should be evaluated in use for microelectronics work in order to determine if improved filtration does indeed have as beneficial effect on quality.
2. Theoretical calculations have shown that dirty air from the room can penetrate into the clean area of a laminar flow bench.
3. A testing program should be undertaken to determine the amount of contaminants which penetrate the clean area during normal work at the clean bench.

#### VII. ACKNOWLEDGMENTS

Mr. Seymour Schwartz and Mr. V. DeLaria of NASA Electronics Research Center contributed to this program by providing direction to the effort. Mr. J. Stockham of IITRI provided a direct contribution to the effort concerned with particle counting and leak detection. Dr. P. R. Kelly of IITRI served as consultant for the work concerned with the medical application of laminar flow equipment.

PART II

MEDICAL APPLICATION OF LAMINAR FLOW EQUIPMENT

## MEDICAL APPLICATIONS OF LAMINAR FLOW EQUIPMENT

### I. INTRODUCTION

The laminar flow concept for creating ultra clean environments was originally developed for the Atomic Energy Commission. Since then laminar flow equipment has been widely used in the aerospace and electronics industries and to a lesser degree in the medical profession. This report describes the laminar flow concept, the commercially available equipment, and their applications to the medical profession. A list of equipment manufacturers, and a bibliography of pertinent references appear in the appendix of this report.

### II. THE LAMINAR FLOW CONCEPT

Ordinarily air is not clean, it is contaminated to various degrees by solid, liquid, and gaseous contaminants. The amount and type of contamination is obviously dependent on the nature of the sources of contamination. That is, outdoor air in a rural area may be relatively free of industrial contaminants such as sulfur dioxide, fly ash, and carbon monoxide. Indoor air may contain relatively high concentration of lint, epidermis flakes, and microorganisms.

Because air is generally dirty a clean environment in an area can be maintained only by sealing the area against the influx of contaminated air or by providing some mechanism by which contaminants are removed from the air. Sealing is sometimes impractical for areas in which people must work, since a physical

barrier must be interposed between the workers and the clean area. This is often done, however, in glove boxes where the working area is sealed and physical manipulations are possible only through glove ports. For those functions where materials must be moved into and out of the area rapidly and where a high degree of manual dexterity is required sealing of the clean area is often impossible and the other alternative must be employed; that is, removing the contaminants from the air in the clean area. Ideally, all contaminants would be removed from all incoming air and all contaminants would be removed from the air already in the area as soon as they are generated. This ideal is impossible to achieve, but it can be approached by careful application of present technology.

In the laminar flow concept all entering air is cleaned by passing it through high efficiency particulate air (HEPA) filters. The clean air then flows through the enclosed clean area at a low velocity, generally 100 ft/min. Ideally, the flow is unidirectional, that is, all air parcels move in the same direction with no turbulence. Thus the clean area is continually swept by clean air greatly reducing the residence time of contaminants generated within the clean area. This concept is illustrated in Figure 12, a schematic representation of a portable laminar flow clean room.

The laminar flow concept does not provide a complete solution to all contamination problems and the limitations should be understood for proper application of laminar flow equipment.

Prefilter

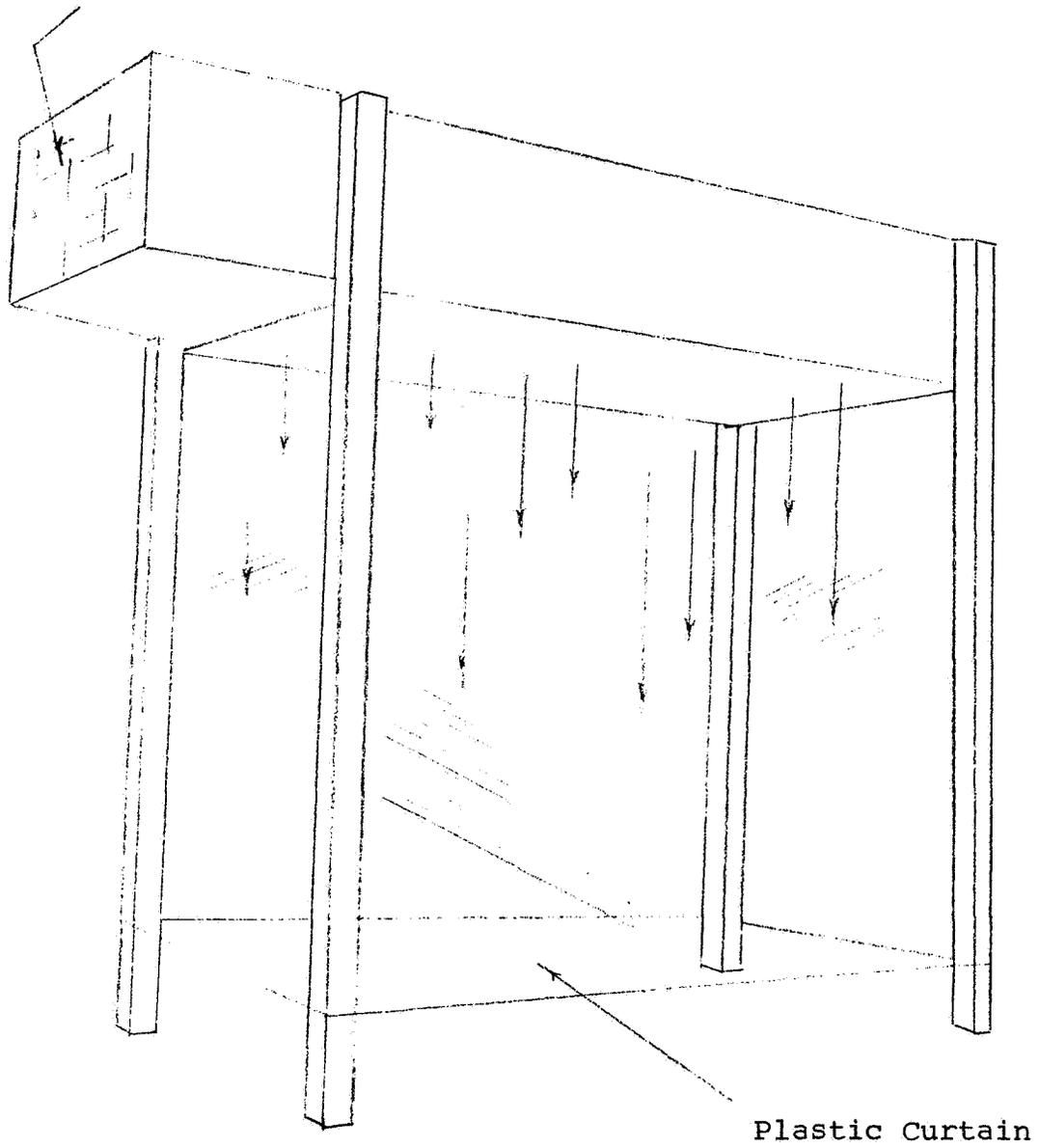


Figure 12

PORTABLE LAMINAR FLOW CLEAN ROOM

The major deficiency of the laminar flow concept is related to the fact that objects in the clean area, both animate and inanimate, cause deviation from the ideal unidirectional air flow pattern. This deficiency can be partially overcome by proper choice of airflow direction, that is, vertical or horizontal flow directions.

### III. MEDICAL APPLICATIONS OF LAMINAR FLOW EQUIPMENT

Since the laminar flow concept provides a means by which it is possible to produce a relatively microorganism free environment without greatly inhibiting the movement of personnel it can be beneficially applied to operating rooms, treatment of burn patients, treatment of patients with depressed immunological defense mechanisms, and laboratory functions requiring sterile conditions.

Several laminar flow operating theaters have been built and the efficiency of these systems in reducing the amount of microorganisms present has been evaluated<sup>1,2</sup>. These reports indicate that significant reductions in microorganism concentration is possible with the use of the laminar flow concept. The HEPA filters were capable of removing microorganisms with such efficiency that no organisms could be detected unless the rooms were occupied. The presence of people in the rooms did produce measurable levels of microorganisms near the floor of the vertical flow rooms. However, sampling probes placed near the incision during surgery demonstrated that microorganism counts of less than one organism per cubic foot can be achieved.

Because of the low rate of infection experienced both with and without the use of laminar flow systems, a large amount of data must be obtained for statistical significance. This data is not yet available and it is still impossible to determine the degree of reduction of infection incidence which may result from the use of laminar flow operating rooms.

Treatment of burn patients and patients with depressed immunological resistance mechanisms requires effective reverse isolation, since exposure of these patients to airborne microorganisms can be disastrous. In recent years considerable success was achieved in this area with the use of plastic isolators. These isolators are essentially clear plastic bags large enough to completely enclose the patient. The bags are inflated and kept at a slightly positive pressure with filtered air. These isolators are not laminar flow devices, since no attempt is made to maintain a unidirectional air flow, but rather entry of contaminated air is prevented by maintaining a slight pressure on the system.

Although the isolators can be effective in preventing the influx of contaminated<sup>3,4</sup> air they do restrict the activities of the patient and are depressing psychologically to a patient who must be continuously confined in a plastic bag, sometimes for many months.

Laminar flow rooms offer the possibility of maintaining a patient in a sterile environment which allows greater freedom of movement<sup>5</sup>. This type of confinement would undoubtedly be more acceptable to the patient psychologically.

Laminar flow equipment suitable for laboratory functions such as formula preparation, bacteriological studies, and intravenous preparations range from the smallest bench with a working area of approximately four square feet to clean rooms which can be built to any size requirements.

#### IV. FILTRATION EFFICIENCY OF LAMINAR FLOW EQUIPMENT

The HEPA filters used in laminar flow equipment use as a filtering medium a glass fiber mat similar in appearance to blotting paper. This mat is pleated in order to provide a large filtering area in a relatively small cross-sectional area. Corrogated aluminum or paper separators are interposed between the pleats of the filter in order to maintain separation of the pleats and allow flow of air between the pleats. The pleated media together with the separators is sealed into a plywood or metal frame.

The HEPA filters are very efficient, generally rated as 99.97% efficient on dioctyl phthalate smoke of  $0.3 \mu$  in diameter. Although microorganisms as small as one hundredth of a micron are known to exist these always grow in solutions containing dissolved solids and droplets containing these small organisms are generally large enough to be trapped by the HEPA filter. Air from which all particles greater than  $1 \mu$  have been removed, should be sterile.<sup>6</sup> Generally air passed through HEPA filters is sufficiently free of microorganisms so that they cannot be detected in the clean area. When they are detected they can usually be

traced either to a leak in the system or to a source within the area. For medical and biological application problems of avoiding contamination in laminar flow enclosures are not problems of filtration, but rather problems of sources within the enclosure, such as people or objects which are brought into the clean area.

## V. COMMERCIALY AVAILABLE LAMINAR FLOW EQUIPMENT

### A. Clean Rooms

Laminar flow clean rooms are usually individually designed for the particular application of the user. Modular construction techniques are often employed so that a wide range of sizes can be constructed from a few basic modular units. Air velocities lower than 100 ft/min are often used in order to reduce the power requirements of the air handling systems. Good results are obtainable in vertical flow clean rooms with velocities as low as 20 ft/min.

A wide range of accessory equipment is available such as air conditioning units, pass-through air locks, air showers to clean personnel and objects entering the room, and particle monitoring equipment.

Portable cleanrooms are also available. These are generally of the downflow type. The filters and blower are supported near the ceiling by a framework. Side curtains of either cloth or plastic form the walls of the room. These curtains are short enough to provide an open perimeter near the floor of the room so that the air flow is downward from the filters and exhausts horizontally along the floor.

## B. Benches and Hoods

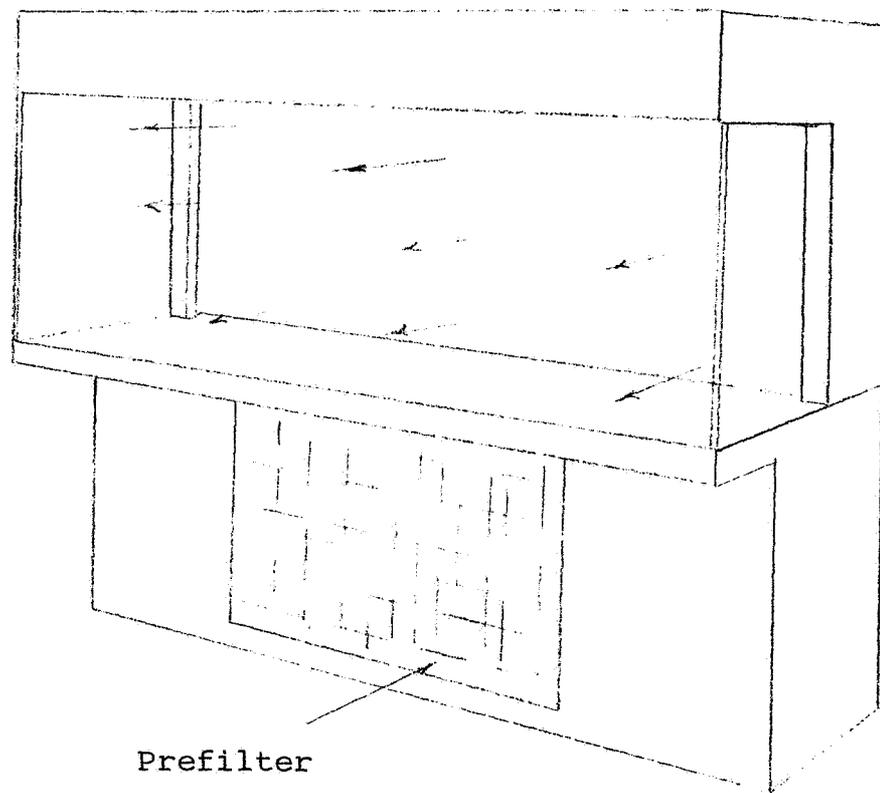
Laminar flow benches are predominantly of the horizontal or vertical flow types. In the horizontal flow bench, Figure 13, the air stream flows from the filters at the back wall of the bench toward the front. A worker stationed at the bench thus faces into the barely perceptible air stream. Since HEPA filters are 24 in. by 24 in. in area the laminar flow benches are generally some multiple of 24 in. in width and 24 in. in depth or height. Many accessories are available to suit the needs of the user. Stainless steel work surfaces, sinks, and non obstructive lighting fixtures are available. Laminar flow benches can be placed side by side with pass-through doors between them so that objects can be passed from station to station without exposure to dirty room air.

Vented hoods are available for work with materials or organisms which should not be allowed to escape into the room. These are similar to the fume hoods found in chemical laboratories with the principal difference being the clean laminar stream in the working area of the hood.

A list of manufacturers supplying the type of equipment discussed here appears in Appendix 1.

## VI. CHOOSING EQUIPMENT

The choice of laminar flow equipment for a particular application is determined by many factors, among them cost. Some of the design features of the various equipment and their relationship to cost and contamination control are discussed here.



Prefilter

Figure 13

HORIZONTAL FLOW LAMINAR FLOW BENCH

Laminar flow benches are available at costs ranging from little more than \$300 to \$4000 or more. Price is directly related to size and also to accessory equipment. The degree of contamination control is relatively independent of the cost of the unit. That is, a low priced unit that does not leak and is capable of providing 100 ft/min of velocity in the laminar flow volume should be just as effective in controlling contamination as a higher priced unit. The higher priced units can be expected to provide quieter and more vibration-free operation, better lighting, and better control of air velocity, also instruments may be provided to indicate air velocity.

Portable clean rooms or tents are generally higher priced than benches chiefly because they are larger and provide a larger working area. Fixed wall clean rooms are the most expensive laminar flow devices and costs again depend largely on size and accessory equipment.

The most important consideration in choosing laminar flow equipment is the air flow pattern at the critical area where contamination must be avoided. Ideally this critical area should be exposed to an unobstructed flow of clean air. Thus, if many objects must be placed in the vicinity of the critical area a vertical flow unit, Figure 14, may give better results than a horizontal flow unit.

Open laminar flow equipment such as benches are susceptible to contamination by dirty air from the room. This dirty air can penetrate into the clean area if it is propelled into the stream

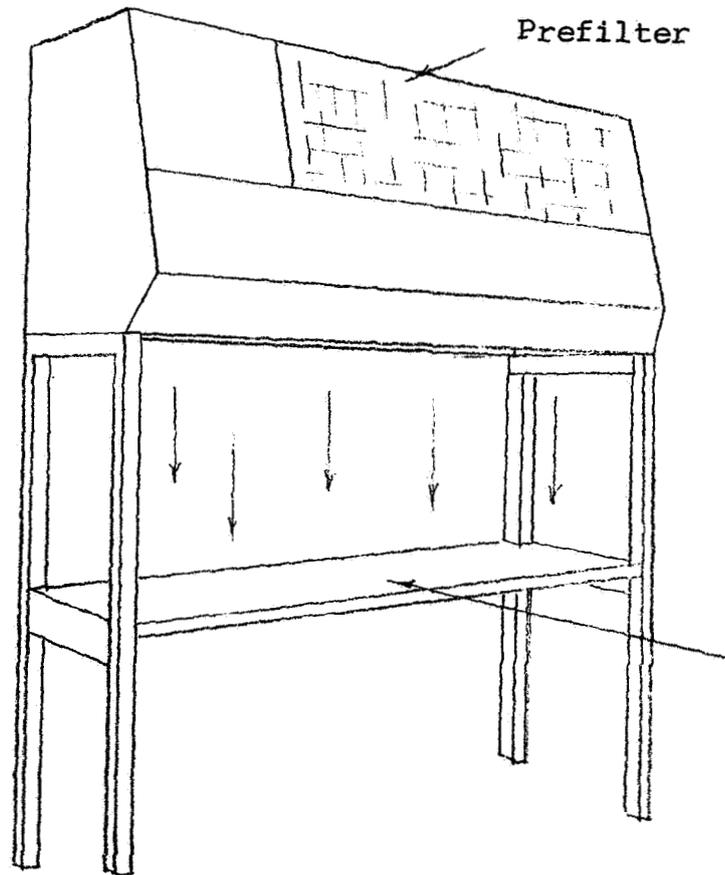


Figure 14

VERTICAL FLOW LAMINAR FLOW BENCH

by moving objects or air currents in the room. Clean rooms are susceptible to contamination by people working in the room and careful measures must be instituted, similar to those in conventional operating rooms, to reduce contamination to a minimum. Other techniques for maintaining sterile conditions can be used to advantage with laminar flow equipment. Laminar flow equipment cannot replace sterilization by autoclaving or chemical means. It can only aid in preventing contamination of already sterile objects. Autoclaving and chemical sterilization methods are much more reliable than ultraviolet ray sterilization. Ultraviolet ray sterilization is sometimes not completely effective because the rays cannot penetrate readily below the surface of objects as heat and chemicals can.

#### VII. CONCLUSIONS AND RECOMMENDATIONS

1. Laminar flow equipment is of great potential value in the treatment of burn and cancer chemotherapy patients.
2. Insufficient data is available to determine whether laminar flow equipment in the present state of technology can significantly reduce the incidence of post operative infection.
3. A greater effort should be made in developing laminar flow equipment and accessories for specific use in operating rooms. In particular, lighting systems should be developed which do not obstruct the flow of clean air.

Appendix A

MANUFACTURERS OF LAMINAR FLOW EQUIPMENT

## MANUFACTURERS OF LAMINAR FLOW EQUIPMENT

### A. HEPA Filters

1. Cambridge Filter Corporation  
P.O. Box 1255  
Syracuse 1, New York
2. Mine Safety Appliance Company  
201 N. Braddock Avenue  
Pittsburgh 8, Pennsylvania
3. Flanders Filters Incorporated  
P.O. Box 718  
Riverhead, Long Island, New York

### B. Laminar Flow Benches and Rooms

1. Ranney Industries Corporation  
P.O. Box 585  
Farmingdale, New Jersey 07727
2. Weber Showcase and Fixture Company  
1340 Monroe Avenue N.W.  
Grand Rapids, Michigan 49502
3. Air Control, Incorporated  
125 Noble Street  
Norristown, Pennsylvania 19401
4. Optic-Aire Systems, Incorporated  
730 E. Water Street  
Syracuse, New York 13210
5. Liberty Industries, Incorporated  
598 Deming Road  
Berlin, Connecticut
6. Farr Company  
Los Angeles 9, California
7. Matthews Research Incorporated  
4306 Wheeler Avenue  
Alexandria, Virginia
8. Madl Industries, Incorporated  
2900 Tanager Avenue  
Los Angeles, California 90022

C. Particle Counters

1. Royco Instruments, Incorporated  
141 Jefferson Drive  
Menlo Park, California 94025
2. Phoenix Precision Instrument Company  
3803 N. Fifth Street  
Philadelphia, Pennsylvania
3. Bausch and Lomb Incorporated  
Rochester, New York 14602

Appendix B

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