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Environmental Protection Technology Series

DESIGN OF MINIMUM-WEIGHT DIFFUSION BATTERIES

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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DESIGN
OF MINIMUM-WEIGHT
DIFFUSION BATTERIES

by

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SUMMARY

The relationship between functional requirements and the dimensions of rectangular channel diffusion batteries was analyzed to determine the optimum configuration with respect to weight and volume.

For a given penetration and minimum gas flow, the minimum weight and volume of a diffusion battery are determined by the thickness and spacing of the plates which form the walls of the channels. The number of batteries required to cover a given range of particle sizes is determined by the spread between the minimum and maximum available gas flow rates.

The extent to which battery weight can be reduced is ultimately limited by the stiffness of the plate material and by manufacturing tolerances.

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1. INTRODUCTION

A widely used technique for determining the size of particles in aerosols makes use of the mechanism of molecular diffusion to change the particle concentration in the aerosol by an amount that is proportional to particle size. The separation is carried out in an array of small bore tubes or channels, collectively called a diffusion battery, through which the aerosol is drawn at velocities in the viscous flow range.

As the particles are carried through the battery, their random Brownian motions displace some of them to the channel walls where they are held by Van der Waals and other adhesive forces. Since the magnitude of the Brownian motion is a function of particle size, the rate at which particles strike the wall and are removed from the stream is also a function of their size. The decrease in particle concentration in the aerosol as it flows through the battery provides a basis for calculating the diffusion coefficient of the particles, and their size.

Until recently, the measurement of particle sizes in aerosols was largely a laboratory exercise. Currently, however, particulates in the atmosphere and in the industrial exhaust gases are being monitored extensively in the field.

While the weight and volume of laboratory apparatus is seldom of concern, field work is often seriously hampered by equipment that is heavy or bulky.

The diffusion batteries currently in use weigh in excess of fifty pounds and are often the heaviest piece of equipment in a test setup. For this reason, it was felt that the possibility of optimizing the dimensions of the battery for minimum weight should be investigated.

The objectives of this study were: first, to analyze the relationship between the physical dimensions of the battery and operational parameters to determine if an optimum configuration exists, and second, to design a series of optimum weight batteries based upon the results of the study.

The technical discussion which follows is limited to the first of these objectives. The theoretical foundation of the diffusion method has been extensively covered in the literature and is not considered here in detail. The design calculations for a specific series of batteries are included in the appendix.

2. TECHNICAL DISCUSSION

2.1 Theory of Operations

The function of a diffusion battery is to decrease the particle concentration in a sample stream by an amount which is proportional to the diffusion coefficient of the particles. The accuracy with which particle sizes can be determined by the diffusion method depends to a considerable degree upon the level to which modes of transport other than diffusion, primarily turbulence and gravitational settling, can be reduced. Thus, the operating range of the diffusion battery is limited to the viscous flow region and to particles smaller than 1μ diameter.

The number of particles per unit volume of gas leaving a diffusion battery is related to the number entering by an equation of the general form.

$$\frac{n}{n_o} = A_1 e^{-B_1(Dy)} + A_2 e^{-B_2(Dy)} + Ane^{-B_n(Dy)} \qquad \ldots(1)$$

in which n is the particle concentration leaving the battery, n_o is the initial concentration, A_x and B_x are experimentally determined constants, D is the diffusion coefficient, and y is a function of battery dimensions and gas flow rate. The ratio $\frac{n}{n_o}$ is called penetration.

If the values of the constants in this equation are known, the diffusion coefficient, D, can be calculated from the known flow rate, and the measured values of n and n_o. This applied however, only to monodisperse aerosols. For polydisperse aerosols, the apparent diffusion coefficient varies as a function of dispersity as the flow rate is changed. The relationship between dispersity, flow rate, and penetration, provides a means of determining the particle size distribution in real aerosols, which are usually more or less polydisperse. The calculations required in this method, however, are laborious, and if a large number of tests are involved it is practical only if a computer is available.

Fuchs et al (1) have proposed a semigraphical method of determining size distribution directly from test data, which appears suitable for data reduction in the field. Their method involves matching curves of penetration ($\frac{n}{no}$) vs log y to pre-plotted curves for various distributions and values of the mean particle radius and standard deviation. For a given mean particle radius, the standard deviations (σ) give a family of curves which intersect at $\frac{n}{n_o} \sim .4$ as shown in Figure 1.

To determine the distribution by this method, at least three points on the $\frac{n}{n_o}$ vs log y curve are required, with the middle near $\frac{n}{n_o} = 0.4$ and the upper and lower points near 0.8 and 0.2 respectively.

The preplotted curves are calculated from a modification of an equation derived by DeMarcus (2) for batteries having rectangular channels:

$$\frac{n}{no} = .9149\, e^{-1.885\, Dy} + .0592 e^{-22.33\, Dy} + .026 e^{-151\, Dy} \quad ...(2)$$

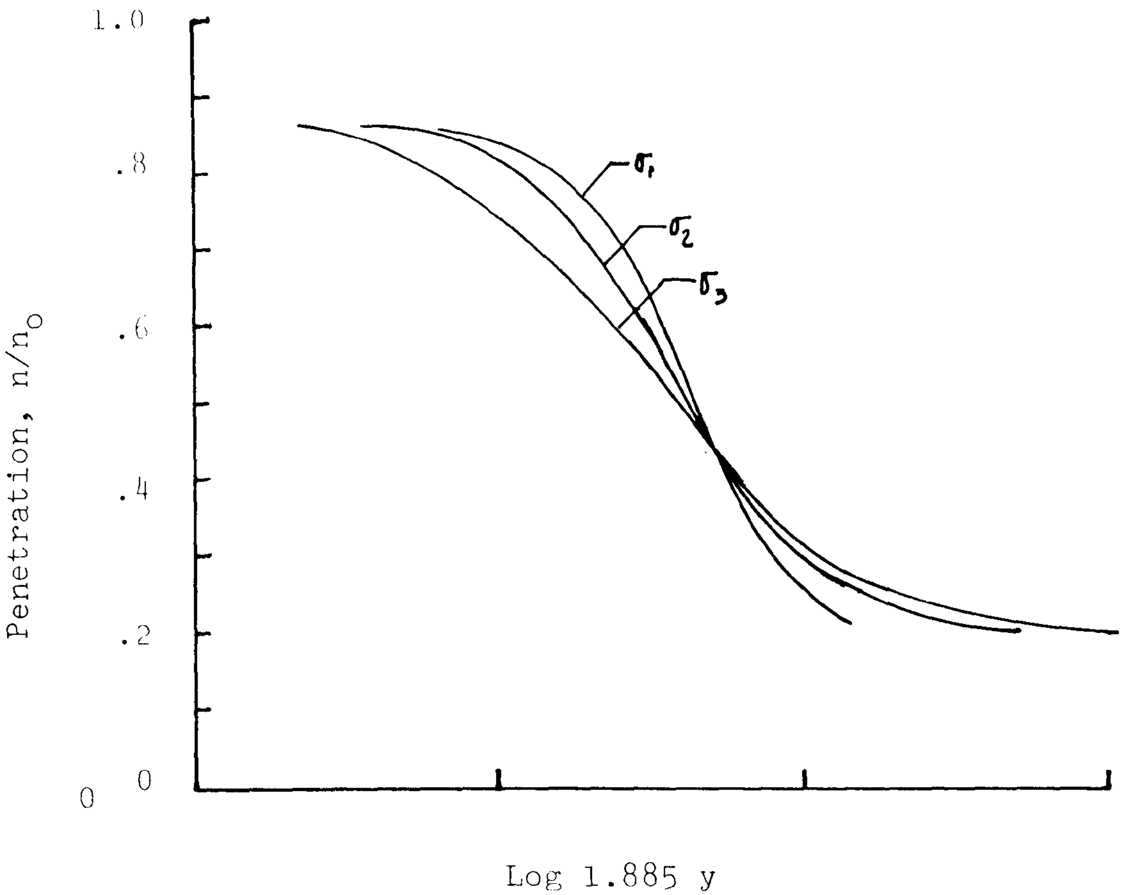

Figure 1. Typical Plot of Penetration vs y for Constant Mean Radius and Varying Standard Deviation of Particle Radius.

where $D = kT \dfrac{1 + \frac{Al}{Z} + B\left(\frac{l}{z}\right) e^{-\frac{bz}{l}}}{6\pi\mu}$

in which

k = Boltzmann Constant 1.38047×10^{-16} erg/K

T = Absolute temperature °K

Z = Particle radius (cm)

μ = 18.3×10^{-5} gm/cm-sec is the viscosity of air at 23°C and 760 mm hg

l = $.653 \times 10^{-5}$ (cm) is the mean free path

A = 1.246

B = .042

b = .87

$$\text{and } y = \frac{L}{b^2 \bar{v}} \qquad \ldots (3)$$

L = Length of battery channel

b = ½ width of a channel

$\bar{v}$ = average gas velocity

A plot of D vs particle radius is given in Figure 2.

The parameter y, eq. (3) is the experimental variable which is varied during a test by varying the average velocity $\bar{v}$. Since the range of particle sizes of interest is known, the range of y values required can be calculated from equation 2, and from this, the dimensions of the battery and flow rates required can be

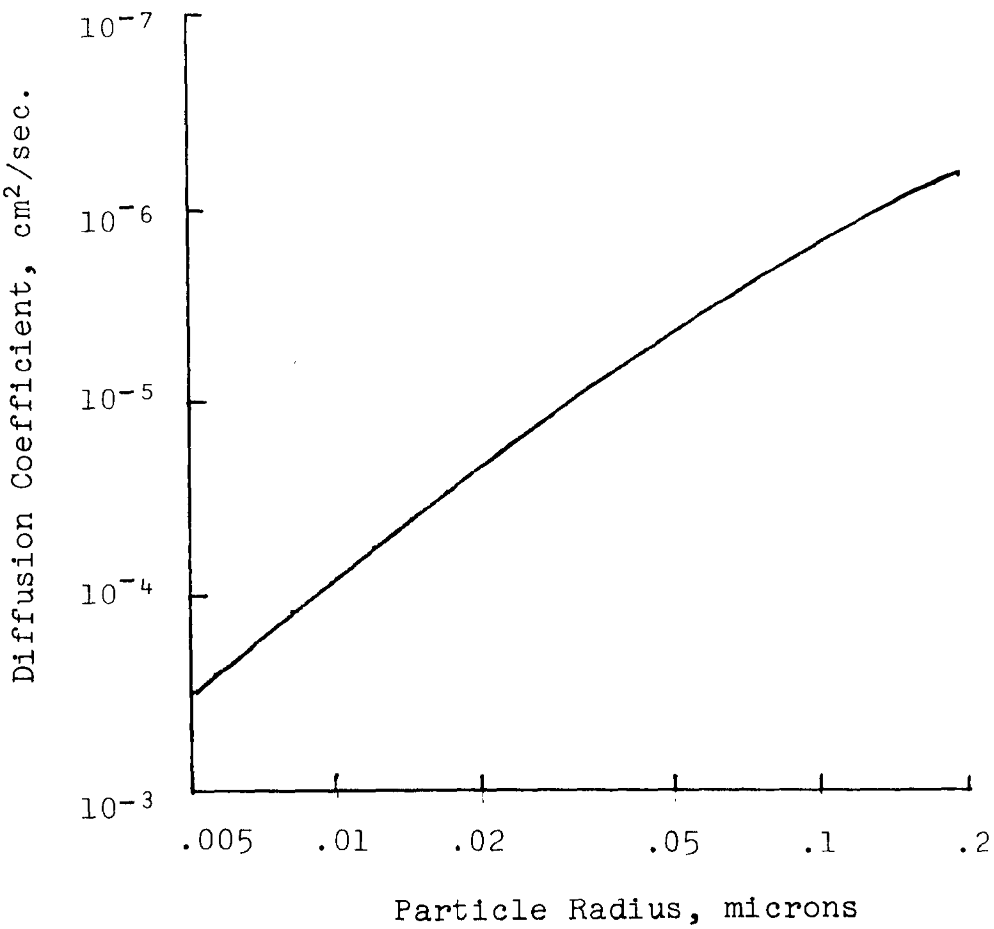

Figure 2. Particle Radius vs Diffusion Coefficient

determined from equation 3. Generally the available flow rates, both maximum and minimum, are also known so that the basic dimensions of the battery core are fixed.

To convert (3) into a more useable form,

Let A_a = total flow area, cm^2

$b = \frac{w}{2}$ where w is the width of 1 channel (cm)

Q = total volume flow rate $\left(\frac{cm^3}{sec}\right)$

then

$$\bar{N} = \frac{Q}{A_a} \text{ cm/sec}$$

$$b^2 = \frac{w^2}{4} \text{ cm}^2$$

Substituting into 3,

$$y = \frac{4LA_a}{w^2Q} \left(\frac{sec}{cm^2}\right) \qquad \ldots (4)$$

But LA_a = flow volume V_a

so

$$y = \frac{4V_a}{w^2Q} \left(\frac{sec}{cm^2}\right) \qquad \ldots (5)$$

From (5), for a fixed value of y, the value of V_a varies inversely with Q and w^2. For a given channel width, w, and minimum flow rate Q_{min}

$$V_{a_{min}} = \frac{y_{max}Q_{min}}{4} \, w^2 \ (cm^3) \qquad \ldots (6)$$

2.2 Core Volume and Weight

The total volume of the battery core consists of the volume of the channels and the volume of the plates which form the walls of the channels. The weight of the core is simply the volume of the plates times the density of the plate material. To simplify the equations relating plate volume V_p to other parameters, the number of plates is assumed to be equal to the number of channels. Since the number of channels will be large for the larger batteries, this approximation results in less than 1% error for the size range in which weight is of concern.

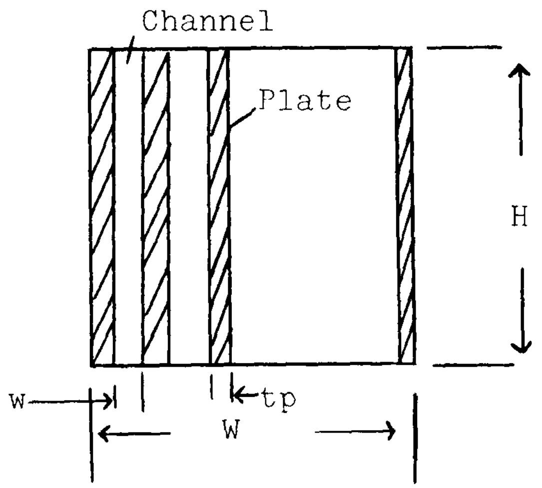

Figure 3. Frontal Area of Core

rom eq. (6)

$$V_{a_{min}} = \frac{Y_{max} Q_{min}}{4} w^2$$

r

$$LA_a = \frac{y_{max} Q_{min}}{4} w^2$$

From Fig. 3

$$A_a = WN_cH \qquad \ldots(7)$$

Where N_c = number of channels

and

$$V_a = WN_cHL \qquad \ldots(8)$$

$$V_p = t_pN_cHL \qquad \ldots(9)$$

Total volume, V_T, therefore is

$$V_T = (W + t_p)N_cHL \qquad \ldots(10)$$

And the core weight is

$$W_{Tc} = V_p\rho_p$$

$$= t_pN_cHL\rho_p \qquad \ldots(11)$$

Solving (7) for N_c

$$N_c = \frac{A_a}{wH} \qquad \ldots(12)$$

A

But $A_a = \left(\frac{y_{max}Q_{min}}{4}\right) w^2$

and $N_c = \left(\frac{y_{max}Q_{min}}{4}\right) \frac{w}{HL} \qquad \ldots(13)$

Substituting this value of N_c into (11)

$$W_{Tc} = tpw \left(\frac{Y_{max} Q_{min}}{4}\right) \rho_p \qquad \ldots(14)$$

2.3 Total Battery Weight

The total weight of the battery includes both the weight of the core and the weight of the shell and end plates. To the basic weight of the core must be added the weight of spacers which separate the plates.

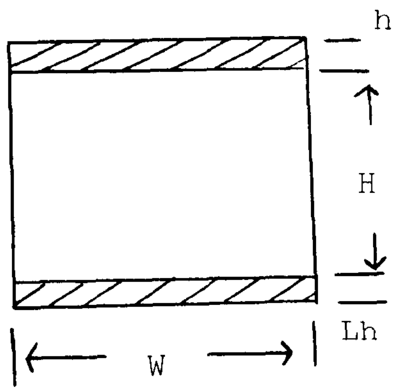

Figure 4. Area of Spacers

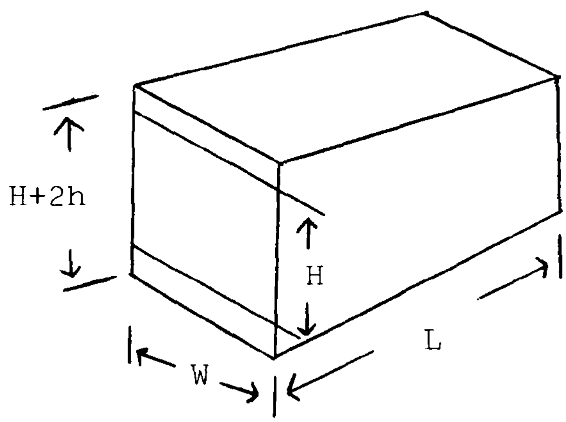

Figure 5. External Dimensions of Core and Internal Dimensions of Shell

From Figure 4, the combined area of plates and spacers in the area of the spacers, is 2hw and the volume is 2 hwl. Since WL = $\frac{V_{Tc}}{H}$

$$V_s = \frac{2hV_{Tc}}{H}$$

and

$$W_{Tc} = \left(\frac{2hV_{Tc}}{H}\right) \rho_p \qquad \text{...(15)}$$

From Eq. (10)

$$V_{Tc} = (w + t_p)N_{c_{HL}}$$

Substituting into (15)

$$W_{Ts} = [2h(w+t_p)N_cL]\rho_p \qquad \text{...(16)}$$

From (14)

$$N_cL = \left(\frac{y_{max}Q_{min}}{4}\right) \frac{W}{H}$$

giving

$$W_{Ts} = [2h(w + t_p)\left(\frac{y_{max}Q_{min}}{4}\right) \frac{W}{H}]\rho_p \qquad \text{...(17)}$$

Equation 17 indicates that the added weight due to the spacers decreases as the height of the core increases. In practice, the height of the core will be limited by the flatness of the plate material and by the problem of uniformly distributing the incoming flow over a long narrow face.

The weight of the external shell can be estimated using the dimensions shown in Figure 4, as internal dimensions and assuming flat end plates.

$$W_{T_{ex}} = 2\{(H'W + (H' + W)L\} \; t_s \rho_s$$

where H' = (2h + H). The minimum weight in this case occurs when H' = W+L. These proportions, however, would not be practical in a large battery for the reasons given above.

2.4 Effect of Reynolds Number and Pressure Drop Limitations

Reynolds Number

The upper limit of the Reynolds number for viscous flow between parallel plates is approximately 2000. Below this limit, turbulence is eventually damped out and laminar flow established.

Since turbulence is damped out more quickly at lower Reynolds numbers, an upper limit of Re = 200 is generally used in diffusion battery design. This also reduces the effect of entrance disturbances which reduces the effective length of the battery by creating a region of turbulence for a distance down stream from the entrance.

The Reynolds number for viscous flow between parallel plates is given by:

$$Re = w\bar{v} \left(\frac{\rho}{\mu}\right) \qquad \ldots(18)$$

where ρ is the density of the gas, and μ is the viscosity.

Substituting $\frac{Q}{A_a}$ for $\bar{v}$,

$$Re = \frac{wQ}{A_a} \left(\frac{\rho}{\mu}\right) \qquad \ldots(19)$$

Solving for Q,

$$Q = \frac{A_a}{w} \left(\frac{Re\mu}{\rho}\right)$$

and

$$Q_{max} = \frac{A_a}{w} \left(\frac{Re_{max}\mu}{\rho}\right) \qquad \ldots(20)$$

From (14)

$$A_a = \left(\frac{Y_{max}Q_{min}}{4}\right) \frac{w^2}{L}$$

Substituting into (20)

$$Q_{max} = \frac{W}{L} \left(\frac{Y_{max}Q_{min}}{4}\right) \left(\frac{Re_{max}\mu}{\rho}\right) \qquad \ldots(21)$$

which is the maximum flow for a battery designed for the given values of Y_{max} and Q_{min}, as limited by the allowable Reynolds number.

Pressure Drop

For viscous flow between parallel plates the pressure drop, ΔP is

$$\Delta P = \frac{3\mu\overline{N}}{b^2}$$

Making the appropriate substitutions,

$$\Delta P = \frac{12\ LQ}{w^2 A_a} \qquad \ldots(22)$$

or $$\Delta P_{max} = \frac{12\mu L Q_{max}}{w^2 A_a} \qquad \ldots(23)$$

Solving for Q_{max}

$$Q_{max} = \frac{w^2 A_a}{L} \quad \frac{\Delta P_{max}}{12\mu} \qquad \ldots(24)$$

Substituting for A_a from (13)

$$Q_{max} = \frac{Y_{max} Q_{min}}{4} \quad \frac{w^4}{L^2} \quad \frac{12\mu}{\Delta P_{max}} \qquad \ldots(25)$$

In general, Reynolds number and pressure drop limits are of concern only in the smallest batteries, that is, for low values of y, and maximum flow rates.

2.5 Residence Time as a Function of Battery Geometry

Residence time is of interest since it determines the minimum length of time required for a test run at some value of flow rate. It can be shown that residence time, for a given value of y, is a function only of channel width.

From equation (5)

$$y = \frac{4V_a}{w^2 Q}$$

but $\frac{V_a}{Q} = T$, is the time required for a particle to pass through the battery, or residence time, therefore

$$y = \frac{4T}{w^2}$$

$$T = \frac{yw^2}{4} \qquad \ldots(26)$$

2.6 Number of Units Required

Let $Y_1 = Y_{max}$, $Y_2 = Y_{min}$

$Q_1 = Q_{min}$, $Q_2 = Q_{max}$

Then, from Equation (5)

$$Y_1 Q_1 = \frac{4LA_a}{w^2} = Y_2 Q_2 = \text{Constant}$$

$$\text{Log } Y_1 + \text{Log } Q_1 = \text{Log } Y_2 + \text{Log } Q_2$$

$$\text{Log } Y_1 - \text{Log } Y_2 = \text{Log } Q_2 - \text{Log } Q_1$$

$$\Delta \text{Log } Y_{1-2} = \text{Log}\left(\frac{Q2}{Q1}\right)$$

If Q_1 and Q_2 are constant for the full range of Y, then $\Delta \text{Log } Y_{1\ 2}$ is the same for all units and

$$N_u = \frac{\text{Log } Y_{max} - \text{Log } Y_{min}}{\Delta \text{Log } Y_{1-2}}$$

$$= \frac{\text{Log}\left(\frac{Y_{max}}{Y_{min}}\right)}{\text{Log}\left(\frac{Q_{max}}{Q_{min}}\right)} \qquad \ldots(27)$$

3. CONCLUSIONS

The foregoing analysis indicates that when the limits of the parameter y, and the minimum flow rate have been established, the minimum weight and volume of the battery are determined primarily by the thickness and density of the plate material and the width of the flow channels. The thinner the plates, and the narrower the channels, the lighter the battery. This is true, in particular, of the largest batteries in which the weight of the plates is large relative to the weight of the external shell. In these cases, so long as the required flow volume is maintained, the shape of the volume has relatively little effect upon the total weight of the battery.

Depending upon the spread between maximum and minimum flow rates, battery weight decreases rapidly as the required y value decreases. In practical terms, only the largest battery in a series is of concern from a weight or volume standpoint.

The maximum weight of a battery, therefore, depends primarily upon the properties of the plate material and the tolerances which can be maintained upon channel width during manufacture.

The practical minimum to which plate thickness can be carried is set by the degree of flatness which can be maintained in the plates. as installed. This is essentially a function of the height of the plates and their initial flatness, if it is assumed that the plates are thick enough to support themselves without buckling.

The minimum channel width for a particular application depends upon the inherent waviness of the plate material and the anticipated assembly tolerances. In general, waviness is more difficult to account for and, in most cases, will be the limiting factor. Additional leveling operations will probably be required on sheet material to be used for plates at channel widths below one millimeter.

4. REFERENCES

1. Fuchs, N. A., I. B. Stechkina, and V. I. Starosselkii, 1962
Brit. J. Appl. Phys. Vol. 13.

2. DeMarcus, W. C. 1952
U.S. Atomic Energy Comm. ORNL 1413.

APPENDIX

DIFFUSION BATTERY DESIGN

Input Variables

A series of batteries covering the following range of variables is required.

1. Particle size .3μ dia. to .01μ dia.
2. Penetration $\frac{n}{n_o} = .2$ to $\frac{n}{n_o} = .8$
3. Flow range 1 liter/min. (16.67 cm^3/sec) to 4.5 liter/min. (75 cm^3/sec)
4. Maximum Pressure Drop 2500 dyne/cm^2
5. Maximum weight 50 pounds

Calculations

The range of y required to give the desired penetration can be calculated from equation (2). Neglecting the second and third terms, which are small relative to the first.

$$\frac{n}{n_o} = .9149\, e^{-1.885\, Dy}$$

Solving for y,

$$y = \frac{\ln\left(\frac{n}{.9149 n_o}\right)}{-1.885D}$$

The maximum value of y occurs when $\frac{n}{n_o} = .2$ and the particle diameter is .3μ. From Figure 2, for r = .15, D = 1.25x10^{-6}.

Substituting in the above equation,

$$y = \frac{\ln\left(\frac{.2}{.9199}\right)}{(-1.885)(1.25\text{x}10^{-6})} \qquad \text{sec/cm}^2$$

$$= 6.45\text{x}10^{-6}$$

And for the minimum value of y, $\frac{n}{n_o} = .8$, $D = 5.3\text{x}10^{-4}$

$$y = \frac{\text{Ln}\left(\frac{.8}{.9141}\right)}{(-1.885)(5.3\text{x}10^{-4}}$$

$$= 134 \text{ sec/cm}^2$$

From equation (6)

$$V_{a_{min}} = \left(\frac{y_{max}Q_{min}}{4}\right) w^2$$

$$= \left(\frac{6.45 \text{ x } 10^{-5} \text{ x } 16.67}{4}\right) w^2$$

$$= (26.88 \text{ x } 10^5)w^2 \text{ cm}^3$$

And, from (14)

$$W_{Tc} = (\text{tpw}) \left(\frac{y_{max}Q_{min}}{4}\right) \rho_p \quad \text{gm}$$

$$W_{Tc} = (26.88 \text{ x } 10^{-5}) \ (\text{tpw } \rho_p) \quad \text{gm}$$

Figure 6 shows the relationship between core weight and the parameter $\frac{y_{max}Q_{min}}{4}$ for various values of (tpw) and aluminum plates.

Assuming a maximum weight of 40 pounds for the core, as defined by equation (14) and aluminum plates,

$$(\text{tpw}) = \frac{40.453}{(26.88\text{x}10^{-5}) \ (2.71)} \quad \text{cm}^2$$

$$= 2.487 \text{ x } 10^{-3} \quad \text{cm}^2$$

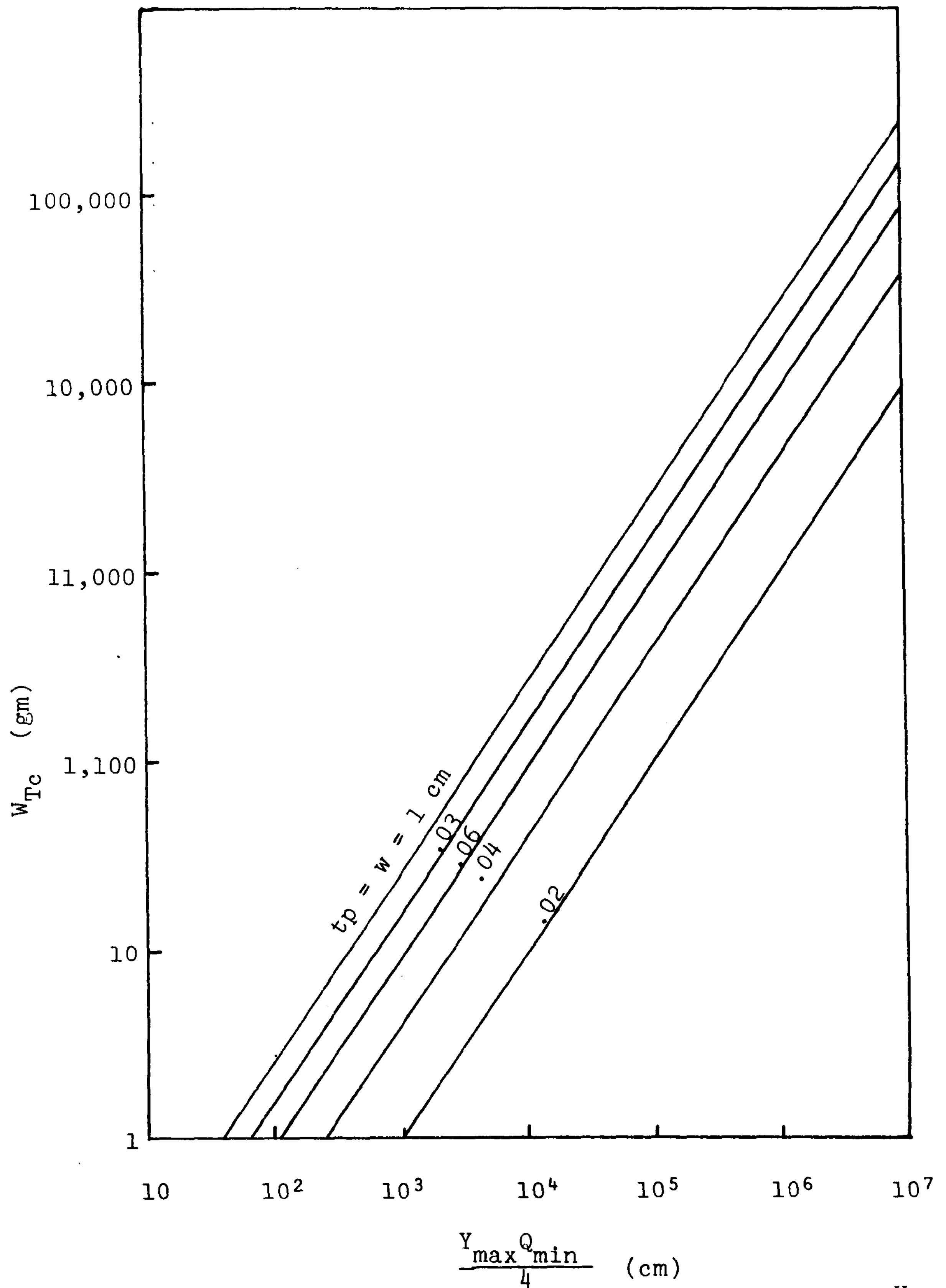

Figure 6. Relationship between Core Weight and Parameter $\frac{Y_{max}Q_{min}}{4}$

If tp = W,

$$W = (2.487 \times 10^{-3})^{\frac{1}{2}} = tp$$
$$= .0499\,\mathrm{cm} \quad (.0196\ \mathrm{in})$$

It is assumed that the spacers will be bonded to the plates. Bond line thickness will be approximately .001 in (.0025 cm). Spacers of .016 (.0406 cm) aluminum with two bond lines give channels .0457 cm wide.

The active volume then becomes

$$V_a = (26.88 \times 10\ )\ (0.457) \quad \mathrm{cm}^3$$
$$= 5614\ \mathrm{cm}^3$$

Assuming a length of 50 cm,

$$A_a = \left(\frac{5614}{50}\right) = 112\ \mathrm{cm}$$

To maintain channel width within acceptable limits, using commercially available aluminum sheet, the height of the channels will be limited to 2.5 inches (6.35 cm) giving an area of 0.290 cm^2 per channel, and a total of

$$N_c = \frac{112}{.290} = 386\ \text{channels}$$

With the spacer arrangement as shown, the weight of the core is 40.4 pounds. (See Figure 7.)

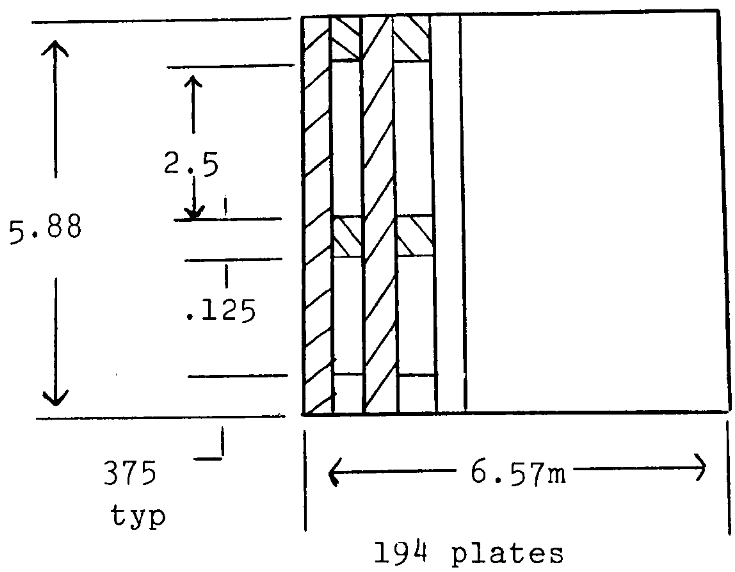

Figure 7. Core Assembly

If the external shell is made of .125 aluminum plate, the weight of the shell will be approximately 8 pounds giving a total weight of 48.4 pounds exclusive of accessories such as tube fillings and handle.

Number of Units Required

Using equation (28)

$$N_u = \frac{\mathrm{Ln}\ \dfrac{6.45\mathrm{x}10^5}{134}}{\mathrm{Ln}\ \dfrac{75}{16.67}} = 6 \text{ units}$$

However, it is not necessary that the range of y be completely covered. In this case 4 units appear to provide sufficient coverage. The relationship of the individual units to y and V_a is shown in Figure 8.

Figures 9 through 12 show the relationship between flow rate and penetration for various particle diameters for each unit, and can be used to determine the flow rate for a desired penetration.

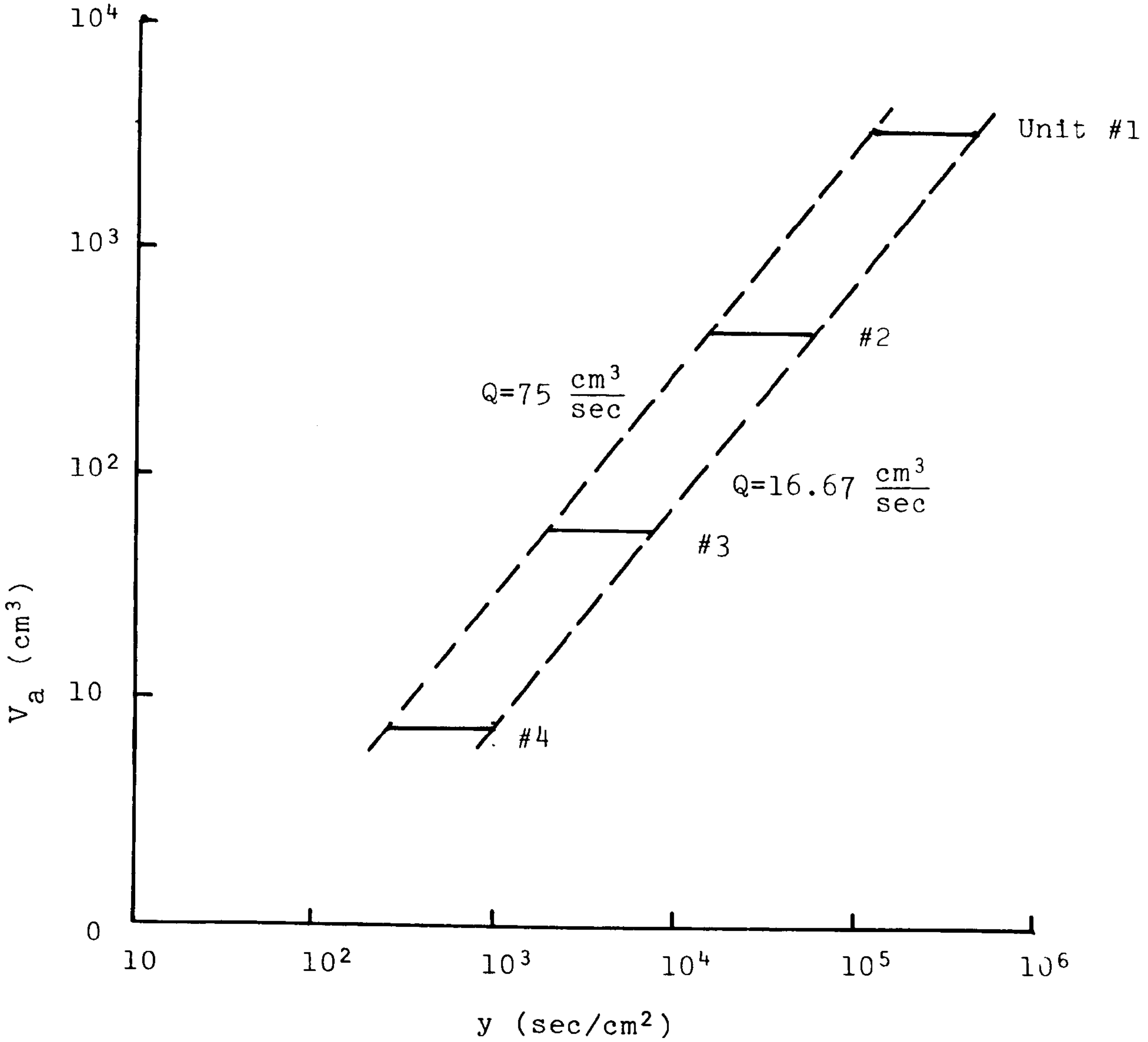

Figure 8. y vs V_a

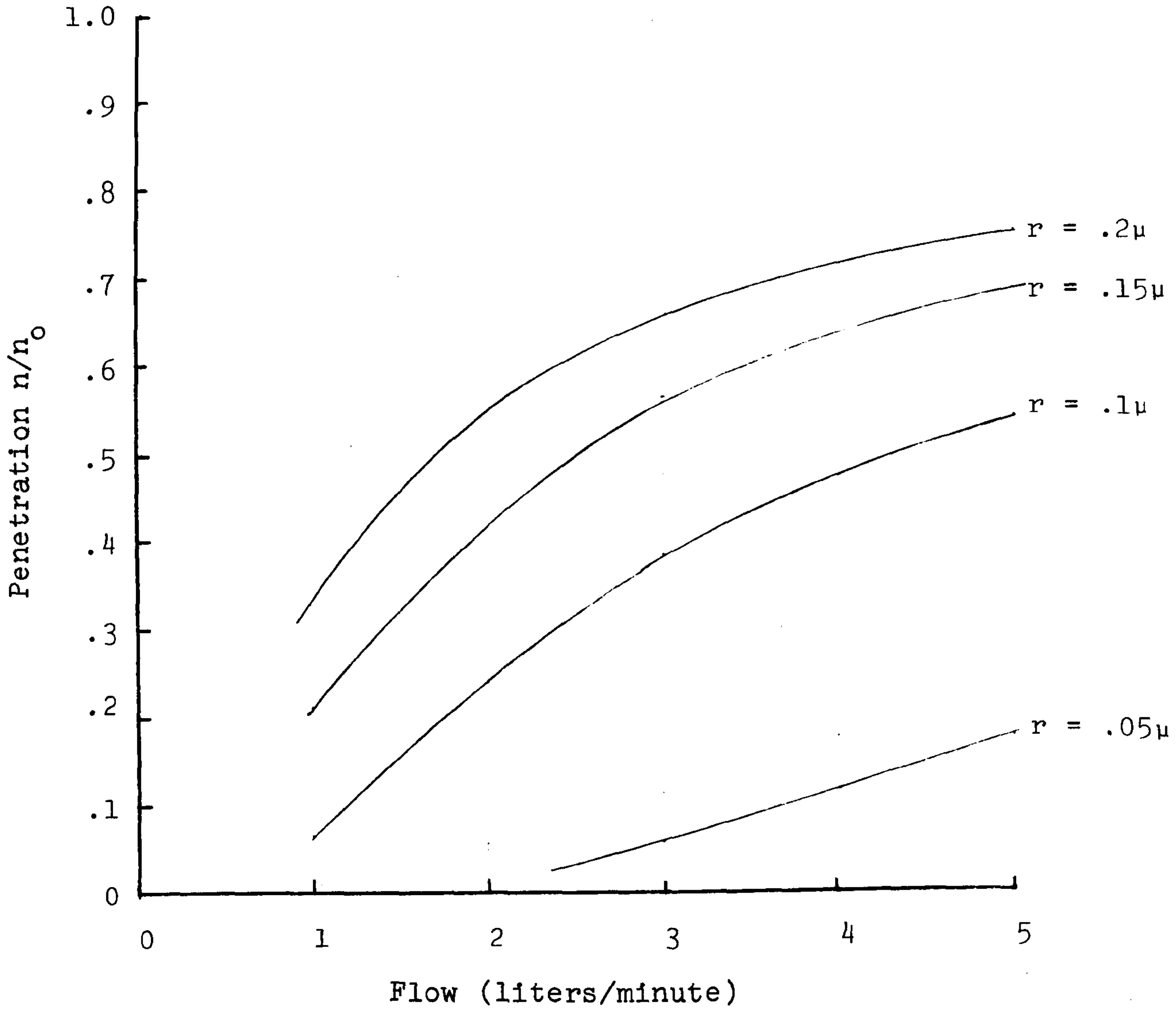

Figure 9. Penetration vs Flow for Unit 1

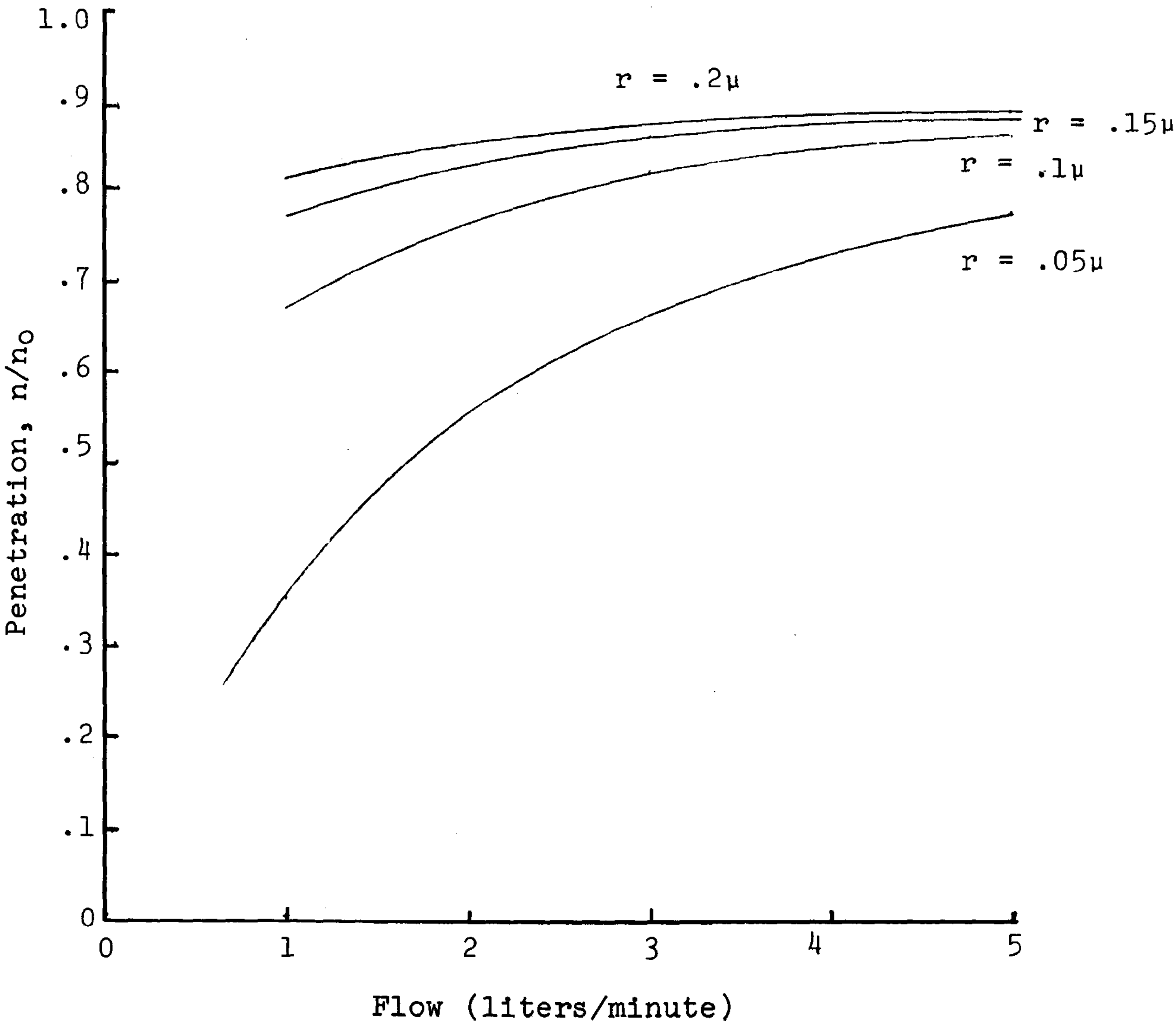

Figure 10. Pentration vs Flow for Unit 2

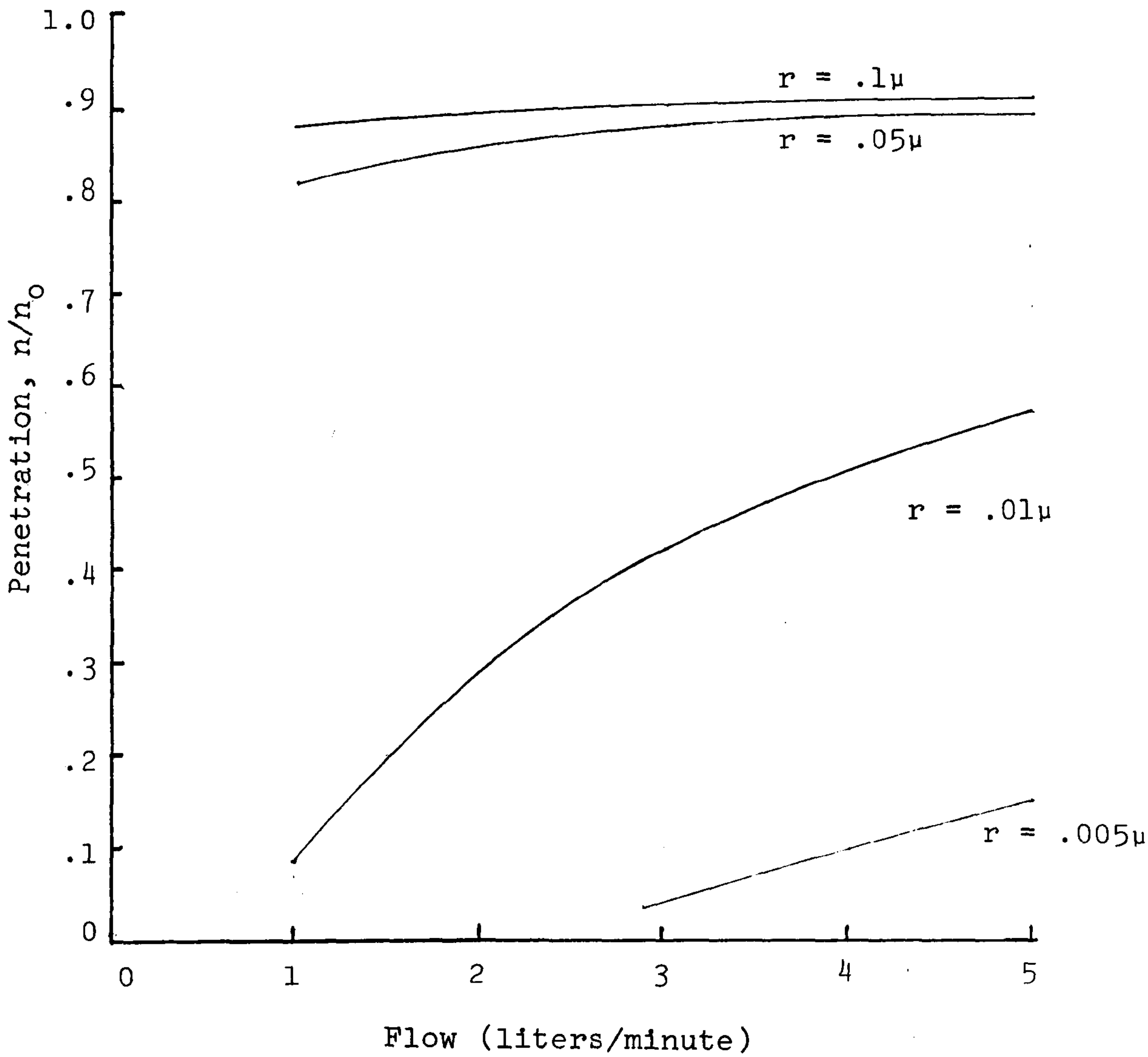

Figure 11. Penetration vs Flow for Unit 3

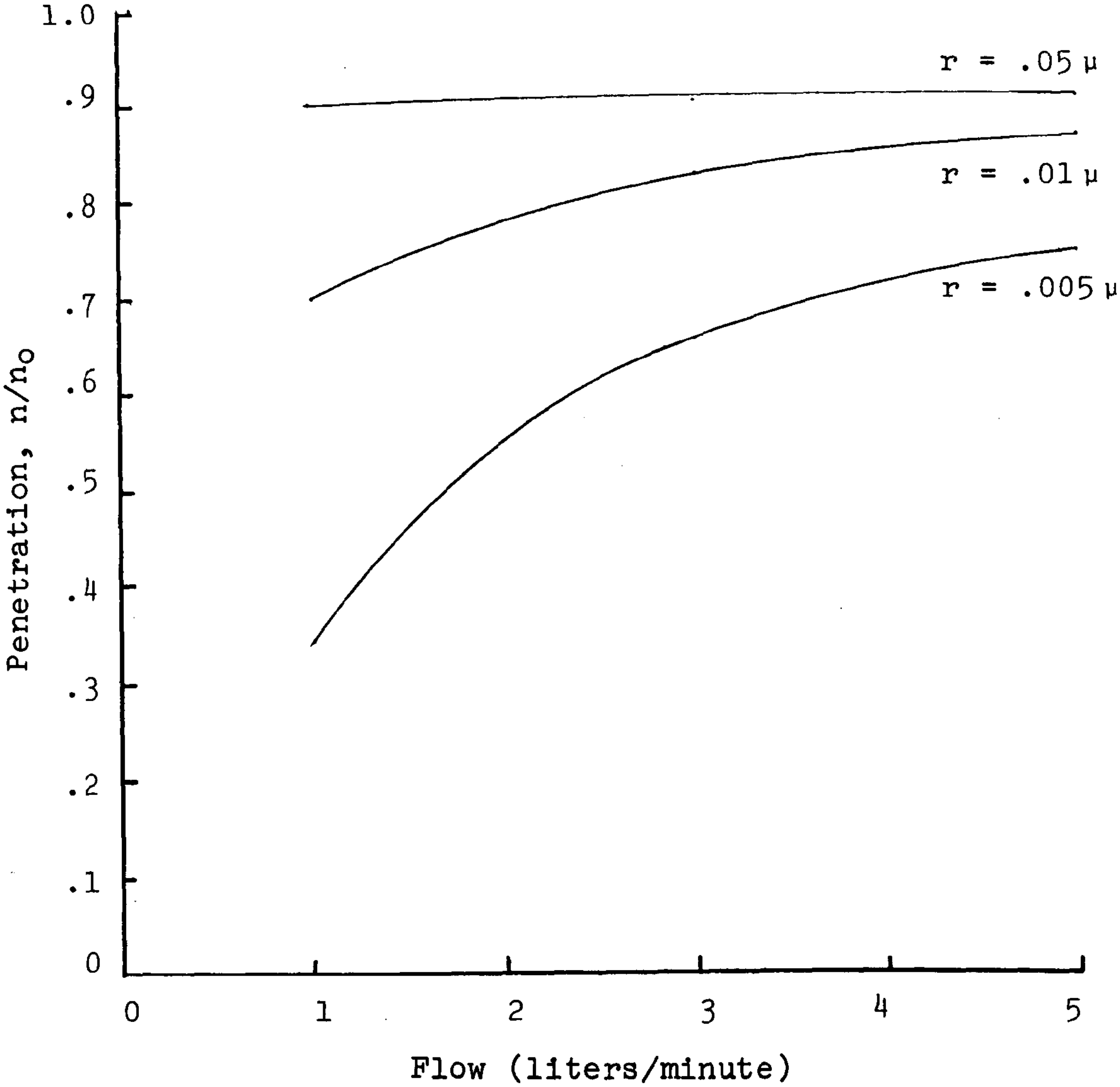

Figure 12. Penetration vs Flow for Unit 4

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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16. ABSTRACT The report gives results of an analysis of the relationship between functional requirements and the dimensions of rectangular-channel diffusion batteries, to determine the optimum configuration with respect to weight and volume. For a given penetration and minimum gas flow, the minimum weight and volume of a diffusion battery are determined by the thickness and spacing of the plates which form the walls of the channels. The number of batteries required to cover a given range of particle sizes is determined by the spread between the minimum and maxiumum available gas flow rates. The extent to which battery weight can be reduced is ultimately limited by both plate material stiffness and manufacturing tolerances.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Flue Gases	Air Pollution Control	13B	21B
Size Determination		Stationary Sources	14B	
Measurement		Diffusion Batteries		
Diffusion		Particulates		
Design				
Aerosols			07D	

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