1948 — 20 Years of Research Progress — 1968

ARL 68-0024
FEBRUARY 1968

Aerospace Research Laboratories

MICROSCOPIC PARTICLE SEPARATION AND APPLICATIONS

ROBERT POPLAWSKI, CAPT, USAF
ROGER A. MILLER, CAPT, USAF
ENERGETICS RESEARCH LABORATORY

Project No. 7116

OFFICE OF AEROSPACE RESEARCH

United States Air Force

BEST

AVAILABLE

COPY

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Agencies of the Department of Defense, qualified contractors and other government agencies may obtain copies from the

Defense Documentation Center
Cameron Station
Alexandria, Virginia 22314

This document has been released to the

CLEARINGHOUSE
U.S. Department of Commerce
Springfield, Virginia 22151

for sale to the public.

Copies of ARL Technical Documentary Reports should not be returned to Aerospace Research Laboratories unless return is required by security considerations, contractual obligations or notices on a specified document.

400 · April 1968 - CO455 - 30-634

AD 667 557

MICROSCOPIC PARTICLE SEPARATION AND APPLICATIONS

Robert Poplawski, et al

Aerospace Research Laboratories
Wright Patterson Air Force Base, Ohio

February 1968

ARL 68-0024

MICROSCOPIC PARTICLE SEPARATION AND APPLICATIONS

CAPT ROBERT POPLAWSKI
CAPT ROGER A. MILLER

ENERGETICS RESEARCH LABORATORY

This paper is to be presented at the meeting on "Helicopter Propulsion Systems" sponsored by the AGARD Propulsion and Energetics Panel, held in Ottawa, Canada, 10-14 June 1968.

FEBRUARY 1968

Project No. 7116

AEROSPACE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report was written for presentation at the "Helicopter Propulsion Systems" meeting sponsored by the AGARD Propulsion and Energetics Panel, to be held in Ottawa, Canada, 10-14 June 1968.

The work deals with part of a continuing in-house research program conducted in the Energetics Research Laboratory under Project Nr 7116, "Energy Conversion Research". Specifically, this report only covers those inertial devices which operate at low pressure drops (less than 5 psi) and low to moderate particulate loadings (10-3000 mgm particulate/ft^3 of air).

Detailed information on the high pressure drop devices can be found in numerous Aerospace Research Laboratories Reports, e.g., ARL 65-66, 65-219, 66-0218, and 67-0234; and various other technical publications.

ABSTRACT

The Energetics Research Laboratory of the Aerospace Research Laboratories (ARL) has been engaged in ultra-microscopic particle separation studies since 1961. The application of this research ranges from the protection of turbine engines from dust and/or sea spray to applications in the field of air pollution. This paper presents not only the theory of these devices and laboratory experimental results, but also, field testing results on selected units. The important trade-offs between design parameters and the selection processes required to tailor an ARL type dust separator to a specific application are discussed and other important areas of application are suggested.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Hans J. P. von Ohain and Lt Col Melvin R. Keller for the technical foundations and guidance in the preparation of this report. Mr. Richard Childs of the Army Tank Automotive Center (ATAC) and Mr. Edward S. Issenman of the Systems Engineering Group (SEG) of the Research and Technology Division (RTD) are thanked for their invaluable assistance in areas of application. In addition, ATAC is also thanked for their financial assistance in carrying out the experimental program.

We also wish to thank the many technicians who obtained the experimental data and the secretaries who typed this report under other than "normal" conditions.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT)

LIST OF ILLUSTRATIONS (CONT)

LIST OF TABLES

I. INTRODUCTION

A. PROBLEMS

Erosion, deposition and gross damage due to dust ingestion has drastically reduced engine life expectancies. In field tests conducted by General Electric, T-58 turbine powered helicopters would fail after only 80 minutes of operation in a dusty environment[1]. In other tests on nearly 30 engines, engine life was reduced nearly 90%. In addition to reducing turbine engine life, the Army Tank Automotive Center (ATAC) has found that even diesel and gasoline powered vehicles were subject to premature engine failure[2]. Under actual combat conditions in South Vietnam, helicopter engine life was reduced by over 70%. The total cost of repairing equipment which failed due to Vietnam's red dust exceeded $100, 000, 000 in 1965[3,4]. However, if the engines were protected by even a crude separator, engine life expectancies could be expected to increase by over 100%[5]. Although dust ingestion significantly reduces engine life and thereby increases the cost of operations, the results are normally catastrophic, i.e., results in severe injury or death. Air pollution, however, seriously affects health and damages or destroys vegetation.

Particulate matter, carbon monoxide, sulfur oxides, nitrogen oxides, and hydrocarbons are the chief constituents of air pollution[6]. Particulate matter causes sickness and premature death, metal corrosion and unsightly deposits. Carbon monoxide causes headache, loss of visual acuity and reduces muscular coordination. The sulfur oxides corrode materials, reduce visibility, damage vegetation, and add to the number of respiratory diseases and premature deaths. Nitrogen oxides and hydrocarbons contribute to the formation of photo-chemical smog which damages vegetation, deteriorates rubber, and probably increases the susceptibility to or causes various respiratory diseases. The aforementioned results of air pollution are incomplete since it is impossible to estimate the total effect on the health of plants and animals. However, some typical results of "heavy-smog" on human beings is shown in Table I. Added to the incalculable number of diseases and premature deaths is $11,000,000,000 a year in property damage[7]. Primarily as a result of the economic loss incurred by air pollution and engine dust ingestion, large sums of money have been spent to develop and advance filtration techniques. The next section considers some of the techniques and their range of application. However, in view of the broad nature of the filtration techniques, only a cursory glance at the entire spectrum is possible.

B. FILTRATION TECHNIQUES

The elimination of dusts, smokes, and mists (particulate matter) can be accomplished by: Gravitational settling, inertial and centrifugal separators, washing and wet scrubbing, electrostatic precipitation, filtration, sonic and ultrasonic agglomeration, etc. Each method has various ranges of application depending upon: The flow rates encountered (both particulate and gas); the energy available to operate the separator (electrical and/or fluid); the space available for the separator; the type, size, shape and concentration of the particles; the funds available to purchase and maintain the separator; and many other factors[8,9,10,11]. Since the most important parameter is the particle size the device can separate, the range of application of any separator is quoted as a function of its particle size separation capability. Typical ranges of application of the various types of gas cleaning equipment is shown in Figure 1. Of all the types shown, ultrasonic techniques and thermal precipitators have very limited ranges of applications and are not suited to the air pollution problem. In the dust ingestion case, only the centrifugal separators possess many of the performance characteristics necessary for application to the engine ingestion problem[13,14]. These characteristics are:

1. Efficient separation of micron size particles.
2. Low pressure drop thru the separator.
3. Hi flow rate capability.

TABLE I

SOME RECENT REPORTS OF AIR POLLUTION — "HEAVY SMOG"[7]

LOCATION & DATE	DURATION OF SIEGE	SOME RESULTS
Donora, Pa. Oct. 1948	4 Days	1) 5,910 of the town's 14,000 residents became ill. 2) Twenty persons died.
London Dec. 1952	5 Days	1) 4,000 deaths as a result of siege.* 2) 8,000 more deaths within two months*
1956		1000 excess deaths
1962		300 excess deaths
New York City 1953	10 Days	200 excess deaths
1963		400 excess deaths
Nov. 1966	4 Days	80 excess deaths

* Estimate of British Committee on Air Pollution

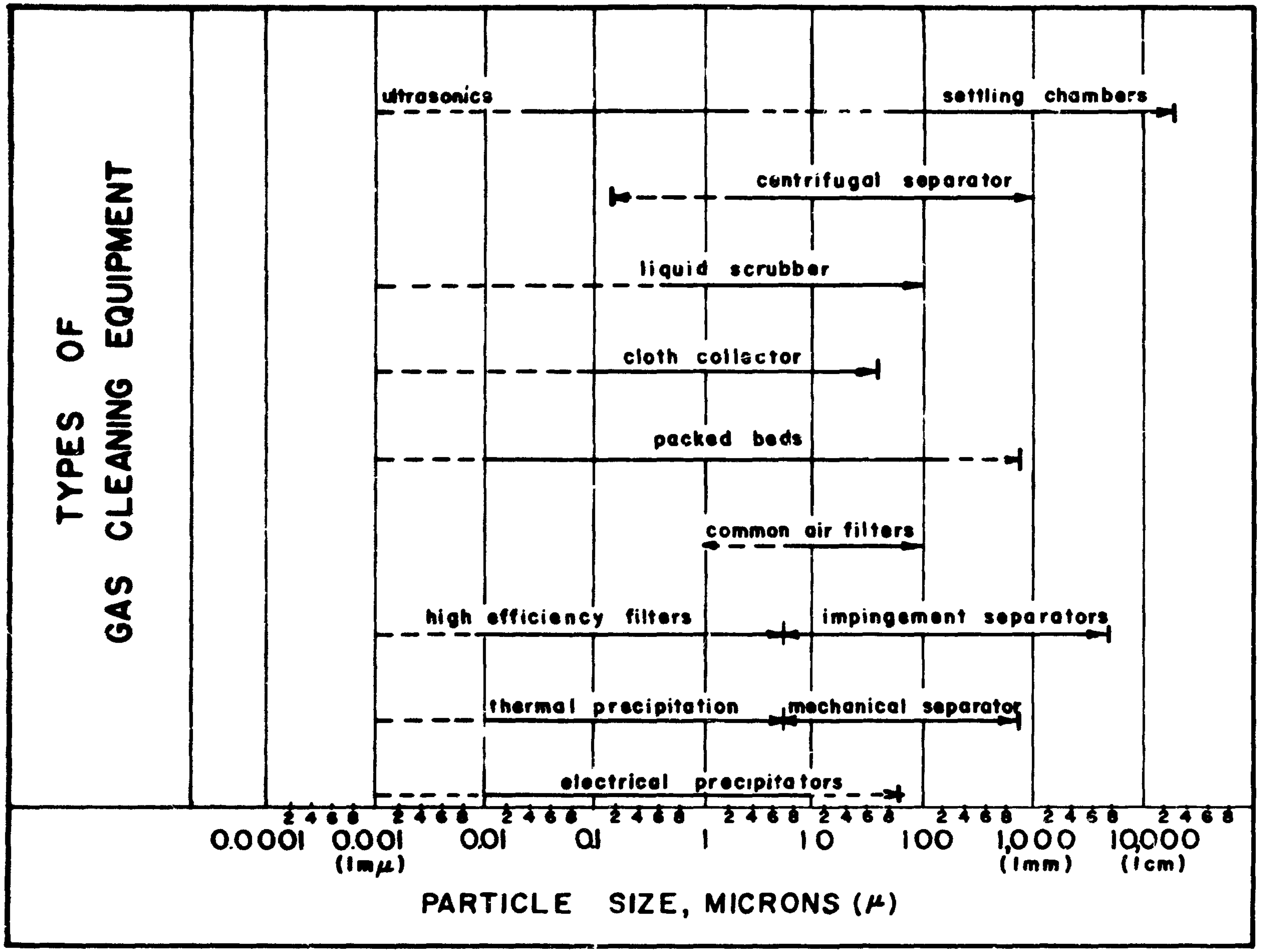


FIG. I GAS CLEANING EQUIPMENT FOR VARIOUS PARTICLE SIZES[12]

4. Low ejection energies for continuous dust removal.
5. Usable for mobile installations.
6. Little or no maintenance requirements.

Fortunately, the engine separator characteristics are also compatible with the requirements of an air pollution separator (lessen the air pollution problem by removing particulate matter). In addition, both the particle sizes of the dusts encountered by various engines (see Figure 2) and the particle sizes of the various forms of particulate (see Figure 3 for typical distributions) matter overlap in a broad range. This overlapping extends from one micron to approximately 1000 microns. Since the range of centrifugal separators is from one-tenth to one thousand microns (see Figure 1), the centrifugal separators (hereafter called inertial separators) are basically capable of solving the two problems. In addition, the inertial separators simplicity, low initial and maintenance cost, and ruggedness make the units highly desirable in both applications.

Application of the inertial separator to both the engine ingestion and air pollution problem is basically a complex problem since scientific, engineering and management requirements and capabilities must be satisfied. However, some general comments can be made on the range of application depending upon the inertial separators' capabilities and the inherent characteristics of the problem(s). The next section considers some of the broad areas of application.

C. APPLICATION OF INERTIAL TECHNOLOGY

As one might logically expect, the range of application of an inertial separator depends primarily upon the requirements the device must meet. In general, these requirements vary for each particular application and as might be expected, certain requirements must be "weighed" more heavily than others in different applications. However, the single most important restriction on the separators application is the area available for the devices installation. Specifically, the inertial separators' flow rate per unit frontal area is

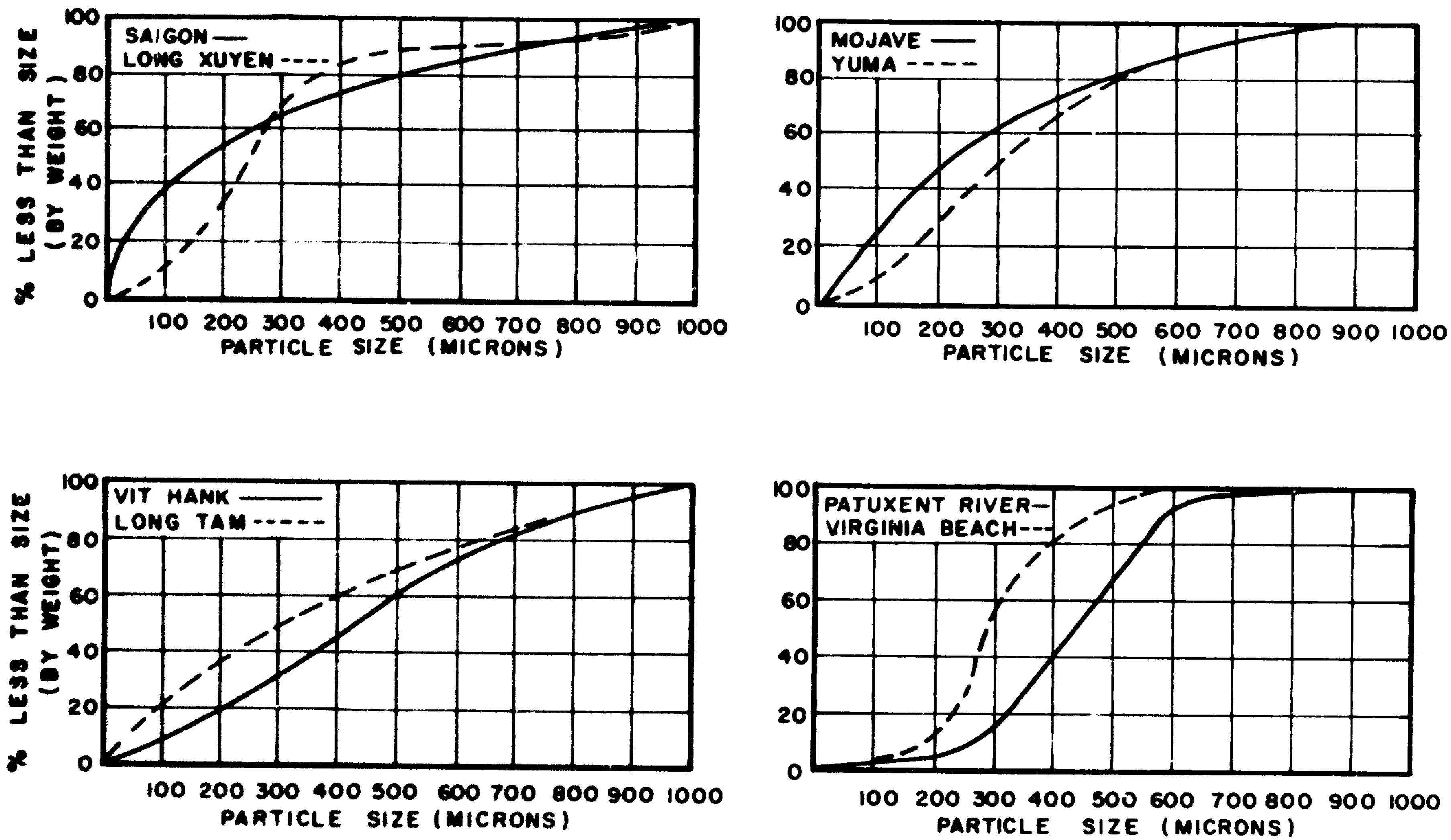


FIG. 2 TYPICAL SAND PARTICLE SIZE DISTRIBUTION IN THE UNITED STATES AND VIETNAM [15]

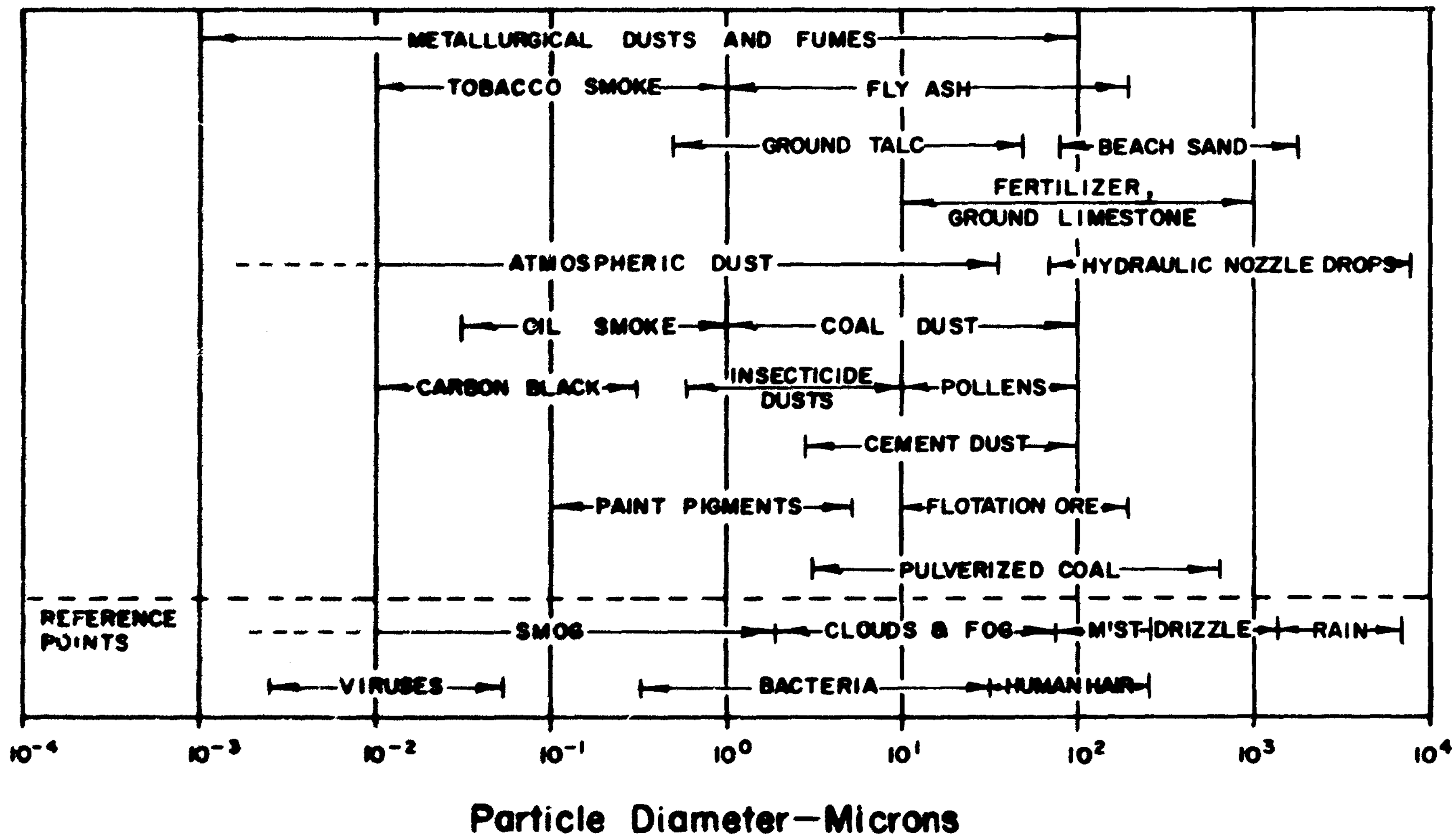


FIG. 3 TYPICAL SIZE RANGES OF DIFFERENT PARTICLES AND DISPERSOIDS.[12]

normally below 3 lb m/sec ft^2 of separator frontal area (Q/A), with a total pressure drop of approximately 4 inches of H_2O (ΔP), and separation efficiencies above 95% (η_s) (3, 5, 11, 13, 14). Thus, the inertial separator cannot be used in space restricted areas. Table II shows some typical turbine engines with their corresponding flow rates and engine diameters. In all cases, except one, the flow rate per unit engine frontal area exceeds 3 lb m/sec ft^2. As a result, only a highly limited application of the inertial separator is seemingly possible. A note of caution however, if the space available for the separator is increased and/or the separation efficiency requirement is decreased (both at the same pressure drop conditions), the inertial separator can be used on other engines[3]. For example, both turbine powered and reciprocating engine surface vehicles have lower engine flow rates and/or more space available for the installation of a separator. Thus, surface vehicles which operate in an extremely dusty environment can use an inertial particle separator for cleaning the inlet engine air.

In addition to being used to reduce or eliminate the engine dust ingestion problem, the inertial separator can also be used to lower the total amounts of pollutants dumped into the atmosphere. Figure 4 shows both the amounts and the principal sources of the main pollutants. Since the inertial separators are not normally used for separation of particles below approximately one micron, only the particulate matter can be effectively removed from the atmosphere by the inertial separators. Thus, it appears only a maximum of about 22,000,000,000 pounds of air pollutants can be eliminated through the use of the inertial separator. Stated another way, it could reduce the total particulate pollution available to every individual in the United States by over 100 pounds. However, since particulate matter acts as a catalyst in the formation of other pollutants the total reduction may be far more substantial than one might initially expect.

In ddition to the aforementioned areas of application, the intertial separator also have applications in areas of advanced nuclear, electrical,

TABLE II SELECTED TURBINES & THEIR VARIOUS USES

TURBINE ENGINE	ENGINE UTILIZATION	MASS FLOW RATE ENGINE DIAMETER	FLOW RATE PER UNIT ENGINE FRONTAL AREA
T 34 PRATT & WHITNEY	CARGO AIRCRAFT C-133	62 lbm/sec 34 inches	9.85 lbm/sec ft^2
T 35 LYCOMING	HELICOPTERS Army UH-1(Iroquois) USAF YH-40 & HH-43 FIXED WING Army OV-1	10.45—12.2 lbm/sec 23—23.7 inches	3.63 —— 3.99 lbm/sec ft^2
T 55 LYCOMING	HELICOPTER Army CH-47(Chinook)	21.5—23 lbm/sec 24.25 inches	6.72 —— 7.19 lbm/sec ft^2
T 56 ALLISON	CARGO AIRCRAFT C — 130	32.5 lbm/ sc 26.9—27.25 inches	8.06 —— 8.23 lbm/sec ft^2
T 58 GENERAL ELECTRIC	HELICOPTER CH-3 & UH-1-F	12.6—13.95 lbm/sec 16 inches	9.02 —— 9.97 lbm/sec ft^2
T 63 ALLISON	HELICOPTER Army OH-4A Bell Light OH-5A Hiller Obs. OH-6A Hughes	2.75-2.98 lbm/sec 14—15 inches (Dia here is 4" less than width of eng)	2.45 —— 2.57 lbm/sec ft^2
T 64 GENERAL ELECTRIC	VTOL AIRCRAFT XC—142 (Tri-Service)	24.5 lbm/sec 20 inches	7.80 lbm/sec ft^2

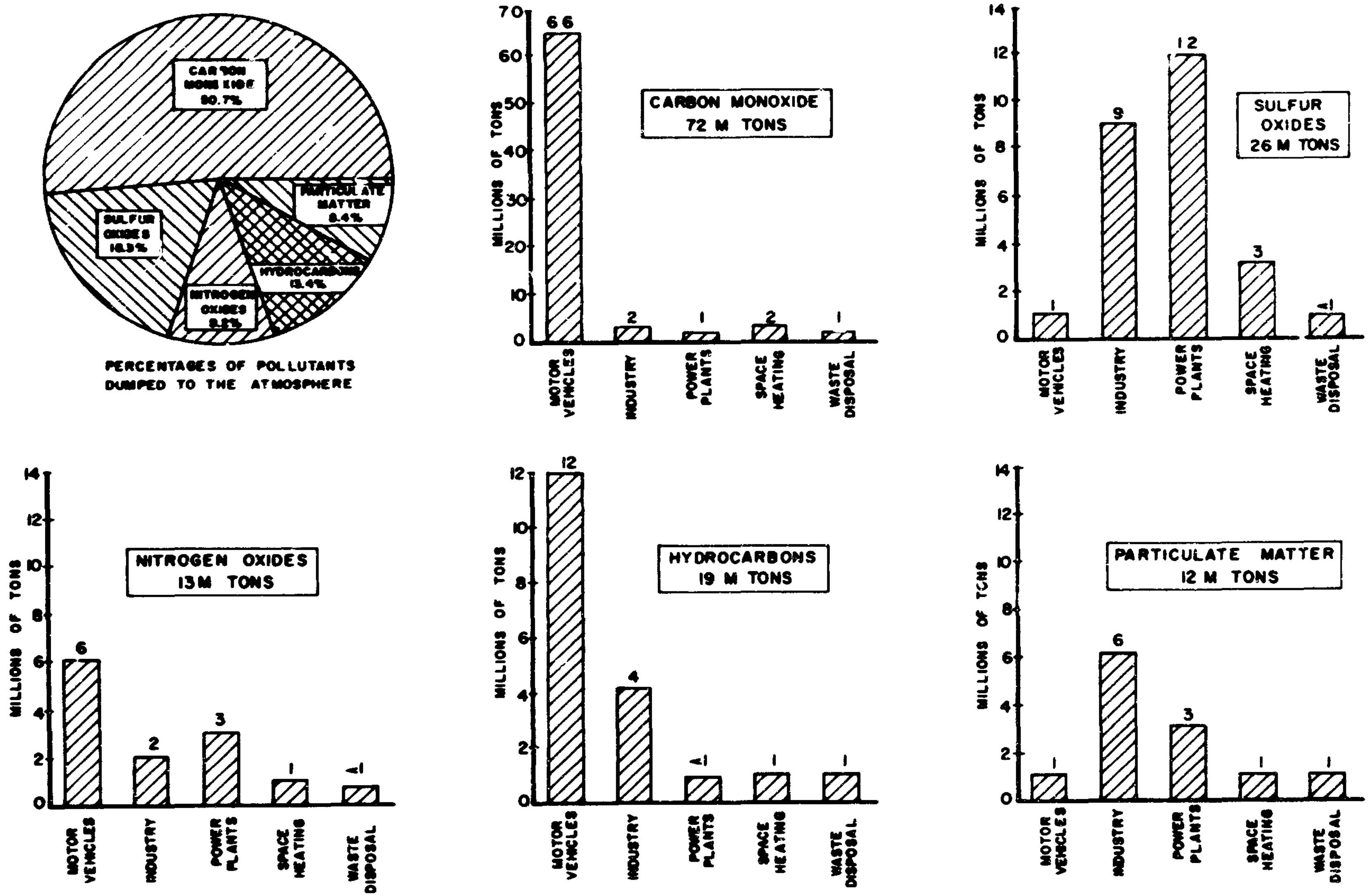


FIG. 4 PRINCIPAL AIR POLLUTANTS; THE AMOUNTS AND THE SOURCES (6)

and chemical propulsion, pumping techniques and other advanced energy conversion and transfer processes. Since all these areas depend upon multi-component and multi-phase flows and microscopic separation, a portion of the Energetics Research Laboratory at the Aerospace Research Laboratories (ARL/ARE) has concentrated in the general and fundamental research area of inertial separators since 1961. This report however, only covers a portion of the work on the low pressure devices designed after the early part of 1965. This latter effort was largely initiated at the request of ATAC, and has been spurred on by organizations within the Departments of Defense and Commerce.

II. THEORETICAL CONSIDERATIONS

A. BASIC DESIGNS AND PERFORMANCE MEASUREMENT

Based on theoretical studies conducted in 1961[16], the first high pressure reverse flow swirl chamber was constructed and tested at the Aerospace Research Laboratories (ARL)[17]. A schematic of a reverse flow vortex chamber is shown in Figure 5. The figure illustrates the basic fluid and particle flow paths which are common to most reverse flow devices. As a result of the information obtained from the early reverse flow separators[18,19,20,21], low pressure devices were designed fabricated and tested (low pressure, normally less than 5 psi). Basically, the low pressure ARL separators fall into two of the three dust separator categories (dust as used in this report refers to dusts, smokes and/or mists). The three categories are: the reverse, the partial reverse or partial through flow, and through flow separator. Essentially, all the ARL separators fall into the first two categories. The three basic types of separators are schematically illustrated in Figure 6 with their corresponding fluid and particle paths. In the full reverse separator, all the air is internally reversed (axial component) within the separator while in the partial reverse (or partial through flow) separator, only a portion of the air need be reversed. As one might expect, essentially no (or very little) air is reversed in the through flow separator. The basic particle-fluid pattern in the reverse separators is as follows.

The gas-particle mixture is admitted at an outer radius by means of swirl vanes or an inlet scroll. In either case, the mixture is given a tangential velocity component. The mixture then proceeds in an axial direction toward the end wall of the chamber continually centrifuging the particles toward the outer wall from which they are removed by either an injector or ejector. Upon reaching the vicinity of the end wall, continuity requires that the "small" particles, entrained with the fluid, flow radially inward and accelerate to higher velocities (the fluid must conserve its moment of momen-

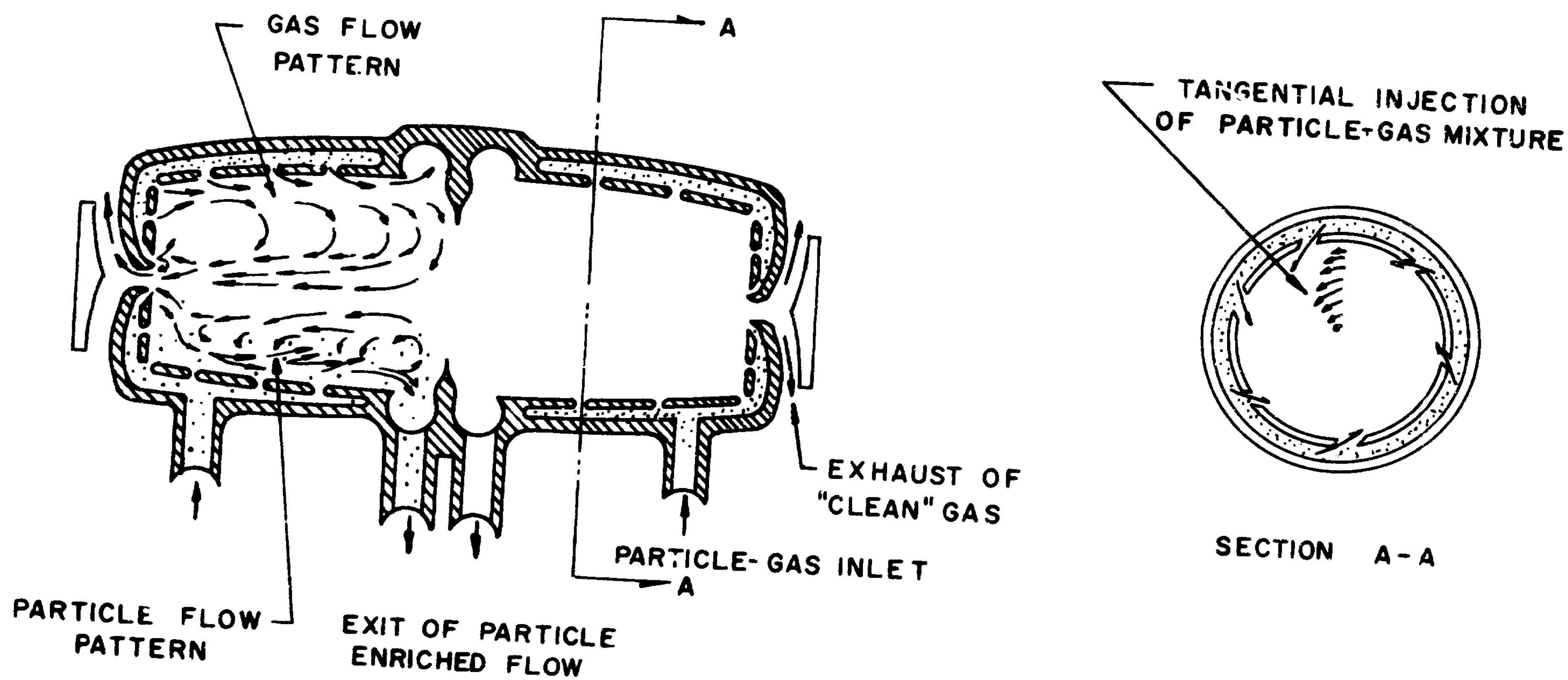


FIG. 5 SIMPLIFIED FLOW DIAGRAM OF A SWIRL CHAMBER WITH REVERSED SECONDARY FLOW

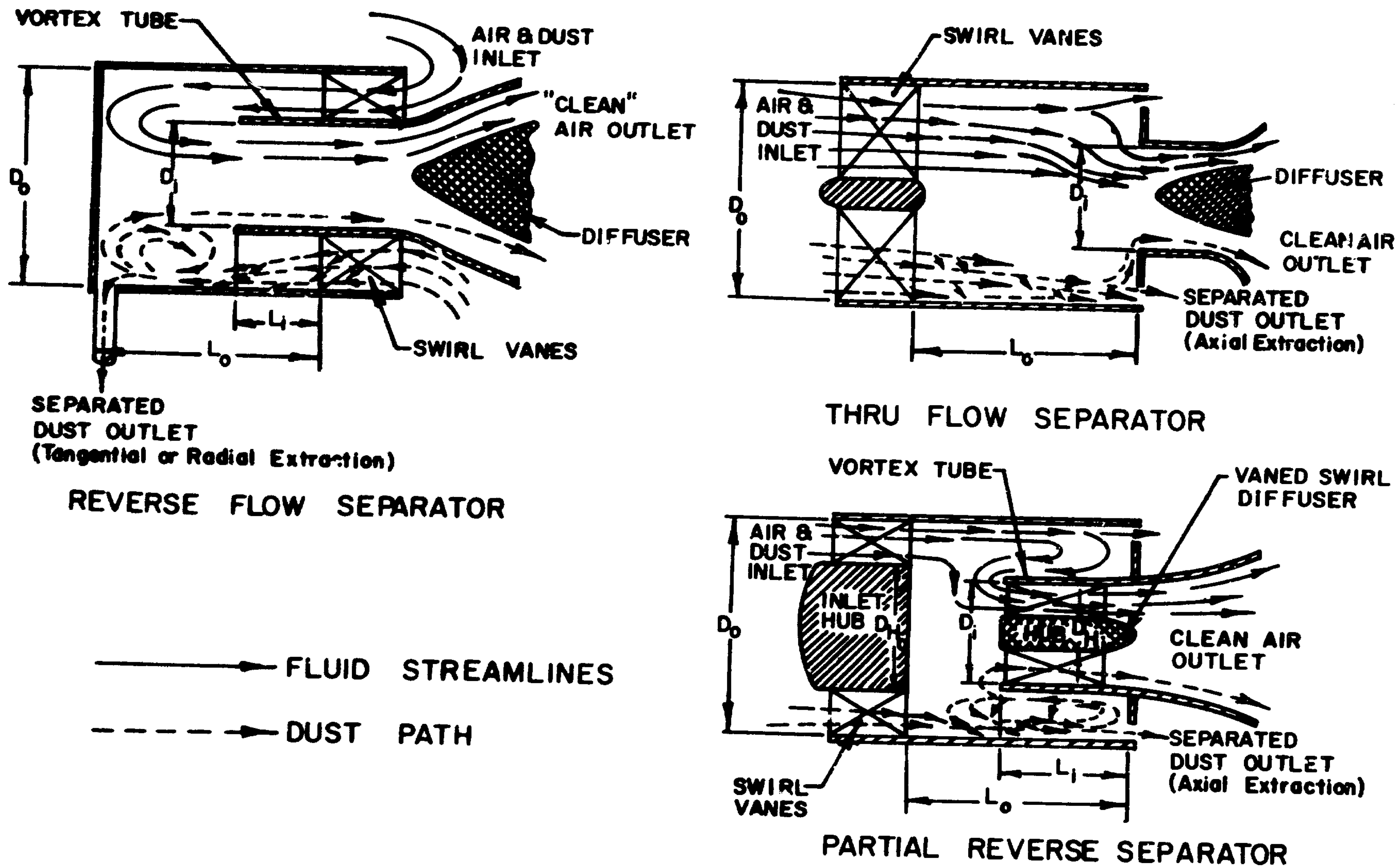


FIG. 6 THE REVERSE, THE PARTIAL REVERSE OR PARTIAL THRU, AND THE THRU FLOW SEPARATORS, SIMPLIFIED MERIDIONAL FLOW FIELD.

tum) reaching a maximum inside the exit radius. Continuity then requires the fluid to turn and proceed in the axial direction toward the exit of the separator (exit vortex tube). While traveling from the end wall to the exit of the device, the particles are gradually centrifuged out to larger radii and swept toward the injector (ejector) region of the device. Upon reaching the vicinity of the end wall some of the particle enriched flow is ejected out of the separator and the cycle continues.

In all three types of separators the tangential velocity profile can be composed of three separate regions (see Figure 7). They are the free vortex, the transition, and the forced vortex region. In the free vortex regime, the product of the local velocity and radius is ideally a constant ($vr = k \simeq$ constant). The intermediate region between the two regimes is called the transition region.

Since the potential vortex ($vr \simeq$ constant) can produce the high rotational velocities necessary for the separation of micron size particles and since the rigid body core tends to stabilize the flow field and thereby reduce the effects of perturbations in the flow, the aforementioned flow field is ideally suited for inertial particle separators. In addition, since the effects of the three regime flow field on the axial flow patterns are well understood, gains in separator performance can be made by modifying the exit of the separator. These gains will be discussed later, particularly in respect to the elimination of chamber backflow (see Figure 8) through the use of various types of diffusers (see Figure 6). It is sufficient now to say that the devices are aimed at maximizing the separator's performance over the entire range of operation.

Evaluation of the performance of a particulate separator is normally extremely difficult if sufficient data are not available. In order to avoid this difficulty, the performance of the separators was measured according to four characteristics:

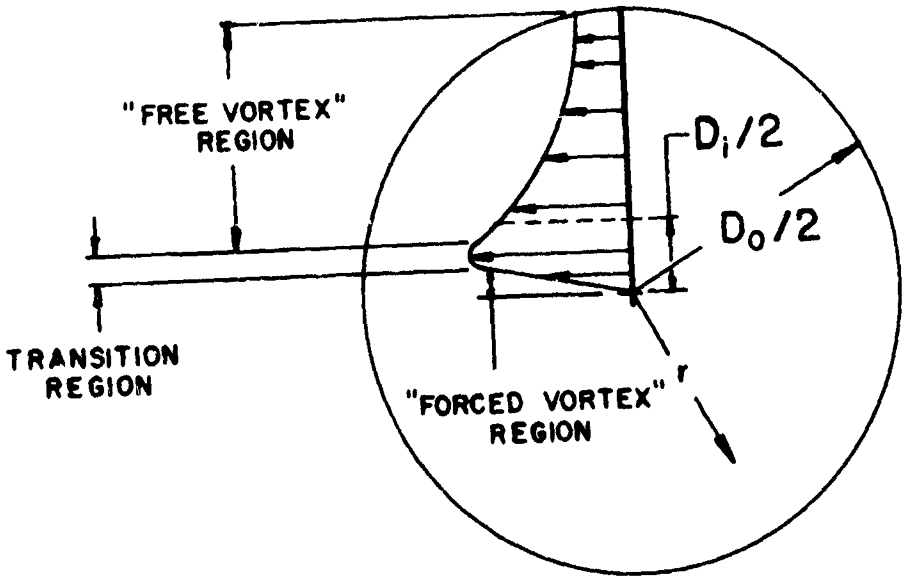


FIG. 7 POSSIBLE TANGENTIAL VELOCITY PROFILES IN THE REVERSE, PARTIAL REVERSE, AND THRU FLOW SEPARATORS

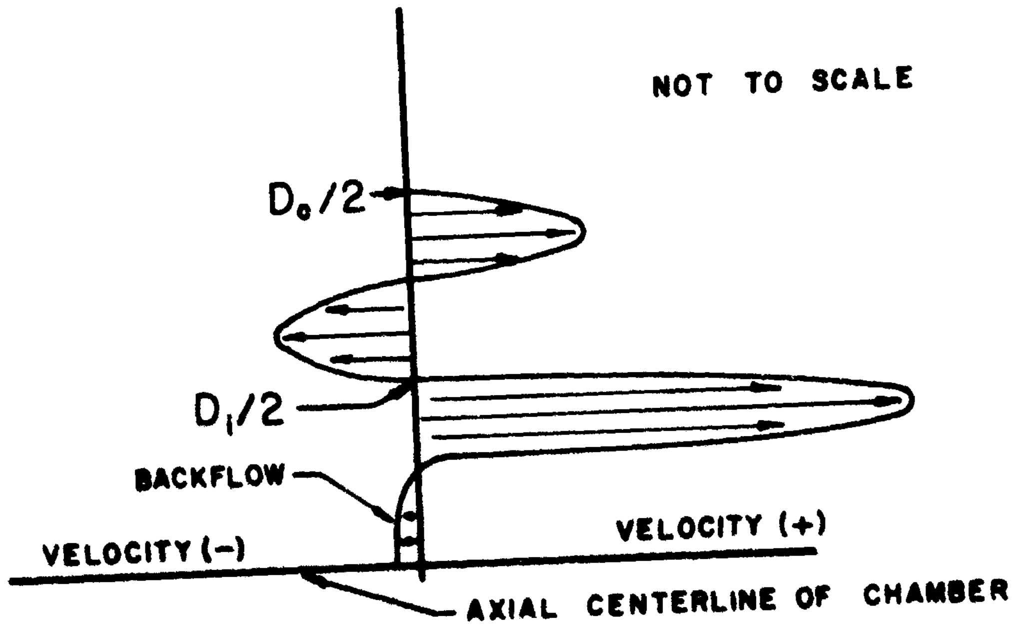


FIG. 8 POSSIBLE AXIAL VELOCITY PROFILE IN A PARTIAL REVERSE FLOW SEPARATOR NEAR THE INLET OF THE VORTEX TUBE

(1) Separation Efficiency (η_s) - The amount of dust the chamber will separate when the dust is mixed with air and drawn into the separator. Computed as a ratio of the amount of dust collected at the dust outlet to the amount injected. A standardized test dust is normally used to determine the separation efficiency (AC 0-200 Micron Arizona Road Dust - see Table III for stated AC distribution).

(2) Total Pressure Drop (ΔP) - The total pressure drop through the device. Normally, measured at the end of the clean air outlet and usually expressed in inches of water (approximately 27.7 inches of water/psi).

(3) Compactness (Q/A and L) - Quantitatively measured as the total through flow rate per unit separator frontal area and the overall separator length. Normally expressed as cfm/ft^2 of separator and inches, respectively. The total amount of air entering the separator, minus the scavenging air, is the total through flow.

(4) Scavenging air (β) - The amount of air drawn through the "separated" dust outlet (see Figure 6). Expressed as a percentage of the total through flow through the chamber.

The above four characteristics were selected since they essentially completely describe the performance capability of a dust separator. Extended discussions on the characteristics can be found in a report by Finchak[22] and in many of his references. Since many particulate separators are basically the same but different in size, the next section develops some means of predicting a separator's capability if data are available on a different size unit. As one might expect, the separation and scaling concepts section deals only with those areas which affect the performance characteristics.

TABLE III

DISTRIBUTION OF COARSE AIR CLEANER TEST DUST*

SIZE RANGE (Microns)	AMOUNT BY MASS (Percent)
0—5	12 ±2%
5—10	12 ±3%
10—20	14 ±3%
20-40	23 ±3%
40-80	30 ±3%
80-200	9 ±3%

*0—200μ Arizona road dust, prepared by A-C Spark Plug Division, G M C, Flint, Mich.

B. SEPARATION AND SCALING CONCEPTS

Frequently, it becomes necessary to determine the capability of a dust separator at a condition on which no experimental data are available. In other cases, one desires to change the physical dimensions of the chamber and again estimate the capability of the devices. In both cases, some fundamental laws apply which enable one to closely predict the new performance characteristics. Basic to the successful application of these "scaling" laws is an understanding of the physical requirements necessary for particle separation. These requirements are:

(1) The particle must be subjected to a sufficiently high rotational velocity (high ω);

(2) There must be sufficient particle "stay time" in the high rotational velocity field (long residence time), and

(3) There must be no significant perturbations in the flow field that would cancel the two previous effects.

All three requirements are covered in many reports[17,18,19,23].

Basically, particle residence time can be hopefully varied by controlling the chamber's geometry, while turbulence is essentially eliminated in the central regions of the flow be establishing a potential vortex within the chamber[17,23]. Since these two requirements were adequately covered in other reports, and since they do not normally enter into the scaling of the separator's performance, they will not be considered any further. The rotational velocity however, is strongly influenced by geometric scaling. The remaining portions of this section considers the effect of scaling on the rotational velocity and the separator performance parameters.

(1) Rotational Velocity and Scaling: It has been shown[17] that the minimum rotational velocity required for particle separation is proportional to the viscosity of the fluid and inversely proportional to the product of the particle density and the square of its diameter. Thus, if it is

necessary to separate a particle one-half of the original diameter, the rotational velocity must be increased by four. Since the outer regime of the tangential flow field in the reverse flow chambers (under investigation at ARL) closely approximates a potential vortex ($vr \simeq$ constant), a higher rotational velocity can be obtained by decreasing the radius of the exit vortex tube. However, decreasing radius also reduces the total area available for the flow and thereby reduces the through flow of the separator. The reduction in through flow per unit frontal area of a single separator is avoided by geometrically scaling down the entire unit (separator). By proper scaling, the rotational velocity varies inversely as the scale factor (assuming $\omega_1/\omega_2 = (r_2/r_1)^2$), that is:

$$\frac{\omega_n}{\omega_o} = \frac{1}{S} \tag{1}$$

where "S" is the scale factor, and ω_n and ω_o are the new and old rotational velocities, respectively. Since the rotational velocity required for separation varies as the square of the particle diameter, the new particle size that the geometrically scaled unit can separate varies as the square root of the scale factor, that is:

$$\frac{d_n}{d_o} = (S)^{1/2} \tag{2}$$

where d_n and d_o are the new and old particle diameters, respectively. Thus, if the original chamber was scaled down by a factor of four ($S = 1/4$) and it was capable of separating particles down to 20 microns, the new scaled chamber could separate particles down to 10 microns.

With equation (2) and the particle size distribution, one would think it would be possible to accurately predict the separation efficiency of the scaled separator. This, however, is not possible since nearly all particulate matter is composed of irregular shaped particles which agglomerate and change the apparent particle size. Thus, experimental data must be obtained to determine the apparent particle sizes (and not of the "ultimate" particle sizes) of the particulate matter. With knowledge of the apparent size and equation (2), an accurate prediction of separation efficiency can be made. In addition to influencing the separation efficiency, geometric scaling can also modify the particulate separator's compactness. The last portion of this section considers the influence of scaling on a separator's compactness and some of the design problems encountered in scaling down a separator.

(2) Compactness and Scaling Problems: Besides improving the separation efficiency, the scaling down of a separator also results in the reduction of the separator's total length ($L_n/L_o = S$). In addition, since the scaled units are usually clustered together in a panel, substantial savings can be realized by reducing separator development costs. Development costs are lowered since the scaled down separator can be used as the basic unit in various sized panels (depending upon the application). Thus, complete redesign, fabrication and testing cycles are eliminated.

The advantages gained by scaling down the separator are partially offset by the reduction in the separator's through flow. To obtain the same through flow, the scaled units must be clustered together. The number of scaled down units required are:

$$\frac{N_n}{N_o} = \left(\frac{1}{S}\right)^2 \tag{3}$$

where N_n and N_o are the number of the new and old units respectively. Thus, if a separator was geometrically reduced by a factor of three ($S = 1/3$), nine scaled units would be required to obtain the same through flow (at the same total pressure drop). By being forced to cluster many single units to obtain the same total flow, (see Figure 9 for a forty-six unit cluster), the compactness of the scaled down units also degenerates. This is because the flow rate per unit frontal area of the clustered separator tends to decrease. The amount of decrease depends upon the arrangement and the spacing between the individual cans.

Since the spacing between the cans is normally determined by the requirements of the scavenging air system, the scavenging air requirement should be kept as small as possible. Furthermore, since the smaller the original separator's scavenging air requirement, the lower the scavenging air requirement in the scaled unit. One should be extremely careful to select a design which requires a minimum amount of scavenging air and thus reduce the physical dimensions of the clustered separator. In addition to causing a degeneration in the compactness, geometrically scaling down a separator and clustering the individual units also introduces serious design problems. They are: (1) Designing for efficient dust removal; (2) Designing to assure equal flow through the separator (both the through and scavenging air flows); and (3) Designing for ease in fabrication and/or assembly. The detail problems involved in each area is beyond the scope of this report and will not be considered. It is sufficient to say that extreme caution must be used when designing a clustered separator so as not to degrade the separator's efficiency; i.e., decrease η_s and/or increase β at the same ΔP.

Having a basic understanding of the scaling laws and the requirements for particle separation it is possible to realistically predict the performance of various types of separators. It is particularly important to realize that the scaling equations are based on the same total pressure drop through the old and the new (scaled) separator. Determination of the through flow at a different pressure drop can be calculated from the "Fan Law"[24].

$$\frac{Q_1}{Q_2} = \left(\frac{\Delta P_1}{\Delta P_2}\right)^{1/2} \qquad (4)$$

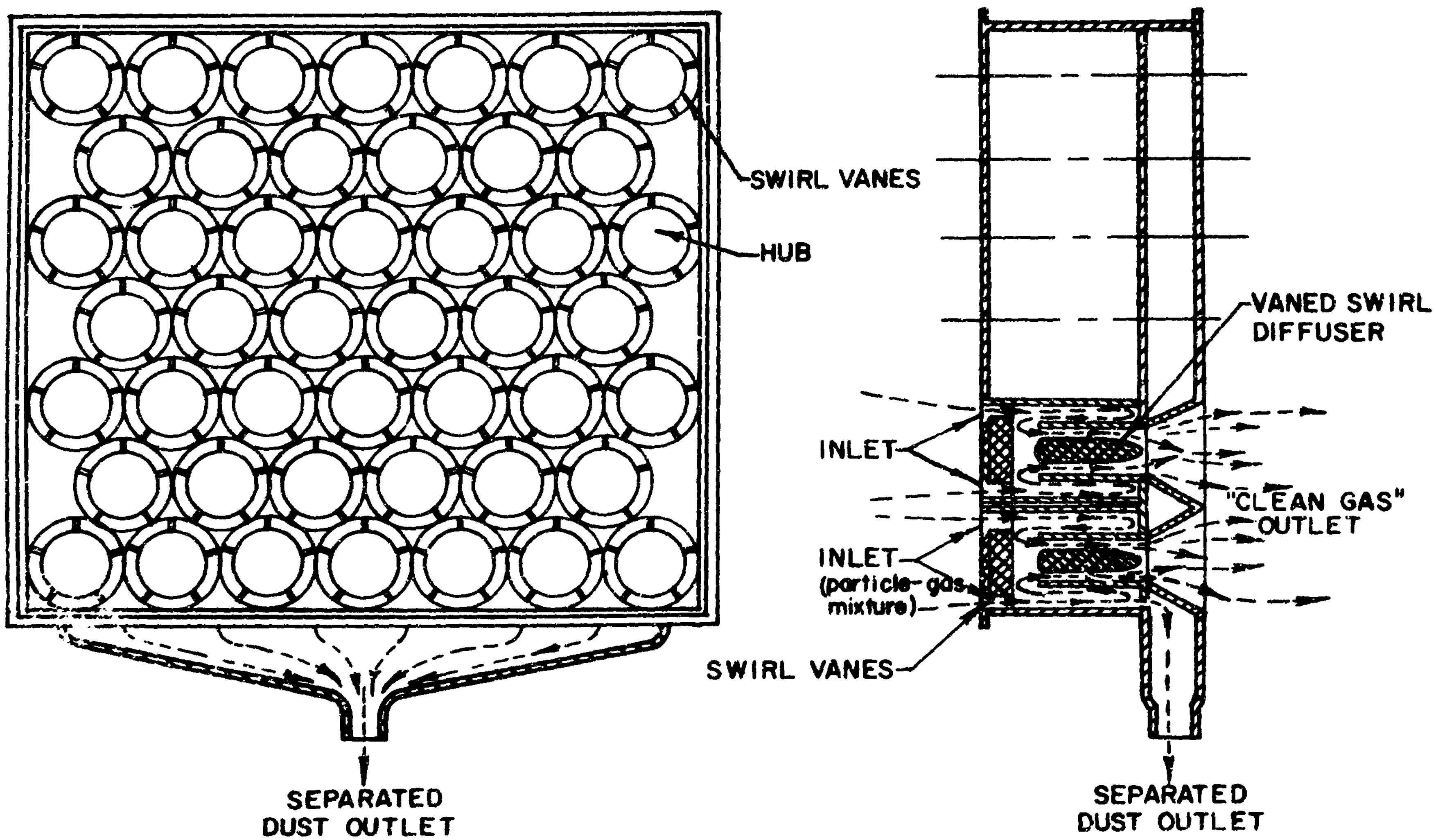


FIG. 9 SCHEMATIC OF A FORTY-SIX UNIT CLUSTER SEPARATOR SHOWING THE GENERAL FLOW PATHS.

Thus, if the flow rate of a separator is 200 cfm (Q_2) at 4 inches of water (ΔP_2), the flow rate at 16 inches of water is 400 cfm. Equation (4) essentially completes the section on separation and scaling concepts while Table IV summarizes the scaling concepts. Needless to say, additional reference will be made to the concepts as the need arises, especially in the discussions on the experimental data. The next section of this report outlines the experimental test program.

TABLE IV

SUMMARY ON EFFECTS OF GEOMETRIC SCALING

	ORIGINAL PERFORMANCE	SCALED PERFORMANCE
η_{sep}	$f\,[d_o]$ *	$f\,[d_o(S)^{1/2}]$ *
ΔP	ΔP_o	ΔP_o
Q/A	Q_o/A_o	Q_o/A_o
L	L_o	SL_o
β	β_o	$\gtrapprox \beta_o$
N	N_o	N_o/S^2
ω	ω_o	ω_o/S

* "f" is a function

III. EXPERIMENTAL TEST PROGRAM AND RESULTS

After a study of the theoretical considerations of dust separation and the requirements for such equipment, an experimental test program was established at ARL. The maximizing of separation efficiency (η_s) and through flow/unit frontal area (Q/A) combined with the minimizing of pressure drop (ΔP) and dust ejection energy (β), were of course, the goals of this program. These parameters are interrelated and trade-offs are associated with any design. The test program to evaluate and study these trade-offs evolved around the basic segments of a dust separator. Schematically the program could be summarized as a study of:

(1) Induction Systems, effects of:
- a. scroll inlets
- b. Multi-scroll (radial vanes) inlets
- c. Axial vanes
- d. End wall admissions

(2) Exduction Systems, effects of:
- a. Scroll outlets (dual chambers)
- b. Diffuser/back-up plate design
  - 1) axial flow
  - 2) swirl or radial flow
- c. Energy recovery - exit vanes

(3) Dust Ejection Systems, effects of:
- a. Injector vs ejector system
- b. Effects of radial distance between core and dust ejection region.
- c. Radial, axial or tangential extraction

(4) Geometric Configuration and Parameters, effects of:
- a. L/D ratio
- b. Diameter ratio

c. Inlet and exit vane angles

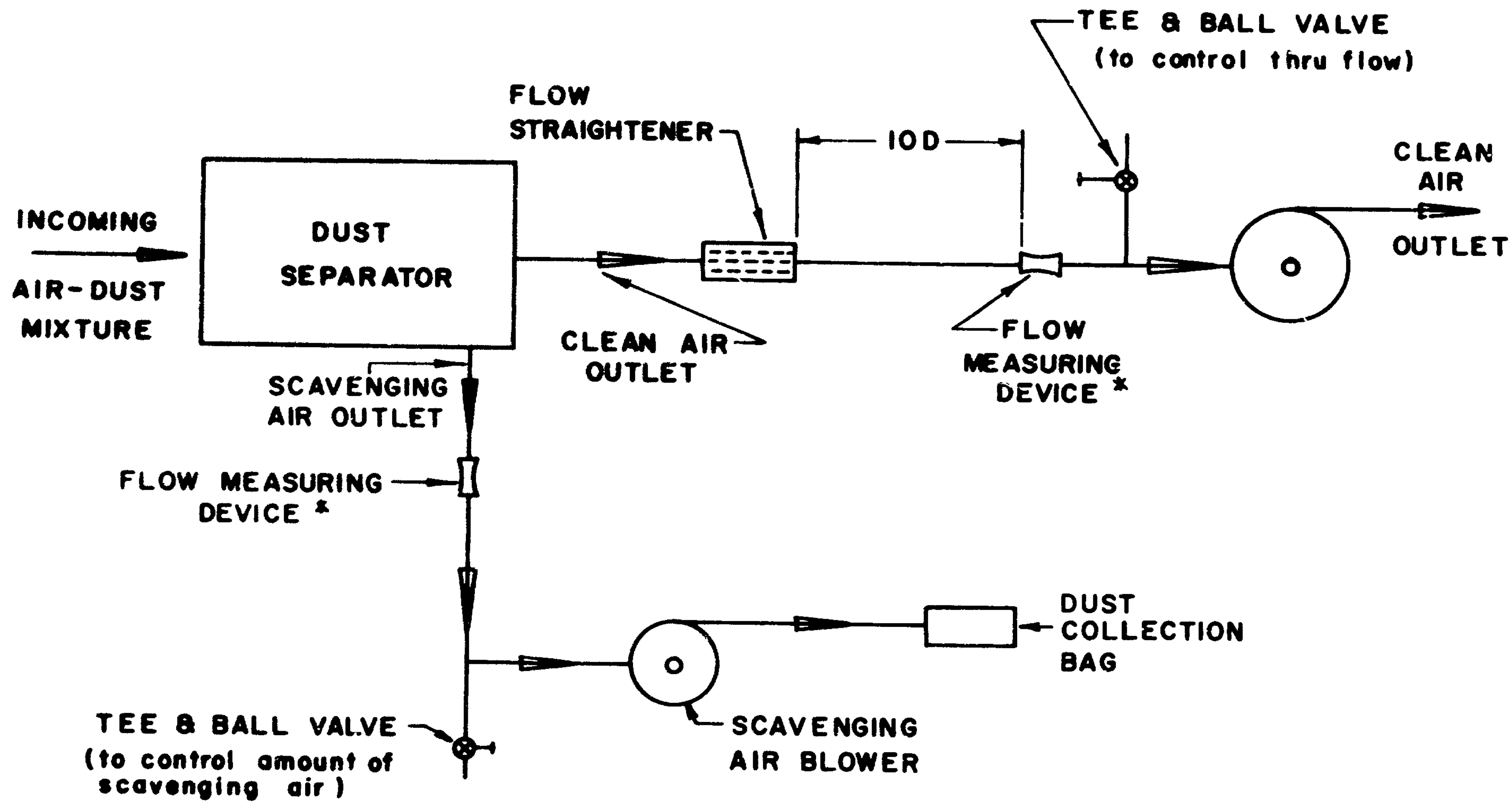
d. Length ratio (vortex tube to total length)

e. Size vs separation (scaling)

The program summary as outlined above is very clear and concise. As test hardware was designed and built however, the program appears slightly more "cloudy" because each chamber was designed with a multiplicity of purposes. Early in the program, test chambers were characteristically large - 12" in diameter. The large size allowed use of diagnostic techniques, such as, velocity probe measurements, aemometer core speed measurements, etc., which are much more difficult to use on small chambers. The results from the large chambers were scaled to smaller units depending on the application envisioned. As the program progressed, 5" diameter units were utilized in the geometric studies, and then clustered separators of 5" diameter, 2-1/2" diameter, 1-7/8" diameter, and 1" diameter units were built and tested. After a discussion of the testing procedures, the test results will be presented in the order indicated.

A. TEST PROCEDURE

The test equipment is shown in Figure 10. It consists of a blower, scavenging air blower, flow rate and pressure drop instrumentation, and the separator to be tested. Flow measurements are made by taking velocity measurements in the flow duct with a pitot probe or by using laminar flow elements. Manometers calibrated to four (4) significant decimal places are used where needed to obtain the desired accuracy. Separation efficiency is determined by feeding a measured amount of the test dust into the separators, and then collecting and weighing the dust ejected by the separator. Any residual dust build up in a separator is determined by either cleaning the separator or weighing it before and after a run. Each dust test is re-run at least three times to guarantee reproducibility and determine the error spread.



* Either a pitot-static probe or Merian laminar flow element used to measure the flow rate. Pitot probe measured the total pressure drop.

FIG. 10 TYPICAL EXPERIMENTAL ARRANGEMENT FOR TESTING DUST SEPARATORS

B. EARLY EXPERIMENTAL WORK

(1) Scroll Inlet - Scroll Outlet Chambers: The first chamber designed at ARL to specifically remove dust from air (The Mark I) is shown in Figure 11; the basic flow pattern work had been done on high pressure droplet separators, and low pressure ratio "dust retaining" chambers. The chamber is a dual cell cluster with tangential scroll inlets and a single scroll outlet. Using coarse test dust (see Table III) this unit had a separation efficiency of 92%. On A.C. special fine dust (0-5μ) the efficiency was 75%. A flow rate of 500 cfm at a pressure drop of 7-1/2" H_2O was obtained with this unit.

Two sets of modified inlet scrolls were designed and tested on this unit. These scrolls were designed to increase through flow in the unit by increasing inlet area. The inlet areas were increased 1.5 and 2.0 times respectively, and the through flow correspondingly increased from 500 to 750 and 1000 cfm (at 7-1/2" H_2O). The separation efficiency decreased however, from 75% on the 0-5μ mixture to 65% and 60% respectively.

A plexiglass scroll inlet-scroll outlet chamber was also built and tested. It was built primarily as a tool for flow pattern visualization, see Figure 12, however, it is smaller than the steel chamber (Figure 12) by a scale factor $\sqrt{1/3}$. The flow rate on this chamber is then 1/3 that of the Mark I. Separation efficiency on this unit increased correspondingly from 75% to 85% on the 0-5μ test dust, and from 92% to 96% on 0-200μ dust.

These early scroll type chambers were used to run dust ejection studies. Since the chamber is below atmospheric pressure, energy must be supplied to remove the separated dust. Tests showed that about 1% of the flow must be scavenged to adequately remove the separated dust. This 1% can be removed by either applying suction to the ejector port with a blower or ejector (possibly powered by compressor bleed air) or creating a localized high pressure region by injecting higher pressure air into the

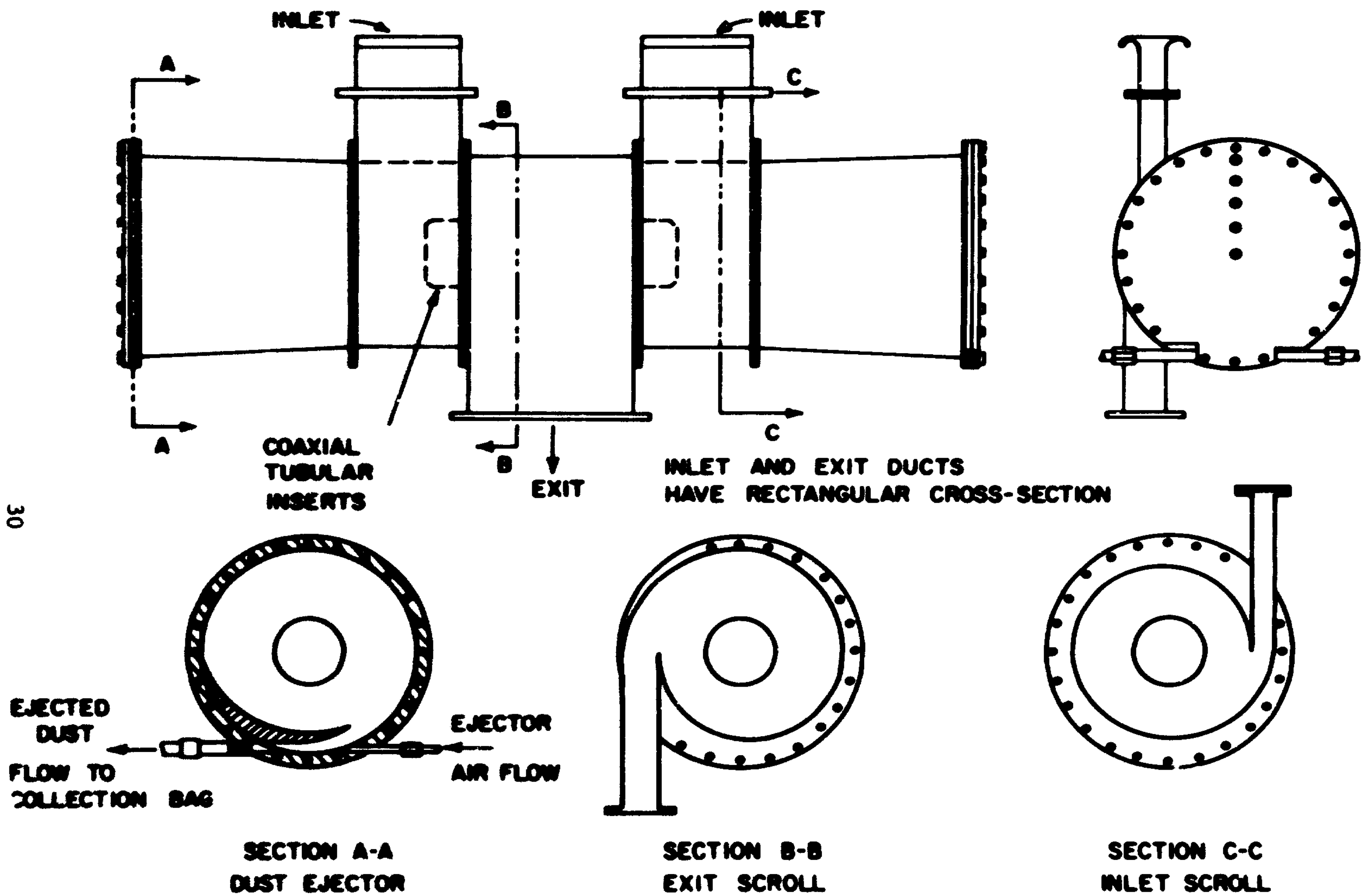


FIG. 11 ARL DUST SEPARATOR (MARK I)
SCROLLED INLET AND OUTLET

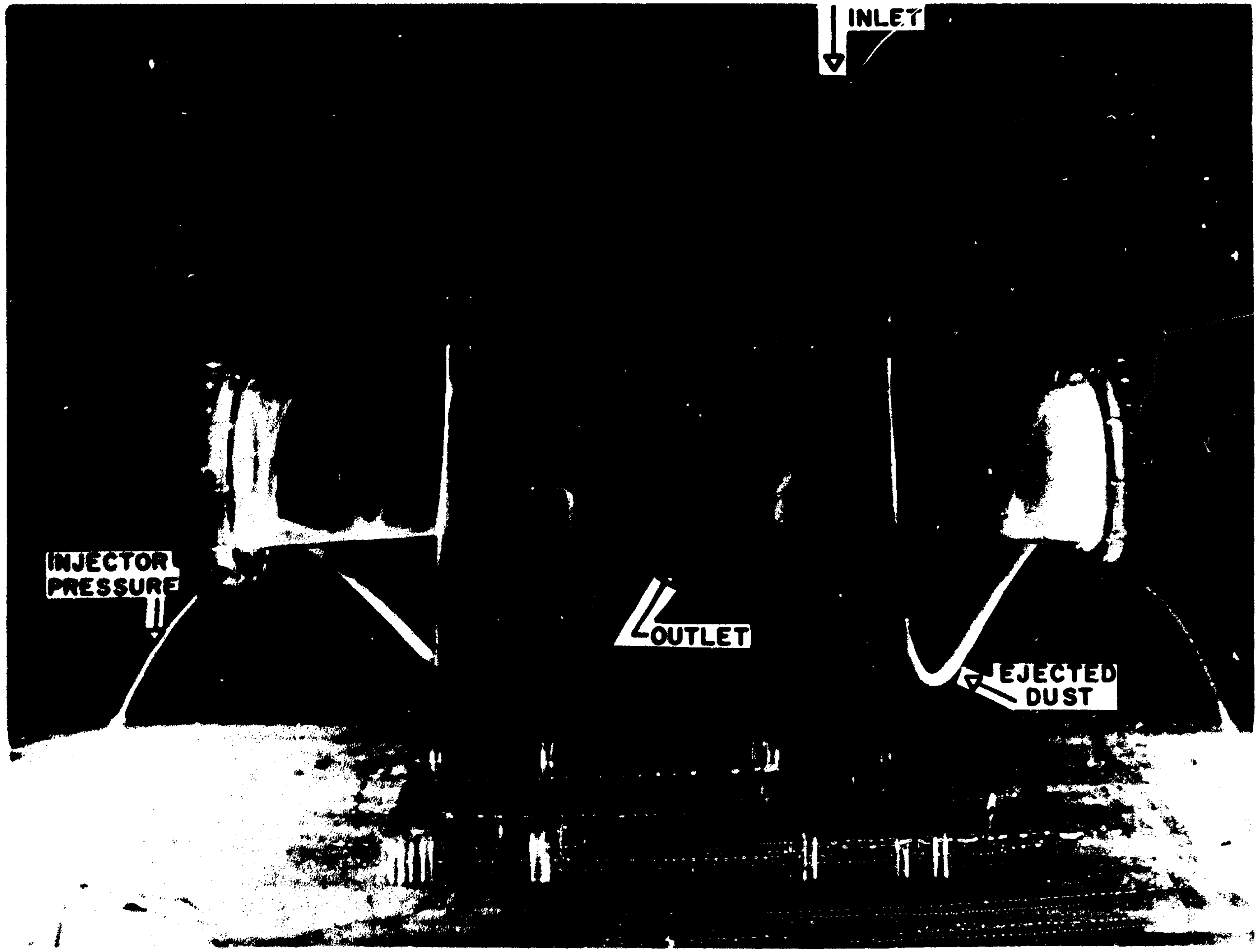


FIG. 12 PLEXIGLAS FLOW VISUALIZATION CHAMBER IN OPERATION

chamber in the vicinity of the dust ejector port. If compressor bleed air is used to power either an ejector or injector, about 1/4 of 1% of through flow is required. Since any of these three methods are adequate for good separation, the final selection of scavenge mode-ejector, injector, or scavenge blower must be made on a systems basis.

(2) Vane Inlet-Scroll Outlet Chambers: Clustering of small dust separator units is simplified using a vaned inlet configuration. This consideration led to an early dual cell design with vane inlet and scroll outlet, (see Figure 13). The purpose of the dual cell is to use a single energy recovering scroll exhaust. In essence it might be said that the two cells form their own diffuser. Tests with these early chambers and diffuser plates showed that more recovery was available using properly designed diffusers than by clustering by dual cells.

This first vaned inlet separator was capable of separating 71% of the 0-5μ test dust. The flow rate however, was only 800 cfm at 7" H_2O. The low flow rate was due to an improper vane design, the height to width ratio being too large. The chamber did yield some insight into vane inlet design, and led to the geometric configuration study chambers to follow.

The vaned inlet scroll outlet chamber was utilized for velocity probes and aneometer core speed measurements. The velocity measurements were made using a 1/8" diameter three-dimensional probe. The probe measurements confirmed the profile discussed in Section II with the transition occurring at a diameter of about 67% of the vortex tube. The probe indicated a maximum ω at this point on the order of 9,500 rpm (at ΔP = 4" H_2O) as shown by the velocity profile, Figure 14. The paddle-wheel aneometer and associated test techniques were the same as those reported by Pinchak and Poplawski[18]. These measurements indicated core speeds of 16,500 rpm (at ΔP = 7" H_2O) in the core region of the separator. The axial velocities shown in Figure 14 indicate a "back" flow into the chamber. This back flow is caused by improper diffuser matching and is detrimental not only to the Q/A, but to core speed and thus separation efficiency.

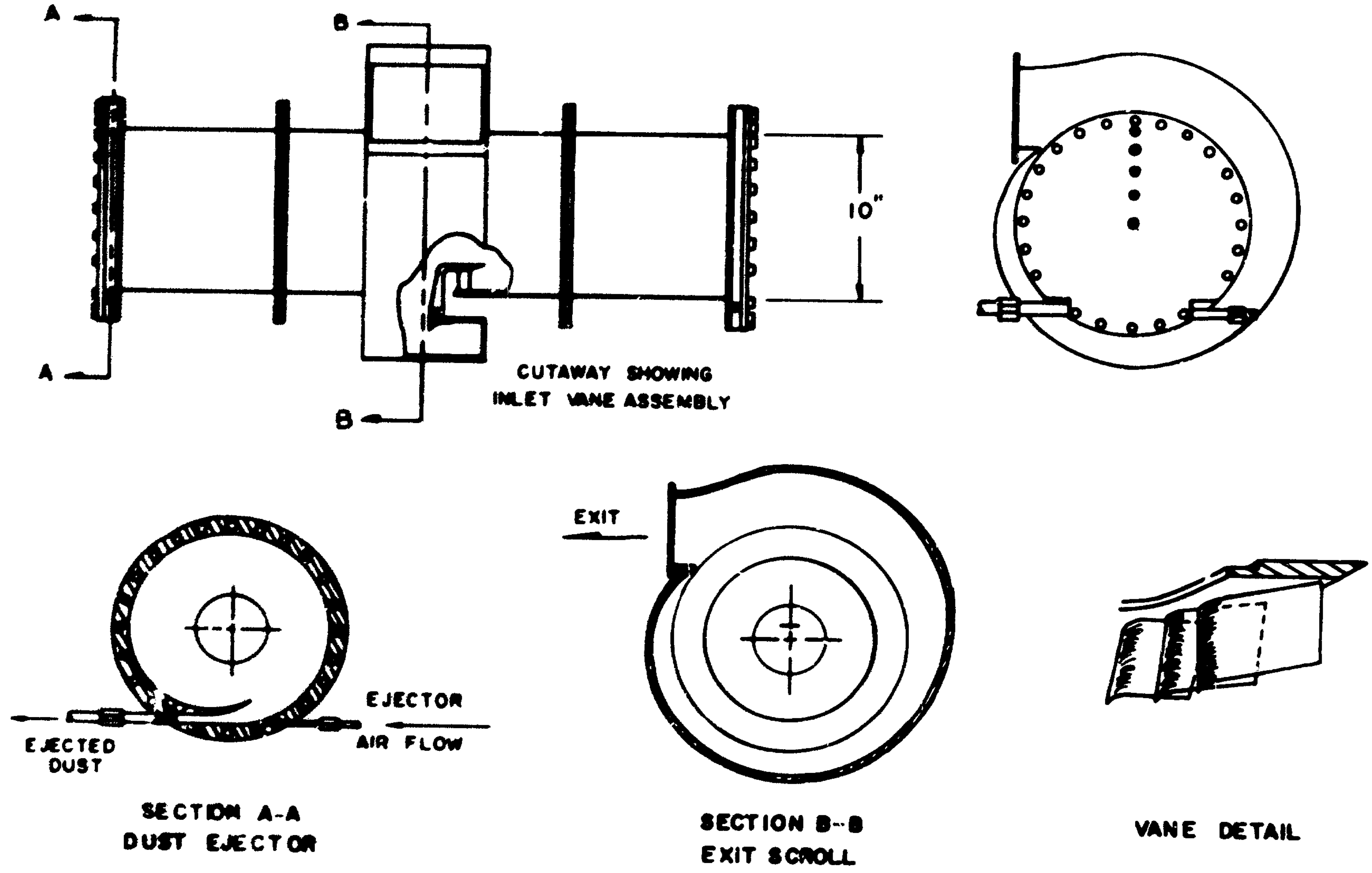


FIG. 13 ARL DUST SEPARATOR MK II
VANE INLET – SCROLL OUTLET

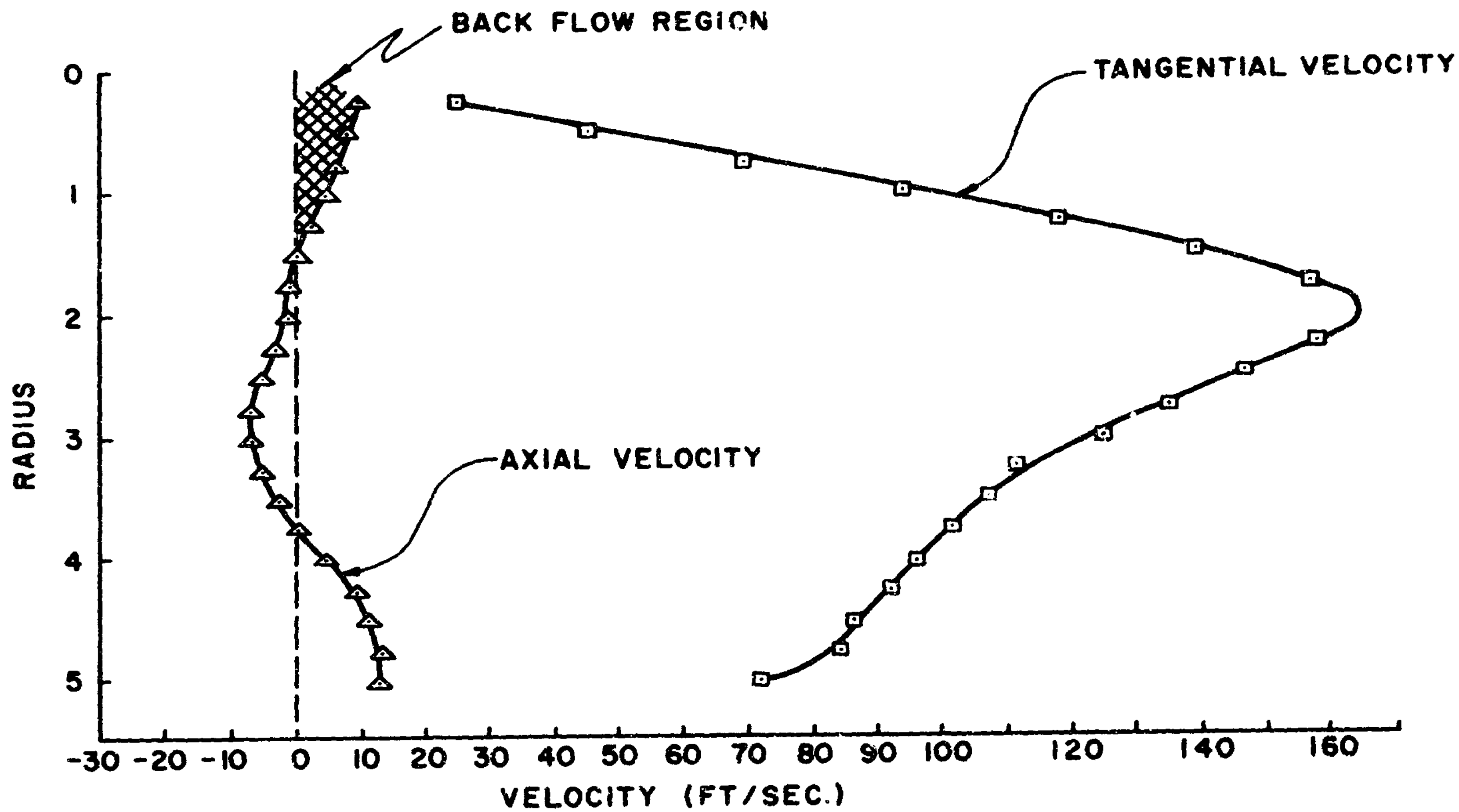


FIGURE 14 VELOCITY PROFILES IN A VANED INLET SCROLL OUTLET (MARK II) DUAL CHAMBER

(3) Geometric Configuration Studies: The geometric parameters of length to diameter ratio (L/D, where $D = D_o$ here), diameter ratio (D_o/D_i), and inlet vane angle are extremely important considerations in the design of a dust separator. Two full reversed flow chambers were used in a study of these geometric parameters. The first chamber, shown in Figure 15, had radial vanes. Three diameter ratios of 1.4, 1.8, and 2.0 were obtained in this unit by varying D_o with a fixed $D_i = 2.5''$. The L/D was variable between 1.67 and 6.0 by telescoping the outside can. The second chamber, of the type shown in Figure 6, had axial vanes. Diameter ratios of 1.6, 2.25, and 2.8 were obtained by varying the D_i with a fixed $D_o = 5''$. The L/D was fixed at 1.5, but three sets of inlet vanes with helix angles of 23^o, 28^o and 33^o were used. The vanes were constructed from plexiglas and dimentional stability is quite a problem. The indicated angle was to have a tolerance of $\pm 1/2^o$, but $\pm 2^o$ is much more realistic.

The aerodynamic data on the radial vane chamber is presented in Figures 16, 17, and 18; and separation data is shown in Table V. The fact that L/D has only a slight effect on flow rate is highlighted in Figure 17. Diameter ratio does have a marked effect on flow rate as shown in Figure 18. An increase in L/D from 1 to 10 increases Q/A by 1 cfm/in^3 but increases the volume by 10 times, yet a decrease in diameter ratio from 2.0 to 1.4 increases Q/A by 1-1/2 times with no change in volume (if D_i is varied). The separation data shows that over the range of variables studied, there is only minimal dependence of separation efficiency on L/D or D_o/D_i. A very weak maximum in separation efficiency is indicated at an L/D of 3 however.

The aerodynamic data on the axial vane chamber is presented in Figures 19 and 20, and separation data is given in Table V. Although the L/D was constant at 1.5, the marked effect of D_o/D_i is illustrated by Figure 20. The effects of inlet vane angle is shown in Figure 19. The

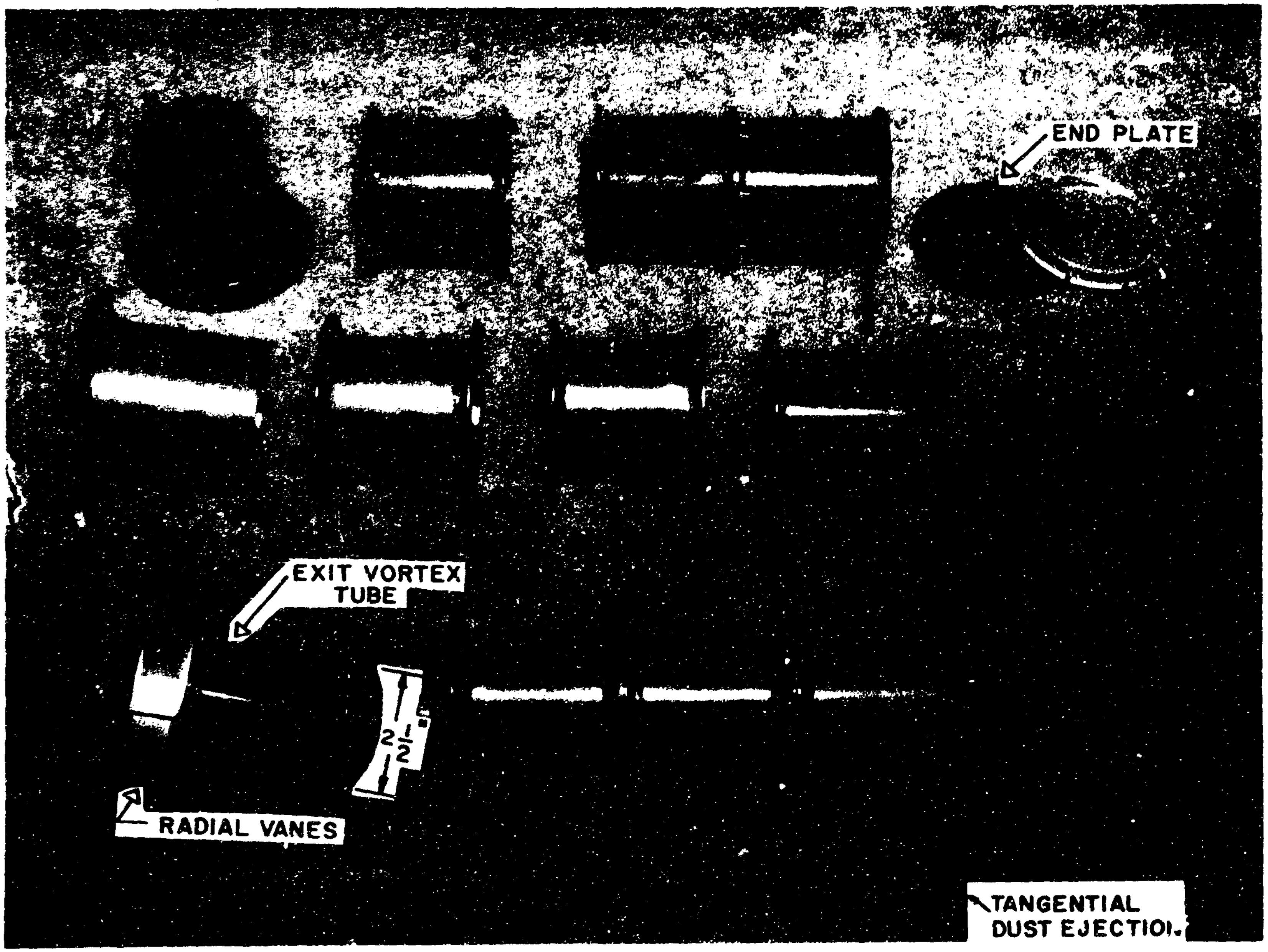


FIG.15 RADIAL VANE CHAMBER WITH VARIABLE L/D & D_o/D_i

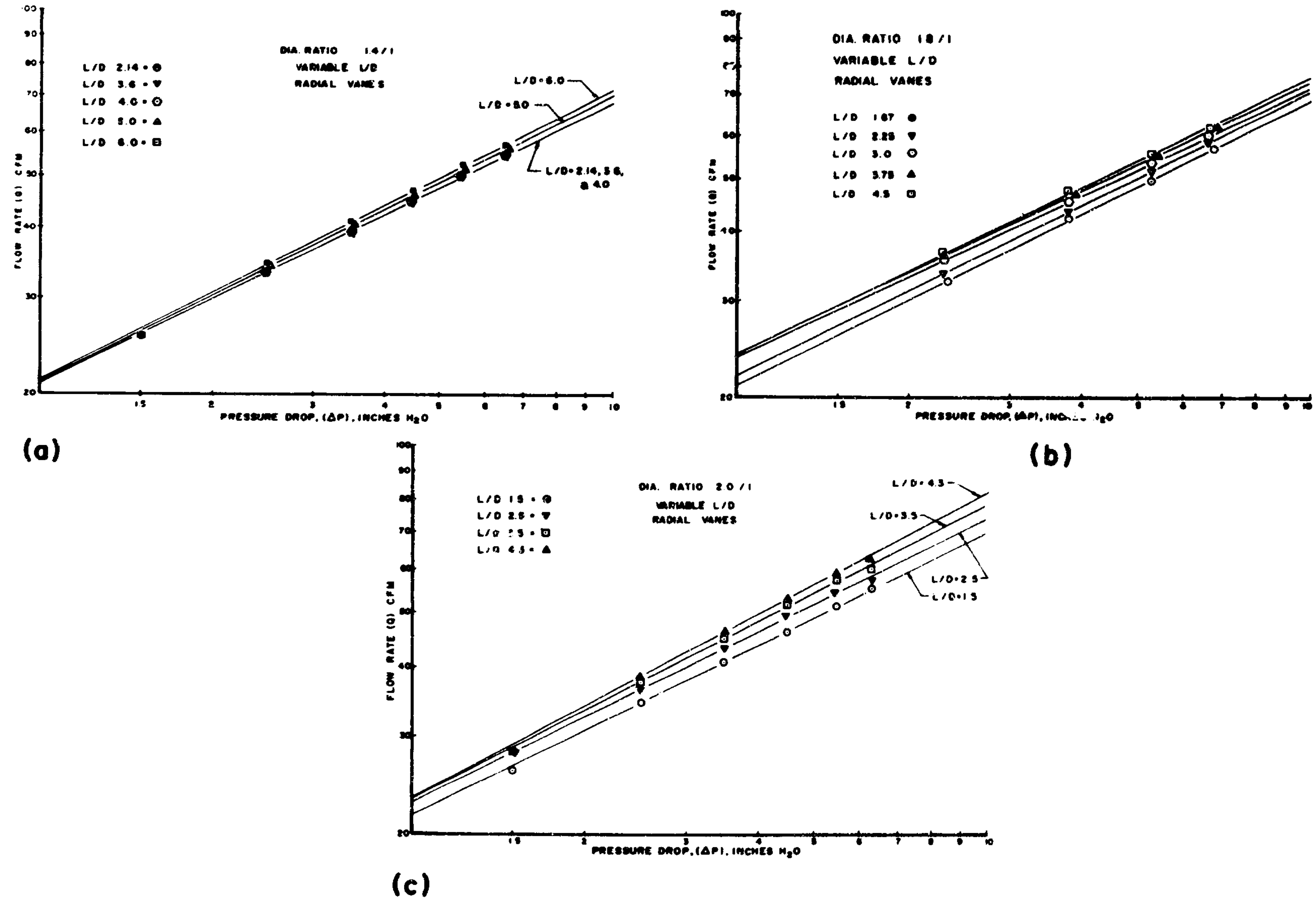


FIGURE 16 FLOW CHARACTERISTICS OF A REVERSED FLOW SEPARATOR WITH VARIABLE L/D AND DIAMETER RATIOS.

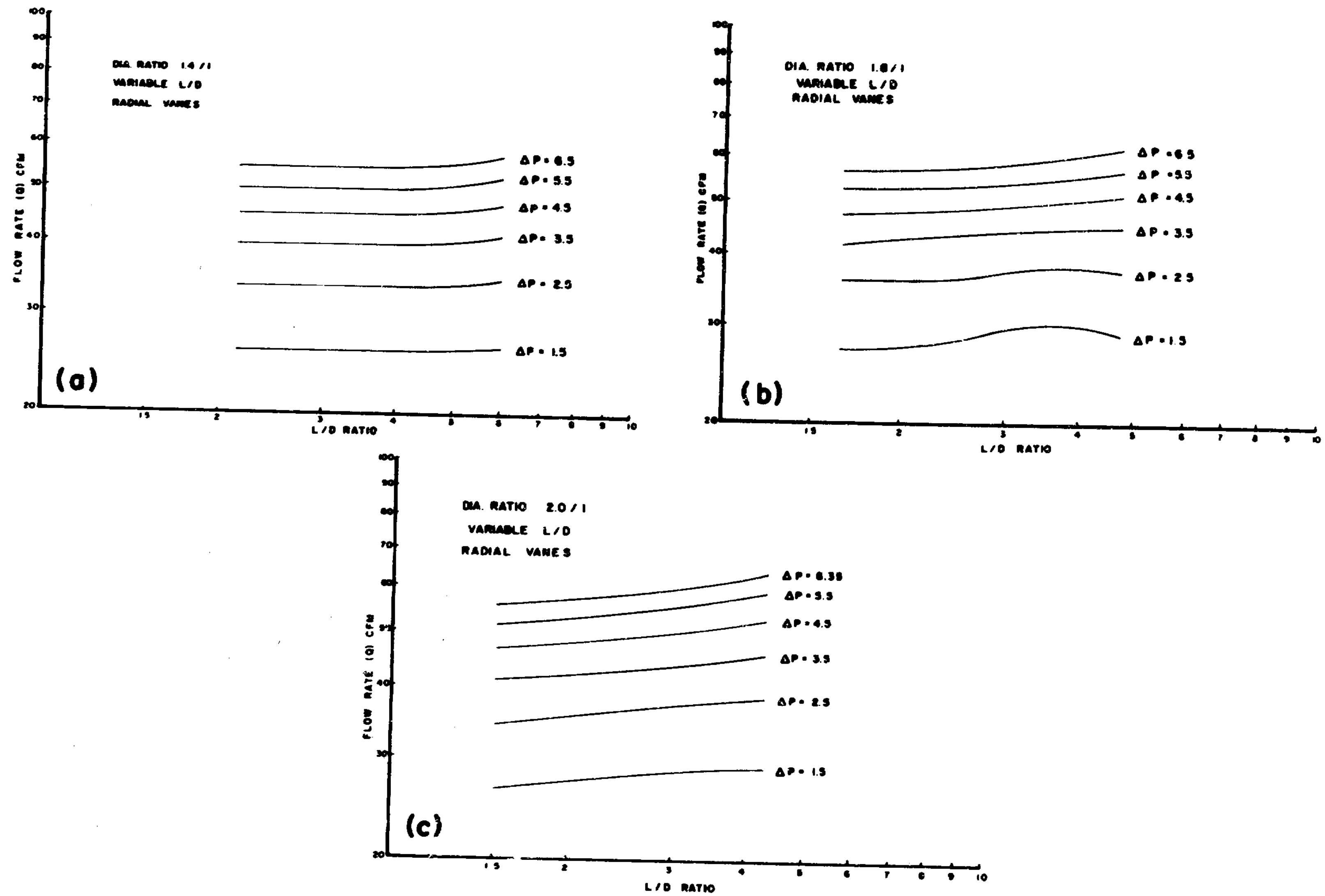


FIGURE 17 FLOW CHARACTERISTICS OF A REVERSED FLOW SEPARATOR AS A FUNCTION OF L/D.

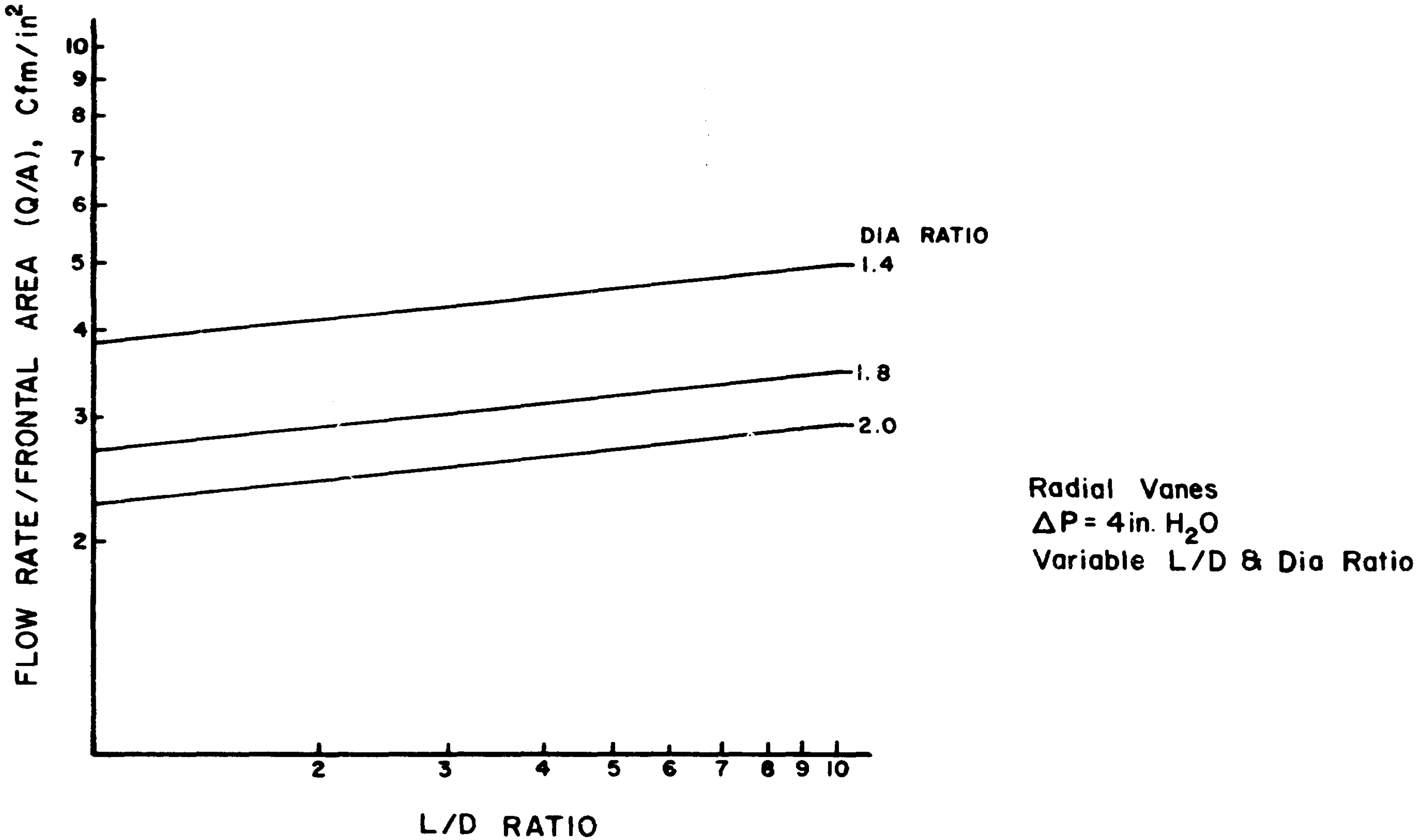


FIGURE 18 GEOMETRIC CONFIGURATION STUDY

TABLE V

SEPARATION EFFICIENCIES OF GEOMETRIC CONFIGURATION STUDY CHAMBERS

SEPARATION EFFICIENCY OF RADIAL VANE CHAMBER
0-200μ Coarse Dust, $\Delta P = 4'' H_2O$

DIAMETER RATIO	L/D RATIO			
	1.67	2.14	3	4
1.4	96.8		95.7	96
1.8		96.1	97.2	96.6
2.0	96.0		97.3	96.8

SEPARATION EFFICIENCY OF AXIAL VANE CHAMBER
0-200μ Coarse Dust, $\Delta P = 4'' H_2O$

DIAMETER RATIO	INLET VANE ANGLE		
	23^o	28^o	33^o
1.60	93.9	95.3	91.6
2.25	94.3	94.1	94.6
2.80	95.2	94.2	95.1

TABLE VI

SIZE DISTRIBUTION OF "WHITE WASHED SAND"*

SIZE RANGE μ	% By Mass
0-53	1
53-62	2
62-210	20
210-590	74
590-850	3

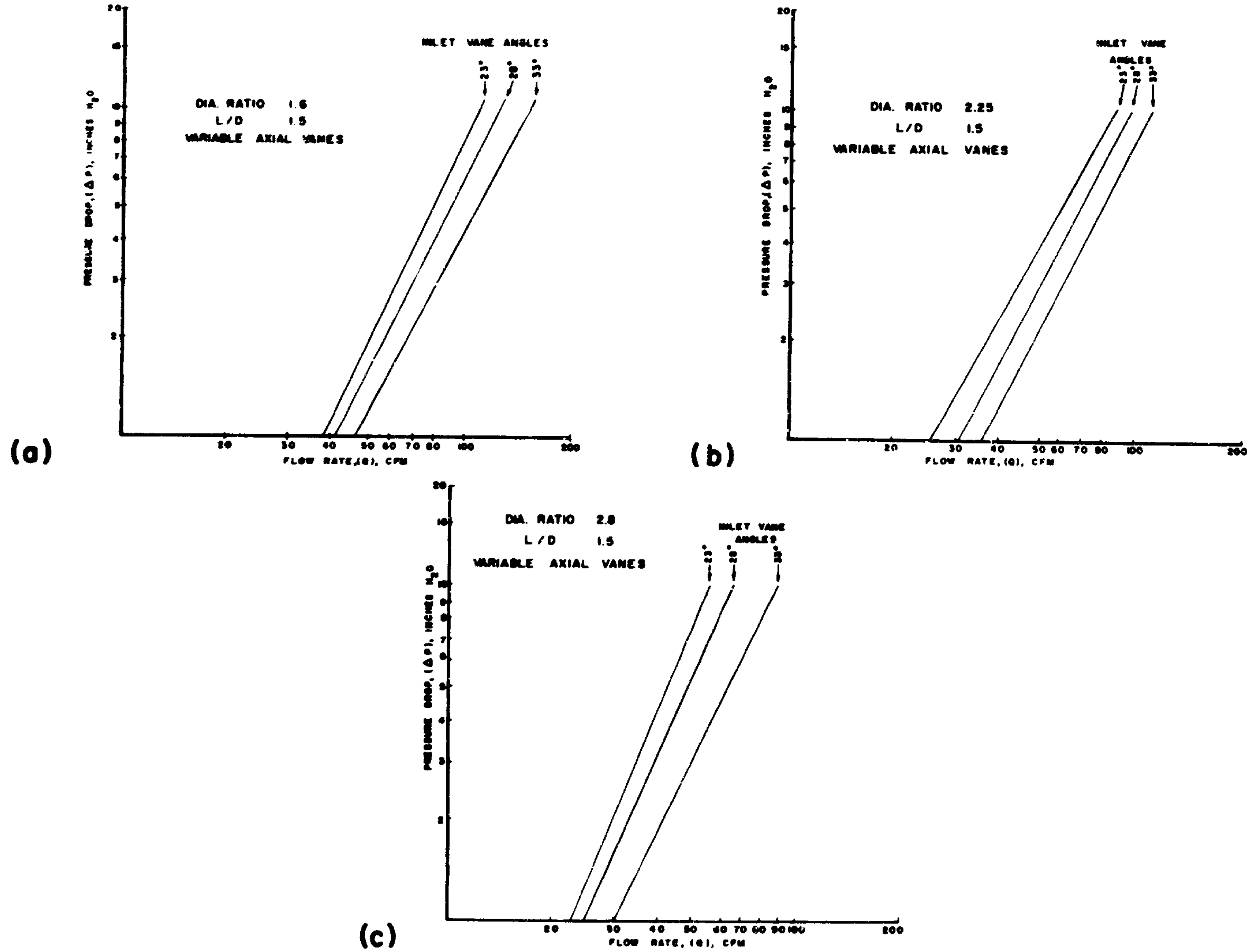


FIGURE 19 FLOW CHARACTERISTICS OF A REVERSED FLOW SEPARATOR WITH VARIABLE VANE ANGLE AND DIAMETER RATIO.

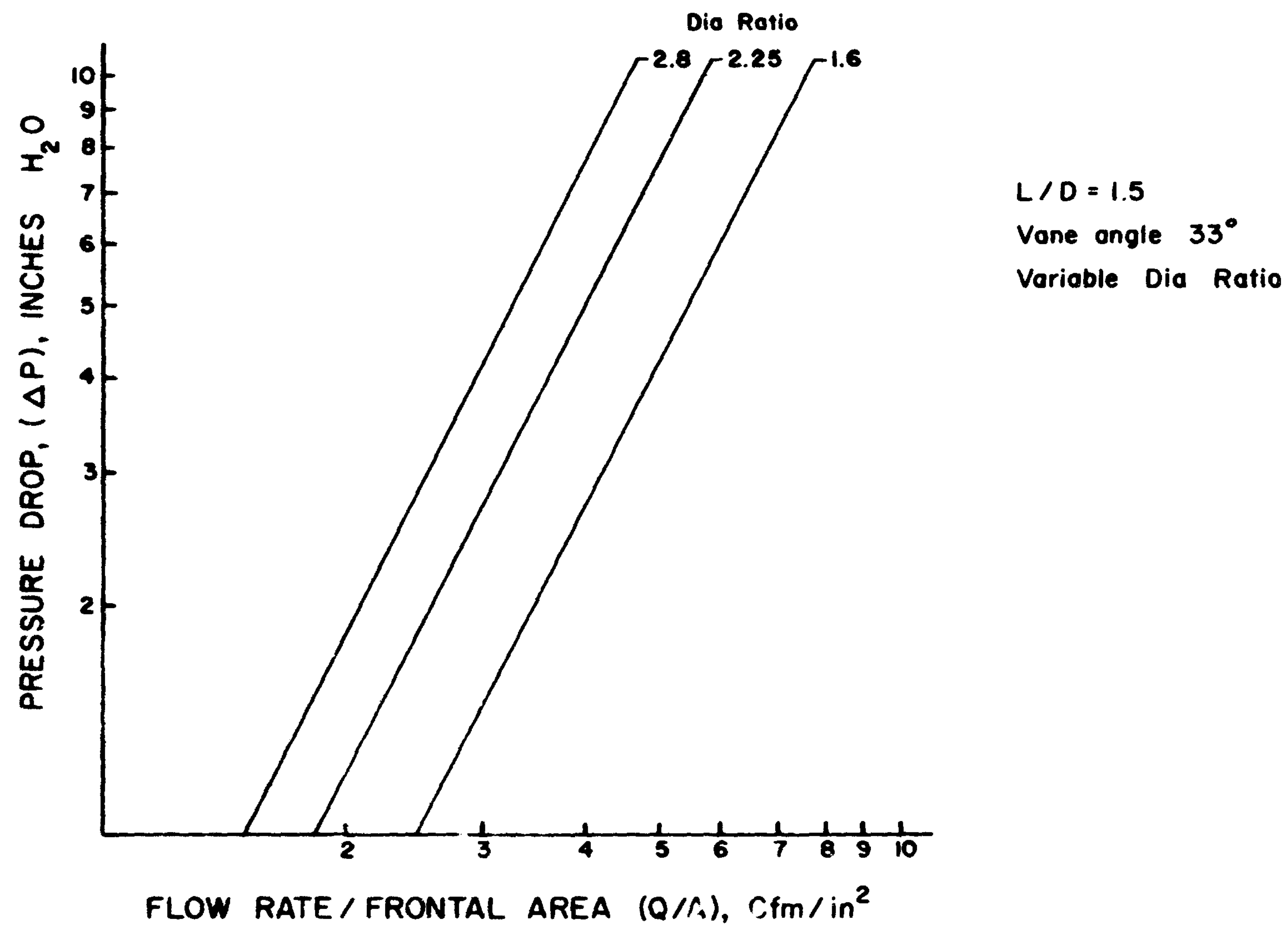


FIGURE 20 GEOMETRIC CONFIGURATION STUDY

increase in flow rate with increasing vane angle is due to an increasing area phenomenon. The flow rate characteristics can be improved if the vaneless diffuser is replaced by a vaned swirl straightener diffuser. The vaned type diffuser has been used extensively on partial reversed flow units and on most of the latter full diffused flow units. The results from both chambers show that within the limits of the variables studied, the Q/A increases with increasing L/D, increasing vane angle and decreasing D_o/D_i. The D_o/D_i effects predominate over the L/D effects, and no maximum appears with respect to vane angle. The separation data indicates an increase in separation efficiency with D_o/D_i, and a very "weak" maximum at an L/D around 3. Separation efficiency also increases slightly with increasing vane angle. The process of selecting an L/D, D_o/D_i, and vane angle is one of trade-offs and optimization. This selection process must be done with a specific application and set of performance requirements in mind. The next section illustrates some of these applications and the design used.

C. SCALING AND CLUSTERING APPLICATIONS

(1) Runway Sweeper: Within the Air Force inventory are street-cleaner type vacuum cleaner units especially designed to clean runways and taxiways. These units are required to prevent Foreign Object Damage (FOD) in the jet engines used on today's aircraft. The runway cleaner units in the inventory use cloth-bag filters to remove dust from the air vacuumed from the runway. These filters created dual problems: (1) they needed cleaning and periodic replacement, and (2) a filter by-pass system was required for wet weather operation. Representatives of the Systems Engineering Group (SEG) of the Research and Technology Division (RT' consulted ARL concerning the feasibility of using an ARL type inertial filter in the runway sweeper. The resulting design has been specified for all future Air Force runway sweepers and will probably be retrofitted on units already in the inventory.

The runway sweeper specifications supplied to ARL required the filter system to have a flow rate of 12,000 cubic feet per minute (cfm) at 10 inches of water pressure drop (ΔP). The dust separator should separate 100% of all particles 50 microns (μ) and larger and fit in a space 96 inches by 30 inches by 120 inches. The dust separator should also be durable, inexpensive, and have a long life cycle. To meet these specifications it was decided to use 6 separators operating in parallel, each with a flow rate of 2,000 cfm at ΔP of 10 inches of water. A separation efficiency of 100% of 20μ and above was chosen to meet exhaust specifications mentioned by SEG representatives. Figures 21 and 22 show the unit as designed and its installation in the runway sweeper. The unit is in the reverted configuration, discussed in Section II, with scroll inlets. The aerodynamic characteristics are given in Figure 23. The unit was tested in the laboratory for separation efficiency and good agreement with the design goals was achieved. The 90% achieved on $0\text{-}200\mu$ AC test dust generally reaffirmed the 100% separation of 20μ particles and above. Seiving the $0\text{-}200\mu$ dust through a 53μ grid yielded a test sample with a distribution of $0\text{-}53\mu$. The separator had a 46% efficiency on this special mixture. The separator was also tested with sand to check on any "bounce" phenomena within the unit. White washed sand, see size distribution Table VI was used and the separation efficiency was found to be 100%.

<u>(2) 16 Unit Cluster:</u> A clustered dust separator containing sixteen 5-inch diameter, reverse flow units was designed and built to test clustering principles. The 5-inch diameter, although not optimum, was selected because: (a) exact single unit data were available from the 5-inch diameter separator used for geometric configuration studies; (b) manufacturing procedures were simplified; and (c) any needed modifications or improvements could be incorporated into the separator with relative ease. Figure 24 shows the completed clustered dust separator and Figure 25 summarizes the laboratory performance obtained from it. The unit uses 1% bleed air

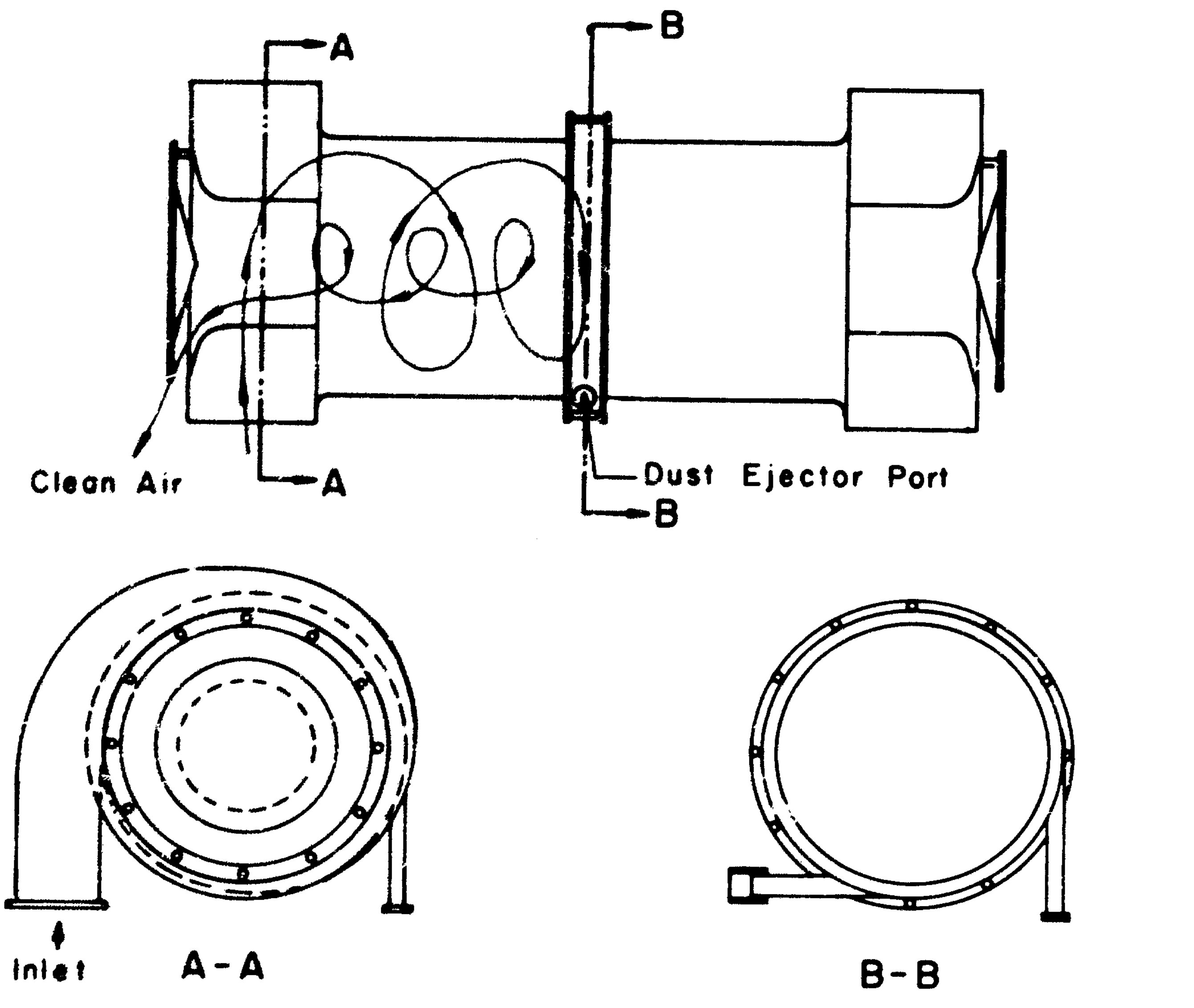


FIG. 2! ARL INERTIAL SEPARATOR FOR RUNWAY SWEEPER

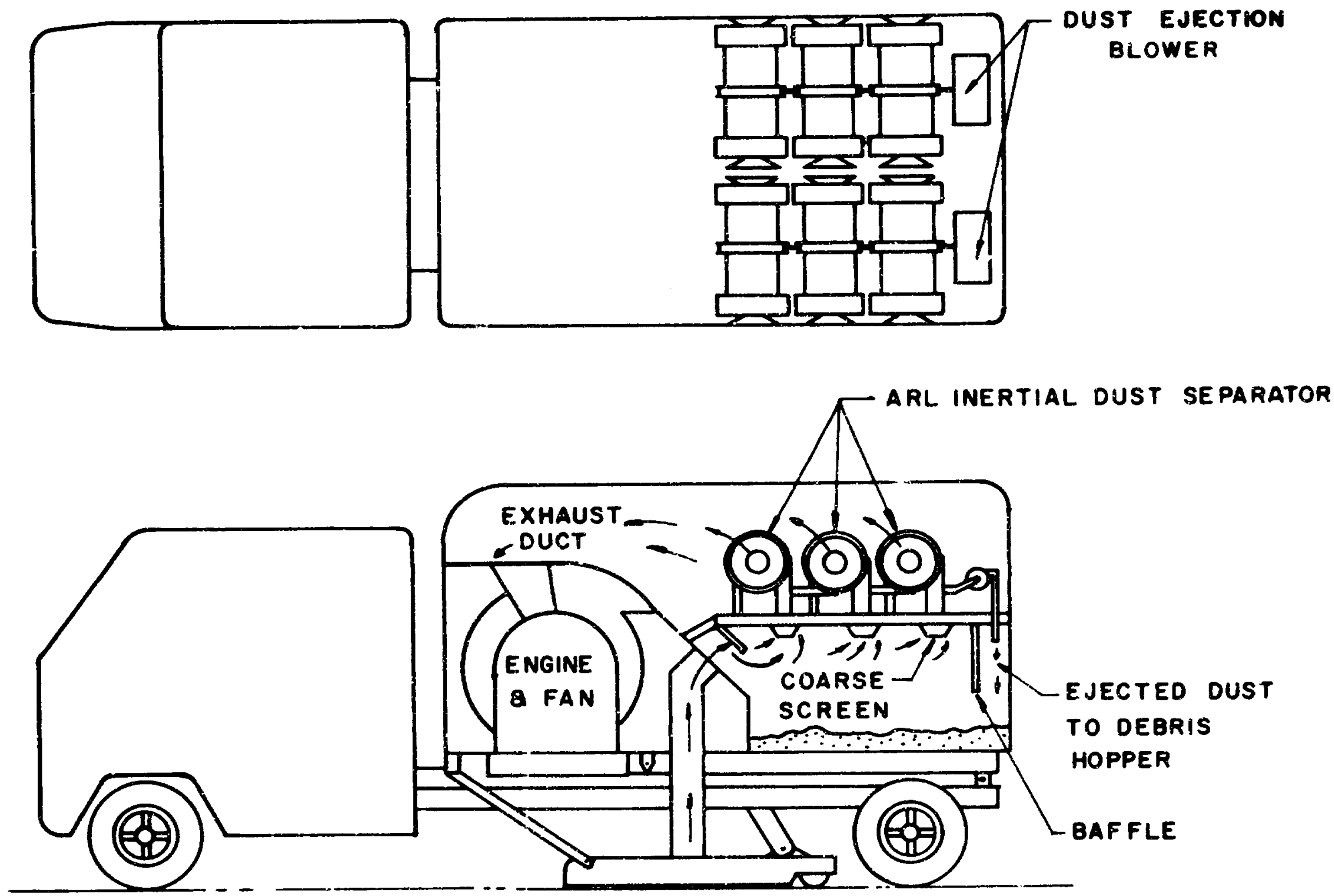


FIG. 22 RUNWAY SWEEPER USING ARL INERTIAL SEPARATORS

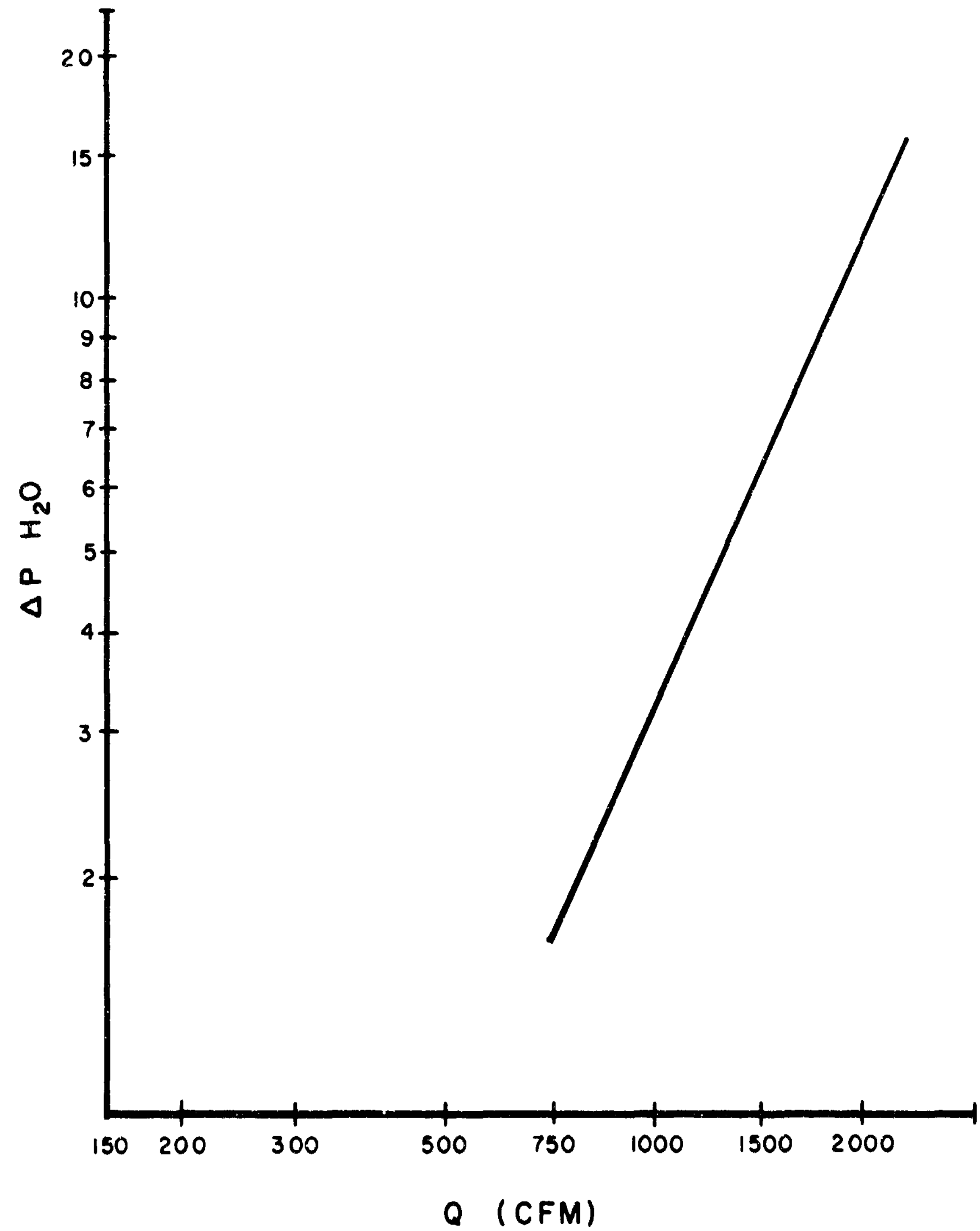


FIGURE 23 FLOW PARAMATERS OF ARL DUST SEPARATOR FOR RUNWAY SWEEPER

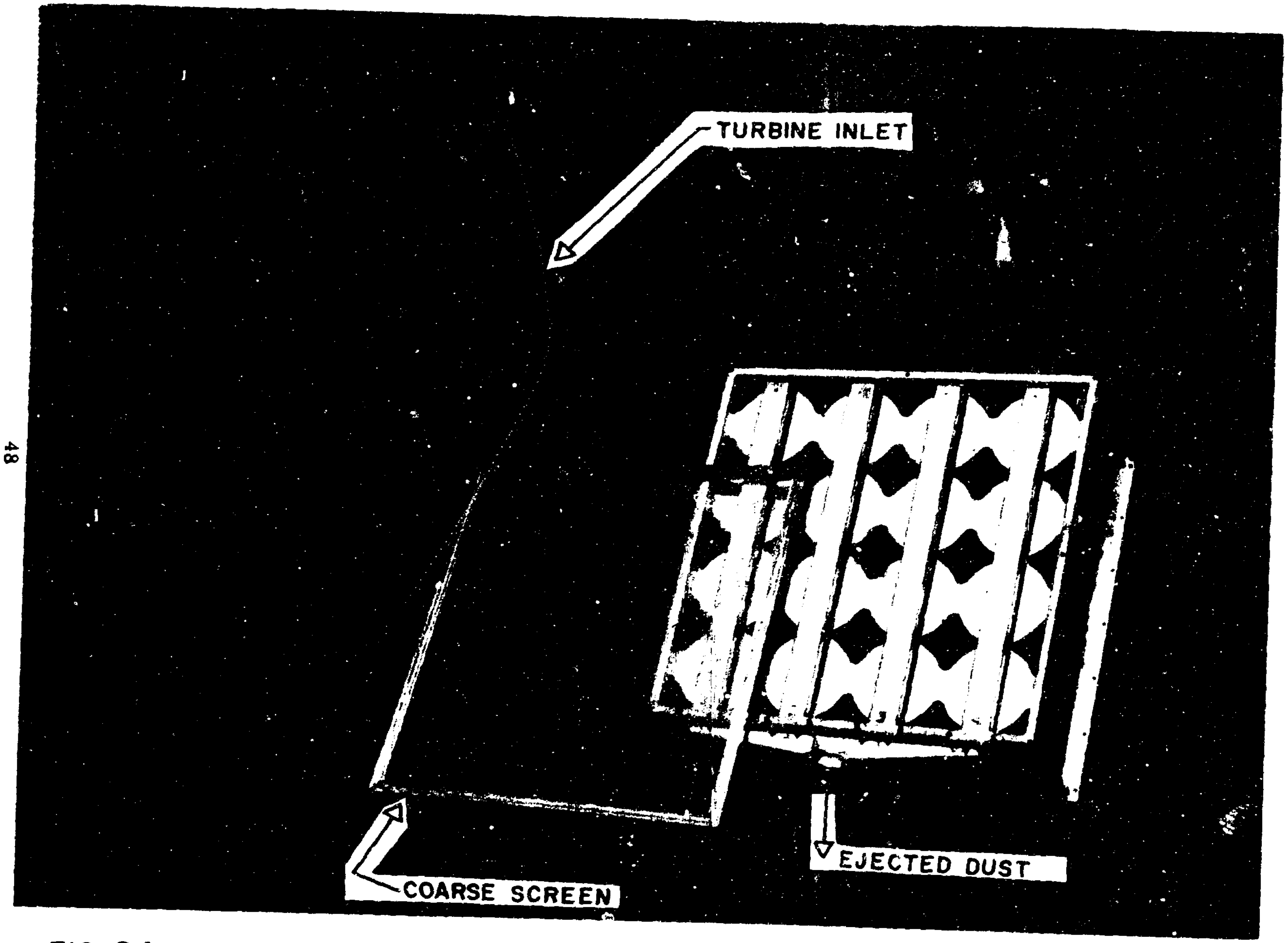


FIG. 24 16 UNIT CLUSTERED SEPARATOR — FULL REVERSE FLOW

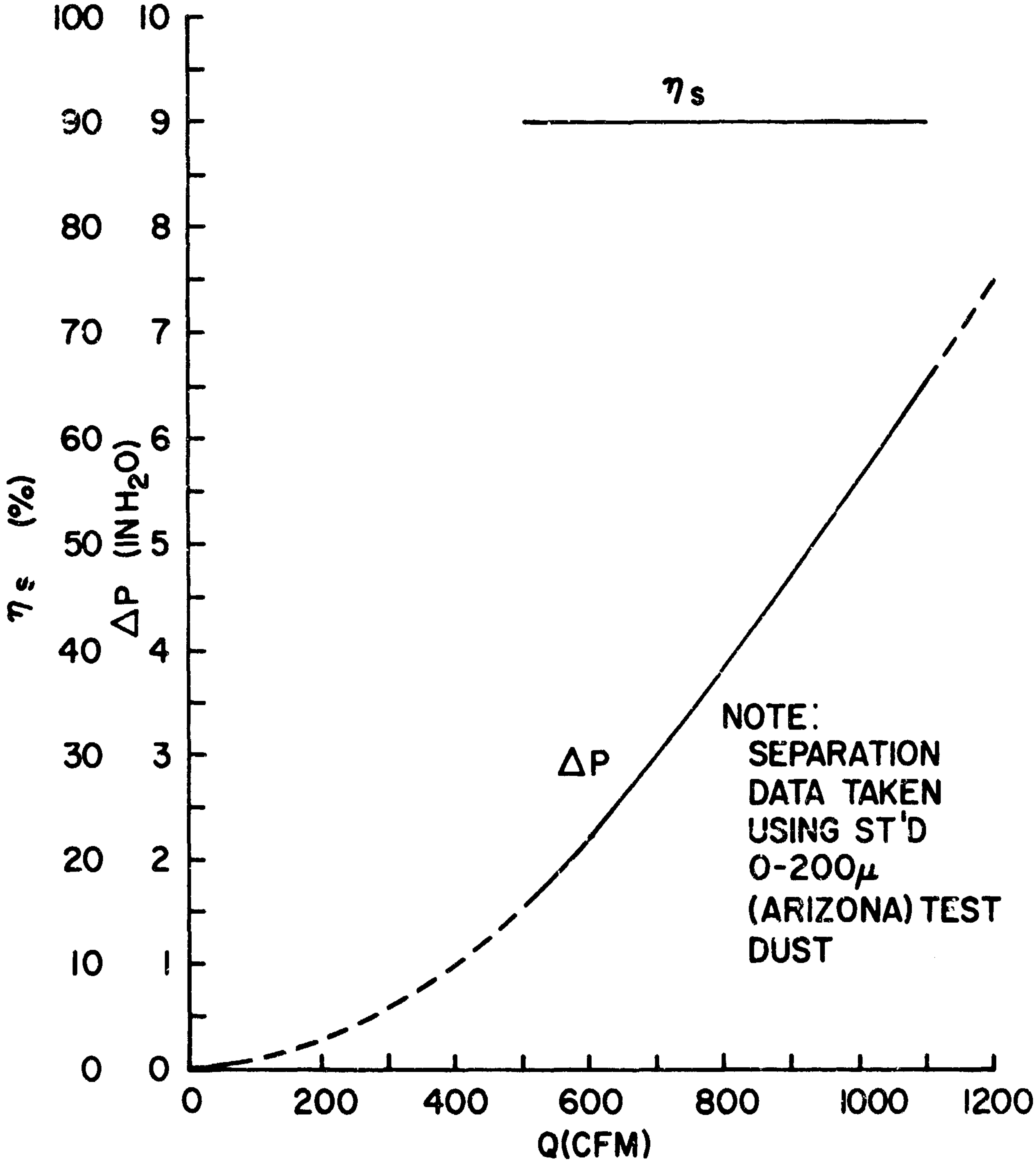


FIGURE 25 PERFORMANCE PARAMETERS ON 16 UNIT CLUSTERED SEPARATOR-FULL REVERSE FLOW

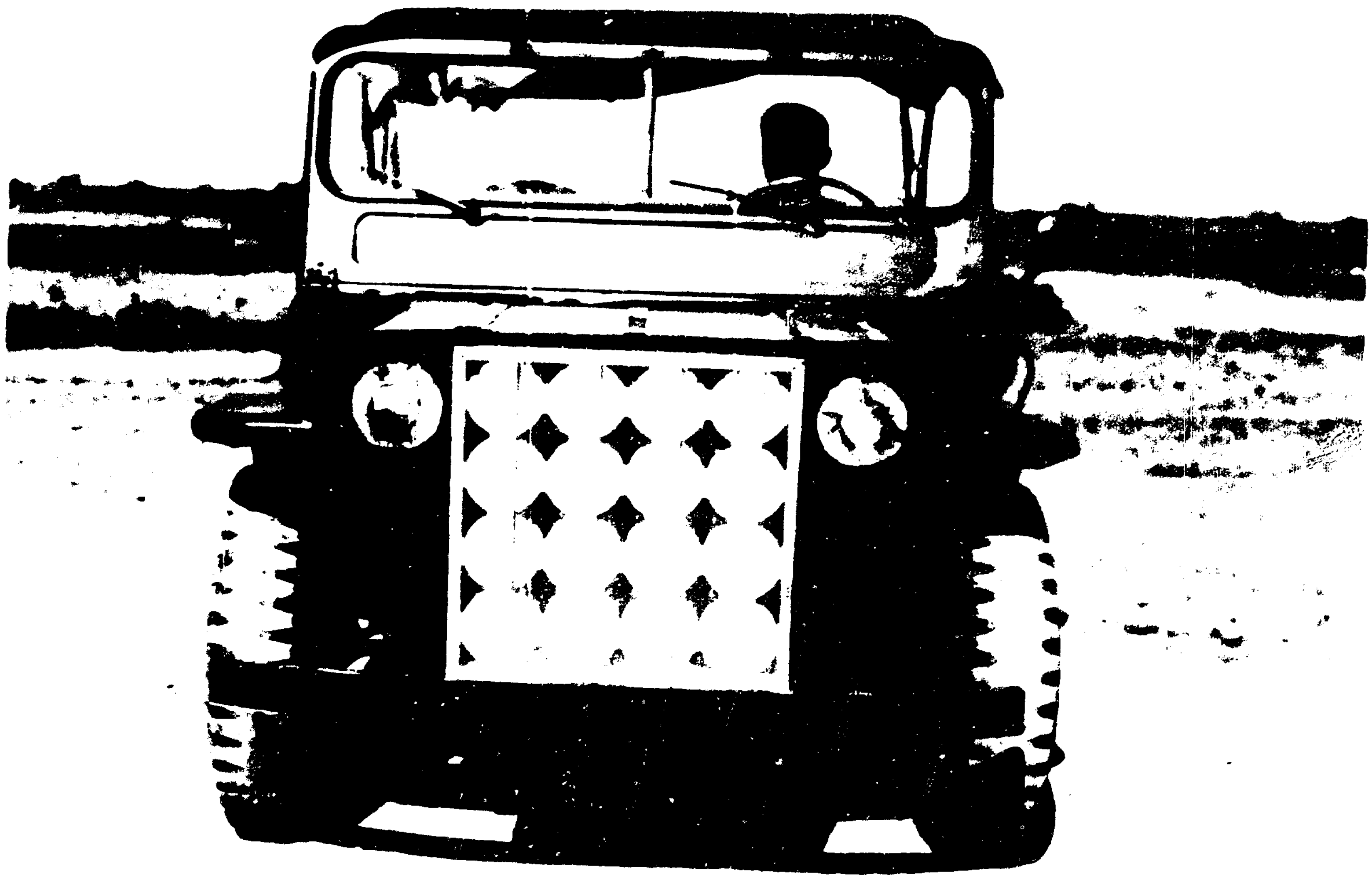


FIG. 26 16 UNIT CLUSTER MOUNTED ON TURBINE POWERED JEEP to scavenge the removed dirt and dust. Overall cluster measurements are 21-3/8" x 21-3/8" x 11".

After laboratory testing the 16 unit separator was mounted on an experimental gas turbine powered jeep[28]. The 70 hp turbine was built by the Williams Research Corporation for ATAC After the installation, the vehicle was field tested on the U.S. Army Yuma Proving Ground's dust course (see Figure 27). The vehicle was tested on the dust course according to Yuma Proving Grounds standard operating procedures. Because of the special nature of the separator, however, a lead vehicle was used throughout the testing to stir up a denser cloud. The jeep was instrumented for separator pressure drop, engine-exhaust gas temperature, and engine rpm. The separator efficiency was obtained by collecting the dust ejected from the separator and that which passed through the separator. The dust-collection system was designed and operated in such a manner that the separator operated under identical conditions with or without the dust collection system.

The vehicle was run in dust and gravel for slightly more than 150 miles and in dust cloud concentrations varying up to that shown in Figure 27. The average separation efficiency from the Yuma field test was slightly greater than 93%, and was generally independent of the dust cloud concentration in which the vehicle was operating. The 93% field separation efficiency compares well to the 90% obtained in the laboratory. This excellent agreement between laboratory and field results highlights the fact that the laboratory testing techniques were valid and representative of actual field conditions.

The 16 unit cluster performed as designed with approximately 100% separation of 5μ and larger particles. This separation capability was indicated by the 90% efficiency on 0-200μ A.C. test dust. The scaling laws show that scaling the size of each unit in the cluster down shall increase separation efficiency. Therefore, a new cluster was designed and built

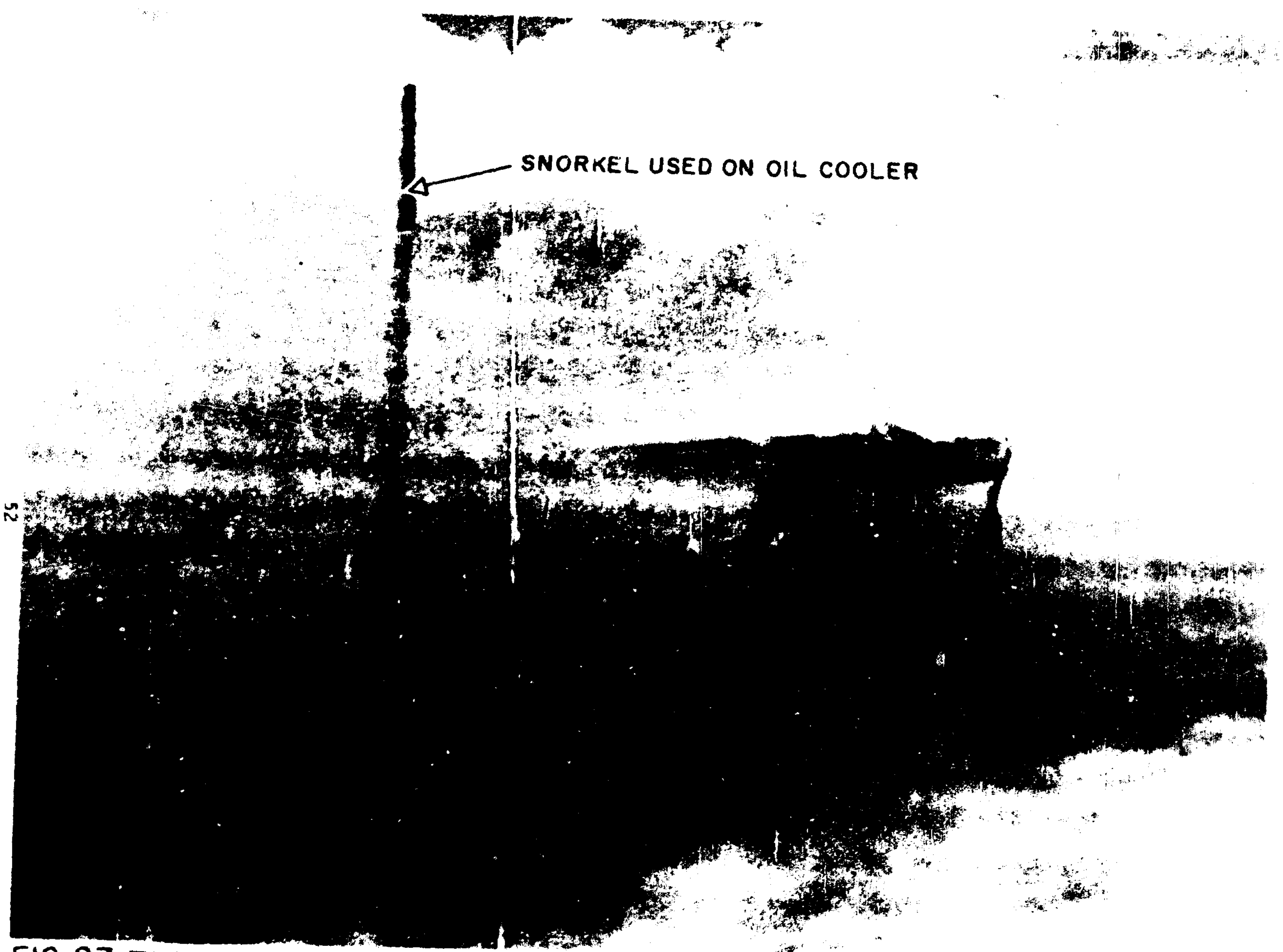


FIG. 27 TURBINE JEEP WITH 16 UNIT SEPARATOR OPERATING IN DUST

with 2-1/2" diameter separators (S = 1/2). The cluster contained 64 units as shown in Figure 28 but exactly the same frontal area as the 16 unit cluster. The ΔP verses Q (or Q/A) for each cluster was nearly identical, but the Q/V was essentially doubled. As predicted by the scaling laws, the separation efficiency increased substantially from 90% to 97% for 0-200μ A.C. test dust.

A decrease in predicted flow rate was encountered on this 64 unit cluster. This 20% decrease in flow rate was caused by reducing the number of inlet vanes from 15 (on the 16 unit cluster) to 10. The reduction was initiated by design considerations only. Because the vanes were cast in aluminum in a straight not helical configuration, a decrease in the number of vanes necessitates an increase in vane overlap angle. On straight vanes, an increase in overlap angle decreases area and therefore, decreases flow.

(3) 46 Unit Cluster: A cluster of 46 semi-reverse flow separators was built and tested at ARL. The unit, (see Figure 9), was built as a test of not only clustering principles, but to study the problems unsolved in the dust ejection plenum. Each separator in the cluster is 1-7/8" in diameter x 4-3/4" overall. The overall cluster measurements are 13-11/16" x 12-3/16" x 4-3/4". The inlet vanes are set at 28° while the energy recovering exduction vanes have a 35° leading edge angle. The unit uses 2-1/2% bleed air to scavenge the removed dirt and dust. Figures 29 and 30 show the aerodynamic and separation efficiency characteristics of the chamber. The slightly lower separation efficiency achieved at low through flow rates with 2-1/2% bleed normally would not appear in most system installations. This is because a "constant" flow rate scavenging device is normally used in a system and is designed to give 2-1/2% bleed at the high through flows. At the lower through flows the bleed air is more like 3-5% and the effects of the decrease in separation efficiency are minimized. Increasing the bleed air to 5% does not substantially increase separation at the higher flow rates however.

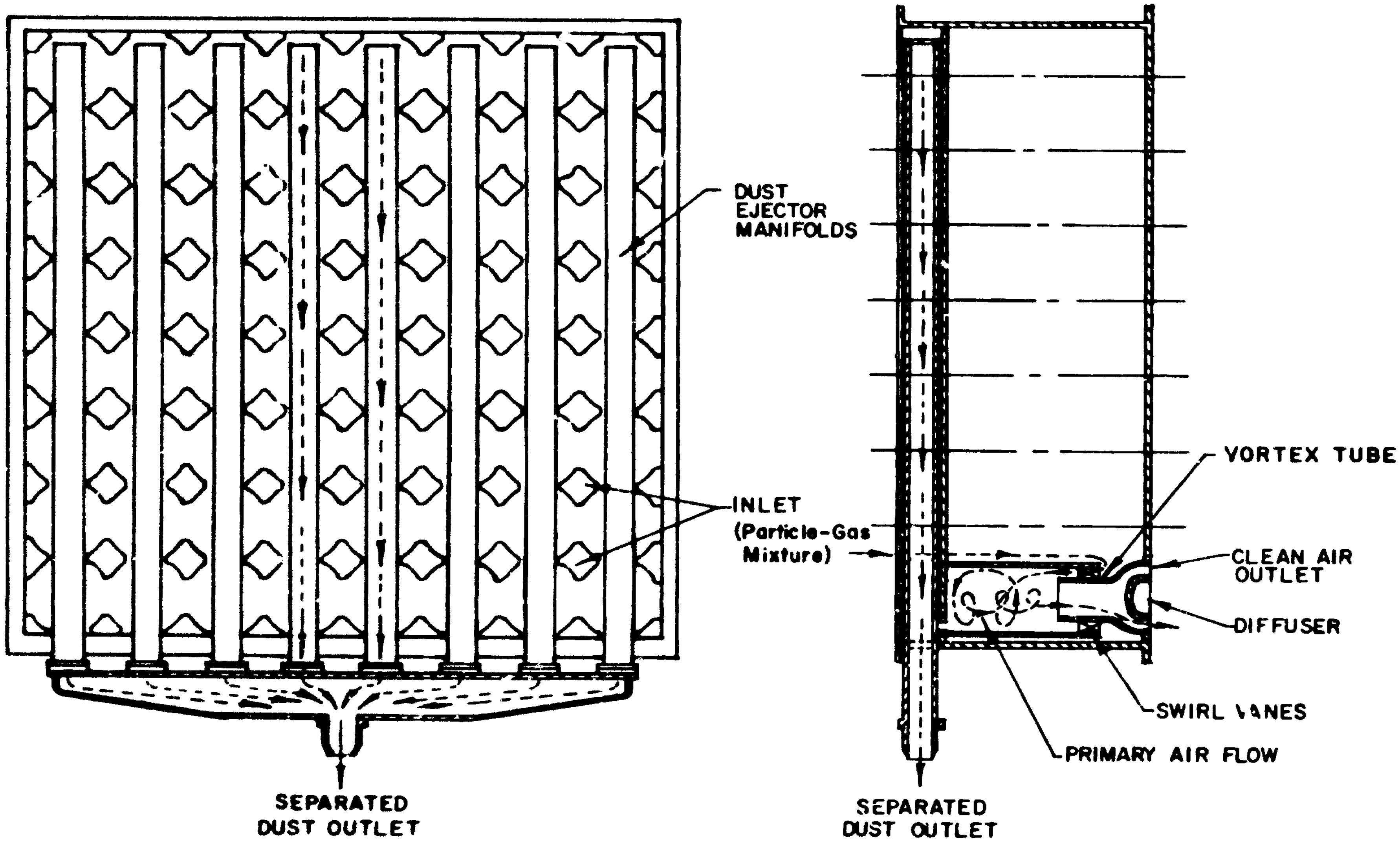


FIG. 28 SCHEMATIC OF A SIXTY-FOUR UNIT CLUSTER SEPARATOR SHOWING THE GENERAL FLOW PATHS.

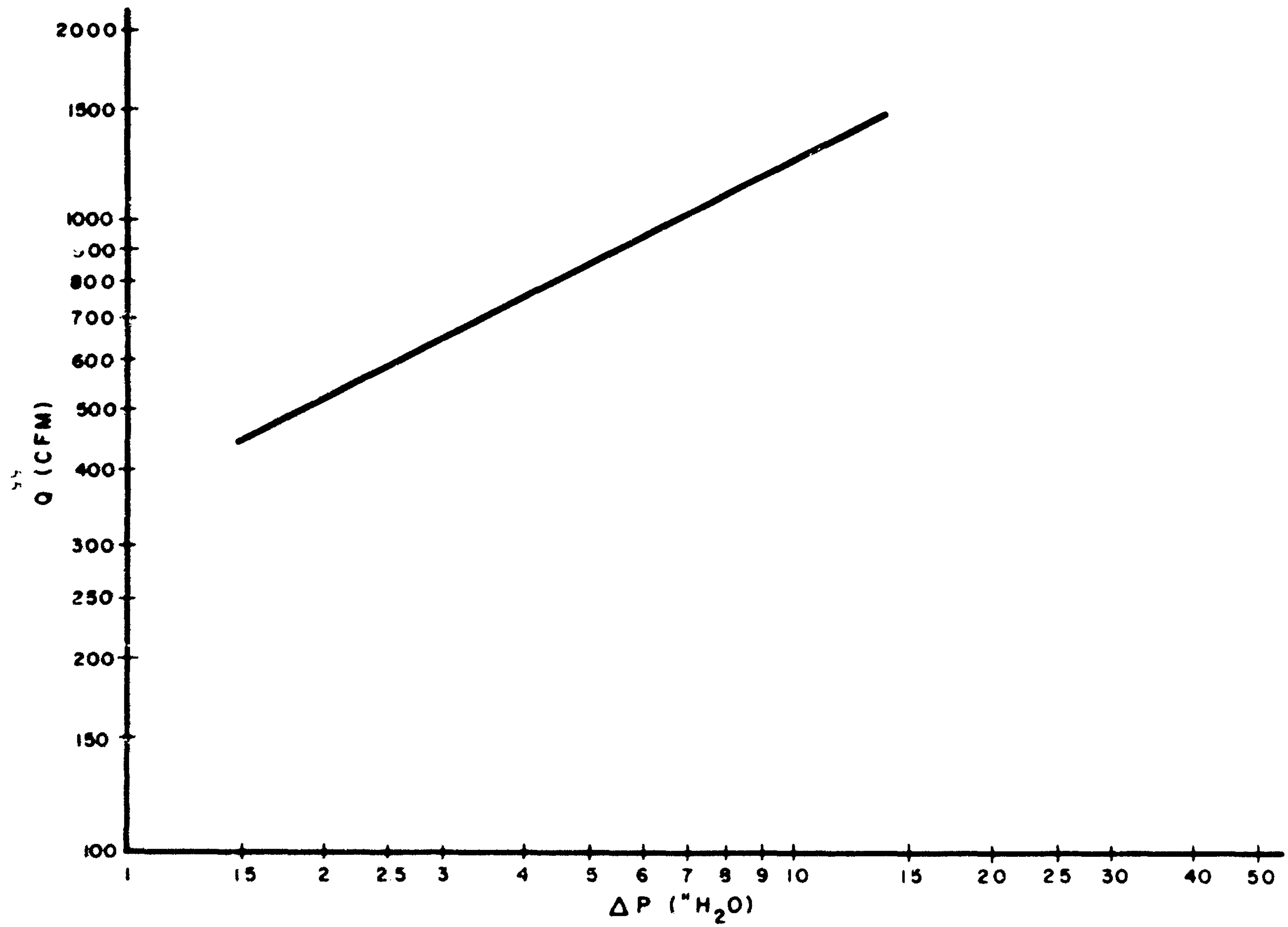


FIGURE 29 FLOW PARAMETERS OF 46 UNIT CLUSTERED SEPARATOR-PARTIALLY REVERSED FLOW

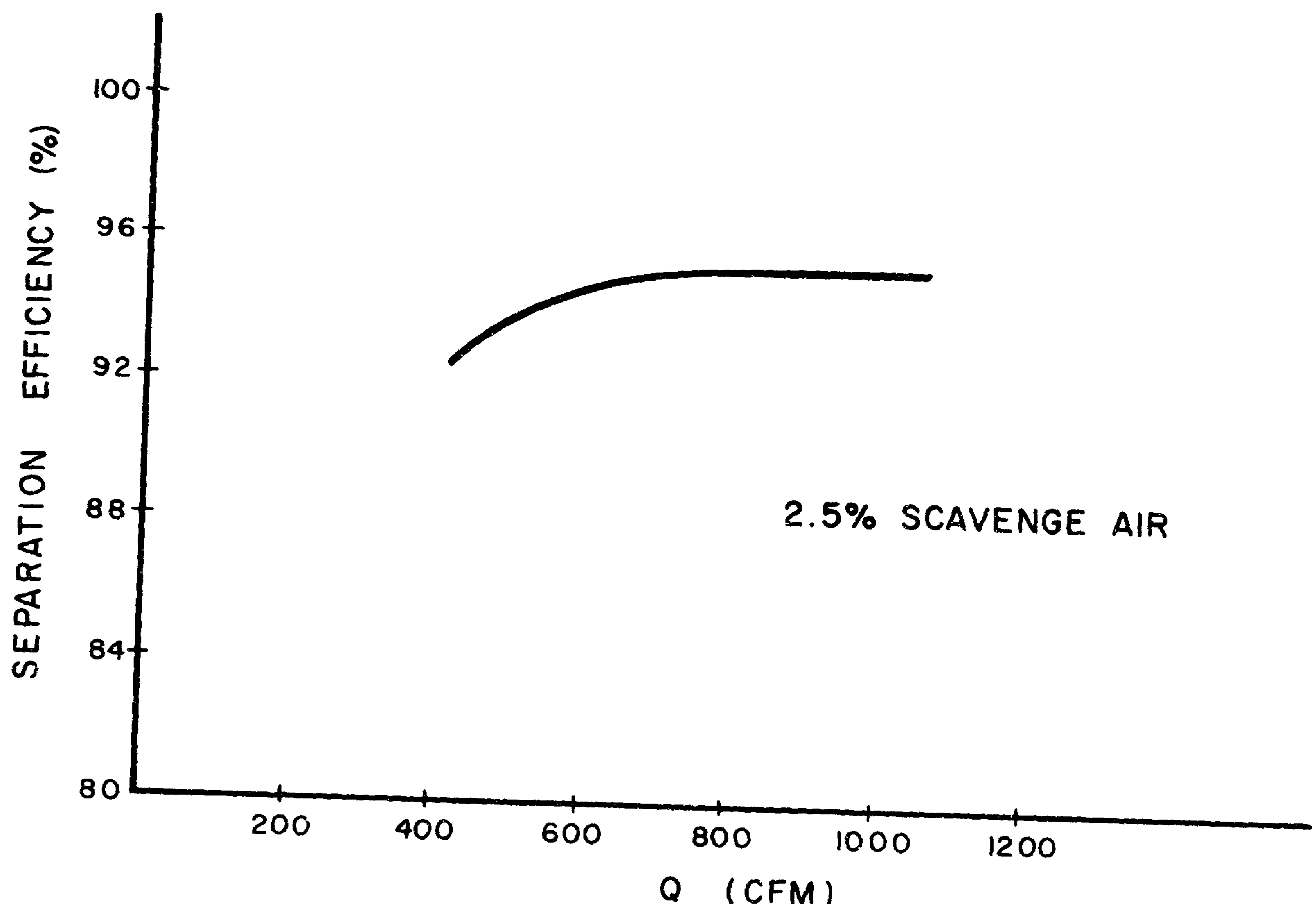


FIGURE 30 SEPARATION PARAMETERS ON 46 UNIT CLUSTERED SEPARATOR — PARTIALLY REVERSED FLOW

This partial-reversed-flow clustered separator has also been tested for separation in salt water spray. The testing was conducted by Naval personnel at the Ship Engineering Center (NAVSEC), Philadelphia Naval Shipyards. Figures 31 and 32 show the NAVSEC test facilities.

Separation efficiency measurements are taken by the use of impactors as shown in Figure 33. One impactor is placed in the duct before the separator, another in the duct behind the separator. Separation efficiency is then determined by comparing concentrations of sea-spray before and after the separator.

The ARL separator worked extremely well as a sea-spray separator. Figures 34, 35 and 36 show separation efficiency of the ARL separator compared to several commercial separator units (26). The Donaldson unit is a through flow type similar to those shown in Figure 6, and the York Demister is a barrier filter composed of stainless steel mesh. The excellent sea-spray separation results of the barrier type are offset by extremely poor performance in dust or sand (27).

The "two-way" performance (sand-dust and sea-spray) of ARL's separator leads to several interesting applications. Turbine-powered landing craft under study by the Navy, for instance, will require engine protection (28). Large naval vessels, such as turbine powered destroyers, may find sufficient protection from sea-spray by ducting, etc., but small hover craft class vehicles, or surf vehicles have separator requirements. Efforts are continuing between ARL and the Office of Naval Research(ONR) to exploit these and other possible applications of ARL's separator technology to naval separator requirements.

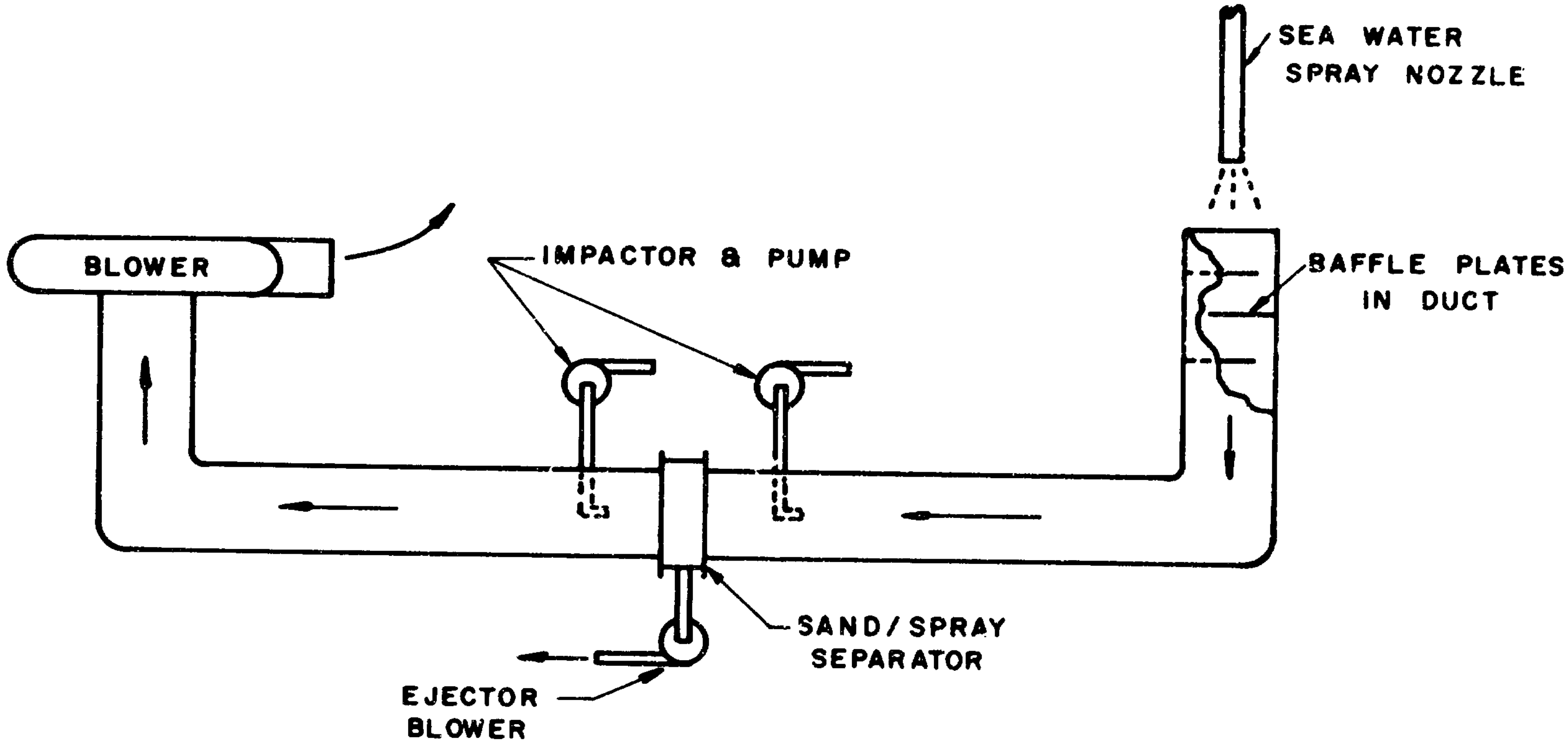


FIG. 31 FACILITIES SCHEMATIC, SEA SPRAY APPARATUS
NAVAL SHIP ENGINEERING CENTER

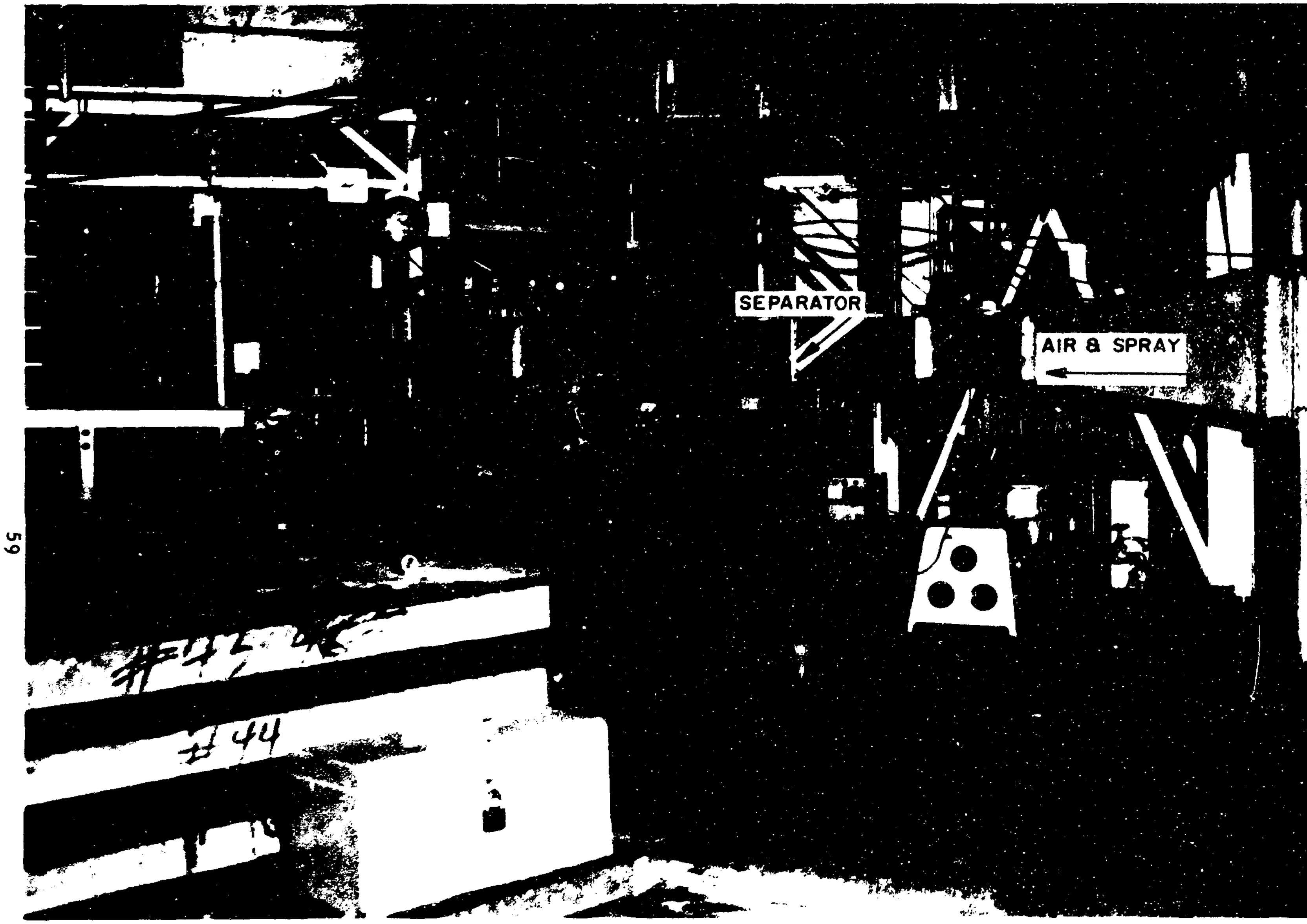


FIG. 32 SALT SPRAY TEST FACILITIES AT SHIP ENGINEERING CENTER, PHILADELPHIA, PA.

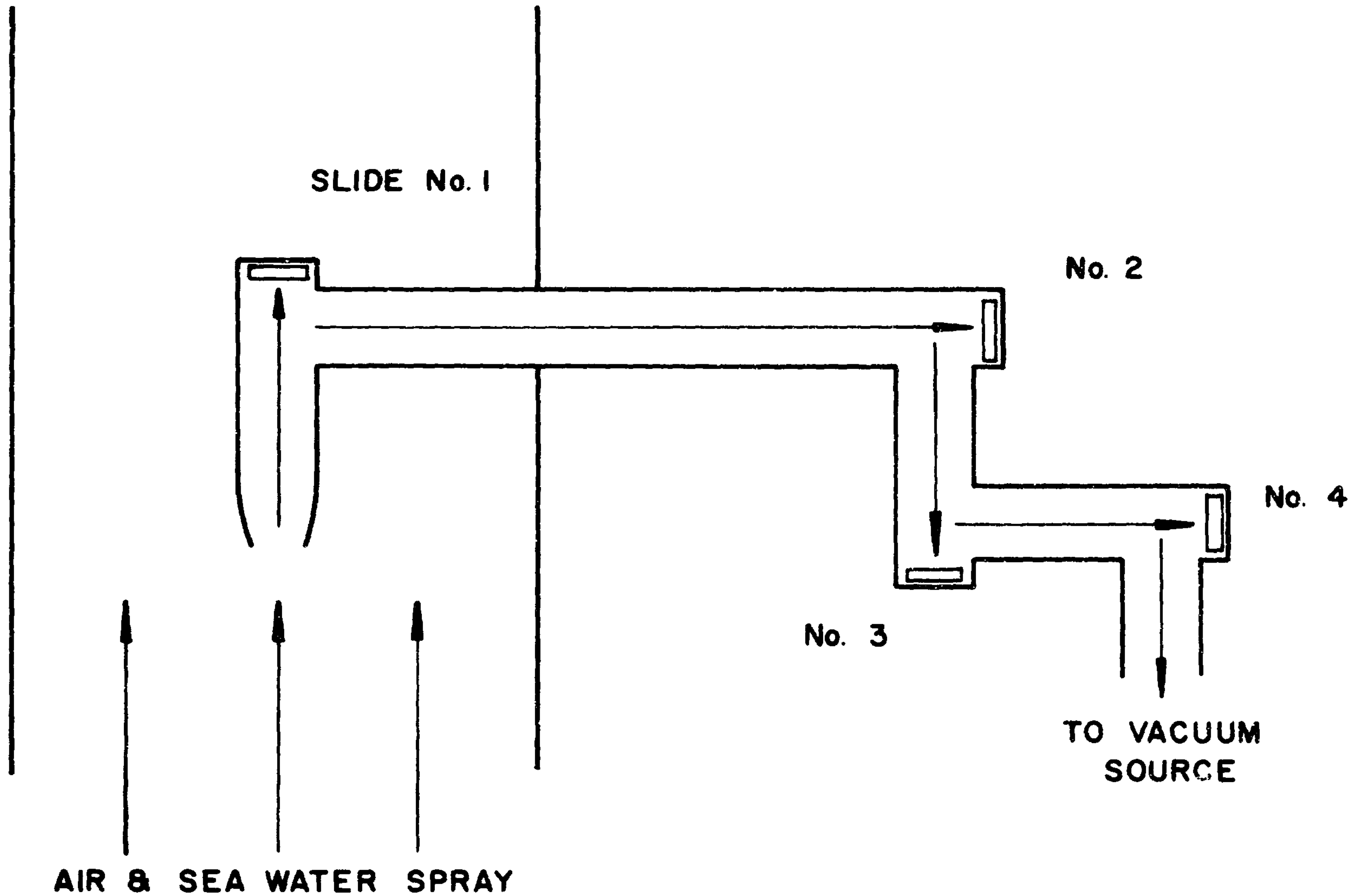


FIG. 33 NAVSEC IMPACTOR TUBE SCHEMATIC

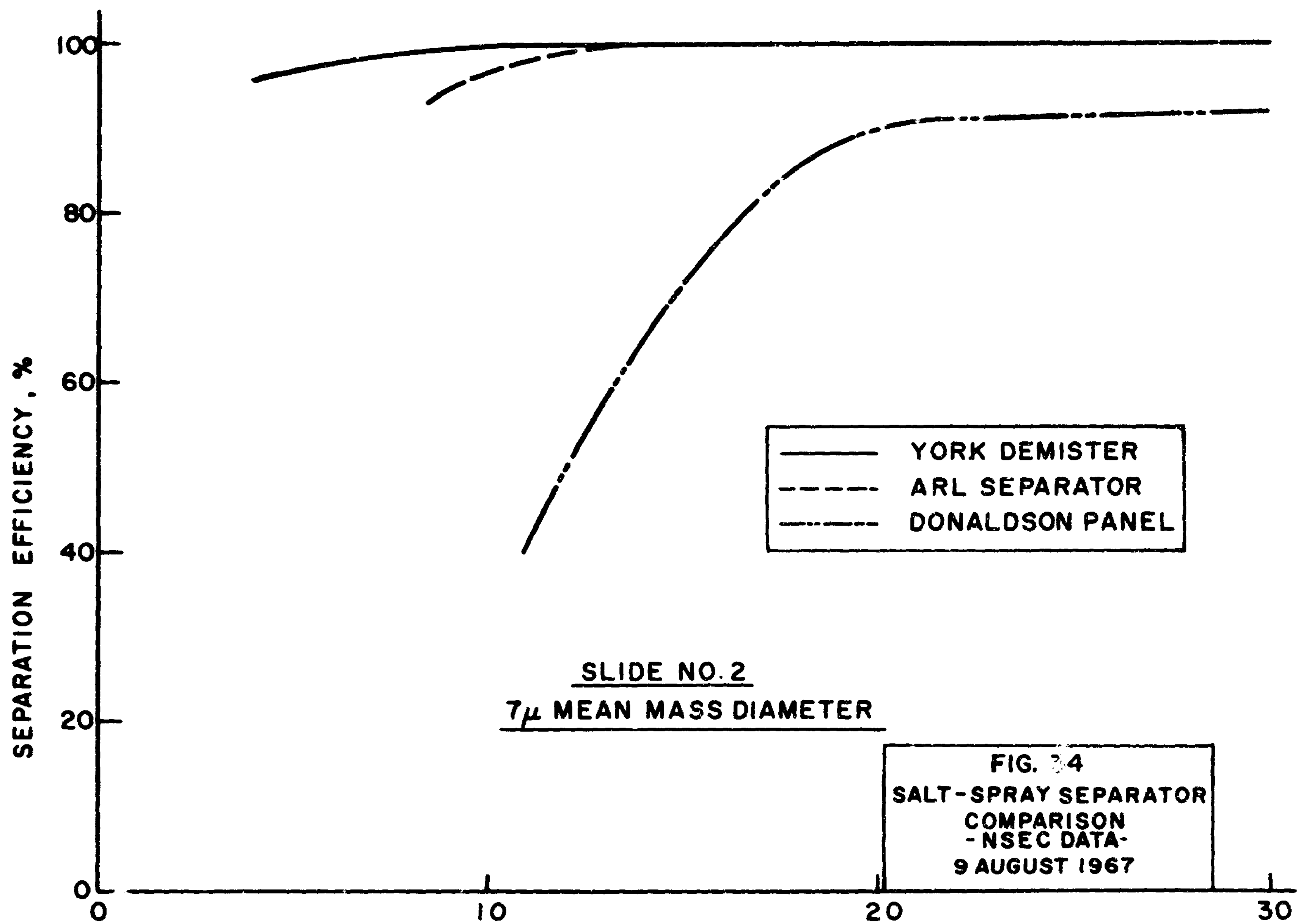


FIG. 34 FILTER APPROACH VELOCITY, FT/SEC.

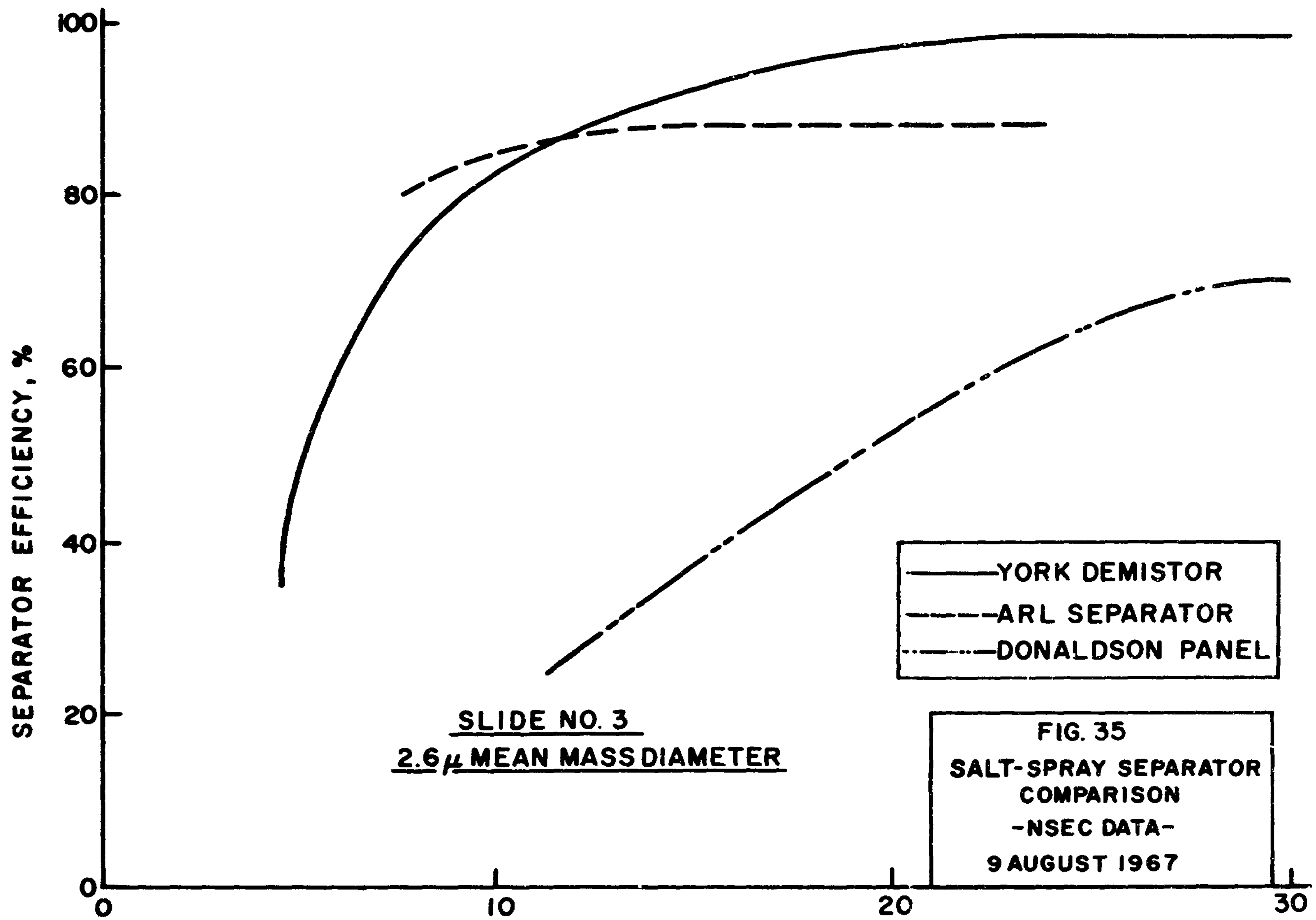


FIG. 35 FILTER APPROACH VELOCITY, FT/SEC.

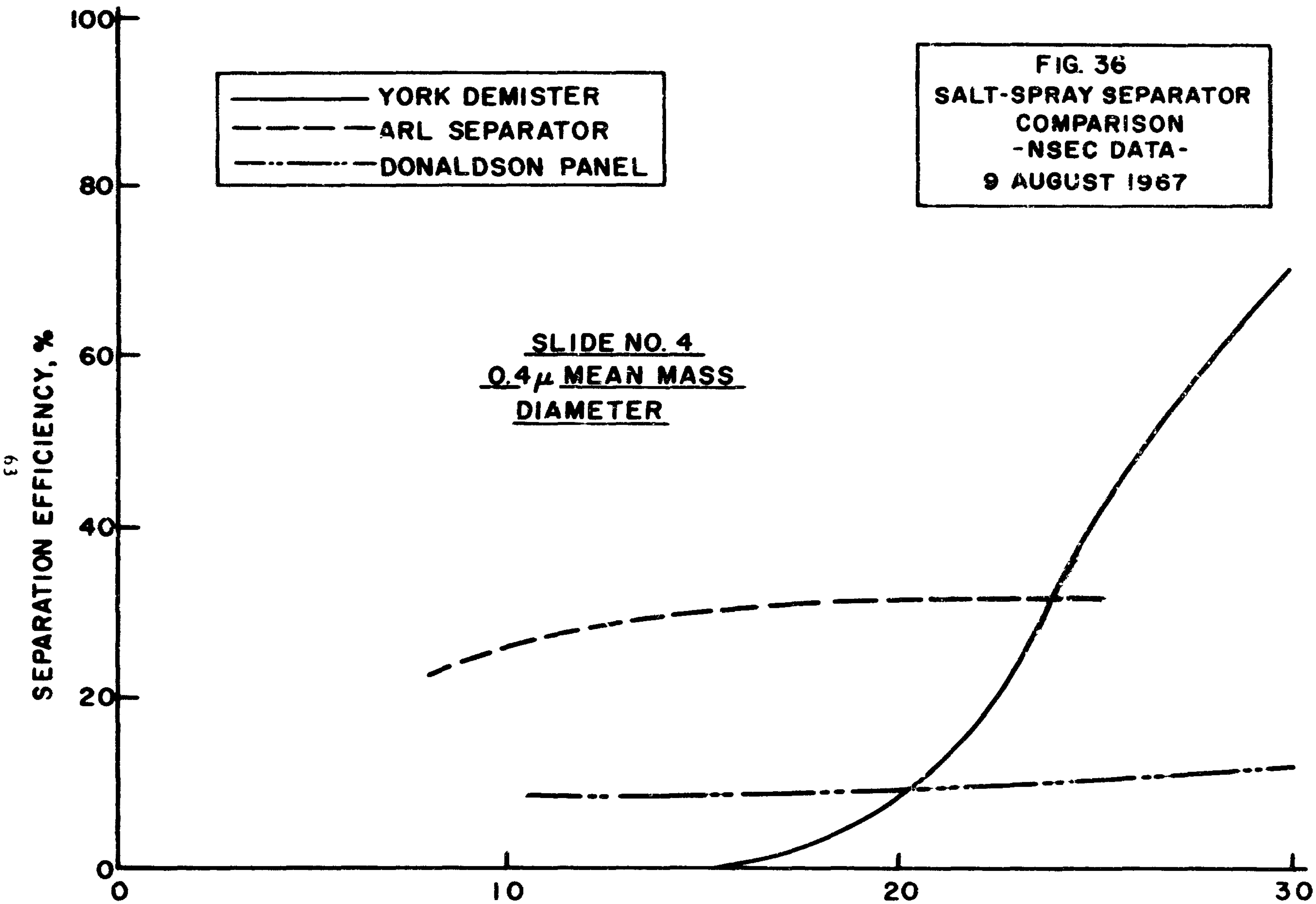


FIG. 36 FILTER APPROACH VELOCITY, FT/SEC.

IV. CONCLUDING COMMENTS

Although the results obtained from the research efforts at the Aerospace Research Laboratories (ARL) on inertial separators are manyfold, the program is not yet complete. Separation efficiencies in excess of 98% (on 0-200μ AC dust), low (or no) dust removal energies, and fairly high through flow/frontal areas have been demonstrated. ARL units have been laboratory tested by the Army at ATAC, and the Navy at NAVSEC in dust and sea-spray; and field tested on a turbine vehicle. Configuration studies, however, will be continued on ARL dust separators while the program undergoes evaluation and application to specific turbine powered vehicles.

A segment of the ARL in house program is now devoted to studying the feasibility of using inertial separators to remove sub micron size particles from gases. These separators are small and operate at a higher pressure loss than those used for turbine protection. In current experiments, tobacco smoke (.01-1μ size range) is used as the contaminate and early results indicate approximately 50% separation efficiency. The objective of this work is to improve performance of the smoke separators for future application to air pollution control.

REFERENCES

1. "Erosion and the T-58 Engine Program Status - December 1964", General Electric Report.

2. Private Communication, Mr. Richard Childs, Army Tank Automotive Center (ATAC), Warren, Michigan

3. Poplawski, Robert, "Potential Scope of Application of the ARL Separator for Turbine Powered Vehicles". Proceedings of the Counter-insurgency Research and Development Symposium, 14-16 June 1966, Advanced Research Projects Agency, Washington, D.C., pp519-539

4. Journal of the Armed Forces, 6 August 1966

5. "Dust Concentration Measurements on the U.S. Army Overland Train Mark II", by Donaldson Co. Inc., for U.S. Army Transportation Research Command, Fort Eustis, Virginia. Task 1D54 3006 D40402, Contract DA 49-177-AMC-24 (T). TRECOM Tech. Report Nr. 125.1.3, March 1965

6. "The Sources of Air Pollution and Their Control", U.S. Department of Health Education and Welfare - Public Health Service Division of Air Pollution. Public Health Service Publication Nr. 1548; 1966

7. "Menace in the Skies", TIME, January 27, 1967, Vol 89, Nr. 4 pp 48-52

8. Green, H.L., Lane, W.R., "Particulate Clouds: Dusts, Smokes and Mists", D. Van Nostrand Co. Inc., Princeton, New Jersey 1957

9. Lapple, C.E., "Dust and Mist Collection", Chem Eng Handbook, Edited by Perry, J.H., 3rd Edition, McGraw-Hill Book Co.

10. Cyclones in Industry, Edited by Rietema, K., and Verver, C.G., Elsevier Publishing Company, Amsterdam, 1961

11. "Cyclone Dust Collectors", American Petroleum Institute, Feb 1955

12. Lapple, C.E., Stanford Research Institute. Chart showing Characteristics of Particles and Particle Dispersions, 1959

13. Mund, M.G., and Wright, T.E., "Design, Development and Application of Air Cleaners for Gas Turbines", SAE Paper 538B Presented at SAE Summer Meeting, 11-15 June 1962, Atlantic City

14. Miller, R.A., and Poplawski, R., "The Inertial Particle Separator for Military Turbine Powered Vehicles", Proceedings of the OAR Research Applications Conference, 5 April 1966, Washington, D.C. pp 44-69

15. "Analysis of Sands Encountered in Lycoming Gas Turbine Engine Operation" by Lycoming (Division of AVCO Corporation), Stratford, Connecticut, Report Number 125.1.3, March 1965

16. Fiorino, T.D., Jr., and Poplawski, R., "Experimental Optimization of the Reversed Flow Vortex Chambers", ARL 65-66, Apr 66.

17. Pinchak, A.C., and Poplawski, R., "On the Attainment of Extremely High Rotational Velocities in a Confined Vortex Flow", AIAA Second Annual Meeting, San Francisco, California, 26-29 July 1965, Paper Nr. 65-400

18. Poplawski, R., and Pinchak, A.C., "Aerodynamic Performance of Reversed Flow Vortex Chambers", ARL 65-219, October 1965

19. Poplawski, R., and Pinchak, A.C., "Aerodynamic Effects of Secondary Flows in Confined Vortices", Research Review, OAR, Vol IV, Nr. 11, January 1966, 11 18-22

20. Fletcher, E.C., Gyarmathy, G., and Hasinger, S., "Separation of Submicron Condensate Particles in a Vortex Chamber", ARL 66-0218 November 1965

21. Hasinger, S., Mills, R.H., and von Ohain, H.J.P., Aerospace Research Laboratory Internal Document (not circulated). January 1962

22. Pinchak, A.C., "A Review of the State of the Art of Cyclone-Type Separators", ARL 67-0047, March 1967

23. Kendall, J.M., Jr., "Experimental Study of a Compressible Viscous Vortex", JPL Technical Report Nr 32-290, June 5, 1962

24. Lee, John D., "An Experimental Study of the Flow in a Low Pressure Swirl Chamber", Aeronautical and Astronautical Research Laboratory, Ohio State University, Air Force Contract Nr 33(615)-1063, 1967

25. Moore, Mark B., Theory and Application of Mechanical of Engineering Measurements, D. Van Nostrand Co. Inc., Princeton, N.J. October 1960

26. Miller, Roger A., "Field Testing the ARL Dust Separator", Research Review, OAR, Vol VI, Nr. 1, January 1967, 11 1-6

27. Kaufman, R.E., and Pollini, R.J., "Recent Sea-Salt-in-Air Implications as Highlighted by Marine Gas Turbine Requirements", ASME Paper Nr 67-GT-44, 9 January 1967

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Aerospace Research Laboratories
Energetics Research Laboratory (ARE)
Wright Patterson AFB, Ohio 45433

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
Microscopic Particle Separation and Applications

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific. Final.

5. AUTHOR(S) (First name, middle initial, last name)
Capt Robert Poplawski and Capt Roger A. Miller

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1968	86	27

8a. XXXXXXXXXXXXXXXX
In-House Research
b. PROJECT NO. 7116 - 00 03
c. DoD Element 61445O1F
d. DoD Subelement 681308

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
ARL 68-0024

10. DISTRIBUTION STATEMENT
1. This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES
TECH OTHER

12. SPONSORING MILITARY ACTIVITY
ARL (ARE)
Wright-Patterson AFB, Ohio 45433

13. ABSTRACT
The Energetics Research Laboratory of the Aerospace Research Laboratories (ARL) has been engaged in ultra-microscopic particle separation studies since 1961. The application of this research ranges from the protection of turbine engines from dust and/or sea spray to applications in the field of air pollution. This paper presents not only the theory of these devices and laboratory experimental results, but also, field testing results on selected units. The important trade-offs between design parameters and the selection processes required to tailor an ARL type dust separator to a specific application are discussed and other important areas of application are suggested.

DD FORM 1 NOV 65 1473

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ultra Microscopic						
Particle Separation						
Turbine Engines						
Sea Spray						
Dust Separator						
Air Pollution						

Security Classification