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# DESIGN AND CALIBRATION OF AN IN-STACK, LOW-PRESSURE IMPACTOR

D.A. LUNDGREN, R.W. VANDERPOOL

UNIVERSITY OF FLORIDA  
ENVIRONMENTAL ENGINEERING  
SCIENCES DEPARTMENT  
410 BLACK HALL  
UNIVERSITY OF FLORIDA  
GAINESVILLE FL 32603

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ENGINEERING & SERVICES LABORATORY  
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SUMMARY

This project involved design, fabrication, calibration and field testing of a high-flow, low-pressure impactor for in-stack sampling of particulate exhaust from jet engine test cells. A ten-stage impactor was developed with particle collection cutpoints ranging from 10 to 0.05 micrometers aerodynamic diameter at flow-rates of 0.5 actual cubic feet per minute, minimum. Fluid-flow modeling and critical orifice behavior necessary to predict impactor stage cutpoints is combined with laboratory calibration data in a predictive computer program. Field evaluation and laboratory calibration results are included. These lead to recommendations for further research or development in this area.

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PREFACE

This report was prepared by the University of Florida, Department of Environmental Engineering Sciences, 410 Black Hall, Gainesville FL 32611, under contract F08635-C-0136, Task 83-03, for the Air Force Engineering and Services Center, Engineering and Services Laboratory (AFESC/RDVS), Tyndall Air Force Base FL 32403-6001.

This report documents work performed between January 1985 and October 1987. The Air Force Project officer was Maj Paul E. Kerch.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the Air Force, nor can this report be used for advertising commercial products.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Services (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.



PAUL E. KERCH, Maj, USAF, BSC  
Project Officer



NILS AKERLIND, Jr., Maj, USAF  
Chief, Environics Division



KENNETH T. DENBLEYKER, Maj, USAF  
Chief, Environmental Sciences Branch



LAWRENCE D. HOKANSON, Colonel, USAF  
Director, Engineering and Services  
Laboratory

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SECTION I  
INTRODUCTION

A. OBJECTIVE

Accurate characterization of jet engine exhaust emissions is important for a number of reasons. In evaluating aircraft engine performance and design, one measurement parameter of interest is the characteristics of the engine exhaust emissions. In addition to engine type and operating conditions, smoke production is also a strong function of jet fuel composition. Accurate evaluation of various fuels and fuel additives, therefore, must involve measurement and description of the engine's exhaust emissions. Understanding the mechanics of smoke formation and smoke properties will ultimately lead to the development of better fuels and fuel additives to reduce plume exhaust opacity. Since exhaust plume opacity is primarily a function of the plume's particle size characteristics, accurate measurement and description of in-stack particle size is essential.

B. BACKGROUND

Although a number of instrument types are commercially available for the measurement of particle size, none meet the exact requirements of jet engine test cell sampling. Optical particle sizing instruments cannot provide size information below about 0.1 micrometers diameter. Furthermore, since the instrument's optics and electronics are not compatible with high-temperature environments, the exhaust gas must first be diluted and conditioned before entering the device. Dilution and conditioning can result in significant changes in the aerosol's size characteristics. Finally, optical sizing devices can only provide particle number measurements and cannot provide particle mass measurements nor samples for chemical analysis.

Electrical aerosol analyzers can provide size information below 0.1 micrometers, but provide no size information above approximately 0.3 micrometers. Similar to optical sizing devices, electrical aerosol analyzers cannot be used in in-field conditions and must sample diluted, conditioned aerosol. Electrical sizing devices also provide particle number distributions and not mass distributions nor samples for analysis.

Diffusion classifiers are better suited to in-stack sampling conditions and can measure particles less than 0.1 micrometers. Their size fractionating characteristics are not sharp, however, and problems are associated with measurement of the long, chain-agglomerate aerosols typical of jet engine exhausts. Although diffusion classifiers do provide particle mass information, stage weight gains are normally too low to be quantified gravimetrically. Like electrical sizing devices, diffusion classifiers are unable to provide accurate size information for particles greater than 0.5 micrometers.

#### C. SCOPE

There has existed the need, therefore, for the development of an in-stack device specifically for the measurement of jet engine emissions. Based on a review of current particle sizing devices and the specific requirements of test cell sampling, a low-pressure impactor type of instrument was selected for the project design. Unlike conventional impactors which operate at ambient pressure and thus can only resolve particles down to 0.3 micrometers, low-pressure impactors can operate at pressures below 50 mm mercury. This low-pressure environment results in reduced particle drag and allows collection and sizing of particles below 0.05 micrometers diameter. Sampling at elevated temperature allows collection of particles as small as 0.01 micrometers. In essence, a low-pressure impactor can fractionate a combustion aerosol over its entire size range and provide mass concentration as a function of particle size.

## SECTION II

### DESIGN THEORY AND IMPACTOR DESCRIPTION

Design of a low-pressure impactor requires careful consideration of the parameters which affect its performance. The collection characteristics of an impactor stage are traditionally described in terms of a dimensionless impaction parameter or Stokes number (STK)

$$STK = \frac{\rho_p D_p^2 C V}{9 \mu W} \quad (1)$$

where  $\rho_p$  is the particle density,  $D_p$  is the particle diameter,  $C$  is the dimensionless Cunningham slip correction factor,  $\mu$  is the fluid dynamic viscosity,  $W$  is the jet diameter, and  $V$  is the average jet velocity. Additional factors, affecting the collection characteristics are the jet geometry, the fluid Reynolds number in the jet, the throat length,  $T$ , and the jet-to-plate separation distance,  $S$ . Extensive impactor studies have shown that the collection efficiency of a stage is a sole function of the Stokes number if jet Reynolds numbers are limited between 500 and 3000 and if jet  $T/W$  and  $S/W$  values are within accepted limits. Considering these factors and limiting the flow to the incompressible regime ( $V < 1/3$  sonic velocity), the smallest particle cutpoint which can be achieved at atmospheric pressure, using the smallest commercially available drill size is approximately 0.3 micrometers. Cutpoints smaller than this size can only be achieved by operating the impactor at reduced pressure to increase the slip correction factor or by using very small jet diameters, formed by chemical etching processes, to increase jet velocities.

Design of the low-pressure impactor was based on a number of practical considerations and specific requirements. The first requirement is that the impactor must operate at a reasonably high sampling flow rate. Since collected mass deposits are usually quantified gravimetrically, it is often important to sample as much of the stack gas as possible. Although high particle mass concentrations are often encountered in industrial sampling, extremely low mass concentrations can sometimes occur. For example, the mass concentration downstream of an efficiently operated scrubber or electrostatic precipitator may be a small fraction of that concentration upstream of the device. Even in a situation where the mass concentration is reasonably high, circumstances may permit only short sampling times. An example of this test condition is sampling a jet engine at full military power. It was considered desirable, therefore, that the impactor operate at a flow rate of at least 0.5 acfm. Of course, higher operational flow rates require correspondingly higher pumping capacities. Pump selection for stack sampling must consider portability, as well as satisfy the necessary pumping requirements.

Accurate measurement of the gas temperature and pressure within the impactor is also important. As discussed later, the performance of the impactor's low-pressure stages is a particularly strong function of gas temperature and pressure. Variations in mass flow rate, gas density and viscosity, stage pressure drops, and particle slip correction factors must all be evaluated with respect to the gas conditions.

Finally the designed impactor must withstand the high temperature, high vibration, and corrosive environments encountered during stack sampling. The unit should be constructed of stainless steel and should operate with or without o-rings. It is also desirable that the unit be fitted with either filter-type or greased impaction substrates. For the sensitive quantitation of collected mass deposits, the impaction substrates should be small enough to

fit in most electronic balances.

Based on these considerations, a 10-stage cascade impactor was designed and constructed for in-stack use. Complete shop drawings of the impactor components are presented in Appendix E. The unit consists of six ambient pressure stages followed by four low-pressure stages. A noncollecting critical orifice section is located between the ambient and low-pressure stages and is used both to control flow through the device and to supply reduced pressure air to the four low-pressure stages. Temperature and pressure taps were installed below the critical orifice section to monitor the properties of the gas entering the low-pressure stages. The unit is constructed of Number 316 stainless steel and is cylindrically shaped with a diameter of 3 inches and a length of 10 inches (Figure 1). Impaction substrates consist of 2.5-inch diameter circular plates constructed of 0.003-inch stainless steel shim stock. These plates are designed to fit over stationary supports below each stage and can either be greased themselves or fitted with fibrous filters.

Critical dimensions of the impactor are given in Table 1. At standard conditions, the unit has a sampling flow rate of 1.00 cfm. Flow through the impactor is provided by a Rietschle Model CLF 26 pump (Figure 2) which weighs approximately 100 pounds and has a capacity of 16 acfm. Pressure below the critical orifice is controlled by a recirculation valve at the pump inlet. Design cutpoints for the 10 impactor stages vary logarithmically and were intended for comparison purposes to approximately equal the channel diameters of the TSI Inc. Model 3030 electrical aerosol analyzer. The six ambient stages provide cutpoints from about 10 micrometers to 0.5 micrometers. Following the critical orifice, whose downstream pressure is normally operated at 170 mm mercury, the four low-pressure stages provide cutpoints as low as 0.05 micrometers at standard conditions. A 47 mm diameter glass fiber filter

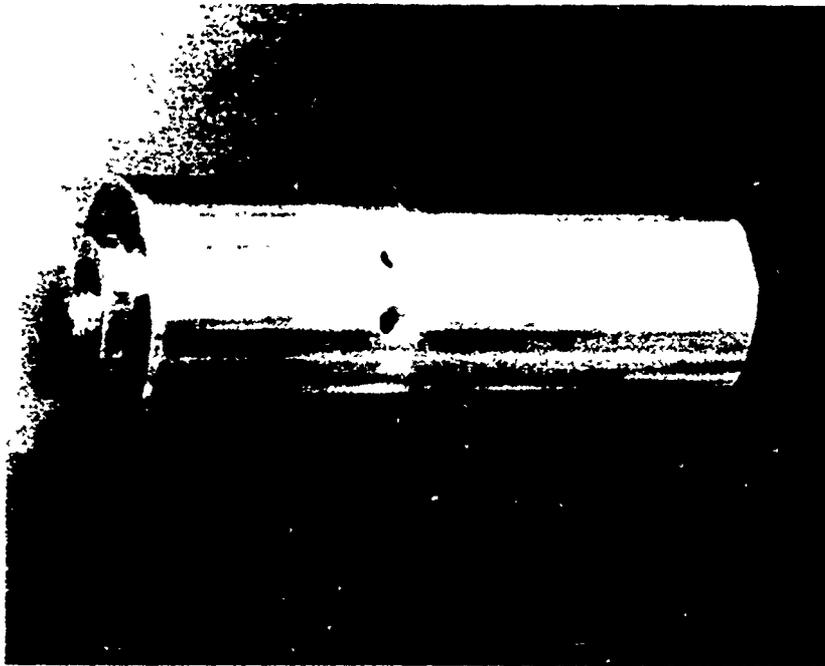


Figure 1. Photograph of Assembled Low-Pressure Impactor.

TABLE 1. CRITICAL STAGE DIMENSIONS OF LOW-PRESSURE IMPACTOR

| STAGE   | W (cm) | n   | S/W | T/W |
|---------|--------|-----|-----|-----|
| 1       | 1.27   | 1   |     |     |
| 2       | 0.352  | 12  | 2.2 | 2.3 |
| 3       | 0.211  | 18  | 1.9 | 1.9 |
| 4       | 0.118  | 36  | 2.2 | 1.8 |
| 5       | 0.071  | 56  | 3.6 | 2.2 |
| 6       | 0.041  | 100 | 6.2 | 1.9 |
| ORIFICE | 0.062  | 9   | --  | 6.4 |
| 7       | 0.065  | 120 | 4.8 | 1.8 |
| 8       | 0.052  | 150 | 3.8 | 2.0 |
| 9       | 0.034  | 320 | 4.1 | 1.6 |
| 10      | 0.0256 | 512 | 4.2 | 2.1 |

W = jet diameter

n = no. of jets per stage

S/W = ratio of jet to plate distance to jet diameter

T/W = ratio of jet throat length to jet diameter



Figure 2. Photograph of Rietschle Model CLF Sampling Pump.

may be operated at the impactor outlet to quantify the aerosol mass below the cutpoint of the final low-pressure stage.

SECTION III  
MODELING OF FLUID FLOW

Most existing low-pressure impactors are intended to operate at sampling conditions similar to the room conditions under which they were calibrated. As small changes in air temperature and pressure will not significantly affect the impactor's performance, extensive predictive modeling of the fluid flow is normally not performed. The wide range of temperature and pressures experienced in industrial sampling, however, can dramatically affect the particle collection characteristics of an in-stack low-pressure impactor. During jet engine test cell operation, for example, temperatures can exceed 1000°F. Variations in mass flow rate, gas density and viscosity, stage pressure drop, and particle slip correction factors must all be evaluated with respect to the gas conditions. While changes in the performance of an impactor's ambient stages can be predicted with some confidence, extreme variations in the fluid properties of the low-pressure stages with temperature and pressure are more difficult to predict. Therefore, special attention has been given in the laboratory to the fluid flow characteristics of the low-pressure stages as well as to the behavior of the critical orifice section as a function of temperature and pressure.

The behavior of the impactor's ambient stages can adequately be described by modeling the fluid flow as an incompressible process. This assumption is justified as long as the jet velocities are confined below one-third sonic velocity. As will be discussed, the ambient stages of the impactor will always operate under incompressible conditions regardless of the sampling conditions. For incompressible flow, the nozzle jet velocity can be calculated simply by dividing the volumetric flow rate per nozzle by the cross sectional area of the nozzle. For circular nozzles with jet diameter  $D_j$ , the

aerodynamic cutpoints can be calculated by rearranging Equation (1)

$$\sqrt{C} D_{p50} = \sqrt{\frac{9 \mu W}{\rho p V}} \sqrt{STK50} \quad (2)$$

The gas dynamic viscosity,  $\mu$ , is essentially independent of pressure but varies with absolute temperature

$$\mu \text{ (poise)} = \frac{T(K)^{1.5}}{0.068 \times T(K) + 7.8} \times 10^{-6} \quad (3)$$

The particle slip correction factor,  $C$ , is a function of both absolute temperature and pressure and has been empirically derived (Reference 1)

$$C = 1 + 1.246 Kn + 0.42 Kn \exp(-.87/Kn) \quad (4)$$

$$Kn = 0.0653 (2/P D_p) (T/296) (1 + 110/296)/(1 + 110/T) \quad (5)$$

where

Kn = Knudson number  
P = Stage inlet pressure, atm  
D<sub>p</sub> = Particle diameter, micrometers  
T = Absolute temperature, °K

Unlike the ambient stages, the behavior of the impactor's low-pressure stages cannot be adequately predicted using an incompressible flow model. For converging nozzles, jet velocities up to the sonic limit may be reached if the

stage pressure is sufficiently high. As will be discussed, the jet velocity for a given stage must be calculated as a function of the pressure drop across the stage. Since it is not practical to measure stage pressure drops during in-stack use of the impactor, they must be predicted as a function of the stage dimensions and stack gas conditions.

Development of a predictive flow model is most conveniently accomplished by modeling the nozzle flow field assuming isentropic (adiabatic and frictionless) flow relationships. Although no nozzle flow is perfectly isentropic, differences in the observed and predicted fluid behavior can be accounted for by the introduction of empirically derived discharge coefficients. Following the basic modeling approach of Biswas and Flagan (Reference 2), generalized discharge coefficients have been developed for the sharp-edged orifices of the low-pressure impactor. Derivation of the discharge coefficients was based on extensive pressure drop measurements as a function of orifice size, flow rate, jet geometry, and gas properties.

Assuming frictionless flow, the jet velocity is a function of the jet pressure ratio,  $r = P/P_o$ , where  $P$  is the nozzle downstream static pressure and  $P_o$  is the static pressure at the nozzle inlet. For decreasing pressure ratios, the ideal jet velocity increases until the sonic limit is reached at  $r'$

$$r' = (2/(k+1))^{k/(k-1)} \quad (6)$$

where  $k$  is the ratio of specific heats ( $C_p/C_v$ ) and is equal to 1.4 for air. At the critical pressure ratio, the nozzle becomes "choked" and no increase in velocity is possible. For pressure ratios above the critical, the jet core velocity can be calculated

$$V_c = \sqrt{\frac{2k}{k-1} R T_o (1-r^{(k-1)/k})} \quad (7)$$

where  $R$  is the specific gas constant ( $2.87 \times 10^6 \text{ cm}^2/\text{sec}^2 \text{ }^\circ\text{K}$  for air) and  $T_o$  is the nozzle inlet temperature ( $^\circ\text{K}$ ). As will be discussed, the isentropic or core velocity best physically represents the velocity at the core of the velocity profile and is not indicative of the average jet velocity.

For the development of a generalized predictive model, it is useful to express the measured mass flow rate through a nozzle in dimensionless form

$$m = \frac{\dot{m} \sqrt{R T_o}}{A P_o} \quad (8)$$

where  $\dot{m}$  is the measured mass flow rate ( $\text{g}/\text{sec}$ ) and  $A$  is the nozzle cross-sectional area ( $\text{cm}^2$ ). If  $\dot{m}$  is chosen to represent the total mass flow rate through the stage, then  $A$  should represent the total cross-sectional area of the stage jets.

By comparison, the theoretical dimensionless isentropic mass flow rate can be calculated for pressure ratios above the critical value (i.e.,  $r > r'$ )

$$m' = r^{1/k} \sqrt{\frac{2k}{(k-1)} (1-r^{(k-1)/k})} \quad (9)$$

The nonideal behavior of the impactor nozzles was observed and quantified in the laboratory. For each of the low-pressure stages and the critical orifice section, the mass flow rate was measured as a function of the pressure ratio across the stage. Use of a micromanometer allowed accurate measurement of stage pressure drops as low as 0.1 mm mercury. For each stage, mass flow rates were measured for  $r$  values ranging from 0.2 to 0.95. Measurements were made at inlet pressures ranging from 760 mm mercury to 100 mm mercury. Stage pressure drops were also measured as a function of inlet temperatures from 296K.

Results of the tests were similar to those obtained by Biswas and Flagan (Reference 2) at standard temperature and pressure conditions. In general, smaller orifices were observed to behave less ideally than larger orifices. In addition, the smaller the pressure ratio (i.e., greater pressure drop), the greater the deviation from ideal flow. The difference in the measured and predicted mass flow rate represents the nonideal nature of each nozzle at the test conditions. This nonideal behavior can be corrected through the use of the nozzle discharge coefficient,  $C_d$ , which is defined as the measured dimensionless mass flow rate divided by the predicted isentropic flow rate. Since the actual mass flow rate is always less than the isentropic mass flow rate, the discharge coefficient is always less than unity. For a nozzle of

given dimensions and geometry, the discharge coefficient is not constant but depends on the inlet temperature and pressure and the pressure drop across the nozzle.

Flow through a nozzle can be modeled as that of developing laminar flow in a pipe of diameter  $D$  and length  $T$ . It has been shown that the discharge coefficient is a function of the dimensionless parameter,  $Re D/T$ , where the Reynolds number is a function of the core velocity and the fluid properties at the nozzle inlet. The relationship between the discharge coefficient and the parameter  $Re D/T$  is clearly demonstrated in Figure 3 for the low-pressure stages operated at a wide range of flow conditions.

Good correlation between the discharge coefficient and the calculated  $Re D/T$  values is achieved by the power relationship

$$C_d = 0.233 (Re D / T)^{0.178} \quad (10)$$

Although the general form of the equation is similar to that reported in the earlier work (Reference 2), differences in jet geometry and the manner in which the Reynolds number was evaluated do not allow direct comparison of the equations between the two separate studies. The discharge coefficient appears to be constant at  $Re D/T$  values above approximately 2000. Theoretically, the discharge coefficient will reach a maximum value of 0.93 at high  $Re D/T$  values. Regardless of the sampling conditions, however,  $Re D/T$  values greater than 2000 cannot be achieved in the low-pressure stages. Equation (10),

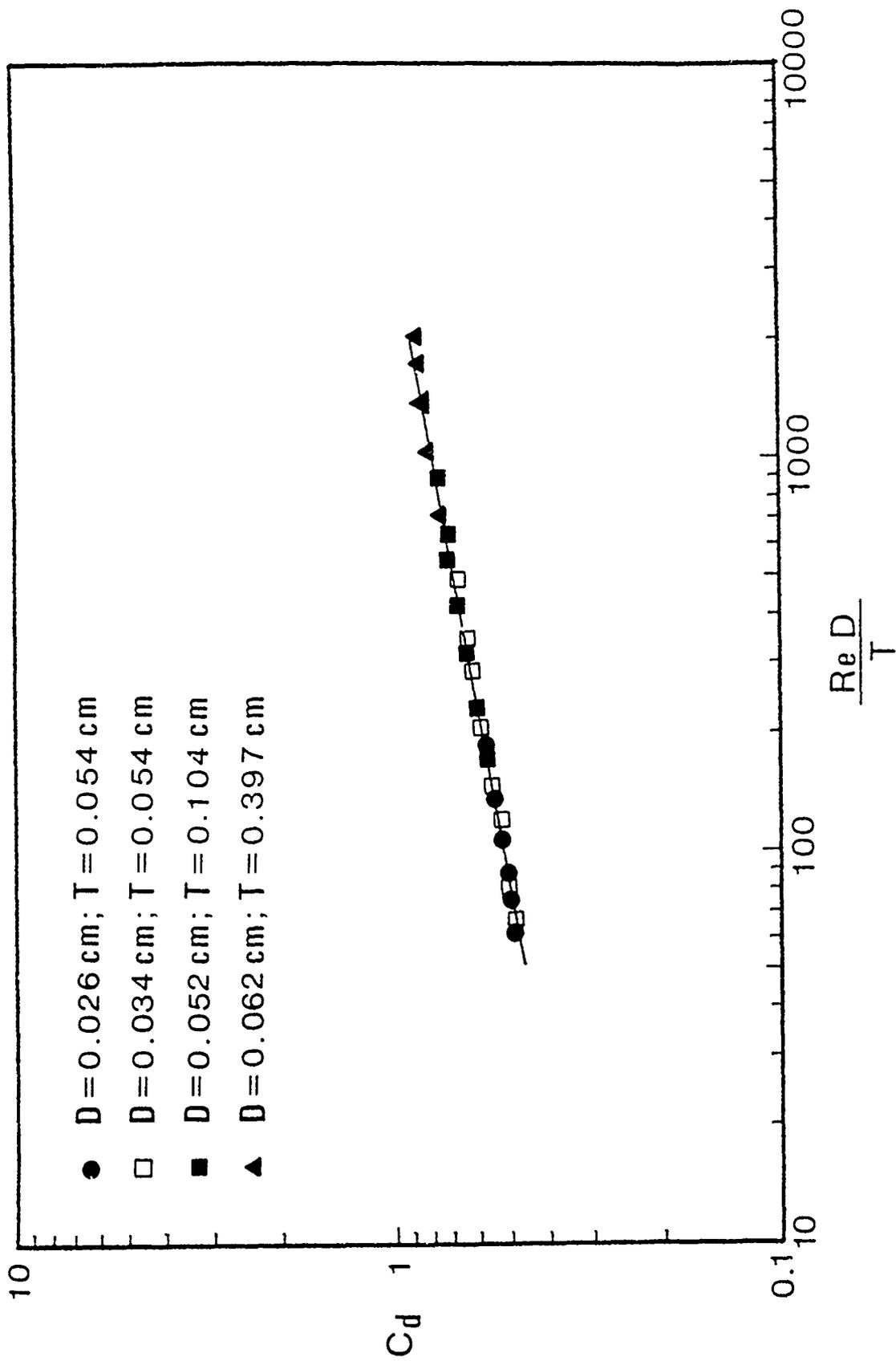


Figure 3. Discharge Coefficient as a Function of  $ReD/T$  Value.

therefore, accurately represents the behavior of the low-pressure stages under all possible sampling conditions. This general approach enables the prediction of a stage's pressure drop solely from its critical dimensions and the fluid properties at the stage inlet.

Incorporating the discharge coefficient into Equations (8) and (9)

$$\frac{\dot{m} \sqrt{R T_0}}{A P_0} = C_d r^{1/k} \sqrt{\frac{2k}{(k-1)} (1-r)^{(k-1)/k}} \quad (11)$$

Prediction of a stage's pressure drop at given conditions involves solving Equation (11) for the stage pressure ratio,  $r$ . Since the discharge coefficient is also a function of the pressure ratio, the equation cannot be solved directly. An iterative solution, however, can be obtained fairly rapidly using any of the various root-solving techniques.

As an example, consider flow through the 9th stage of the low-pressure impactor where:

$$\begin{aligned} \dot{m} &= 0.566 \text{ g/sec} \\ T_0 &= 296 \text{ OK} \\ P_0 &= 150 \text{ mm mercury} \end{aligned}$$

The root of Equation (11) at these conditions is found to exist at  $r = 0.900$  where  $C_d = 0.664$ . The predicted downstream pressure, therefore, is 135 mm mercury which is the product of the pressure ratio and the stage inlet pressure.

## SECTION IV

### CRITICAL ORIFICE BEHAVIOR

As previously discussed, the particle collection characteristics of a low-pressure impactor are a strong function of the fluid mass flow rate through the device. In the low-pressure impactor, flow is not controlled directly by the user but indirectly through the pressure reducing critical orifice section. As shown in Figure 4, the mass flow rate through the critical orifice section is not constant but varies considerably with inlet temperature and pressure. Special attention has been given, therefore, to the critical orifice section with respect to its behavior at various sampling conditions.

Similar to predicting the performance of the low-pressure stages, prediction of a critical orifice's behavior can best be approached by assuming isentropic flow relationships and correcting nonideal fluid behavior with empirical discharge coefficients.

For a choked nozzle, the mass flow rate becomes

$$\dot{m} = \frac{C_d A P_o}{\sqrt{R T_o}} (2/k+1)^{1/(k-1)} \sqrt{\frac{2k}{(k+1)}} \quad (12)$$

As in the previous discussion, the discharge coefficient is a function of the  $Re D/T$  value where the Reynolds number is evaluated using sonic velocity at the orifice inlet temperature

$$v_{\text{sonic}} = \sqrt{\frac{2k}{(k+1)} R T_o} \quad (13)$$

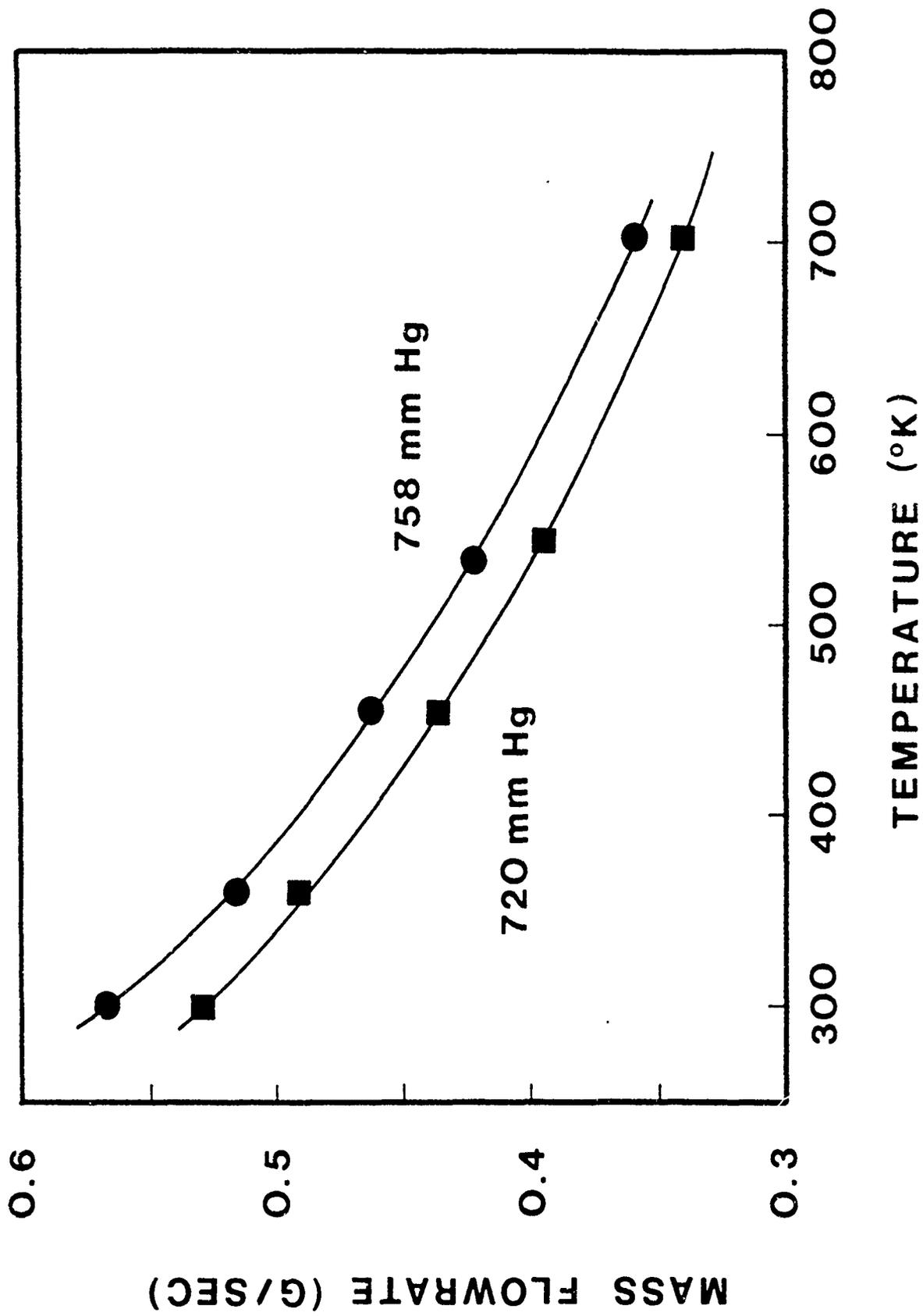


Figure 4. Measured Mass Flow Rate as a Function of Stack Temperature and Pressure.

Equation (12) should be evaluated in terms of the orifice inlet pressure and not the impactor inlet pressure. In the low-pressure impactor, the collective pressure drop through the six ambient stages at standard conditions results in an orifice inlet pressure of 741 mm mercury when a 760 mm mercury pressure exists at the impactor inlet. When sampling at conditions other than ambient, the pressure at the critical orifice inlet will vary accordingly.

Estimation of the orifice inlet pressure is a complex iterative process which involves making a first estimate of the orifice inlet pressure, calculating the mass flow rate based on that pressure, then calculating the cumulative pressure drop through the impactor's ambient stages. If the calculated 6th stage outlet pressure is not equivalent to the estimated orifice inlet pressure, then the estimate must be revised and the process repeated until a matching condition is reached.

A more direct estimate of the mass flow rate through the device can be made based on the extensive measurements of mass flow rate as a function of impactor inlet temperature and pressure. Introducing separate nozzle discharge coefficients as a function of temperature and pressure, the mass flow rate can be empirically determined

$$\dot{m} = 0.570 P/760 (296/T)^{0.5} Cd(P)/Cd(T) \quad (14)$$

where

$\dot{m}$  = Mass flow rate, g/sec  
P = Stack pressure, mm mercury  
T = Stack temperature, °K  
Cd(P) = Pressure discharge coefficient, dimensionless  
Cd(T) = Temperature discharge coefficient,  
dimensionless

The separate discharge coefficients for the nonideal nature of the critical orifice nozzles have been derived from the data

$$Cd(P) = 0.295 (P)^{0.171} \quad (15)$$

$$Cd(T) = 0.946 - 9.24 \times 10^{-5} T(K) \quad (16)$$

These coefficients allow a rapid determination of mass flow rate as a function of the stack conditions without the complex iterative technique previously described. It should be noted, however, the equations given for the temperature and pressure discharge coefficients only apply to this specific impactor and do not apply to other low-pressure impactors.

## SECTION V

### PREDICTION OF STAGE CUTPOINTS

As indicated in Equation (1), the cutpoint of an impactor stage is a strong function of the fluid velocity at the jet exit. Isentropic flow relationships were assumed earlier as the most convenient means of predicting stage pressure drops. The measured nonideal behavior of the nozzles, however, led to the introduction of discharge coefficients as corrections to the ideal, frictionless flow. The jet velocity calculated using isentropic relationships, therefore, does not accurately represent the average velocity in the jet. Viscous effects at the nozzle walls are significant in the low-pressure stages and may result in a parabolic velocity profile at the jet exit. The calculated isentropic velocity, therefore, possibly best represents the velocity at the core of the velocity profile where frictional effects are negligible.

By assuming adiabatic flow conditions, the average velocity at the jet exit can be calculated from mass continuity

$$V_j = \frac{\dot{m}}{A} \frac{T}{\rho_{in} T_{in}} \frac{P_{in}}{P} \quad (17)$$

where  $A$  is the stage total nozzle area and  $\rho_{in}$ ,  $T_{in}$ , and  $P_{in}$  represent the fluid density, temperature, and pressure at the impactor inlet (not the stage inlet). Note that previous prediction of the stage outlet pressure is required. In addition to the pressure drop, adiabatic expansion of the fluid

at the jet exit results in a temperature drop across the jet from  $T_0$  to  $T$ . By energy conservation, the outlet temperature can be estimated in terms of the inlet temperature and the average jet velocity

$$T = T_0 - \frac{v^2 (k-1)}{2 k R} \quad (18)$$

The average velocity at the jet exit thus, becomes

$$v_j = \frac{\dot{m}}{A \rho_{in}} \frac{P_{in}}{P} \left( 1 - v_j^2 \frac{(k-1)}{2kR T_{in}} \right) \quad (19)$$

Dissipation of the jet velocity between the stages results in recovery of the fluid temperature to that of the impactor inlet temperature. The inlet temperature to all impactor stages is thus, equivalent to the stack temperature.

Prediction of a stage's collection characteristics requires that the Cunningham slip correction factor be evaluated in terms of the fluid pressure immediately above the impaction plate. Although this pressure may be estimated from theoretical flow considerations, actual measurements of the

static pressure at the impaction plate (Reference 2) have shown that this pressure is essentially equivalent to the stagnation pressure at the stage inlet. Calibration results also indicate that the slip correction factor should be evaluated in terms of the fluid conditions at the stage inlet (Reference 3, 4, and 5).

SECTION VI  
EXPERIMENTAL METHODS

The particle collection characteristics of each impactor stage were evaluated using monodisperse calibration aerosols of solid ammonium fluorescein. Calibration aerosols were produced by two separate generation systems depending on the size of the particle required. For the calibration of the ambient stages, particles were generated with a vibrating orifice aerosol generator (VOAG) (TSI Inc. Model 3050). The VOAG works on the principle of the controlled mechanical breakup of a liquid jet into uniform droplets of known size. When the liquid solution consists of a nonvolatile solute dissolved in a volatile solvent, the droplets dry to form an aerosol of known size. For the calibration of the low-pressure impactor, the liquid solution consisted of fluorescein powder dissolved in aqueous ammonia. The droplets produced dried to form spherical particles of solid ammonium fluorescein. Following their production, the particles were mixed with dilution air then charge neutralized by exposure to a  $^{85}\text{Kr}$  radioactive source. The aerosol was then sampled using the low-pressure impactor at 1.00 cfm for the calibration tests. An optical microscope was used to verify the size and quality of the generated particles before each test.

Most of the calibration tests were performed using impaction substrates greased with petroleum jelly. Limited tests were also performed with other impaction surfaces to determine their relative collection characteristics. Run times for the calibration of the ambient stages varied from 1 minute to 30 minutes depending on the mass concentration of the sampled aerosol. Normally, five separate particle sizes were generated for each of the ambient stages tested. Collected aerosol mass deposits were quantified by fluorometric techniques. After each test, the impaction substrate was first immersed in 15

mL of methylene chloride to dissolve the grease coating. For the petroleum jelly impaction substrate, methylene chloride was found to be a more effective solvent than either benzene or hexane. Following a 10 minute extraction time, 30 mL of 0.1 N  $\text{NH}_4\text{OH}$  was added and the solution was transferred to a test tube. The test tube was then lightly shaken to thoroughly mix the two solvents and effect the transfer of the collected ammonium fluorescein to the aqueous phase. After allowing 20 minutes for gravity separation of the two immiscible phases, a sample of the aqueous phase was removed and analyzed using a calibrated fluorometer. In three separate tests to check the efficiency of the extraction technique, the average recovery was measured to be 95 percent. Use of 30 mL aqueous solutions enabled detection of as little as 0.03 micrograms fluorescent mass deposits.

For calibration of the sixth ambient stage and the four low-pressure stages, monodisperse aerosols were generated using a TSI Inc. Model 3071 electrostatic classifier. Polydisperse aerosols were first generated by atomizing fluorescein using a constant feed rate atomizer. The polydisperse aerosol was then dried through a heating section and a diffusion dryer and placed in a Boltzman equilibrium charge distribution by exposure to a  $^{85}\text{Kr}$  radioactive source. Monodisperse particles of the desired size were then produced by electrical classification within the classifier. The aerosol was then diluted to the necessary volume using clean, dry dilution air. The system's dilution air was controlled to maintain an impactor inlet pressure of one atmosphere. This was necessary to achieve the desired 1.00 cfm flow rate through the impactor. Following charge neutralization through a  $^{85}\text{Kr}$  source, a fraction of the aerosol was then continuously sampled into a TSI Inc. Model 3030 electrical aerosol analyzer. This allowed verification of the mean size of the calibration aerosol continuously during the test. Measurement of the

aerosol's number concentration also allowed determination of the run time necessary to achieve detectable mass deposits. The remainder of the aerosol flow was then sampled by the low-pressure impactor for the calibration test.

The electrostatic classifier extracts particles of the same electrical mobility. Since the polydisperse aerosol can consist of multiple-charged particles, the output aerosol can contain not only singly-charged particles of the desired size but also some multiple-charged particles of larger sizes. This interference effect is more significant for the generation of particles greater than 0.1 micrometers diameter. As will be discussed, the presence of these multiple-charged particles can significantly affect measured collection efficiencies and must be accounted for during the calibration.

## SECTION VII

### CALIBRATION RESULTS

Calibration of the impactor's ambient stages was performed primarily with aerosols generated from the VOAG. Because of the lower size limitations of the VOAG, however, calibration of the impactor's 6th stage was performed using aerosols generated from the electrostatic classifier. Run times for calibration of the ambient stages varied from 1 minute to 30 minutes depending on the mass concentration of the sampled aerosol. Normally, five separate particle sizes were generated for each of the ambient stages tested. Each test series consisted of three separate runs performed under identical test conditions. Reported collection efficiencies are the arithmetic average of the three test results. The impactor was operated at near-standard temperature and pressure conditions and the flow rate was measured to be 1.00 cfm.

The particle collection characteristics of the impactor's ambient stages are presented in Figure 5. Cutpoints for Stages 2 through 6 were measured to be 5.5, 2.9, 1.78, 0.95, and 0.50 micrometers aerodynamic diameter. The first stage of the impactor was not calibrated as its performance will vary with the size of the inlet nozzle necessary for in-stack isokinetic sampling. With the exception of the 6th stage, the collection efficiency curves shown in Figure 5 are generally quite sharp and provide cutpoints close to those predicted by standard impactor theory using incompressible flow relationships (Reference 7). The higher measured slope of the 6th stage's efficiency curve was due primarily to the inability of the electrostatic classifier to provide quality calibration aerosol in this size range. The 6th stage curve shown in Figure 5 includes corrections to the measured collection efficiencies for the high percentage of generated doublets and triplets which can be expected in this

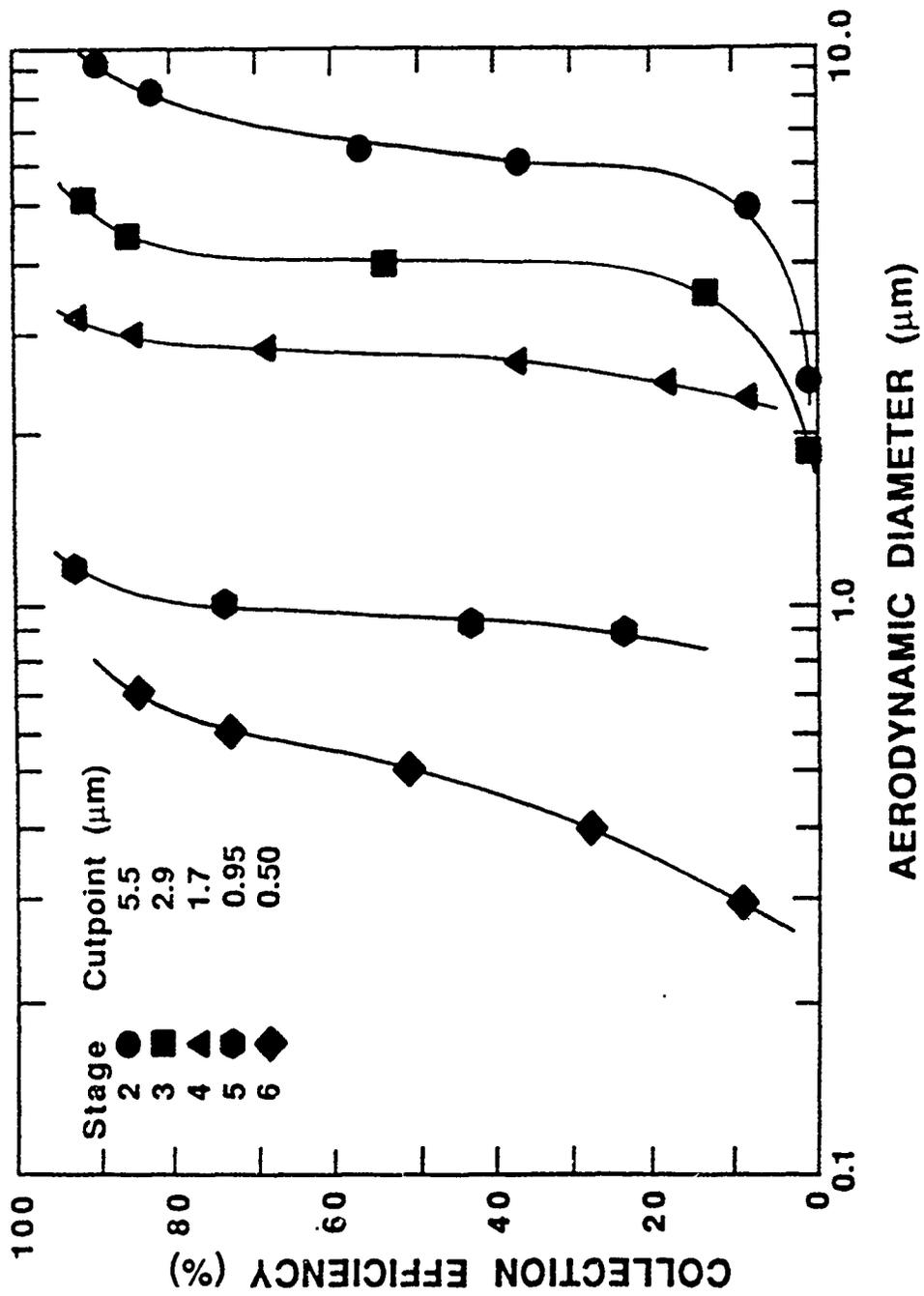


Figure 5. Collection Efficiency versus Aerodynamic Particle Size for Stages 2-6.

size range from the classifier.

Monodisperse aerosols for the calibration of the four low-pressure stages were generated using the electrostatic classifier. As opposed to the ambient stages, calibration of the low-pressure stages involved run times from 2 to 5 hours per run. For this reason, only two runs per test condition were performed. The high repeatability of the test results normally indicated that a third run was unnecessary.

Unlike the behavior of the ambient stages, the performance of the low-pressure stages varies as a function of the operating pressure below the critical orifice. During design of the low-pressure impactor, an operating pressure of 150 mm mercury was expected to achieve the desired cutpoints based on the stage dimensions and design flow rate. Upon construction of the low-pressure impactor, however, the measured stage pressure drops were found to be higher than expected. Since higher pressure drops result in correspondingly higher jet velocities, it was predicted that a 150 mm mercury orifice pressure would lead to smaller stage cutpoints than desired.

The proper operating orifice pressure was ultimately selected based on measured collection efficiencies as a function of orifice pressure. Tests were performed using the 3rd low-pressure stage which had a design cutpoint of approximately 0.1 micrometers. Collection efficiencies were measured as a function of particle size for orifice pressures of 160, 170, and 190 mm mercury. As shown in Figure 6, three separate curves were produced at the three different operating pressures with the 170 mm mercury operating pressure providing a cutpoint closest to the design value of 0.1 micrometers. As a results of these tests, an orifice pressure of 170 mm mercury was selected for all subsequent calibration tests of the low-pressure stages.

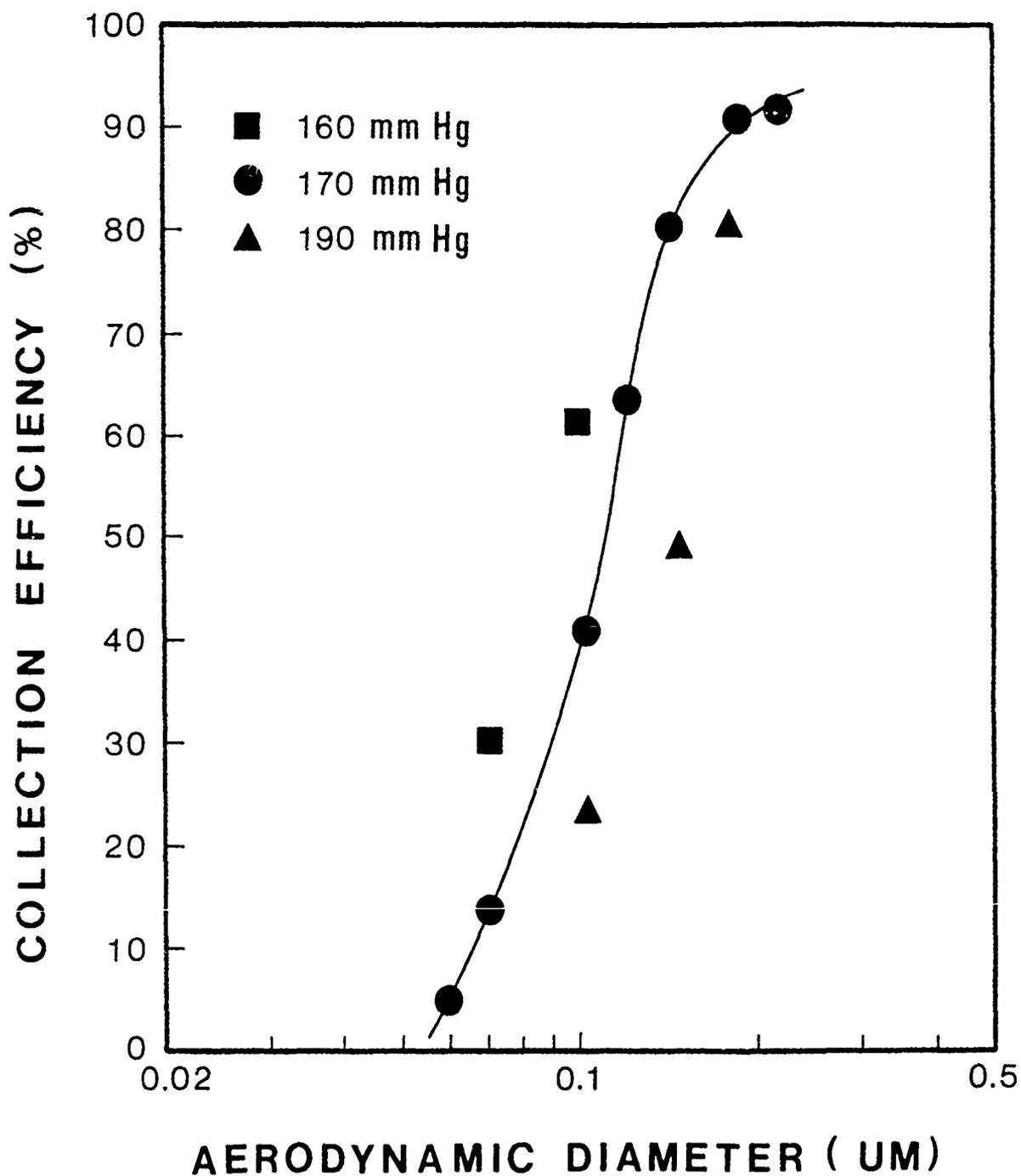


Figure 6. Stage 9 Measured Efficiency versus Operating Pressure.

The measured performance of the four low-pressure stages is summarized in Figure 7. The curves indicate that the impactors should fractionate an aerosol into fairly sharp, well-defined size fractions. Note also that no solid particle bounce is evident from the greased impaction substrates. Measured cutpoints were 0.32, 0.20, 0.11 and 0.047 micrometers aerodynamic diameter.

Initial calibration of the impactor's first low-pressure stage (Stage 7) produced some unexpected results. Unlike the other low-pressure stages, calibration of Stage 7 resulted in a very poor efficiency curve (Figure 8). Since the only difference between Stage 7 and the remaining low-pressure stages was the absence of a collection plate above the jet nozzles, a plate was installed and the efficiency tests repeated. As shown in Figure 8, addition of the plate significantly improved the stage's collection characteristics and resulted in a measured cutpoint closer to the predicted value. Currently, the exact effect of the plate's presence on the stage's performance is not well understood. The effect, however, is significant and an impaction plate above Stage 7 has been incorporated into the final design. The height of this plate above the jet nozzles has been reduced to minimize loss of particles exiting the critical orifices.

The operational characteristics of the low-pressure impactor at the calibration conditions is presented in Table 2. Calculations were made based on the measured flow rate of 1.00 acfm. The average jet velocities and jet core velocities for the low-pressure stages were calculated from the measured fluid properties. Jet Reynolds numbers and predicted stage cutpoints were evaluated in terms of the average jet velocities. In general, use of the average jet velocity in the efficiency calculations leads to reasonable prediction of a stage's performance. Predicted stage cutpoints were normally within 10 percent of the measured values. It is evident, however, that use of

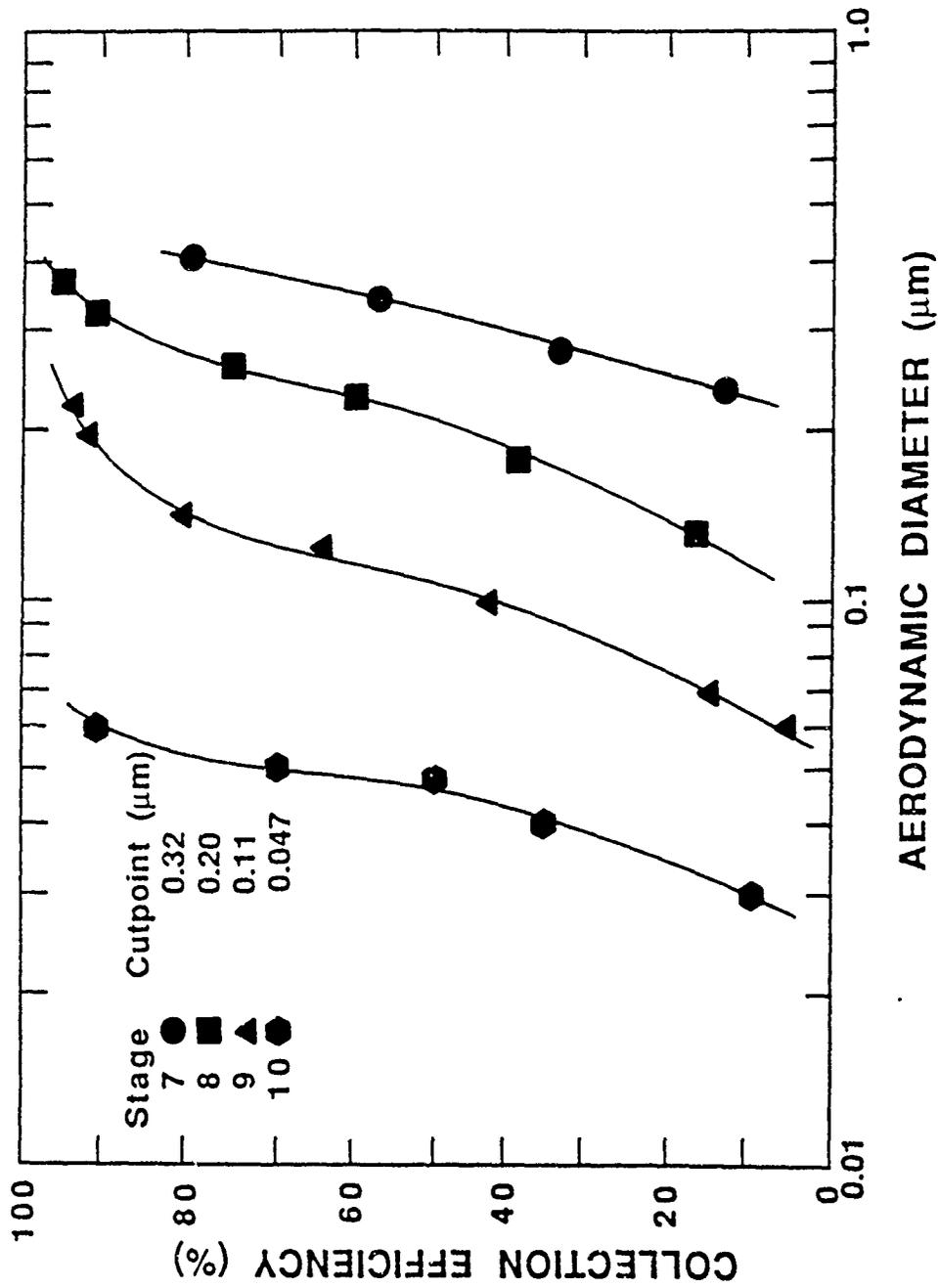


Figure 7. Collection Efficiency versus Aerodynamic Particle Size for Stages 7-10.

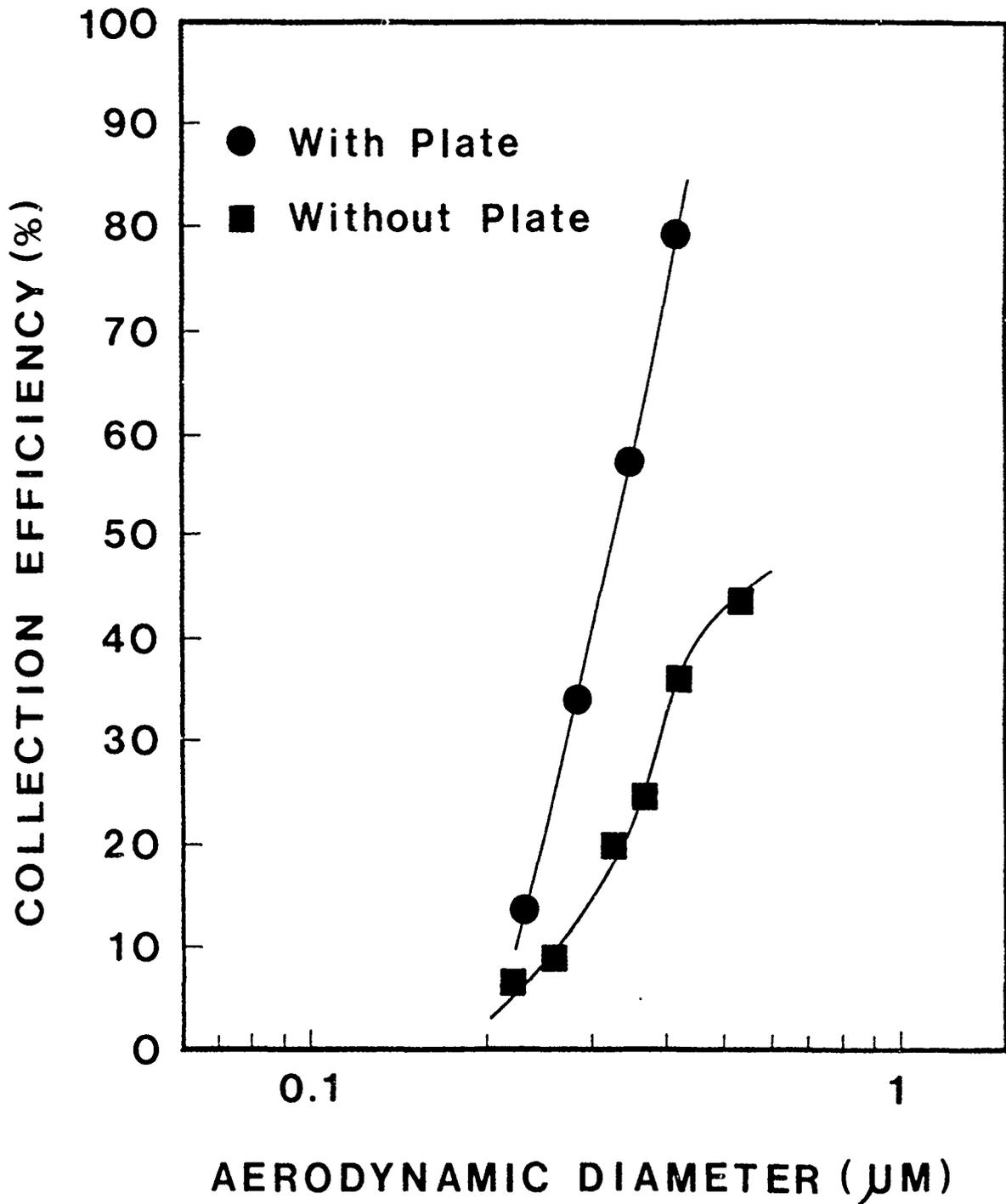


Figure 8. Stage 7 Collection Efficiency with and without Upper Support Plate.

TABLE 2. OPERATING CHARACTERISTICS OF LOW-PRESSURE IMPACTOR

| STAGE   | Po<br>(mm Hg.) | P<br>(mm Hg.) | V core<br>(cm/sec) | V avg<br>(cm/sec) | Re   | Pred Dp50<br>(um) | Meas. Dp50<br>(um) | $\sqrt{SFK}$ |
|---------|----------------|---------------|--------------------|-------------------|------|-------------------|--------------------|--------------|
| 1       | 760            | 760           | --                 | 330               | 3200 | 11.0              | --                 | --           |
| 2       | 760            | 760           | --                 | 410               | 940  | 5.8               | 5.5                | 0.47         |
| 3       | 760            | 760           | --                 | 760               | 1070 | 3.1               | 2.9                | 0.47         |
| 4       | 760            | 756           | --                 | 1220              | 920  | 1.9               | 1.7                | 0.44         |
| 5       | 754            | 750           | --                 | 2140              | 980  | 1.1               | 0.95               | 0.45         |
| 6       | 750            | 741           | --                 | 3600              | 1000 | 0.56              | 0.50               | 0.44         |
| ORIFICE | 741            | 170           | --                 | --                | --   | --                | --                 | --           |
| 7       | 170            | 164           | 8120               | 5540              | 531  | 0.35              | 0.32               | 0.42         |
| 8       | 164            | 153           | 10750              | 7510              | 543  | 0.22              | 0.20               | 0.44         |
| 9       | 153            | 138           | 15000              | 8790              | 399  | 0.12              | 0.11               | 0.45         |
| 10      | 138            | 113           | 18200              | 11860             | 363  | 0.055             | 0.047              | 0.40         |

the higher jet core velocities would lead to an overprediction of a stage's collection efficiency.

Limited tests were conducted with the 9th impactor stage to determine the effect of substrate coating on particle collection. The collection efficiency of 0.11 micrometers aerodynamic diameter solid particles was measured using coatings of silicone spray, apiezon grease, and petroleum jelly. Results shown in Figure 9 indicate that all the viscous, nonvolatile greases provide adequate particle retention characteristics even at high jet velocities. Use of an uncoated plate, however, results in a lower measured collection efficiency for this particle size. Due to an apparent filtering effect, use of glass-fiber substrates result in higher measured efficiencies than obtained with greased substrates. This result is similar to that observed by Rubow and Marple (Reference 6) during calibration of the micro-orifice impactor. The efficiency curve, however, is not unacceptable and possibly suggests that filter substrates may be used effectively in the low-pressure stages for collection of sub-micron particles. Fibrous substrates may be especially useful for in-stack conditions where elevated temperatures may preclude the use of greased impaction substrates.

Particle losses in the 9th impactor stage were measured using 0.11 micrometers solid particles. Following a 10-hour sampling time, both the stage nozzles and stage walls were washed, using separate 0.1 N  $\text{NH}_4\text{OH}$  solutions. Losses in each section were found to be less than 1 percent of the total aerosol mass sampled.

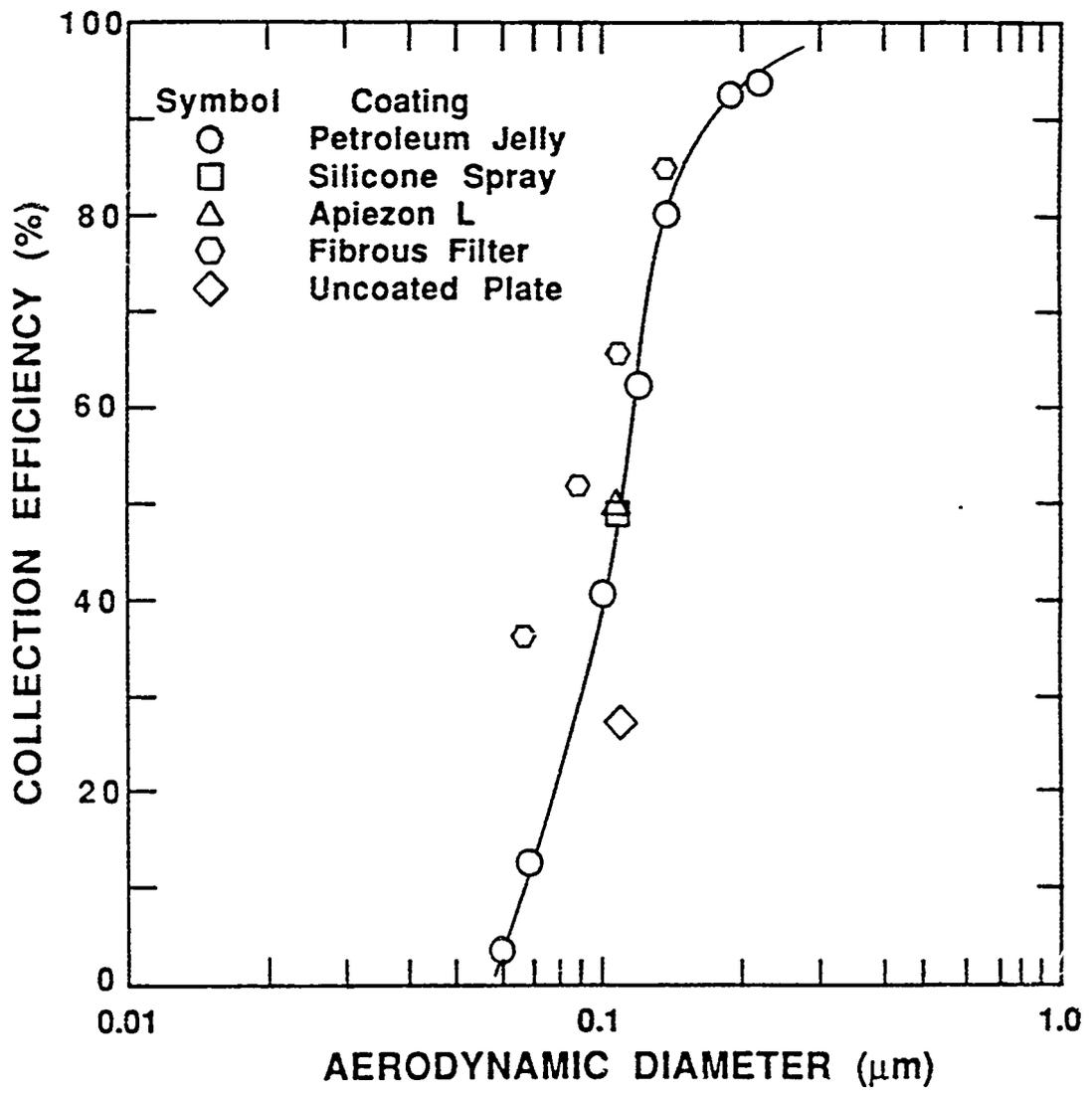


Figure 9. Stage 9 Collection Efficiency versus Substrate Coating.

## SECTION VIII

### PREDICTION OF IN-STACK PERFORMANCE

As discussed, the particle collection characteristics of the low-pressure impactor are not constant but will vary significantly with the sampling conditions. In predicting the performance of the low-pressure impactor as a function of temperature and pressure, two factors must be considered. First, the mass flow rate through the device is not constant but varies with the fluid properties at the inlet to the flow controlling critical orifice. Variations in mass flow rate will naturally affect the collection characteristics of the stages. The second factor which must be considered is that changes in the fluid properties (i.e. density, viscosity, mean free path, etc) with temperature and pressure will also greatly affect stage performance.

The primary effect of variations in stack pressure is the change in mass flow rate through the device. Inspection of Equation (14) for the critical orifice indicates that mass flow rate is nearly linear with orifice inlet pressure. The slight deviation from linearity is due to the fact that the discharge coefficient is also pressure dependent. As a result of this near linear response of mass flow rate with pressure, the volumetric flow rate through the impactor's ambient stages remains fairly constant with pressure. Therefore, the cutpoints of the impactor's ambient stages do not vary significantly with changes in stack pressure.

The pressure below the critical orifice section is controlled by the user and thus, is independent of stack pressure. As a result, the only variation in the performance of the low-pressure stages with stack pressure is caused by changes in the mass flow rate through the device. Reductions in mass flow rate with decreasing stack pressure result in higher cutpoints for the low-pressure stages. Care must be taken when sampling under conditions of low

stack pressure that the cutpoints of the low-pressure stages do not exceed those desired. The problem can be corrected by reducing the operating pressure below the critical orifice to achieve the desired cutpoints. The overall effect of variations in stack pressure on impactor performance is shown in Figure 10. The low-pressure stage cutpoints were calculated based on an orifice pressure of 170 mm mercury. Note that overlap between Stage 6 and Stage 7 cutpoints only occurs at stack pressures below 500 mm mercury.

Figure 11 shows the effect of orifice operating pressure on impactor performance. The data represents sampling at standard temperature and pressure stack conditions. Since the flow rate is independent of operating pressure, variations in orifice pressure do not affect the collection characteristics of the impactor's ambient stages. The performance of the low-pressure stages, of course, is greatly affected by orifice pressure. In fact, at standard sampling conditions overlap between Stages 6 and 7 occurs at orifice pressures above 230 mm mercury.

Temperature variations also affect the impactor's particle collection characteristics. As in the case of reduced inlet pressures, elevated temperatures result in lower mass flow rates through the device. As shown in Figure 12, however, the combined effects of elevated temperatures do not result in large variations in the performance of the impactor's ambient stages.

Temperature effects are more pronounced in the impactor's low-pressure stages. As shown in Figure 12, the combined effects of elevated temperature can greatly reduce the low-pressure stage cutpoints. An unavoidable effect of elevated temperature is the reduction in low-pressure stage jet Reynolds numbers. In addition, increases in volumetric flow rate and viscosity with temperature result in higher stage pressure drops. In fact, care must be

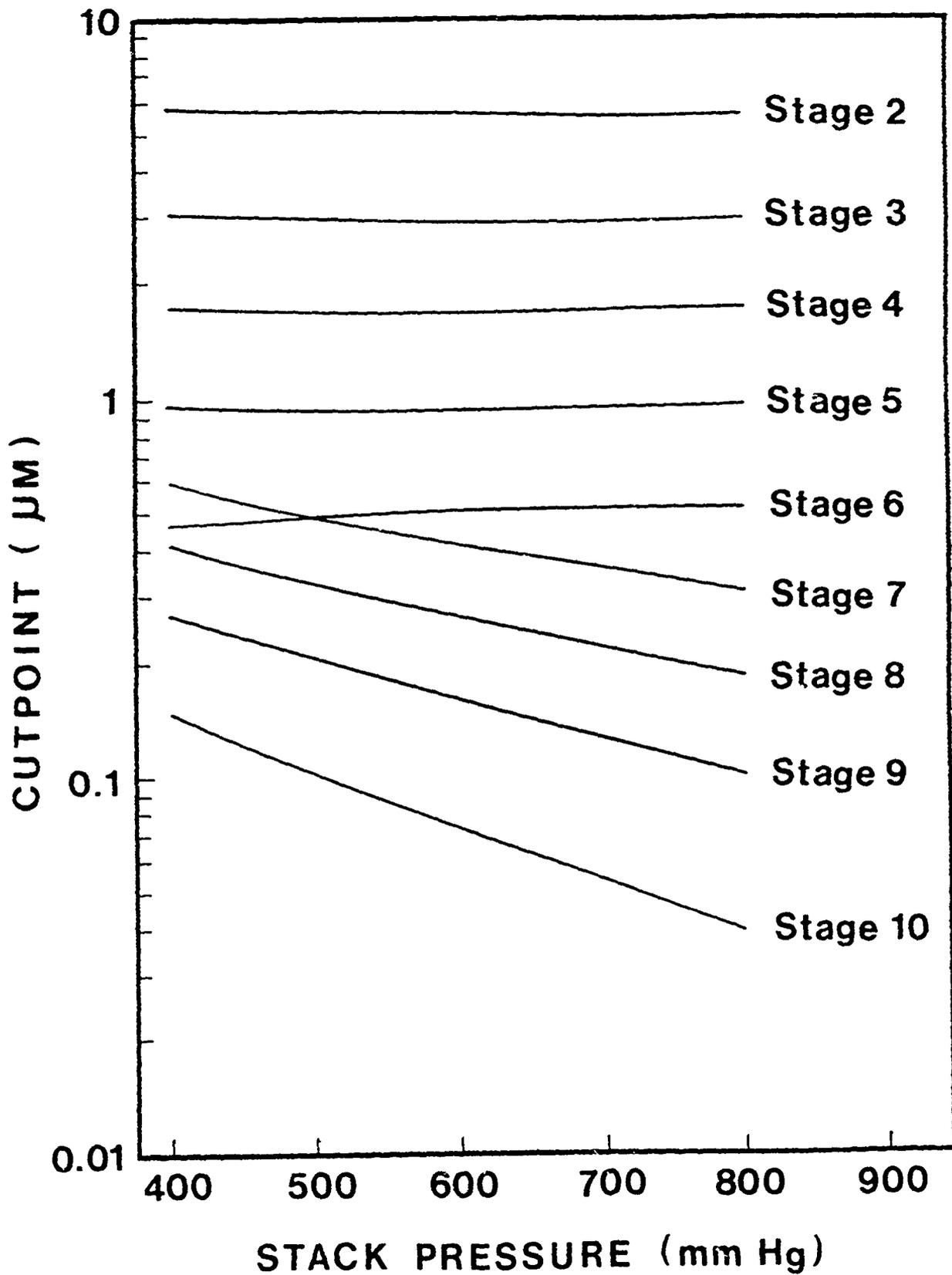


Figure 10. Predicted Cutpoints as a Function of Stack Pressure. Orifice Pressure Equals 170 mm Hg.

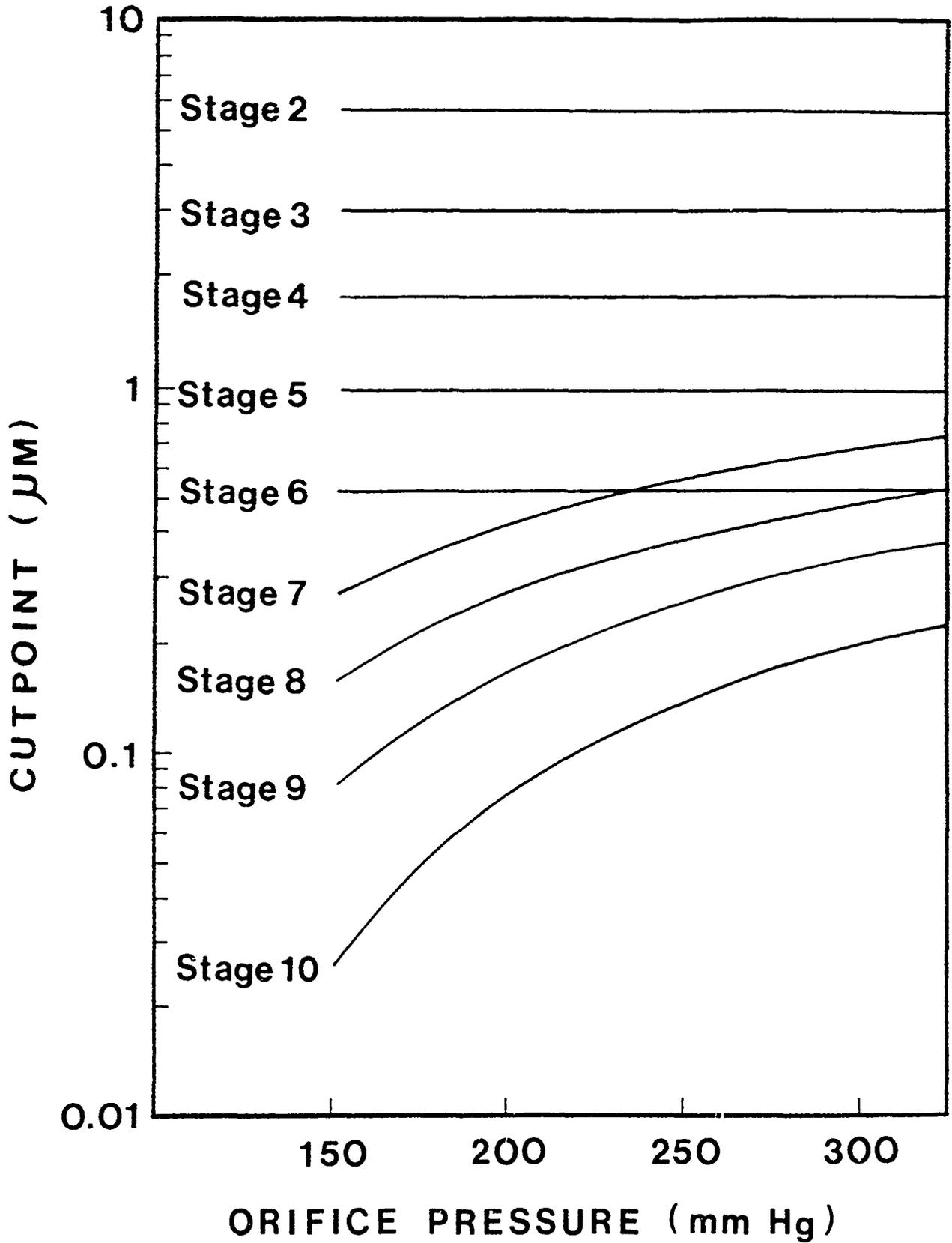


Figure 11. Predicted Stage Cutpoints as a Function of Orifice Operating Pressure.

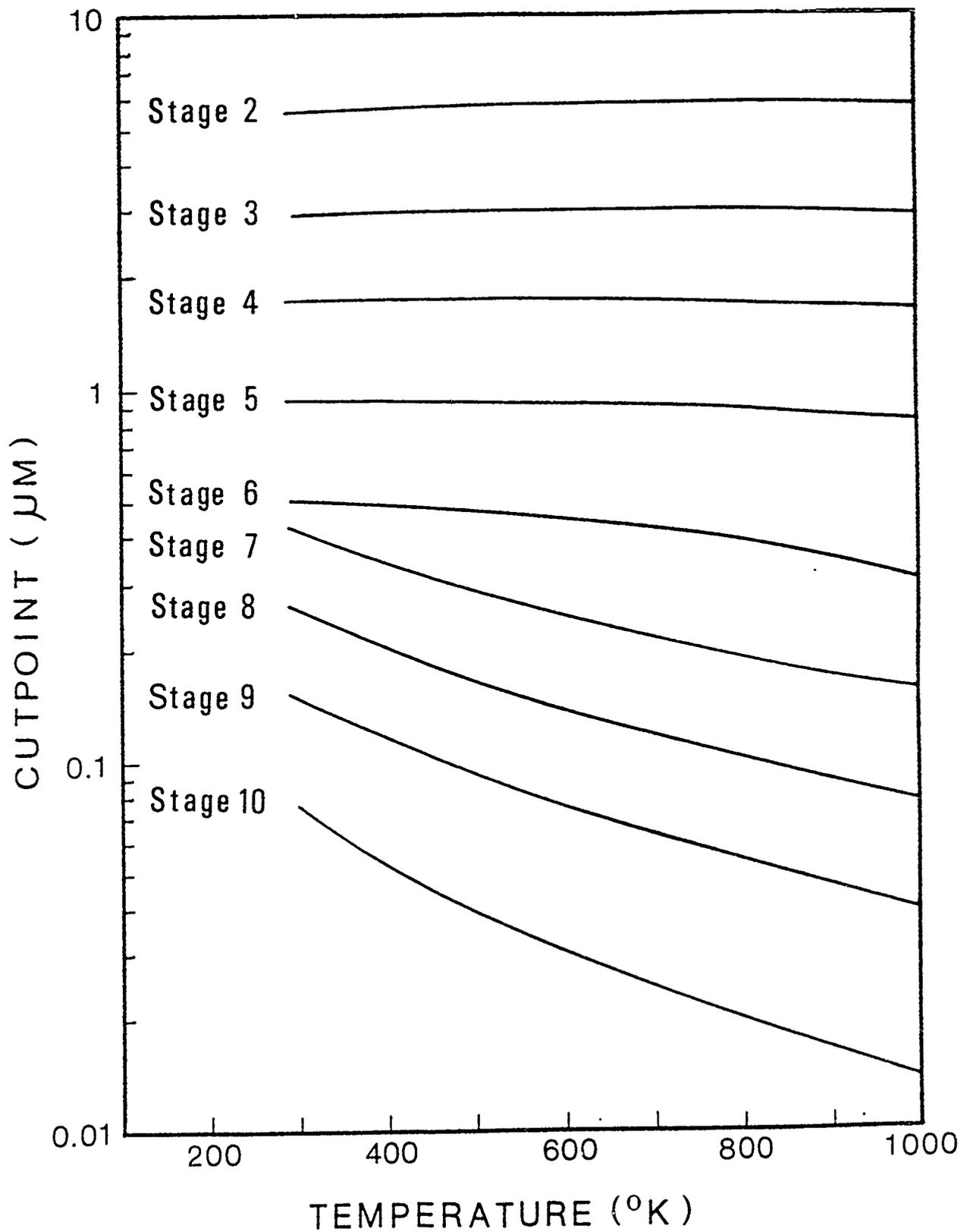


Figure 12. Predicted Stage Cutpoints as a Function of Stack Temperature. Orifice Pressure Equals 170 mm Hg.

taken at elevated temperature to ensure that choked flow does not develop in the final low-pressure stage. This can be accomplished by an increase in the absolute pressure below the critical orifice.

In industrial sampling, variations in stack temperature are more common than variations in stack pressure. This is especially true in sampling of jet engine exhausts where the stack pressure is essentially equal to ambient pressure. Temperatures in excess of 800°F are commonly encountered during sampling of jet engine exhausts. As a general rule, sampling at temperatures between 200°F and 500°F should be performed, using an orifice pressure of 225 mm mercury. An orifice pressure of 250 mm mercury is recommended for sampling at temperatures between 500°F and 800°F.

## SECTION IX

### PROGRAM DESCRIPTION AND OPERATION

As previously discussed, the in-stack performance of the low-pressure impactor is a strong function of the sampling temperature and pressure conditions. Variations in mass flow rate, fluid properties, stage pressure drops, jet velocities, and particle slip correction factors must all be considered when calculating stage cutpoints. Obviously, such a calculation for all 10 stages is quite complex and time-consuming and is thus, best performed by computer. An IBM compatible data reduction program has been developed for the low-pressure impactor. A listing of the IBM version is given in Appendix A along with a sample printout.

Upon booting the program, the user is prompted for specific data related to the stack gas sampling conditions. Input data includes the stack gas pressure, sampling time, critical orifice temperature and pressure, and estimated stack gas moisture content, and inlet nozzle diameter. The option exists for entering stage weight gains from an actual sampling test or using sample weight gains as supplied by the program. Individual stage weight gains must be entered in consistent mass units of milligrams so that the program output can be interpreted correctly.

The computer program is generally divided into four main sections. The fluid mass flow rate through the impactor is first calculated, based on the stack gas temperature and pressure. The pressure drop through each of the low-pressure stages is then determined from the mass flow rate and the fluid properties. Jet velocities for the impactor's ambient stages are calculated assuming incompressible flow while compressible flow relationships are used to calculate jet velocities in the four low-pressure stages. The aerodynamic cutpoints for each of the 10 impactor stages are based on the stage average

jet velocity and the fluid properties.

Execution of the data reduction program requires approximately 20 seconds. For the user's information, the nozzle jet velocity and Reynolds number for each stage is then displayed on the monitor. The hardcopy output consists of cutpoint, weight gain, percent Wt.  $\leq D_p$ , and  $DM/VD \log D_p$  for each of the ten stages. Values of  $DM/VD \log D_p$  for stages 1 and 10 are based on an assumed upper particle size of 30 micrometers and a lower size of 0.001 micrometers, respectively. Values are expressed in milligrams per dry standard cubic meter. Additional program output echoes the input data of the test run sampling conditions. The total standard volume of gas sampled is also recorded.

The program is useful for predicting the performance of the low-pressure impactor at various operating conditions. Before actual sampling, it is recommended that the user run the program at the expected sampling conditions. While the performance of the impactor's ambient stages is solely a function of the stack gas conditions, the behavior of the four low-pressure stages can be controlled by adjusting the operating pressure below the critical orifice. As discussed, care must be taken to ensure that none of the low-pressure stages reaches critical velocity. The program will notify the user if such a condition has been reached. The orifice pressure can also be adjusted to avoid overlap between Stage 6 and 7 when sampling at low stack pressures or high stack temperatures.

## SECTION X

### FIELD EVALUATION OF THE LOW-PRESSURE IMPACTOR

Tests were conducted at McClellan Air Force Base, Sacramento, California, from August 11 to August 22, 1986, to field-evaluate the low-pressure impactor (LPI) while sampling the exhaust from a jet engine test cell. Measurements were also made, using a Lundgren Diffusion Classifier (LDC).

The primary purpose for testing the low-pressure impactor was to determine how well it would operate under field conditions. As far as mechanical operation was concerned, the impactor operated very well. No mechanical problems were encountered with the impactor, impactor pump, or the temperature/pressure/flow controls. The pump itself is very heavy (100 pounds) but a crane was available to lift it to the roof.

Although the impactor incorporates a built-in final filter, the filter area is small and it could not be used at the normal flow, reduced pressure operating condition because of very high pressure drop. For these field evaluation tests an external, large diameter filter was used with the impactor. Although this filter worked mechanically, it developed an air leak at its low-pressure operating condition. A more compact, leak proof filter holder is needed for use with the impactor.

An old-style Cahn electronic balance, from the University of Florida, was sensitive to engine vibration and was very slow to stabilize on routine weighing of the impactor collection deposits. This caused weighing difficulties and increased the weighing error. A newer model Cahn electronic balance, used with the diffusion classifier, was much quicker to stabilize, but was also affected by the engine vibration.

Assembly of the grease-coated impactor collection surfaces was adequate but could be improved by development of an impaction collection surface configuration which is more convenient to handle and to weigh in the Cahn balance. The collected aerosol deposits had a proper appearance and in other ways looked ideal. Particle deposits, or particle losses, were not apparent within the impactor (other than on the intended collection surfaces). The impactor housing and stages were otherwise very convenient to assemble and disassemble.

Field testing of the impactor was conducted before laboratory calibration of the low pressure section was completed. Unfortunately, a design/manufacturing problem was found during calibration. A design correction was made to the impaction surface to nozzle plate spacing in order to obtain satisfactory particle classification in the unit's last four stages (the low-pressure section). These changes have been incorporated into the low-pressure section and it now performs very well, as shown by the calibration data presented elsewhere in this report. Unfortunately, the field-tested impactor did not incorporate these necessary changes and the size-classification of the submicron aerosol is not exactly known. Because the submicron fraction represents the majority of the jet engine aerosol, the size distribution data recovered from the impactor tests is somewhat in error.

Comparisons were to be made between aerosol size distributions measured by the low-pressure impactor and diffusion classifier. An exact comparison is not possible because of the impactor aerosol size-classification problem. Both instruments did clearly show that most of the aerosol is submicron (about 90 percent less than 1 micrometer in diameter) and both instruments show that the aerosol size distribution has a mass median diameter of about 0.1 micrometer.

Comparisons were made between the jet engine aerosol produced while burning normal jet fuel and while burning fuel with either a ferrocene or cerium additive. The purpose of the additive is to reduce plume opacity. Therefore, the aerosol measurement objective was to determine what change occurred in the aerosol concentration and size distribution. Although the low-pressure impactor size distribution data may be somewhat in error, this data is presented and compared. A total of 13 aerosol distributions were measured, using the low-pressure impactor. All tables and figures related to the field evaluation of the low-pressure impactor are presented in Appendix B and C. These tests are listed in Table B-1 together with test date and time. Fuel differences, incomplete data, and sampling procedure development during the first five tests make this data less suitable for comparison. Data sheets for each of the thirteen test runs are included in the appendix.

For comparison, the last eight test run results were used and the general aerosol comparison values are listed in Table B-2. Differential plots of the aerosol mass in each measured size interval is shown in Figure B-1, with cumulative distributions shown in Figure B-2.

The use of ferrocene or cerium as a fuel additive appears to have reduced the aerosol mass emission by about 10 percent. The effect on size distribution was slight (within the accuracy limitations of the measurements) but does appear to reduce the aerosol mass in the general 0.1 to 0.3 micrometer diameter size range. This is the size range most important for visual effects and does correlate with the observed reduction in opacity.

For all tests conducted at McClellan AFB, the diffusion classifier (LDC) and low-pressure impactor (LPI) were run at fairly compatible time periods at nearly adjacent locations. Optimum sampling times and preparation times are not equal for the two instruments, therefore, the comparisons could not be

identical. In total, eleven test runs were made with the diffusion classifier at times and conditions listed in Table C-1. Data sheets for the eleven tests are included in the appendix.

Test runs directly comparable to the low-pressure impactor data for the engine tests with and without cerium were obtained and used to "compare" LPI and LDC results. These data are plotted in Figures C-1 and C-2 and certain distribution parameters are listed in Table C-2. Tests 8 and 10 with the diffusion classifier were obtained at overlapping times with tests 10 and 11 and 12 and 13 with the low-pressure impactor.

Ferrocene data were not as directly comparable for the two measurement instruments. Test 7 for the LDC compares directly with Tests 8 and 9 of the LPI for a non-additive comparison. A test comparable to LPI Tests 6 and 7 was not available as the LDC was performed with Teflon filters on that day, because of the possible interest in later chemical analysis of the aerosol deposits. Teflon however, did not provide reliable weight values for mass distribution comparison. Test 4 was the only good ferrocene distribution obtained with the diffusion classifier. Fuel burned during this test was different (JP-4 and JP-5 mix rather than only JP-4), therefore, LDC Test 1 is also listed and plotted to show the difference resulting from the fuel and/or from lack of test reproductability or difference in day to day test results.

Conclusions drawn from the diffusion classifier tests are similar in that the aerosol is 90 percent less than one micrometer diameter and has a mass median diameter of about 0.1 micrometer. Data also show a decrease in the 0.1 to 0.3 aerosol mass fraction (that responsible for most of the aerosol visibility). Although the aerosol mass does not appear to be reduced significantly with the cerium or ferrocene additive, the mean particle size does appear to be shifted to a smaller size (less than 0.1 micrometer).

Caution must be used in comparing the low-pressure impactor and diffusion classifier results. The impactor provides inertially classified samples based upon an aerodynamic equivalent size. The diffusion classifier provides classification based upon a diffusion (or a diffusional equivalent) diameter. For spherical particles these diameters, through careful calibration, are equivalent. Unfortunately, jet engine aerosol is a flocculant, carbon chain agglomerant aerosol with which neither the impactor nor the diffusion classifier have been calibrated. Conceptionally, both instruments worked well and qualitatively agree as to the aerosol distribution shape.

A second note or comment should be made as to the plotting of data. Impactor classifications are quite sharp and data can be directly plotted. Diffusion classification is very gradual (meaning it is a weak function of particle size); therefore, the raw weight values need to be processed to present a better representation of the actual aerosol distribution shape. Examples of raw data plots versus processed data plots are shown in Figure C-1 and Figure C-3.

The Figure C-3 plot results from direct use of weight gain values from the LDC stages. The Figure C-1 plot results from using Twomey's algorithm to reduce the data to the most probable distribution form.

Because this was the first attempt to use the low-pressure impactor in the field and because of other measurement problems the above data analysis/comparison should not be extropolated or interpreted further.

## SECTION XI

### CONCLUSIONS AND RECOMMENDATIONS

A 10-stage, high flow rate low-pressure impactor has been designed and constructed for the sampling of industrial aerosols. The unit is physically well-suited to the requirements of sampling aircraft jet engine exhausts. The impactor consists of six ambient pressure stages, followed by four low-pressure stages and operates at a sampling flow rate of 1.00 cfm at standard temperature and pressure.

Unlike ambient impactors whose cutpoints can be reasonably predicted using incompressible flow theory, prediction of the low-pressure impactor's performance required use of a compressible fluid model. Measurement of the non ideal fluid behavior through the low-pressure stages under compressible flow conditions led to the development of empirical discharge coefficients for the sharp entry nozzles of the impactor. Use of these coefficients allows prediction of stage pressure drops as a function of the nozzle dimensions and the fluid properties at the nozzle inlet. A computer program has been written which incorporates the fluid flow theory to predict stage pressure drops as well as stage cutpoints. These calculations are made as a function of stack temperature, stack pressure, and critical orifice operating pressure.

The collection characteristics of the impactor's ambient stages were calibrated using monodisperse aerosols generated primarily with the vibrating orifice aerosol generator. Cutpoints for stages 2 through 6 were measured to be 5.5, 2.9, 1.78, 0.95 and 0.50  $\mu\text{m}$  aerodynamic diameter. These collection efficiency curves were generally quite sharp and their cutpoints agreed well with those predicted using standard impactor theory.

Calibration of the four low-pressure stages was performed using monodisperse aerosols generated with an electrostatic classifier. All low-pressure collection efficiency tests were conducted using a critical orifice absolute pressure of 170 mm Hg. Calibration results indicate that the four low-pressure stages should fractionate an aerosol into fairly sharp, well-defined size fractions. Measured cutpoints of stages 7 through 10 were found to be 0.52, 0.20, 0.11, and 0.047  $\mu\text{m}$  aerodynamic diameter. Agreement between the stage's predicted and calibrated cutpoints was optimum when the Cunningham slip correction factor was evaluated in terms of the stagnation pressure at the stage inlet.

Calibration of the impactor's first low-pressure stage initially resulted in a very poor efficiency curve. Later installation of a non collecting impaction plate above the stage significantly improved the stage's collection characteristics. Since the exact effect of the plate's presence on the stage's performance is not well-understood, this subject is recommended for further research. Accurate understanding of the fluid behavior in the region between the critical orifice and the first low-pressure stage is essential to future low-pressure impactor design.

During calibration, no solid particle bounce was evident from greased impaction substrates, even at the high jet velocities typical of the low-pressure stages. Use of uncoated impaction plates, however, resulted in significantly poorer stage performance. It is evident that some type of substrate is necessary to achieve adequate particle retention. Another needed area of research is the review and evaluation of various, substrates capable of providing adequate particle retention during high-temperature sampling without undergoing unacceptable weight loss. Limited test results using glass-fiber substrates suggest they may be of value during high-temperature sampling of submicron aerosols where the use of currently available greases

may be inappropriate.

Limited field tests of the low-pressure impactor indicated that the unit can sample under the rigid conditions of jet engine test cell sampling. No major mechanical problems were encountered with the impactor during the test cell sampling. Two minor modifications can be suggested, however, to the impactor's design. The pressure drop through the unit's 47 mm diameter after filter is unacceptably high. A compact, lower-pressure-drop filter holder should be designed and fitted to the impactor's outlet section. It is also recommended that a newer type of impaction plate should be designed to provide more convenient handling and weighing.

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APPENDIX A  
LOW-PRESSURE IMPACTOR  
DATA REDUCTION PROGRAM

SAMPLE TEST DATA

\*\*\*\*\* AIR FORCE LOW PFESSURE IMPACTOR \*\*\*\*\*

| STAGE | CUTPOINT (UM) | WT (MG) | %WT · DF | DM/(V LOG DF) |
|-------|---------------|---------|----------|---------------|
| 1     | 11.3          | 0.000   | 100      | 0.00          |
| 2     | 5.7           | 0.300   | 95       | 2.07          |
| 3     | 3.0           | 0.330   | 90       | 2.42          |
| 4     | 1.7           | 0.690   | 79       | 6.21          |
| 5     | 0.950         | 1.840   | 49       | 14.51         |
| 6     | 0.480         | 0.910   | 34       | 6.37          |
| 7     | 0.248         | 0.550   | 25       | 3.96          |
| 8     | 0.142         | 0.410   | 18       | 3.53          |
| 9     | 0.075         | 0.490   | 10       | 3.66          |
| 10    | 0.027         | 0.330   | 5        | 1.53          |
| 11    | -----         | 0.341   | 0        | 0.50          |

STACK PFESSURE MM HG = 760

ORIFICE TEMPERATURE DEG F = 300

ORIFICE PFESSURE MM HG = 170

SAMPLING TIME MIN = 20

GAS MOISTURE CONTENT % = 0

INLET NOZZLE DIAMETER (IN) .5

VOLUME SAMPLED DSCM = .482

NOTE: VALUES OF DM/ (V LOG DF) ARE BASED ON AN ASSUMED UPPER PARTICLE SIZE OF 30 MICROMETERS AND A LOWER SIZE OF 0.001 MICROMETERS. VALUES ARE EXPRESSED IN UNITS OF MG/DSCM

NOTE: STAGE WEIGHT GAINS ARE SAMPLE DATA ONLY

```

100 CLS
110 PRINT TAB(22);"*** AIR FORCE LOW PRESSURE IMPACTOR ***":PRINT
120 PRINT:PRINT
130 FOR J=1 TO 1000:NEXT
140 DIM FN(12),WT(12),PC(12),FL(12),DM(12),SZ(12),ST(12),RE(12)
150 INPUT "TITLE HEADING OF PAPER=";TI$:PRINT
160 TB=INT((79-LEN(TI$))/2 )
170 INPUT "ENTER STACK PRESSURE MM HG ";PS
180 INPUT "ENTER SAMPLING TIME MIN ";TM
190 INPUT "ENTER ORIFICE PRESSURE MM HG ";OP
200 INPUT "ENTER ORIFICE TEMPERATURE DEG F ";TF
210 INPUT "ENTER GAS MOISTURE CONTENT % ";PW
215 INPUT "ENTER INLET NOZZLE DIAMETER (IN)";WW
216 W(1)=WW*2.54
220 PRINT
230 REM READ SAMPLE STAGE WT GAINS (MG)
240 FOR J=1 TO 11:READ WT(J):NEXT J
250 INPUT "DO YOU WISH TO ENTER STAGE WT GAINS? ";AN$
260 IF AN$="" THEN GOTO 240
270 IF AN$="Y" THEN PRINT:GOTO 290
280 GOTO 340
290 FOR J=1 TO 10
300 PRINT "ENTER STAGE ";J;" WT GAIN MG";:INPUT " ";WT(J)
310 IF WT(J)<0 THEN WT(J)=0
320 NEXT J
330 INPUT "ENTER AFTERFILTER WT GAIN MG ";WT(11)
340 REM CALC DEG K AND VISCOSITY
350 TK=(TF-32)/1.8+273
360 MU=(TK1.5)/(6.800001E-02*TK+7.8)*.000001
370 REM DEFINE STAGE NOZZLE DIAMETERS
380 FOR J=2 TO 10
390 READ W(J)
400 NEXT J
410 REM DEFINE STAGE ORIFICE LENGTHS
420 FOR J=1 TO 10
430 READ L(J)
440 NEXT J
450 REM DEFINE STAGE ORIFICE AREAS
460 FOR J=1 TO 10
470 READ A(J)
480 NEXT J
490 REM DEFINE STAGE SQR(STOKES) NUMBERS
500 FOR J=1 TO 10:READ ST(J):NEXT J
510 REM CALC CD VALUES FOR CRITICAL ORIFICE FOR TEMP AND PRESSURE
520 CP=.295*PS.171
530 CT=.946-.0000924*TK
540 REM CALC MASS FLOWRATE
550 MF=.57*PS/760*SQR(296/TK)*CP/.917*.916/CT
560 REM CALC ACTUAL FLOW AND AMBIENT STAGE VELOCITIES
570 Q=MF*TK/293*760/PS/.0012
580 FOR J=1 TO 6
590 V(J)=Q/A(J)
600 PN(J)=PS

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```

610 RE(J)=.0012*PN(J)/760*296/TK*V(J)*W(J)/MU
620 NEXT J
630 PN(7)=0P
640 REM ALGORITHM FOR CALCULATING PRESSURE DROPS
650 FOR J=7 TO 10
660 PN=PN(J)*1010000!/760
670 M1=MF*SQR(2870000!*TK)/A(J)/PN
680 REM DEFINE R UPPER AND LOWER LIMITS: .9 IS FIRST ESTIMATE
690 RL=.4:RU=1:R=.8
700 V(J)=SQR(2.8/.4*2870000!*TK*(1-R^(.4/1.4)))
710 RE(J)=.0012*293/TK*PN(J)/760*V(J)*W(J)/MU
720 RR=RE(J)*W(J)/L(J)
730 REM CALCULATE DISCHARGE COEFFICIENT
740 CD=.233*RR^.178
750 REM CALC M2 VALUE
760 M2=CD*R^.714*SQR(2.8/.4*(1-R^(.4/1.4)))
770 REM CHECK FOR MATCH AND ADJUST R VALUE
780 IF M1/M2 < 1 THEN RL=R
790 IF M1/M2 > 1 THEN RU=R
800 RO=R
810 R=(RL+RU)/2
820 IF ABS(R/RO-1) < .0005 THEN GOTO 850
830 GOTO 700
840 REM CALC OUTLET PRESSURE AND SET NEXT STAGE INLET PRESSURE
850 PO(J)=INT(PN(J)*R+.5)
860 IF R<.53 THEN V(J)=SQR(2.8/2.4*2870000!*TK)
870 PN(J+1)=PO(J):PN(7)=0P
880 NEXT J
890 REM FIND LOW PRESSURE STAGE AVERAGE VELOCITIES
900 FOR J= 7 TO 10
910 IF PO(J)/PN(J)<.53 THEN V(J)=SQR(2.8/1.4*2870000!*TK):GOTO 1010
920 VL=0:VU=50000!:V=15000
930 M1=V
940 M2=Q*PS/(A(J)*PO(J))*(1-V^2*.4/(2.8*2870000!*TK))
950 IF M1/M2 < 1 THEN VL=V
960 IF M1/M2 > 1 THEN VU=V
970 VO=V
980 V=(VU+VL)/2:V(J)=V
990 IF ABS(V/VO-1)<.0005 THEN GOTO 1010
1000 GOTO 930
1010 RE(J)=.0012*PN(J)/760*296/TK*V(J)*W(J)/MU
1020 NEXT J
1030 CLS:FOR J=1 TO 1000:NEXT:PRINT:PRINT:PRINT
1040 PRINT TAB(27) "IMPACTOR OPERATING CONDITIONS":PRINT:PRINT:PRINT
1050 PRINT TAB(20)"STAGE";TAB(33)"VEL (CM/SEC)";TAB(52)"REYNOLDS NO.":PRINT
1060 FOR J=1 TO 10
1070 V(J)=INT (V(J)):RE(J)=INT(RE(J))
1080 PRINT TAB(21) USING "##";J;:PRINT TAB(36) USING "#####";V(J);:PRINT TAB(55)
  USING "#####";RE(J)
1090 NEXT J
1095 IF PO(10)/PO(9)>.53 THEN GOTO 1098
1096 PRINT:PRINT:PRINT " * NOTE: THE LPI SHOULD NOT BE OPERATED UNDER THESE C
ONDITIONS. STAGE 10"
1097 PRINT " HAS REACHED CRITICAL FLOW. THE ORIFICE PRESSURE SHOULD BE INC
REASED."

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1098 FOR J=1 TO 5000:NEXT
1100 FOR J=1 TO 10
1110 REM DEFINE UPPER AND LOWER PARTICLE SIZE
1120 SL=.0005:SU=20:SZ=1
1130 REM CALC CN=F(T,SZ,P)
1140 REM CALC KNUDSEN NUMBER
1150 PA=FN(J)/760
1160 KN=.0653*(2/(PA*SZ))*(TK/296)*(1+110/296)/(1+110/TK)
1170 CN=1+1.246*KN+.42*KN*EXP(-.87/KN)
1180 M1=SQR(CN)*SZ
1190 M2=SQR(9*MU*W(J)/V(J))*ST(J)*10000!
1200 IF M1/M2<1 THEN SL=SZ
1210 IF M1/M2>1 THEN SU=SZ
1220 SO=SZ
1230 SZ=(SL+SU)/2
1240 IF ABS(SO/SZ-1)<.0005 THEN GOTO 1270
1250 GOTO 1160
1260 REM SET CUTPOINT
1270 SZ(J)=SZ
1280 NEXT J
1290 SZ(11)=.001
1300 PRINT
1310 REM CALC %<DF
1320 SM=0
1330 FOR J=1 TO 11
1340 SM=SM+WT(J)
1350 NEXT J
1360 FOR J=1 TO 11
1370 PC(J)=INT(WT(J)/SM*100+.5)
1380 NEXT J
1390 PL(1)=100 - PC(1)
1400 FOR J=2 TO 11
1410 PL(J)=PL(J-1)-PC(J)
1420 NEXT J
1430 REM CALC STANDARD VOLUME (M^3)
1440 FM=PW/100
1450 DE=.0012*MS/29
1460 VL=MF*TM*60/(.0012*1000000!)/(1+FM)
1470 REM CALC DELTA MASS/(V LOGDP) MG/M^3
1480 DM(1)=WT(1)/(VL*LOG(30/SZ(1))/2.3026)
1490 FOR J=2 TO 10
1500 DM(J)=WT(J)/(VL*LOG(SZ(J-1)/SZ(J))/2.3026)+.0001
1510 NEXT J
1520 DM(11)=WT(11)/(VL*LOG(SZ(10)/.001)/2.3026)
1530 FOR J=1 TO 3:BEEP:NEXT
1540 LPRINT TAB(TB);TI$:LPRINT:LPRINT:LPRINT
1550 LPRINT TAB(15);
1560 LPRINT "***** AIR FORCE LOW PRESSURE IMPACTOR *****"
1570 FOR J=1 TO 5:LPRINT:NEXT
1580 LPRINT TAB(5)"STAGE";SPC(6)"CUTPOINT (UM)";SPC(5)"WT (MG)";SPC(7)"%WT < DF"
;SPC(5)"DM/(V LOG DP)":LPRINT
1590 SZ(11)=.001
1600 FOR J=1 TO 10
1610 D=3:IF J<5 THEN D=1
1620 SZ=(INT(SZ(J) *10^D+.5))/10^D

```

```

1630 D=2
1640 IF WT(J)<0 THEN WT(J)=0!
1650 WT=WT(J)
1660 IF DM(J)<0 THEN DM(J)=0!
1670 PL=PL(J)
1680 DM=(INT(DM(J)*1000+.5))/1000
1690 LPRINT TAB(6) USING "##";J;
1700 IF J<5 THEN LPRINT TAB(19) USING "##.#";SZ;:GOTO 1720
1710 LPRINT TAB(19) USING "##.###";SZ;
1720 LPRINT TAB(34) USING "##.###";WT;:LPRINT TAB(51) USING "###";PL;:LPRINT TAB
(63) USING "###.##" ;DM
1730 NEXT J
1740 C$="-----":PL=0:J=11:WT=WT(J):DM=DM(J)
1750 LPRINT TAB(6) USING "##";J;:LPRINT TAB(20);C$;:LPRINT TAB(34) USING "##.###
";WT;:LPRINT TAB(51) USING "###";PL;:LPRINT TAB(63) USING "###.##" ;DM
1760 REM ECHO INPUT DATA
1770 K=6:FOR J=1 TO 3:LPRINT:NEXT
1780 LPRINT TAB(K)"STACK PRESSURE MM HG = ";PS:LPRINT
1790 LPRINT TAB(K)"ORIFICE TEMPERATURE DEG F = ";TF:LPRINT
1800 LPRINT TAB(K)"ORIFICE PRESSURE MM HG = ";OP:LPRINT
1810 LPRINT TAB(K)"SAMPLING TIME MIN = ";TM:LPRINT
1820 LPRINT TAB(K)"GAS MOISTURE CONTENT % = ";PW:LPRINT
1825 LPRINT TAB(K) "INLET NOZZLE DIAMETER (IN)";WW:LPRINT
1830 VL=(INT(VL*1000))/1000
1840 LPRINT TAB(K)"VOLUME SAMPLED DSCM = ";VL:LPRINT:LPRINT
1850 LPRINT TAB(K)"NOTE: VALUES OF DM/ (V LOG DP) ARE BASED ON AN ASSUMED UPPER
PARTICLE"
1860 LPRINT TAB(K+6)"SIZE OF 30 MICROMETERS AND A LOWER SIZE OF 0.001 MICROMETER
S."
1870 LPRINT TAB(K+6)"VALUES ARE EXPRESSED IN UNITS OF MG/DSCM"
1880 IF AN$<>"Y" THEN LPRINT:LPRINT TAB(K)"NOTE: STAGE WEIGHT GAINS ARE SAMPLE D
ATA ONLY"
1890 END
1900 REM SAMPLE WT GAINS (MG)
1910 DATA 0,.3,.33,.69,1.84,.91,.55,.41,.49,.33,.341
1920 REM NOZZLE DIAMETERS (CM)
1930 DATA .352,.211,.118,.0714,.0412,.065,.0523,.0343,.0256
1940 REM ORIFICE LENGTHS (CM)
1950 DATA 2,.813,.411,.218,.157,.076,.119,.104,.056,.053
1960 REM STAGE ORIFICE TOTAL AREAS (CM^2)
1970 DATA 1.266,1.167,.629,.393,.224,.133,.398,.322,.296,.2646
1980 REM STAGE SQR(STOKES) VALUES
1990 DATA .47,.47,.44,.45,.44,.42,.45,.44,.45,.40

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APPENDIX B  
LOW-PRESSURE IMPACTOR  
FIELD EVALUATION TEST RESULTS

TABLE B-1. LOW-PRESSURE IMPACTOR TEST TIMES

| TEST # | DATE      | TIME     | LENGTH | VOLUME | CONCENTRATION | FUEL  | ADDITIVE  |
|--------|-----------|----------|--------|--------|---------------|-------|-----------|
| 1      | 13 Aug 86 | 10:30 am | 10 min | 0.25   | 7.80          | JP4/5 | None      |
| 2      | 14 Aug 86 | 9:00 am  | 20 min | 0.50   | 9.60          | JP4/5 | None      |
| 3      | 14 Aug 86 | 2:30 pm  | 20 min | 0.50   | 7.64          | JP4/5 | Ferrocene |
| 4      | 15 Aug 86 | 8:30 am  | 20 min | 0.50   | 8.70          | JP4/5 | Ferrocene |
| 5      | 15 Aug 86 | 2:00 pm  | 20 min | 0.50   | 6.16          | JP4   | Ferrocene |
| 6      | 18 Aug 86 | 10:00 am | 20 min | 1.00   | 7.38          | JP4   | Ferrocene |
| 7      | 18 Aug 86 | 11:00 am | 20 min |        |               | JP4   | Ferrocene |
| 8      | 19 Aug 86 | 10:00 am | 20 min | 1.00   | 8.25          | JP4   | None      |
| 9      | 19 Aug 86 | 11:00 am | 20 min |        |               | JP4   | None      |
| 10*    | 20 Aug 86 | 8:30 am  | 20 min | 1.00   | 8.66          | JP4   | None      |
| 11     | 20 Aug 86 | 9:30 am  | 20 min |        |               | JP4   | None      |
| 12     | 21 Aug 86 | 9:30 am  | 30 min | 1.50   | 7.63          | JP4   | Cerium    |
| 13     | 21 Aug 86 | 10:30 am | 30 min |        |               | JP4   | Cerium    |

\*Changed to different engine.

TABLE B-2. AEROSOL COMPARISON VALUES (LOW-PRESSURE IMPACTOR)

| TEST #  | ENGINE      | TEST CONDITION            | CONCENTRATION<br>mg/cu. m | AEROSOL    |    | MASS FRACTION |              |
|---------|-------------|---------------------------|---------------------------|------------|----|---------------|--------------|
|         |             |                           |                           | MMD*<br>um |    | <1 um<br>%    | <0.1 um<br>% |
| 6 & 7   | J-79-GE-15A | Ferrocene at<br>85% power | 7.38                      | 0.065      | 94 | 63            |              |
| 8 & 9   | J-79-GE-15A | No additive               | 8.25                      | 0.08       | 94 | 57            |              |
| 10 & 11 | J-79-GE-15A | No additive               | 8.66                      | 0.10       | 88 | 49            |              |
| 12 & 13 | J-79-GE-15A | Cerium                    | 7.63                      | 0.12       | 86 | 45            |              |

\*MMD for Low-Pressure Impactor is an Aerodynamic Equivalent Particle Size.

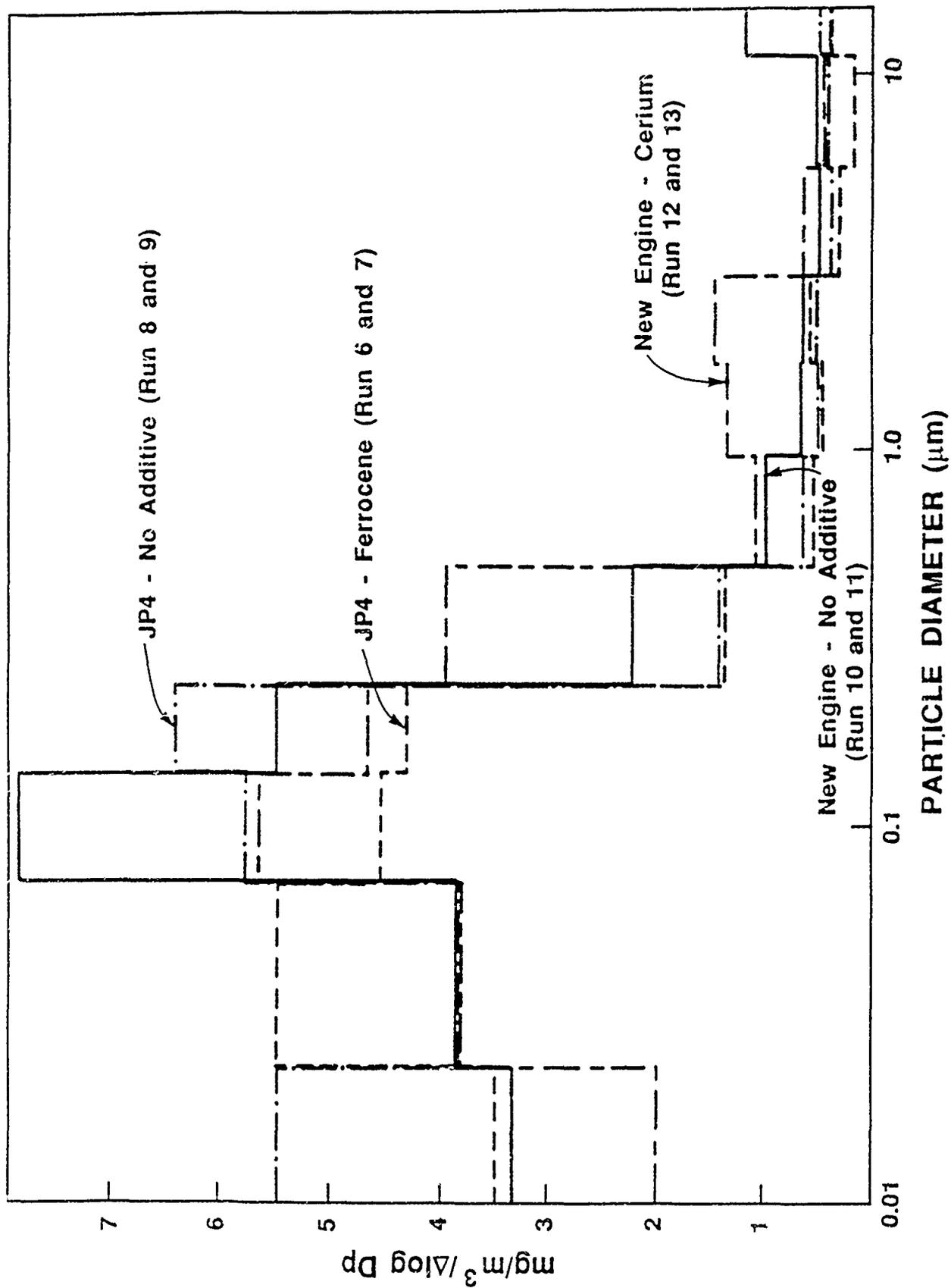


FIG B-1. Mass Distribution Histograms from Low-Pressure Impactor Tests

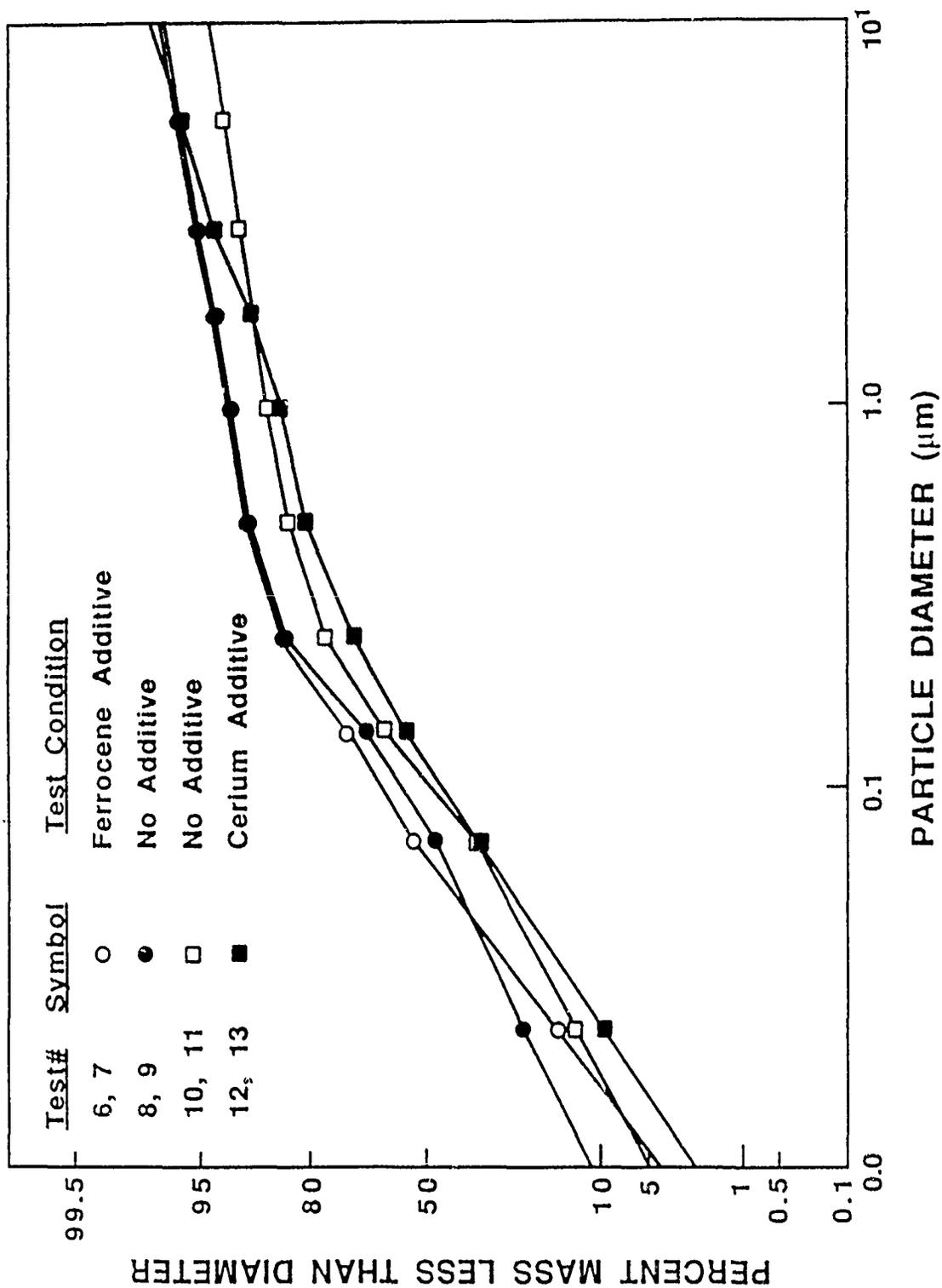


FIG 8-2. Cumulative Distribution Data from Low-Pressure Impactor Tests

TABLE B-3. LOW-PRESSURE IMPACTOR DATA SHEET

Test Number: 1  
 Date: 8-13-86  
 Time: 10:30  
 Gas flow rate: 25 lpm (std.)  
 Sampling time: 10 min.  
 Sampling volume: 0.25 cu. m (std.)  
 Test Condition: 85% Power  
 Fuel: JP 4/5 - No Additive  
 Engine: J-79-GE-15A  
 Gas temperature: 198 F  
 Stack pressure: 760 mm Hg  
 Impactor pressure: 157 mm Hg

| Stage Number | Dp50 $\mu$ m  | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\Sigma W} - \%$ | $\% < Dp$ |
|--------------|---------------|----------------|------------------------|------------------|------------------------------|---------------------------|-----------|
| 1            | 11.2          | --             |                        | 0.43             | --                           | --                        | --        |
| 2            | 5.6           | --             |                        | 0.30             | --                           | --                        | --        |
| 3            | 2.9           | --             |                        | 0.29             | --                           | --                        | --        |
| 4            | 1.7           | --             |                        | 0.23             | --                           | --                        | --        |
| 5            | .96           | .04            | .16                    | 0.25             | 0.64                         | 2.1                       | 97.9      |
| 6            | .49           | .01            | .04                    | 0.29             | 0.14                         | 0.5                       | 97.4      |
| 7            | .24           | .24            | .96                    | 0.31             | 3.10                         | 12.3                      | 85.1      |
| 8            | .14           | .08            | .32                    | 0.23             | 1.39                         | 4.1                       | 81.0      |
| 9            | .072          | .14            | .56                    | 0.29             | 1.93                         | 7.2                       | 73.8      |
| 10           | .023          | .47            | 1.88                   | 0.50             | 3.76                         | 24.1                      | 49.7      |
| Filter       | .01<br>(.001) | .97            | 3.88                   | 0.36<br>(1.36)   | 10.78                        | 49.7                      |           |

Total Aerosol Concentration = 7.80 mg/cu. m

TABLE B-4. LOW-PRESSURE IMPACTOR DATA SHEET

| Stage Number | Dp50 $\mu$ m  | Weight Gain mg | Concentration mg/cu. m | $\Delta \log p$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\Sigma W} - \%$ | % < Dp |
|--------------|---------------|----------------|------------------------|-----------------|------------------------------|---------------------------|--------|
| 1            | 11.2          | --             |                        | 0.43            | --                           |                           |        |
| 2            | 5.6           | --             |                        | 0.30            | --                           |                           |        |
| 3            | 2.9           | .02            | .04                    | 0.29            | .14                          | .04                       | 99.6   |
| 4            | 1.7           | .10            | .20                    | 0.23            | .87                          | 2.1                       | 97.5   |
| 5            | .96           | .08            | .16                    | 0.25            | .64                          | 1.7                       | 95.8   |
| 6            | .49           | .28            | .56                    | 0.29            | 2.21                         | 5.8                       | 90.0   |
| 7            | .24           | .46            | .92                    | 0.31            | 2.97                         | 9.6                       | 80.4   |
| 8            | .14           | .98            | 1.96                   | 0.23            | 8.52                         | 20.4                      | 60.0   |
| 9            | .072          | 1.19           | 2.38                   | 0.29            | 8.21                         | 24.8                      | 35.2   |
| 10           | .023          | .94            | 1.88                   | 0.50            | 3.76                         | 19.6                      | 15.6   |
| Filter       | .01<br>(.001) | .75            | 1.50                   | 0.36<br>(1.36)  | 4.17<br>(1.10)               | 15.6                      |        |

Test Condition: 85% Power  
 Fuel: JP 4/5 - No Additive  
 Engine: J-79-GE-15A  
 Gas temperature: 181 F  
 Stack pressure: 760 mm Hg  
 Impactor pressure: 156 mm Hg

Test Number: 2  
 Date: 8-14-86  
 Time: 9:00  
 Gas flow rate: 25 lpm  
 Sampling time: 20 min.  
 Sampling volume: 0.50 cu. m

Total Aerosol Concentration = 9.60 mg/cu. m

TABLE B-5. LOW-PRESSURE IMPACTOR DATA SHEET

Test Number: 3  
 Date: 8-14-86  
 Time: 14:30  
 Gas flow rate: 25 lpm  
 Sampling time: 20 min.  
 Sampling volume: 0.50 cu. m  
 Test Condition: 85% Power  
 Fuel: JP 4/5 Ferrocene  
 Engine: J-79-GH-15A  
 Gas temperature: 206 F  
 Stack pressure: 760 mm Hg  
 Impactor pressure: 155 mm Hg

| Stage Number | Dp50 um       | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\Sigma W} \cdot \%$ | %<Dp |
|--------------|---------------|----------------|------------------------|------------------|------------------------------|-------------------------------|------|
| 1            | 11.2          | --             |                        | 0.43             |                              |                               |      |
| 2            | 5.6           | --             |                        | 0.30             |                              |                               |      |
| 3            | 2.9           | --             |                        | 0.29             |                              |                               |      |
| 4            | 1.7           | --             |                        | 0.23             |                              |                               |      |
| 5            | .96           | .05            | .06                    | 0.25             | .24                          | .8                            | 99.2 |
| 6            | .49           | .09            | .18                    | 0.29             | .62                          | 2.4                           | 96.8 |
| 7            | .24           | .48            | .96                    | 0.31             | 3.10                         | 12.6                          | 84.2 |
| 8            | .14           | .71            | 1.42                   | 0.23             | 6.17                         | 18.6                          | 65.6 |
| 9            | .072          | .85            | 1.70                   | 0.29             | 5.86                         | 22.2                          | 43.4 |
| 10           | .023          | 1.45           | 2.90                   | 0.50             | 5.80                         | 37.9                          | 5.5  |
| Filter       | .01<br>(.001) | 0.21           | .42                    | 0.36<br>(1.36)   | 1.17<br>(0.31)               | 5.5                           |      |

Total Aerosol Concentration = 7.64 mg/cu. m3

TABLE B-6. LOW-PRESSURE IMPACTOR DATA SHEET

Test Number: 4  
 Date: 8-15-86  
 Time: 8:30  
 Gas flow rate: 25 lpm  
 Sampling time: 20 min.  
 Sampling volume: 0.50 cu. m  
 Test Condition: 85% Power  
 Fuel: JP 4/5 Ferrocene  
 Engine: J-79-GE-15A  
 Gas temperature: 180 F  
 Stack pressure: 760 mm Hg  
 Impactor pressure: 156 mm Hg

| Stage Number | Dp <sub>50</sub> um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log D_p$ | $\frac{W/V}{\Delta \log D_p}$ | $\frac{W - \%}{\Sigma W}$ | %<Dp |
|--------------|---------------------|----------------|------------------------|-------------------|-------------------------------|---------------------------|------|
| 1            | 11.2                | --             |                        | 0.43              | --                            |                           |      |
| 2            | 5.6                 | --             |                        | 0.30              | --                            |                           |      |
| 3            | 2.9                 | --             |                        | 0.29              | --                            |                           |      |
| 4            | 1.7                 | .02            | .04                    | 0.23              | .17                           | 0.5                       | 99.5 |
| 5            | .96                 | .07            | .14                    | 0.25              | .56                           | 1.6                       | 97.9 |
| 6            | .49                 | .02            | .04                    | 0.29              | .14                           | 0.5                       | 97.4 |
| 7            | .24                 | .33            | .66                    | 0.31              | 2.13                          | 7.6                       | 89.8 |
| 8            | .14                 | .58            | 1.16                   | 0.23              | 5.80                          | 13.3                      | 76.5 |
| 9            | .072                | .89            | 1.78                   | 0.29              | 6.14                          | 20.4                      | 56.1 |
| 10           | .023                | 1.40           | 2.80                   | 0.50              | 5.60                          | 32.2                      | 23.9 |
| Filter       | .01<br>(.001)       | 1.04           | 2.08                   | 0.36<br>(1.36)    | 5.78<br>(1.53)                | 23.9                      |      |

Total Aerosol Concentration = 8.70 mg/cu. m

TABLE B-7. LOW-PRESSURE IMPACTOR DATA SHEET

| Stage Number | Dp50 um       | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W - \%}{\Sigma W}$ | % < Dp |
|--------------|---------------|----------------|------------------------|------------------|------------------------------|---------------------------|--------|
| 1            | 11.2          | --             |                        | 0.43             | --                           |                           |        |
| 2            | 5.6           | --             |                        | 0.30             | --                           |                           |        |
| 3            | 2.9           | --             |                        | 0.29             | --                           |                           |        |
| 4            | 1.7           | --             |                        | 0.23             | --                           |                           |        |
| 5            | .96           | .03            | .06                    | 0.25             | .24                          | 1.0                       | 99.0   |
| 6            | .49           | .10            | .20                    | 0.29             | .69                          | 3.2                       | 95.8   |
| 7            | .24           | .13            | .26                    | 0.31             | .84                          | 4.2                       | 91.6   |
| 8            | .14           | .31            | .62                    | 0.23             | 2.70                         | 10.1                      | 81.5   |
| 9            | .072          | .66            | 1.32                   | 0.29             | 4.55                         | 21.4                      | 60.1   |
| 10           | .023          | 1.02           | 2.04                   | 0.50             | 4.08                         | 33.1                      | 27.0   |
| Filter       | .01<br>(.001) | .83            | 1.66                   | 0.36<br>(1.36)   | 4.61<br>(1.22)               | 27.0                      |        |

Test Condition: 85% Power  
 Fuel: JP 4 - Ferrocene  
 Engine: J-79-Git-15A  
 Gas temperature: 205 F  
 Stack pressure: 760 mm Hg  
 Orifice pressure: 160 mm Hg

Test Number: 5  
 Date: 8-15-86  
 Time: 14:00  
 Gas flow rate: 25 lpm  
 Sampling time: 20 min.  
 Sampling volume: 0.50 cu. m

Total Aerosol Concentration = 6.16 mg/cu. m

TABLE B-8. LOW-PRESSURE IMPACTOR DATA SHEET

Test Number: 6 & 7  
 Date: 8-18-86  
 Time: 10:00 & 11:00  
 Gas flow rate: 25 lpm (std.)  
 Sampling time: 20 min + 20 min.  
 Sampling volume: 0.5 + 0.5 = 1.00 cu. m (std.)  
 Test Condition: 85% Power  
 Fuel: JP 4 - Ferrocene  
 Engine: J-79-GE-15A  
 Gas temperature: 186 & 194 F  
 Stack pressure: 760 mm Hg  
 Orifice pressure: 156 & 156 mm Hg

| Stage Number | Dp <sub>50</sub> um | Weight Gain |            | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W - \%}{\Sigma W}$ | % < Dp |
|--------------|---------------------|-------------|------------|------------------------|------------------|------------------------------|---------------------------|--------|
|              |                     | Test #6 mg  | Test #7 mg |                        |                  |                              |                           |        |
| 1            | 11.2                | 0.19        | .19        | .19                    | 0.45             | .44                          | 2.7                       | 97.4   |
| 2            | 5.6                 | 0.05        | .05        | .05                    | 0.30             | .17                          | 0.7                       | 96.7   |
| 3            | 2.9                 | 0.08        | .08        | .08                    | 0.29             | .28                          | 1.1                       | 95.6   |
| 4            | 1.7                 | 0.13        | .13        | .13                    | 0.23             | .57                          | 1.7                       | 93.9   |
| 5            | .96                 | 0.12        | .12        | .12                    | 0.25             | .48                          | 1.6                       | 92.3   |
| 6            | .49                 | 0.15        | .15        | .15                    | 0.29             | .52                          | 2.0                       | 90.3   |
| 7            | .24                 | .22         | .19        | .41                    | 0.31             | 1.32                         | 5.6                       | 84.7   |
| 8            | .14                 | .60         | .38        | .98                    | 0.23             | 4.26                         | 13.3                      | 71.4   |
| 9            | .072                | .75         | .55        | 1.30                   | 0.29             | 4.48                         | 17.6                      | 53.8   |
| 10           | .023                | 1.46        | 1.26       | 2.72                   | 0.50             | 5.44                         | 36.9                      | 16.9   |
| Filter       | .01                 | 0.49        | 0.76       | 1.25                   | 0.36             | 3.47                         | 16.9                      |        |
|              | (.001)              |             |            |                        | (1.36)           | (0.92)                       |                           |        |

Total Aerosol Concentration = 7.38 mg/cu. m

TABLE B-9. LOW-PRESSURE IMPACTOR DATA SHEET

Test Number: 8 & 9  
 Date: 8-19-86  
 Time: 10:00 & 11:00  
 Gas flow rate: 25 lpm  
 Sampling time: 20 min + 20 min.  
 Sampling volume: 0.5 + 0.5 = 1.00 cu. m (std.)  
 Test Condition: 85% Power  
 Fuel: JP 4 - No Additive  
 Engine: J-79-GE-15A  
 Gas temperature: 184 & 196 F  
 Stack pressure: 760 mm Hg  
 Orifice pressure: 158 & 158 mm Hg

| Stage Number | Dp50 $\mu$ m | Weight Gain |            | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W - \%}{\Sigma W}$ | % < Dp |
|--------------|--------------|-------------|------------|------------------------|------------------|------------------------------|---------------------------|--------|
|              |              | Test #8 mg  | Test #9 mg |                        |                  |                              |                           |        |
| 1            | 11.2         | 0.21        | 0.27       | .21                    | 0.43             | .49                          | 2.5                       | 97.5   |
| 2            | 5.6          | 0.11        | 0.73       | .11                    | 0.30             | .37                          | 1.3                       | 96.2   |
| 3            | 2.9          | 0.10        | 0.92       | .10                    | 0.29             | .34                          | 1.2                       | 95.0   |
| 4            | 1.7          | 0.12        | 0.79       | .12                    | 0.23             | .52                          | 1.5                       | 93.5   |
| 5            | .96          | 0.12        | 0.62       | .12                    | 0.25             | .48                          | 1.5                       | 92.0   |
| 6            | .49          | 0.18        | 0.43       | .18                    | 0.29             | .62                          | 2.2                       | 89.8   |
| 7            | .24          | 0.16        | 0.27       | .43                    | 0.31             | 1.39                         | 5.2                       | 84.6   |
| 8            | .14          | 0.73        | 0.73       | 1.46                   | 0.23             | 6.35                         | 17.7                      | 66.9   |
| 9            | .072         | 0.74        | 0.92       | 1.66                   | 0.29             | 5.72                         | 20.1                      | 46.8   |
| 10           | .023         | 1.11        | 0.79       | 1.90                   | 0.50             | 3.80                         | 23.0                      | 23.8   |
| Filter       | .01          | 1.34        | 0.62       | 1.96                   | 0.36             | 5.44                         | 23.8                      |        |
|              | (.001)       |             |            |                        | (1.36)           | (1.44)                       |                           |        |

Total Aerosol Concentration = 8.25 mg/cu. m

TABLE B-10. LOW-PRESSURE IMPACTOR DATA SHEET

Test Number 10 & 11  
 Date: 8-20-86  
 Time: 8:30 & 9:30  
 Gas flow rate: 25 lpm (std.)  
 Sampling time: 20 min + 20 min.  
 Sampling volume: 0.5 + 0.5 = 1.00 cu. m  
 Test Condition: 85% Power  
 Fuel: JP 4 - No Additive  
 Engine: J-79-GE-15  
 Gas temperature: 195 & 195 F  
 Stack pressure: 760 mm Hg  
 Orifice pressure: 155 & 157 mm Hg

| Stage Number | Dp50 um       | Weight Gain |             | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W - \%}{\sum W}$ | % < Dp |
|--------------|---------------|-------------|-------------|------------------------|------------------|------------------------------|-------------------------|--------|
|              |               | Test #10 mg | Test #11 mg |                        |                  |                              |                         |        |
| 1            | 11.2          | 0.49        | .49         | .49                    | 0.43             | 1.14                         | 5.7                     | 94.3   |
| 2            | 5.6           | 0.15        | .15         | .15                    | 0.30             | .50                          | 1.7                     | 92.6   |
| 3            | 2.9           | 0.14        | .14         | .14                    | 0.29             | .48                          | 1.6                     | 91.0   |
| 4            | 1.7           | 0.14        | .14         | .14                    | 0.23             | .61                          | 1.6                     | 89.4   |
| 5            | .96           | 0.16        | .16         | .16                    | 0.25             | .64                          | 1.9                     | 87.5   |
| 6            | .49           | 0.28        | .28         | .28                    | 0.29             | .97                          | 3.2                     | 84.3   |
| 7            | .24           | .43         | .25         | .68                    | 0.31             | 2.19                         | 7.9                     | 76.4   |
| 8            | .14           | .58         | .67         | 1.25                   | 0.23             | 5.43                         | 14.4                    | 62.0   |
| 9            | .072          | 1.20        | 1.09        | 2.29                   | 0.29             | 7.90                         | 26.5                    | 35.5   |
| 10           | .023          | .92         | .98         | 1.90                   | 0.50             | 3.80                         | 21.9                    | 13.6   |
| Filter       | .01<br>(.001) | .47         | .71         | 1.18                   | 0.36<br>(1.36)   | 3.28<br>(0.87)               | 13.6                    |        |

Total Aerosol Concentration = 86.6 mg/cu. m

TABLE B-11. LOW-PRESSURE IMPACTOR DATA SHEET

Test Number: 12 & 13  
 Date: 8-21-86  
 Time: 9:30 & 10:30  
 Gas flow rate: 25 lpm (std.)  
 Sampling time: 30 min + 30 min  
 Sampling volume: 0.75 + 0.75 = 1.50 cu. m  
 Test Condition: 85% Power  
 Fuel: JP 4 - Cerium  
 Engine: J-79-GE-15  
 Gas temperature: 188 & 195 F  
 Stack pressure: 760 mm Hg  
 Orifice pressure: 156 & 158 mm Hg

| Stage Number | Dp50 um | Weight Gain |              | Test #13 mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W - \%}{\Sigma W}$ | % < Dp |
|--------------|---------|-------------|--------------|-------------|------------------------|------------------|------------------------------|---------------------------|--------|
|              |         | Test #12 mg | Test 12 & 13 |             |                        |                  |                              |                           |        |
| 1            | 11.2    | 0.24        | 0.24         |             | .16                    | 0.43             | .37                          | 2.1                       | 97.9   |
| 2            | 5.6     | 0.19        | 0.19         |             | .13                    | 0.30             | .43                          | 1.7                       | 96.2   |
| 3            | 2.9     | 0.27        | 0.27         |             | .18                    | 0.29             | .62                          | 2.4                       | 93.8   |
| 4            | 1.7     | 0.49        | 0.49         |             | .33                    | 0.23             | 1.43                         | 4.3                       | 89.5   |
| 5            | .96     | 0.49        | 0.49         |             | .33                    | 0.25             | 1.32                         | 4.3                       | 85.2   |
| 6            | .49     | 0.46        | 0.46         |             | .31                    | 0.29             | 1.07                         | 4.0                       | 81.2   |
| 7            | .24     | 0.65        | 0.70         | 0.70        | .90                    | 0.31             | 2.90                         | 11.8                      | 69.4   |
| 8            | .14     | 0.80        | 0.79         | 0.79        | 1.06                   | 0.23             | 4.61                         | 13.9                      | 55.5   |
| 9            | .072    | 1.18        | 1.26         | 1.26        | 1.63                   | 0.29             | 5.62                         | 21.4                      | 34.1   |
| 10           | .023    | 1.44        | 1.40         | 1.40        | 1.89                   | 0.50             | 3.78                         | 24.8                      | 9.3    |
| Filter       | .01     | 0.39        | 0.68         | 0.68        | .71                    | 0.36             | 1.97                         | 9.3                       |        |
|              | (.001)  |             |              |             |                        | (1.36)           | 0.52                         |                           |        |

Total Aerosol Concentration = 7.63 mg/cu. m

APPENDIX C  
DIFFUSION CLASSIFIER  
FIELD EVALUATION TEST RESULTS

TABLE C-1. DIFFUSION CLASSIFIER TEST TIMES

| TEST | DATE      | TIME  | LENGTH | VOLUME<br>(cu. m) | CONCENTRATION<br>(mg/cu. m) | FUEL  | ADDITIVE  |
|------|-----------|-------|--------|-------------------|-----------------------------|-------|-----------|
| 1    | 13 Aug 86 | 12:25 | 40 min | 0.81              | 7.83                        | JP4/5 | None      |
| 2    | 14 Aug 86 | 8:55  | 40 min | 0.84              | 7.85                        | JP4/5 | None      |
| 3    | 14 Aug 86 | 14:10 | 40 min | 0.82              | 6.16                        | JP4/5 | Ferrocene |
| 4    | 15 Aug 86 | 8:10  | 60 min | 1.27              | 6.30                        | JP4/5 | Ferrocene |
| 5    | 15 Aug 86 | 13:33 | 60 min | 1.22              | 4.82                        | JP4   | Ferrocene |
| 6    | 18 Aug 86 | 9:48  | 60 min | 1.20              | 6.79                        | JP4   | Ferrocene |
| 7    | 19 Aug 86 | 10:04 | 60 min | 1.24              | 6.64                        | JP4   | None      |
| 8*   | 20 Aug 86 | 8:25  | 60 min | 1.26              | 5.94                        | JP4   | None      |
| 9    | 20 Aug 86 | 12:41 | 40 min | 0.82              | 5.89                        | JP4   | None      |
| 10   | 21 Aug 86 | 9:09  | 90 min | 1.88              | 5.90                        | JP4   | Cerium    |
| 11   | 21 Aug 86 | 11:04 | 20 min | --                | --                          | JP4   | Cerium    |

\*Changed to a different engine.

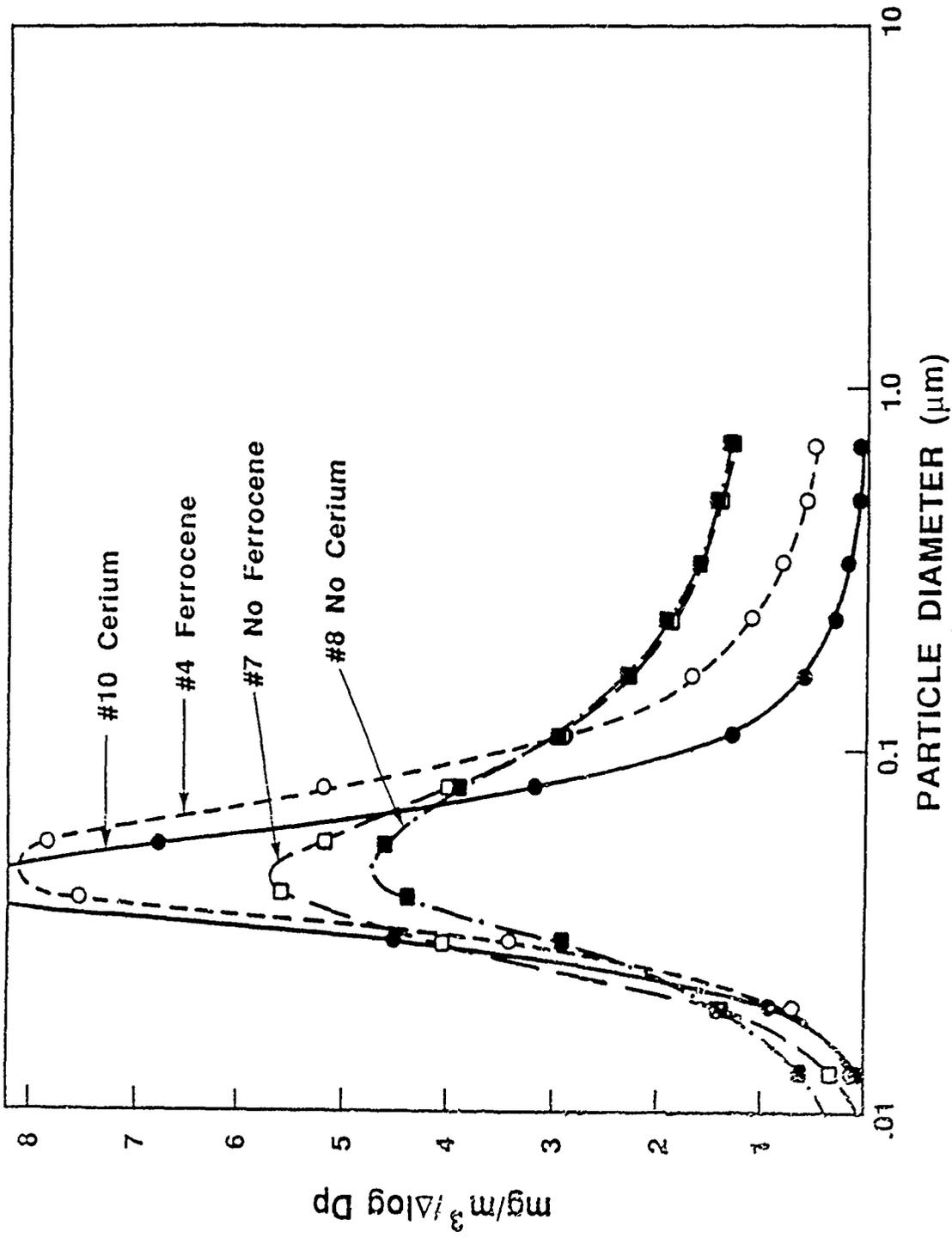


FIG C-1. Reduced Mass Distribution Plots from Diffusion Classifier Tests

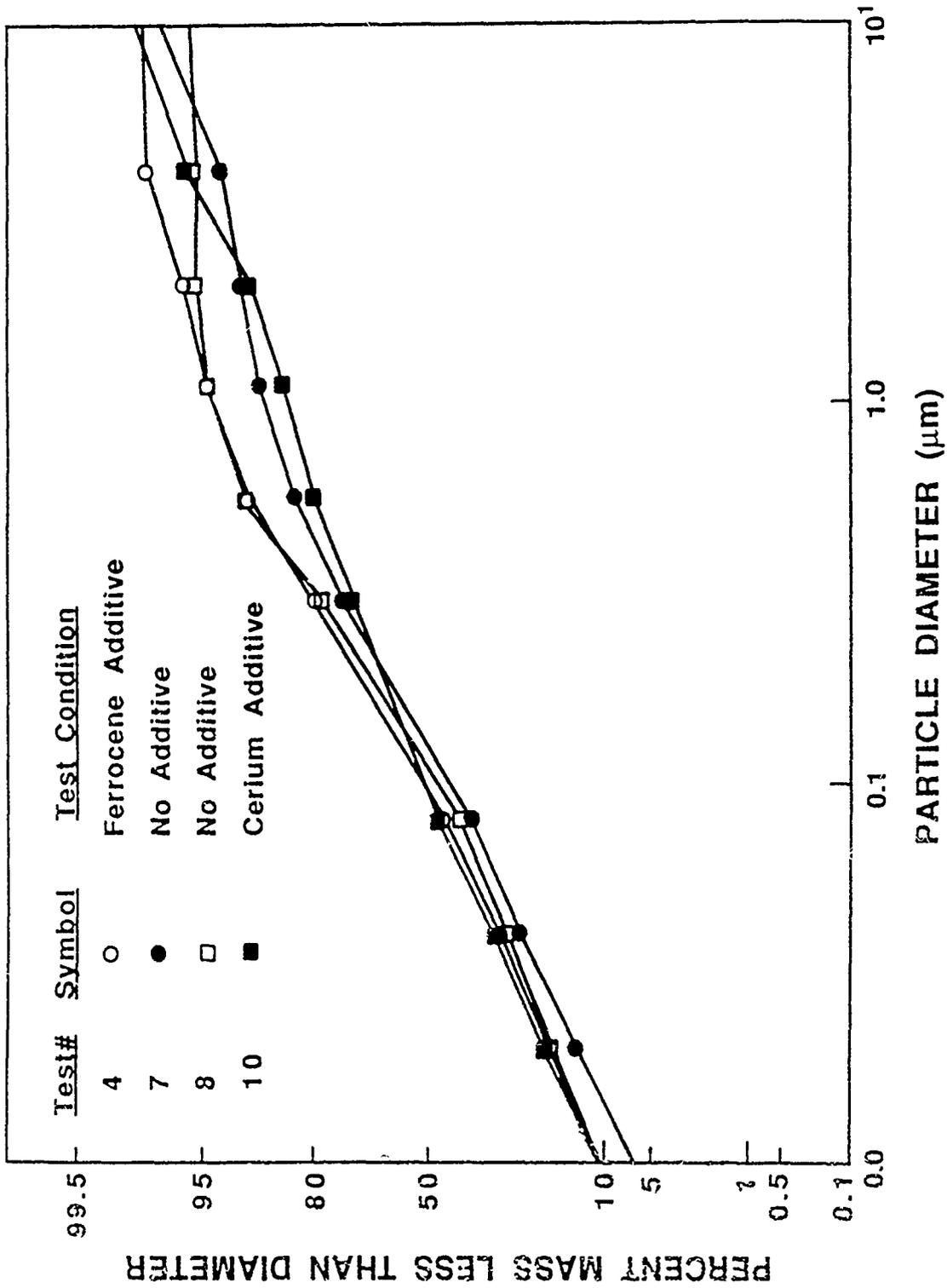


FIG C-2. Cumulative Distribution Data from Diffusion Classifier Tests

TABLE C-2. AEROSOL COMPARISON VALUES (Diffusion Classifier)

| TEST # | ENGINE      | TEST CONDITION | AEROSOL               |             | MASS FRACTION |              |
|--------|-------------|----------------|-----------------------|-------------|---------------|--------------|
|        |             |                | CONCENTRATION<br>mg/m | MMD**<br>um | <1 um<br>%    | <0.1 um<br>% |
| 1      | J-79-GE-15A | No additive    | 7.83                  | 0.11        | 92            | 48           |
| 7      | J-79-GE-15A | No additive    | 6.64                  | 0.12        | 89            | 44           |
| 4      | J-79-GE-15A | Ferrocene      | 6.30                  | 0.095       | 94            | 52           |
| 8      | J-79-GE-15  | No additive    | 5.94                  | 0.11        | 94            | 48           |
| 10     | J-79-GE-15  | Cerium         | 5.90                  | 0.09        | 85            | 52           |

\*\*MMD For Diffusion Classifier is a diffusional equivalent particle size.

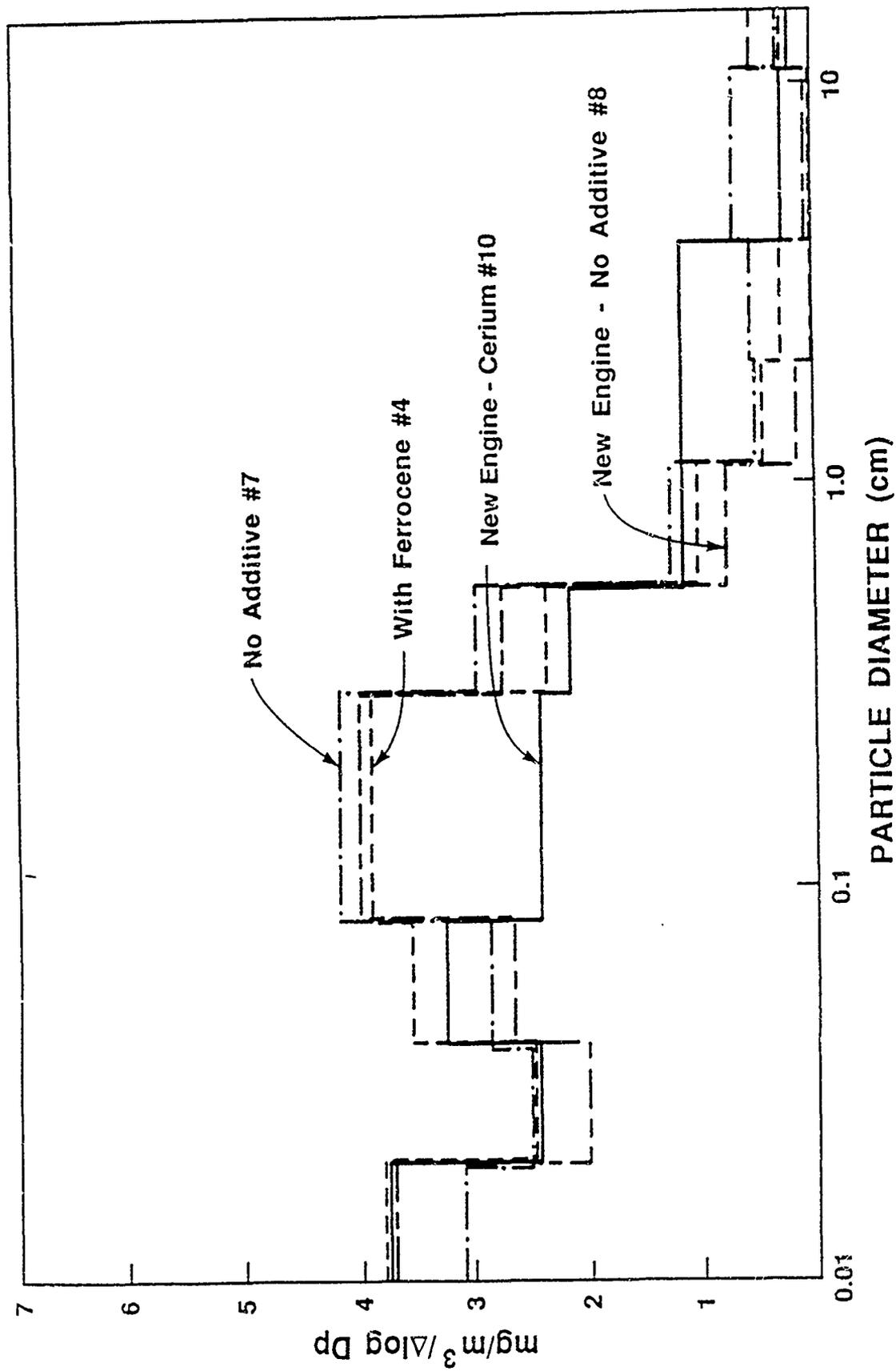


FIG. C-3. Direct Plot of Diffusion Classifier Mass Distribution Data

TABLE C-3. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 1  
 Date: 8-13-86  
 Time: 12:25  
 Sampling Time: 40 min.  
 Sampled Volume: 0.81 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4/5  
 Engine: J-79-GE-15A  
 Gas Temperature: 200 F  
 Additive: None

| Stage Number | Dp50 um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\sum W} - \%$ | %Dp   |
|--------------|---------|----------------|------------------------|------------------|------------------------------|-------------------------|-------|
| 1            | >20     | 0.156          |                        |                  |                              |                         |       |
| 2            | 11-20   | --             | 0.19                   | 0.44             | 0.43                         | 2.46                    | 97.55 |
| 3            | 4-11    | 0.085          | 0.10                   | 0.44             | 0.23                         | 1.34                    | 96.21 |
| 4            | 2-4     | 0.108          | 0.13                   | 0.30             | 0.43                         | 1.70                    | 94.51 |
| 5            | 1.1-2   | 0.111          | 0.14                   | 0.26             | 0.54                         | 1.75                    | 92.76 |
| 6            | .55-1.1 | 0.363          | 0.45                   | 0.30             | 1.50                         | 5.72                    | 87.04 |
| 7            | .3-.55  | 0.739          | 0.91                   | 0.26             | 3.50                         | 11.64                   | 75.40 |
| D-40         | .08-.3  | 2.187          | 2.70                   | 0.57             | 4.74                         | 34.44                   | 40.96 |
| D-20         | .04-.08 | 0.513          | 0.63                   | 0.30             | 2.10                         | 8.08                    | 32.88 |
| D-10         | .02-.04 | 0.882          | 1.09                   | 0.30             | 3.63                         | 13.89                   | 18.99 |
| D-0          | <0.02   | 1.206          | 1.49                   | 1.00             | 1.49                         | 18.99                   |       |
|              |         | --             |                        |                  |                              |                         |       |
|              |         | 6.35           |                        |                  |                              |                         |       |

Total Concentration - 7.83 mg/cu. m

TABLE C-4. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 2  
 Date: 8-14-86  
 Time: 8:55  
 Sampling Time: 40 min.  
 Sampled Volume: 0.84 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4/5  
 Engine: J-79-GE-15A  
 Gas Temperature: 175 F  
 Additive: None

| Stage Number | Dp50 um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\Sigma W} - \%$ | $\% \Delta Dp$ |
|--------------|---------|----------------|------------------------|------------------|------------------------------|---------------------------|----------------|
| 1            | >20     | 0.089          |                        |                  |                              |                           |                |
| 2            | 11-20   | 0.019          | 0.13                   | 0.44             | 0.29                         | 1.64                      | 98.36          |
| 3            | 4-11    | 0.057          | 0.07                   | 0.44             | 0.15                         | 0.86                      | 97.50          |
| 4            | 2-4     | 0.151          | 0.18                   | 0.30             | 0.60                         | 2.29                      | 95.21          |
| 5            | 1.1-2   | 0.155          | 0.18                   | 0.26             | 0.71                         | 2.35                      | 92.86          |
| 6            | .55-1.1 | 0.408          | 0.49                   | 0.30             | 1.62                         | 6.19                      | 86.67          |
| 7            | .3-.55  | 0.791          | 0.94                   | 0.26             | 3.62                         | 12.00                     | 74.67          |
| D-40         | .08-.3  | 1.890          | 2.25                   | 0.57             | 3.95                         | 28.67                     | 46.00          |
| D-20         | .04-.08 | 0.774          | 0.92                   | 0.30             | 3.07                         | 11.74                     | 34.26          |
| D-10         | .02-.04 | 1.368          | 1.63                   | 0.30             | 5.43                         | 20.75                     | 13.51          |
| D-0          | <0.02   | 0.891          | 1.06                   | 1.00             | 1.06                         | 13.51                     |                |
|              |         | ---            |                        |                  |                              |                           |                |
|              |         | 6.59           |                        |                  |                              |                           |                |

Total Concentration - 7.85 mg/cu. m

\*Dirty Screens Used

TABLE G-5. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 3  
 Date: 8-14-86  
 Time: 14:10  
 Sampling Time: 40 min.  
 Sampled Volume: 0.82 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4/5  
 Engine: J-79-GE-15A  
 Gas Temperature: 175 F  
 Additive: Ferrocene

| Stage Number | Dp <sub>50</sub> um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log D_p$ | $\frac{W/V}{\Delta \log D_p}$ | $\frac{W}{\sum W} - \%$ | %<Dp  |
|--------------|---------------------|----------------|------------------------|-------------------|-------------------------------|-------------------------|-------|
| 1            | >20                 | 0.062          |                        |                   |                               |                         |       |
| 2            | 11-20               | 0.005          | 0.08                   | 0.44              | 0.19                          | 1.32                    | 98.64 |
| 3            | 4-11                | 0.036          | 0.04                   | 0.44              | 0.10                          | 0.71                    | 97.93 |
| 4            | 2-4                 | 0.056          | 0.07                   | 0.30              | 0.23                          | 1.11                    | 96.82 |
| 5            | 1.1-2               | 0.067          | 0.08                   | 0.26              | 0.31                          | 1.32                    | 95.50 |
| 6            | .55-1.1             | 0.225          | 0.27                   | 0.30              | 0.91                          | 4.45                    | 91.05 |
| 7            | .3-.55              | 0.503          | 0.61                   | 0.26              | 2.36                          | 9.94                    | 81.11 |
| D-40         | .08-.3              | 0.918          | 1.12                   | 0.57              | 1.97                          | 18.14                   | 62.97 |
| D-20         | .04-.08             | 0.639          | 0.78                   | 0.30              | 2.60                          | 12.63                   | 50.34 |
| D-10         | .02-.04             | 1.656          | 2.02                   | 0.30              | 6.73                          | 32.73                   | 17.61 |
| D-0          | <0.02               | 0.891          | 1.09                   | 1.00              | 1.09                          | 17.61                   |       |
|              |                     | 5.06           |                        |                   |                               |                         |       |

Total Concentration - 6.16 mg/cu. m

\*Dirty Screens Used

TABLE C-6. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 4  
 Date: 8-15-86  
 Time: 8:10  
 Sampling Time: 60 min.  
 Sampled Volume: 1.27 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4/5  
 Engine: J-79-GE-15A  
 Gas Temperature: 177 F  
 Additive: Ferrocene

| Stage Number | Dp50 um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\Sigma W} - \%$ | %<Dp  |
|--------------|---------|----------------|------------------------|------------------|------------------------------|---------------------------|-------|
| 1            | >20     | 0.064          | 0.11                   | 0.44             | 0.25                         | 1.74                      | 98.14 |
| 2            | 11-20   | 0.080          | --                     | 0.44             | --                           | 0                         | 98.14 |
| 3            | 4-11    | --             | 0.09                   | 0.30             | 0.30                         | 1.49                      | 96.65 |
| 4            | 2-4     | 0.120          | 0.12                   | 0.26             | 0.46                         | 1.96                      | 94.69 |
| 5            | 1.1-2   | 0.157          | 0.31                   | 0.30             | 1.03                         | 4.94                      | 89.75 |
| 6            | .55-1.1 | 0.397          | 0.61                   | 0.26             | 2.35                         | 9.61                      | 80.14 |
| 7            | .3-.55  | 0.772          |                        |                  |                              |                           |       |
| D-40         | .08-.3  | 2.709          | 2.13                   | 0.57             | 5.74                         | 33.74                     | 46.40 |
| D-20         | .04-.08 | 1.341          | 1.06                   | 0.30             | 3.52                         | 16.70                     | 29.70 |
| D-10         | .02-.04 | 0.945          | 0.74                   | 0.30             | 2.47                         | 11.77                     | 17.93 |
| D-0          | <0.02   | 1.440          | 1.13                   | 1.00             | 1.13                         | 17.93                     |       |
|              |         | --             |                        |                  |                              |                           |       |
|              |         | 8.03           |                        |                  |                              |                           |       |

Total Concentration - 6.30 mg/cu. m

TABLE C-7. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 5  
 Date: 8-15-86  
 Time: 13.55  
 Sampling Time: 60 min.  
 Sampled Volume: 1.22 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4  
 Engine: J-79-GE-15A  
 Gas Temperature: 195 F  
 Additive: Ferrocene

| Stage Number | Dp50 $\mu$ m | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\Sigma W} - \%$ | %<Dp  |
|--------------|--------------|----------------|------------------------|------------------|------------------------------|---------------------------|-------|
| 1            | >20          |                |                        |                  |                              |                           |       |
| 2            | 11-20        | 0.052          | 0.04                   | 0.44             | 0.10                         | 0.88                      | 99.02 |
| 3            | 4-11         | 0.061          | 0.05                   | 0.44             | 0.11                         | 1.04                      | 97.98 |
| 4            | 2-4          | 0.060          | 0.05                   | 0.50             | 0.16                         | 1.02                      | 96.96 |
| 5            | 1.1-2        | 0.152          | 0.11                   | 0.26             | 0.42                         | 2.24                      | 94.72 |
| 6            | .55-1.1      | 0.304          | 0.25                   | 0.50             | 0.83                         | 5.17                      | 89.55 |
| 7            | .3-.55       | 0.577          | 0.47                   | 0.26             | 1.82                         | 9.81                      | 74.74 |
| D-40         | .08-.3       | 1.269          | 1.04                   | 0.40             | 2.60                         | 21.58                     | 58.16 |
| D-20         | .04-.08      | 1.377          | 1.13                   | 0.48             | 2.35                         | 23.42                     | 34.74 |
| D-10         | .02-.04      | 0.216          | 0.18                   | 0.50             | 0.59                         | 3.67                      | 31.07 |
| D-0          | <0.02        | 1.827          | 1.50                   | 1.00             | 1.50                         | 31.07                     |       |
|              |              | --             |                        |                  |                              |                           |       |
|              |              | 5.88           |                        |                  |                              |                           |       |

Total Concentration - 4.82 mg/cu. m

\*Used 60 screens rather than 40

TABLE C-8. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 6  
 Date: 8-18-86  
 Time: 9:48  
 Sampling Time: 60 min.  
 Sampled Volume: 1.20 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4  
 Engine: J-79-GE-15A  
 Gas Temperature: 188 F  
 Additive: Ferrocene

| Stage Number | Dp50 um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\sum W} - \%$ | %<Dp  |
|--------------|---------|----------------|------------------------|------------------|------------------------------|-------------------------|-------|
| 1            | >20     | --             |                        |                  |                              |                         |       |
| 2            | 11-20   | 0.136          | 0.11                   | 0.44             | 0.26                         | 1.69                    | 98.32 |
| 3            | 4-11    | 0.132          | 0.11                   | 0.44             | 0.25                         | 1.62                    | 96.70 |
| 4            | 2-4     | 0.106          | 0.09                   | 0.30             | 0.29                         | 1.30                    | 95.40 |
| 5            | 1.1-2   | 0.184          | 0.15                   | 0.26             | 0.59                         | 2.25                    | 93.15 |
| 6            | .55-1.1 | 0.390          | 0.32                   | 0.30             | 1.08                         | 4.77                    | 88.38 |
| 7            | .3-.55  | 0.655          | 0.53                   | 0.26             | 2.03                         | 7.75                    | 80.63 |
| D-40         | .08-.3  | 1.818          | 1.51                   | 0.57             | 2.65                         | 22.25                   | 58.38 |
| D-20         | .04-.08 | 0.342          | 0.28                   | 0.30             | 0.95                         | 4.19                    | 54.19 |
| D-10         | .02-.04 | 3.069          | 2.56                   | 0.30             | 8.53                         | 37.56                   | 16.63 |
| D-0          | <0.02   | 1.359          | 1.13                   | 1.00             | 1.13                         | 16.63                   |       |
|              |         | --             |                        |                  |                              |                         |       |
|              |         | 8.17           |                        |                  |                              |                         |       |

Total Concentration - 6.79 mg/cu. m

(Teflon filters for chemical analysis)

TABLE C-9. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 7  
 Date: 8-19-86  
 Time: 10:04  
 Sampling Time: 60 min.  
 Sampled Volume: 1.24 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4  
 Engine: J-79-GE-15A  
 Gas Temperature: 195 F  
 Additive: None

| Stage Number | Dp50 um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\Sigma W} - \%$ | % < Dp |
|--------------|---------|----------------|------------------------|------------------|------------------------------|---------------------------|--------|
| 1            | >20     | --             |                        |                  |                              |                           |        |
| 2            | 11-20   | 0.139          | 0.11                   | 0.44             | 0.25                         | 1.68                      | 98.52  |
| 3            | 4-11    | 0.388          | 0.31                   | 0.44             | 0.71                         | 4.70                      | 93.62  |
| 4            | 2-4     | 0.202          | 0.16                   | 0.30             | 0.54                         | 2.45                      | 91.17  |
| 5            | 1.1-2   | 0.163          | 0.13                   | 0.26             | 0.51                         | 1.98                      | 89.19  |
| 6            | .55-1.1 | 0.470          | 0.38                   | 0.30             | 1.26                         | 5.70                      | 83.49  |
| 7            | .3-.55  | 0.957          | 0.77                   | 0.26             | 2.97                         | 11.60                     | 71.89  |
| D-40         | .08-.3  | 2.803          | 2.26                   | 0.57             | 3.96                         | 34.04                     | 37.85  |
| D-20         | .04-.08 | 1.053          | 0.85                   | 0.30             | 2.83                         | 12.76                     | 25.09  |
| D-10         | .02-.04 | 0.918          | 0.74                   | 0.30             | 2.47                         | 11.13                     | 13.96  |
| D-0          | <0.02   | 1.152          | 0.93                   | 1.00             | 0.93                         | 13.96                     |        |
|              |         | --             |                        |                  |                              |                           |        |
|              |         | 8.25           |                        |                  |                              |                           |        |

Total Concentration - 6.64 mg/cu. m

(Teflon filters for chemical analysis)

TABLE C-10. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 8  
 Date: 8-20-86  
 Time: 8:25  
 Sampling Time: 60 min.  
 Sampled Volume: 1.26 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4  
 Engine: J-79-GE-15A  
 Gas Temperature: 196 F  
 Additive: None

| Stage Number | Dp50 um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\sum W} - \%$ | $\% < Dp$ |
|--------------|---------|----------------|------------------------|------------------|------------------------------|-------------------------|-----------|
| 1            | >20     | --             |                        |                  |                              |                         |           |
| 2            | 11-20   | 0.298          | 0.24                   | 0.44             | 0.54                         | 3.97                    | 96.08     |
| 3            | 4-11    | 0.046          | 0.04                   | 0.44             | 0.08                         | 0.61                    | 95.47     |
| 4            | 2-4     | 0.005          | 0.00                   | 0.30             | 0.01                         | 0.04                    | 95.45     |
| 5            | 1.1-2   | 0.053          | 0.04                   | 0.26             | 0.16                         | 0.71                    | 94.72     |
| 6            | .55-1.1 | 0.296          | 0.23                   | 0.30             | 0.78                         | 3.95                    | 90.77     |
| 7            | .3-.55  | 0.886          | 0.70                   | 0.26             | 2.70                         | 11.81                   | 78.96     |
| D-40         | .08-.5  | 2.790          | 2.21                   | 0.57             | 3.88                         | 57.20                   | 41.76     |
| D-20         | .04-.08 | 0.972          | 0.77                   | 0.30             | 2.57                         | 12.96                   | 28.80     |
| D-10         | .02-.04 | 0.756          | 0.60                   | 0.30             | 2.00                         | 10.08                   | 18.72     |
| D-0          | <0.02   | 1.404          | 1.11                   | 1.00             | 1.11                         | 18.72                   |           |
|              |         | --             |                        |                  |                              |                         |           |
|              |         | 7.50           |                        |                  |                              |                         |           |

Total Concentration - 5.94 mg/cu. m

TABLE C-11. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 9  
 Date: 8-20-86  
 Time: 12:41  
 Sampling Time: 40 min.  
 Sampled Volume: 0.82 cu. m std.  
 Test Condition: 85% Power  
 Fuel: JP4  
 Engine: J-79-GE-15A  
 Gas Temperature: 197 F  
 Additive: None

| Stage Number | Dp50 um | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\sum W} - \%$ | $\% < Dp$ |
|--------------|---------|----------------|------------------------|------------------|------------------------------|-------------------------|-----------|
| 1            | >20     | --             |                        |                  |                              |                         |           |
| 2            | 11-20   | 0.134          | 0.16                   | 0.44             | 0.36                         | 2.77                    | 97.22     |
| 3            | 4-11    | 0.111          | 0.14                   | 0.44             | 0.32                         | 2.30                    | 94.92     |
| 4            | 2-4     | 0.145          | 0.18                   | 0.30             | 0.60                         | 3.00                    | 91.92     |
| 5            | 1.1-2   | 0.117          | 0.14                   | 0.26             | 0.54                         | 2.42                    | 89.50     |
| 6            | .55-1.1 | 0.210          | 0.26                   | 0.30             | 0.87                         | 4.35                    | 85.15     |
| 7            | .3-.55  | 0.563          | 0.69                   | 0.26             | 2.65                         | 11.67                   | 73.48     |
| D-40         | .08-.3  | 1.179          | 1.44                   | 0.57             | 2.53                         | 24.43                   | 49.05     |
| D-20         | .04-.08 | 0.765          | 0.93                   | 0.30             | 3.10                         | 15.85                   | 33.20     |
| D-10         | .02-.04 | 0.675          | 0.82                   | 0.30             | 2.73                         | 13.99                   | 19.21     |
| D-0          | <0.02   | 0.927          | 1.13                   | 1.00             | 1.13                         | 19.21                   |           |
|              |         | --             |                        |                  |                              |                         |           |
|              |         | 4.826          |                        |                  |                              |                         |           |

Total Concentration - 5.89 mg/cu. m

\* Use dirty screens

TABLE C-12. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 10      Test Condition: 85% Power  
 Date: 8-21-86      Fuel: JP4  
 Time: 9:09      Engine: J-79-GE-15A  
 Sampling Time: 90 min.      Gas Temperature: 190 F  
 Sampled Volume: 1.88 cu. m std.      Additive: Cerium

| Stage Number | Dp50 $\mu$ m | Weight Gain mg | Concentration mg/cu. m | $\Delta \log Dp$ | $\frac{W/V}{\Delta \log Dp}$ | $\frac{W}{\sum W} - \%$ | %<Dp  |
|--------------|--------------|----------------|------------------------|------------------|------------------------------|-------------------------|-------|
| 1            | >20          | --             |                        |                  |                              |                         |       |
| 2            | 11-20        | 0.162          | 0.09                   | 0.44             | 0.20                         | 1.46                    | 98.52 |
| 3            | 4-11         | 0.232          | 0.12                   | 0.44             | 0.28                         | 2.09                    | 96.43 |
| 4            | 2-4          | 0.637          | 0.34                   | 0.30             | 1.13                         | 5.73                    | 90.70 |
| 5            | 1.1-2        | 0.552          | 0.29                   | 0.26             | 1.13                         | 4.97                    | 85.73 |
| 6            | .55-1.1      | 0.639          | 0.34                   | 0.30             | 1.13                         | 5.75                    | 79.98 |
| 7            | .3-.55       | 1.039          | 0.55                   | 0.26             | 2.13                         | 9.35                    | 70.63 |
| D-40         | .03-.3       | 2.529          | 1.35                   | 0.57             | 2.37                         | 22.76                   | 47.87 |
| D-20         | .04-.08      | 1.827          | 0.97                   | 0.30             | 3.24                         | 16.44                   | 31.43 |
| D-10         | .02-.04      | 1.377          | 0.73                   | 0.30             | 2.44                         | 12.39                   | 19.04 |
| D-0          | <0.02        | 2.115          | 1.12                   | 1.00             | 1.12                         | 19.04                   |       |

--  
11.11

Total Concentration ~ 5.90 mg/cu. m

TABLE C-13. DIFFUSION CLASSIFIER DATA SHEET

Test Number: 11      Test Condition: 85% Power  
 Date: 8-21-86      Fuel: JP4  
 Time: 9:09      Engine: J-79-GE-15A  
 Sampling Time: 90 min.      Gas Temperature: 190 F  
 Sampled Volume: 1.88 m std.      Additive: Cerium

| Stage Number | Dp50 um | Weight Gain mg | Concentration mg/m | $\Delta \log D_p$ | $\frac{W/V}{\Delta \log D_p}$ | $\frac{W}{\sum W} - \%$ | %<Dp |
|--------------|---------|----------------|--------------------|-------------------|-------------------------------|-------------------------|------|
| 1            | >20     | {              |                    |                   |                               |                         |      |
| 2            | 11-20   | {              |                    |                   |                               |                         |      |
| 3            | 4-11    |                |                    |                   |                               |                         |      |
| 4            | 2-4     |                |                    |                   |                               |                         |      |
| 5            | 1.1-2   |                |                    |                   |                               |                         |      |
| 6            | .55-1.1 |                |                    |                   |                               |                         |      |
| 7            | .3-.55  |                |                    |                   |                               |                         |      |
| D-40         | .03-.3  |                |                    |                   |                               |                         |      |
| D-20         | .04-.08 |                |                    |                   |                               |                         |      |
| D-10         | .02-.04 |                |                    |                   |                               |                         |      |
| D-0          | <0.02   |                |                    |                   |                               |                         |      |

\*Run together with Test #10.  
 Used Teflong filters for chemical analysis.

APPENDIX D

LOW-PRESSURE IMPACTOR ASSEMBLY PROCEDURE

## LOW-PRESSURE IMPACTOR ASSEMBLY PROCEDURE

1. Clean all surfaces of the impactor thoroughly. Normally, washing the impactor parts with soap and water should be sufficient. Rinse parts thoroughly and air dry. If significant deposits of combustion aerosol are apparent or if grease is to be removed, the use of methylene chloride or similar solvent is recommended. Avoid contact of the solvent with the impactor's O-rings. Inspect the impaction jets and critical orifice for plugging. If normal cleaning procedures are not effective in clearing the jets, ultrasonic cleaning of the parts in methylene chloride is recommended.
2. Wipe all O-rings free of foreign material and inspect for cracks. Replace if necessary. The O-rings are of 2-5/8 inches diameter and 0.07-inch thick. Viton O-rings are recommended due to their higher temperature tolerance.
3. Select the proper impaction plate substrate depending on the expected sampling conditions. Greased impaction substrates may be used if sampling temperatures do not exceed 400°F. Use of greased substrates above this temperature will result in erroneous test results due to volatilization of the grease. For temperatures above 400°F, glass-fiber filter substrates are recommended. Due to the high jet velocities which occur in the low-pressure impactor, it is important that the grease chosen be viscous and nonvolatile. Both Apiezon L and Apiezon H are recommended for this purpose.

4. Apply a thin layer of grease to the 10 stainless steel foil collection plates. If glass-fiber substrates are to be used, they may be placed on the foil substrates and secured by bending over three hold-down tabs. All substrates should be conditioned in an oven for at least 2 hours at the expected sampling temperature. The substrates should then be placed in a dessicator until the time of their use.
5. Prior to the impactor assembly, the impaction plates should be weighed to 0.01 mg and the weights recorded. Proper handling of the substrates at all times is critical to obtaining accurate test results.
6. Assemble the low-pressure impactor being careful during the handling of the pre-weighed collection surfaces. Assembly of the impactor begins by sliding the 10th impaction plate (Figure D-3) over the bottom support pedestal. The 10th impactor stage is then stacked on top of the support. Continue loading the impaction plates and stages until the four low-pressure stages are loaded. Check the interstage o-rings for proper sealing. Slide the low-pressure housing over the stack and screw in place hand tight. Load the remaining six ambient section plates and stages and check the o-ring seals. Complete the assembly by sliding the impactor inlet housing over the stack and tighten the entire assembly with a wrench.

The viton o-rings have a maximum temperature rating of approximately 500°F. If the sampling temperature is to exceed this value, the impactor must be operated without o-rings. Tests have shown that the unit will seal adequately without o-rings at high temperature. It is important,

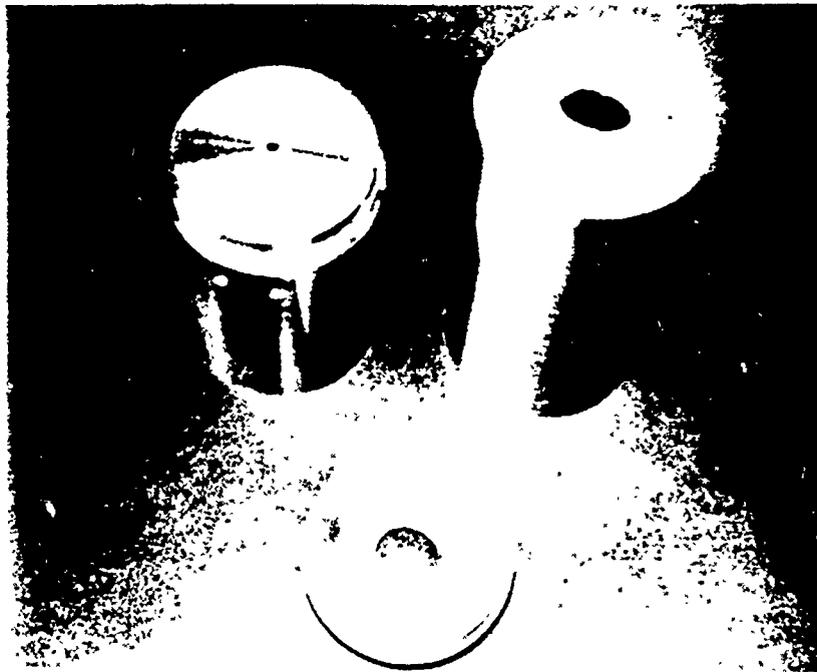


Figure D-1. Photograph of Low-Pressure Impactor Housing Parts with End-Cap.

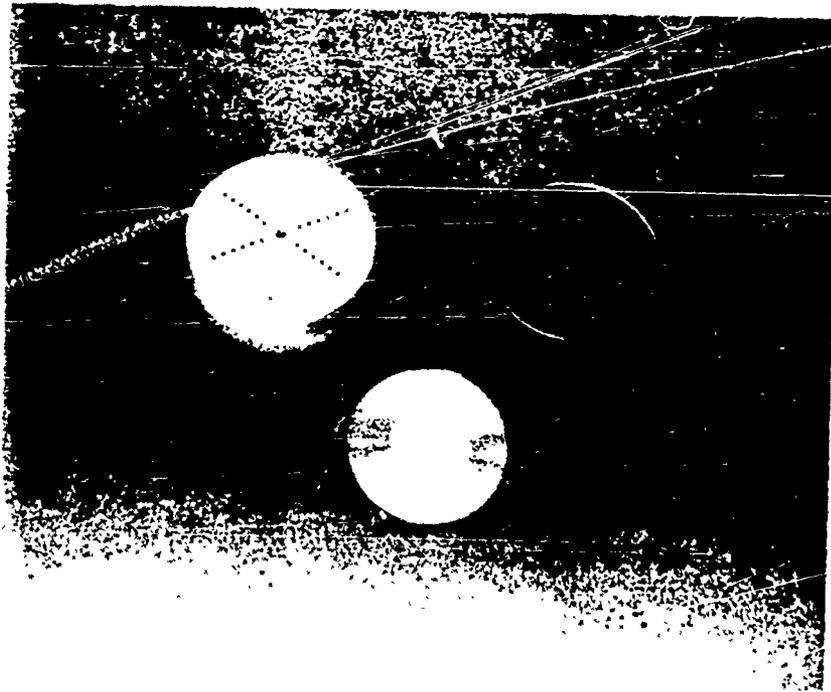


Figure D-2. Photograph of Typical Stage with Impact Plate and O-ring.

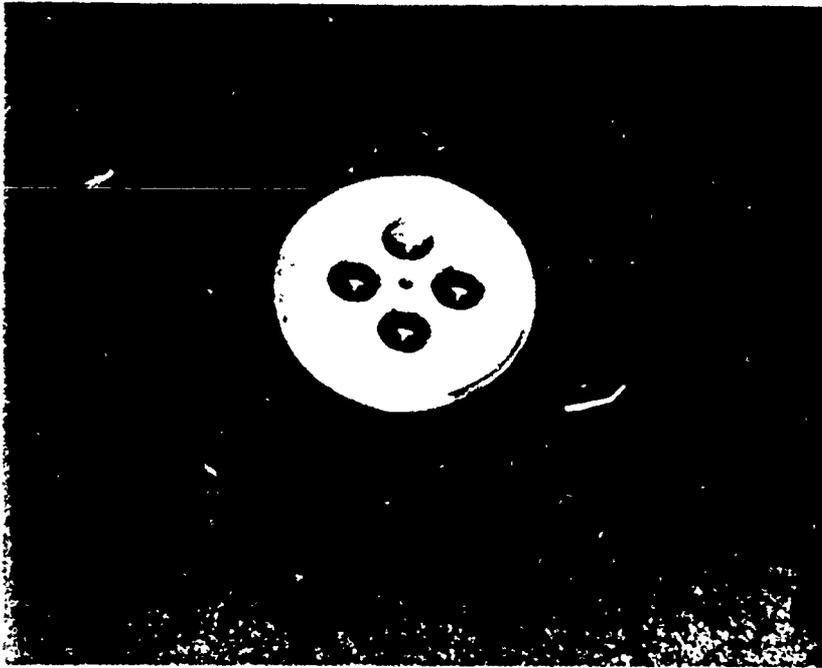
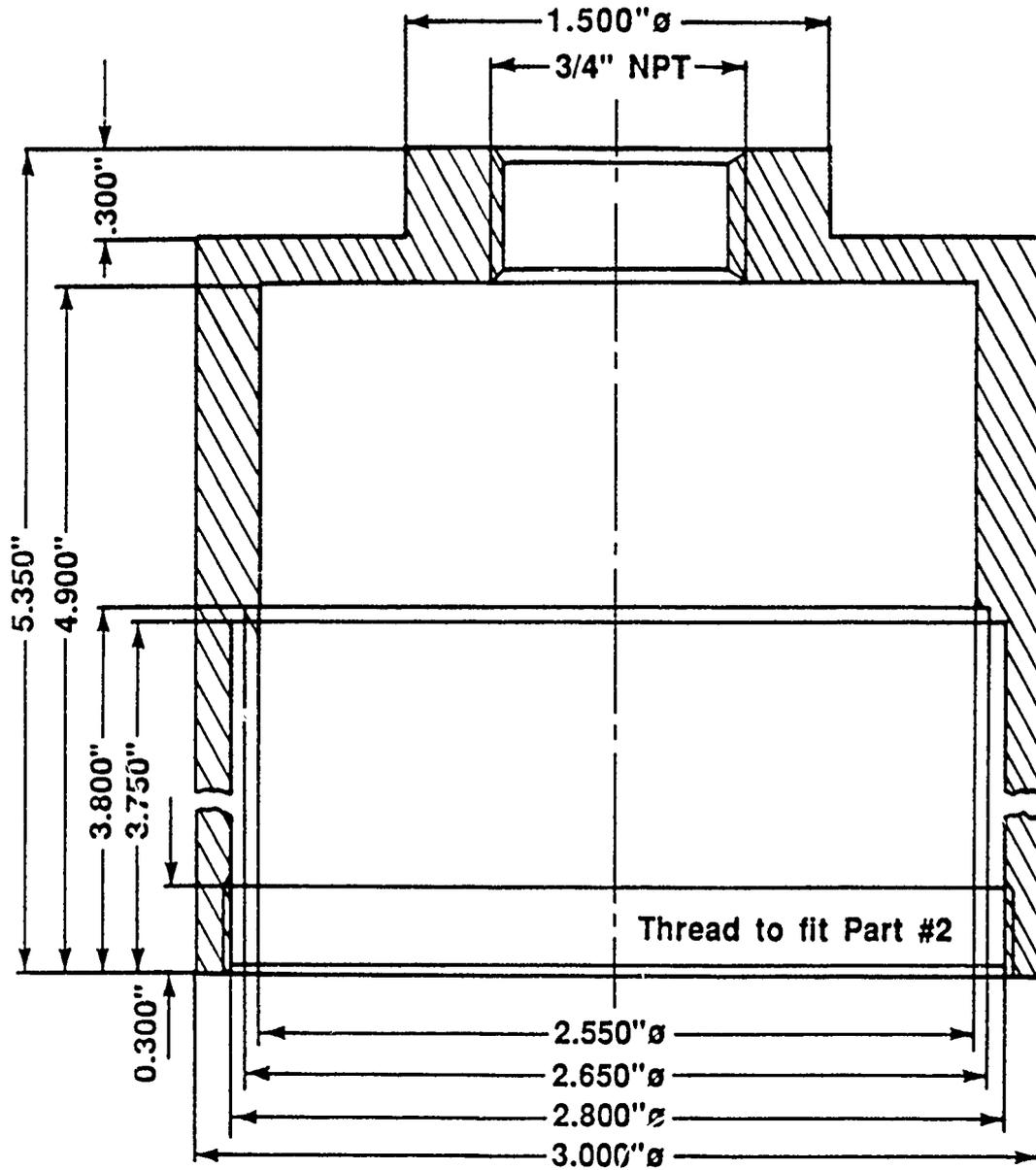


Figure D-3. Photograph of Stage 10 Support Plate.

however, that the impactor be assembled only hand-tight to avoid seizing of the fittings during high temperature operation. If the fittings are over-tightened without o-rings, disassembly after high-temperature operation can be extremely difficult.

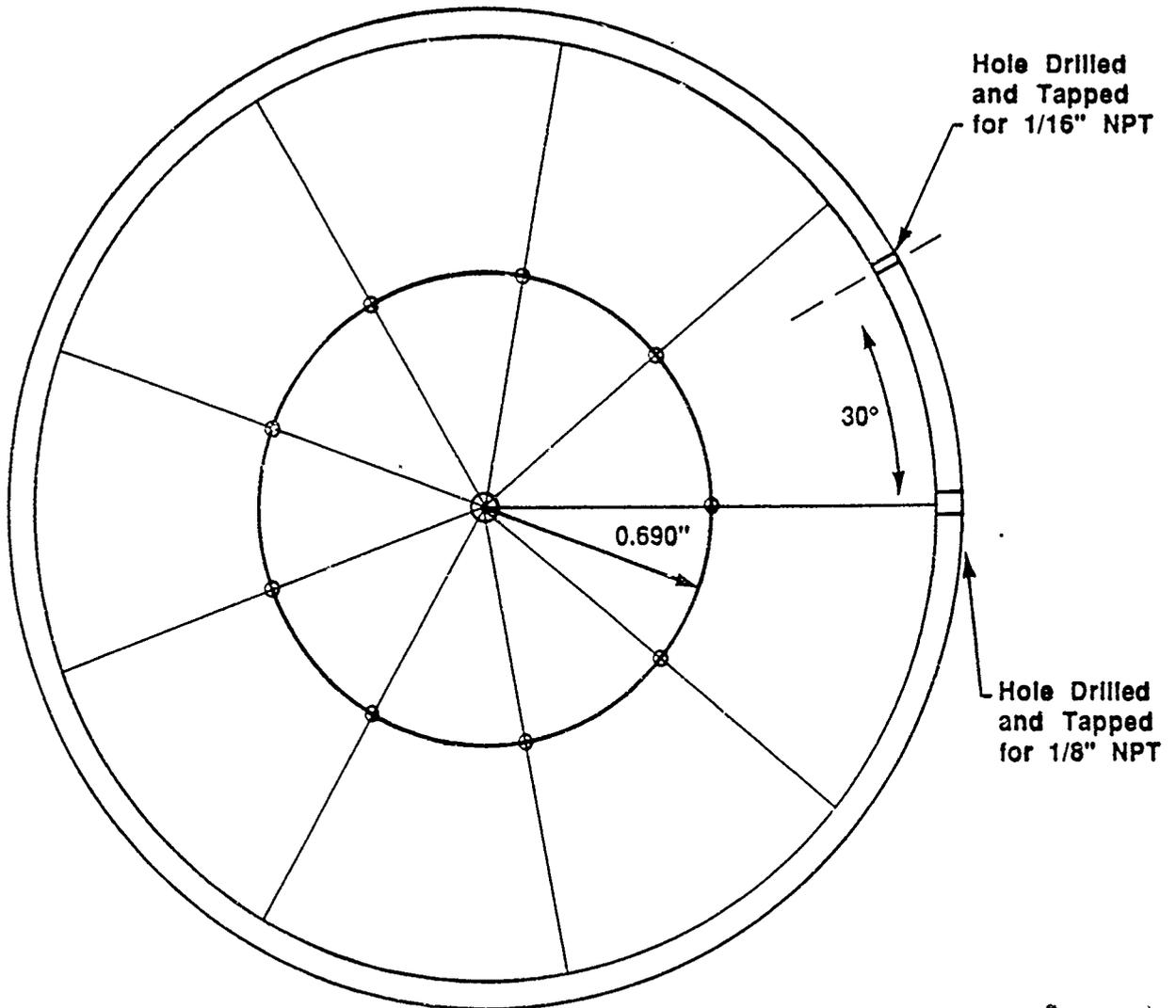
7. Attach the temperature and pressure probes to the low-pressure housing of the impactor.
8. Leak-check the impactor prior to actual sampling. Begin by capping the impactor inlet and connecting the impactor to the sampling pump including an in-line quarter turn valve. Place the impactor under an absolute pressure of 170 mm Hg and close the quarter-turn valve. Turn off the pump and observe the pressure reading over time. A significant increase in the impactor interior pressure over time indicates an unacceptable leak. Disassemble and check all fittings and seals. Applying a thin layer of high-temperature grease to the housing threads may correct the problem. Reassemble the impactor and repeat the leak-check.
9. Following the actual test sampling, allow the impactor to cool somewhat prior to disassembling. It is recommended that the collection surfaces be weighed both immediately after the test, as well as after a 3 hour period in a dessicator. Again, proper handling of the collection surfaces is critical to accurate test results.

APPENDIX E  
DESIGN DRAWINGS OF LOW-PRESSURE IMPACTOR

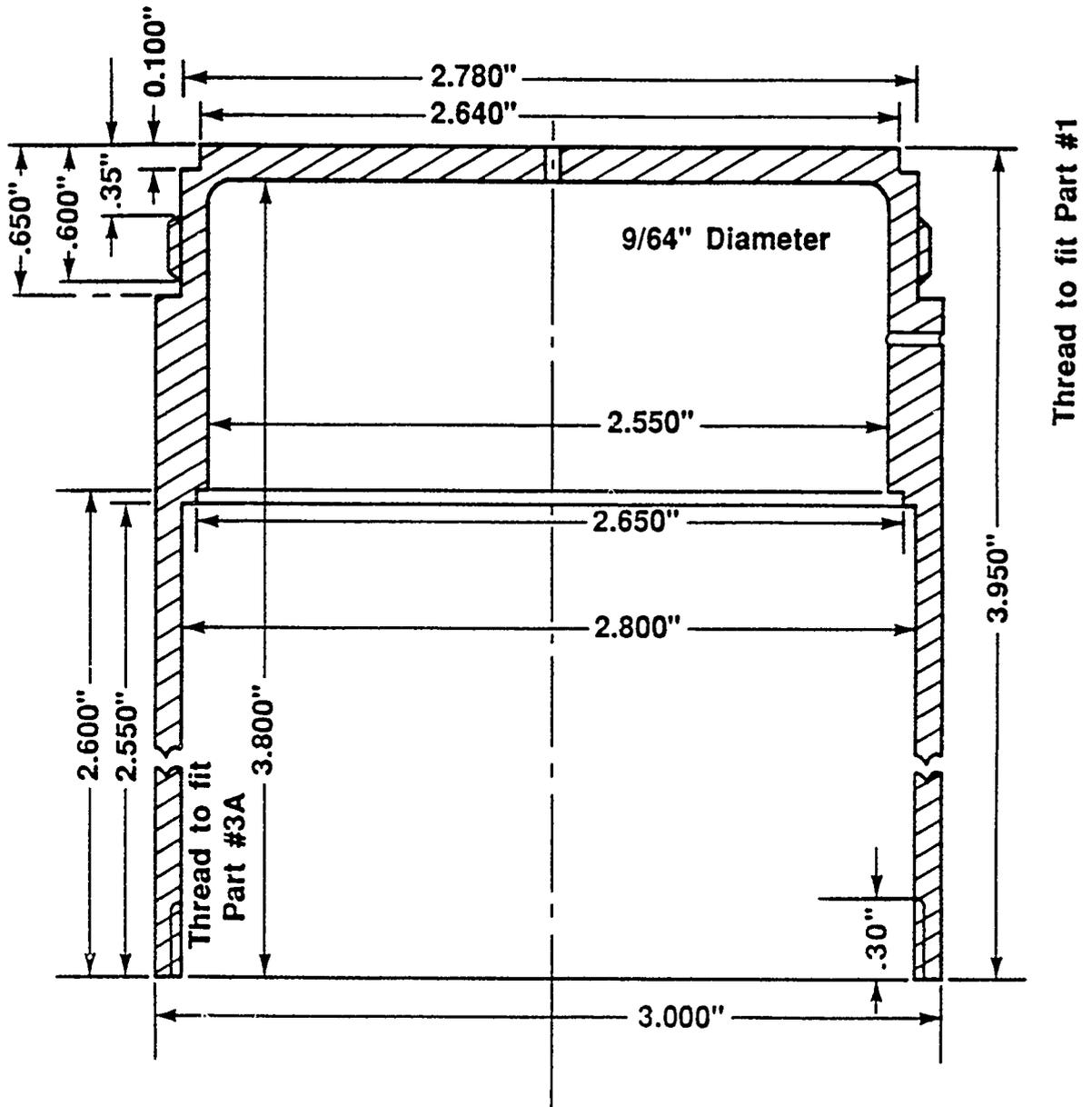


|                                 |
|---------------------------------|
| Air Force Low-Pressure Impactor |
| Inlet Housing Part #1           |

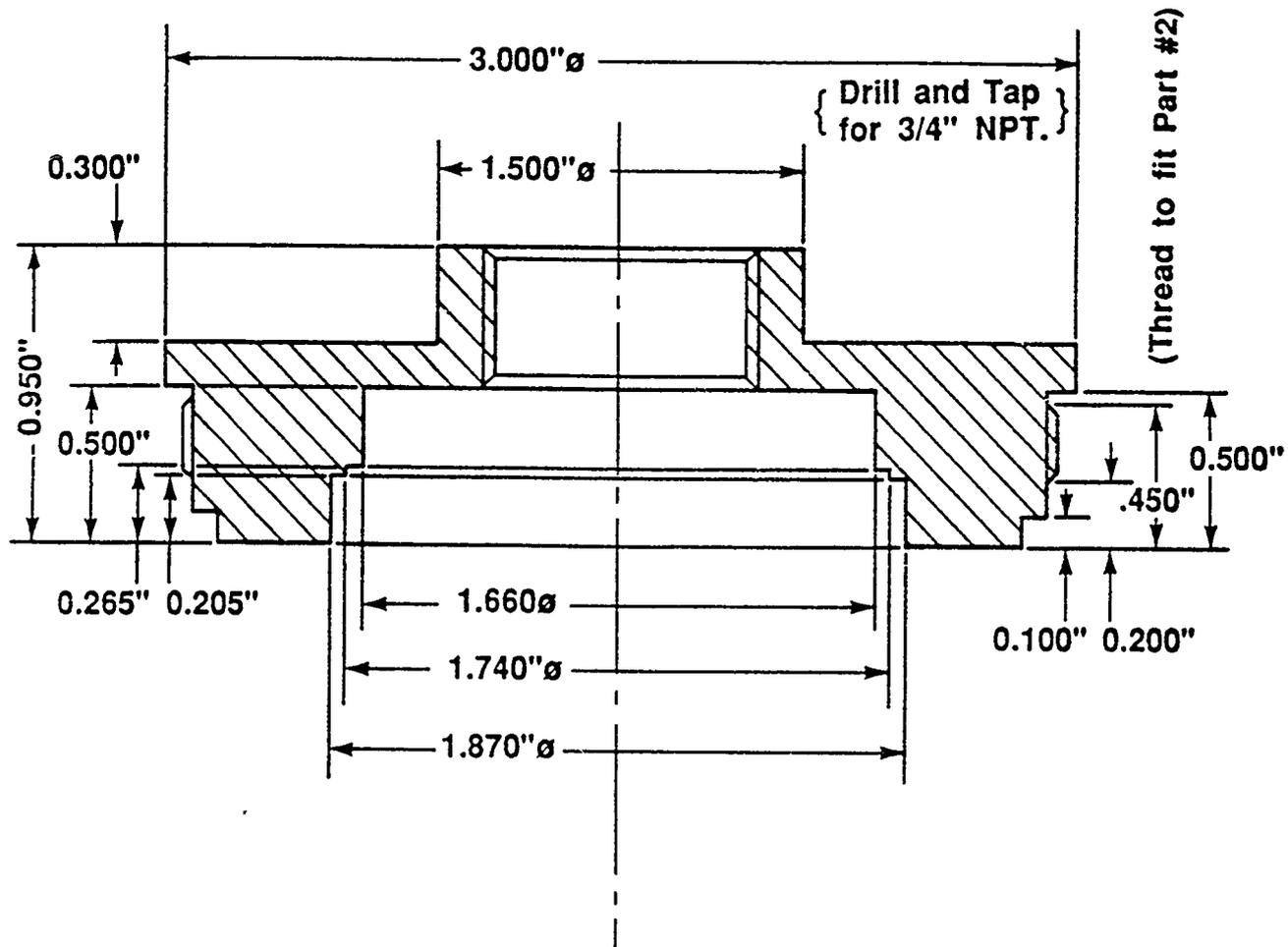
9 Holes (#72 Drill - 0.025")  
Each Hole 40° Apart, 0.690" from Center  
Center Hole 9/64" Diameter



|  |
|--|
| <b>Air Force Low-Pressure Impactor</b> |
| <b>Low-Pressure Section - Top View</b> |

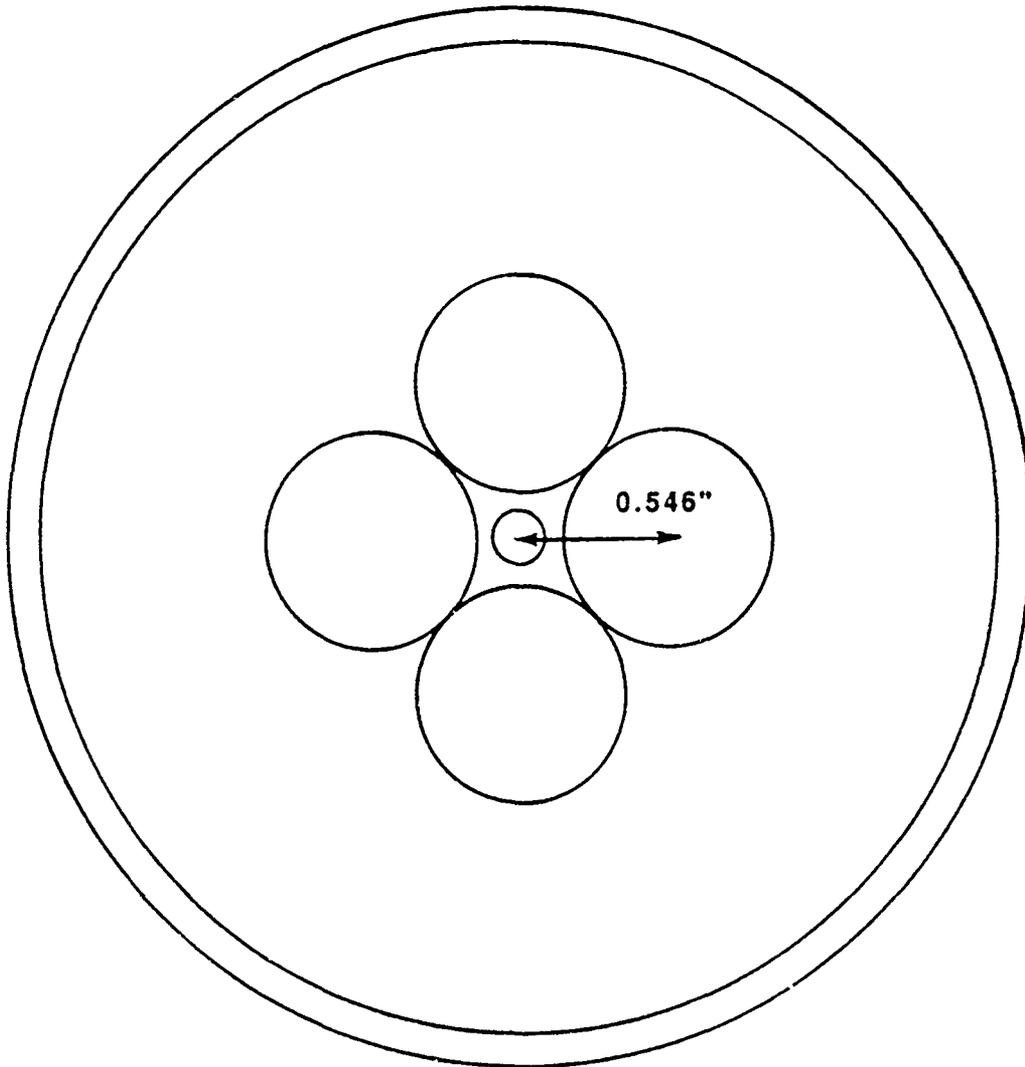


|                                 |
|---------------------------------|
| Air Force Low-Pressure Impactor |
| Low-Pressure Section Part #2    |



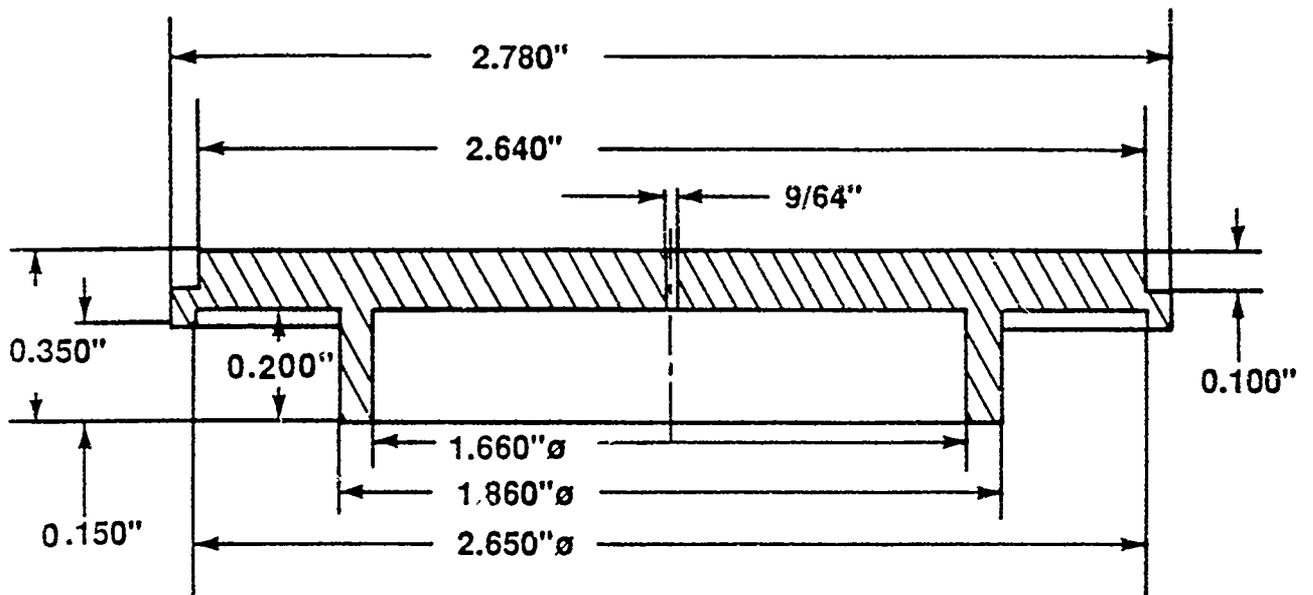
|                                 |
|---------------------------------|
| Air Force Low-Pressure Impactor |
| Housing Cap Part #3A            |

4 Holes  $9/16"$   
Each Hole  $90^\circ$  Apart,  $0.546"$  from Center  
Center Hole  $9/64"$  Diameter

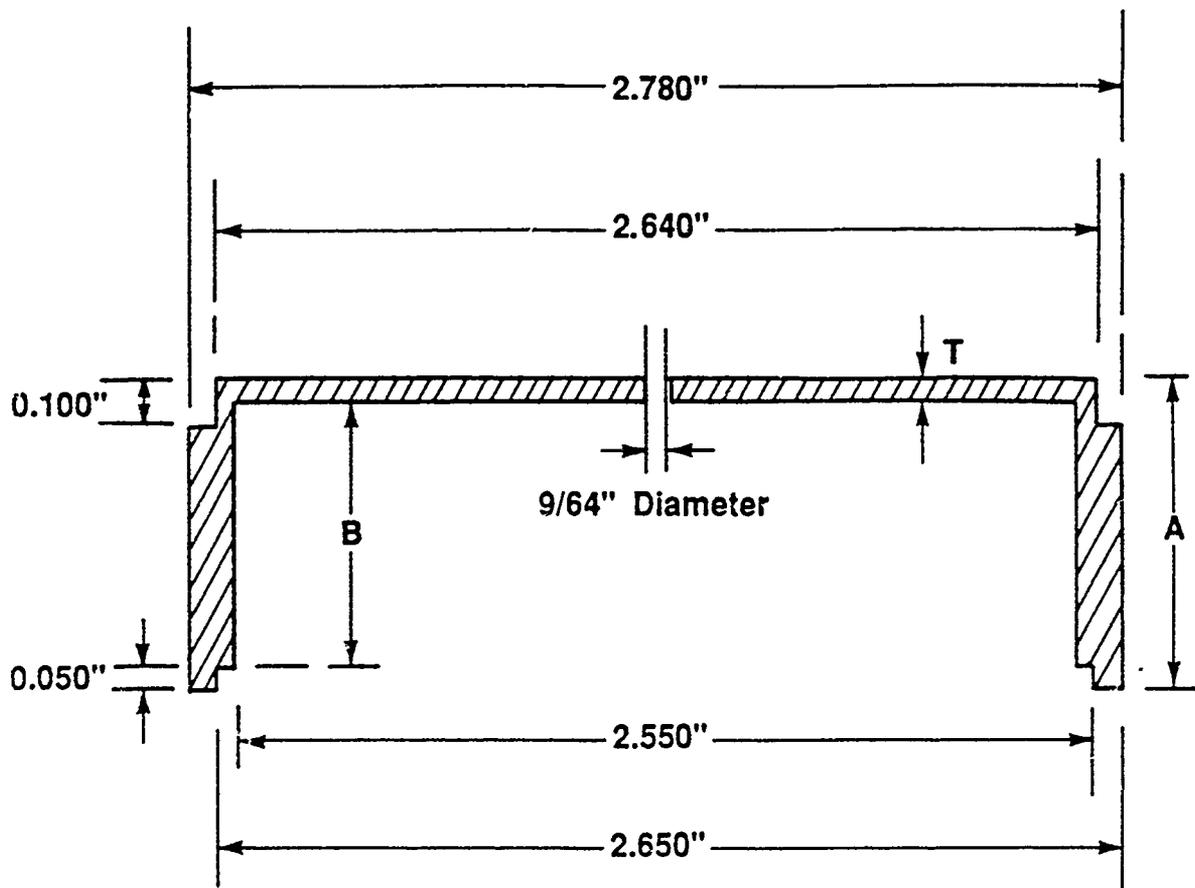


Air Force Low-Pressure Impactor

Stage 10 Pedestal Support Part # 3B - Top View



|                                    |
|------------------------------------|
| Air Force Low-Pressure Impactor    |
| Stage 10 Pedestal Support Part #3B |



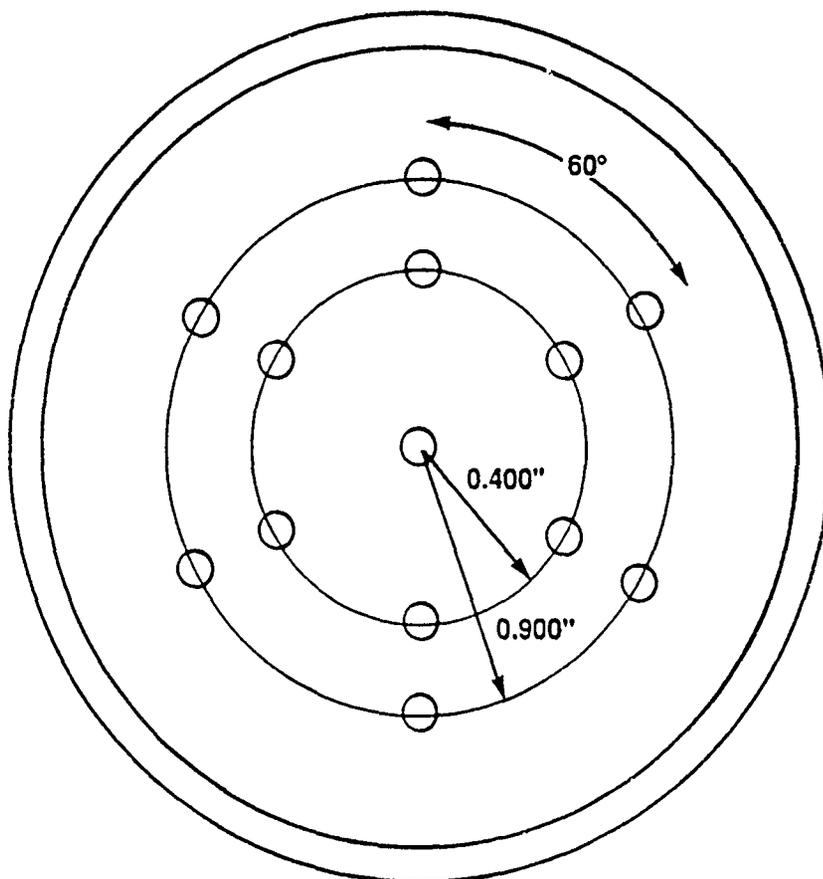
See Table 1 for A, B, and T Values.  
 See additional drawings for Hole Patterns.

|                                 |
|---------------------------------|
| Air Force Low-Pressure Impactor |
| Impactor Stages Part #4A - 4 I  |

TABLE 1

| Stage | A (in) | B (in) | T (in) |
|-------|--------|--------|--------|
| 2     | 1      | 0.70   | 0.3    |
| 3     | 0.72   | 0.56   | 0.16   |
| 4     | 0.590  | 0.50   | 0.090  |
| 5     | 0.560  | 0.50   | 0.060  |
| 6     | 0.530  | 0.50   | 0.030  |
| L1    | 0.550  | 0.50   | 0.050  |
| L2    | 0.540  | 0.50   | 0.040  |
| L3    | 0.530  | 0.50   | 0.030  |
| L4    | 0.530  | 0.50   | 0.030  |

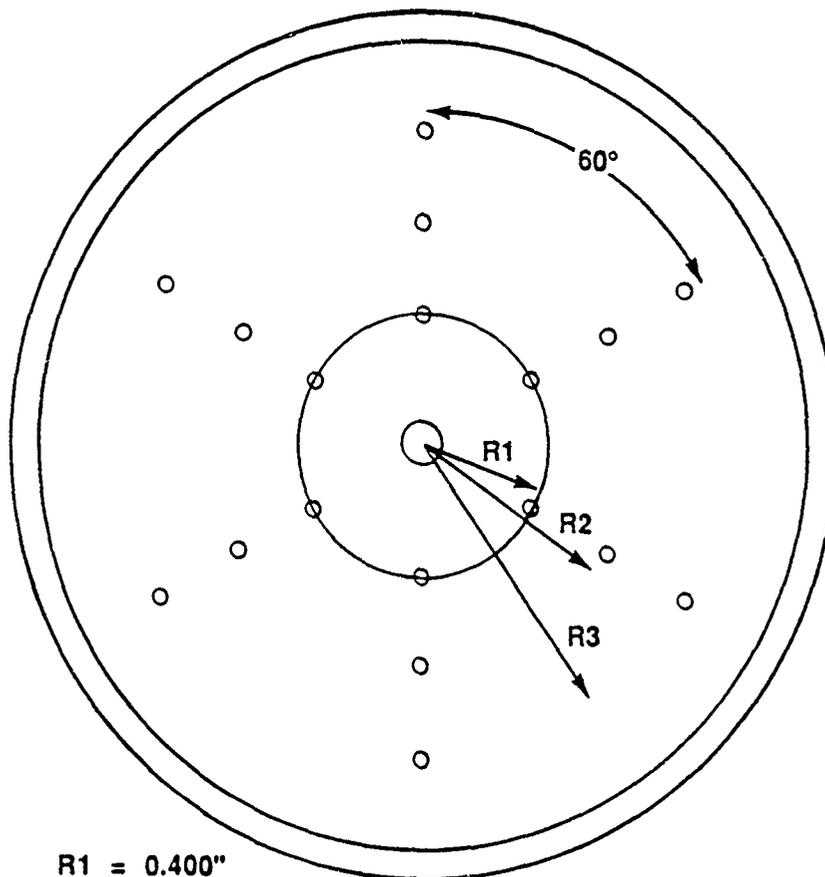
**Degrees Between Radials: 60**  
**2 Holes Per Radial**  
**Hole Diameter : 0.141" (#28 Drill)**  
**Center Hole 9/64" Diameter**



**Air Force Low-Pressure Impactor**

**Impactor Stage 2 Part #4A**

Degrees Between Radials: 60  
3 Holes Per Radial  
Hole Diameter : 0.082" (#45 Drill)  
Center Hole 9/64" Diameter

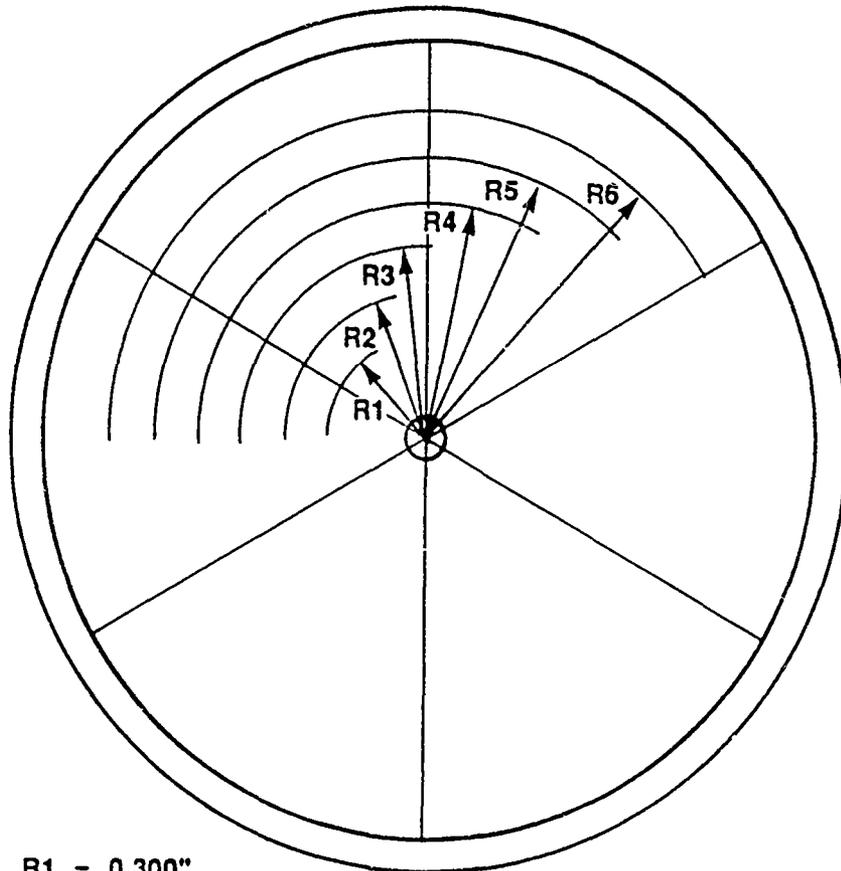


R1 = 0.400"  
R2 = 0.700"  
R3 = 1.000"

Air Force Low-Pressure Impactor

Impactor Stage 3 Part #4B

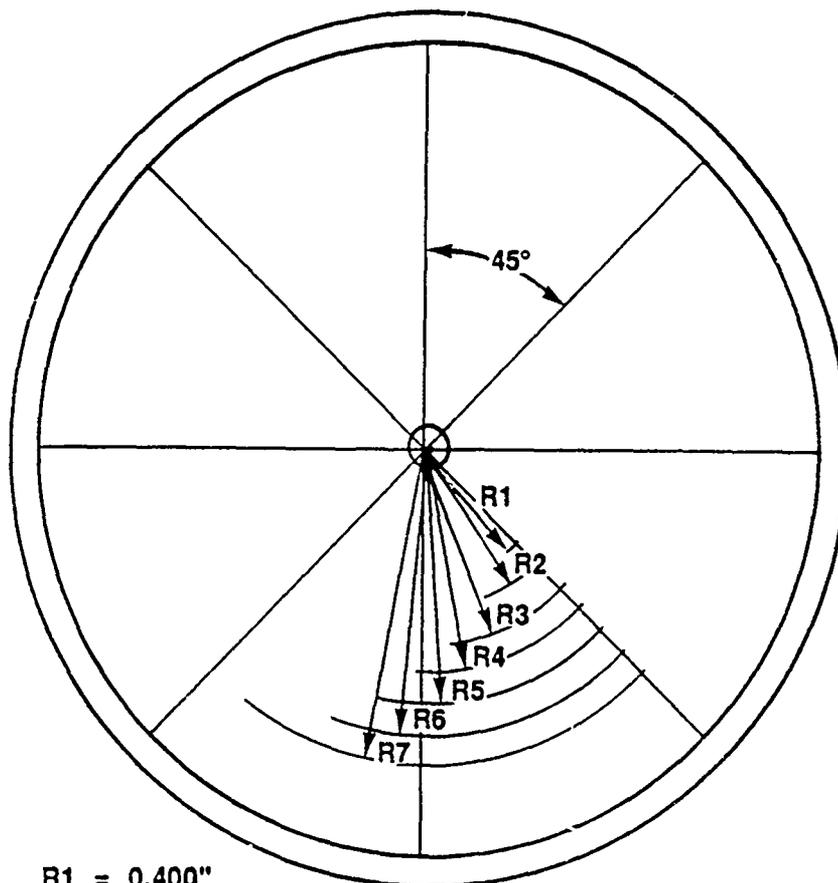
36 Holes (#56 Drill - 0.046"ø)  
6 Holes Per Radial  
6 36 Degree Radials  
Center Hole 9/64" Diameter



- R1 = 0.300"
- R2 = 0.450"
- R3 = 0.600"
- R4 = 0.750"
- R5 = 0.900"
- R6 = 1.050"

|  |
|--|
| <b>Air Force Low-Pressure Impactor</b> |
| <b>Impactor Stage 4 Part #4C</b>       |

56 Holes (#70 Drill - 0.028"ø)  
8 45 Radials  
7 Holes Per Radial  
Center Hole 9/64" Diameter

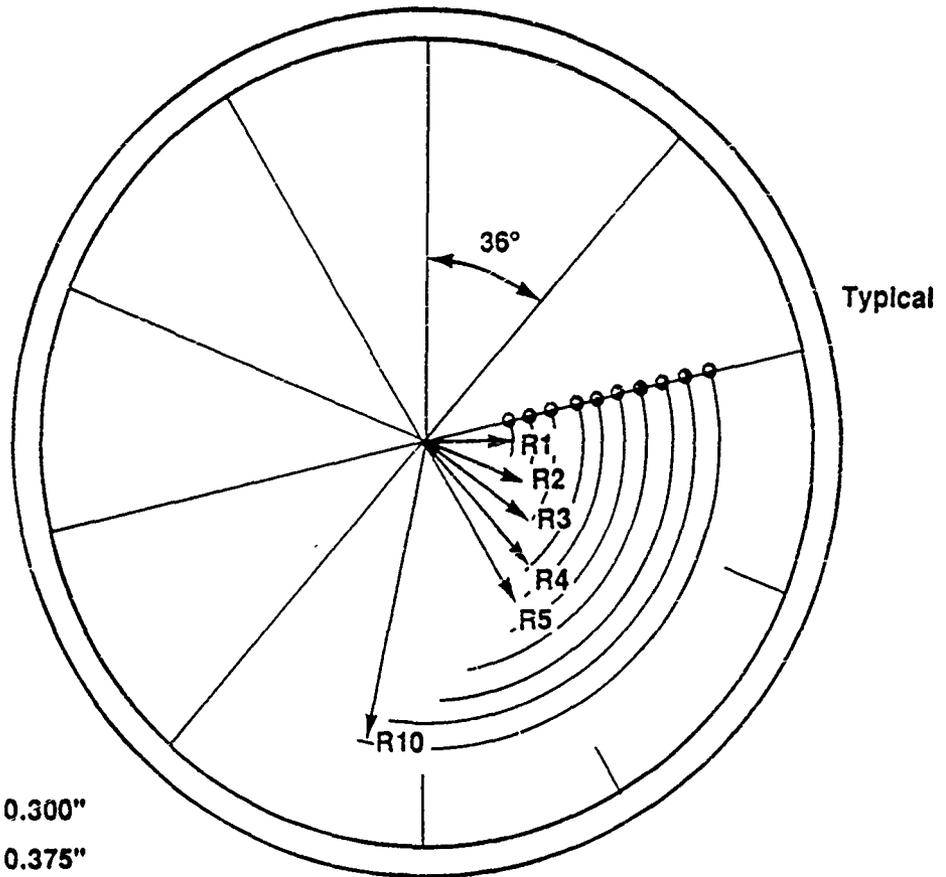


R1 = 0.400"  
R2 = 0.500"  
R3 = 0.600"  
R4 = 0.700"  
R5 = 0.800"  
R6 = 0.900"  
R7 = 1.000"

**Air Force Low-Pressure Impactor**

**Impactor Stage 5 Part #4D**

100 Holes (#78 Drill - 0.016")  
10 36° Radials  
10 Holes Per Radial  
Center Hole 9/64" Diameter

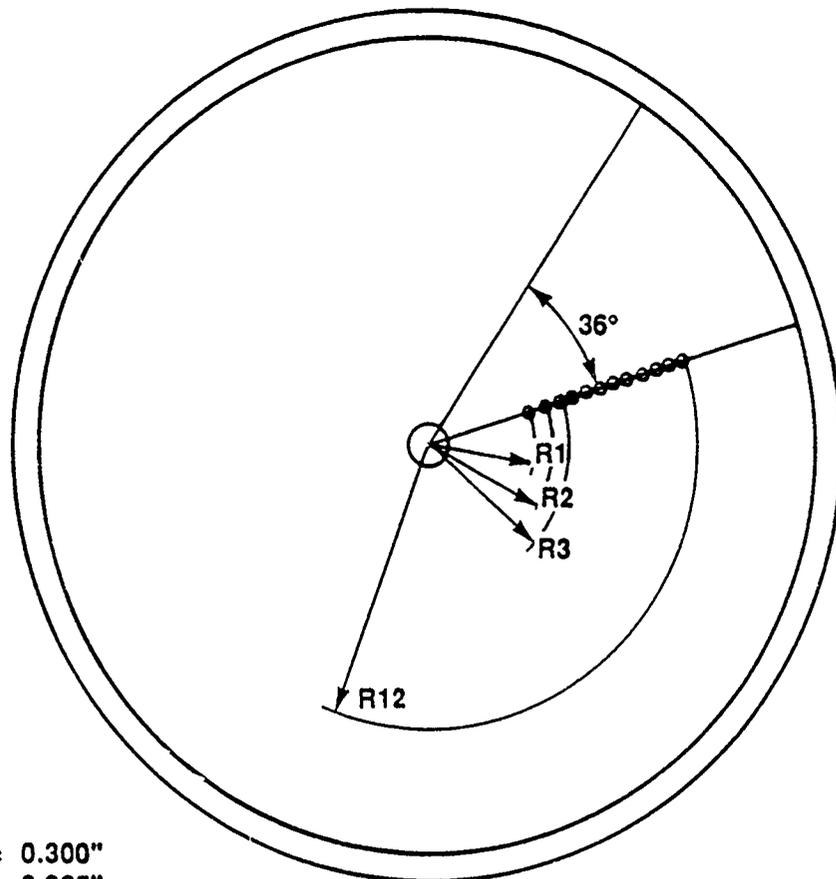


- R1 = 0.300"
- R2 = 0.375"
- R3 = 0.450"
- R4 = 0.525"
- R5 = 0.600"
- R6 = 0.675"
- R7 = 0.750"
- R8 = 0.825"
- R9 = 0.900"
- R10 = 0.975"

Air Force Low-Pressure Impactor

Impactor Stage 6 Part #4E

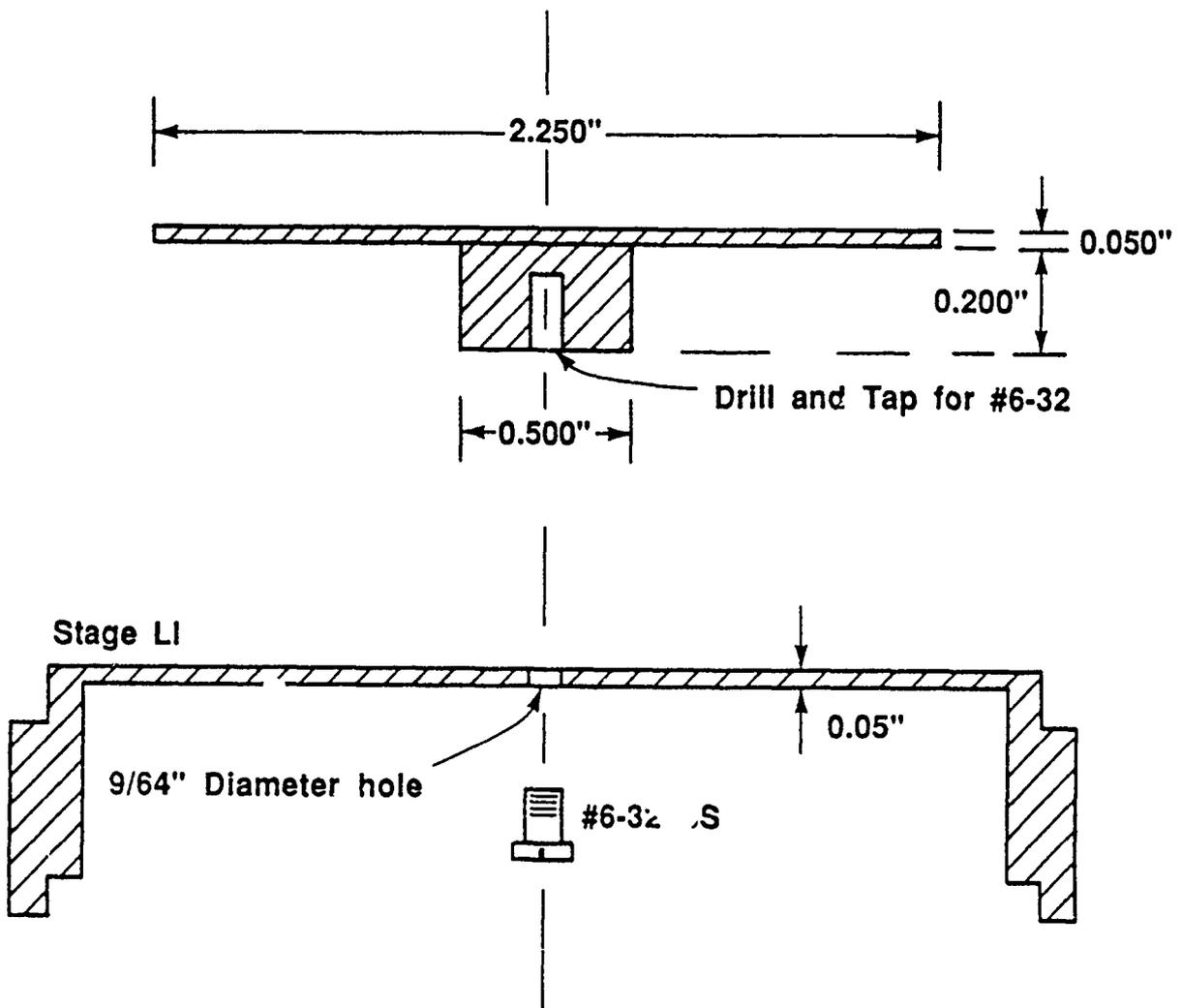
120 Holes (#71 Drill - 0.026")  
10 36° Radials  
12 Holes Per Radial



- R1 = 0.300"
- R2 = 0.365"
- R3 = 0.430"
- R4 = 0.495"
- R5 = 0.560"
- R6 = 0.625"
- R7 = 0.690"
- R8 = 0.755"
- R9 = 0.820"
- R10 = 0.885"
- R11 = 0.950"
- R12 = 1.015"

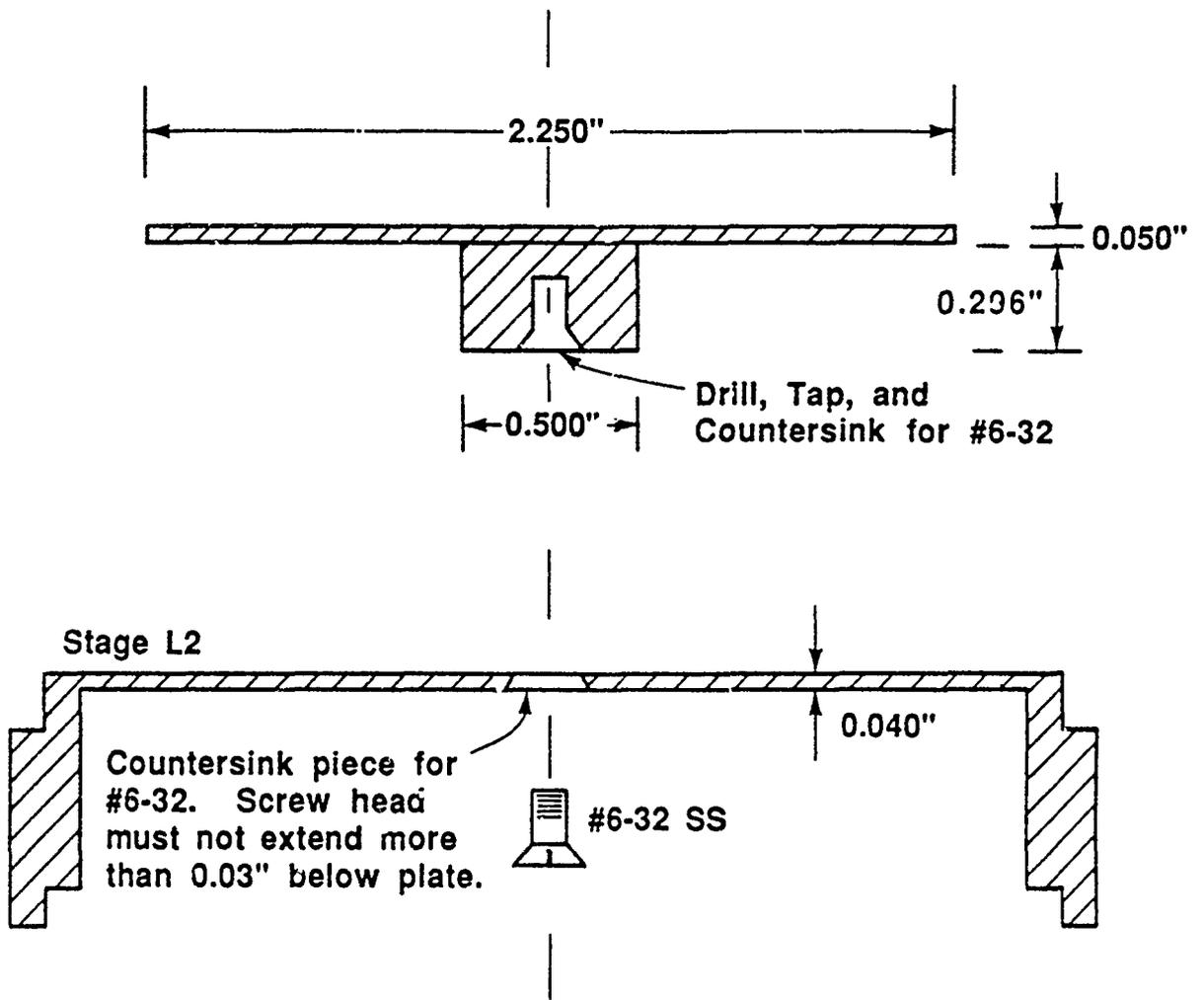
Air Force Low-Pressure Impactor

Impactor Stage L1 Part #4F

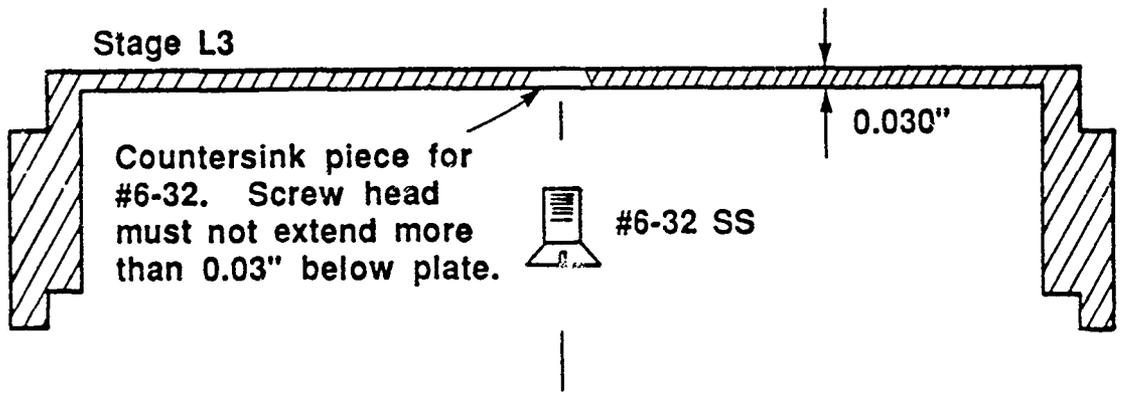
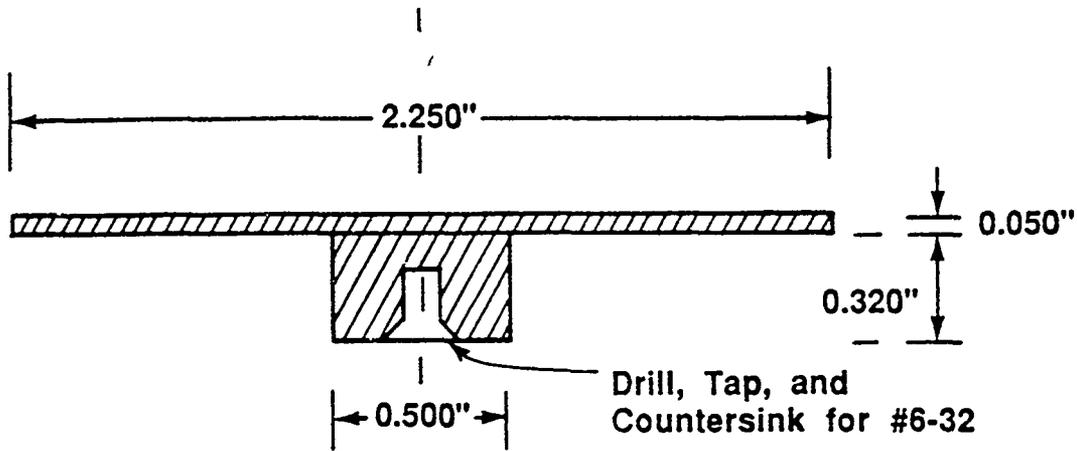


**Air Force Low-Pressure Impactor**

**Impactor Stage L1 with Pedestal**

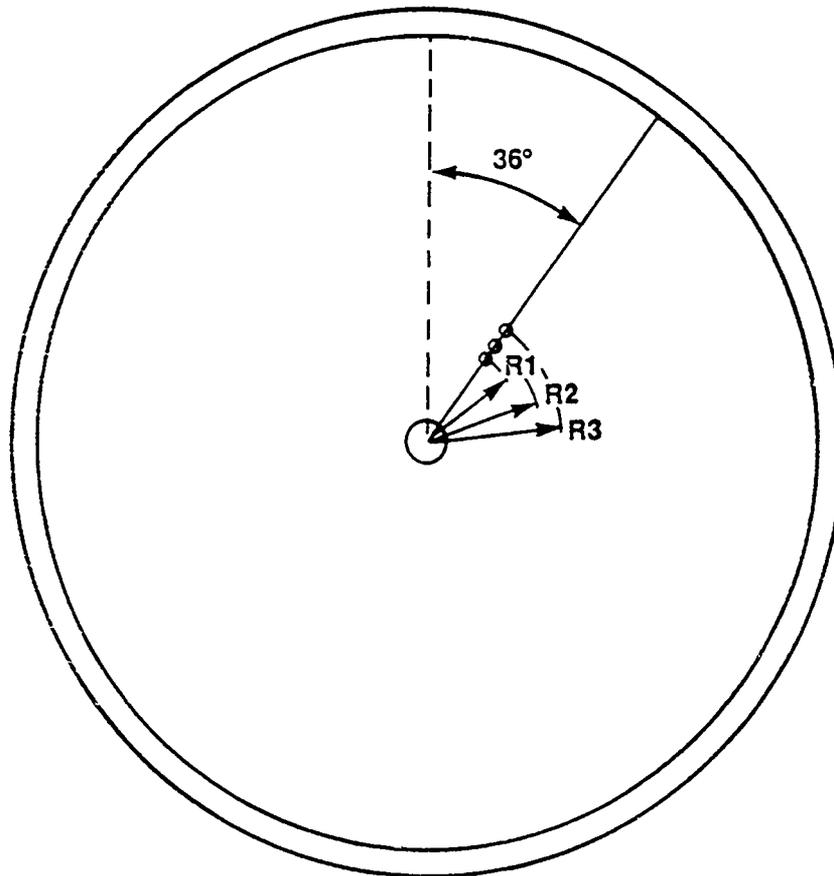


|                                 |
|---------------------------------|
| Air Force Low-Pressure Impactor |
| Impactor Stage L2 with Pedestal |



|                                 |
|---------------------------------|
| Air Force Low-Pressure Impactor |
| Impactor Stage L3 with Pedestal |

150 Holes (#76 Drill - 0.020")  
10 36° Radials  
15 Holes Per Radial  
Center Hole 9/64" Diameter

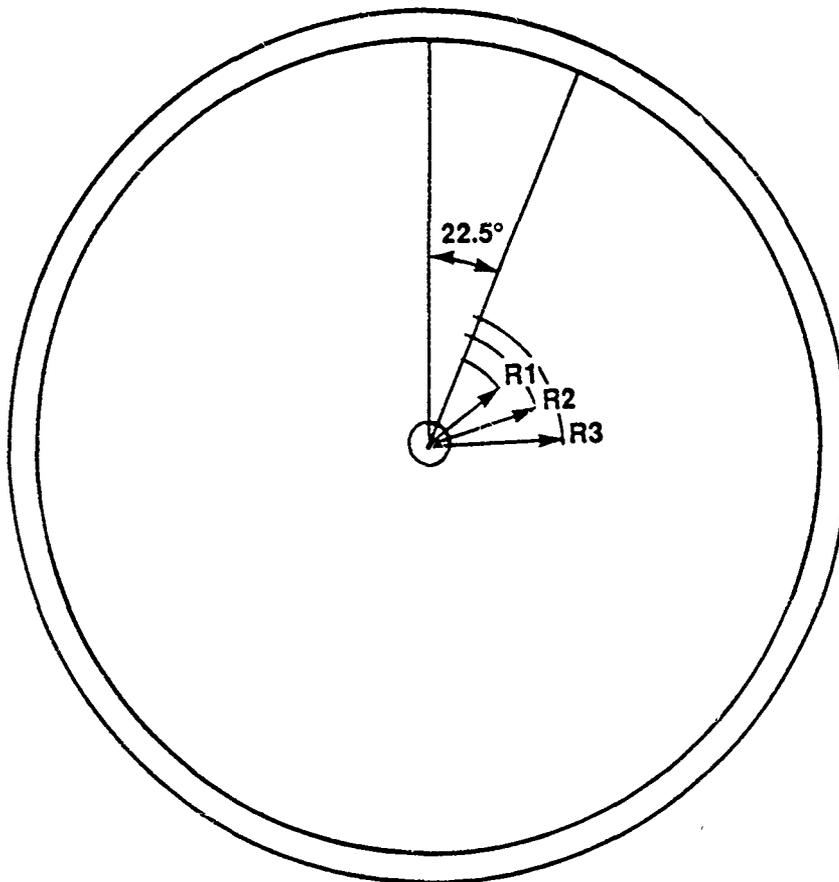


|             |              |
|-------------|--------------|
| R1 = 0.300" | R10 = 0.750" |
| R2 = 0.350" | R11 = 0.800" |
| R3 = 0.400" | R12 = 0.850" |
| R4 = 0.450" | R13 = 0.900" |
| R5 = 0.500" | R14 = 0.950" |
| R6 = 0.550" | R15 = 1.000" |
| R7 = 0.600" |              |
| R8 = 0.650" |              |
| R9 = 0.700" |              |

**Air Force Low-Pressure Impactor**

**Impactor Stage L2 Part #4G**

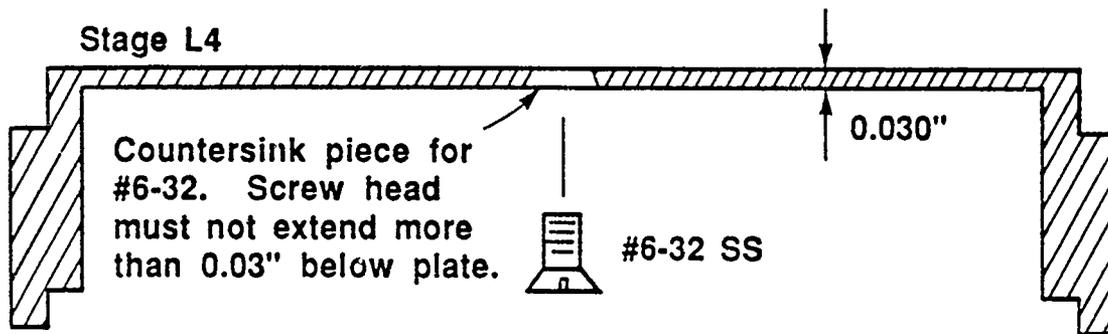
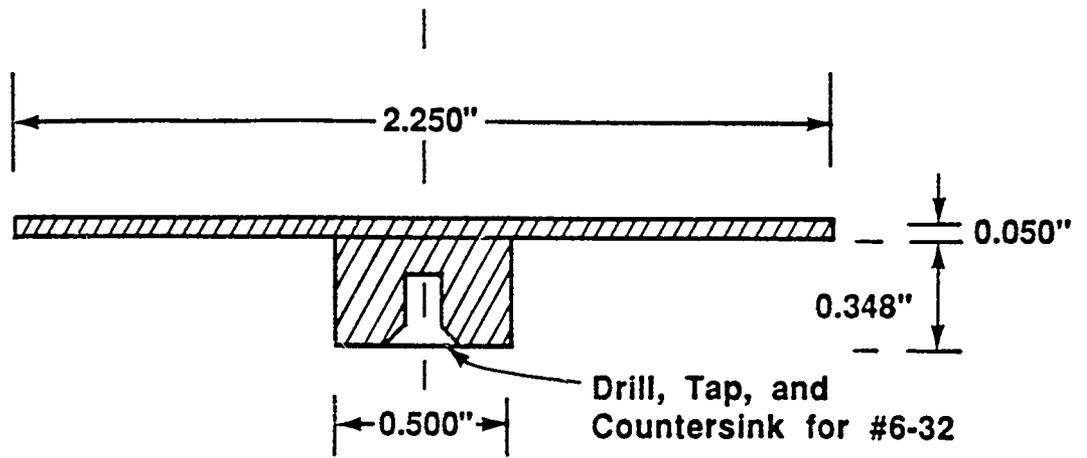
**320 Holes (#80 Drill - 0.0135")**  
**16 22.5" Radials**  
**20 Holes Per Radial**  
**Center Hole 9/64" Diameter**



|              |              |
|--------------|--------------|
| R1 = 0.300"  | R11 = 0.700" |
| R2 = 0.340"  | R12 = 0.740" |
| R3 = 0.380"  | R13 = 0.780" |
| R4 = 0.420"  | R14 = 0.820" |
| R5 = 0.460"  | R15 = 0.860" |
| R6 = 0.500"  | R16 = 0.900" |
| R7 = 0.540"  | R17 = 0.940" |
| R8 = 0.580"  | R18 = 0.980" |
| R9 = 0.620"  | R19 = 1.020" |
| R10 = 0.660" | R20 = 1.060" |

**Air Force Low-Pressure Impactor**

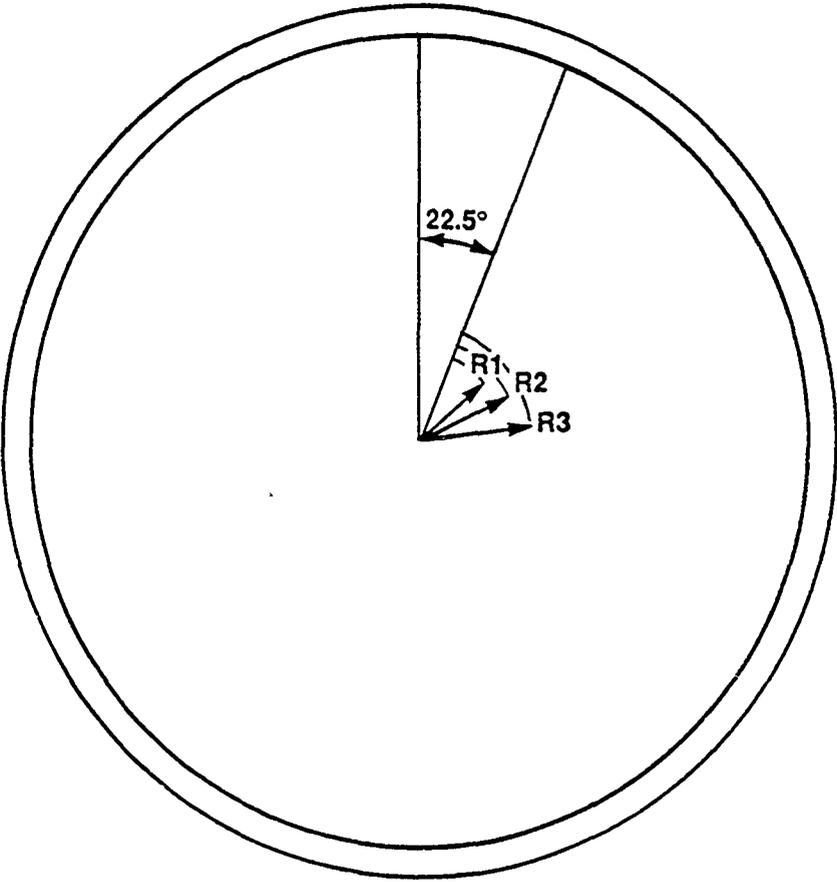
**Impactor Stage L3 Part #4H**



|                                 |
|---------------------------------|
| Air Force Low-Pressure Impactor |
| Impactor Stage L4 with Pedestal |

544 Holes (#87 Drill - 0.010")  
16 22.5° Radials  
34 Holes Per Radial  
Center Hole 9/64" Diameter

Note: See Table 2 for Values of R.

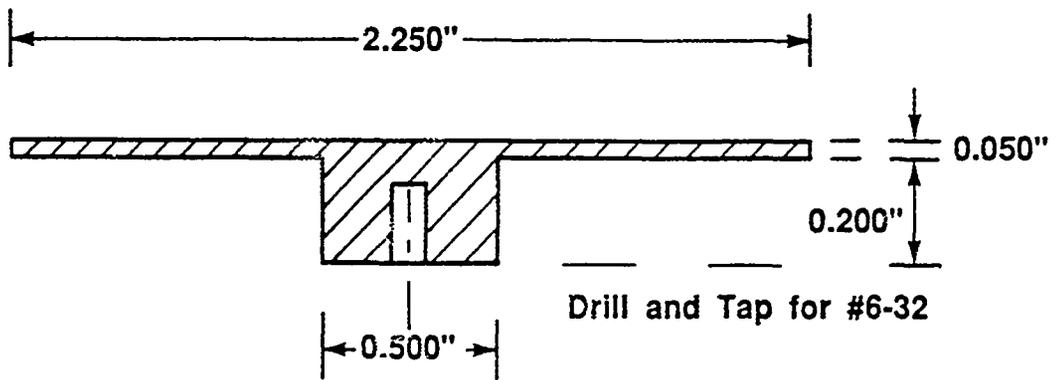


|                                 |
|---------------------------------|
| Air Force Low-Pressure Impactor |
| Impactor Stage L4 Part #4 I     |

TABLE 2

Values of  $\bar{F}$  for Impactor Stage L4

|            |           |
|------------|-----------|
| R1-0.275"  | R18-0.700 |
| R2-0.300"  | R19-0.725 |
| R3-0.325"  | R20-0.750 |
| R4-0.350"  | R21-0.775 |
| R5-0.375"  | R22-0.800 |
| R6-0.400"  | R23-0.825 |
| R7-0.425"  | R24-0.850 |
| R8-0.450"  | R25-0.875 |
| R9-0.475"  | R26-0.900 |
| R10-0.500" | R27-0.925 |
| R11-0.525" | R28-0.950 |
| R12-0.550" | R29-0.975 |
| R13-0.575" | R30-1.000 |
| R14-0.600" | R31-1.025 |
| R15-0.625" | R32-1.050 |
| R16-0.650" | R33-1.075 |
| R17-0.675" | R34-1.100 |



**Air Force Low-Pressure Impactor**

**Ambient Stage Pedestals Part #5**