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STUDY OF VISIBLE EXHAUST SMOKE FROM AIRCRAFT JET ENGINES

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FINAL REPORT

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16. Abstract The objective of this study was to relate the visibility of inflight jet exhaust to the SAE smoke number. A method based on photographic photometry was developed for measuring the optical density of smoke plumes. This method was related to visibility and to the smoke number through transmissometer measurements and visibility theory. A portable transmissometer, capable of operating over a wide range of optical path lengths and under varying ambient light conditions was fabricated for use on this study. The mathematical expression relating the transmission measurements to the smoke number was derived. Liminal visibility requirements of smoke trails, developed from light scattering theory, correlated with actual visual observations and the transmissometer and photometry measurements. Test results, with the engines investigated, indicate that SAE smoke numbers below 23 were associated with invisible exhaust plumes. Samples of the exhaust smoke showed the particles to be composed of lacy agglomerates. At the nozzle, the geometric median particle diameter was 0.052 μm. At a distance of 10 nozzle diameters the geometric median particle diameter was 0.13 μm at cruise condition.

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PREFACE

This report was prepared by the IIT Research Institute for the Federal Aviation Administration and the National Air Pollution Control Administration. The work effort was a part of a program of the Aircraft Division, Systems Research and Development Service, Federal Aviation Administration, and the Division of Motor Vehicle Research and Development, National Air Pollution Control Administration.

The work was administered under the direction of Mr. G. R. Slusher who served as project manager. Provision of the facilities, conduct of the tests and collection and reduction of the data for the SAE smoke numbers were furnished by the Propulsion Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

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INTRODUCTION

(1.) Purpose

The purpose of this research program was to develop techniques for the objective determination of visibility of jet exhaust smoke and to relate these techniques to the smoke number obtained for engines mounted in test cells. Use of the established relationships should enable the prediction of in-flight visibility of smoke trails from test cell data. A theoretical model of smoke trail visibility using the physical and optical properties of the smoke particles was included in the research effort.

(2.) Background

Smoke trails from aircraft turbine engines are a symbol of air pollution. Elimination of these smoke trails would erase a source of pollution complaints and improve visibility in and around jetports. Engine smoke is currently determined by a filter stain technique described by The Society of Automotive Engineers (Reference 1). The results are expressed as a numerical value known as the SAE smoke number. This technique is applied to engine test cell operations. A need exists for an objective measure of the visibility of smoke trails of aircraft in-flight, especially at take-off and approach power conditions, and to relate this measurement to the SAE smoke number. The only currently accepted method for specifying the visual quality of smoke trails from aircraft in-flight is the Ringelmann method (Reference 2). This is a subjective measurement. Results are highly dependent upon the conditions under which the measurements are performed (Reference 3).

Two techniques were developed to accomplish the objectives of this program. The first involved a transmissometer to measure the light attenuation of the smoke, and the second was photographic photometry. A special two-path transmissometer was developed for measuring the optical attenuation of smoke from test cell engines and engines of tied-down aircraft. The transmissometer is described in Appendix A. Photographic photometry was developed for evaluating the visibility of smoke from aircraft in-flight and from tied-down aircraft. This procedure is described in Appendix B.

The following measurements were made during this program:

(1) Photographic photometry measurements and Ringelmann observations of in-flight jet aircraft exhaust were made at Chicago's O'Hare Airport and at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey. Aircraft studied included a variety of commercial jets and the F-100, F-105, CV-880, and the Lockheed Jetstar.

(2) Photographic photometry and transmissometer measurements, Ringelmann observations, and the filter stain technique were all used to evaluate smoke emissions from tied-down aircraft at NAFEC. Aircraft used were the F-100, CV-880, and the Jetstar. NAFEC personnel obtained the SAE smoke numbers.

(3) Transmissometer measurements and SAE smoke numbers were made on test engines. One, a J-57 engine, was mounted on a static, sea-level, open-air test stand; the other, a JT-12 engine was mounted as a flight installation in a test wind tunnel. Samples of exhaust smoke were obtained during these tests using a specially constructed sampling rig described in Appendix C.

Quantitative data from the instrumental techniques were correlated with the subjective Ringelmann observations and visibility theory. The correlation established the relationship between the smoke number, the optical attenuation, photographic photometry, and the visual appearence of jet smoke.

DISCUSSION

(3.) Modeling Studies

(3.1) Light-Scattering Theory

The visibility of a smoke plume is a function of the optical and physical properties of the particles comprising the plume, the width of the plume, and the contrast between the plume and its background.

Where a smoke particle is small in relation to the wavelength of incident light, the total attenuation of light, i.e., extinction, E, is given by the expression:

$$E = \frac{24\,\alpha\, n^2 k}{(n^2 + n^2k^2) + 4(n^2 - n^2k^2 - 1)} \qquad (1)$$

where,

$\alpha = \frac{2\pi r}{\lambda}$

λ = wavelength of light, μm

r = particle radius, μm

n, k = functions of the refractive index, η, of the particle.

The refractive index, η, of a particle is a complex number when the particle both absorbs and scatters the incident light. In these instances, the refractive index is equal to $n(1 - ik)$, where n is the coefficient that defines the scattered light and nk the coefficient that defines the absorbed light. The term i is the operator $\sqrt{-1}$. The complex refractive index of carbon, the major particulate component of turbojet engine exhaust (Reference 4), for incident light of wavelength 0.490 μm is 1.59 (1-1.05i). Thus, $n = 1.59$ and $k = 1.05$.

The extinction of light is due to two separate and distinct phenomena; light scattering, S, and light absorption, A. The phenomena are defined as follows:

$$S = \frac{8\,\alpha^4}{3}\left|\frac{\eta^2 - 1}{\eta^2 + 2}\right|^2 \qquad (2)$$

$$A = E - S$$

Substituting the best available information into Equations (1) and (2), the following values for E, S, and A result:

$$E = 0.9$$

$$S = 0.1$$

$$A = 0.8$$

Thus, the extinction of light by turbojet engine smoke is due to 11% scattering of light and 89% absorption of light.

The attenuation of light by a smoke cloud, where the cloud is so diffuse that complications due to particle interactions are not encountered, is given by the expression:

$$I = I_o e^{-\pi r^2 CLE} \quad (3)$$

where,

I_o = the intensity of the incident light

I = the intensity of the transmitted light

C = number concentration of smoke particles

E = extinction coefficient

r = particle radius

L = depth of cloud intervening between I_o and I.

The ratio I/I_o is the transmission, T, of light through the smoke.

Thus,

$$2.303 \log T = -\pi r^2 CLE \quad (4)$$

Equation (4) illustrates the dependence of light transmittance through a smoke plume on the length of the viewing path. Thus, the position of the observer in relation to the smoke plume is important to plume visibility.

If the path length, the particle size, and the extinction coefficient are known, it is possible to calculate the number of particles per unit volume of gas that will produce various levels of light attenuation. The data in Table 1 is an example. The path length chosen is the diameter of the J-57

TABLE 1

RELATIONSHIP BETWEEN RINGELMANN NUMBER, LIGHT TRANSMISSION, AND PARTICLE CONCENTRATION OF TURBOJET ENGINE EXHAUST

Percent Transmission	Ringelmann Number	Particle Concentration at Engine Nozzle Millions of Particles/cm^3 (1)
98	--	17
95	1/4	50
90	1/2	100
80	1	
60	2	
40	3	
20	4	

(1) Particle concentration data is calculated from equation 4 using a path length of 56 cm and a particle size radius of 0.026 μm. The path length is the nozzle diameter of the J-57 engine and the particle size is the geometric median particle radius of the exhaust particles at the nozzle under cruise conditions, Table 2.

turbojet engine exhaust nozzle, 56 cm. The geometric median particle diameter of exhaust smoke at the nozzle of the J-57 engine is 0.052 μm, Table 2. The data in Table 1 show that particle concentrations of 1×10^8 particles/cm^3 correspond to transmission values of 90% or an equivalent Ringelmann number of 1/2.

(3.2) Visibility Requirements

The visibility requirements for jet smoke trails is similar to those of line targets such as wires, poles, and antennas. Two basic factors are involved in line target visibility. The target must be wide enough to be resolved by the unaided eye and must have sufficient contrast from the background to be distinguished. Tests by Douglas (Reference 5) show flagpoles and radio towers can be resolved if the angle subtended at the eye of the viewer is greater than 3 or 4 sec. of arc. Assuming a nondiffusing smoke track and no attenuation by the intervening atmosphere, a 2 ft. smoke track could be seen at a distance of 20 miles. Obviously, the angle subtended is not a factor limiting the visibility of jet smoke trails. The relationship between angle subtended and contrast is shown in Figure 1. These data (Reference 6) were developed in the IITRI laboratory under ideal conditions; a black line target (contrast = -1) subtending only 0.6 sec. of arc was visible.

Contrast, C_p, between a smoke plume of luminance, B_p, viewed against an extended background of luminance B_b, is given by the expression:

$$C_p = \frac{B_p - B_b}{B_b} \qquad (5)$$

From this equation, a totally light absorbing line target has a contrast of -1 and a black smoke plume will have a contrast ranging from 0 to -1 depending on the amount of background light transmitted through the plume. For a plume that scatters a negligible amount of light such as a carbon particle smoke (Reference 7)

$$C_p = T - 1 \qquad (6)$$

where T is the transmission.

TABLE 2

PARTICLE SIZE DISTRIBUTIONS OF EXHAUST FROM THE J-57 ENGINE (1)

Sampler Location, Engine Diameters from Engine Nozzle.	Engine Thrust Setting	Particle Size Distribution Geometric Median Dia. μm d_g	Particle Size Distribution Geometric Standard Deviation σ_g
0	Approach	---	---
	75% Norm.	0.053	1.63
	Cruise	0.052	1.46
2-1/2	Approach	0.084	1.33
	75% Norm.	0.084	1.40
	Cruise	0.076	1.51
10	Approach	0.096	1.38
	75% Norm.	---	---
	Cruise	0.13	1.40

(1) Data obtained from electron microscope samples collected by the IITRI sampler described in Appendix C.

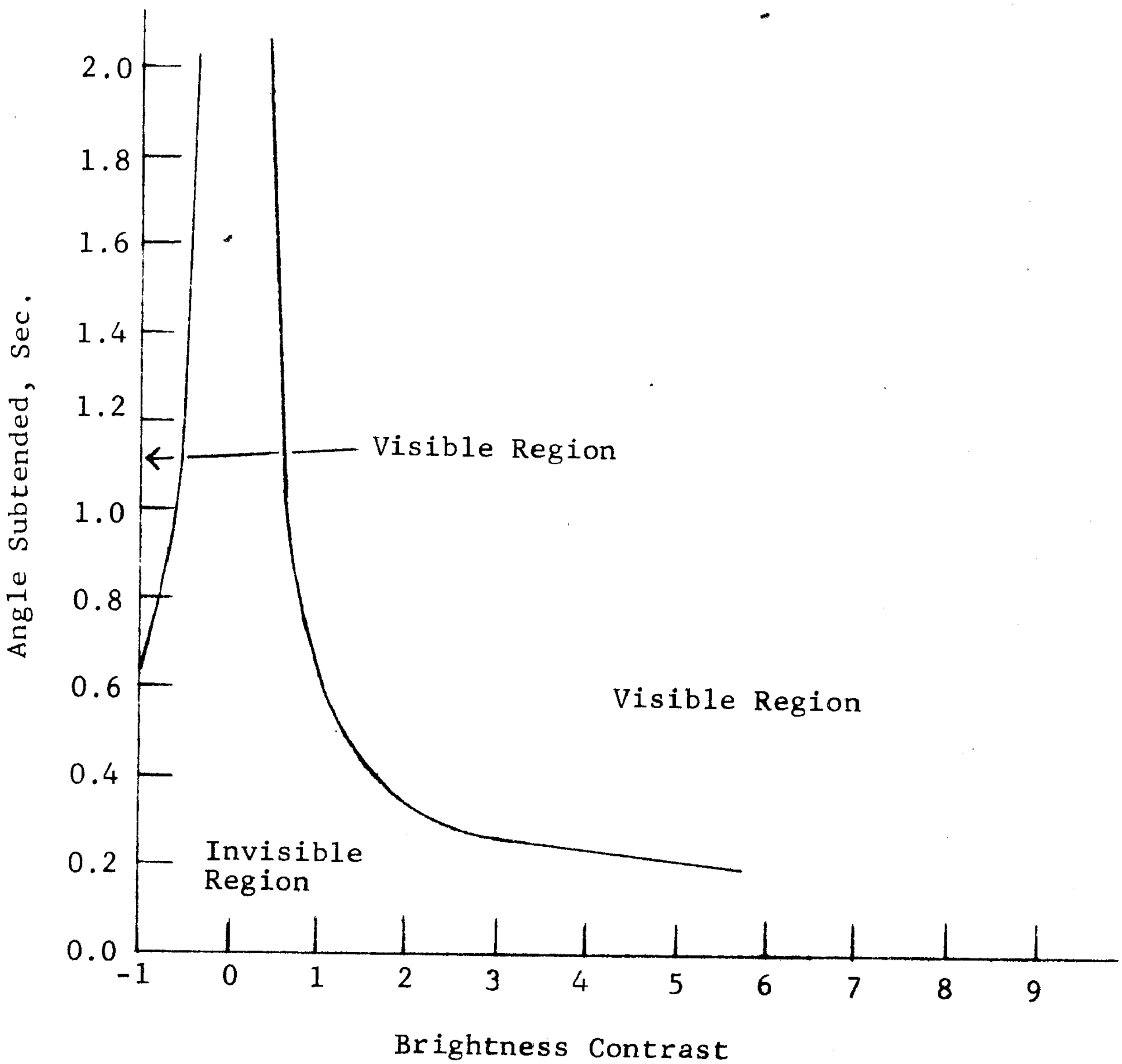


FIGURE 1. VISIBILITY OF LINE TARGETS.

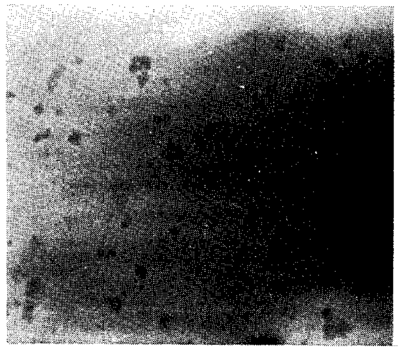
Middleton (Reference 8) discusses the liminal contrast for visibility of a variety of target shapes, sizes, and luminance levels. For targets and luminance levels that approach conditions under which jet engine exhaust plumes are usually viewed the liminal contrast ranges from about 1 to 5%. The visual range of objects in natural light is usually based on the assumption that the liminal contrast is 2%. On this basis, the liminal contrast value of 2% was selected for jet exhaust trails. Substituting 2% into Equation (6) indicates that jet smoke with transmission values of 98% or higher will be invisible.

In conclusion, the modeling studies show that carbon smokes attenuate light mainly by absorption. This factor permits the use of a simple expression to relate contrast and transmission measurements to liminal visibility. This relationship indicates that jet smoke must transmit more than 98% of the incident light to be invisible. Observing the J-57 engine at the nozzle and perpendicular to the exhaust flow, theory predicts that a smoke with a 98% transmission will have a particle concentration of 1.7×10^7 particles/cm^3.

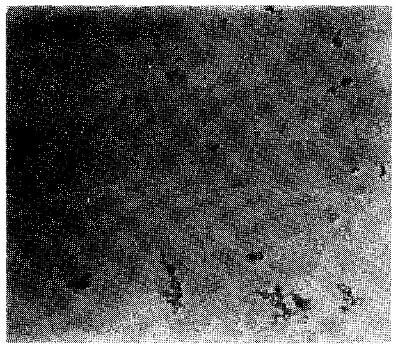
The mass concentration of the smoke particles can be computed from number concentration data if the particle density is known. Because of the lacy agglommerated structure of turbojet exhaust particles, as shown in Figure 2, handbook densities cannot be used. If the value of 0.04 g/cm^3 reported by Horvath and Charlson (Reference 9) for carbon flocs is used, the mass concentration of the smoke producing a transmitted value of 98% is 0.05 mg/m^3. Values found in the literature for exhaust particulates are 36 mg/m^3 for a PW-JT8D turbofan engine (Reference 10) and 0.5 and 27.0 mg/m^3 for an unstated turbojet engine at approach and takeoff power. (Reference 11)

(3.3) Theory Relating the Smoke Number and Optical Transmission of Jet Exhaust Plumes

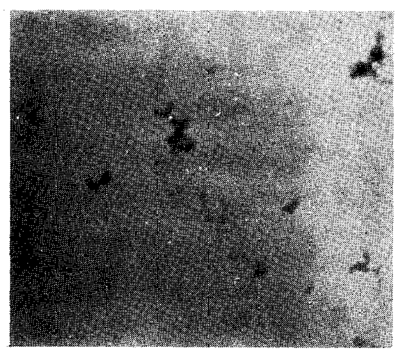
It is the purpose of this theoretical analysis to relate the SAE smoke number, the mass flow of an engine, and the dimensions of the nozzle, to the optical attenuation of the smoke plume. The first relationship considered is the effect of particle concentration in the exhaust gas on the staining of the filter paper.



at engine nozzle



2-1/2 nozzle diameters from the engine nozzle



10 nozzle diameters from engine nozzle

1µm

FIGURE 2. ELECTRON PHOTOMICROGRAPHS OF JET ENGINE EXHAUST PARTICLES. J57 ENGINE AT CRUISE.

(3.3.1) Reflectivity of Soot Deposit on Filter Paper

The reflectivity of soot deposit on filter paper may be represented by:

$$I_R = I_o 10^{-K_1 \left(\frac{mQ}{a}\right)^b} \qquad (7)$$

where,

I_o = incident light flux
I_R = reflected light flux
m = total mass of gas through the filter
Q = number of particles per unit mass of gas
K_1 = specific attenuation coefficient
a = area of filter paper
b = a number expressing the exponential retention of tne filter.

Equation (7) can be restated as:

$$R = \frac{I_R}{I_o} = 10^{-K_1 \left(\frac{mQ}{a}\right)^b} \qquad (8)$$

where,

R = absolute reflectivity of the stained spot.
Taking the logarithm of Equation (8) gives:

$$\log_{10} \frac{1}{R} = D_R = K_1 \left(\frac{mQ}{a}\right)^b \qquad (9)$$

where D_R is the optical reflection density of the soot deposit. The validity of this equation may be tested as follows:
Taking the logarithm of Equation (9) we have:

$$\log D_R = b(\log m + \log Q - \log a) + \log K_1 \qquad (10)$$

In a given smoke sampling system, the area, a, of the filter and K_1 are constants.

Equation (10) shows that if Q is constant at a given power setting and different masses of gas are filtered, a straight line will result when log D_R is plotted against log m. The slope of this line will be b. If the power setting is changed, resulting in a different value of Q, another straight line with slope b will result, providing Q remains constant as m is varied. Data for a variety of power settings, therefore, yield a family of parallel straight lines. These lines are offset because of the different particle concentrations, Q, produced at the different power settings. Plots of this type (Reference 12) give a series of parallel straight lines. Data presented in Reference 13 were replotted and resulted in parallel straight lines for approach, cruise and takeoff power. (The line for idle was poorly defined by the data points and appeared to have a slightly different slope. This is not surprising since the smoke numbers for this low power setting are less accurate.) The importance of the relationship is that the slope of the lines is dependent on the filtering characteristics of the filter. Thus, the filter must be specified. Changes in filter specifications will be difficult to accommodate.

(3.3.2) Optical Transmission of Smoke Plume

The transmission of light through a smoke cloud may be represented by the expression:

$$I_T = I_o \, 10^{-C\,L\,K_2} \tag{11}$$

where,

I_o = incident flux

I_T = transmitted flux

K_2 = specific absorption coefficient

L = optical path length

C = concentration of particles/unit volume of gas in the plume.

Equation (11) may be rewritten as:

$$T = \frac{I_T}{I_o} = 10^{-C\,L\,K_2} \tag{12}$$

where,

T = transmission

or:

$$\log_{10} \frac{1}{T} = D_T = C\ L\ K_2 \qquad (13)$$

where D_T is the optical transmission density of the plume. Equations (12) and (13) are universally accepted expressions and need no test for validity.

(3.3.3) Relating D_R to D_T and Operating Parameters

Neither Equation (9) nor Equation (13) are particularly useful for the study of engine exhaust because they contain the quantities Q and C. Neither of these expressions are measured directly by the filter stain technique or by the transmissometer. However, the reflection density of the filter stain can be related to the transmission density of the plume at the engine nozzle through the use of engine parameters and measured values. Thus, theory may be tested by experimentation.

If each unit mass of gas and unit volume of gas issuing from the nozzle of an engine at fixed operating condition contains the same number of particles (this is not always strictly true, for at times the smoke issues in a series of puffs) Equation (14) can be written:

$$N = MQ \qquad (14)$$

where,

M = mass of gas per unit time passing through the engine

N = number of particles per unit time in the exhaust.

The particle concentration/unit volume, C, is:

$$C = \frac{N}{AV} = \frac{MQ}{AV} \qquad (15)$$

where,

V = gas velocity (or particle velocity)

A = area of the nozzle.

Substituting this value for C in Equation (13) gives:

$$D_T = \frac{MQ}{AV} L\, K_2 \tag{16}$$

Rearranging the above equation to solve for Q gives:

$$Q = D_T \left(\frac{AV}{MLK_2}\right) \tag{17}$$

Substituting this value for Q into Equation (9) gives:

$$D_R = K_1 \left[D_T \frac{m}{a} \frac{AV}{MLK_2}\right]^b \tag{18}$$

Equation (18) relates the filter stain reflection density to the transmission density of the plume through the mass flow M, the area A of the nozzle, and the velocity V of the gas flow at the nozzle. This equation may be simplified if the relationship between velocity and mass flow is substituted. A reasonable assumption for velocity in subsonic flow is:

$$V = K_3 \frac{M}{A} \tag{19}$$

where K_3 is the reciprocal of the gas density. Substituting for V in Equation (18) gives:

$$D_R = K_1 \left[D_T \frac{m}{a} \frac{1}{L} \frac{K_3}{K_2}\right]^b \tag{20}$$

Equation (20) establishes the relationship between the filter stain density and the transmission density of the plume. The optical path length L is the diameter of the nozzle. The optical density is also measured at the nozzle. The mass flow M of the engine has been eliminated by the use of Equation (19).

Taking the log of Equation (20) gives:

$$\log D_R = b\ (\log D_T - \log L + \log m - \log a + \log K_3 - \log K_2) + \log K_1 \tag{21}$$

A simple means for testing the validity of Equation (21) would be to plot the reflection density of the filter stain D_R against the transmission density D_T of the plume on log-log paper for a series of values of Q resulting from running the engine at different power settings. The quantities m and a are held constant in the smoke sampling system as the power setting is varied. All other parameters in the equation are constant including b which is related to the retention of the filter material. If the equation is valid a straight line with slope b should result. By substituting into Equations (20) and (21) known values of all parameters and measured values of plume transmission and corresponding values of filter stain reflection density it should be possible to evaluate the constants and predict the optical transmission from the filter stain for any engine in terms of D_R and the nozzle diameter L.

(3.3.4) Relating Smoke Number to Filter Density

The smoke number is defined as:

$$\overline{SN} = (1 - \frac{R_s}{R_w})100 \tag{22}$$

where,

R_s = diffuse reflectance of the smoke spot
R_w = diffuse reflectance of clean filter paper.

Restating Equation (21), we have:

$$\frac{R_w}{R_s} = \frac{100}{100-\overline{SN}} \tag{23}$$

or,

$$\log_{10} \frac{R_w}{R_s} = D_R = 2 - \log_{10}\ (100-\overline{SN}) \tag{24}$$

where,

D_R = reflective density of the smoke stains.

Equation (24) gives the relationship between smoke number $\overline{SN}$ and reflection density, D_R. Hence by using this value and Equations (20) or (21) it should be possible to predict the transmission of the smoke plume as a function of $\overline{SN}$ and nozzle diameter L.

(4.) Static Tests of Engines and Aircraft

Static engine and aircraft tests were performed at NAFEC by both IITRI and FAA personnel. A number of different engines and aircraft were studied. These were: 1) a J-57-P-37A Pratt and Whitney Engine mounted on a Static, Sea Level, Open Air Test Stand; 2) a JT-12-6 engine mounted as a flight installation in a test wind tunnel; and 3) several aircraft tied-down on the National Guard run-up area at the NAFEC/Atlantic City Airport. These aircraft were an F-100, a CV-880, and a Lockheed Jetstar.

Various types of instrumentation were applied on each of the tests so that correlations between the results were possible.

(4.1) J-57-P-37A Engine Mounted in the Test Cell

The J-57 engine instrumentation consisted of an IITRI transmissometer to obtain smoke transmission data, the G.E. smoke sampler (Appendix D) to obtain smoke numbers, and the IITRI smoke sampler to obtain particle size data and smoke numbers.

Table 3 summarizes the data obtained. The transmission value reported is the one-way transmission as determined by the transmissometer and was obtained by taking the square root of the two-way measured-transmission value. The SAE smoke number is calculated as described in Appendix D. The other smoke numbers reported are variants of the SAE smoke numbers. They were obtained by substituting a Millipore filter for the standard Whatman filter or using a white backing rather than a black backing when measuring the reflectance of the filter deposits. For all power settings, no visual detection of smoke could be made by looking across the exhaust at 90° to the jet nozzle. However, the irregular dark background of the test cell was not conducive to visible observations. Smoke could be seen only by looking along the plume path. It appeared as puffs with low obscuration values, even at the higher power settings.

Data in Table 3 show that smoke numbers collected through the IITRI probe are nearly identical to those collected through the NAFEC probe when both are located at the nozzle. Since the NAFEC probe was designed for isokinetic sampling, it is concluded that isokinetic sampling is not required for smoke number determination. Since both probes gave similar results at the nozzle, the differences between the smoke numbers obtained as the IITRI probe was moved downstream from the nozzle reflect the effect of plume dilution and expansion.

(4.2) Light Transmission of J-57 Engine Exhaust for Various Path Lengths

Visual observations of smoke plumes with both tied-down aircraft and aircraft in-flight indicated that the visibility of the smoke was dependent upon the viewing geometry. It was observed that a plume may be invisible when viewed at right angles to the plume axis, but visible as the plume was observed at other angles. The phenomena is due to the increase in the attenuation caused by the longer optical path through the plume. To illustrate this phenomena under controlled conditions, experiments with the J-57 test cell engine were conducted. The transmissometer was used to measure the light attenuated by the plume at four angles, 90°, 45°, 30°, and 19.5°,to the plume axis. These correspond to 1, 1.4, 2 and 3 times the normal (90°) path length through the plume. The engine was operated at a series of selected power settings for each angle. The results of these measurements are summarized in Table 4.

A distinct decrease in transmission as the path length through the smoke is increased is noted. If the visibility threshold is taken to be 98% transmission (see page 9) then a smoke which is invisible when viewed at 90° may become clearly visible when viewed at other angles. The results are not precise, because at the smaller angles (30° and 19.5°) it was necessary to place the corner reflector approximately 30 and 50 ft. downstream from the nozzle of the engine to protect it from the blast. The plume had become much wider at this point. Nevertheless, the principle of increased absorption with path length is clearly demonstrated.

TABLE 3

SMOKE NUMBERS AND TRANSMISSION DATA OF JET SMOKE

J-57 ENGINE MOUNTED IN TEST CELL

Test Number		Distance in Nozzle Dia. From Engine To IITRI Probe and Transmisso.	Engine Gas Flow Lbs/Sec	Engine Thrust Setting	Smoke Numbers (1)									IITRI Transmissome
					G. E. Smoke Sampler								IITRI Sampler	
					Whatman Filters (2)				Millipore Filters (3)				Millipore Filters (3)	
					NAFEC Probe		IITRI Probe		NAFEC Probe		IITRI Probe		IITRI Probe	
IITRI	NAFEC				White Backing	Black Backing (4)	White Backing	Black Backing	White Backing	Black Backing	White Backing	Black Backing	White Backing (5)	Percent Transmission
6	31	0	53	Idle	21	12	16	--	10	10	6	6	9	99.3
7	33	0	94	Approach	36	27	34	25	26	25	21	18	68	98.4
8	35	0	114	75% Norm.	49	40	48	41	38	37	41	40	94	96.3
9	37	0	145	Cruise	55	47	54	47	49	48	47	46	>100	95.6
2	23	2-1/2	53	Idle	19	11	19	11	10	9	8	8	6	99.0
3	25	2-1/2	94	Approach	35	26	33	24	24	24	20	18	30	97.3
4	27	2-1/2	120	75% Norm.	50	42	42	34	43	42	31	30	59	95.8
5	29	2-1/2	148	Cruise	58	51	--	--	54	53	--	--	58	96.0
10	39	10	53	Idle	21	14	10	6	10	10	4	4	0	99.5
11	41	10	94	Approach	35	27	22	15	24	23	13	12	9	98.1
12	43	10	114	75% Norm.	48	40	34	25	43	42	21	20	26	97.0
13	45	10	145	Cruise	55	48	39	31	48	46	28	27	40	95.0
14	47	10	168	Takeoff	58	51	--	--	--	--	--	--	40	89.4(6)

(1) The NAFEC probe was always located at the engine nozzle. The IITRI probe was located at the distances from the engine nozzle given in column 3. All G. E. smoke sampler data were collected and analyzed by NAFEC personnel.

(2) Whatman filter data were obtained by interpolating reflectance readings to a filtration density of 0.3 ft^3/in^2.

(3) Millipore filter data were obtained by interpolating reflectance readings to a filtration density of 0.0565 ft^3/in^2.

(4) The SAE smoke number.

(5) Because the IITRI sampler filtered diluted exhaust it was necessary to extrapolate the data to a filtration density of 0.0565 ft^3/in^2 at thrust settings other than idle.

(6) This value appears to be erroneous. The value of 94.2% reported in Table 4 appears more reasonable.

TABLE 4

LIGHT TRANSMISSION AS A FUNCTION OF PATH LENGTH

J-57 Engine in Test Cell

Engine Thrust Setting	Percent Transmission Relative Optical Path Through Plume (1)			
	1	1.4	2	3
Idle	98.2	99.0	98.9	97.8
Approach	97.0	97.0	96.4	93.0
75% Norm.	95.3	94.5	92.0	85.8
Cruise	94.3	92.4	89.0	82.2
Takeoff	94.2	91.6	88.0	79.6

(1) Relative paths correspond to angles of 90°, 45°, 30°, and 19.5° to the plume axis.

(4.3) JT-12-6 Engine Mounted in Wind Tunnel

The JT-12-6 engine instrumentation consisted of the IITRI transmissometer, GE smoke sampler, and IITRI smoke sampler. No visual or photographic observations of smoke could be made. The transmissometer was located at a distance of 7-1/2 nozzle diameters downstream from the engine nozzle and viewed the smoke plume through windows located on opposite sides of the tunnel. The IITRI smoke sampling probe was also placed 7-1/2 nozzle diameters from the engine. It was connected to the dilution apparatus by a heated sampling line. This was necessary because personnel safety considerations prevented the placement of the dilution apparatus just outside the wind tunnel at the point where the probe was placed.

Table 5 summarizes the data obtained on the JT-12-6 engine. The JT-12-6 engine gave transmission values exceeding 98% at all power settings. Based on the modeling study, this engine should not produce a visible smoke. The SAE smoke numbers were less than 25 at all power settings.

(4.4) Tied-Down Aircraft Tests

(4.4.1) F-100 Single-Engine Aircraft

An F-100 aircraft, operated by the New Jersey National Guard, was obtained for study. This aircraft has a J-57-P21A engine, similar to the engine tested in the test cell. The plane was tied-down at the National Guard run-up area at the NAFEC/Atlantic City Airport. The exhaust was analyzed with the IITRI transmissometer, the GE smoke sampler, by photographic photometry, and by visual observations. A photograph of the instrumentation is shown in Figure 3. The test results are summarized in Table 6.

The smoke numbers of the F-100 engine are similar to those obtained with the test cell engine. The smoke number at cruise is higher than at takeoff. This inconsistency is due to the movement of the aircraft at takeoff power. The nose wheel depresses and the tail of the aircraft rises at takeoff power; thus, the location of the sampling probe in relation to the engine nozzle is disturbed. The data show a a distinct correlation between transmission and photographic

TABLE 5

SMOKE NUMBERS AND TRANSMISSION DATA OF JET SMOKE JT-12-6 ENGINE MOUNTED IN WIND TUNNEL

Test Number		Engine	Engine	Smoke Numbers [1]									IITRI
				G. E. Smoke Sampler								IITRI Sampler	
				Whatman Filters [2]				Millipore Filters [3]				Millipore Filter [3]	
		Gas Flow	Thrust	NAFEC Probe		IITRI Probe		NAFEC Probe		IITRI Probe		IITRI Probe	Transmissometer [6] Percent
IITRI	NAFEC	Lbs/Sec	Setting	White Backing	Black Backing [4]	White Backing	Black Backing	White Backing	Black Backing	White Backing	Black Backing	White Backing [5]	Transmission
WT-1,2	77,78	31	Approach	6	4	5	4	2	3	1	2	3	99.1
WT-4,5,7	80,81	46	Cruise	29	21	14	10	21	20	8	7	13	98.3
WT-6,8,9	82,83	56	Takeoff	33	25	18	12	30	29	11	10	17	98.1

(1) The NAFEC probe was always located at the 12 o'clock position at the engine nozzle. The IITRI probe was always in the center of the wind tunnel 7-1/2 nozzle diameters from the engine. All G. E. smoke sampler data were collected and analyzed by NAFEC personnel.

(2) See note 2, Table 3.

(3) See note 3, Table 3.

(4) The SAE smoke number.

(5) See note 5, Table 3.

(6) Transmissometer located 7-1/2 nozzle diameters from engine nozzle. Path length was the diameter of the wind tunnel at this location.

TABLE 6

SMOKE QUALITY FROM A TIED-DOWN F-100 AIRCRAFT

J-57-P21A ENGINE

Engine Thrust Setting	Engine Gas Flow Lbs/Sec	IITRI Transmissometer % Transmission (1)	Photometry % Transmission (1)	Smoke Number Whatman Filter (2)		Visual Transmission Across Plume, % (3)	
				Black Backing	White Backing	At Nozzle	Well Behind Aircraft
Idle	53	98	100	9	15	Clear	Clear
Approach	94	97	100	23	31	Clear	Clear
Cruise	137	95	<100	54	62	Clear	90-95 (4)
Takeoff	159	94	91-94	48 (5)	58 (5)	Clear	90-95 (4)

(1) The transmissometer viewed the exhaust at the nozzle and at right angles to the direction of plume travel. The photographs were taken similarly by lying on the ground and photographing the exhaust against a sky background.

(2) SAE smoke number.

(3) Viewed against the normal background of the sky horizon.

(4) Smoke is not continuous but billowy.

(5) Low smoke numbers are attributed to the movement of the aircraft at takeoff power.

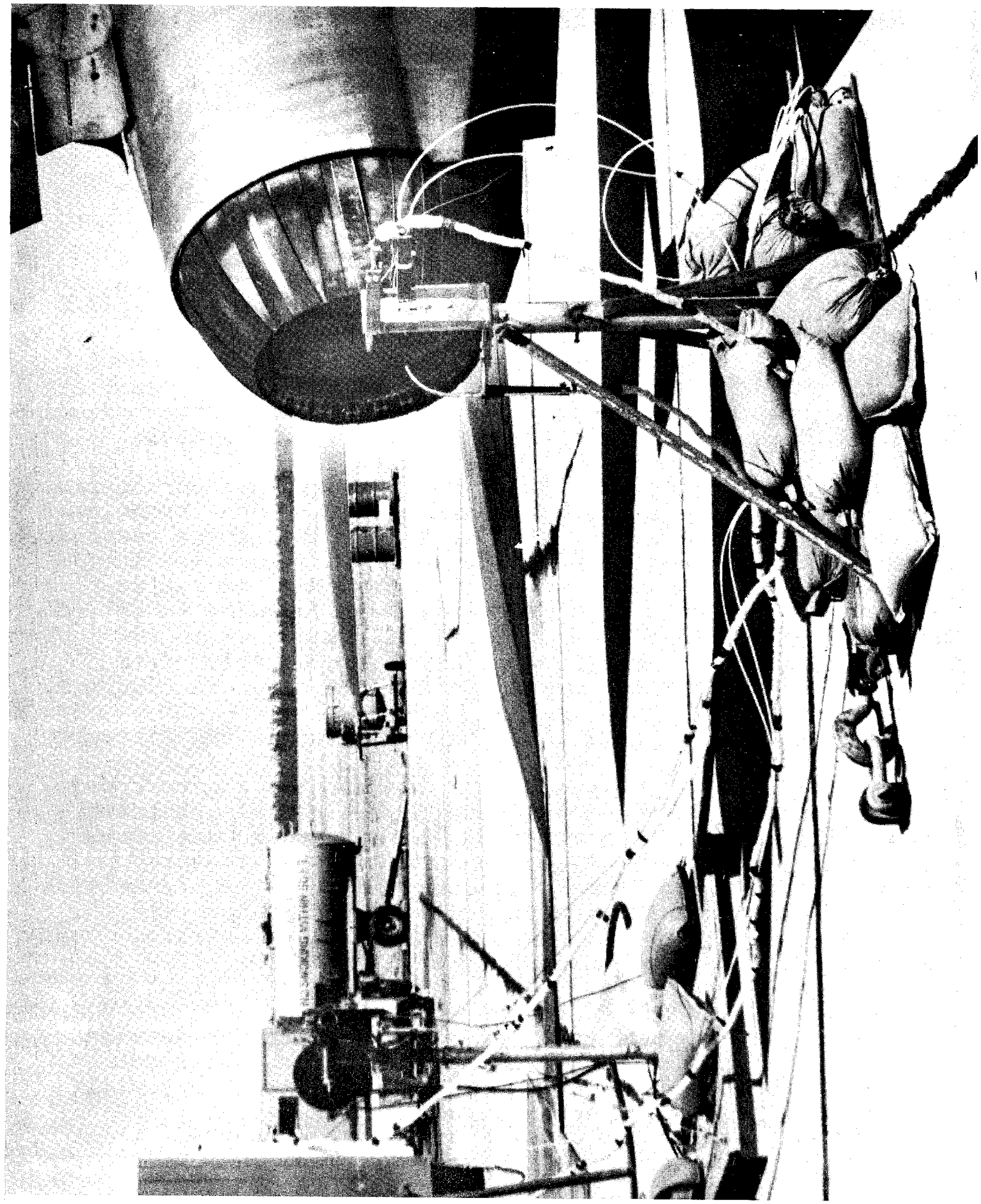


FIGURE 3. SMOKE INSTRUMENTATION.

photometry. Also, smoke with transmission values higher than 97% and smoke number values less than 23 are invisible. Smokes with transmissions less than 97% and smoke numbers above 23 are visible.

(4.4.2) Convair 880 Aircraft

The left outboard engine of a CV-880 aircraft, operated by the FAA, was studied with the same methods used for the F-100 aircraft. The engine was a CJ805-3B. Results are summarized in Table 7. The data show excellent agreement between the transmission values obtained by the transmissometer and by photographic photometry. Plumes with transmission values of 98% and SAE smoke number of 23 or less were not visible.

Conditions were ideal for photographic photometry. The plume was well above the horizon, and the sky density below the plume was essentially the same as above. For these reasons, a takeoff microdensitometer trace is shown in Figure 4. The values presented in Table 7, as well as the other tables reporting photometry data, are for the maximum decrease in optical density. For the illustrated example, this value is in the center of the plume. A positive print of the negative from which the microdensitometer trace was made is shown in Figure 5.

(4.4.3) Multiple Engines of Convair 880 Aircraft

Multiple engines of the Convair 880 aircraft were tested using the IITRI transmissometer, photographic photometry and visual estimates of obscuration. These results are summarized in Table 8. In most cases, the transmission measured photographically is less than that measured with the transmissometer. This is apparently due to ground interference with the plume. The height of the transmissometer was approximately that of the engines. The photographs, however, show the plume down to the horizon line which is well below the line of sight of the transmissometer. The microdensitometer traces, Figure 6, show a continuous increase in the density down to the horizon line. Since the obscuration values given in the tables are the maximum obscuration values (at the ground line) they will be higher than the transmissometer values because the transmissometer was fixed at the approximate average exhaust height with the engines. At the time the test was made the influence of engine tilt and ground dirt was not fully recognized.

TABLE 7

SMOKE QUALITY FROM THE NUMBER 1 ENGINE OF A TIED-DOWN CV-880 AIRCRAFT

CJ805-3B ENGINE

Engine Thrust Setting	Engine Gas Flow Lbs/Sec	IITRI Transmissometer Reading % Transmission (1)	Photographic Photometry % Transmission (1)	Smoke Number Whatman Filter (2) Black Backing	Smoke Number Whatman Filter (2) White Backing	Visual Transmission Across Plume, % At Nozzle	Visual Transmission Across Plume, % Well Behind Aircraft
Idle	42	98	96	23	32	100	100
Approach	124	89	87	60	67	90-95	80-90 (3)
Cruise	147	87	85	69	73	90-95	75-85 (4)
Takeoff	163	87	86	65 (6)	70 (6)	90-95	75-85 (5)

(1) See note 1, Table 6.

(2) SAE smoke number.

(3) Smoke is not continuous but billowy. The smoke puffs have a transmission of 80%. Integrating the clear sky and the puffs yield an estimated visual transmission of 80-90%. Viewing the smoke from in front of the engine, the transmission varies from 40-60%.

(4) Integrated puffs and background sky give transmission values of 75-85%. When viewed from in front of the engine the transmission is 40%.

(5) Smoke is more uniform in composition, not so puffy.

(6) Low smoke numbers are attributed to movement of the aircraft at takeoff power.

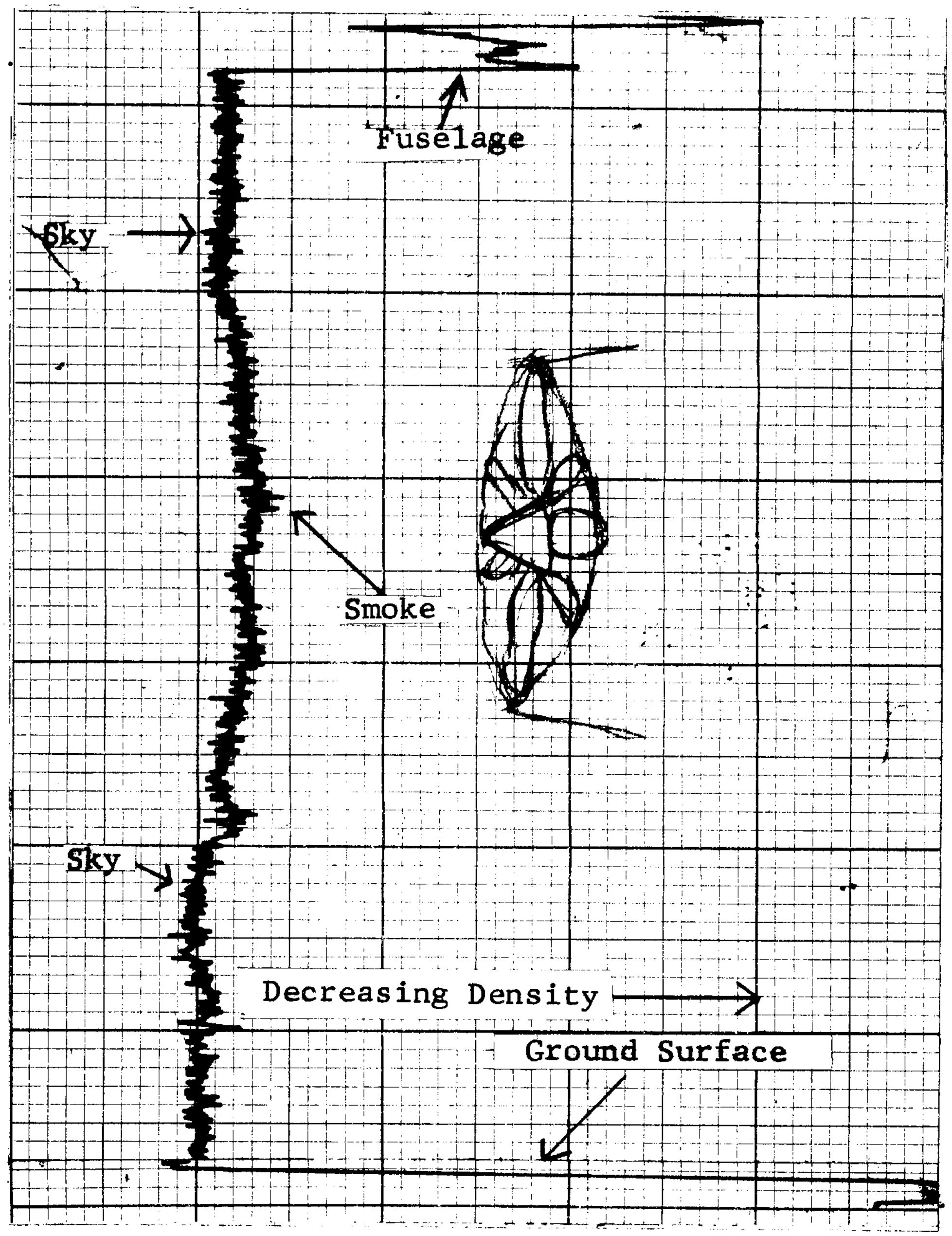


FIGURE 4. MICRODENSITOMETER TRACE OF NUMBER 1 ENGINE OF CONVAIR 880 AIRCRAFT - TAKEOFF POWER.

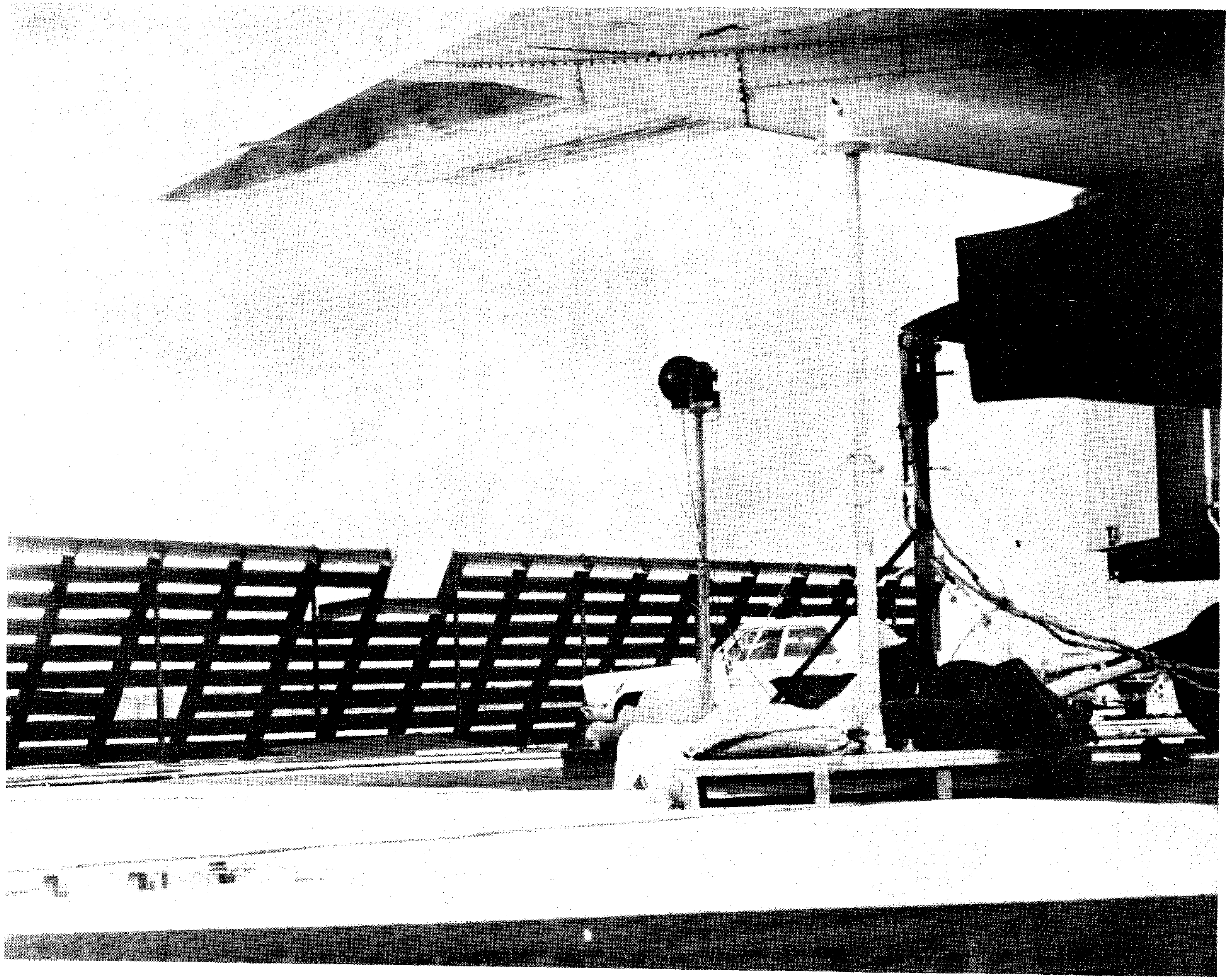
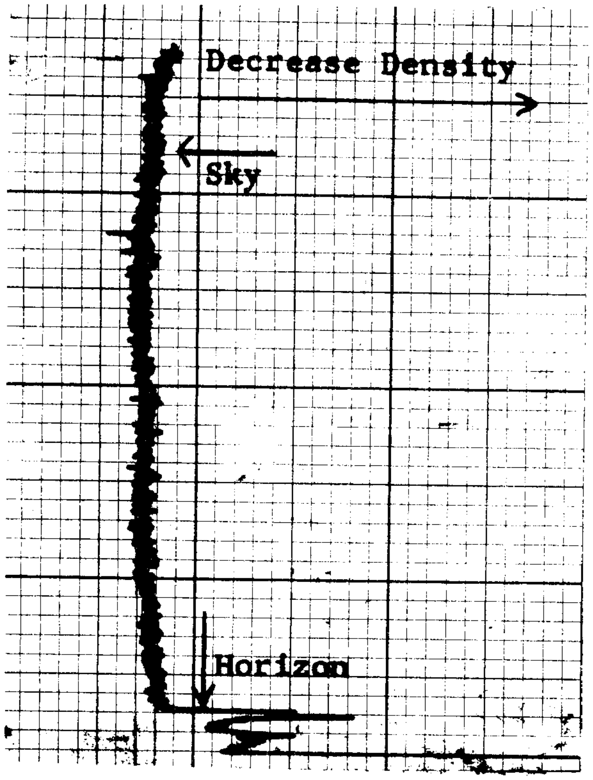
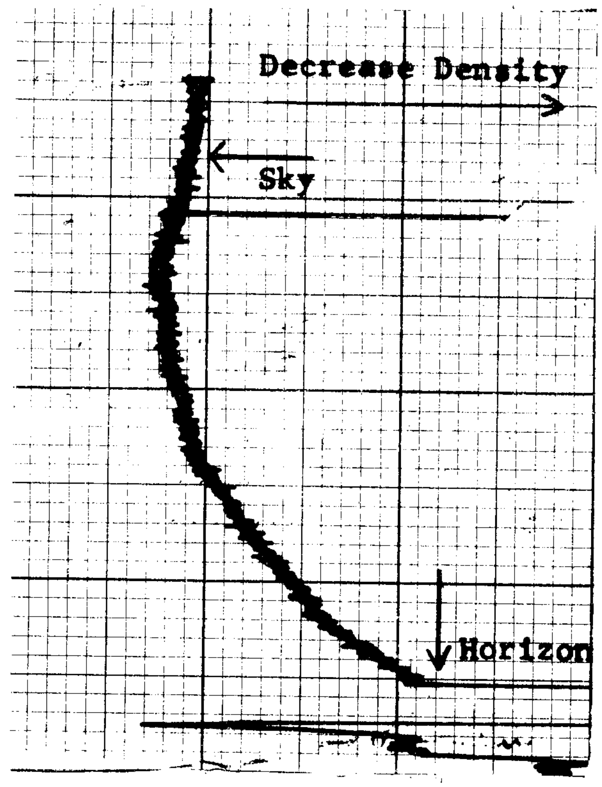


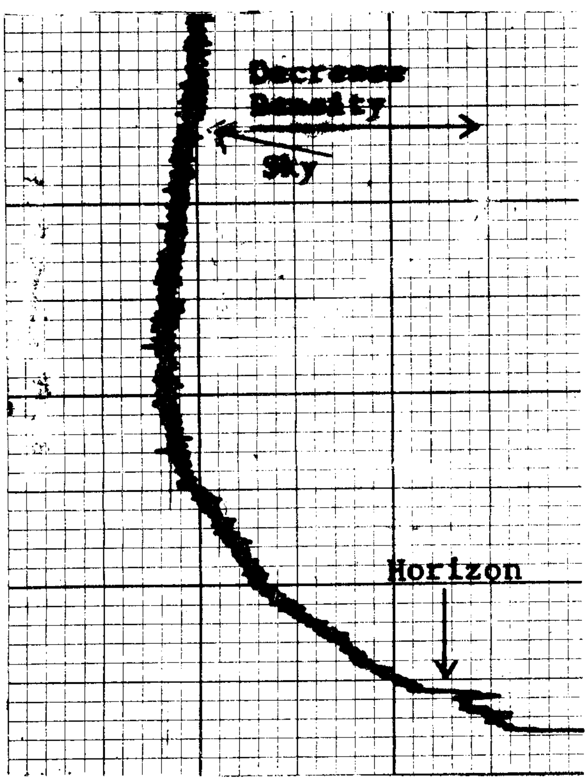
FIGURE 5. NUMBER 1 ENGINE OF CONVAIR 880 AIRCRAFT. TAKEOFF POWER.



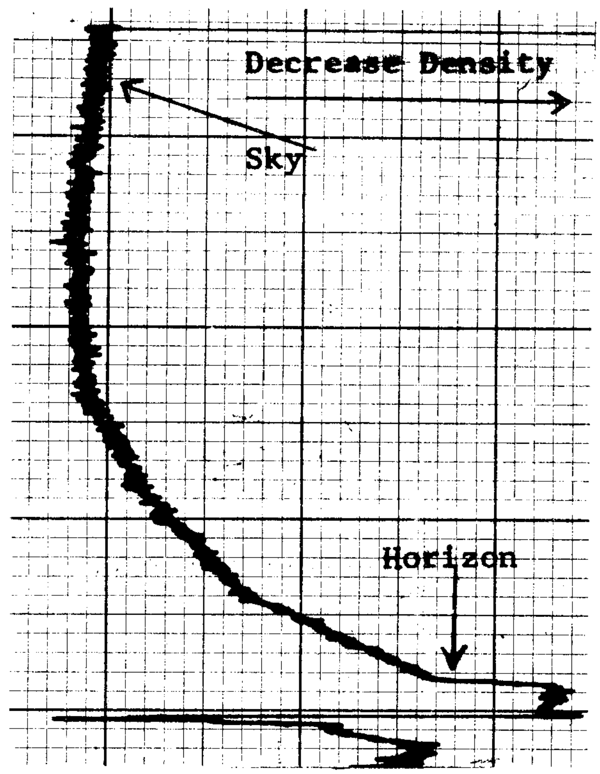
Idle Power



Approach Power



Cruise Power



Take-Off Power

FIGURE 6. MICRODENSITOMETER TRACES FROM TIED-DOWN CONVAIR 880 AIRCRAFT - ENGINES 1, 2, and 3 OPERATING.

TABLE 8

CV-880 AIRCRAFT TIED-DOWN MULTIPLE ENGINE OBSERVATION

Engine Number in Operation (1)	Engine Thrust Setting	IITRI Transmissometer % Transmission (2)	Photographic Photometry % Transmission	Visual Transmissions % Transmission
1	Idle	99	96	100
1	Approach	91	87-94	80-95
1	Cruise	89	85	75-85
1	Takeoff	89	86	75-85
1-2	Idle	98	91	100
1-2	Approach	81	63	---
1-2	Cruise	74	49	---
1-2	Takeoff	71	49	---
1-2-3	Idle	95	95	100
1-2-3	Approach	65	49	85
1-2-3	Cruise	52	38	80-85
1-2-3	Takeoff	43	37	75-80
1-2-3-4	Idle	94	94	100
1-2-3-4	Approach	61	44	70-75
1-2-3-4	Cruise	38	28	70-75
1-2-3-4	Takeoff	30	38 (3)	70-75

(1) The number 1 engine is the left outboard engine.

(2) Transmissometer located past the tail of the aircraft at the nozzle as in previous tests

(3) It is believed that the power was being reduced when the photograph was taken.

All values obtained with either technique show a similar variation with power setting and number of engines.

The results of the multiengine study were largely nullified because of ground dirt becoming airborne during the tests. The aircraft was positioned at the run-up area with engines 3 and 4 exhausting over the ground rather than concrete. The blown ground dirt and the downward tilt of the plume is the reason why the microdensitometer traces continue to increase in density down to the horizon. However, the effect of combining smoke plumes should be predictable from consideration of increased path length.

(4.4.4) Lockheed Jetstar Aircraft

A Jetstar, owned by the FAA, was observed in the same manner as the Convair 880 aircraft. This aircraft's engine is similar to the JT-12-6 engine studied in the wind tunnel. No smoke was visible at any angle of viewing and no smoke could be detected photographically.

No transmission data were obtained with the IITRI transmissometer because of an amplifier malfunction. Repairs could not be completed in time to make the tests. Smoke numbers for the Number 4 engine were measured with the GE smoke sampler and the results are shown in Table 9.

Results show that probe location must be studied if representative smoke numbers are to be obtained. Also, a single probe location may not be a representative location for all power settings. For example, the 3 o'clock probe position gave smoke at takeoff averaging about 30% lower than the 6 o'clock position. At approach, the 3 o'clock position gave smoke numbers 25-30% higher than the 6 o'clock position. The SAE smoke numbers were below 23 at the 3 o'clock position for all thrust settings. The SAE smoke number at the 6 o'clock position reached 35 at takeoff thrust.

(4.5) Discussion and Summary of Results of Static Engine and Aircraft Tests

This discussion will show the empirical relationship between the visibility, luminance, and smoke number. Table 10 is a collection of data taken from Tables 3, 5, 6, 7 and 9, arranged to show more clearly the comparison of smoke