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RELATIONSHIP BETWEEN THE SAE SMOKE NUMBER AND JET AIRCRAFT SMOKE VISIBILITY

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FINAL REPORT

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16. Abstract

A method was developed using the Society of Automotive Engineers (SAE) smoke numbers for calculating the exhaust smoke transmission for turbine engines, number of plume paths, and viewing angles. Criteria were developed relating the SAE smoke number to engine airflow and thus to engine size for conditions of visible and invisible smoke. Transmission of multiple plumes was calculated and presented.

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1. INTRODUCTION.

a. Purpose. The purpose of this project was to analyze the Society of Automotive Engineers (SAE) smoke number and transmission measurements previously reported and to develop a method of using the SAE smoke number for calculating the transmission of turbine engine exhaust, combination of plumes, and viewing angles. A secondary purpose was the establishment of exhaust smoke visibility criteria for turbine engines.

b. Background.

(1) Producing jet engines and aircraft with less smoke involved the development of single combustion chambers and fuel nozzles in the burner facility. Measurement of transmission of exhaust smoke was considered as a means of evaluating improvements or modifications; however, measurements of optical transmission of burner rig exhaust was not practical as the levels were low (less than 1 percent in most instances). Measurement of optical transmission during engine stand testing was also not practical, as in many cases the levels were also low and the test stands did not incorporate the desired features for transmission measurements.

(2) A practical method of smoke measurement for combustion facility and test stand use was specified by the SAE in Aerospace Recommended Practice (ARP) 1179 entitled, "Aircraft Gas Turbine Engine Exhaust Smoke Measurement" (Reference 1). The SAE smoke measurement method involved filtering different volumes of exhaust gases and evaluating the density of the resulting stains. The gases were collected in the plane of the jet nozzle with a sampling probe and sampling line, and the volumes were accurately measured with a wet-test meter. The graduated series of stains obtained were evaluated by measuring the optical diffuse reflectance with a reflectometer. The smoke number associated with each volume was calculated from the following equation:

$$\text{Smoke} = \text{Number} = SN = \left(1 - \frac{R_S}{R_W}\right) \qquad (1)$$

where, R_S was the diffuse reflectance of the smoke stained filter, and R_W was the diffuse reflectance of the clean filter paper. The SAE smoke number was obtained by plotting smoke number versus gas weight per unit area of filter stain (semi-log plot) and entering the curve to obtain the number at .0230 pound per square inch.

2. DISCUSSION.

a. Smoke Parameter.

(1) The SAE smoke number as determined, was influenced by the density of the smoke and not by the plume size or diameter. The transmission measurements, on the other hand, were affected by the diameter of the plume as well as the density of the smoke.

(2) The object was to derive a mathematical expression incorporating the SAE smoke number or smoke density and a parameter proportional to the diameter of the plume. The expression would relate to or plot directly against transmission. For this analysis, the diameter of the plume at a given distance from the jet nozzle was expressed as a function of the airflow of the engine. Utilizing the flow equation and solving for the area and then solving for the diameter:

$$W_a = \rho AV \qquad (2)$$

$$A = W_a/\rho V \qquad (3)$$

$$d = \sqrt{W_a 4/\pi\rho V} \qquad (4)$$

(3) Referring to Table 3 of Reference 2, no measurable change in transmission was indicated in these tests regardless of whether the sampling probe and the transmissometer were installed at the jet nozzle (Tests Nos. 6 through 9), 2 1/2 nozzle diameters downstream from the jet nozzle (Tests Nos. 2 through 5), or 10 nozzle diameters downstream (Tests Nos. 10 through 14). In fact, the average of the transmission measurements at the jet nozzle for conditions of idle through cruise was identical to the average for these conditions at 10 nozzle diameters (230 inches) downstream. Over this distance the gas velocity changed on the order of 50 percent, and the gas density changed almost 65 percent. These observations indicate that the gas velocity and density have little effect on measurements of transmission and they, together with the constant $4/\pi$, were omitted from Equation No. 4, resulting in:

$$d \cong \sqrt{W_a} \qquad (5)$$

(4) Since by Reference 2, the relationship between the transmission of the smoke, the smoke number and the nozzle diameter is predictable, the following is arbitrarily defined:

$$\text{Smoke Parameter} = \sqrt{W_a} \times D_R \qquad (6)$$

where, $D_R = 2 - \log_{10}(100 - \text{SAE SN})$ (7)

D_R is defined as the reflective density as calculated from the SAE smoke number.

b. Smoke Number Normalization. Smoke was filtered with Whatman No. 4 paper for determination of the SAE smoke number. As shown in Figure 1, the buildup of smoke particles on Whatman paper was not linear. This was attributed to loading within the paper as well as on its surface, and some particles may have passed through the paper. Figure 1 was prepared by plotting the SAE smoke number using black backing against the smoke number as determined from using Millipore membrane filters. The smoke particles built up on the surface of the Millipore membrane and produced a more linear indication. The first step was to adjust the SAE smoke number in accordance with Figure 1. The adjusted smoke number was then converted to reflective density, D_R by Equation No. 7.

c. Reduction of Smoke Number and Transmission Data.

(1) The transmission measurements for various angles in the J57-P37 engine exhaust, Table 4 of Reference 2, and the CV-880 aircraft multiple engine transmission data, Table 8 of Reference 2, were plotted against the number of plumes on Figure 2. The purpose of Figure 2 was to eliminate scatter in the transmission measurements for use in preparing the final illustration. The scatter of the transmission measurements shown at third and fourth path lengths was attributed to the entrainment of ground dirt by the exhaust wake of Number 3 engine during testing of the CV-880 aircraft at engine power conditions of Cruise and Takeoff.

(2) Reduction of the data in accordance with Equation Nos. 6 and 7 and Figures 1 and 2 was accomplished in Tables 1 and 2. The data in the final two columns were plotted in Figure 3, except for the CV-880 aircraft figures at takeoff power conditions. During data acquisition, the aircraft moved or pivoted on the landing gear shocks, producing a relative displacement of several inches of the sampling probe at the jet nozzle. The low smoke number at takeoff conditions was attributed to displacement of the jet nozzle. The equivalent of two or three exhaust paths was recorded during the testing of the J57-P37 engine by installing the transmissometer such that it viewed a path through the plume that was equal to two or three normal plume diameters.

d. Calculation of Jet Aircraft Smoke Transmission.

(1) As shown in Figure 3, the relationship between smoke transmission and smoke parameter (square root of the airflow times the reflective density) was a straight line. Utilizing the simple equation for straight lines, an expression for transmission was calculated:

$$T = -1.62\sqrt{W_a} \quad D_R + 100.0 \qquad (8)$$

(2) When the SAE smoke number is known for a given engine, the smoke number may be adjusted in accordance with Figure 1; the reflective density may be calculated by Equation 7; and the smoke transmission may then be calculated by Equation 8.

(3) Calculation of jet aircraft smoke transmission was demonstrated with the following example: The visual appearance of the JetStar aircraft exhaust trail with three engines being viewed at Takeoff Power was just on the threshold of visibility. Calculation of the transmission for this condition resulted in a value of 95.9 percent as shown in Table 3. For the J57-P21A engine (Table 6, Reference 2) this point of visibility was found to correspond to a transmission value of 95.0 percent. A value of transmission of 95.5 percent was then selected as the limit beyond which any plume or number of plumes will always be visible when viewed at 90°.

e. Smoke Numbers for Visible and Invisible Smoke. Invisible smoke is defined by Conclusion No. 1 of Reference 2, "Considerations of turbojet visibility indicate that smoke plumes with transmission values greater than 98 percent will be invisible." Figure 4 was then developed using 98.0 percent for the value of transmission which would always result in an invisible trail (Curve A), and by using a transmission value of 95.5 percent for trails that would always be visible (Curve B). Curve B is applicable regardless of the viewing angle to the path of the plume. For instance, at Curve B for a given engine the plume will always be visible. As the smoke number decreases, the viewing angle to the axis of the plume must decrease from 90° to maintain this same persistence of visibility, until (at the smoke number corresponding to Curve A) this viewing angle must be decreased to 24°.

f. Transmission of Multiple Plumes.

(1) Optical transmission may be calculated for a combination of plume paths. Equation No. 7 was utilized to calculate the reflective density, and Equation No. 8 was then used to calculate the optical tansmission for various engine airflows. SAE smoke numbers of 20, 35, and 50 were selected to cover the area of interest. Transmission for one through four plume paths is presented in Figures 5, 6, and 7.

(2) Examination of the illustrations emphasized that the SAE smoke numbers were not linear, and were, in fact, logarithmic. This feature affects high-sensitivity of the smoke number for transmission values of 95.5 to 98.0 percent, an area of maximum interest. The transmission was calculated for round, separate plumes. In certain aircraft, the engines are configured to produce essentially one large combination plume. Calculated smoke transmission for such a plume would be greater (less visible smoke) than the transmission of individual multiple plumes, while the smoke density remains constant.

(3) Coalescence of parallel jets will result in an increase in calculated transmission as the effective diameter will decrease. Thus, the transmission presented in Figures 5, 6, and 7 for separate plumes are the most severe cases, least visibility.

(4) Hypothetically, an observer may rarely be in position to view across three and four separate plumes, and is always in position to view across large combination plumes. Coalescence of parallel jets may also increase an observer's path of view through the smoke and thus increase smoke visibility.

SUMMARY OF RESULTS

A smoke parameter was developed to relate the SAE smoke number with transmission. SAE smoke numbers and transmission measurements from Reference 2 were reduced, and the smoke parameter was plotted against transmission resulting in a straight line. An equation for optical transmission was then developed. Calculation of jet aircraft smoke transmission was demonstrated using the JetStar aircraft. The relationship between the SAE smoke number and engine size for visible and invisible smoke was established, and transmission of multiplumes was calculated for SAE smoke numbers of 20, 35, and 50.

CONCLUSIONS

Based upon the results reported herein, it is concluded that:

1. Light transmission of smoke trails from turbine engine aircraft can be calculated when the SAE smoke number is known.

2. Transmission of jet aircraft smoke plumes can be calculated for any number of plume paths or viewing angles.

3. SAE smoke number information as a function of engine airflow with threshold curves of constant transmission may be utilized as engine criteria for visible and invisible smoke.

REFERENCES

1. Aerospace Recommended Practice, ARP1179, Aircraft Gas Turbine Engine Exhaust Smoke Measurement, Society of Automotive Engineers, Inc., Two Pennsylvania Plaza, New York, New York 10001

2. Stockham, John, and Betz, Howard, Study of Visible Exhaust Smoke From Aircraft Jet Engines, Systems Research & Development Service, Federal Aviation Administration, Report No. FAA-RD-71-22.

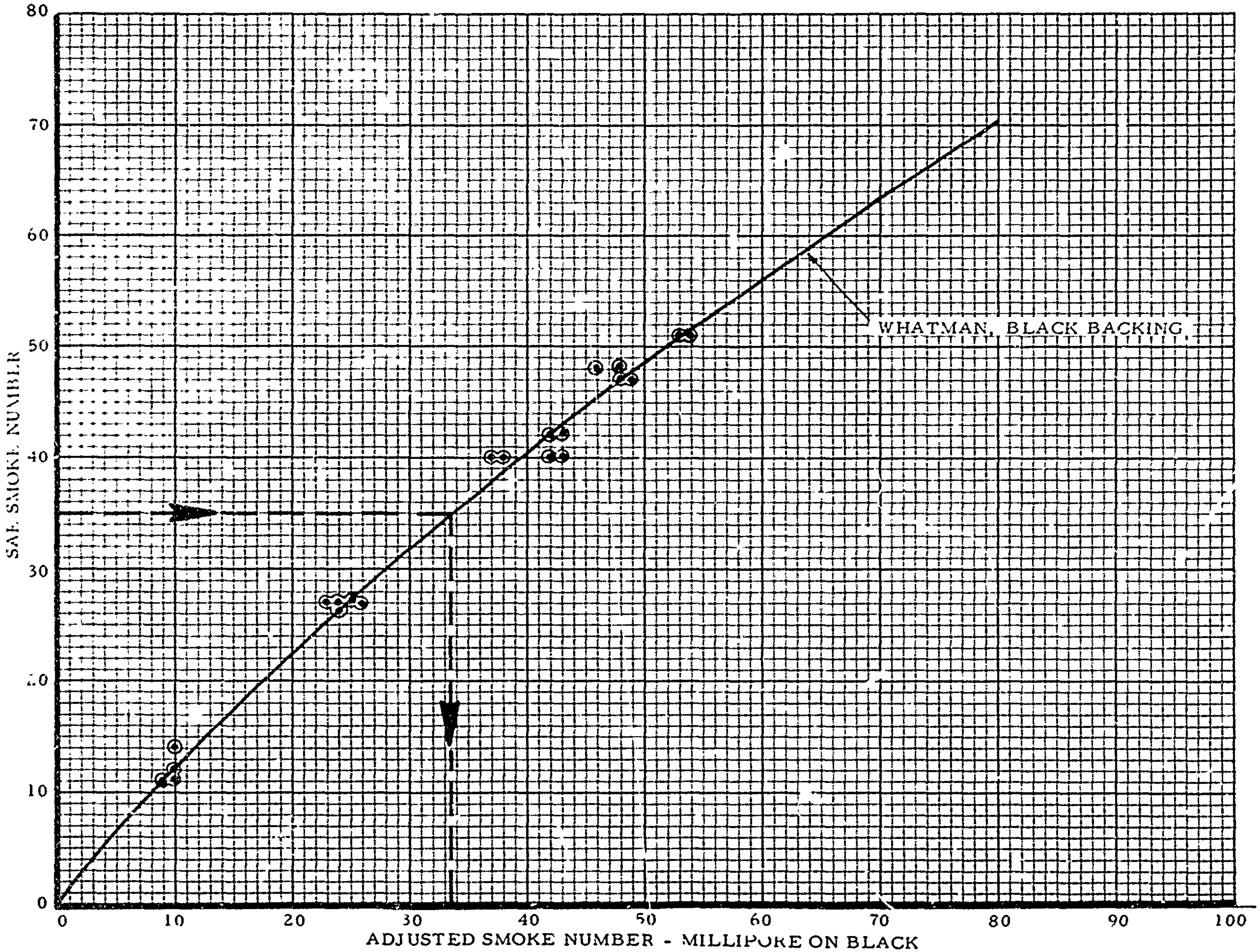

FIGURE 1 - SMOKE NUMBER ADJUSTMENT

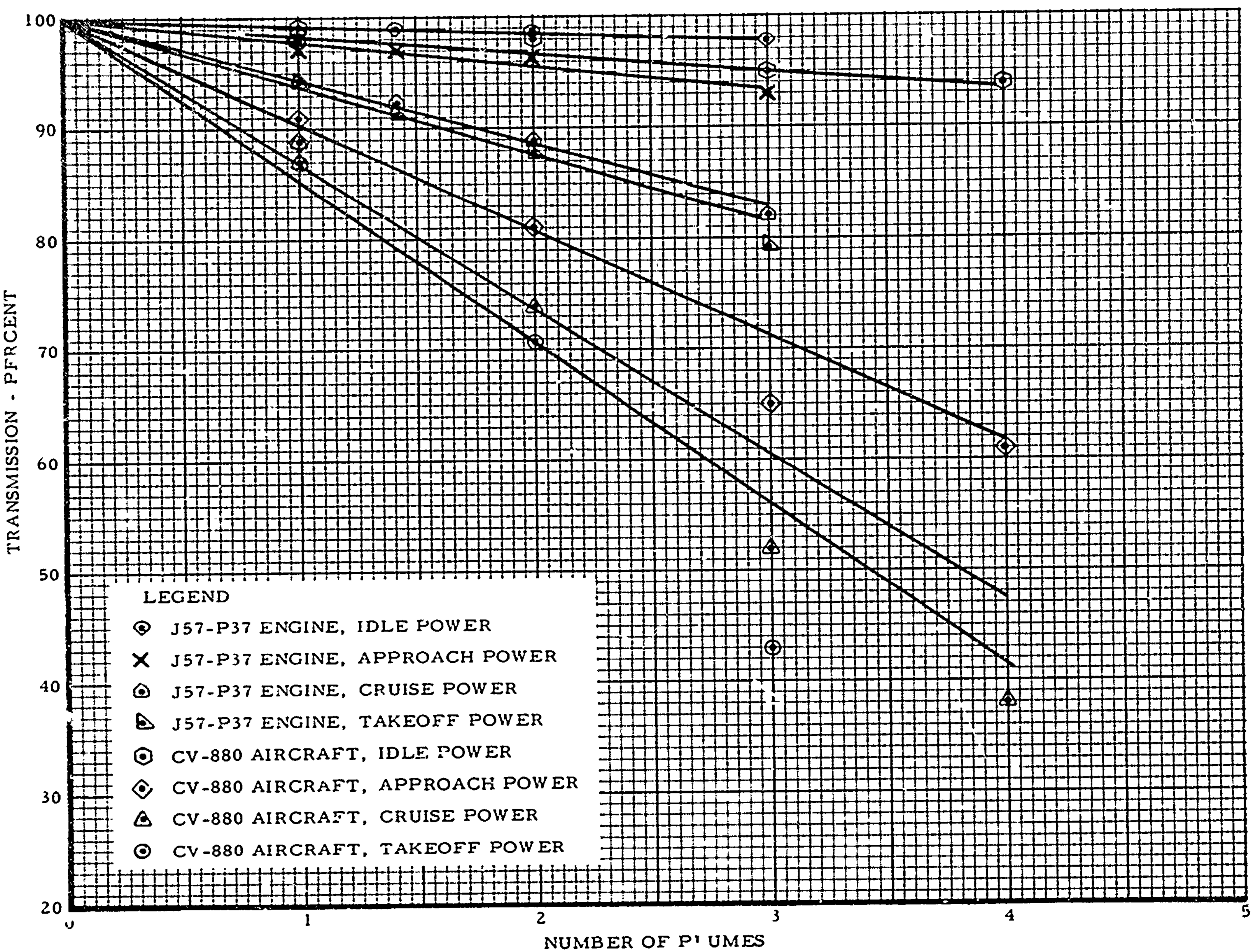

FIGURE 2 - EFFECT OF ENGINE EXHAUST PATH ON OPTICAL TRANSMISSION

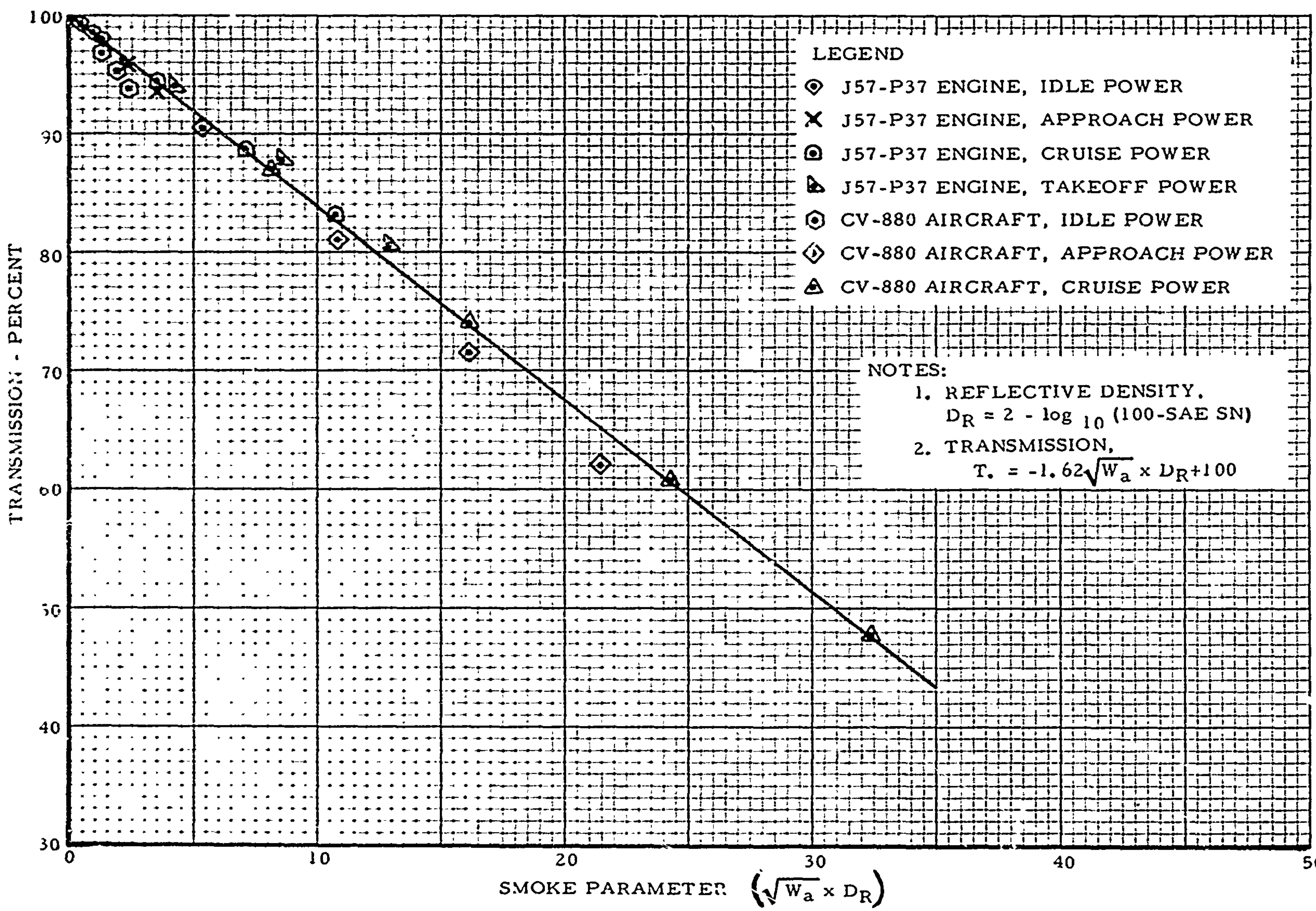

FIGURE 3 - SMOKE PARAMETER VS OPTICAL TRANSMISSION

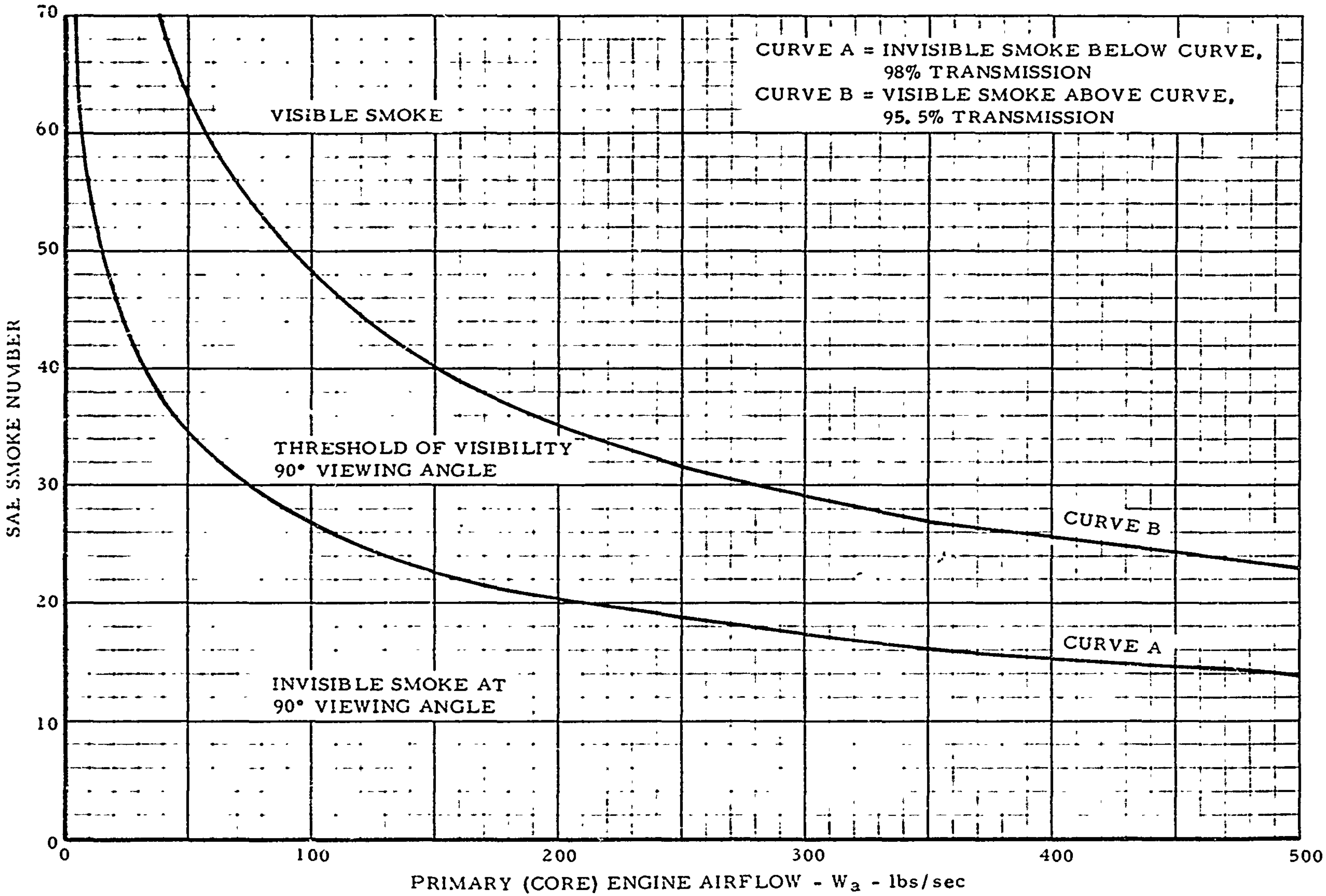

FIGURE 4. SAE SMOKE NUMBER FOR VISIBLE AND INVISIBLE SMOKE

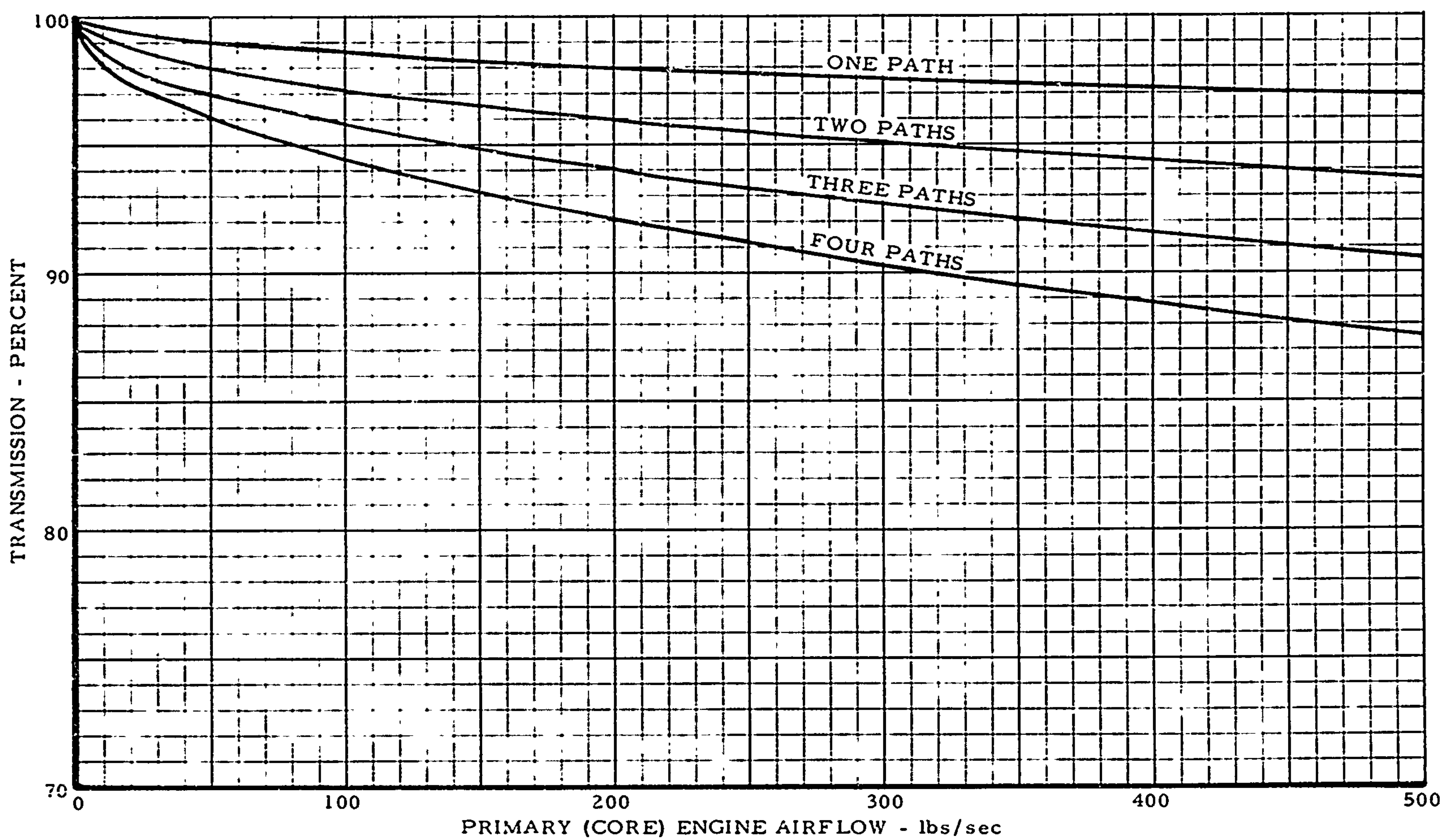

FIGURE 5. TRANSMISSION FOR MULTIPLE PLUMES - SAE SMOKE NO. 20

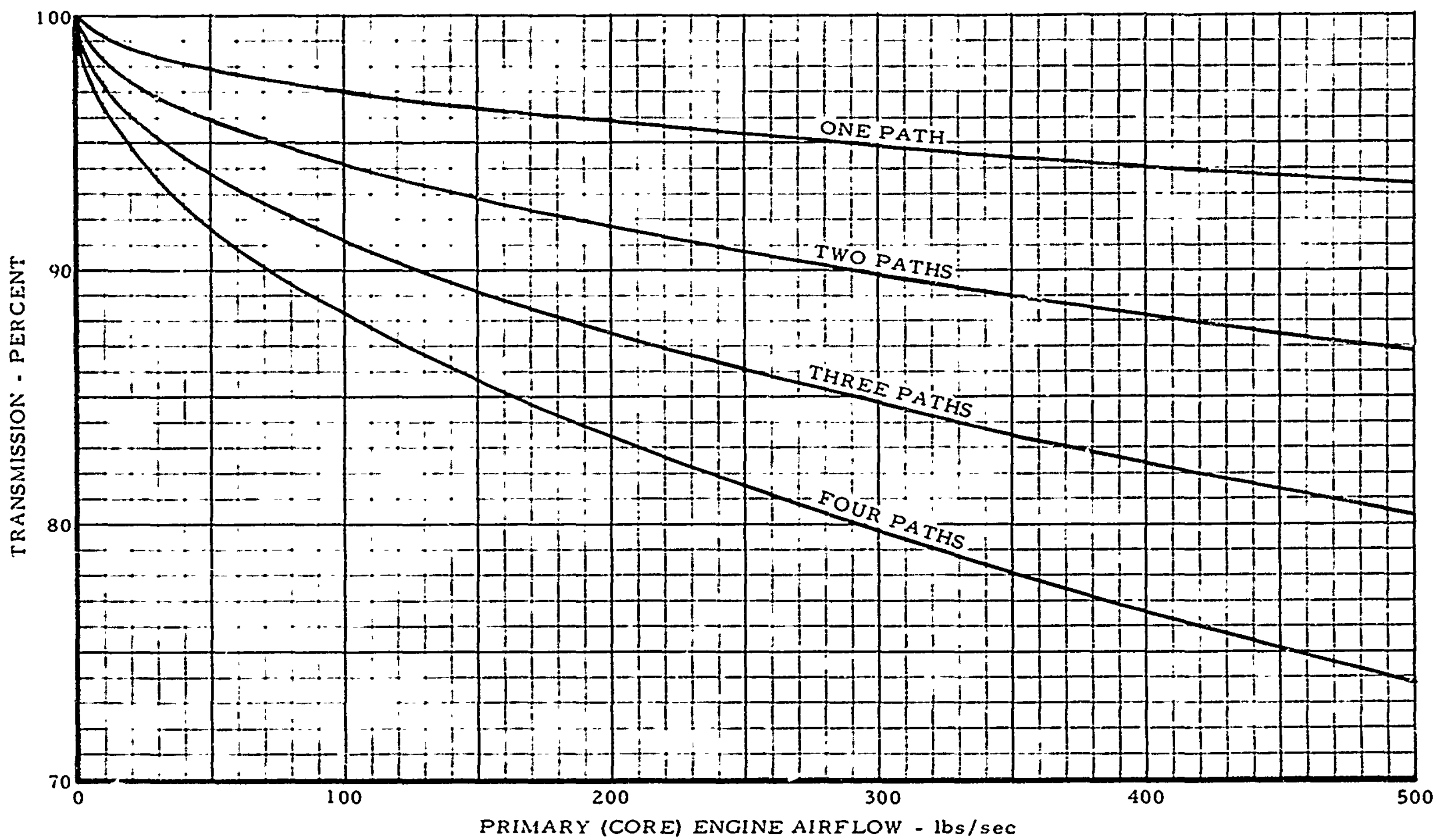

FIGURE 6. TRANSMISSION FOR MULTIPLE PLUMES - SAE SMOKE NO. 35

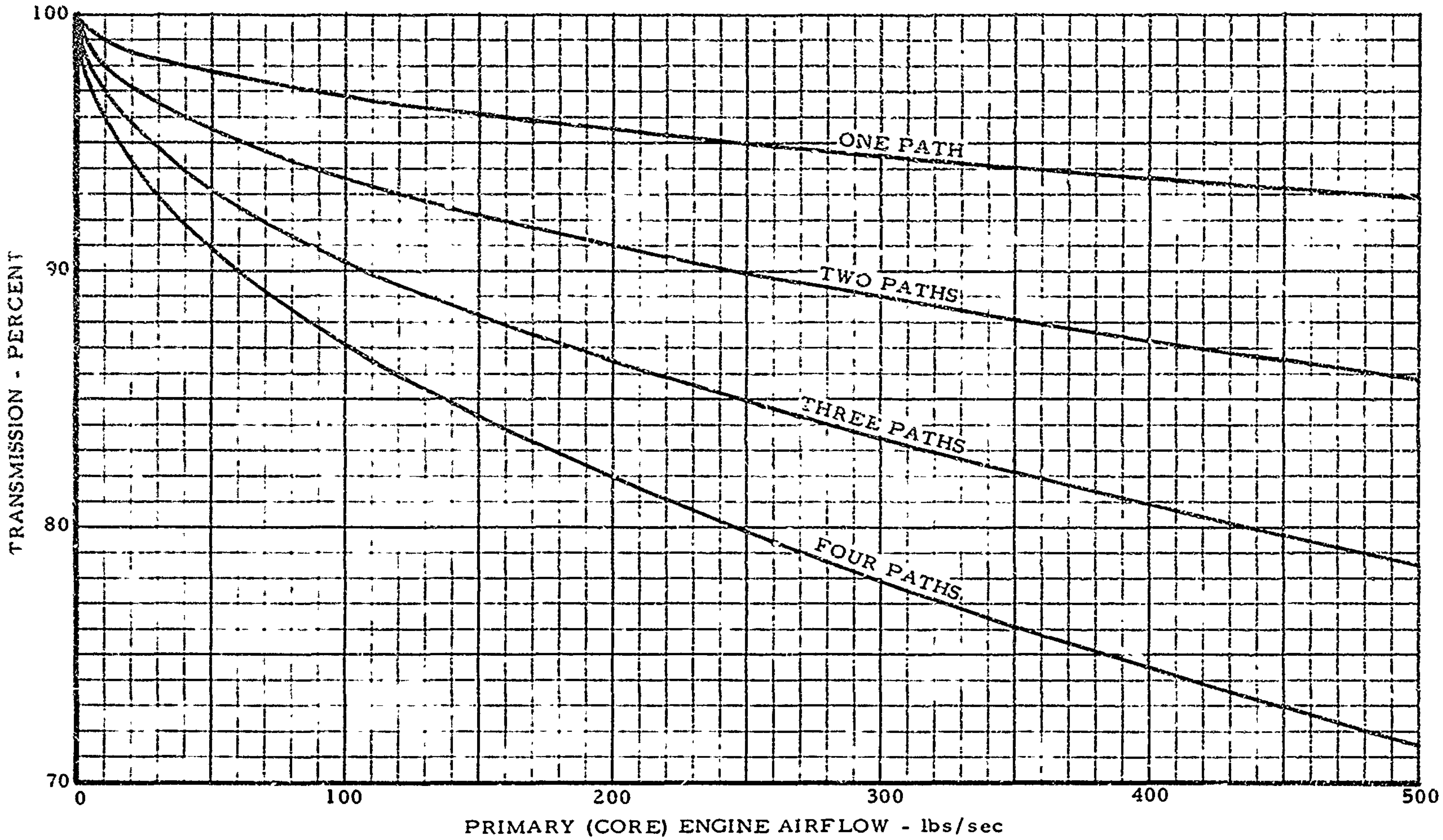

FIGURE 7. TRANSMISSION FOR MULTIPLE PLUMES - SAE SMOKE NO. 50

TABLE 1. - DATA REDUCTION CV-880 AIRCRAFT, CJ805-3B ENGINE

1	2	3	4	5	6	7	8
Engine Power Conditions	Airflow (W_a) lb/sec	$\sqrt{W_a}$	SAE S/N (black)	Adj SAE S/N	D_R	$\sqrt{W_a} \times D_R$	Trans % From Fig. 2
Idle, 1 Eng	35	5.92	23	20.8	.101	5.98	98.4
App., 1 Eng	136	11.67	60	65.4	.461	5.38	90.3
CR, 1 Eng	152	12.33	69	78	.658	8.11	87.0
T.O., 1 Eng	167	12.92	65	72.3	.558		85.2
Idle, 2 Eng						1.19	96.9
App., 2 Eng						10.76	81.0
CR, 2 Eng						16.22	74.0
T.O., 2 Eng							71.0
Idle, 3 Eng						1.79	95.2
App., 3 Eng						16.14	71.4
CR, 3 Eng						24.33	60.6
T.O., 3 Eng							56.0
Idle, 4 Eng						2.39	93.8
App., 4 Eng						21.52	62.0
CR, 4 Eng						32.44	47.5
T.O., 4 Eng							41.6

TABLE 2. - DATA REDUCTION J57-P37 ENGINE

1	2	3	4	5	6	7	8	9
Engine Power Conditions	Path Length	Airflow W_a lb/sec	$\sqrt{W_a}$	SAE S/N Black	Adj SAE S/N Black	D_R	$\sqrt{W_a} \times D_R$	Trans % From Fig. 2
Idle	1	53	7.28	14	12	.056	.41	99.2
App.	1	94	9.7	27	24.5	.122	1.18	98.0
75% N	1	114	10.68	40	39.5	.218	2.33	
CR	1	145	12.04	48	49.3	.295	3.55	94.3
T.O.	1	168	12.96	51	53.2	.330	4.28	94.0
Idle	2						.815	98.7
App.	2						2.36	95.8
75% N	2						4.66	
CR	2						7.10	88.8
T.O.	2						8.56	87.9
Idle	3						1.22	98.0
App.	3						3.54	93.5
75% N	3						6.99	
CR	3						10.65	83.1
T.O.	3						12.84	81.7

TABLE 3. - CALCULATION OF JETSTAR AIRCRAFT SMOKE TRANSMISSION

Engine Power Conditions	Number of Paths	Airflow lb/sec	$\sqrt{W_a}$	SAE S/N	ADJ SAE S/N	D_R	$\sqrt{W_a} \cdot D_R$	Calculated Transmission-% Equation 8
Takeoff	1	56	7.48	25	23	.114	.85	98.6
Takeoff	2						1.70	97.2
Takeoff	3						2.55	95.9
Takeoff	4						3.40	94.5