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PREDICTIVE MODEL FOR JET ENGINE TEST CELL OPACITY

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A computer program (written in FORTRAN for a CDC 6600) was developed to predict the plume opacity of jet engine test cells. The data input required for the model includes: the particle density, concentration, and size distribution in the exhaust gas, and the effective stack diameter. Previous data obtained for J-57 engines were used to test the model, and the difference

between the theoretical and measured transmittance was generally within one percent.

The program also predicts the theoretical effect of using electrostatic precipitators or venturi scrubbers to treat the exhaust emissions. These predictions indicate that control devices larger than the test cells would have to be installed to even achieve a minimal effect on the observed visibility.

PREFACE

This report was prepared at the Department of Chemical Engineering, New Jersey Institute of Technology, 323 High Street, Newark, New Jersey 07102, under contract No. FO 8635-80-CO222 with the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403. Capt. D. Berlinrut managed the program for the Air Force Engineering and Services Center. The work was begun July 1, 1980 and completed September 30, 1981.

The author, Dr. Gordon A. Lewandowski, is indebted to the following individuals and organizations: Dr. W. Wong of New Jersey Institute of Technology for his valuable suggestions regarding stable generation of the complex Riccati-Bessel functions; Exxon Research & Engineering Co. (ERE) for release of their opacity computer program which was used to check the results of the program presented in this report; and S. Shaw of ERE for her efforts to obtain the release of their program and for guidance in its use.

This report has been reviewed by the Public Affairs Office and may be released to the National Technical Information Service (NTIS), where it will be available to the general public, including foreign nations.

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

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SECTION I

INTRODUCTION

A generalized schematic of a jet engine test cell is shown in Figure 1. Generally, the width of a plume issuing from a test cell is approximated by the stack dimension. The stacks are usually square; however, they contain acoustical baffles which considerably reduce the open area. For the calculations made in this report, the plume width was assumed to be the square root of the net open stack area.

Dimensions can vary considerably, depending upon the particular cell design, but the principle of operation is always the same. An engine that has been repaired, or otherwise maintained, is placed in the cell to test it under flight conditions before being remounted on the aircraft. The engine is considered a mobile emission source which is governed by Federal rather than state regulations. However, the test cell is immobile, and on that basis a U.S. District Court upheld the right of the State of California to regulate test cell emissions (Reference 1) which occasionally violate state visibility requirements of Ringelmann 1 (20% opacity). Since the U.S. Air Force has a large number of test cells in California, this court ruling can have a significant impact on Air Force operations and capital expenditures.

In order to satisfy state regulations, there are three possible alternatives: (1) design smokeless engines and install them on all existing aircraft; (2) introduce fuel additives to minimize soot formation; (3) use particulate control devices to treat the test cell exhaust.

The first of these alternatives is already being pursued as a result of the military incentive to reduce visibility of in-flight aircraft. However, replacement is very costly and time consuming, due to the variety and number of existing aircraft and aircraft engines.

The second alternative can be effective. However, fuel additives are organo-metallic compounds (e.g., Ferrocene), which deposit metallic oxides on engine surfaces. Considering the cost of the engine and its maintenance, and the cost of the aircraft, anything that may permanently alter engine parts is considered highly undesirable.

The third alternative does not affect the engine. Because of this, it is the only alternative which state regulatory authorities can impose. Nevertheless, particulate control

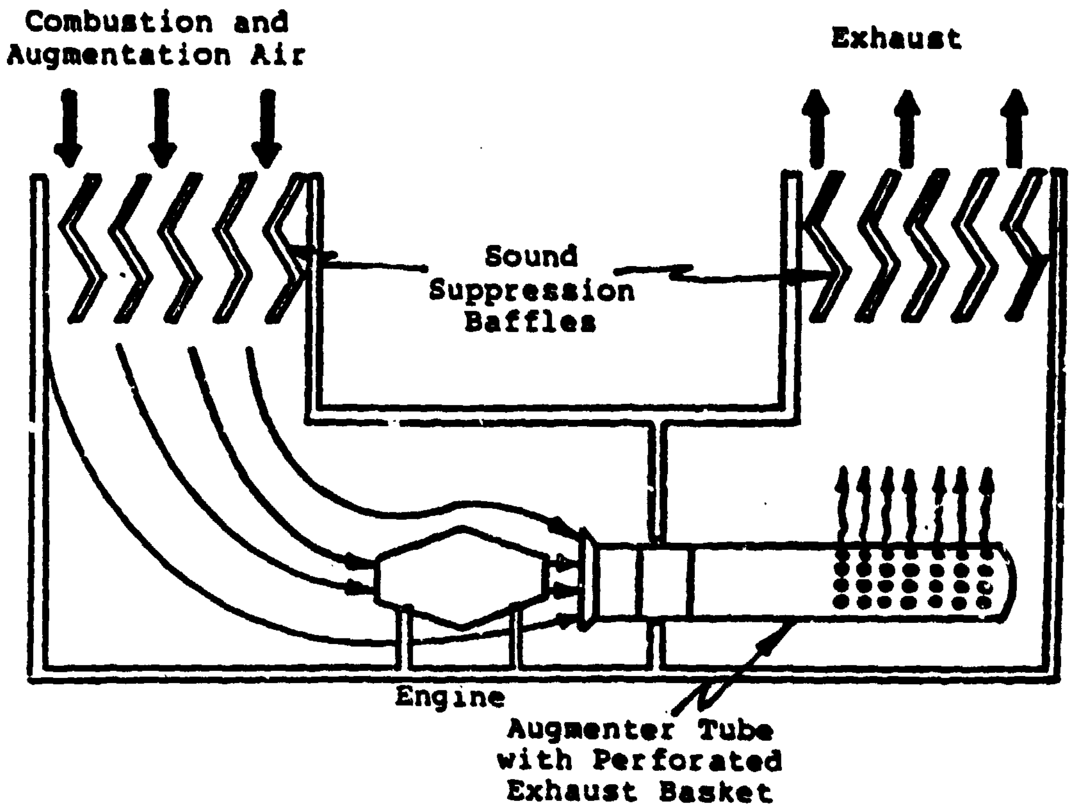


Figure 1. Generalized Test Cell Schematic

devices cannot be designed to meet an opacity requirement, only a specified degree of particulate removal.

The purpose of this study was to establish the connection between test cell particulate emissions and plume visibility as a basis for specifying control devices that could be mounted on the test cell exhaust stack. In addition, theoretical calculations were made to see under what conditions electrostatic precipitators or venturi scrubbers might satisfy opacity regulations.

SECTION II

SMOKE NUMBER

Much data on jet engine particulate emissions are in the form of SAE smoke numbers (SN), which measure the relative contrast of a standard filter paper exposed to the exhaust emissions for a standard period of time. A few investigators (References 2-6) have taken simultaneous measurements of particle loading ("soot density") and smoke number. Fewer studies (References 6-8) have determined plume opacity as a function of smoke number. These data, which are generally of poor quality, are plotted in Figures 2 and 3 for various engines.

Also presented in Figures 2 and 3 are empirical correlations based on Reference 9. The correlation in Figure 3 includes the results of Connor and Hodkinson's work (References 10, 11) relating observed visibility to plume transmittance.

As can be seen, there is about as much error in predicting the Ringelmann number directly from the smoke number, as there is in predicting mass loading. However, in order to determine opacity from loading, the particle size distribution must be known (involving an additional error), and a computer program used to make the calculation. In either case, the use of smoke numbers is a very unreliable tool in predicting test cell plume opacity.

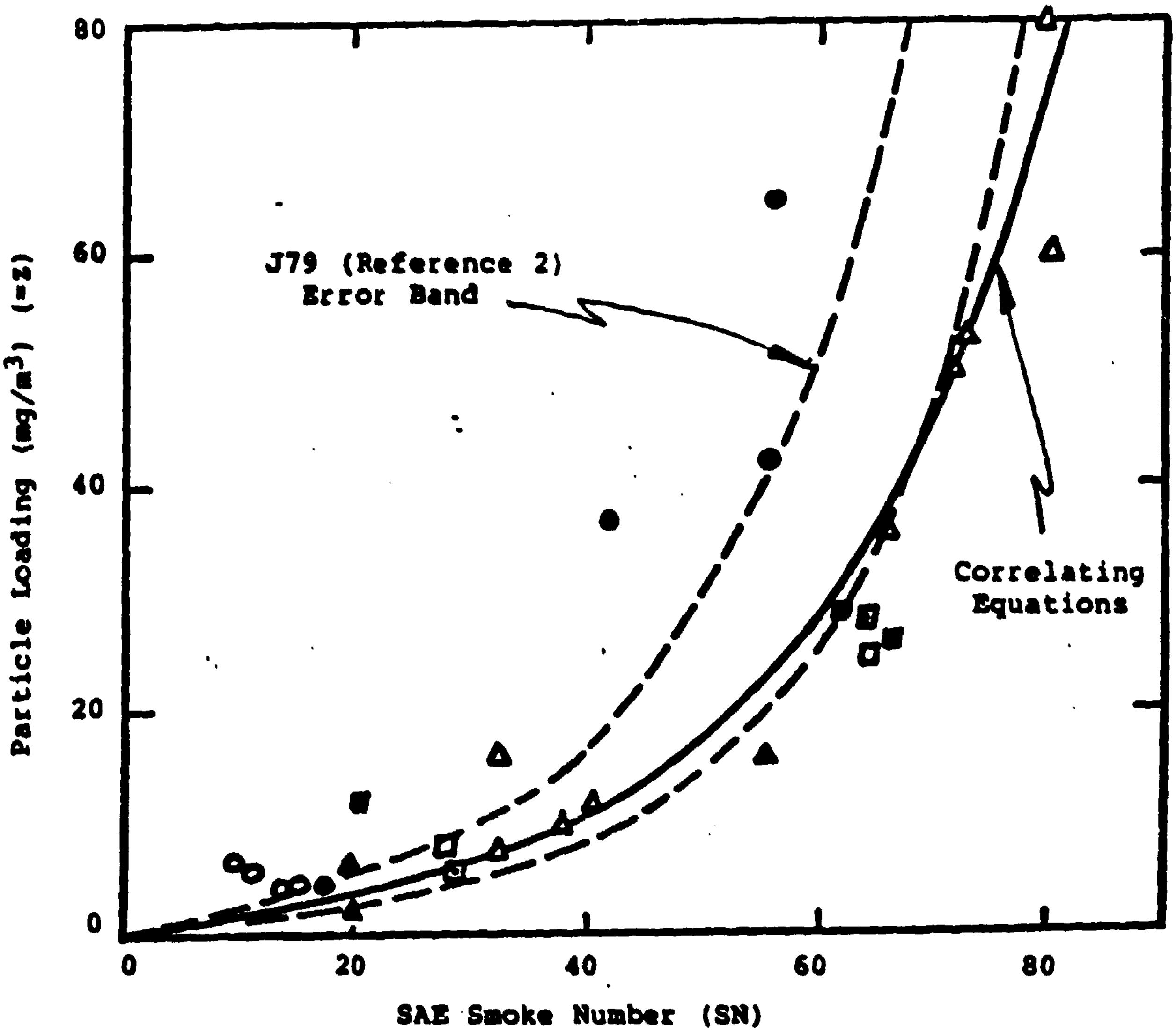


Figure 2. Relationship Between SAE Smoke Number and Soot Density (Reference 6)

- JT8D & J52-P-6 A
- J57-P-10 (Reference 4)
- J57-P-8
- T56 (501)
- T58-GE-10
- T64-GE-413
- TF30 (Reference 5)
- T400 (at Max. Power)
- TPE331-5-X21 (Reference 3)

Correlating Equations:

$$\ln\left(1 - \frac{SN}{100}\right) = -(.0468Z)^{0.9} \quad SN < 40$$

$$\ln\left(1 - \frac{SN}{100}\right) = -(.0316Z)^{0.6} \quad SN \geq 40$$

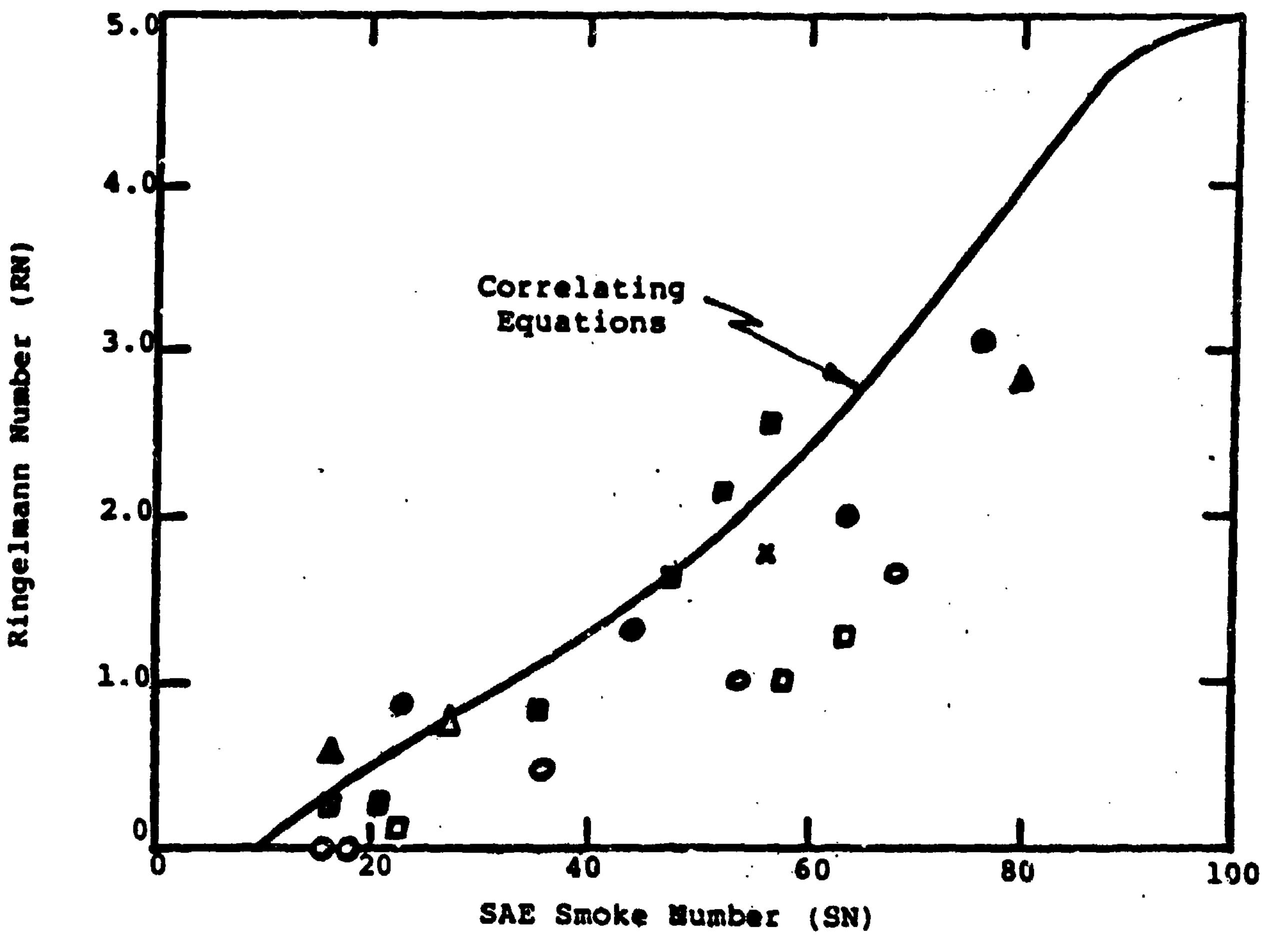


Figure 3. SAE Smoke Number vs. Ringelmann Reading (Reference 6)

<u>Correlating Equations:</u>

- ○ J79 (Reference 2)
- ● J79-GE-10 (Reference 8)
- ⊟ J65 (clean)
- ■ J57-P-8
- □ J57 (Reference 7)
- ⊕ J52-P-6A
- △ J52-P-6A (Smokeless)
- ▲ TF30-P-8
- ▲ TF30-P-6 (Smokeless)
- ✕ T56-A-10

$$\ln\left(\frac{T}{100}\right) = -(0.194L)\left[-\ln\left(1-\frac{SN}{100}\right)\right]^{2.08} \quad SN \geq 30$$

(L = plume width ≈ 3.5 m)

$$\ln\left(\frac{T}{100}\right) = -(0.0617L)\left[-\ln\left(1-\frac{SN}{100}\right)\right], \quad SN \leq 30$$

$RN = -.0375T + 4.5, \quad 15 \leq T \leq 85$

$RN = -.0800T + 8.1, \quad 95 \geq T > 85$

$RN = -.0667T + 5.0, \quad T < 15$

SECTION III

VISIBILITY EQUATIONS

Jet engine exhaust emissions largely consist of fine particles of unburned carbon. Because they are black, and therefore absorb much of the incident light intensity, carbon particles will exhibit very little back-scattering of ambient light. The visibility of black plumes is almost entirely a function of the relative contrast between the background sky-light and the amount of such light transmitted through the plume (Figure 4). This relative contrast is independent of observer position and can be calculated by the following equation (Reference 11):

$$T = \frac{B_T}{B_o} = \exp\left[\left(\frac{-3WD}{2\rho_p}\right) \frac{1}{I} \sum_i \left(\frac{Q_{ext}}{d_p}\right)_i\right]$$

where: T = transmittance, or relative plume brightness

B_T = brightness of light transmitted through the plume

B_o = background sky brightness

W = particle loading

D = plume diameter

ρ_p = particle density

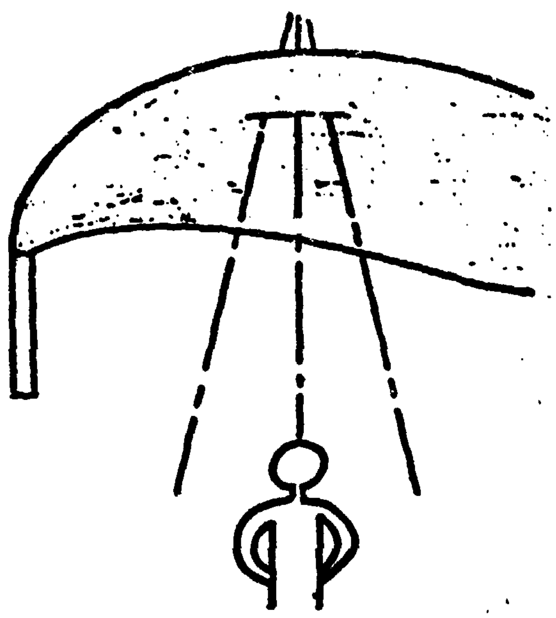
I = total number of particle sizes

d_p = particle size

Q_{ext} = extinction coefficient, or ability of a given particle to reduce the intensity of the transmitted light

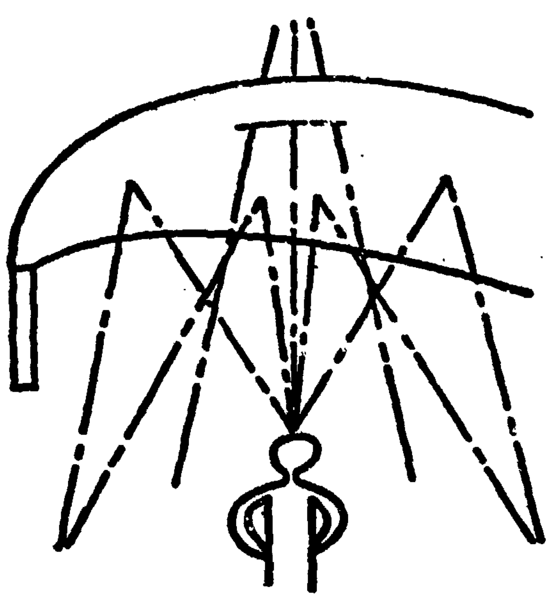
subscript i = i^{th} particle size in the distribution

The extinction coefficient for any given particle is determined by the following equation (References 11 and 12):



Black Plumes

For transmitted light, the observer sees only relative contrast with background sky brightness.



White Plumes

Scattered light originates from both in front and behind the observer. Therefore, the relative position of the sun is significant.

Figure 4. Visibility

$$Q_{ext} = \frac{2}{x^2} \sum_n (2n + 1) \mathrm{Real}(a_n + b_n)$$

where: $x = \pi d_p/\lambda$

$\lambda =$ wavelength of light in which the plume is viewed (the computer program allows this value to be input, or if left blank assumes an average value for skylight of 0.550 microns)

a_n & b_n are complex Riccati-Bessel function of order "n":

$$a_n = \frac{\psi_n'(y)\psi_n(x) - m\psi_n(y)\psi_n'(x)}{\psi_n'(y)\xi_n(x) - m\psi_n(y)\xi_n'(x)}$$

$$b_n = \frac{m\psi_n'(y)\psi_n(x) - \psi_n(y)\psi_n'(x)}{m\psi_n'(y)\xi_n(x) - \psi_n(y)\xi_n'(x)}$$

$y = mx$

$m =$ complex refractive index. This is a function of the wavelength of light (λ) at which it is measured, and also the method of generating the soot particles. The computer program allows this value to be input, or if left blank assumes a value for amorphous carbon at 0.550 microns of: 1.96 - 0.66i (References 13, 14). (Note: Because the transmitted light is altered both in phase and magnitude, a vector is needed to express the effect of the particles. As in electrical engineering, a vector can be expressed as a complex number with real and imaginary parts. This is the case for the particle refractive index.)

Since these equations involve series functions of complex numbers, their solution is not simple. Instabilities can easily arise (particularly with large values of x), which cause the extinction coefficient to oscillate wildly and even produce negative values. In order to generate stable functions, the following method is used (References 12, 15):

$$P_n(z) = \frac{d[\ln\psi_n(z)]}{dz} = \frac{\psi_n'(z)}{\psi_n(z)}$$

$$Q_n(z) = \frac{d[\ln\xi_n(z)]}{dz} = \frac{\xi_n'(z)}{\xi_n(z)}$$

(where z = y or x)

Therefore: $$a_n = \frac{\psi_n(x)}{\xi_n(x)} \left[\frac{P_n(y) - mP_n(x)}{P_n(y) - mQ_n(x)}\right]$$

$$b_n = \frac{\psi_n(x)}{\xi_n(x)} \left[\frac{mP_n(y) - P_n(x)}{mP_n(y) - Q_n(x)}\right]$$

$$\psi_n'(z) = \psi_{n-1}(z) - \frac{n}{z}\psi_n(z)$$

$$\xi_n'(x) = \xi_{n-1}(x) - \frac{n}{x}\xi_n(x)$$

Therefore: $$P_n(z) = \frac{\psi_{n-1}(z) - \frac{n}{z}\psi_n(z)}{\psi_n(z)} = \frac{\psi_{n-1}(z)}{\psi_n(z)} - \frac{n}{z}$$

$$= \frac{J_{\nu-1}(z)}{J_\nu(z)} - \frac{(\nu - 1/2)}{z}$$

where J = Bessel function

$\nu - 1/2 = n$

Using Lentz's continued fraction method[15]:

$$\frac{J_{\nu-1}}{J_\nu} = \frac{|w_1|w_2,w_1||w_3,w_2,w_1|\ldots\ldots}{|w_2||w_3,w_2|\ldots\ldots\ldots\ldots\ldots}$$

$$w_p = (-1)^{p+1} \frac{2(\nu + p - 1)}{z}$$

$$|w_p, w_{p-1}, \ldots\ldots, w_1| = w_p + \cfrac{1}{w_{p-1} + \cfrac{1}{w_{p-2} + \cfrac{1}{\ldots\ldots}}}$$

Convergence is reached for $J_{\nu-1}/J_\nu$ when $|w_p, \ldots, w_1|$ in the numerator equals $|w_p, \ldots, w_2|$ in the denominator.

$Q_n(x)$ is generated by the following recursion formula:

$$Q_n(x) = \frac{1}{\frac{n}{x} - Q_{n-1}(x)} - \frac{n}{x}$$

$$(\text{where } Q_o(x) = -i)$$

Since

$$\frac{\psi_{n-1}(x)}{\psi_n(x)} = \frac{J_{\nu-1}(x)}{J_\nu(x)}$$

$$\psi_n(x) = \psi_{n-1}(x) \left[\frac{J_\nu(x)}{J_{\nu-1}(x)}\right]$$

$$(\text{where } \psi_o(x) = \sin x)$$

Finally,

$$\xi_n(x) = \psi_n(x) + i\beta_n(x)$$

$$\beta_n(x) = \left(\frac{2n-1}{x}\right)\beta_{n-1}(x) - \beta_{n-2}(x)$$

$$(\text{where } \beta_o(x) = \cos x, \text{ and } \beta_1(x) = \frac{\cos x}{x} + \sin x)$$

Following Wiscombe (Reference 12) the order (n) of these functions varies from 1 to N, where:

$$N = x + 4x^{1/3} + 2, \qquad x \geq 4200$$

$$N = x + 4.05x^{1/3} + 2, \qquad 8 < x < 4200$$

$$N = x + 4x^{1/3} + 1, \qquad x \leq 8$$

These equations can be used to generate the requisite Riccati-Bessel functions, the extinction coefficient, and finally the transmittance.

Once the transmittance (T) is calculated, the Ringelmann number may be obtained from the empirical correlation of Connor and Hodkinson (References 10, 11), Figure 5.

A computer program was written to perform these calculations. The FORTRAN listing and sample runs are given in the Appendices.

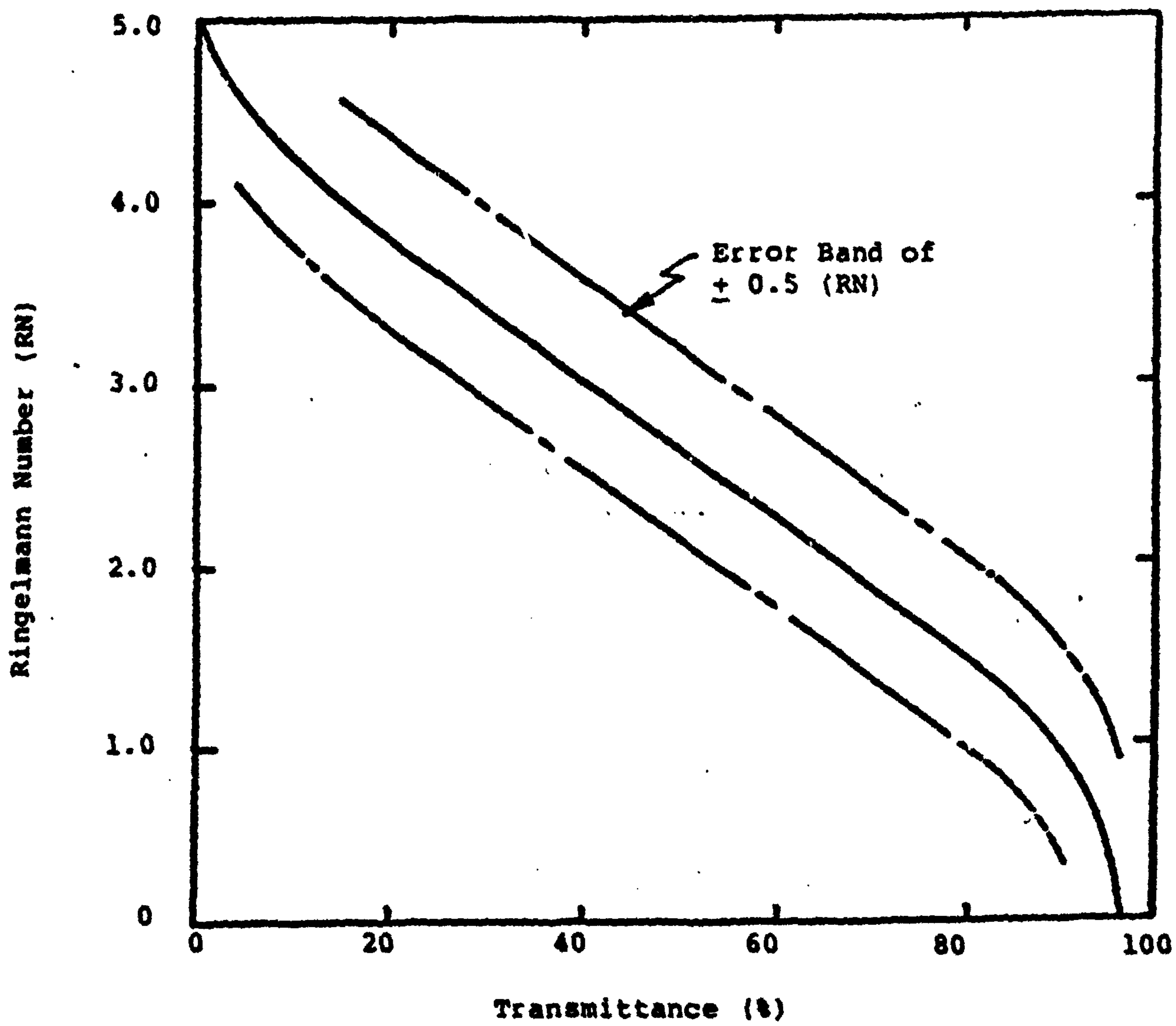


Figure 5. Black Plume Ringelmann Number Correlation with Transmittance (References 10, 11)

SECTION IV

ELECTROSTATIC PRECIPITATOR (ESP) EQUATIONS

A standard mathematical model (Reference 16) was used for predicting the ability of a wire-and-plate ESP to operate as a particle control device:

$$w_i = \frac{8.85\times10^{-5}\ E_c E_p d_{pi}}{\mu}\left(\frac{\xi}{\xi + 2}\right)$$

$$\eta_i = 1 - \exp\left(\frac{-A_p w_i K}{Q}\right)$$

$$\eta = \sum_i \eta_i m_i$$

where: η = overall fractional collection efficiency

η_i = fractional collection efficiency for particles of size d_{pi}

m_i = inlet mass fraction of particles of size d_{pi}

A_p/Q = specific collection area of the ESP (A_p = total collection surface in m^2; and Q = gas flow in m^3/sec)

w_i = theoretical migration velocity of particles of size d_{pi}, in m/sec

K = empirical constant

ξ = dielectric constant of the particles (dimensionless)

μ = gas viscosity, in cp

E_c = electric field strength near the discharge electrodes, in kV/cm

E_p = electric field strength near the collecting plates, in kV/cm

d_p = particles size, in microns

This model is based on a field-charging mechanism and is valid for particles larger than 0.5 microns.

If the collection efficiency for an ESP is plotted against the particle size, the resulting curve will exhibit a minimum in the range of 0.2 to 0.7 microns. Above that range, a field-charging mechanism predominates and the efficiency declines with particle size. Below that range, a diffusion-charging mechanism predominates and the efficiency increases with decreasing particle size. Since most of the particles emitted from a test cell are smaller than 0.2 μm, a large K value of 600 was used in order to compensate for the lack of a diffusion-charging mechanism in the model equations.

In order to reduce the amount of input data needed to run the computer program and avoid a prior design of the ESP, the following values were assumed:

$$\xi = 3, \text{ for carbon}$$

$$\mu = 0.024 \text{ cp, for air at } 350^{\circ}\text{F and 1 atm}$$

$$E_C = E_P = \frac{40 \text{ kV}}{(4.5 \text{ inches})(2.54 \text{ cm/inch})} = 3.50 \text{ kV/cm}$$

(where 9 inches is generally used as the plate-to-plate spacing in utility-type ESP's, with a secondary voltage of 40 kV).

The computer program takes the uncontrolled test cell emission data, calculates the fractional efficiencies, and then determines the outlet particle size distribution and loading. This information then goes to the visibility portion of the program where the outlet Ringelmann number is calculated.

SECTION V

SCRUBBER EQUATIONS

A standard mathematical model (Reference 17) was used to describe the particle collection efficiency of a high energy venturi scrubber. As with the ESP model, this also required an empirical factor (f) to make the model agree approximately with actual data:

$$\ln(1 - \eta_i) = -\left(\frac{18}{55}\right)\left(\frac{\rho_\ell}{\rho_p}\right)\left(\frac{Q_\ell}{Q_g}\right)\left(\frac{d_d}{d_{p_i}}\right)^2 \frac{1}{C_i}\ \{(k_i f + 0.7)$$

$$- 1.4 \ln\left(\frac{k_i f + 0.7}{0.7}\right) - \left(\frac{0.49}{k_i f + 0.7}\right)\}$$

This equation is written in dimensionless form, and therefore any consistent set of units may be used:

η_i = fractional collection efficiency for particles of size d_{pi}

ρ_ℓ = liquid density

ρ_p = particle density

Q_ℓ = liquid flow rate

Q_g = gas flow rate

C_i = Cunningham correction factor for gas viscosity; for particles that are the same size or smaller than the mean free path of the gas molecules (λ)

$= 1 + \frac{2\lambda}{d_{p_i}} [1.23 + 0.41 \exp \left(\frac{-0.44\ d_{p_i}}{\lambda}\right)]$ (dimensionless)

k_i = Stokes' parameter = $\frac{C_i \rho_p d_{p_i}^{\ 2}}{9 \mu_g d_d} Vg_T$ (dimensionless)

f ~ 0.5 (dimensionless empirical factor based on the author's experience)

Vg_T = gas velocity in the venturi throat

$$= \sqrt{\frac{\Delta P_T}{\rho_\ell} \frac{Q_g}{Q_\ell} g_c}$$

ΔP_T = pressure drop across the venturi throat

g_c = Newton's Law conversion factor

The following equations require specific units:

d_d = mean drop size in the venturi throat (Reference 18), in microns

$$= \frac{1920}{Vg_T} \sqrt{\frac{\sigma_\ell}{\rho_\ell}} + 3.69 \left(\frac{\mu_\ell}{\sqrt{\sigma_\ell \rho_\ell}}\right)^{0.45} \left(\frac{1000\ Q_\ell}{Q_g}\right)^{1.5}$$

σ_ℓ = surface tension of scrubbing liquid, in dynes/cm

ρ_ℓ = density of scrubbing liquid, in g/cc

μ_ℓ = viscosity of scrubbing liquid, in cp

Q_ℓ = flow rate of scrubbing liquid, in gpm

Q_g = gas flow rate, in cfm

Vg_T in ft/sec

λ = mean free path of gas molecules, in microns

$$= \frac{3.78\ \mu_g}{\sqrt{P_g \rho_g}}$$

μ_g = gas viscosity, in cp

P_g = gas pressure, in psia

ρ_g = gas density, in lbm/ft^3

Again, in order to minimize the input data requirements, the following operating conditions were assumed:

(1) water is the scrubbing liquid at 70°F

(2) gas properties are those of air at 350°F and 1 atm pressure.

For venturi scrubbers, Q_ℓ / Q_g (the liquid-to-gas ratio) is generally 5 to 30 gpm/1000 cfm, and ΔP_T is 10 to 70 inches of water.

The computer program takes the uncontrolled test cell emission data, calculates the fractional efficiencies, and then determines the outlet particle size distribution and loading. This information then goes to the visibility portion of the program where the outlet Ringelmann number is calculated.

As with electrostatic precipitators, the primary collection mechanism for venturi scrubbers should theoretically change in the range 1.0 to 0.1 μm. Above 1 μm, the particles are collected by an inertial mechanism, while below 0.1 μm a diffusional mechanism should prevail. Again, this would imply a trough in the fractional efficiency curve for particles in the 1.0 to 0.1 μm range. However, in practice, the collection efficiency of venturi scrubbers continues to decline below 0.1 μm, indicating that the predominant mechanism remains inertial. This means that standard venturi scrubbers are inherently less efficient than ESP's in collecting particles smaller than 0.5 μm. One method of overcoming this deficiency has been to induce condensation in the gas stream, either before the scrubber (by quenching), or afterward (by utilizing a two-phase ejector). However, these methods cannot as yet be mathematically modelled with any confidence and have not been included in the computer program.

SECTION VI

RESULTS & DISCUSSION

Grems (Reference 19) measured the particle size distribution, loading, and transmittance from a test cell at McClellan Air Force Base. However, the particle density was unknown. In the present study, this density was used as an empirical parameter to fit the computer results to Grems' data. Excellent agreement was obtained for a particle density of 0.92 g/cc (Table 1). For comparison, computer results are also shown for a particle density of 1.0 g/cc.

Soot particles are porous spheres of carbon, having a high void fraction. Solid carbon has a density of 1.8 to 2.1 g/cc. Therefore, a particle density of 0.92 g/cc implies a void fraction of about 0.53.

Although Grems' data indicated a bimodal particle size distribution, a straight-line log-normal fit was made by the computer program (see Figure 6).

Table 2 shows computer predictions of plume visibility when an electrostatic precipitator or venturi scrubber is used. For the ESP, a specific collection surface of $3281/m^2$ per 1000 m^3/min of gas (1000 ft^2/1000 cfm) corresponds to an upper limit in commercial applications. Since the gas flow from a test cell is on the order of 200,000 scfm, 200,000 ft^2 of collecting plate would be required. However, even such a large ESP has only a small effect on the Ringelmann number because of the small particle size. The size range which has the greatest effect on visibility matches the wavelength of visible light--i.e., 0.2 to 0.7 microns. This is precisely the range in which an ESP or any other control device, is least efficient. Therefore, purchase of an electrostatic precipitator larger than the test cell would only have a marginal effect on plume visibility during the few hours per week the test cell is in use.

Similarly, a venturi scrubber designed for the limit of its range of operability would also have a marginal effect on test cell plume visibility. At a liquid-to-gas ratio of 30 gpm/1000 cfm (4.01 m^3/min water per 1000 m^3/min gas) the scrubber would produce 6000 gpm of waste water for a typical installation; and at a pressure drop of 70 inches of water (131 mm mercury) a 2400 hp tail fan would be required. Under these conditions, the computer predicts an overall particle collection efficiency of 49% with a visibility improvement of 0.5

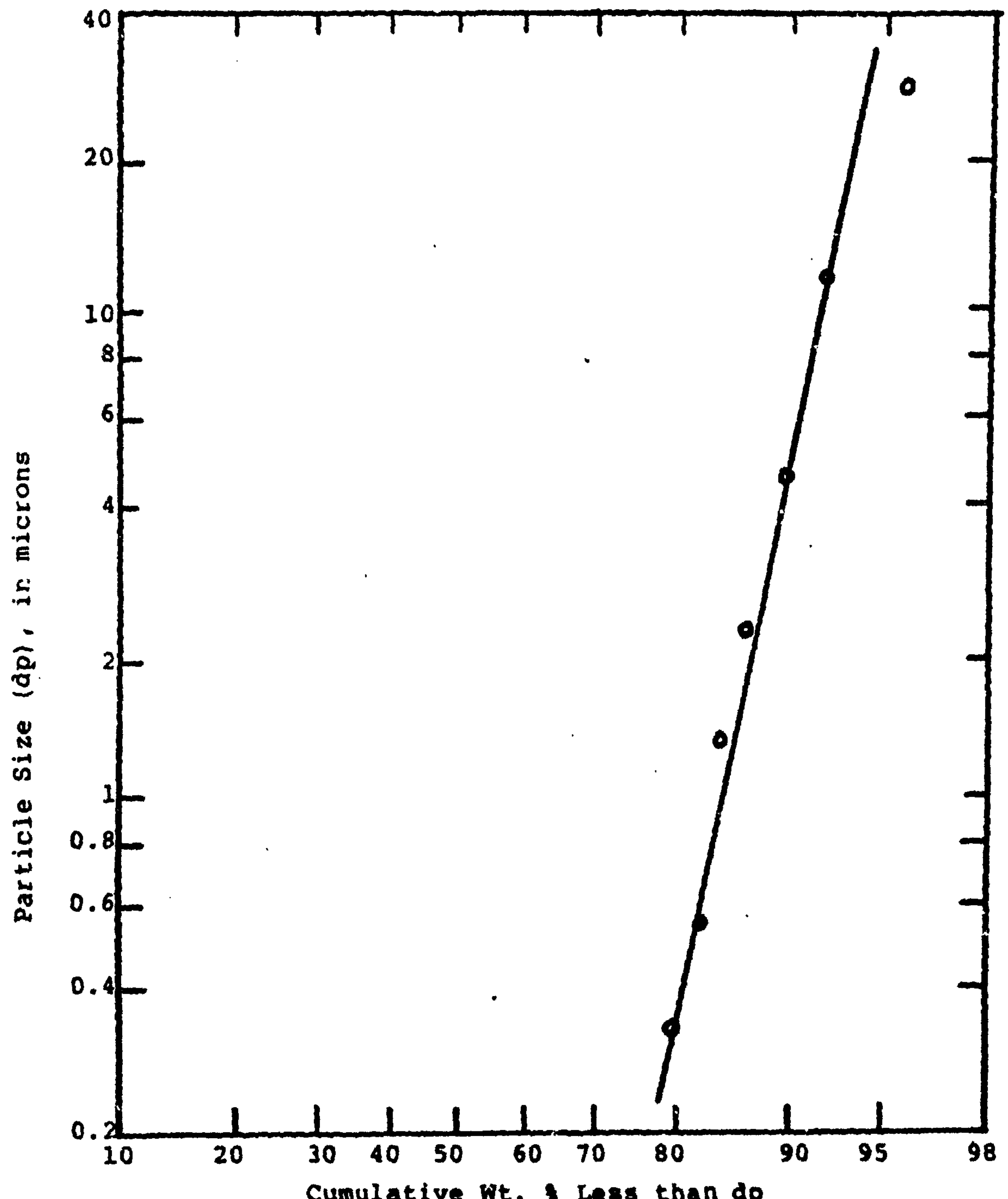


Figure 6. Log-Normal Plot of Size Distribution from Grems' Data (Reference 19)

TABLE 1. COMPARISON OF COMPUTER PREDICTIONS WITH GRENS' DATA FOR J57 ENGINE (Reference 19).

Fuel Firing Rate (lbm/hr)	Particle Loading (mg/m^3)	Measured Particle Size Distribution: Cum Wt % less than	Measured Particle Size Distribution: Aerodynamic Diameter* (=d_p for ρ_p=1.0 g/cc)	Measured Transmittance	Predicted Transmittance (for ρ_p = 1.0 g/cc)	d_p* (for ρ_p = 0.92 g/cc)	Predicted Transmittance (for ρ_p = 0.92 g/cc)
1000	2.16	93.5	23 m	96%	88.3%	24.0 m	87.4%
		91.4	10.5			10.9	
		91.4	4			4.2	
		87.8	2			2.1	
		84.9	1.1			1.15	
		79.9	0.57			0.59	
		73.5	0.33			0.34	
2500	1.95	95.7	28	88	89.4	29.2	88.6
		92.1	11.5			12.0	
		89.7	4.5			4.69	
		86.6	2.2			2.29	
		84.5	1.3			1.36	
		82.7	0.54			0.56	
		79.3	0.33			0.34	
8620	6.08	98.6	22	66	67.9	22.9	65.6
		96.8	9.3			9.70	
		95.1	3.5			3.65	
		92.8	1.7			1.77	
		90.5	0.94			0.98	
		83.8	0.47			0.49	
		77.4	0.23			0.24	
8620	6.34	97.7	21	66	68.4	21.9	66.2
		97.7	9.4			9.80	
		97.4	3.5			3.65	
		95.8	1.7			1.77	
		94.8	0.92			0.96	
		94.2	0.46			0.48	
		88.3	0.22			0.23	

Net open exhaust area = 700 ft^2 (700 = 26.5 ft, or 8 meters); refractive index for amorphous carbon at 550 nm = 1.96-0.66i

*For a cascade impactor, $d_{P1}\sqrt{\rho_{P1}} = d_{P2}\sqrt{\rho_{P2}}$

TABLE 2. COMPARISONS OF CONTROLLED AND UNCONTROLLED EMISSIONS.

UNCONTROLLED EMISSIONS: (Plume Width = 8 Meters)

Particle Loading (mg/m^3)	Particle Density (g/cc)	Particle Size (μm)	Cum.Wt. % Less Than	Transmittance (%)	Ringelmann Number
6.34	0.92	21.9	97.7	66.2	1.5-2.5
		9.80	97.7		
		3.65	97.4		
		1.77	95.8		
		0.96	94.8		
		0.48	94.2		
		0.23	88.2		

CONTROLLED EMISSIONS:

(1) with ESP: SCA = 3281 m^2 /1000 m^3/min

Outlet Particle Loading (mg/m^3)	Collection Efficiency (%)	Transmittance (%)	Ringelmann Number
2.93	53.8	82.8	0.9-1.9

(2) with Venturi Scrubber: L/G = 4.01 m^3/min water per 1000 m^3/min Gas
ΔP = 131 mm Hg

Outlet Particle Loading (mg/m^3)	Collection Efficiency (%)	Transmittance (%)	Ringelmann Number
3.26	48.6	81.0	1.0-2.0

Ringelmann number. Operating data with a scrubber (not a venturi) at the Jacksonville Naval Air Station (Reference 20) indicate an average particle collection efficiency of about 75%. However, there was considerable uncertainty in the accuracy of the data. Stockham, et al. (Reference 21) also report an average collection efficiency of 48% with water injection into the augmentor tube. Again, this is not venturi scrubber data, but it does indicate the validity of the order of magnitude of the predicted results. It should be noted that opacity measurement with a scrubber operating is virtually impossible, since the scrubber will emit a large and obscuring steam plume of its own.

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APPENDIX A

COMPUTER INPUT DATA FORMAT

The following pages give the format for the input data needed to run the computer program. The particle loading should be determined by EPA Method 5, and the particle size distribution by cascade impactor (Reference 19). The plume width can be approximated by the square root of the net open stack area (the actual stack cross-section minus the area occupied by acoustical baffles). For soot particles, the refractive index is 1.96-0.66i at a wavelength of 550 nm, and the particle density was estimated empirically as 0.92 g/cc.

Examples are given for:

(1) Grems' data[19]

(2) an electrostatic precipitator with a specific collection area of 1000 ft^2/1000 cfm (3281 m^2 of collecting plate per 1000 m^3/min of gas)

(3) a venturi scrubber with a liquid-to-gas ratio of 30 gpm/1000 cfm (4.01 m^3/min of water per 1000 m^3/min of gas) at a pressure drop of 70 inches of water (131 mm Hg).

<u>CARD #1</u>

This card contains the title of the case being run, inserted between columns 9 and 10.

CARD #2

This card contains the number of data pairs in the particle size distribution. The minimum number is 2, and the maximum is 100, inserted as an integer between columns 11 and 15 (right justified).

CARD #3 a, b, c, etc.

This card(s) contains the data pairs for the particle size distribution. Columns 1-10, 21-30, 41-50, and 61-70 contain values of the cumulative weight percent less than particle size d_p; while columns 11-20, 31-40, 51-60, and 71-80 contain the corresponding values of d_p. Therefore, a maximum of four data pairs can fit on one card. If there are more data pairs (as per CARD #2), these are put on subsequent cards, until the total number of data pairs (cumulative weight percent less than d_p, and d_p) is equal to the number specified in CARD #2. All values are floating point numbers, with four digits (or blanks) to the right of the decimal point (right justified).

CARD #4

This card contains the following physical parameters:

columns 11-15--the effective stack diameter in meters (based on the net open area) expressed as a floating point number, with two digits (or blanks) to the right of the decimal point (right justified) columns 16-22--the particle loading in mg/m^3, as a floating point number, with two digits (or blanks) to the right of the decimal point (right justified)

columns 23-28--the particle density in g/cm^3, as a floating point number, with two digits (or blanks) to the right of the decimal point (right justified)

columns 29-46--the particle refractive index. Columns 29-37 contain the real part, and 38-46 the imaginary part; both as floating point numbers with two digits (or blanks) to the right of the decimal point (right justified). If these columns are left completely blank, a value for amorphous carbon of 1.96-0.66i is assumed by the program. Note that the refractive index and the wavelength that follows must be consistent

columns 47-53--the wavelength of light (in microns) at which the refractive index was measured, and at which the plume is presumed to be viewed. This must be expressed as a floating point number with three digits (or blanks) to the right of the decimal point (right justified). If columns 29-46 were left blank, these columns should also be left completely blank, in which case the program assumes a value of 0.550 microns.

CARD #5

This card contains (in column 2) an integer number which indicates whether or not a particulate control device (electrostatic precipitator or venturi scrubber) has been installed on the test cell exhaust:

zero (0) means no control device

1 means an electrostatic precipitator

2 means a venturi scrubber

These are the only permissible cases.

CARD #6

This card depends on the code given in CARD #5.

(a) If there is no control device (0 in column 2 of CARD #5), CARD #6 does not exist.

(b) If an electrostatic precipitator is indicated by CARD #5, CARD #6 must contain the specific collection area (in m^2 of plate area per 1000 m^3/min of exhaust gas) in columns 11-17 as a floating point number with one digit (or blank) to the right of the decimal point (right justified).

(c) If a venturi scrubber is indicated by CARD #5, CARD #6 must contain the liquid-to-gas ratio (in m^3/min water per 1000 m^3/min exhaust gas) in columns 11-15; and the scrubber pressure drop (in mm mercury) in columns 16-23; both expressed as floating point numbers, with two digits (or blanks) to the right of the decimal point (right justified).

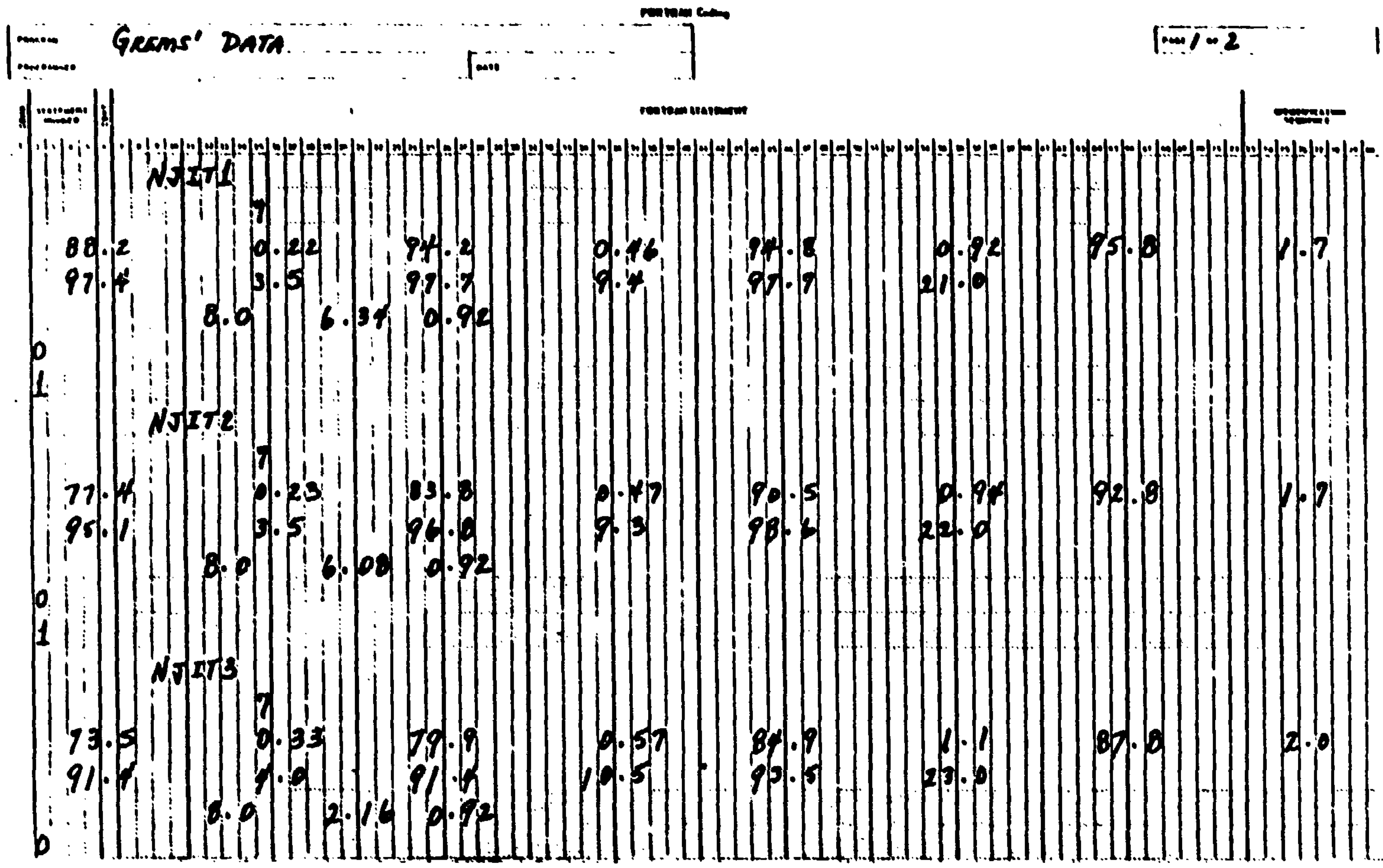
CARD #7

This card contains (in column 2) a code which tells the computer if more cases are to follow:

zero (0) signifies no more cases

1 means an additional case follows

For each additional case, CARDS #1 to 7 must be repeated, even if some of the data remain the same.



GREMS' DATA

PAGE 1-2

NJIT1
7
88.2 0.22 94.2 0.46 94.8 0.92 95.8 1.7
97.4 3.5 97.7 9.4 97.7 21.0
8.0 6.34 0.92
0
1
NJIT2
7
77.4 0.23 83.8 0.47 90.5 0.94 92.8 1.7
95.1 3.5 96.8 9.3 98.6 22.0
8.0 6.08 0.92
0
1
NJIT3
7
73.5 0.33 79.9 0.57 84.9 1.1 87.8 2.0
91.4 4.0 91.4 10.5 93.5 23.0
8.0 2.16 0.92
0

Figure A-1. Computer Input Data Format

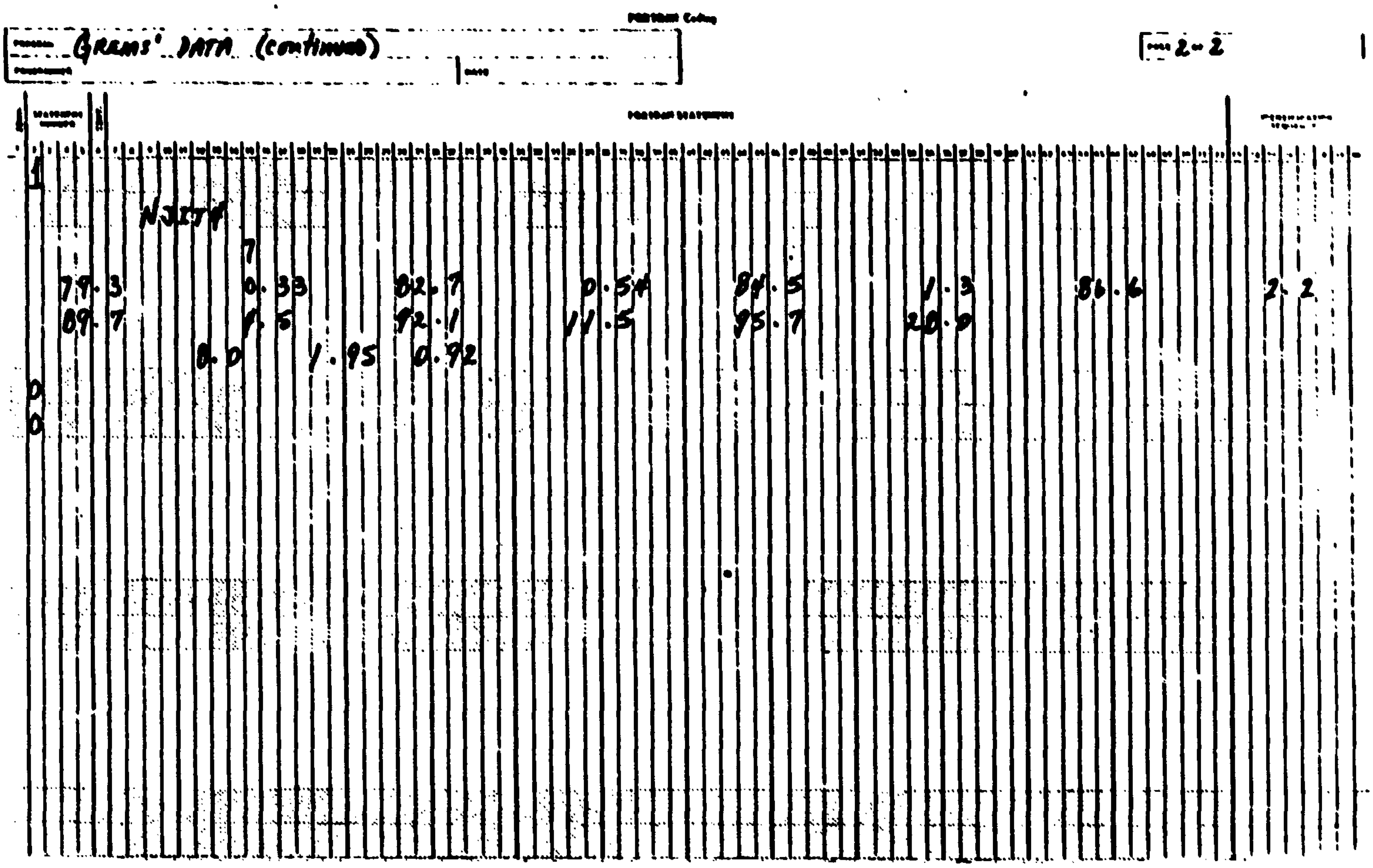


Figure A-1. Continued. Computer Input Data Format

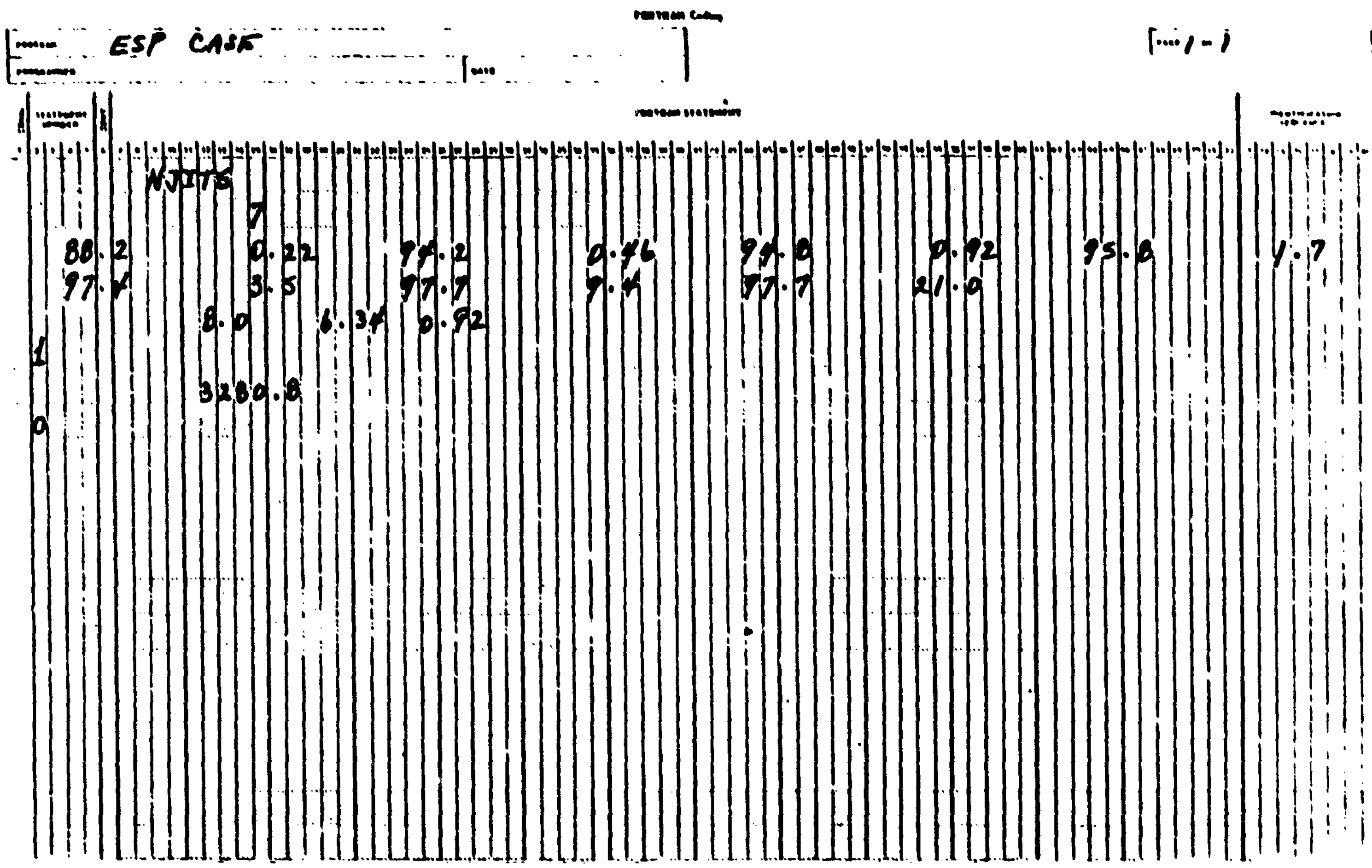


Figure 1-A. Continued. Computer Input Data Format

FORTRAN Coding

PROGRAM: SCRUBBER CASE

PAGE 1 - 1

```
      NJSTG
             7
  88.2       0.22       94.2          0.46       94.8          0.92      95.8      1.7
  97.4       3.5        97.7          9.4        97.7          21.0
          8.0     6.34  0.92
2
          4.01   131.0
0
```

Figure A-1. Continued. Computer Input Data Format

APPENDIX B

OUTPUT FORMAT

Example outputs are given on the next few pages for the input data shown in the previous section (i.e. Grems' data, an ESP, and a venturi scrubber).

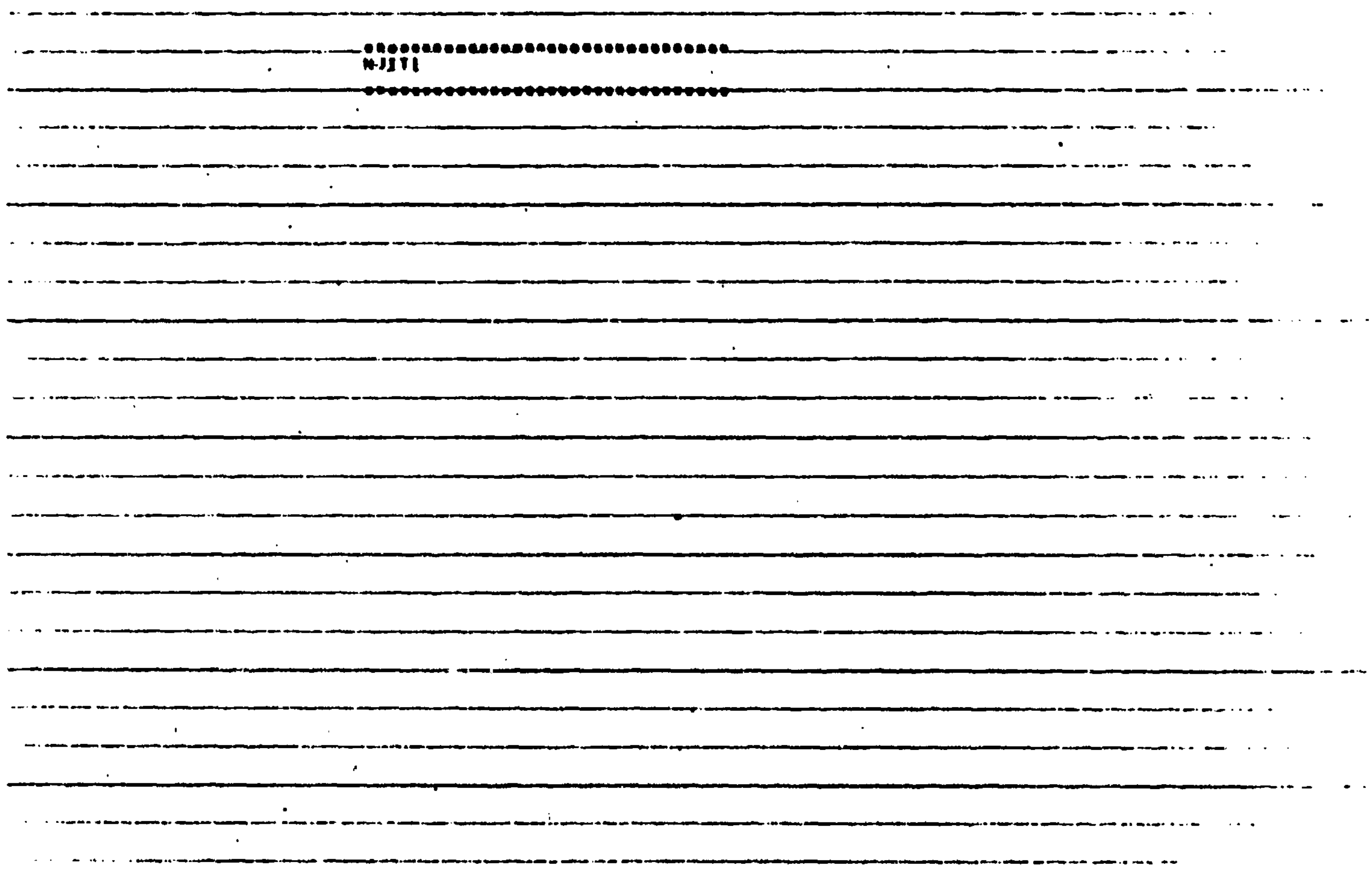


Figure B-1. Output Format

```
PLUME WIDTH (IN METERS) =          8.00        PARTICLE DENSITY (IN G/CC) =        .92
OUTLET LOADING (IN MG/M3) =        6.34        REFRACTIVE INDEX: REAL PART         1.96
LIGHT WAVELENGTH (IN MICRONS) =    .550                          IMAGINARY PART    -.06

                    OUTLET PARTICLE SIZE DISTRIBUTION

          CUMULATIVE WEIGHT PERCENT            PARTICLE SIZE
        LESS THAN STATED PARTICLE SIZE           (MICRON)

                     1.0                          .000
                     2.0                          .000
                     3.0                          .000
                     4.0                          .000
                     5.0                          .000
                    10.0                          .000
                    15.0                          .000
                    20.0                          .000
                    30.0                          .000
                    40.0                          .000
                    50.0                          .000
                    60.0                          .001
                    70.0                          .004
                    80.0                          .022
                    85.0                          .060
                    90.0                          .213
                    95.0                         1.302
                    96.0                         2.381
                    97.0                         4.659
                    98.0                        11.317
                    99.0                        45.973

                      RINGELMANN NUMBER RANGE

                            1.5 - 2.5

                 PERCENT LIGHT TRANSMITTED =  66.15
```

Figure B-1. Continued. Output Format

NJIT2

Figure B-1. Continued. Output Format

PLUME WIDTH (IN METERS) = 8.00
OUTLET LOADING (IN MG/M3) = 6.00
LIGHT WAVELENGTH (IN MICRONS) = .550

PARTICLE DENSITY (IN G/CC) = .92
REFRACTIVE INDEX: REAL PART 1.96
IMAGINARY PART -.66

OUTLET PARTICLE SIZE DISTRIBUTION

CUMULATIVE WEIGHT PERCENT LESS THAN STATED PARTICLE SIZE	PARTICLE SIZE (MICRON)
1.0	.000
2.0	.000
3.0	.000
4.0	.000
5.0	.000
10.0	[illegible]
15.0	[illegible]
20.0	[illegible]
30.0	[illegible]
40.0	[illegible]
50.0	[illegible]
60.0	[illegible]
70.0	[illegible]
80.0	[illegible]
85.0	[illegible]
90.0	1.767
95.0	[illegible]
96.0	[illegible]
97.0	[illegible]
98.0	14.253
99.0	34.473

RINGELMANN NUMBER RANGE

1.5 — 2.5

PERCENT LIGHT TRANSMITTED = 65.63

Figure B-1. Continued. Output Format

M-JIT3

Figure B-1. Continued, Output Format

```
PLUME WIDTH (IN METERS) =              0.00        PARTICLE DENSITY (IN G/CC) =           .92
OUTLET LOADING (IN MG/M3) =            2.16        REFRACTIVE INDEX: REAL PART           1.46
LIGHT WAVELENGTH (IN MICRONS) =        .550                          IMAGINARY PART       -.06

                         OUTLET PARTICLE SIZE DISTRIBUTION

              CUMULATIVE WEIGHT PERCENT              PARTICLE SIZE
           LESS THAN STATED PARTICLE SIZE               (MICRON)

                         1.0                               .000
                         2.0                               .000
                         3.0                               .000
                         4.0                               .000
                         5.0                               .000
                        10.0                               .000
                        15.0                               .000
                        20.0                               .000
                        30.0                               .001
                        40.0                               .004
                        50.0                               .013
                        60.0                               .041
                        70.0                               .145
                        80.0                               .639
                        85.0                              1.506
                        90.0                              4.976
                        95.0                             27.090
                        96.0                             44.349
                        97.0                             81.430
                        98.0                            182.489
                        99.0                            650.179

                         RINGELMANN NUMBER RANGE

                                .0 - 1.0

                    PERCENT LIGHT TRANSMITTED =    87.37
```

Figure B-1. Continued. Output Format

```
********************************
NJIT4
********************************
```

Figure B-1. Continued. Output Format

PLUME WIDTH (IN METERS) = 6.00

OUTLET LOADING (IN MG/M3) = 1.95

LIGHT WAVELENGTH (IN MICRONS) = .550

PARTICLE DENSITY (IN G/CC) = .92

REFRACTIVE INDEX: REAL PART 1.96

IMAGINARY PART -.66

OUTLET PARTICLE SIZE DISTRIBUTION

CUMULATIVE WEIGHT PERCENT LESS THAN STATED PARTICLE SIZE	PARTICLE SIZE (MICRON)
1.0	.000
2.0	.000
3.0	.000
4.0	.000
5.0	.000
10.0	.000
15.0	.000
20.0	.000
30.0	.000
40.0	.002
50.0	.005
60.0	.023
70.0	.092
80.0	.464
85.0	1.7[illegible]
90.0	4.449
[illegible]	28.[illegible]
[illegible]	45.3[illegible]
[illegible]	96.[illegible]
[illegible]	233.1[illegible]
99.0	942.456

RINGELMANN NUMBER RANGE

.5 — 1.5

PERCENT LIGHT TRANSMITTED = 88.59

Figure B-1. Continued. Output Format

```
                         ************************************
                          NJITS
                         ************************************

*** AN ELECTROSTATIC PRECIPITATOR HAS BEEN ASSUMED  AS A CONTROL DEVICE ***
THE SPECIFIC COLLECTION SURFACE IS 3280.8 M2 PER 1000 M3/MIN
WHICH PRODUCES AN OVERALL COLLECTION EFFICIENCY OF 53.77 %

ESP INLET LOADING = 6.34 MG/M3

                 INLET PARTICLE SIZE DISTRIBUTION

                    CUM.WT.%          MICRONS
                       1.0              0.030
                       2.0              0.330
                       3.0              0.000
                       4.0              0.000
                       5.0              0.000
                      10.0              0.030
                      15.0              0.000
                      20.0              0.000
                      30.0              0.000
                      40.0              0.000
                      50.0              0.000
                      60.0              0.001
                      70.0              0.004
                      80.0              0.022
                      85.0              0.060
                      90.0              0.213
                      95.0              1.382
                      96.0              2.381
                      97.0              4.650
                      98.0             11.317
                      99.0             65.977
```

Figure B-1. Continued. Output Format

PLUME WIDTH (IN METERS) = 8.00
OUTLET LOADING (IN MG/M3) = 2.93
LIGHT WAVELENGTH (IN MICRONS) = 0.550

PARTICLE DENSITY (IN G/CC) = 0.92
REFRACTIVE INDEX: REAL PART 1.96
IMAGINARY PART -0.66

OUTLET PARTICLE SIZE DISTRIBUTION

CUMULATIVE WEIGHT PERCENT LESS THAN STATED PARTICLE SIZE	PARTICLE SIZE (MICRON)
1.0	0.000
2.0	0.000
3.0	0.000
4.0	0.000
5.0	0.000
10.0	0.000
15.0	0.000
20.0	0.000
30.0	0.000
40.0	0.000
50.0	0.000
60.0	0.000
70.0	0.000
80.0	0.000
85.0	0.000
90.0	0.000
95.0	0.000
96.0	0.000
97.0	0.000
98.0	0.000
99.0	0.000

RINGELMANN NUMBER RANGE

0.9 - 1.9

PERCENT LIGHT TRANSMITTED = 82.00

Figure B-1. Continued. Output Format

PLUME WIDTH (IN METERS) =	8.00	PARTICLE DENSITY (IN G/CC) =	0.92
OUTLET LOADING (IN MG/M3) =	3.26	REFRACTIVE INDEX: REAL PART	1.96
LIGHT WAVELENGTH (IN MICRONS) =	0.550	IMAGINARY PART	-0.66

OUTLET PARTICLE SIZE DISTRIBUTION

CUMULATIVE WEIGHT PERCENT LESS THAN STATED PARTICLE SIZE	PARTICLE SIZE (MICRON)
1.0	0.000
2.0	0.000
3.0	0.000
4.0	0.000
5.0	0.000
10.0	0.000
15.0	0.000
20.0	0.000
30.0	0.000
40.0	0.000
50.0	0.000
60.0	0.000
70.0	0.001
80.0	0.003
85.0	0.005
90.0	0.009
95.0	0.026
96.0	0.035
97.0	0.051
98.0	0.084
99.0	0.182

RINGELMANN NUMBER RANGE

1.6 - 2.0

PERCENT LIGHT TRANSMITTED = 88.99

Figure B-1. Continued. Output Format

PLUME WIDTH (IN METERS) = 8.00   PARTICLE DENSITY (IN G/CC) = 0.92
OUTLET LOADING (IN MG/M3) = 3.26   REFRACTIVE INDEX: REAL PART 1.96
LIGHT WAVELENGTH (IN MICRONS) = 0.550   IMAGINARY PART -0.66

OUTLET PARTICLE SIZE DISTRIBUTION

CUMULATIVE WEIGHT PERCENT LESS THAN STATED PARTICLE SIZE	PARTICLE SIZE (MICRON)
1.0	0.000
2.0	0.000
3.0	0.000
4.0	0.000
5.0	0.000
10.0	0.000
15.0	0.000
20.0	0.000
30.0	0.000
40.0	0.000
50.0	0.000
60.0	0.000
70.0	0.001
80.0	0.003
85.0	0.005
90.0	0.009
95.0	0.026
96.0	0.035
97.0	0.051
98.0	0.084
99.0	0.182

RINGELMANN NUMBER RANGE

1.0 - 2.0

PERCENT LIGHT TRANSMITTED = 80.99

Figure B-1. Continued. Output Format

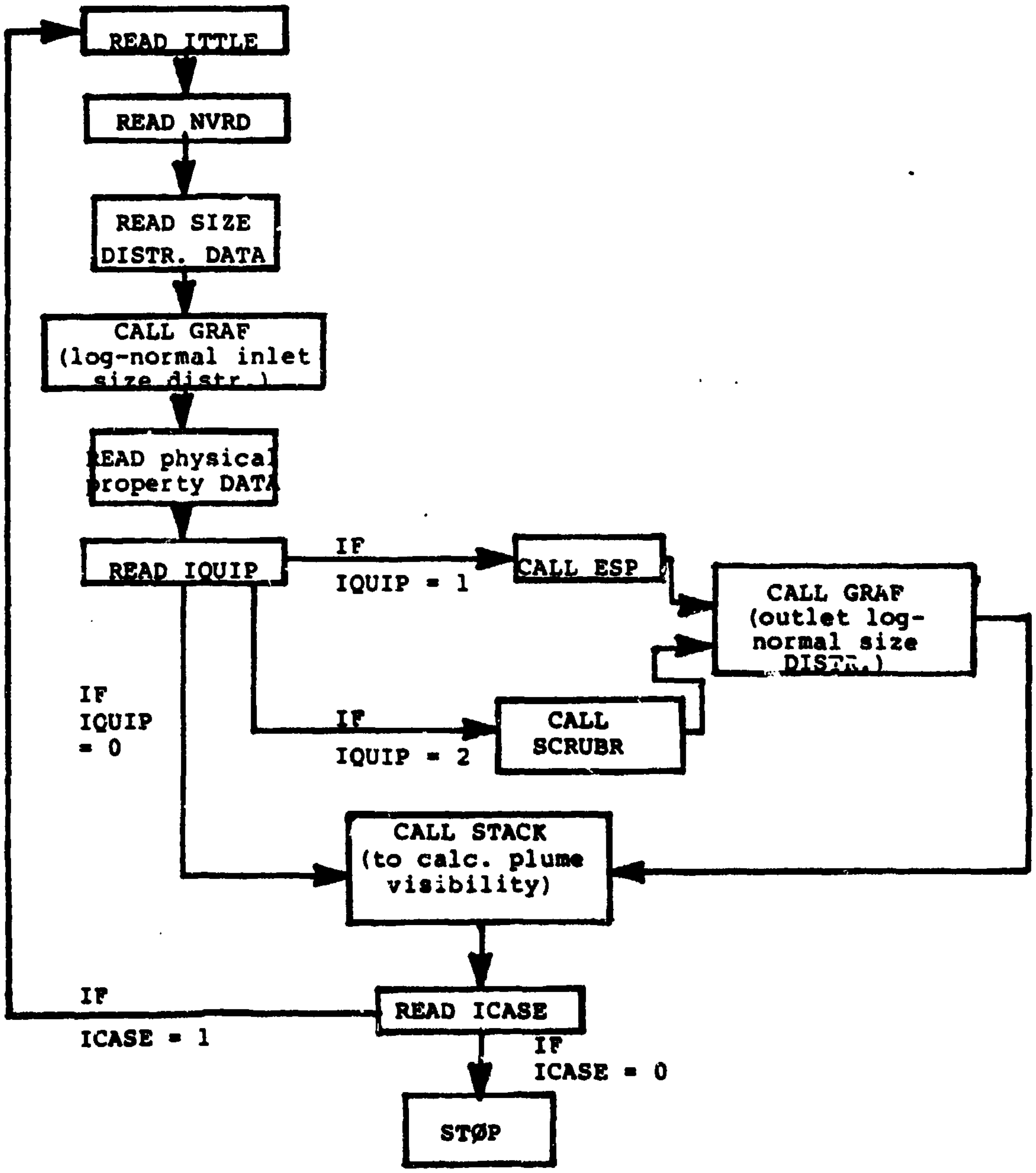
APPENDIX C

FORTRAN LISTING

The following FORTRAN program performs the various visibility and control calculations. It was originally written on a UNIVAC 90/80-3, and later converted for use on a CDC 6600. The version shown here is for the CDC 6600.

COMPUTER PROGRAM FLOW CHART

Figure C-1.



```
PROGRAM NJIT2      767176  OPT=1                FTN 4.8+528        30/07/81  13.02.18       PAGE    1

      PROGRAM NJIT2 (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C ************************************************************************
C
C     THIS PROGRAM WAS WRITTEN IN 1981 BY GORDON A. LEWANDOWSKI
C     OF THE NEW JERSEY INSTITUTE OF TECHNOLOGY
C     UNDER AIR FORCE CONTRACT NO. F08635-80-C0222
C
C ************************************************************************
      COMMON/ANDRO/INUMO,CLCW(101)
      COMMON/ASCHIM/ALB,PO,EFFS,NS
      COMMON/AESP/EFF,SCAIN
      COMMON/ACHAR/XLAM,PATH,REFRAC
      COMMON/ACON/ZI,RHOP
C
C *** COMMON BLOCKS ARE USED TO TRANSFER DATA BETWEEN THE
C     MAIN-PROGRAMS AND SUBROUTINES.
C     ANDRO,ASCHIM,AESP,ACHAR,ACON,AND RNOUT ARE THE
C     NAMES OF THE COMMON BLOCKS. *****
C
      COMPLEX REFRAC
      DIMENSION DP(101),DPRD(101),CWRD(101)
      DIMENSION DPF(101),CWF(101),SUMF(101)
      DIMENSION DPS(101),CWDS(101),SUMS(101),PTLN(101)
      CLCW(1)  = .01
      CLCW(2)  = 1.00
      CLCW(101) =99.99
      DO 9 JI=3,100
      CLCW(JI)  = CLCW(JI-1) + 1.00
    9 CONTINUE
C
C *** CLCW IS A FUNCTION THAT DIVIDES THE CUMULATIVE WEIGHT
C     DISTRIBUTION INTO EQUAL INCREMENTS OF 1%. ****
C
    1 CONTINUE
      INDRO=0
C
C *** READ AND PRINT TITLE ****
C
      READ(5,1010)TITLE
 1010 FORMAT(8X,A10)
      WRITE(6,4)
    4 FORMAT(1H1,//40X,32(*=*))
      WRITE(6,5)TITLE
    5 FORMAT(40X,A10)
      WRITE(6,3)
    3 FORMAT(/40X,32(*=*))
C
C *** READ SIZE DISTRIBUTION AS CUMULATIVE WEIGHT % LESS THAN (CWRD)
C     PARTICLE SIZE (DPRD) IN MICRONS ******
C
      READ (5,1030)NVRD
 1030 FORMAT(10X, I5)
      READ(5,1035) (CWRD(J),DPRD(J),J = 1,NVRD)
 1035 FORMAT (8F10.4)
      IF(DPRD(1).EQ.0.0) DPRD(1) = 0.0001
      IF(CWRD(1).EQ.0.0) CWRD(1) = 0.0001
C
C *** SUBROUTINE *GRAF* FITS THE RAW DISTRIBUTION DATA TO A
C     STRAIGHT LINE, LOG-NORMAL EQUATION. THAT EQUATION IS THEN
C     USED TO INTERPOLATE OR EXTRAPOLATE THE SIZE DISTRIBUTION AS NEEDED
C
      CALL GRAF(DPRD,CWRD,NVRD,DP)
```

Figure C-2. Computer Source Code Listing

```
C                                                                       00011200
C *** READ PLUME CHARACTERISTICS: PLUME WIDTH (PATH) IN METERS,          00011300
C     PARTICLE LOADING (ZI) IN MG/M3, PARTICLE DENSITY (RHOP)           00011400
C     IN G/CC, COMPLEX REFRACTIVE INDEX OF PARTICLES (REFRAC), AND      00011500
C     WAVELENGTH OF LIGHT (XLAM) IN WHICH THE PLUME IS OBSERVED         00011600
C     (IN MICRONS) ******                                               00011700
C                                                                       00011800
      READ(5,1040) PATH,ZI,RHOP,REFRAC,XLAM                             00011900
 1040 FORMAT(10X,F5.2,F7.2,F6.2,2F9.2,F7.3)                             00012000
C                                                                       00012200
C *** IF NO VALUE IS GIVEN FOR REFRAC, THE VALUE FOR AMORPHOUS          00012300
C     CARBON AT 550 NM IS ASSUMED (1.96 - 0.66I).                       00012400
C     IF NO VALUE IS GIVEN FOR XLAM, AN AVERAGE WAVELENGTH FOR          00012500
```

Figure C-2, Continued. Computer Soruce Code Listing

```
      C     VISIBLE LIGHT IS ASSUMED OF 0.550 MICRONS. ******
      C
            RIML = REAL(REFRAC)
            RIIM = AIMAG(REFRAC)
            IF(RIML.EQ.0.0) GO TO 9999
            GO TO 9998
       9999 IF(RIIM.EQ.0.0) GO TO 9997
            GO TO 9998
       9997 REFRAC = (1.54,-0.66)
            RIML = REAL(REFRAC)
            RIIM = AIMAG(REFRAC)
       9998 IF(XLAM.EQ.0.0) XLAM = 0.550
            READ(5,1070) IQUIP
       1070 FORMAT(1X,I1)
            IF(IQUIP.EQ.0) GO TO 6
            IF(IQUIP.EQ.1) GO TO 7
            GO TO 8
      C
      C *** READ ESP SPECIFIC COLLECTION AREA (SCA) AS M2 OF PLATE AREA
      C     PER 1000 M3/MIN OF GAS *****
      C
          7 READ(5,1050) SCA
       1050 FORMAT(10X,F7.1)
            CALL ESP(DP,DPE,CWDE)
      C
      C *** SUBROUTINE "ESP" CALCULATES THE OUTLET PARTICLE SIZE
      C     DISTRIBUTION AND LOADING FROM AN ELECTROSTATIC PRECIPITATOR.
      C     THIS DISTRIBUTION IS THEN NORMALIZED BY CALLING "GRAF". ***
      C
            IF(INORO.EQ.1) GO TO 11
            CALL GRAF(DPE,CWDE,NE,DP)
            GO TO 6
      C
      C *** READ SCRUBBER DATA: LIQUID/GAS RATIO (ALG) AS M3/MIN LIQUID
      C     PER 1000 M3/MIN GAS; AND PRESSURE DROP (PD) AS MM. MERCURY **
      C
          8 READ(5,1060) ALG,PD
       1060 FORMAT(10X,F5.2,F8.2)
      C
      C **** SUBROUTINE "SCRUBR" CALCULATES THE OUTLET PARTICLE SIZE
      C      DISTRIBUTION AND LOADING FROM A HIGH ENERGY VENTURI SCRUBBER.
      C      THIS DISTRIBUTION IS THEN NORMALIZED BY CALLING "GRAF". ***
      C
            CALL SCRUBR(DP,DPS,CWDS)
            IF(INORO.EQ.1) GO TO 11
            CALL GRAF(DPS,CWDS,NS,DP)
            GO TO 6
      C
      C *** SUBROUTINE "STACK" PERFORMS THE VISIBILITY CALCULATIONS. ****
      C
      6     CALL STACK(DP)
         11 READ(5,1080) ICASE
       1080 FORMAT(1X,I1)
            IF(ICASE.EQ.0) GO TO 2
            GO TO 1
          2 STOP
            END
```

Figure C-2. Continued. Computer Source Code Listing

```
FUNCTION EINV       76/176   OPT=1                    FTN 4.8+528       30/07/81  13.02.18     PAGE    1

      FUNCTION EINV(RCW)                                                00019600
C                                                                       00019700
C***  "EINV" IS AN INVERSE NORMAL DISTRIBUTION FUNCTION USED BY         00019800
C      SUBROUTINE GRAF TO DETERMINE THE STRAIGHT LINE LOG-NORMAL        00019900
C      PARTICLE SIZE DISTRIBUTION. ****                                 00020000
C                                                                       00020100
      DNUM =  RCW/100.                                                  00020200
      IF(RCW.EQ.0.0) GO TO 30                                           00020300
      IF(RCW.EQ.100.0) GO TO 40                                         00020400
      IF(DNUM.GE.0.50) GO TO 10                                         00020500
      SGN = -1.0                                                        00020600
      GO TO 20                                                          00020700
   10 DNUM = 1.0 - DNUM                                                 00020800
      SGN = 1.0                                                         00020900
   20 FF2 = 1.0/(DNUM **2)                                              00021000
      ETASQ = ALOG(FF2)                                                 00021100
      ETA = SQRT(ETASQ)                                                 00021200
      EINV = SGN * (ETA-(2.515517 + 0.802853*ETA                        00021300
     1 + 0.010328*ETASQ)/(1. + 1.432788 * ETA + 0.189269                00021400
     2* ETASQ + 0.1308E-02 * ETA * ETASQ))                              00021500
      RETURN                                                            00021600
   30 EINV = -5.0                                                       00021700
      RETURN                                                            00021800
   40 EINV = 5.0                                                        00021900
      RETURN                                                            00022000
      END                                                               00022100
```


Figure C-2. Continued. Computer Soruce Code Listing

```
SUBROUTINE GRAF        76/176   OPT=1                    FTN 4.8+528        30/07/81  13.42.18        PAGE     1

      SUBROUTINE GRAF(DPHD,CUMD,NVHD,DP)
C
C *** GRAF - USES THE METHOD OF LEAST SQUARES TO FIT THE RAW
C     PARTICLE SIZE DISTRIBUTION DATA TO A STRAIGHT LINE
C     LOG-PROBABILITY CURVE ********
C
      COMMON/ANDRU/INHMD,CLCV(101)
      DIMENSION DPHD(101),CUMD(101),DP(101)
      SUMY=0.0
      SUMX=0.0
      SUMX2=0.0
      SUMXY=0.0
      FNHD=FLOAT(NVHD)
      DO 19 I=1,NVHD
      Y=ALOG10(DPHD(I))
      X=ERINV(CUMD(I))
      X2=X**2.0
      SUMY=SUMY+Y
      SUMX=SUMX+X
      SUMX2=SUMX2+X2
      SUMXY=SUMXY+X*Y
   19 CONTINUE
      SLOPE=(FNHD*SUMXY-SUMX*SUMY)/(FNHD*SUMX2-SUMX**2.0)
      B=(SUMY-SLOPE*SUMX)/FNHD
      DO 21 J=1,101
      X1=ERINV(CLCV(J))
      DP(J)=10.0**(SLOPE*X1+B)
   21 CONTINUE
      RETURN
      END
```

Figure C-2. Continued. Computer Source Code Listing

```
SUBROUTINE ESP        74/176  OPT=1                    FTN 4.8+528        30/07/81  13.02.18        PAGE    1

      SUBROUTINE ESP(DP,DPE,CWDE)
C
C *** RESP CALCULATES THE OUTLET PARTICLE SIZE DISTRIBUTION AND LOADING
C     FROM AN ELECTROSTATIC PRECIPITATOR WITH SPECIFIC COLLECTION SURFAC
C
      COMMON/AESP/EFF,SCA,NE
      COMMON/ANDAD/INDDO,CLCW(101)
      COMMON/ACON/ZI,MOP
      DIMENSION DP(101),DPE(101),CWDE(101),SUME(101)
C
C *** EQUATIONS USED TO CALCULATE ESP EFFICIENCY:
C
C     FRACTIONAL EFFICIENCY = 1 - EXP(-SCA*W/K)
C      BY FIELD CHARGING MECHANISM:
C     W =MIGRATION VELOCITY (M/SEC) =8.85E-05*EC*EP*DP*(CD/(CD+2))/V
C     FOR 40 KV DISCHARGE VOLTAGE AND 4 INCH PLATE-TO-PLATE SPACING:
C     EC = EP = FIELD STRENGTH = 3.50 KV/CM
C     DP = INLET PARTICLE SIZE IN MICRONS
C     CD = DIELECTRIC CONSTANT OF PARTICULATE, WHICH FOR CARBON IS ABOUT
C      FOR AIR AT 350 F:
C     V = GAS VISCOSITY = .024 CP
C     K = FUDGE FACTOR.  SINCE THE MODEL EQUATION FOR THE
C         MIGRATION VELOCITY APPLIES TO PARTICLES LARGER THAN
C         0.5 MICRONS (WHICH IS LARGER THAN MOST OF THE PARTICLES
C         EMITTED BY THE TEST CELL), A "K" VALUE OF 600 WAS USED
C         IN THE PROGRAM.
C   COMBINING EQUATIONS:
C     FRACTIONAL EFFICIENCY = 1 - EXP(-.0758*SCA*DP)
C     WHERE SCA IS IN M2 OF COLLECTING PLATE PER 1000 M3/MIN OF GAS FLOW
C           DP IS IN MICRONS
C     THUS,  EACH PARTICLE SIZE HAS ITS OWN EFFICIENCY. THE OVERALL
C     EFFICIENCY IS THE SUM OF THE EFFICIENCIES FOR EACH PARTICLE SIZE
C     TIMES THE WEIGHT FRACTION FOR EACH SIZE. SINCE BY SUBROUTINE GRAF
C     (AND CLCW), THERE ARE 100 INCREMENTS, ALL OF THE SAME
C     WEIGHT PERCENT, THE OVERALL EFFICIENCY(%) IS SIMPLY THE SUM
C     OF THE FRACTIONAL EFFICIENCIES.
C
      SUM  = 0.0
      A = 0.0758*SCA
      DO 3 IK = 1,100
      DPE(IK) = (DP(IK) + DP(IK+1))/2.0
      SUME(IK) = SUM + EXP(-A*DPE(IK))
      SUM = SUME(IK)
    3 CONTINUE
      EFF = 100.0-SUM
      S = .01*SUM
      WRITE(6,1061)
 1061 FORMAT(//1H ,"**** AN ELECTROSTATIC PRECIPITATOR HAS BEEN ASSUMED
     1AS A CONTROL DEVICE ****")
      WRITE(6,61)SCA
   61 FORMAT(1H ,"THE SPECIFIC COLLECTION SURFACE IS",
     1F7.1,1X,"M2 PER 1000 M3/MIN")
      WRITE(6,1062)EFF
 1062 FORMAT(1H ,"WHICH PRODUCES AN OVERALL COLLECTION EFFICIENCY OF"
     1,F6.2,1X,"%")
      WRITE(6,21) ZI
   21 FORMAT(/1H ,"ESP INLET LOADING =",F5.2,1X,"MG/M3")
      WRITE(6,17)
   17 FORMAT(//1H ,"INLET PARTICLE SIZE DISTRIBUTION")
      WRITE(6,19)
```

Figure C-2. Continued. Computer Source Code Listing

```
   10 FORMAT(/31X,"CUM.WT.%",9X,"MICRONS")                              00031200
      WRITE(6,11)(CLCW(J),DP(J),J=2,4)                                  00031300
      WRITE(6,11)(CLCW(J),DP(J),J=11,21,5)                              00031400
      WRITE(6,11)(CLCW(J),DP(J),J=31,81,10)                             00031500
      WRITE(6,11)(CLCW(J),DP(J),J=86,96,5)                              00031600
      WRITE(6,11)(CLCW(J),DP(J),J=97,100)                               00031700
   11 FORMAT(31X,F6.2,10X,F7.3)                                         00031800
      ZI = ZI*S                                                         00031900
C                                                                       00032000
C *** THE NEXT 9 LINES CALCULATE THE OUTLET CUMULATIVE WT.% FOR EACH    00032100
C     PARTICLE SIZE *****                                               00032200
C                                                                       00032300
      DO 5 IL =1,100                                                    00032400
      CWOE(IL) = WOE(IL)/S                                              00032500
      NE = IL                                                           00032600
      IF(CWOE(IL).GE.100.0) GO TO 15                                    00032700
    5 CONTINUE                                                          00032800
   15 CWOE(IL) = 100.0                                                  00032900
      IF(NE.EQ.1) GO TO 12                                              00033000
      GO TO 16                                                          00033100
   12 WRITE(6,19)                                                       00033200
   19 FORMAT(//14X,"**** COLLECTION EFFICIENCY IS SO HIGH THAT OPACITY  00033300
     1CALCULATION CANNOT BE MADE.")                                     00033400
      WRITE(6,20)                                                       00033500
   20 FORMAT(18X,"HOWEVER, THE RINGELMANN NUMBER IS CERTAIN TO BE       00033600
     1MUCH LESS THAN 1.0")                                              00033700
      INOAD = 1                                                         00033800
   16 RETURN                                                            00033900
      END                                                               00034000
```

Figure C-2. Continued. Computer Source Code Listing

```
SUBROUTINE SCRUBB     76/176   OPT=1                    FTN 4.8+528          30/07/81  13.02.18     PAGE    1

      SUBROUTINE SCRUBB(DP,DPS,CWDS)
C
C *** "SCRUBB" CALCULATES THE OUTLET PARTICLE SIZE DISTRIBUTION AND
C     LOADING FROM A HIGH ENERGY VENTURI SCRUBBER ***
C
      COMMON/ASCRUB/ALG,PD,EFFS,NS
      COMMON/ANORD/INORD,CLCW(101)
      COMMON/AGON/Z1,RHOP
      DIMENSION DP(101),DPS(101),CWDS(101),SUMS(101),PTLN(101)
C
C *** EQUATIONS USED TO CALCULATE SCRUBBER EFFICIENCY (FROM CALVERT):
C        LOG(PT) = -((R/55)*(RHOL/RHOP)*(ALG)*((DD/DP)**2)*(1/CC)*
C                  ((K*F + 0.7) - 1.4*ALOG((K*F + 0.7)/0.7) +
C                  0.49/(K*F + 0.7)))
C        WHERE  PT = PENETRATION = 1 - FRACTIONAL EFFICIENCY
C             RHOL = LIQUID DENSITY
C             RHOP = PARTICLE DENSITY
C              ALG = LIQUID/GAS FLOW RATE
C               DP = PARTICLE SIZE
C               CC = CUNNINGHAM CORRECTION FACTOR
C                  = 1 + (2*LAMBDA/DP)*(1.23 + 0.41*EXP(-0.44*DP/LAMBDA))
C           LAMBDA=  GAS MEAN FREE PATH =0.107 MICRONS FOR AIR AT 350 F
C                                          AND 1 ATM
C                K = VGT*CC*RHOP*(DP**2)/(9*V*DD)
C                V = GAS VISCOSITY = 0.024 CP FOR AIR AT 350  F AND 1 ATM
C              VGT = GAS VELOCITY IN THE VENTURI THROAT
C                  = SQRT((PD*GC)/(RHOL*ALG))
C               PD = PRESSURE DROP ACROSS THE SCRUBBER
C               GC = NEWTON'S LAW CONVERSION FACTOR
C
C              FOR WATER AT 70  F: VGT = 11.56*SQRT(PD/ALG)
C              (FOR VGT IN M/SEC, PD IN MM MERCURY (GENERALLY 10.2
C               TO  131), AND ALG IN M3/MIN WATER PER 1000 M3/MIN GAS
C               (GENERALLY 0.67 TO 4.0))
C
C                F = FUDGE FACTOR = 0.5 (APPROXIMATE, FROM EXPERIENCE OF
C                    B. LEVANDOWSKI)
C               DD = LIQUID DROP SIZE (BY NUKIYAMA-TANASAWA EQUATION)
C                    FOR WATER AT 70  F:
C                          DD = (4991/VGT) + 28.57*(ALG**1.5)
C                          (FOR DD IN MICRONS)
C
      VGT = 11.56*SQRT(PD/ALG)
      DD = (4991.0/VGT) + 28.57*(ALG**1.5)
      SUM = 0.0
      DO 3 IK=1,100
      DPS(IK) = (DP(IK)+DP(IK+1))/2.0
      CC = 1.0 + (0.2137/DPS(IK))*(1.23+0.41*EXP(-4.118*DPS(IK)))
      AK = 4.430*CC*RHOP*(DPS(IK)**2.0)*VGT/DD
      AKF = 0.5*AK+0.7
      PTLN(IK) = -318.0E-06*ALG*((DD/DPS(IK))**2.0)*(AKF-1.4*
     1ALOG(AKF/0.7)-(0.49/AKF))/(RHOP*CC)
      SUMS(IK) = SUM + EXP(PTLN(IK))
      SUM = SUMS(IK)
    3 CONTINUE
      EFFR = 100.0-SUM
      S = .01*SUM
      WRITE(6,10A1)
```

Figure C-2. Continued. Computer Source Code Listing

```
 1041 FORMAT(//10X,"*** A HIGH ENERGY VENTURI SCRUBBER HAS BEEN ASSUMED
     1AS A CONTROL DEVICE ***")
      WRITE(6,61)RLG
   61 FORMAT(15X,"THE LIQUID/GAS RATIO IS",
     1F5.2,1X,"M3/MIN WATER PER 1000 M3/MIN GAS")
      WRITE(6,63)DP
   63 FORMAT(15X,"THE SCRUBBER PRESSURE DROP IS",F7.2,1X,
     1"MM. MERCURY")
      WRITE(6,1042)EFFS
 1042 FORMAT(15X,"WHICH PRODUCES AN OVERALL COLLECTION EFFICIENCY OF"
     1,F6.2,1X,"%")
      WRITE(6,21) ZI
   21 FORMAT(/15X,"SCRUBBER INLET LOADING =",F9.2,1X,"MG/M3")
      WRITE(6,17)
   17 FORMAT(//27X,"INLET PARTICLE SIZE DISTRIBUTION")
      WRITE(6,18)
   18 FORMAT(/3(1X,"CUM.WT.%",9X,"MICRONS"))
      WRITE(6,13)(CLC(J),DP(J),J=2,6)
      WRITE(6,13)(CLC(J),DP(J),J=10,25,5)
      WRITE(6,13)(CLC(J),DP(J),J=30,70,10)
      WRITE(6,13)(CLC(J),DP(J),J=80,95,5)
      WRITE(6,13)(CLC(J),DP(J),J=97,100)
   13 FORMAT(3(1X,F6.1,10X,F7.3))
      ZI = ZI*S
C
C *** THE NEXT 9 LINES CALCULATE THE OUTLET CUMULATIVE WT.% FOR EACH
C     PARTICLE SIZE ***
C
      DO 5 IL =1,100
      CWOS(IL) = SUMS(IL)/S
      NS = IL
      IF(CWOS(IL).GE.100.0) GO TO 15
    5 CONTINUE
   15 CWOS(IL) = 100.0
      IF(NS.EQ.1) GO TO 12
      GO TO 16
   12 WRITE(6,19)
   19 FORMAT(//10X,"*** COLLECTION EFFICIENCY IS SO HIGH THAT OPACITY
     1CALCULATION CANNOT BE MADE.")
      WRITE(6,20)
   20 FORMAT(10X,"HOWEVER, THE RINGELMANN NUMBER IS CERTAIN TO BE
     1MUCH LESS THAN 1.0")
      IWORD = 1
   16 RETURN
      END
```

Figure C-2. Continued. Computer Source Code Listing

```
      SUBROUTINE STACK(DP)
C
C *** "STACK" PERFORMS THE VISIBILITY CALCULATIONS BASICALLY USING
C     THE METHOD OF MALOW & ZEER (JAPCA, VOL.23, PP.676-684,
C     AUGUST 1973). HOWEVER, THERE HAVE BEEN A NUMBER OF IMPORTANT
C     MODIFICATIONS AS DESCRIBED BELOW. *********
C
      COMMON/ACHAR/XLAM,PATH,REFRAC
      COMMON/ACON/Z1,WHOP
      COMMON/ANOOD/NUMO,CLCV(101)
      DIMENSION DP(101),WP(1000),WN(1000),WO(1000),RM2(1000)
      COMPLEX YV,REFRAC,HMJ,HJC,PNY,A2,A3,R2,R3,AN,BN
      COMPLEX Q(1000),WHC(1000),WNC(1000),WDC(1000)
      COMPLEX HIMAG
      HIMAG = (0.0,1.0)
      SIFPR = 0.0
      DO 100 K=1,100
      DPI = (DP(K)+DP(K+1))/2.0
      IF(DPI.GT.50.0) GO TO 24
C
C *** PARTICLES LARGER THAN 50 MICRONS HAVE A NEGLIGIBLE EFFECT
C     ON VISIBILITY, AND THEREFORE, HAVE BEEN EXCLUDED FROM THE
C     CALCULATIONS IN ORDER TO SAVE COMPUTATION TIME. *********
C
      XV = 3.14159277*DPI/XLAM
      YV = REFRAC*XV
      QSUM = 0.0
      RM1X = SIN(XV)
      RM2(1) = -SIN(XV)
      RM2(2) = COS(XV)
      Q(1) = -HIMAG
      E3 = 1.0/3.0
C
C *** MAXIMUM VALUES (NMAX) OF THE ORDER (N) OF THE RICCATI-BESSEL
C     FUNCTIONS ARE GENERATED BY THE FOLLOWING THREE EQUATIONS
C     ACCORDING TO WISCOMBE, W.J., APPLIED OPTICS, VOL.19, PP.1505-
C     1509 (MAY 1980). *****
C
      IF(XV.GE.4200.0) NMAX=XV+4.0*(XV**E3)+2.0
      IF(XV.LT.4200.0) NMAX=XV+4.05*(XV**E3)+2.0
      IF(XV.LE.8.0) NMAX=XV+4.0*(XV**E3)+1.0
      DO 59 N=1,NMAX
C
C *** THE NEXT 16 LINES GENERATE BESSEL FUNCTIONS OF THE ARGUMENT
C     XV ACCORDING TO THE METHOD OF LENTZ, W.J., APPLIED OPTICS,
C     VOL.15, PP.668-671 (MARCH 1976). *******
C
      WP(1) = 2.0*(FLOAT(N)+0.5)/XV
      WN(1) = WP(1)
      WP(2) = -2.0*(FLOAT(N+1)+0.5)/XV
      WN(2) = WP(2)
      WN(2) = WP(2)+(1.0/WP(1))
      WJ = WP(1)*WN(2)/WP(2)
      IP = 1
      L = 1
   12 WP(IP) = 2.0*FLOAT(L)*(FLOAT(N+IP-1)+0.5)/XV
      WN(IP) = WP(IP)+(1.0/WN(IP-1))
      WD(IP) = WP(IP)+(1.0/WD(IP-1))
      WJ = WJ*WN(IP)/WD(IP)
      IF(ABS(WN(IP)-WD(IP)).LE.1.0E-10) GO TO 13
      IP = IP+1
      L = -L
      GO TO 12
C
C ***  PHI AND Q ARE LOGARITHMIC DERIVATIVE FUNCTIONS USED
C         TO CALCULATE AN & BN.
C
```

Figure C-2. Continued. Computer Source Code Listing

```
C        * THE RICCATI-BESSEL FUNCTIONS OF THE FIRST KIND (RR1X)
C          ARE CALCULATED BY FORWARD RECURSION FROM THE BESSEL
C          FUNCTION RATIO (RJ).
C
C        * THE R-B FUNCTIONS OF THE SECOND KIND (RR2) ARE
C          CALCULATED BY FORWARD RECURSION.
C
C        * THE R-B FUNCTIONS OF THE THIRD KIND (RR3) ARE LINEAR
C          FUNCTIONS OF RR1X AND RR2. *****
C
   13 PHX = RJ-(FLOAT(N)/XV)
      RR1X = RR1X/RJ
      RR2(N+2) = (FLOAT(2*N+1)/XV)*RR2(N+1)-RR2(N)
      RR3 = RR1X+RIMAG*RR2(N+2)
      CN = FLOAT(N)/XV
      Q(N+1) = (1.0/(CN-Q(N)))-CN
C
C *** THE NEXT 20 LINES GENERATE BESSEL FUNCTIONS OF THE COMPLEX
C     ARGUMENT YV AGAIN USING THE METHOD OF LENTZ (SEE ABOVE). ***
C
   15 WPC(1) = 2.0*(FLOAT(N)+0.5)/YV
      WNC(1) = WPC(1)
      WPC(2) = -2.0*(FLOAT(N+1)+0.5)/YV
      WDC(2) = WPC(2)
      WNC(2) = WPC(2)+(1.0/WPC(1))
      RJC = WPC(1)*WNC(2)/WPC(2)
      IP = 3
      L = 1
   16 WPC(IP) = 2.0*FLOAT(L)*(FLOAT(N+IP-1)+0.5)/YV
      WNC(IP) = WPC(IP)+(1.0/WNC(IP-1))
      WDC(IP) = WPC(IP)+(1.0/WDC(IP-1))
      RJC = RJC*WNC(IP)/WDC(IP)
      WR = REAL(WNC(IP)-WDC(IP))
      WI = AIMAG(WNC(IP)-WDC(IP))
      IF(ABS(WR).LE.1.0E-10) GO TO 18
      GO TO 19
   18 IF(ABS(WI).LE.1.0E-10) GO TO 17
   19 IP = IP+1
      L = -L
      GO TO 16
C
C *** PHY IS ANOTHER LOGARITHMIC DERIVATIVE FUNCTION. A1,A2,A3 AND
C     B1,B2,B3 ARE USED TO AVOID THE POSSIBILITY OF EXPONENTIAL
C     OVERFLOWS WHEN DIVIDING BY COMPLEX NUMBERS. ****
C
   17 PHY = RJC-(FLOAT(N)/YV)
      A1 = REAL(RR3)*(PHY-REFRAC*Q(N+1))
      A2 = RR1X*(PHY-REFRAC*PHX)/A1
      A3 = RR3*(PHY-REFRAC*Q(N+1))/A1
      AN = A2/A3
      B1 = REAL(RR3*(REFRAC*PHY-Q(N+1)))
      B2 = RR1X*(REFRAC*PHY-PHX)/B1
      B3 = RR3*(REFRAC*PHY-Q(N+1))/B1
      BN = B2/B3
      QSUM = QSUM+FLOAT(2*N+1)*REAL(AN+BN)
   50 CONTINUE
      QEXT = 2.0*QSUM/(XV**2)
      STEPR = STEPR+(QEXT/UP)
  100 CONTINUE
   24 TRANS = EXP(((-(3.0E-03)*Z)*PATH)/(200.0*RHOP))*STEPR)
      TRANSV = TRANS * 100.0
C
```

Figure C-2. Continued. Computer Source Code Listing

```
C *** THE RINGELMANN NUMBER (RNM) IS DETERMINED FROM THE              00057300
C     % TRANSMITTANCE USING THE DATA OF CONNER & HODKINSON             00057400
C     (SEE MALM & ZEE PAPER NOTED ABOVE). THE FOLLOWING                00057500
C     FORTRAN STATEMENTS ARE SIMPLY STRAIGHT-LINE FITS                 00057600
C     OF DIFFERENT PORTIONS OF CONNER & HODKINSON'S                    00057700
C     ORIGINAL DATA CURVE *****                                        00057800
C                                                                      00057900
      IF(TRANSM.GT.95.)GO TO 99                                        00058000
      IF(TRANSM.GT.45.)GO TO 98                                        00058100
      IF(TRANSM.LT.15.)GO TO 97                                        00058200
      RNM=-.0375*TRANSM + 4.5                                          00058300
      GO TO 970                                                        00058400
   99 RNMIN=0.0                                                        00058500
      RNMAX=0.5                                                        00058600
      GO TO 96                                                         00058700
   98 RNM=-.0404*TRANSM + 5.1                                          00058800
      GO TO 970                                                        00058900
   97 RNM=-.0667*TRANSM + 5.0                                          00059000
  970 CONTINUE                                                         00059100
C                                                                      00059200
C *** THE FOLLOWING 2 STATEMENTS EXPRESS THE OBSERVER                  00059300
C     ERROR IN DETERMINING THE RINGELMANN NUMBER ****                  00059400
C                                                                      00059500
      RNMIN = RNM - 0.5                                                00059600
      RNMAX = RNM + 0.5                                                00059700
      IF(RNMAX.GT.5.0) RNMAX=5.0                                       00059800
   96 CONTINUE                                                         00059900
      RIRL = REAL(REFRAC)                                              00060000
      RIIM = AIMAG(REFRAC)                                             00060100
      WRITE(6,1025) PATH, RHOP, ZI, RIRL, XLAM, RIIM                   00060200
 1025 FORMAT(1H1,13X,"PLUME WIDTH (IN METERS) =",11X,F5.2,14X,"PARTICLE 00060300
     1DENSITY (IN G/CC) =",10X,F5.2/14X,"OUTLET LOADING (IN MG/M3) =", 00060400
     2 8X,F5.2,14X,"REFRACTIVE INDEX: REAL PART",10X,F5.2/             00060500
     314X,"LIGHT WAVELENGTH (IN MICRONS) =",5X,F6.3,31X,"IMAGINARY PART" 00060600
     45X,F5.2)                                                         00060700
      WRITE(6,22)                                                      00060800
   22 FORMAT(//51X,"OUTLET PARTICLE SIZE DISTRIBUTION")                00060900
      WRITE(6,5000)                                                    00061000
 5000 FORMAT (/40X,"CUMULATIVE WEIGHT PERCENT",10X,"PARTICLE SIZE"/    00061100
     139X,"LESS THAN STATED PARTICLE SIZE",9X,"(MICRONS)"/)            00061200
 5001 FORMAT(69X,F6.1,22X,F7.3)                                        00061300
      WRITE(6,5001)(CLCW(J),DP(J),J=2,6)                               00061400
      WRITE(6,5001)(CLCW(J),DP(J),J=11,21,5)                           00061500
      WRITE(6,5001)(CLCW(J),DP(J),J=31,81,10)                          00061600
      WRITE(6,5001)(CLCW(J),DP(J),J=86,96,5)                           00061700
      WRITE(6,5001)(CLCW(J),DP(J),J = 97,100)                          00061800
      WRITE(6,1855)                                                    00061900
 1855 FORMAT(/53X,"RINGELMANN NUMBER RANGE")
      WRITE(6,1858)RNMIN,RNMAX                                         00062100
 1858 FORMAT(/57X,F4.1," - ",F4.1)                                     00062200
      WRITE(6,1859)TRANSM                                              00062300
 1859 FORMAT(/49X,"PERCENT LIGHT TRANSMITTED = ",F7.2)
      RETURN                                                           00062500
      END                                                              00062600
```

Figure C-2. Continued. Computer Source Code Listing

APPENDIX D

COMPUTER PROGRAM NOMENCLATURE

A1	=	real part of a_n denominator
A2	=	a_n numerator/A1
A3	=	a_n denominator/A1
AN	=	a_n
AK	=	Stokes' parameter (k) in Calvert's scrubber equations (dimensionless)
AKF	=	AK(f) + 0.7, where f = 0.5
ALG	=	liquid/gas ratio
B	=	intercept of straight-line log-normal equation (in GRAF)
BIMAG	=	i
B1	=	real part of b_n denominator
B2	=	b_n numerator/B1
B3	=	b_n denominator/B1
BJ	=	$J_{\nu-1}/J_\nu$ (with real argument)
BJC	=	$J_{\nu-1}/J_\nu$ (with complex argument)
BN	=	b_n
CC	=	Cunningham correction factor in scrubber equations (dimensionless)
CLCW	=	cum. wt. % in 1% increments
CN	=	n/x
CWDE	=	outlet cummulative wt. % from ESP
CWDS	=	outlet cummulative wt. % from scrubber
CWRD	=	raw cum. wt. % input data

DD	=	scrubber drop size (by Nukiyama-Tanasawa equation), in microns
DHUN		is defined by line 7 of function EINV
DP	=	normalized particle size from subroutine GRAF (in microns)
DPE	=	outlet particle size from ESP (in microns)
DPRD	=	raw particle size data (in microns)
DPS	=	outlet particle size from scrubber (in microns)
DP1	=	average value of DP in interval (microns)
EFF	=	calculated ESP efficiency (%)
EFFS	=	calculated scrubber efficiency (%)
EINV(RCW)	=	inverse normal distribution function (RCW = variable)
ETA		is defined by line 17 of function EINV
ETASQ		is defined by line 16 of EINV
E3	=	1/3
EF2		is defined by line 15 of function EINV
FND	=	FLOAT(NVRD)
G		is defined by line 37 of subroutine ESP
GRAF		is a subroutine that uses the method of least squares to fit the raw particle size distribution data to a straight-line equation
I,IJ,IK,IL		are all counters
ICASE	=	0, when there are no further cases, and = 1 when another set of data cards (i.e. another case) follows
INOGO	=	1 if the electrostatic precipitator, or scrubber, has such a high efficiency that virtually all of the original particle size distribution is collected. Otherwise, it is 0.

IP	=	p (in generating values of w)
IQUIP	=	0, if there is no particle collection device; = 1, if there is an electrostatic precipitator; = 2, if there is a venturi scrubber
ITTLE	=	alphanumeric variable (maximum of 10 letters) corresponding to the case title.
J,JI		are counters
K	=	counter
L	=	$(-1)^{p+1}$ (in generating values of w)
N	=	n (order of Riccati-Bessel functions)
NE	=	number of data pairs for outlet distribution from ESP
NMAX	=	max. value of n
NS	=	number of data pairs for outlet distribution from scrubber
NVRD	=	number of raw data pairs for inlet size distribution
PATH	=	plume width = effective stack diameter (in meters)
PD	=	pressure drop across scrubber (in mm. mercury)
PNX	=	$P_n(x) = \psi_n'(x)/\psi_n(x)$
PNY	=	$P_n(y) = \psi_n'(y)/\psi_n(y)$
PTLN	=	natural log of scrubber penetration
Q	=	$Q_n(x) = \xi_n'(x)/\xi_n(x)$
QEXT	=	extinction coefficient = $\frac{2}{\chi^2}\Sigma(2n+1)\,\mathrm{real}(a_n+b_n)$
QSUM	=	$\Sigma(2n+1)\,\mathrm{real}(a_n+b_n)$
RB1X	=	$\psi_n(x)$
RB2	=	$\beta_n(x)$
RB3	=	$\xi_n(x)$

REFRAC	=	complex refractive index of particle (dimensionless)
RHOP	=	particle density (in g/cc)
RIIM	=	imaginary part of refractive index
RIRL	=	real part of refractive index
RNM	=	calculated Ringelmann number
RNMAX	=	upper estimate of Ringelmann number (=RNM+0.5)
RNMIN	=	lower estimate of RNM
S	=	fractional penetration
SCA	=	specific collection area of ESP (in m^2 per 1000 m^3/min of gas)
SGN		is defined by lines 11 and 14 of EINV
SLOPE	=	slope of straight-line log-normal equation (in GRAF)
STACK		is the subroutine that calculates plume visibility
STEPB	=	$\sum_i \left(\frac{Q_{ext}}{d_p}\right)_i$
SUM	=	% penetration
SUME	=	cumulative wt % penetration for particles of size DPE
SUMS	=	cumulative wt % penetration for particles of size DPS
SUMX	=	ΣX
SUMXY	=	ΣXY
SUMX2	=	$\Sigma(X^2)$
SUMY	=	ΣY
TRANS	=	calculated fractional transmittance = $\exp\left[\left(\frac{-3WD}{2\rho p}\right) \frac{1}{100} \sum_{i=1}^{100} \left(\frac{Q_{ext}}{d_p}\right)_i\right]$

TRANSW = % transmittance

VGT = gas velocity in venturi scrubber throat (in meters/sec)

WD = $|w_p, \ldots, w_2|$, with real arguments

WDC = $|w_p, \ldots, w_2|$, with complex arguments

WI = IMAG(WNC-WDC)

WN = $|w_p, \ldots, w_1|$, with real arguments

WNC = $|w_p, \ldots, w_1|$, with complex arguments

WP = $w_p = (-1)^{p+1} \frac{2(\nu+p-1)}{x}$

WPC = $(-1)^{p+1} \frac{2(\nu+p-1)}{y}$

WR = real (WNC-WDC)

X = EINV(CWRD)

X1 = EINV(CLCW)

X2 = X^2

XLAM = wavelength of light used to view the plume (λ) (in microns)

XV = $\pi dp/\lambda$ (dimensionless)

Y = $\log_{10}$ DPRD

YV = $m\pi dp/\lambda$ (dimensionless)

ZI = particle loading (in mg/m^3)

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