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TI-59 Programmable Calculator Programs for In-stack Opacity, Venturi Scrubbers, and Electrostatic Precipitators

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TI-59 Programmable Calculator Programs for In-stack Opacity, Venturi Scrubbers, and Electrostatic Precipitators

by

S.J. Cowen, D.S. Ensor (Atmospheric Research Group),
and L.E. Sparks

EPA, Particulate Technology Branch
Industrial Environmental Research Laboratory
Research Triangle Park, North Carolina 27711

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U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ABSTRACT

The basic concepts of in-stack opacity as measured by in-stack opacity monitors are explained. Also included are calculator programs that model the performance of venturi scrubbers and electrostatic precipitators. The effect of particulate control devices on in-stack opacity can be predicted by using these programs. The size distribution data input can be either in lognormal or histogram format. The opacity is calculated by using Deirmendjian's approximation to Mie series to obtain extinction efficiencies. Also an alternative opacity program employing the exact Mie series solution is described. The running time for this program is approximately 8 hours while the running time for the approximate program is 30 minutes. The accuracy of these programs is as good as the measured data input.

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SECTION 1

INTRODUCTION

This report has three basic objectives:

1. Provide a handbook for calculating in-stack opacity for particulate control devices on a Texas Instrument, Inc. TI-59 programmable calculator.

2. Describe the latest versions of calculator programs to simulate electrostatic precipitators (ESPs) and scrubbers.

3. Explain the basic concept of in-stack opacity as measured by in-stack opacity monitors.

Developments in calculator technology have allowed mathematical modeling of particle collection in venturi scrubbers and ESPs using a Texas Instrument, Inc., SR-52 programmable calculator as described by Sparks (1978). The development of the more sophisticated TI-59 makes it possible to extend the capabilities of the Sparks' models, especially the ESP model.

Applications of the scientific programmable calculator to gas cleaning technology are further extended in this report to calculations of in-stack opacity. Predicting in-stack opacity is essential for designing control devices to meet strict opacity limitations. The advantages of using a programmable calculator for this purpose are its convenience, inexpensiveness, and simplicity of operation, when compared to a large digital computer.

This report can be viewed as a handbook for calculating in-stack opacity using the output of control device models or as an independent vehicle to compute opacity for given stack conditions.

Calculator programs were developed for a Texas Instrument, Inc., TI-59 programmable calculator with a PC-100A printer. Opacity programs were designed to interface with the ESP and scrubber programs as much as possible. The SR-52 scrubber program was rewritten to conform with the more compact TI-59 coding and to provide data on the outlet particle size distribution. The ESP model is totally new.

Calculator programs are summarized in Table 1. The function of each program, the required data input, and compatible programs are also provided.

The user has a choice of three different in-stack opacity programs (Figure 1), depending upon the type of particle size distribution and particle index of refraction. The opacity calculation procedure for a control device is outlined below. A sample calculation is presented in Section 3.

1. Obtain required data.

2. Select control device.

3. Run control device program.

4. Check output of control device program. If particle size output is in lognormal form, use opacity program No. 1 for lognormal case. If particle size output is a histogram, use opacity program No. 2 for histogram case. Use opacity program No. 5 if the index of refraction is not in following ranges:

   $1.0 \leq$ real part ≤ 1.5

   $0.0 \leq$ imaginary part ≤ 0.25.

   The best lognormal fit of size data is required for this program.

5. Check opacity results:

   a. If opacity is too high, increase the specific collection area (SCA) for ESP or increase the pressure drop (ΔP) for scrubber.

   b. If opacity is too low, decrease SCA for ESP or decrease ΔP for scrubber.

The approximate opacity programs require that the index of refraction be in the ranges 1.0 to 1.5 for the real part and 0.0 to 0.25 for the imaginary part. The long opacity calculation, which is valid for any index of

TABLE 1. CALCULATOR PROGRAM SUMMARY

Program	Calculation	Input required	Can be used with:
1. Approximate Opacity (lognormal)	In-stack opacity on lognormal particle size distribution	Stack diameter, mass concentration, density, index of refraction, wavelength, geometric mass mean diameter, geometric standard deviation	ESP, Scrubber Program with lognormal distribution
2. Approximate Opacity (histogram)	In-stack opacity on histogram particle size distribution	Stack diameter, mass concentration, density, index of refraction, wavelength histogram distribution (mass fractions at particle diameter)	ESP, Scrubber Program with histogram distribution
3. Extinction Efficiency Approximation	Approximates light extinction efficiency for spherical particles	Particle diameter, index of refraction, wavelength	- -
4. Long Extinction Efficiency	Exact light extinction efficiency for spherical particles	Particle diameter, index of refraction, wavelength	- -
5. Long Opacity (lognormal)	In-stack opacity on lognormal distribution	Same as for Program 1, above	ESP, Scrubber Program with histogram distribution
6. Electrostatic Precipitator (histogram)	Penetration in ESP for each particle size and overall penetration outlet concentration for each particle size	Particle diameter, time increments, wire to plate spacing, applied voltage, ion speed, ion mobility, current density, dialectic instant, temperature, viscosity, pressure, specific collection area, precipitation length, gas velocity, normalized standard deviation, gas flow, number of sections, sneakage, fraction of sneakage, histogram particle size distribution	Opacity Program with histogram distribution, or lognormal distribution
7. Scrubber (histogram)	Penetration and outlet concentration of scrubber for each particle size. Overall penetration	Temperature, pressure factor of ~ (0.5), no. of particle diameters, liquid to gas ratio, gas velocity, viscosity, liquid density, particle density	Opacity Program with histogram distribution or lognormal distribution

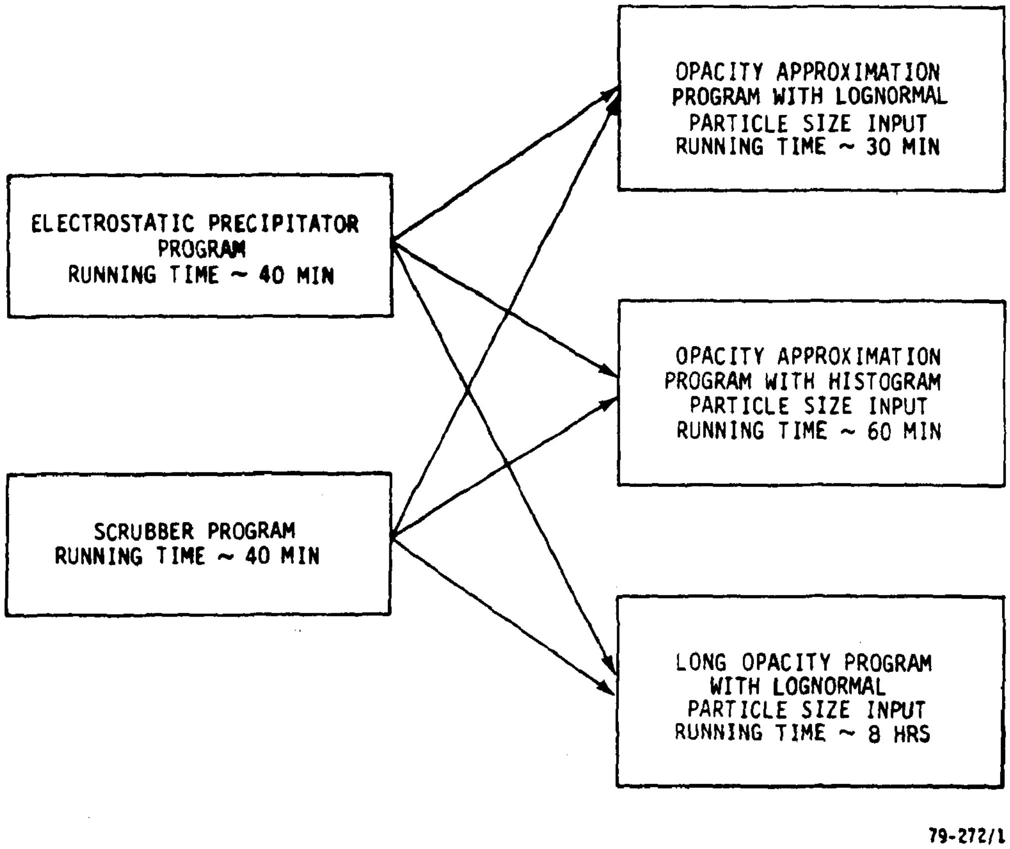

Figure 1. Relationship between control device programs and opacity programs.

refraction, requires a running time of approximately 8 hours. The approximation programs run 30 minutes for the lognormal particle size input and 60 minutes for the histogram particle size input. The error generated by these programs ranges from 5 to 20 percent depending upon particle size distribution. These programs are generally as accurate as the input data; i.e., the errors introduced by the programs are generally less than the errors in the input data. A large digital computer is unlikely to provide better answers unless the input data are essentially free of error.

SECTION 2

CONCLUSION

The calculator programs presented provide a convenient, useful prediction of (1) in-stack opacity, and (2) the influence of venturi scrubbers and ESPs in controlling in-stack opacity. The advantages of these programs include savings of time, money, and effort.

The analysis of both the calculation of in-stack opacity and measurement of opacity parameters shows that error in the calculator programs is less than the measurement error of approximately 20 percent. The ability to predict in-stack opacity depends on the quality of measurement methods, especially particle size.

A major restriction in using the approximate opacity programs is the exclusion of highly absorptive aerosols. The long opacity program is especially designed to predict opacity for highly absorptive aerosols with lognormal distributions. If the size distribution is not lognormal, then either a computer should be used or a lognormal approximation should be made. A major restriction in using the lognormal size input is that the geometric standard deviation of the size distribution should be greater than or equal to 1.009.

SECTION 3

OPACITY AND CONTROL DEVICE PROGRAM INTERACTION

This section is an example of the procedure used to calculate the effect of a particulate control device on in-stack opacity. Since individual programs are detailed in later sections, only information regarding general operation is covered here.

The following problem illustrates the relationship between the opacity and control device programs.

ESP DESIGN FOR OPACITY CONTROL

Suppose the objective is meeting an opacity limitation of 3 percent on a coal-fired utility boiler. The best way to reach this objective may be to use an ESP as the control device. The following information is required to compute the required specific collection area for the ESP:

Inlet grain loading - 3.5 g/m^3

Remember, all mass concentrations and volumetric flows for this report are at actual, not standard, conditions.

Inlet particle size distribution -

Particle Diameter, μm		Mass Fraction	
0.2	Register 25	0.0001	Register 41
0.5	Register 26	0.002	Register 42
0.8	Register 27	0.004	Register 43
1.5	Register 28	0.02	Register 44
2.5	Register 29	0.15	Register 45
4.0	Register 30	0.25	Register 46
8.0	Register 31	0.35	Register 47
10.0	Register 32	0.4	Register 48
12.0	Register 33	0.3	Register 49

Stack diameter = 7 m
Particle refractive index = 1.5 - 0.002i
Particle density = 2.5 g/cm^3
ESP wire-to-plate spacing = 0.1143 m
Applied voltage = 30 kV
Ion speed = 528 m/sec
Ion mobility = 3×10^{-4} m^2/V-sec
Resistivity = 6.71×10^{10} ohm - cm
Current density = 1.3×10^{-4} A/m^2 (calculated from resistivity)
Dielectric constant = 100
Temperature = 150°C
Viscosity = 2.3×10^{-4} poise
Pressure = 76 cm Hg
Precipitator length = 8 m
Gas velocity = 1.25 m/sec
Normalized standard deviation of gas flow = 0.25
Number of sections for sneakage = 4
Sneakage fraction = 0.1

CALCULATION PROCEDURE

1. Estimate SCA to meet desired opacity.
2. Since particle size distribution is in the histogram format, run corresponding ESP program.
3. Obtain outlet size distribution and total mass concentration.
4. Check to determine if size distribution is lognormal.
5. If size distribution is lognormal, use lognormal opacity program. Otherwise, use histogram opacity program.
6. Compare computed opacity with desired opacity. If computed opacity value is too high, use larger SCA for the ESP program. If computed opacity value is too low, use smaller SCA.
7. Run ESP program with revised SCA.
8. Obtain new outlet size distribution and total mass concentration.
9. Use same opacity program from Step 5.
10. Compute new opacity.

Repeat Steps 6 through 10 until calculated opacity approximates design opacity.

SAMPLE CALCULATION

1. Let SCA = 160 m^2/m^3/sec.

2. Run histogram ESP program (program No. 6).

   a. Turn on calculator.

   b. Push 1; enter side one of card 1. Push 2; enter side two.

   c. Push A to enter following data.

   d. Follow calculator prompting. Enter data; push R/S after each entry.

The following is the printing of data entry.

Calculator Prompting	Data to be Entered	
ESP ID	1.	ESP identification
NP	9.	Number of particle diameters
NN	5.	Number of time increments (5-10)
H	0.1143	Wire-to-plate spacing, m
U	3. 04*	Applied voltage, kV
	2.6246719 05 EA	Average field
	1.4998125 05 EP	Field at plate, V/m
V	5.28 02	Ion speed, m/sec
B	3. -04	Ion mobility, m^2/V-sec
J	1.3-04	Current density, A/m^2
	1.031875 13 NO	Ion density, number/cm^3
K	100.	Dielectric constant
T	150.	Temperature, °C
VIS	2.3-04	Viscosity, poise
P	76.	Pressure, cm Hg
SCA	160.	m^2/m^3/sec

* The calculator printout: 3.04 = 3 x 10^4. Press 3 EE 4 +/-.

LENGTH	8.	Length of ESP, m
VEL	1.25	Gas velocity, m/s
SIGMA	0.25	Normalized standard deviation of gas flow
NS	4.	Number of sections for sneakage
S	0.1	Sneakage fraction

Store particle diameters from page 7 in Registers 25-33.

e. Push Trace

f. Enter smallest diameter and push STO 25.

g. Enter next larger diameter, push STO 26, etc.

Store corresponding mass fractions from page 7 in Registers 41-49.

h. Enter mass fraction corresponding to smallest diameter and by pushing STO 41, etc.

Store data on a magnetic card for future use.

i. Push 3, 2nd, write; enter side one of magnetic card labelled data card.

j. Push 4, 2nd, write; enter side two of magnetic card labelled data card.

Inactivate trace mode.

Run card 2 of program No. 6.

k. Push 1; enter side one of card 2. Push 2; enter side two.

l. Push A.

The following output is printed:

2. -01	=D	Particle diameter, µm
6.4 00		Residence time, sec
7.9718505-09		Ideal penetration x mass fraction (Pt(d) x f_i)
7.9718505-05		Ideal penetration (Pt(d))
5.8981305-02		Ideal migration velocity (W(d))
4.3768619-03		Corrected penetration (Pt(d))
4.3768619-07		Corrected penetration x mass fraction (Pt(d) x f_i)

```
      5. -01     =D
    6.4 00

8.7470295-07
4.3735147-04
4.8342334-02
7.7912055-03
1.5582611-05

      8. -01     =D
    6.4 00

1.4282314-06
3.5705784-04
 4.961008-02
7.2059689-03
2.8823875-05
```

Particle diameter, μm
Residence time, sec

Ideal Pt(d) x f_i
Ideal Pt(d)
Ideal W(d)
Corrected Pt(d)
Corrected Pt(d) x f_i

```
    1.5 00     =D
    6.4 00

2.2571985-06
1.1285992-04
5.6808519-02
 4.853973-03
 9.707946-05

    2.5 00     =D
    6.4 00

 3.252111-06
 2.168074-05
6.7119289-02
3.1595545-03
4.7393318-04

     4. 00     =D
    6.4 00

6.9826971-07
2.7930788-06
7.9927288-02
2.2569389-03
5.6423473-04
```

8. 00	=D	
6.4 00		
1.9540703-10		
5.5830579-10		
1.3316321-01		
5.5830579-10		
1.9540703-10		
1. 01	=D	**Particle diameter, μm**
6.4 00		**Residence time, sec**
2.0348601-12		**Ideal Pt(d) x f_i**
5.0871501-12		**Ideal Pt(d)**
1.625269-01		**Ideal W(d)**
5.0871501-12		**Corrected Pt(d)**
2.0348601-12		**Corrected Pt(d) x f_i**
1.2 01	=D	
6.4 00		
1.398674-14		
4.6622467-14		
1.9185434-01		
4.6622467-14		
1.398674-14		
8.5186828-06		**Ideal overall penetration**
1.1800917-03		**Corrected overall penetration**

3. The outlet size distribution is found by using particle diameter and the corrected penetration times the mass fraction (Pt(d) x f_i).

Summarizing these values:

D	Outlet f_i
0.2	4.377×10^{-7}
0.5	1.558×10^{-5}
0.8	2.882×10^{-5}
1.5	9.708×10^{-5}
2.5	4.74×10^{-4}
4.0	5.64×10^{-4}
8.0	1.95×10^{-10}
10.0	2.03×10^{-12}
12.0	1.40×10^{-14}

4. Check to determine if this size distribution is lognormal. First change distribution to cumulative distribution and normalize.

The following results are obtained:

D	Cumulative Outlet f_i	Normalized %
0.2	4.377×10^{-7}	0.037
0.5	1.602×10^{-5}	1.36
0.8	4.484×10^{-5}	3.8
1.5	1.419×10^{-4}	12.03
2.5	6.159×10^{-4}	52.19
4.0	1.180×10^{-3}	100.00
8.0	1.180×10^{-3}	100.00
10.0	1.180×10^{-3}	100.00
12.0	1.180×10^{-3}	100.00

Plot the results on log-probability paper. If the plot is a straight line, use the lognormal opacity program. If not, use the histogram opacity program.

5. In this case, a lognormal distribution is not found (Figure 2).

6. Run histogram opacity program No. 2 using outlet size distribution obtained from ESP program. Do not use cumulative distribution. Since D_{50}'s are used to input particle diameters, the mass fraction f_{i+1} corresponds to D_i of D_{50}.

   a. Enter card 1; Push 1; enter side one.

   b. Push A to enter data.

Enter the following data, pressing R/S after each entry.

```
ND50
           9.      Number of particle diameters
 D50
          0.2  ┐
 D50           │
          0.5  │
 D50           │
          0.8  │
 D50           │
          1.5  │
 D50           │
          2.5  ├   Particle diameters, μm
 D50           │
           4.  │
 D50           │
           8.  │
 D50           │
          10.  │
 D50           │
          12.  ┘
```

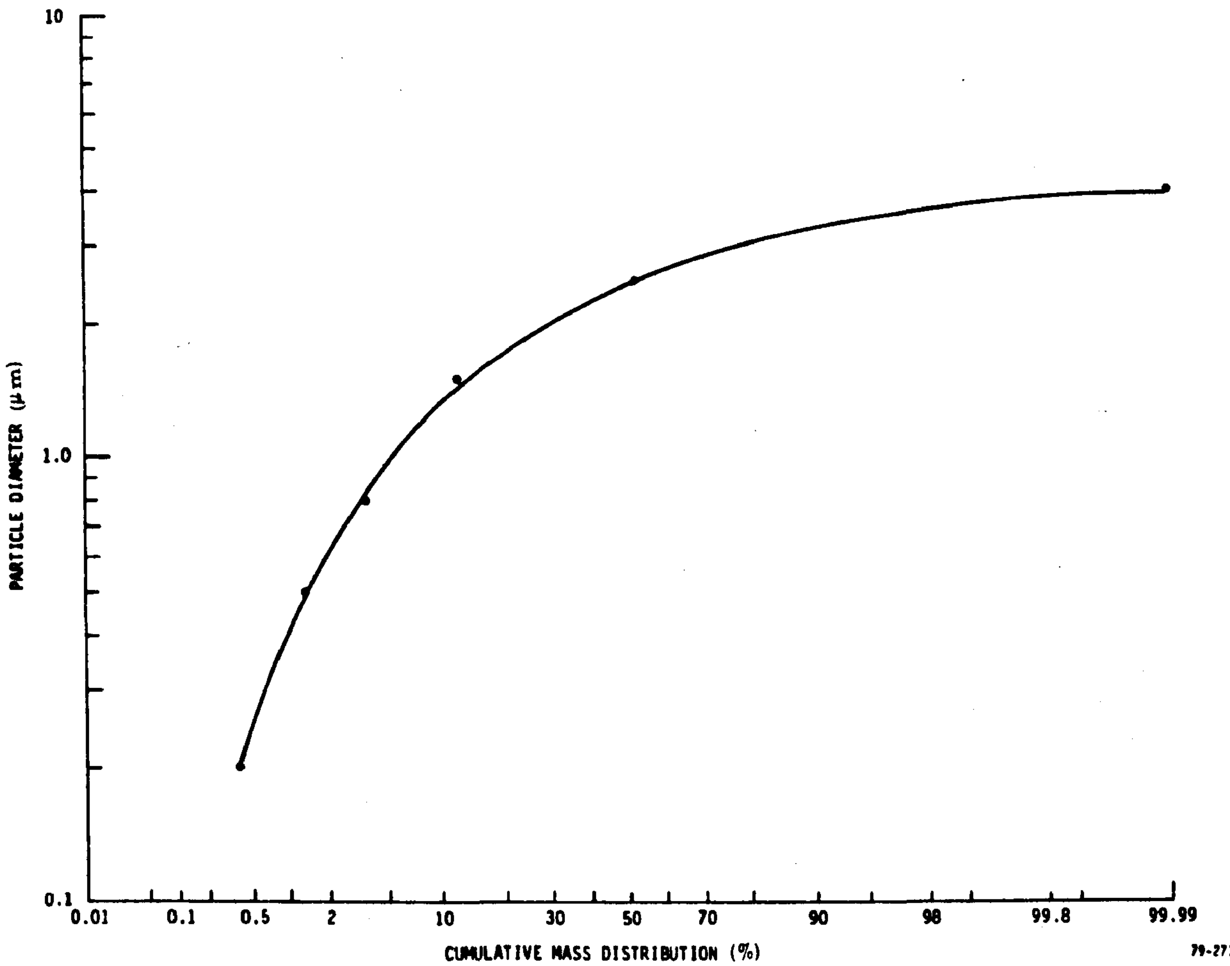

Figure 2. Cumulative particle size distribution plotted on log-probability graph paper.

```
F
    1.558-05
F
    2.882-05
F
    9.708-05
F
     4.74-04
F
     5.64-04      Corresponding mass
F                 fraction
     1.95-10
F
     2.03-12
F
      1.4-14
F
      0.  00
```

c. Enter card 2 by pushing 1; enter side one. Push 2, enter side two.

d. Enter card 3 by pushing A (partition automatically set) Push 3, enter side one of card 3. Push R/S to start data entry. Enter data, pressing R/S after each entry.

This step requires approximately 30 minutes after 0.55 is entered.

```
NEXT CARD
  A
        1.5                 Real part of index of refraction
  B
      0.002                 Imaginary part of index of refraction
  W
       0.55                 Wavelength, µm
2.618259363      =SP        Specific extinction coefficient, cm²/m³
NXT1
```

e. Enter card 4 by pushing 1; enter side one. Push A to start data entry. Enter data, pressing R/S after each entry:

```
MASS?
     0.00413                Inlet mass concentration
STACK DIAMETER?             x overall penetration, g/m³
            7.
DENSITY?
          2.4
 3.104694577     =OP%
```

The predicted opacity is within 3 percent of desired opacity so that further iterations are not required. However, another iteration is presented for purposes of illustration.

6. Change to standard calculator partition by pushing 6, 2nd, Op, 17.

   a. Enter card 2 of program No. 6 by pushing 1; enter side one. Push 2; enter side two.

   b. Enter magnetic card with ESP data stored during Step 2f by pushing 3; enter side one of data card. Push 4; enter side two.

   c. Press D.

   d. Press R/S after each entry.

7. Try SCA equal to 162 $m^2/m^3/sec$

SCA			
	162. $m^2/m^3/sec$		
NP			**Number of particle diameters**
	9.		
	0.2	=D	**Particle diameter, μm**
	6.4		**Residence time, sec**
	7.084817-09		**Ideal Pt(d) x f_i**
	7.084817-05		**Ideal PT(d)**
	5.8981305-02		**Ideal W(d)**
	4.2327131-03		**Corrected Pt(d)**
	4.2327131-07		**Corrected Pt(d) x f_i**

5. -01 =D
6.4 00

7.9409228-07
3.9704614-04
4.8342334-02
7.5041802-03
1.500836-05

8. -01 =D
6.4 00

1.2933254-06
3.2333134-04
4.961008-02
6.942388-03
2.7769552-05

1.5 00 =D
6.4 00

2.0147747-06
1.0073874-04
5.6808519-02
4.6888805-03
9.377761-05

2.5 00 =D
6.4 00

2.8435855-06
1.8957236-05
6.7119289-02
3.0713322-03
4.6069982-04

4. 00	=D	Particle diameter, μm
6.4 00		Residence time, sec
5.9511273-07		Ideal Pt(d) x f_i
2.3804509-06		Ideal Pt(d)
7.9927288-02		Ideal W(d)
2.2159553-03		Corrected Pt(d)
5.5398883-04		Corrected Pt(d) x f_i
8. 00	=D	
6.4 00		
1.4971871-10		
4.2776774-10		
1.3316321-01		
4.2776774-10		
1.4971871-10		
1. 01	=D	
6.4 00		
1.2863926-12		
3.6754074-12		
1.625269-01		
3.6754074-12		
1.2863926-12		
1.2 01	=D	
6.4 00		
9.5295842-15		
3.1765281-14		
1.9185434-01		
3.1765281-14		
9.5295842-15		
7.5481264-06		Ideal overall penetration
1.1516676-03		Corrected overall penetration

8. The new outlet size distribution is summarized as follows:

D	f_i
0.2	4.23×10^{-7}
0.5	1.5×10^{-5}
0.8	2.78×10^{-5}
1.5	9.38×10^{-5}
2.5	4.61×10^{-4}
4.0	5.54×10^{-4}
8.0	1.5×10^{-10}
10.0	1.29×10^{-12}
12.0	9.53×10^{-15}

The outlet mass concentration = inlet mass concentration x overall penetration

$= (3.5\ g/m^3) \times 0.00115 = 0.004025$

9. Use histogram opacity program No. 2.
The output is as follows:

a. Enter card 1 by pushing 1; enter side one. Push A to enter data, pressing R/S after each entry.

ND50	9.	Number of particle diameters
D50	0.2	Particle diameters, μm
D50	0.5	
D50	0.8	
D50	1.5	
D50	2.5	
D50	4.	
D50	8.	
D50	10.	
D50	12.	

```
F
      1.5-05
F
     2.78-05
F
     9.38-05
F
     4.61-04
F
     5.54-04
F
      1.5-10
F
     1.29-12
F
     9.53-15
F
       0.  00
```

(The F values above: Corresponding mass fraction)

b. Enter card 2 by pushing 1; enter side one. Push 2; enter side two.

c. Enter card 3 by pushing A. Push 3, enter side one of card 3. Push R/S to start data entry. Push R/S after each entry.

NEXT CARD		
A		
1.5		Real part of index of refraction
B		
0.002		Imaginary part of index of refraction
W		
0.55		Wavelength
2.614291852	=SP	Specific extinction coefficient
NXT1		

d. Enter card 4 by pushing 1; enter side one. Push A to start data entry, pressing R/S after each entry.

MASS?		
0.004025		Inlet mass concentration x overall penetration, g/m^3
STACK DIAMETER?		
7.		
DENSITY?		
2.4		
3.022451889	=OP%	

The opacity limitation is 3 percent compared to the opacity using an SCA of 162 $m^3/m^3/sec$, which is 3.02 percent. Further iterations could be performed to obtain closer results by further increasing the SCA.

The individual opacity, scrubber, and ESP programs (including their operation and formulations) are described in Sections 5 and 6.

SECTION 4

IN-STACK OPACITY

BACKGROUND

In-stack opacity refers only to opacity (1-transmittance) as measured by transmissometers in a stack. Out-of-stack plume opacity is much more complex and is beyond the scope of this work. An out-of-stack opacity measurement by observation requires understanding the effect of background contrast, light scattering angles, and gas-to-particle conversion of condensable material, such as SO_3. Out-of-stack opacity can also be measured by instrumental techniques such as LIDAR and photometry which are less sensitive to environmental factors than observers. When condensables are present, plume opacity may be much greater than the in-stack opacity, because more light is scattered by increased aerosol concentration.

In-stack opacity does not require the out-of-stack opacity parameters to be characterized. In-stack opacity results from almost totally forward light scattering and light absorption removing light from an incident beam. At scattering angles less than 40°, the difference in particle scattering between spherical and irregularly shaped particles is negligible. Thus particle shape is not a factor in in-stack opacity. Also the problems of background contrast and condensables do not apply to in-stack opacity.

DEFINITION

In-stack opacity is defined as 1 minus the transmittance of light using the stack diameter as the path length. It is an accurate way to characterize plume opacity allowing more objective regulatory control. For many years, the visual appearance of plumes has been used to enforce emission from sources using the Ringelmann scale. Over the last 25 years standard smoke sources have been used, permitting training of inspectors to associate the plume-to-background contrast for given conditions to an in-stack transmittance. In-stack opacity as a supplement to human observers was given legal sanction by the 1971 New Source Performance Standards requiring in-stack transmissometers as continuous monitors.

THEORETICAL SUMMARY

The transmission of light through a volume containing an aerosol is described by the Beer-Lambert law:

$$\text{Opacity} = 1 - \text{transmittance} = 1 - I/I_o = 1 - \exp(-B_E L)$$

where

- I is transmitted light
- I_o is incident light
- B_E is the light extinction coefficient
- L is the illumination path length (generally stack diameter for our case).

Ensor and Pilat (1971) have shown that the aerosol mass concentration is related to optical transmittance through a modified form of the Beer-Lambert law:

$$\frac{I}{I_o} = \exp \frac{-ML\,Sp}{\rho} \qquad (1)$$

where

- M is the particle mass concentration
- Sp is the ratio of the light extinction coefficient to specific particulate volume (m^2/cm^3)
- ρ is the average particle density

The specific extinction coefficient Sp is defined mathematically as

$$Sp = \frac{\frac{3}{2}\int_0^\infty d_p^{\,2} Q(d_p, \lambda, m) n(d_p) d\, d_p}{\int_0^\infty d_p^{\,3} n(d_p) d\, d_p} \qquad (2)$$

where

d_p is the particle diameter

$Q(d_p, \lambda, m)$ is the light extinction efficiency factor

λ is the wavelength of incident light

m is the aerosol index of refraction

$n(d_p)$ is the number of particle size distribution.

Thus, Sp is defined for a given particle size distribution, particle index of refraction, and wavelength of incident light, and is the indicator of light extinction properties of the aerosol mass.

The light extinction efficiency $Q(d_p, \lambda, m)$ is calculated by using Mie equation for the particle size ranges associated with particulate control devices (0.01 to 40 μm diameters). Expressions for the scattering and extinction efficiencies are obtained by solving Maxwell's equations for the interaction of a plane wave with a homogeneous sphere. The complete derivation is explained by Born and Wolf (1959). The solutions were adapted by Deirmendjian (1969) to computational forms and are easily programmed on the TI-59 calculator. (See Section 5, Mie theory extinction efficiency calculation.) However, the size of this program and numerous iterations result in a very slow calculation of Sp. Fortunately, a good approximation of the Mie series calculation was developed empirically by Deirmendjian based on theoretical work by van de Hulst (1957). (See Section 5, extinction efficiency approximation.) This approximation is used with a Simpson's Rule integration to obtain Sp with the TI-59 calculator. The programs were developed for handling lognormal size distribution data or incremental size data. Using the approximation requires less than an hour to obtain the calculation.

In-stack opacity is calculated by summarizing the above formulations as follows:

$$\text{Opacity (\%)} = \left[1 - \exp -\left(\frac{Sp\ ML}{\rho}\right)\right] \times 100 \qquad (3)$$

This assumes a constant particle density and index of refraction. Generally a wavelength of incident light of 0.55 μm is used as representative of the maximum photopic response of the human eye.

SECTION 5

DESCRIPTION OF TI-59 OPACITY PROGRAMS

PROGRAM NO. 1: APPROXIMATE OPACITY PROGRAM WITH LOGNORMAL SIZE DISTRIBUTION INPUT

This program computes in-stack opacity for an aerosol mass with a lognormal particle size distribution. The lognormal size distribution is

$$n(d_p) = \frac{1}{\sqrt{2\pi}\,\ell n\sigma_g d_p} \exp \frac{-\ell n^2 (d_p/d_g)}{2\ell n^2 \sigma_g} \qquad (4)$$

where

d_p is the particle diameter

σ_g is the geometric standard deviation

d_g is the geometric mass mean diameter.

It is important that the geometric mass mean diameter be converted to the number mean diameter since the number distribution is required for the integration. This function is substituted into the integral to calculate the specific extinction coefficient (Sp), and the Simpson's Rule (continuous) approximation is applied to obtain the two integral solutions. The integration program is provided by the master library module for all integrations in this report. The extinction efficiency is calculated using Deirmendjian's approximation of the Mie series.

This program can be divided into four basic operations.

1. Data entry
2. 1st Integration $= \int_{d_i}^{d_n} d_p^{\,3}\, n(d_p)\, d\, d_p$
3. 2nd Integration $= \int_{d_i}^{d_n} d_p^{\,2} Q\; n(d_p)\, d\, d_p$
4. Calculation of opacity and specific extinction coefficient

Each integral above is calculated twice at two ranges of particle diameters:

1. $\int_{0.02}^{4} \Delta d = 0.199$
2. $\int_{4}^{40} \Delta d = 1.8$

The two ranges are used to save calculation time and increase accuracy of the program.

Program Operation

Two magnetic cards are required for operation:

1. Enter cards 1 and 2.
   a. Push 1; enter side one of card 1.
   b. Push 2; enter side two of card 1.
   c. Push A; (sets calculator partition).
   d. Push 3; enter side one of card 2.
2. Enter data in following order:

   Push R/S to start data entry. Push R/S after each entry.

Data	Register
σ_g - (SIGMA) geometric standard deviation	08
DG - mass mean particle diameter, μ m	-
M - particle mass concentration, g/m^3	26
S - stack diameter, m	27
DEN - particle density, g/cm^3	28
W - wavelength of incident light, μ m	20
A - real part of refractive index	12
B - imaginary part of refractive index (positive)	13

Results

Directly following printout of B, the following is listed automatically:

1. Increment size (particle radius) of 1st integration
2. O. SD means end of 1st integration at lower range
3. Increment size (particle radius) of 1st integration at upper range
4. Increment size (particle radius) of 2nd integration at lower range
5. O. SD means end of 2nd integration at lower range
6. Increment size (particle radius) of 2nd integration at upper range
7. Sp = specific extinction coefficient
8. OP (%) = in-stack opacity

Sample Calculation

Given: Standard deviation = 2
Mass mean diameter = 1 μm
Wavelength of light = 0.55 μ m
Real part of refractive index = 1.5
Imaginary part of refractive index = 0
Mass concentration = 0.01 g/m^3
Particle density = 2.4 g/cm^3
Stack diameter = 6.9 m

Solutions:

Procedure	Enter	Press	Enter	Display	Print
1. Enter card 1		1	Side 1	1	
2. Enter card 1		2	Side 2	2 719.29	
3. Enter card 2		A, 3	Side 3	3	
4. Enter data		R/S		3624223013	SIGMA σ
	σ_g (2)	R/S		2 1622	2 DG
	DG (1.0)	R/S		1.0 17	1.0 M
	M (0.01)	R/S		0.01 37	0.01 S
	S (6.9)	R/S		6.9 161731	6.9 DEN
	DEN (2.4)	R/S		2.4 43	2.4 W
	W (0.55)	R/S		0.55 13	0.55 A
	A (1.5)	R/S		1.5 14	1.5 B
	B (0)	R/S		0	0
					0.0995 0 SD 0.0995 0.9 0 SD 0.9
				4.821892388	= Sp
				12.94494106	= OP %

Summary : Sp = 4.82
In-stack opacity = 12.9 %

Uses

This program can be used to estimate in-stack opacity for a given facility. It can also be used with control device model programs to estimate the design parameters required to meet an opacity limitation. See Sparks (1979) for an example of this use. The effect on particle size distribution on the specific extinction coefficient and opacity can be examined by varying the value of particle size distribution σ_g and d_g. Also, the effect on opacity of variables such as particle density, stack diameter, and mass grain loading can be examined for a given size distribution.

Another use of the approximate opacity program is to determine the opacity for bimodal lognormal size distributions. The steps for this calculation are:

1. Determine the specific extinction coefficient Sp for each mode, using standard program operation.

2. Clear calculator display.

3. Sum these specific extinction coefficients.

4. Enter the sum from Step 2.

5. Push subroutine 607.

The printed result will show new specific extinction coefficient Sp and in-stack opacity (OP %).

<u>Sample Calculation</u>

Given:

A bimodal distribution
Mode No. 1 standard deviation = 1.5, mass mean diameter = 0.15 μm
Mode No. 2 standard deviation = 3, mass mean diameter = 5.0 μm
Wavelength of light = 0.55 μm
Real part of refraction index = 1.5
Imaginary part of refractive index = 0.0001
Mass concentration = 0.01 g/m^3
Particle density = 2.4 g/cm^3
Stack diameter = 6.9 m

Solution

Procedure	Enter	Press	Enter	Display	Print
1. Enter card 1		1	Side 1	1	
2. Enter card 1		2	Side 2	2	
		A		719.29	
3. Enter card 2		3	Side 3	3	
4. Enter data Mode No. 1		R/S		3624223013	SIGMA
	σ_g (1.5)	R/S	1.5	1.5	1.5
				1622	DG
	DG (0.15)	R/S	0.15	0.15	0.15
				17	M
	M (0.01)	R/S	0.01	0.01	0.01
				37	S
	S (6.9)	R/S	6.9	6.9	6.9
				161731	DEN
	DEN (2.4)	R/S	2.4	2.4	2.4
				43	W
	W (0.55)	R/S	0.55	0.55	0.55
				13	A
	A (1.5)	R/S	1.5	1.5	1.5
					B
	B (0.0001)	R/S	0.0001	0.0001	0.0001
					0.0995
					0 SD
					0.0995
					0.9
					0. SD
					0.9
				3.55483634 = Sp	
				9.715243089 = OP %	
5. Enter data Mode No. 2		A		719.29	
		R/S		3624223013	SIGMA
	σ_g (3)	R/S	3	3.0	3.0
				1622	DG
	DG (5)	R/S	5	5.0	5.0
				17	M
	M (0.01)	R/S	0.01	0.01	0.01
				37	S
	S (6.9)	R/S	6.9	6.9	6.9
				161731	DEN

Procedure	Enter	Press	Enter	Display	Print
	DEN (2.4)	R/S	2.4	2.4	2.4
				43	W
	W (0.55)	R/S	0.55	0.55	0.55
				13	A
	A (1.5)	R/S	1.5	1.5	1.5
				14	B
	B (0.0001)	R/S	0.0001	0.0001	0.0001
					0.0995
					0 SD
					0.0995
					0.9
					0 SD
					0.9
				1.335841986	= Sp
				3.767731879	= OP %
6. Enter sum of SP					
	.Sp (4.89)	SBR 607			4.89 = Sp
				13.11523626	= OP%

Lognormal Program Caution

This program will produce incorrect results for standard deviation approaching 1.0; i.e., monodisperse aerosols. This logarithm equals zero, and the subsequent division by zero is an undefined operation. The limit for the standard deviation depends upon the geometric mean and the range of particle diameters. Generally, standard deviations greater than 1.009 should provide correct calculations. A flashing display indicates error; however, this is not a serious problem because aerosols found in smoke stacks are not monodisperse.

PROGRAM NO. 2: APPROXIMATE OPACITY PROGRAM WITH HISTOGRAM SIZE DISTRIBUTION INPUT

This program uses the opacity formulation in Section 3 with histogram size data input. Light extinction efficiency is calculated with Deirmendjian's approximation. The advantage of this program is that it allows opacity calculation for aerosol masses with size distributions not conforming to log-normal size distributions. The program is especially designed to handle cascade impactor data, although any size distribution data in histogram form can be used.

The following manipulations of size distribution are performed:

1. Calculation of the geometric mean diameter X_i

$$X_i = \sqrt{D_{50_{i+1}} \cdot D_{50_i}} \tag{5}$$

where D_{50} is the impactor diameter cut point; i.e., the diameter of particles collected with 50 percent efficiency on that stage

2. Calculation of differential mass distribution Y_i

$$Y_i = \frac{f_i}{\log\left(\frac{D_{50_{i+1}}}{D_{50_i}}\right)} \tag{6}$$

where f_i is the fractional mass loading on impactor stage with cut point D_{50_i}

The values of interpolated points for integration are derived by linear analysis (Figure 3). Points outside the range of experimental values are assumed to reside on a linear extension of the boundary lines as shown by the dashed lines. Negative values of the differential mass distribution do not have physical meaning and are set equal to zero.

This method of finite difference differentiation, although a crude approximation, is the best technique for this program, especially considering the limited number of available program steps. This method also allows a maximum of 10 D_{50}'s to be used, so that the data from a low pressure impactor with 10 stages can be used. The error in this program, generated partly by the finite difference differentiation, is similar to that produced by the lognormal opacity program.

The differential mass distribution is converted to the differential number distribution before the continuous Simpson's Rule integration is applied. The integrals solved in this program are identical to those contained in the lognormal opacity program. This program can also be divided into four basic operations:

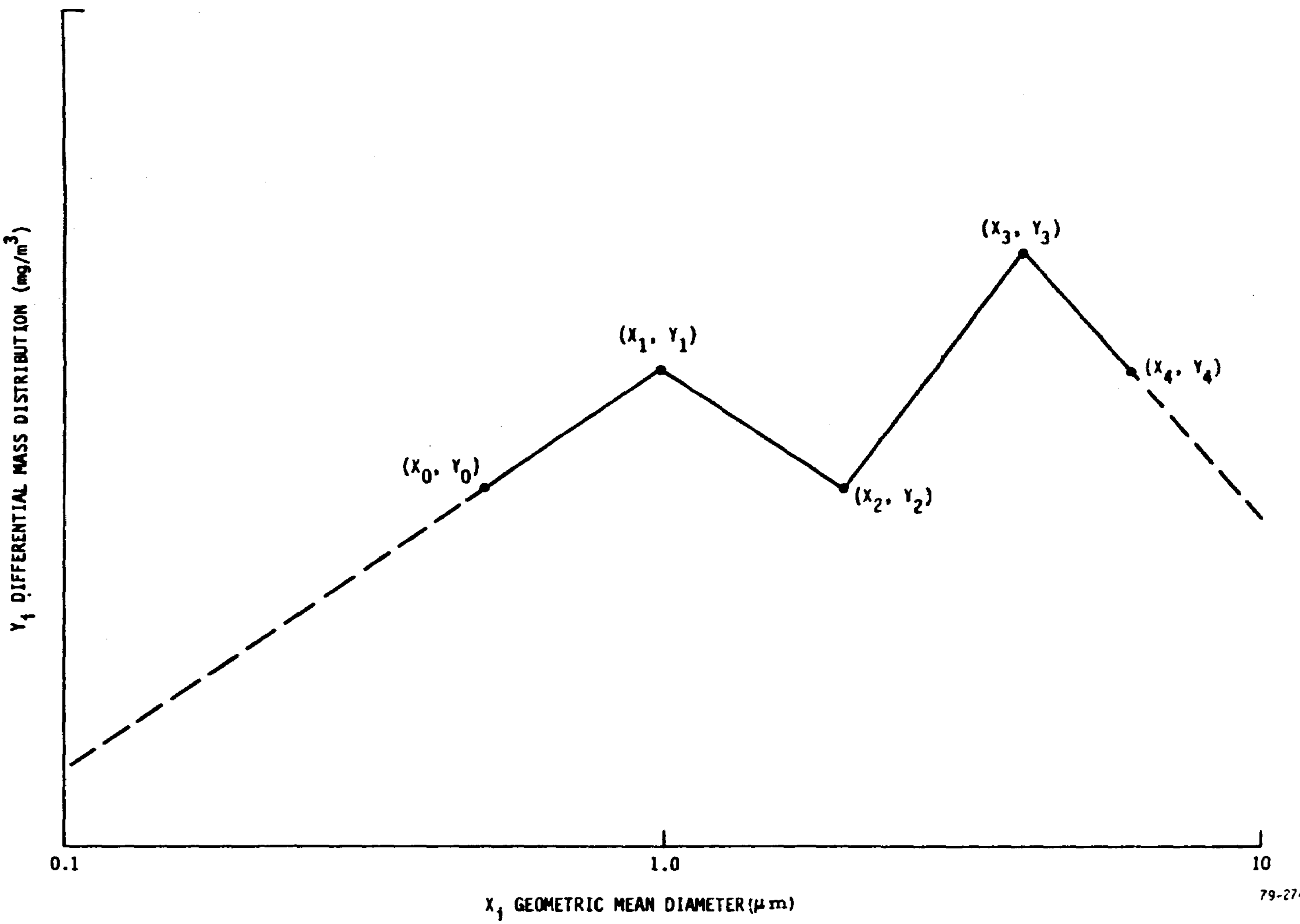

Figure 3. Particle size interpolation procedure used in opacity program.

1. Data entry

2. 1st integration = $\int_{d_i}^{d_n} d_p^{\,2} Q\, n(d_p) d\, d_p$

3. 2nd integration = $\int_{d_i}^{d_n} d_p^{\,3}\, n(d_p) d\, d_p$

Each of these integrations is performed twice at particle diameter ranges, 0.02 to 2.0 and 2.0 to 40.

4. Calculation of opacity and specific extinction coefficient

Program Operation

Card 1 is used to input the number of D_{50}'s (N D50), the D_{50}'s, and the mass fraction f_i in the range D_{50_i} to $D_{50_{i+1}}$. These D_{50}'s are entered starting with the smallest size cutoff. This part of the program computes the geometric mean diameter (X_i) and the differential mass distribution (Y_i):

Enter card 1.

a. Push 1, enter side one of card 1.

b. Push R/S after each entry that will be printed.

ND 50 = number of particle diameter cut points.

D 50 = particle diameter cut point (μm) starting with smallest diameter. (Repeat this step for each particle diameter cut point.)

F = mass fraction in the range D_{50_i} to $D_{50_{i+1}}$. (Repeat this step for the same number of points.)

NEXT CARD = indicates end of this part of program. Proceed to next card.

Cards 2 and 3 are used to compute the integrations. The extinction efficiency using Deirmendjian's approximation is computed for each particle diameter. As described earlier, a linear interpolation of the differential mass distribution is made for each increment of integration. The differential mass distribution must be converted to the differential number distribution for each increment of integration:

1. Enter cards 2 and 3.

   a. Push 1, enter side 1 of card 2.

   b. Push 2, enter side 2 of card 2.

   c. Push A to set partition = 719.29.

   d. Push 3, enter side one of card 3.

2. Enter data.

   a. Push R/S to start data entry.

   b. Push R/S after each entry which will be printed.

   A = real part of refractive index.

   B = imaginary part of refractive index (positive).

   W = wavelength of incident light.

The number of increments is fixed for a running time of 30 minutes. The fixed ranges of integration for high efficiency control devices are 0.02 to 2 μm and 2 to 40 μm in diameter.

Result

Sp = specific extinction coefficient

NXT 1 = end of this part of program. Proceed to card 4.

Card 4 computes the in-stack opacity (percent after some additional data entry):

1. Enter card 4 - - Push 1, enter side one of card 4
   Note: The calculator partition is still equal to 719.29.

2. Enter data.

   a. Push A to start data entry.

   b. Push R/S after card entry that will be printed.

Mass	=	particle mass concentration, g/m^3
Stack diameter	=	stack diameter, m
Density	=	density of particles, g/cm^3
Final result		
OP (%)	=	in-stack opacity, %

Sample Calculation

Calculate the in-stack opacity for the case of nonlognormal aerosol size distribution.

Given the following data:

Index of refraction = 1.5 (imaginary part equal to zero)
Wavelength of light = 0.55 μm
Mass concentration = 0.01 g/m^3
Particle density = 2.4 g/cm^3
Stack diameter = 6.9 m

Cut Point Diameter D_{50}, μm	Mass Fraction F_i
0.2	0.0024
0.5	0.0572
0.7	0.09
1.0	0.185
1.5	0.285
2.5	0.219
4.0	0.105
6.0	0.033
8.0	0.018
12.0	0.0048

Solution

Procedure	Press	Enter	Press	Display	Print
Set partition			6, 2nd, Op, 17	479.59	
1. Enter card 1	1	Side one		1	
2. Enter data	A			31160601	ND_{50}
Note: This part of the program requires 40 seconds after data are input:		$ND_{50}(10)$	R/S		10
				160601	D_{50}
		$D_{50}(0.2)$	R/S		0.2
				160601	D_{50}
		$D_{50}(0.5)$	R/S		0.5
				160601	D_{50}
		$D_{50}(0.7)$	R/S		0.7
				160601	D_{50}
		$D_{50}(1.0)$	R/S		1.0
				160601	D_{50}
		$D_{50}(1.5)$	R/S		1.5
				160601	D_{50}
		$D_{50}(2.5)$	R/S		2.5
				160601	D_{50}
		$D_{50}(4.0)$	R/S		4.0
				160601	D_{50}
		$D_{50}(6.0)$	R/S		6.0
				160601	D_{50}
		$D_{50}(8.0)$	R/S		8.0
				160601	D_{50}
		$D_{50}(12.0)$	R/S		12.0
				21	F
		F(0.0024)	R/S		0.0024

Procedure	Press	Enter	Press	Display	Print
				21	F
		F(0.0572)	R/S		0.0572
				21	F
		F(0.09)	R/S		0.09
				21	F
		F(0.185)	R/S		0.185
				21	F
		F(0.285)	R/S		0.285
				21	F
		F(0.219)	R/S		0.219
				21	F
		F(0.105)	R/S		0.105
				21	F
		F(0.033)	R/S		0.033
				21	F
		F(0.018)	R/S		0.018
				21	F
		F(0.0048)	R/S		0.0048
					NEXT CARD
3. Enter card 2	1	Side one		1	
	2	Side two		2	
4. Enter card 3	A			719.29	
	3	Side one		3	
	R/S			13	A
		A(1.5)	R/S		1.5
				14	B
		B (0.0)	R/S		0.0
				43	W
		W(0.55)	R/S		0.55
					3.095120115 = SP
					NXT 1
5. Enter card 4	1	Side one			
	A			3013363671	MASS?
		Mass (0.01)	R/S		0.01
					STACK DIAMETER?
		Stack Diameter (6.9)	R/S		6.9

Procedure	Press	Enter	Press	Display	Print
					DENSITY?
		Density (2.4)	R/S		2.4
				8.51404322	=OP%

Uses

The main function of this program is the relatively quick (less than 1 hour) approximate determination of in-stack opacity for size distributions in histogram format. This opacity program can also be used to examine the effect of high efficiency particulate control devices.

In-stack Opacity Program Caution

The calculated specific extinction coefficient (Sp) may not be correct because of the extinction efficiency approximation when a particle index of refraction is not in the following ranges:

$1.0 \leq$ real part ≤ 1.5
$0.0 \leq$ imaginary part ≤ 0.25

Table 2 shows that relative errors may vary from 1 to 111 percent for a carbonaceous aerosol (m = 1.96 - 0.66i). This table compares the exact Sp derived numerically on a computer to the three opacity programs for various size distributions. Since the errors are a function of the index of refraction, caution is advised if one attempts to extrapolate the approximate programs to aerosols with different light scattering and absorbing properties. Overall, the magnitude of these errors allows only a very rough estimate of in-stack opacity for high absorptive aerosols. If much more accuracy is desired and if the user takes about 8 hours for the calculation, the long opacity program gives very good results. (See Section 5, long opacity calculation.)

COMPARISON OF APPROXIMATE IN-STACK OPACITY PROGRAMS

The two opacity programs are compared in Table 3 for a refractive index equal to 1.5. This table is presented in the same format as Table 2, with the specific extinction coefficient (Sp) data for various size distributions. Only the index of refraction is changed.

TABLE 2. COMPARISON OF APPROXIMATE TI-59 CALCULATIONS OF Sp WITH EXACT VALUES

$m = 1.96 - 0.66\,i \quad \lambda = 0.55\,\mu m$

σ_g	D_g µm	Exact S_p m^2/cm^3	Approximate Calculation (Histogram Size Data) m^2/cm^3	Approximate Calculation (Lognormal Size Data) m^2/cm^3	Long Calculation (Lognormal Size Data) m^2/cm^3
2	1	5.08	5.76	6.63	5.16
4	1	6.05	10.47	10.79	6.15
6	1	6.02	10.61	12.51	6.07
2	2	2.41	2.73	2.35	2.54
4	2	3.88	5.54	6.18	3.90
6	2	4.34	9.17	8.26	4.39
2	3	1.54	1.60	1.42	1.60
4	3	2.83	3.80	4.25	2.89
6	3	3.44	6.06	6.32	3.56
2	4	1.12	1.12	1.02	1.15
4	4	2.22	2.90	3.2	2.31
6	4	2.86	4.18	5.18	3.05

TABLE 3. COMPARISON OF APPROXIMATE TI-59 CALCULATIONS OF Sp WITH EXACT VALUES

$m = 1.5 \qquad \lambda = 0.55\ \mu m$

σ_g	D_g μm	Exact S_p m^2/cm^3	Approximate (Lognormal Size Data) m^2/cm^3	Approximate (Histogram Size Data) m^2/cm^3
2	1	4.99	4.82	4.92
4	1	3.67	3.73	3.95
6	1	3.06	3.23	3.38
2	2	2.62	2.51	2.99
4	2	2.88	2.87	3.21
6	2	2.62	2.77	2.88
2	3	1.64	1.56	1.91
4	3	2.31	2.316	2.6
6	3	2.27	2.44	2.55
2	4	1.17	1.11	1.31
4	4	1.91	1.94	2.17
6	4	2.0	2.19	2.47

The average relative error for the lognormal size data (opacity program) is 4.1 percent with maximum value of 9.5 percent. The running time for this program is approximately 15 minutes. The greatest contribution to error here is the extinction efficiency approximation. Accuracy cannot be improved by using more increments. However, the opacity from the size distribution σ_g and D_g = 4 can be improved by extending the range of integration up to a particle diameter of 80 μm to avoid truncation error.

The average relative error for the incremental size distribution (opacity program) is 12.2 percent with a maximum error of 23.5 percent. The running time for this program is approximately 30 minutes. The primary cause of error arises from using a crude size distribution interpolation. The second major cause of error is the approximation used to calculate the extinction efficiencies.

PROGRAM NO. 3: EXTINCTION EFFICIENCY (Q_{ext}) APPROXIMATION

Since a major part of the specific extinction coefficient calculation depends on calculating the extinction efficiency, it is worthwhile to briefly describe the algorithms used.

Deirmendjian's approximation for the extinction efficiency is based on van de Hulst's (1957) formulation that does not use the exact Mie series calculation. van de Hulst's formula is

$$Q_{ext}(\rho, m) = 2 - \frac{4\cos g}{\rho}\exp(-\rho\tan g)\sin(\rho - g) + 4\left(\frac{\cos g}{\rho}\right)^2[\cos 2g - \exp(-\rho\tan g)\cos(\rho - 2g)] \quad \text{for } m = a - bi \tag{7}$$

where $\rho = 2x(a-1)$, $x = \frac{\pi dp}{\lambda}$, and $g = \arctan b/(a-1)$; $[m-1] \rightarrow 0$

with

- ρ as van de Hulst's normalized size parameter
- g as the absorption parameter such that $\rho \tan g$ gives the energy absorbed along the axial ray within the sphere.

Deirmendjian then applied the following correction factors to this original theory with great increase in accuracy:

$$D_1 = \frac{(a-1)^2}{1.632a} [f(g) + 1] + \frac{0.2\rho - a + 1}{(a-1)f(g)}, \quad \rho \leq 5(a-1) \qquad (8)$$

$$D_2 = \frac{(a-1)}{8.16a} [f(g)+1]\rho, \quad 5(a-1) < \rho \leq \frac{4.08}{1+3 \tan g} \qquad (9)$$

$$D_3 = \frac{(a-1)[f(g) + 1]}{2a(1 + 3 \tan g)}, \quad \frac{4.08}{1 + 3 \tan g} < \rho \leq \frac{4.08}{1 + \tan g} \qquad (10)$$

$$D_4 = \frac{2.04(a-1)[f(g)+1]}{a f(g) \rho} \quad \rho > \frac{4.08}{1+\tan g} \qquad (11)$$

where

$$f(g) = 1 + 4 \tan g + 3 \tan^2 g \qquad (12)$$

The van de Hulst approximation with $1 + D$ as a correction factor works well for the ranges $1 < a \leq 1.50$ and $0 \leq b \leq 0.25$. Table 4 compares Deirmendjian's approximation with exact Mie values. These discrepancies are the partial cause of the errors previously discussed in Sp calculation.

Program Operation

The extinction efficiency program is operated in accordance with the following procedure:

Enter card 1.

a. Push 1, enter side one of card 1.

b. Push 2, enter side two of card 1.

c. Push A to start data entry.

d. Push R/S after each entry that will be printed.

A = real part of refractive index register.

B = imaginary part of refractive index register.

TABLE 4. COMPARISON OF DEIRMENDJIAN'S APPROXIMATION FOR EXTINCTION EFFICIENCY WITH EXACT MIE VALUE

m	$x = \pi dp/\lambda$	Approximate Q_{ext}	Exact Q_{ext}	Relative Error[a]
1.212-0.0601i	1.0	0.193	0.203	4.9
	3.0	1.07	1.08	0.9
	6.0	2.36	2.37	0.004
	10.0	2.72	2.80	2.9
1.29	1.0	0.079	0.072	9.7
	3.0	1.40	1.36	2.9
	6.5	3.78	3.80	0.5
	10.0	2.97	2.81	5.7
	15.0	1.98	1.97	0.5
1.29-0.0472i	2.0	0.767	0.777	1.3
	5.0	2.84	2.83	0.35
	7.0	3.15	3.21	1.9
	12.0	2.17	2.25	3.6
1.315	2.0	0.648	0.642	0.9
	4.0	2.55	2.63	3.0
	6.5	3.93	3.94	0.25
	10.0	2.30	2.45	6.1
1.308-0.0018i	1.0	0.096	0.087	10.3
	3.0	1.56	1.54	1.3
	6.0	3.76	3.78	0.5
	10.0	2.41	2.55	5.5
1.315-0.0143i	2.0	0.717	0.717	0
	4.0	2.53	2.59	2.3
	6.5	3.66	3.72	1.6
	9.0	2.76	2.89	4.5
1.315-0.1370i	2.0	1.22	1.23	0.8
	4.0	2.41	2.41	0
	6.5	2.60	2.71	4.1
	7.0	2.36	2.48	4.8
1.525	1.0	0.322	0.237	36
	2.0	1.76	1.98	11
	4.0	4.23	4.09	3.4
	6.0	2.43	2.52	3.6
	10.0	2.71	2.87	5.6
1.525-0.0682i	1.0	0.576	0.420	37
	2.0	1.99	2.04	2.5
	4.0	3.50	3.61	3.0
	6.0	2.46	2.61	5.7
	10.0	2.35	2.55	7.8

[a] Relative Error $= \dfrac{\text{Exact value - Approximate value}}{\text{Exact value}}$

Reference: Deirmendjian, 1969.

W = wavelength of incidental radiation

dp = particle diameter

Results

The extinction efficiency Q_{ext} is calculated for aerosol physical and optical characteristics.

Sample Calculation

1. Enter card 1 -- Push 1, enter side one of card 1C

2. Push A

		Press
	A?	
Enter 1.5	1.5	R/S
	B?	
Enter 0	0	R/S
	W?	
Enter 0.56	0.56	R/S
	D?	
Enter 0.2	0.2	R/S
	0.3831940388	Q_{ext}

Uses

The program for calculating only the extinction efficiency with the approximate formulation allows a quick inspection of the various particle diameters to determine their relative contribution to light scattering.

PROGRAM NO. 4: MIE THEORY EXTINCTION EFFICIENCY CALCULATION PROGRAM

To make an exact calculation of extinction efficiency is time consuming with the TI-59. The extinction efficiency, as derived by van de Hulst (1957) using the cross-section theorem of quantum mechanics, is given by:

$$Q_{ex}(m,x) = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1) \, \text{Re} \left\{ a_n + b_n \right\} \qquad (13)$$

where

m is the index of refraction

x is the size parameter $\frac{\pi dp}{\lambda}$

a_n and b_n, the Mie coefficients, are functions only of m and x.

Re indicates the real part of the complex expression.

Deirmendjian adapted the Mie coefficients as derived by van de Hulst into a computational form by manipulating Bessel functions to obtain:

$$a_n(m,x) = \frac{\left\{\left[\frac{A_n(y)}{m} + \frac{n}{x}\right] \mathrm{Re}\left\{w_n(x)\right\} - \mathrm{Re}\left\{w_{n-1}(x)\right\}\right.}{\left(\frac{A_n(y)}{m} + \frac{n}{x}\right) w_n(x) - w_{n-1}(x)} \quad (14)$$

$$b_n(m,x) = \frac{\left(m A_n(y) + \frac{n}{x}\right) \mathrm{Re}\left\{w_n(x)\right\} - \mathrm{Re}\left\{w_{n-1}(x)\right\}}{\left(m A_n(y) + \frac{n}{x}\right) w_n(x) - w_{n-1}(x)} \quad (15)$$

where $$w_n(x) = \frac{2n-1}{x} w_{n-1}(x) - w_{n-2}(x)$$

$$w_o(x) = \sin x + i \cos x$$

$$w_{-1}(x) = \cos x - i \sin x$$

and $$A_n(y) = -\frac{n}{y} + \left[\frac{n}{y} - A_{n-1}(y)\right]^{-1} \qquad y = mx$$

$$A_o(y) = \frac{\sin p \cos p + i \sinh q \cosh q}{\sin^2 p + \sinh^2 q} \qquad \begin{array}{l} p = a x \\ q = b x \end{array}$$

The magnitude of n, the number of terms in the Mie series, determines the time required for calculation. The value of n necessary for accurate evaluation of the extinction efficiency equals 2x.

The Mie theory calculation is used specifically for particle size with a diameter range from 0.1 to 5 μm for a 0.5 μm wavelength. For $x > 40$, the value of the extinction efficiency equals 2 as determined by geometric and diffractive scattering.

Program Operation

1. Enter card ID.
   a. Push 1, enter side one of card 1.
   b. Push 2, enter side two of card 1.
   c. Push A.
   d. Push 3, enter side three of card 2.
2. Press A to start data entry.
3. Press R/S after each entry that will be printed.
4. The data input is identical to the approximate extinction program; i.e., A, B, W, D.

Results

Along with the data printed above, the extinction efficiency is printed.

Sample Calculation

	Enter	Press	Print
1. Enter cards 1 and 2			
	1	enter side one	
	2	enter side two	
	A	Push A	
	3	enter side three	

	Enter	Press	Print
2. Enter data		R/S	
	A(1.5)	R/S	1.5
	B(0)	R/S	0.0
	W(0.56)	R/S	0.56
	D(2.317295971)	R/S	2.317295971

Solution summary: 2.281425886
Extinction efficiency = 2.28

Uses

If time is not critical, the exact extinction efficiency can be computed to determine the critical sizes for light scattering.

PROGRAM NO. 5: LONG OPACITY CALCULATION USING TI-59 AND LOGNORMAL SIZE DISTRIBUTION

This program uses the exact Mie calculation to obtain the extinction efficiency. The size distribution input is lognormal, and the continuous Simpson's Rule integration is used. This calculation will produce very accurate results with an average error less than 5 percent. The major drawback is the time required for this program -- 8 hours. The program integrates from particle diameter 0.02 to 40 µm using Simpson's Rule for 100 increments. The 100 increments are required for sufficient accuracy especially in the lower end of the particle size range.

Program Operation

Card 1 is used for initial data entry.

Enter card 1.

a. Set partition: Press 4, 2nd, Op 17.

b. Press 1, enter side one of card 1.

c. Press 3, enter side two of card 1.

d. Press A to start data entry.

e. Press R/S after each entry which will be printed.

The following data need to be input: SIGMA, DG, W, A, and B.

Card 2 is used to calculate the following integral:

$$\int_{d_o}^{d_n} d_p \, Q_{ext} \, n \, (d_p) \, d \, dp$$

This part of the program requires about 8 hours.

Enter card 2.

a. Push 1, enter side one.

b. Push 2, enter side two.

c. Push RST.

d. Push R/S.

Card 4 is used to calculate the opacity and specific extinction coefficient Sp. The result from Card 1 is divided by the following integral to obtain Sp:

$$\frac{2}{3} \int_{d_o}^{d_n} d_p^{\,2} \, n \, (dp) \, d \, dp$$

This calculation requires about 4 minutes.

The input data for opacity calculation are also entered with this card.

Enter card 4.

a. Push 1, enter side one.

b. Push A to start data entry.

c. Push R/S after each entry which will be printed.

MASS?	Aerosol mass concentration, g/m^3	Register 22
DENS?	Particle density, g/cm^3	Register 23
STCK?	Stack diameter, m	Register 24

Results

The unlabeled output from card 1 is the solution to integral of the extinction efficiency.

The input for card 4 is as follows:

1. Mass concentration (MASS).
2. Aerosol density (DENS).
3. Stack diameter (STCK).

The output for card 4 is

1. Specific extinction coefficient (SP).
2. In-stack opacity (OP %).

All the above are printed automatically.

Sample Calculation

Calculate the in-stack opacity for lognormal size distribution given the following data:

Geometric standard deviation	= 2
Mass median diameter	= 2 μm
Wavelength of light	= 0.56 μm
Mass concentration	= 0.01 g/m^3
Particle density	= 2.4 g/cm^3
Stack diameter	= 6.9 m
Index of refraction (a-bi)	= 1.96 - 0.66i

Solution:

Procedure	Press	Enter	Press	Print	Display
1. Set partition		4	2nd OP 17		639.39
2. Enter card 1	1	side one			
3. Enter card 1	3	side two			
4. Enter data			A		
		σ_g(2)	R/S	SIGMA 2	
		d_g(2)	R/S	DG 2	
		W(0.55)	R/S	W 0.55	
		A(1.96)	R/S	A 1.96	
		B(0.66)	R/S	B 0.66	
					639.39 0.6792158202
5. Enter card 2	1	sides 1			
	2	side 2	RST R/S		
		Enter card 3 a. Push 1, enter side one b. Push A to start data entry			
		MASS (0.01)	R/S	MASS ? 0.01	
		DENS (2.4)	R/S	DENS ? 2.4	
		STCK (6.9)	R/S	STCK DIAM? 6.9	
				2.541602496 Sp	
				7.0465236 OP (%)	

Uses

This program is especially useful for predicting opacity for highly absorptive aerosols with a lognormal particle size distribution. Although the calculation time is much longer, the program accuracy is much greater than the approximate opacity programs (Table 2).

SECTION 6

DESCRIPTION OF TI-59 ELECTROSTATIC PRECIPITATOR AND SCRUBBER PROGRAMS WITH INCREMENTAL SIZE DATA

The theoretical modeling of electrostatic precipitators (ESPs) for computers is fully developed by Gooch, et al. (1975), and for TI-59 programmable calculators by Sparks (1979). EPA publication EPA-600/7-78-026 describes SR-52 calculator programs for ESPs and venturi scrubbers using lognormal size distribution. The TI-59 versions of these programs are in Appendices H and I. The only changes in the venturi scrubber program are (1) Cunningham correction factor and (2) the use of Master Library Simpson Rule integration.

ESP PROGRAM

A new program for ESPs has been developed by Sparks (1979). Because this program is a major improvement in the SR-52 program and has not been reported, a fairly complete discussion of the new TI-59 ESP model is given here.

Recent advances in calculator technology have made available calculators with tremendous computing capability. This computing capability can be used to model electrostatic precipitation without a large computer. This paper describes such a model for the Texas Instruments TI-59 Calculator.

The Model

The ESP model for the TI-59 calculator is based on the EPA/Southern Research Institute (EPA/SoRI) ESP Computer Model Revision I by McDonald (1978). A brief discussion of the theory behind the model and the assumptions in the model are given here. The reader interested in more detail should consult the referenced reports.

Steps in Electrostatic Precipitation Process

The electrostatic precipitation process can be divided into four steps:

1. Corona generation and establishment of electric field.
2. Particle charging.
3. Particle collection.
4. Removal of the collected material.

A complete model of the process would handle all four steps. However, Step 4 is too complex to be modeled at this time and is neglected by both the EPA/SoRI Model and the TI-59 Model. Step 1 is modeled in detail by the EPA/SoRI Model but is neglected in the TI-59 Model. The TI-59 calculator does not have sufficient power to handle the computation used in the computer program. Work is underway to develop approximations for use in the TI-59. When these approximations are developed they will be incorporated into the model. Until then the user must supply the applied voltage and current density as input data.

Particle Charging

Particle charging generally takes place by two mechanisms: field charging and diffusion charging. For large particles, field charging is by far the dominant mechanism. Diffusion charging dominates for very small particles. Particles of major interest in air pollution (those with 0.1 ≤ 1.0 μm) are charged by both mechanisms. Pontius et al (1977) have shown that the following approximation for the charge on a particle agrees with experimental data and detailed theory fairly well.

$$\eta p = \frac{\pi d}{2} C_1 \left\{ \frac{b\, d_p/aE_{Av} Nt}{b\, Nt + C_1} \right\} \left[1 + 2\left(\frac{K-1}{K+2}\right) \right] + C_2 T \ln \left\{ \left(\frac{d_p vNt}{2C_1 C_2 T} \right) + 1 \right\} \quad (16)$$

ηp	=	number of charges	E_{Av}	=	average electric field
C_1	=	$4\,\varepsilon_o/e$	T	=	absolute temperature
C_2	=	k/e	N	=	free ion density
ε_o	=	permitivity of free space	t	=	residence time for charging
e	=	charge on electron	K	=	particle dielectric constant
k	=	Boltzman's constant	v	=	mean thermal speed of ions
b	=	ion mobility	d_p	=	particle diameter
			a	=	particle radius

The charge on a particle, q, in coulombs is given by

$$q = \eta_p e$$

This equation is used in the TI-59 program and in the approximation procedure in the EPA /SoRI model.

The average electric field used in the calculation is given by

$$E_{Av} = U/H \tag{17}$$

where U = the applied voltage, kV
H = wire to plate spacing, m

The free ion density, N, is given by

$$N = bE_{Av}/j \tag{18}$$

where b = average ion mobility, $m^2/V\text{-sec}$
j = current density a/m^2

Particle Collection

Particle collection in an ESP is given by the Deutsch Andersen equation

$$Pt(d_p) \doteq \exp[-\omega(d_p)A/V] \tag{19}$$

where
ωd_p = electrical migration velocity of particles with diameter d_p m/s
A = collector plate area, m^2
V = volumetric flow rate of gas, m^3/s

The ratio A/V is called the specific collection area (SCA).

The electrical migration velocity near the collector plate for small particles is given by Stokes' law as

$$\omega(d_p) = q\,E_pC'/3\pi\mu d_p \tag{20}$$

where q = the particle charge, coul. ($q = e\eta$)
E_p = the electric field at the plate, V/m
C' = the Cunningham correction factor
$= 1 + 2A\dfrac{\lambda}{d_p}$
A = $1.246 + 0.42\ \text{esp}\ (-0.87\ d_p/2\lambda)$
λ = mean free path of gas, μm
$= \lambda_o\left(\dfrac{76}{p}\right)\left(\dfrac{T}{296.2}\right)$

λ_o = mean free path at 23°C and 76 cm Hg pressure

P = barometric pressure, cm Hg

T = temperature, °K

μ = viscosity of gas, kg/m-s (10 poise = 1 kg/m-s)

McDonald reported that for an ESP collecting flyash:

$$E_p = E_{Av}/1.75 \tag{21}$$

This estimate of E_p is used in the TI-59 Model.

McDonald also reported that equation (20) underpredicts the migration velocity for a real ESP. He recommends that the migration velocity be corrected by an empirical factor to improve agreement between predictions and theory. The corrected migration velocity is given by:

$$\omega(d_p) = \omega(d_p)_\mu \times (1.7 - 0.45\ d_p) \tag{22}$$

where $\omega\ (d_p)_\mu$ is the uncorrected migration velocity. Equation (22) applies for $0.2 < d_p < 4/5$ μm. Outside this range equation (20) applies.

Non-Ideal Factors

The Deutsch Andersen equation applies to an ideal situation. Certain non-ideal factors exist in real ESPs which result in higher penetrations than those predicted by equation (19). Chief among these non-ideal factors are non-uniform gas flow, sneakage, and reentrainment. Gooch et al. (1975) have shown that the effects of these non-ideal factors can be estimated from:

$$Pt'(d_p) = \exp\left[\frac{-\omega(d_p)A}{BF\ V}\right] \tag{23}$$

where $Pt'(d_p)$ = the corrected penetration

B = the correction factor for sneakage and reentrainment

F = the correction factor for non-uniform gas flow

$$B = \frac{\ln P + (d_p)}{N_s \ln[S + (1 - S)Pt(d_p)^{1/N_s}]} \tag{24}$$

N_s = number of baffled sections

S = the fraction of particles that are reentrained and that by-pass electrified region per section

$$F = 1 + 0.766\,[1 - Pt(d_p)]\sigma^{1.786} + 0.075\,\sigma \ln[1/Pt(d_p)] \quad (25)$$

σ = the normalized standard deviation of the gas flow ($\sigma = 0.25$ is generally considered good)

Note that both B and F are particle size dependent.

The overall penetration, Pt_o, is given by:

$$Pt_o = \int_0^{\infty} Pt(d_p)f(d_p)dd_p \quad (26)$$

and the corrected overall penetration, Pt_o', is given by:

$$Pt_o' = \int_0^{\infty} Pt(d_p)'f(d_p)dd_p \quad (27)$$

where $f(d_p)$ is the fraction of particles with diameters between d and d + dd.

TI-59 ESP Model

A mathematical model based on the above equations has been programmed for the Texas Instruments TI-59 Calculator. In the TI-59 model the ESP is divided into user specified time increments. The division of the ESP into time increments is necessary to account for the time dependent nature of the particle charging and particle collection process. For each time increment the calculator calculates particle charge, particle migration velocity, and particle penetration through the increment. All these calculations are performed for each particle diameter in the user specified particle size distribution. The penetration of a given particle diameter through the ESP is given by:

$$Pt(d_p) = \prod_{i=1}^{\eta} Pt(d_p)_i \quad (28)$$

where $Pt(d_p)_i$ = penetration of particles of diameter d_p through the i^{th} increment.

An effective migration velocity for each diameter for the entire ESP is calculated from

$$\omega(d_p)_e = \frac{-\ln Pt(d_p)}{A/V} \qquad (29)$$

The penetration corrected for non-ideal factors $Pt(d_p)'$ is calculated from:

$$Pt(d_p)' = \exp - \left(\frac{\omega(d_p)_e \; A/V}{B \times F} \right) \qquad (30)$$

These calculations are performed for each of the m particle diameter in the user specified particle size distribution. The overall penetration is given by:

$$Pt_o = \sum_{i=1}^{m} Pt(d_p)_i f_i \qquad (31)$$

and the corrected penetration:

$$Pt_o' = \sum_{i=1}^{m} Pt(d_p)_i f_i \qquad (32)$$

Conclusion

The TI-59 model provides a useful tool for examining the performance of an ESP. The answers are obtained quickly and without a large expensive computer.

Program Operation for Program No. 6

The first step is to enter the inlet particle size distribution for as many as 16 diameters. Since the histogram opacity program is limited to 10 particle diameters, it is recommended that no more than 10 be used for predicting opacity for an ESP.

Ion speed is calculated from:

$$V = \frac{[(8 \times 8.31 \times 10^7 \times T°K)/(\pi \times 32)]^{1/2}}{100} \qquad (33)$$

Ion mobility is calculated from:

$$b = b_r \times \frac{T°K}{273} \times \frac{76}{P} \quad \text{(See Table 5)} \tag{34}$$

1. The particle diameters are stored in Registers 25-39.

2. The mass fractions f_i at diameters d_i are in Registers 41-55.

   Card 1 is used to enter all other data.

3. Enter data in following order:

   Push A to start data entry. Push R/S after each entry is printed.

ESP	ID - (Any number for identification)	
NP	Number of particle diameters = 15	
NN	Number of time increments (5 to 10)	Register 05
H	Wire to plate spacing (cm)	Register 01
U	Applied voltage (V) The following is printed: Average electric field (V/m) EA Electric field at plates (V/m) EP	 Register 02 Register 01
V	Ion speed (m/sec)	Register 08
B	Ion mobility (m^2/V-sec)	Register 09
J*	Current density (A/m^2) The following is printed: Ion density NO	
K	Dielectric constant	
T	Temperature (°C)	

*J can be estimated from the relationship between J and P given by Hall (see Figure 4).

TABLE 5. REDUCED EFFECTIVE NEGATIVE ION MOBILITIES FOR VARIOUS GAS COMPOSITIONS

Gas Composition (Volume Percent)					Reduced Effective Ion Mobility (cm^2/V-sec)
N_2	CO_2	O_2	SO_2	H_2O	
				100.0	0.67 ± 0.17
		100.0			2.46 ± 0.06
	100.0				1.08 ± 0.03
			100.0		0.35
	(Laboratory air)				1.03
	(Laboratory air)				1.26 - 1.96
79.4	14.7	4.6	0.2	0.6	5.39
73.5	13.6	4.2	0.2	8.4	2.93
65.9	12.2	3.8	0.2	17.8	2.23
71.0	11.2	3.7	0.0	14.0	2.35
75.7	11.6	3.2	0.0	9.4	3.02
75.1	11.5	3.2	0.1	9.9	2.74
78.5	10.9	3.6	0.0	7.0	3.36
78.3	19.8	3.6	0.1	7.0	2.67
77.9	10.8	3.6	0.3	7.0	2.70
77.6	10.7	3.7	0.7	7.0	2.43

Source: McDonald, J.R. A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume 1. EPA Report: EPA-600/7-78-111a. June 1978. p. 75.

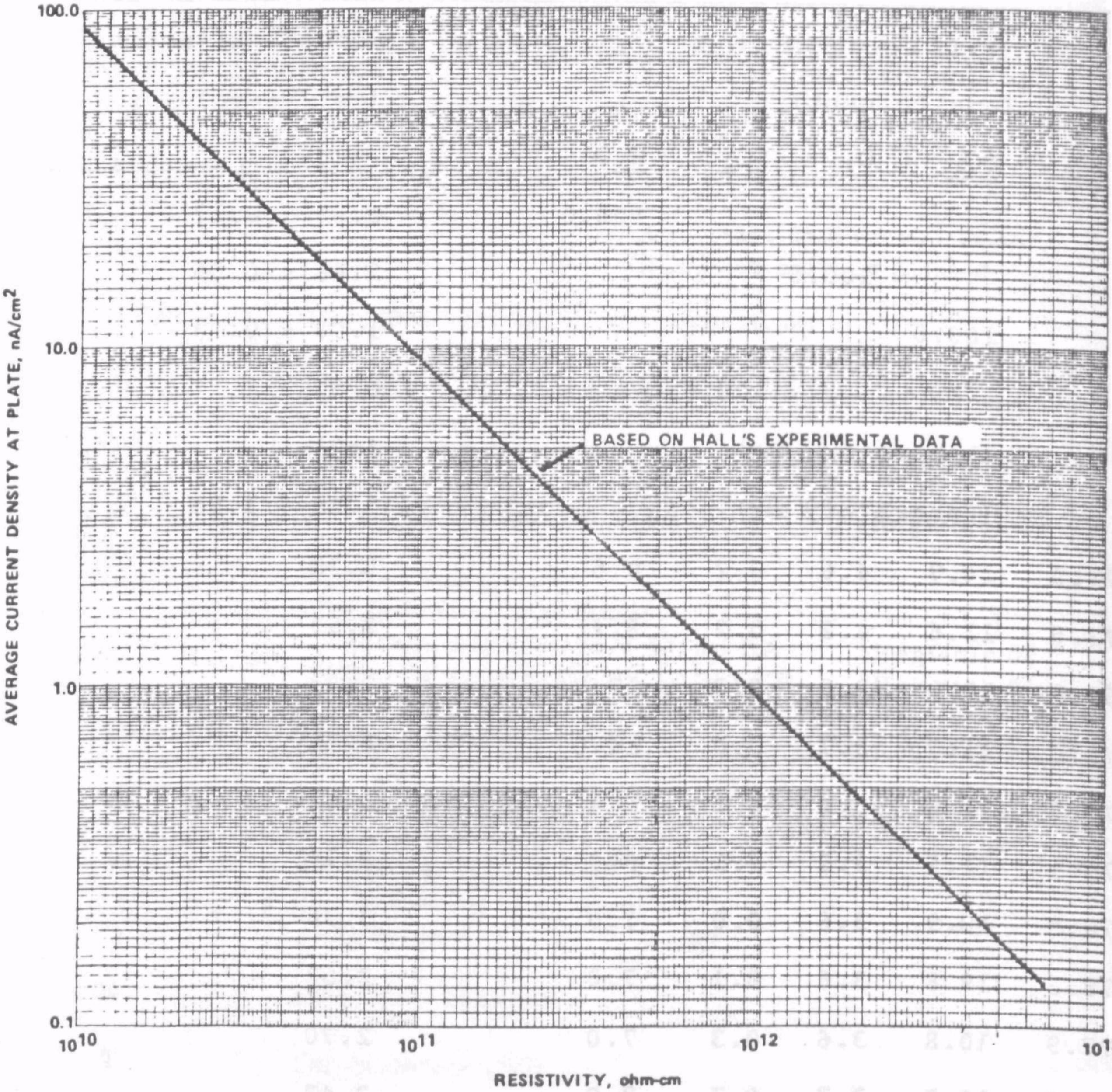

Figure 4. Experimentally determined effect of resistivity on allowable current density in a precipitator (Hall, 1971).

Vis	Viscosity (poise)	Register 04
P	Pressure (cm Hg)	
SCA	Specific collection area ($m^2/m^3/sec$)	Register 03
Length	Length of precipitator (m)	
Vel	Gas velocity (m/sec)	
SIGMA	Normalized standard deviation of gas	Register 06
NS	Number of sections for sneakage	Register 13
S	Fraction of sneakage	Register 14

Card 2 is used to calculate the overall penetration, the outlet size distribution under ideal conditions, the corrected outlet size distribution, ideal migration velocity as a function of diameter, and the ideal and corrected penetrations as a function of diameter.

Press A to obtain above information.

Results

The results for each particle diameter are:

Output
- Particle diameter
- $Pt(d_p) \times f_i$ (Penetration x mass fraction)
- Ideal $Pt(d_p)$ (Ideal penetration)
- Ideal $W(d_p)$ (Ideal migration velocity)
- Corrected $Pt(d_p)$ (Corrected penetration)
- Corrected $Pt(d_p) \times f_i$ (Corrected penetration x mass fraction)

After all the particle size data above are printed, the ideal and corrected penetrations follow:

Sample Calculation

Given:

Size distribution

N = 10

d_p μm		f_i	
0.2	Register 25	0.00033	Register 41
0.4	Register 26	0.00253	Register 42
0.7	Register 27	0.0903	Register 43
1.1	Register 28	0.0815	Register 44
1.6	Register 29	0.0152	Register 45
2.5	Register 30	0.03542	Register 46
3.5	Register 31	0.01652	Register 47
4.5	Register 32	0.01652	Register 48
6.0	Register 33	0.01982	Register 49
8.5	Register 34	0.03304	Register 50

Number of time increments = 5
Wire to plate spacing = 0.1143 cm
Applied voltage = 3.00×10^4 V
Ion speed = 528 m/sec
Ion mobility = 3×10^{-4} m^2/V-sec
Current density = 1.3×10^{-4} A/m^2
Dielectric constant = 100
Temperature = 150°C
Viscosity = 2.3×10^{-4}
Pressure = 76 cm Hg
SCA = 55 m^2/m^3/sec
Length of precipitator = 8 m
Gas velocity = 1.25 m/sec
Normalized standard deviation of gas = 0.25
Number of sections for sneakage = 4
Sneakage fraction = 0.1

Solution

Procedure	Press	Enter	Press	Print
Set Partition	6, 2nd, Op, 17			
Enter card 1	1	Side 1		
	2	Side 2		
Enter data			A	
		ESP ID (1)	R/S	1
		NP (10)	R/S	10
		NN (5)	R/S	5
		H (0.1143)	R/S	0.1143
		U (3.0×10^4)	R/S	3. EE 04 2.6246719 05 EA 1.4998125 05 EP
		V (528)	R/S	5.28 02
		B (3×10^{-4})	R/S	3.0 -04
		J (1.3×10^{-4})	R/S	1.3 -04 1.031875 13 NO
		K (100)	R/S	100
		T (150)	R/S	150
		VIS (2.3×10^{-4})	R/S	2.3 -04
		P (76)	R/S	76
		SCA (55)	R/S	55
		Length (8)	R/S	8
		Vel (1.25)	R/S	1.25
		Sigma (0.25)	R/S	0.25
		NS (4)	R/S	4.0
		S (0.1)	R/S	0.1
Enter size data Press Trace		0.2	STO 25	
		0.4	STO 26	
		0.7	STO 27	
		1.1	STO 28	

Procedure	Press	Enter	Press	Print
		1.6	STO 29	
		2.5	STO 30	
		3.5	STO 31	
		4.5	STO 32	
		6.0	STO 33	
		8.5	STO 34	
		0.00033	STO 41	
		0.00253	STO 42	
		0.0903	STO 43	
		0.0815	STO 44	
		0.0152	STO 45	
		0.03524	STO 46	
		0.01652	STO 47	
		0.01652	STO 48	
		0.01982	STO 49	
		0.03304	STO 50	
Inactivate Trace				
Enter card 2		Side 1 Side 2	A	
		Particle diameter		2. -01 =[illegible]
		Residence time		6.4 00
		Ideal Pt(d) x f_i		1.2872856-05
		Ideal Pt(d)		3.9008653-02
		Ideal W(d)		5.8981305-02
		Corrected Pt(d)		8.4685383-02
		Corrected Pt(d) x f_i		2.7946177-05

Print

```
        4. -01    =I
       6.4 00

1.6956006-04
6.7019787-02
4.9141225-02
1.2236769-01
3.0959027-04

        7. -01    =I
       6.4 00

6.1418485-03
6.8016041-02
 4.887294-02
1.2362949-01
1.1163743-02

       1.1 00    =I
       6.4 00

4.5412242-03
5.5720543-02
5.2498298-02
1.0773313-01
8.7802503-03

       1.6 00    =I
       6.4 00

6.2958231-04
4.1419889-02
5.7890802-02
8.8141568-02
1.3397518-03

       2.5 00    =I
       6.4 00

8.7864081-04
2.4933054-02
6.7119289-02
6.3229764-02
2.2282169-03
```

	Print	
	3.5 00	=D
	6.4 00	
	2.5268282-04	
	1.5295571-02	
	7.6003491-02	
	4.6565039-02	
	7.6925444-04	
	4.5 00	=D
	6.4 00	
	1.8525515-04	
	1.1213992-02	
	8.1647145-02	
	3.8619206-02	
	6.3798929-04	
	6. 00	=D
	6.4 00	
	6.5903855-05	
	3.3251188-03	
	1.0375-01	
	1.9627458-02	
	3.8901621-04	
	8.5 00	=D
	6.4 00	
	1.4549037-05	
	4.4034617-04	
	1.4050817-01	
	7.8121544-03	
	2.5811358-04	
Ideal overall penetration	1.2896608-02	
Corrected overall penetration	2.5915254-02	

Uses

The opacity program can be implemented immediately to determine the effect of an electrostatic precipitator on opacity.

Also, the SCA can be changed to observe its effect on ESP performance. This is performed by entering the inlet size data, then entering card 2 and pressing D.

SCRUBBER PROGRAM WITH INCREMENTAL SIZE DATA

The theory for venturi scrubber computer model has been developed by Yung, et al.(1977), and adapted by Sparks (1978) for SR-52 calculators. Refer to these reports for theoretical derivations and formulations. The SR-52 program presented by Sparks has been written for the TI-59 and a new program for histogram size distribution has been written.

Program No. 7 Operation

1. Enter particle size distribution: diameters in Registers 25-39; mass fractions in Registers 41-55.

2. Enter card 1
   a. Push 1, enter side one.
   b. Push 2, enter side two.
3. Enter data in following order:
   a. Push A to start data entry.
   b. Push R/S after each entry that will be printed.

T	Temperature, °C
P	Pressure, cm Hg
F	Factor - f (0.5)
N	Number of particle diameters
L/G	Liquid to gas ratio, m^3/m^3
UG	Gas velocity, cm/sec

The following is printed:

ΔP	Pressure drop, cm H_2O

VIS	Viscosity, poise
RHO	L-Liquid density, g/cm^3
RHO	P-Particle density, g/cm^3

Results

Directly following the printout of RHO, P, the following is listed for each particle diameter:

Particle diameter

Penetration pt (d_p)

Outlet concentration

Then, after all diameters are printed the following appear:

Overall penetration

Overall efficiency

Sample Calculation

Given:

Size Distribution	Diameter, μm	Mass Fraction, f_i
N = 10	0.2	0.00033
	0.4	0.00253
	0.7	0.0903
	1.1	0.0815
	1.6	0.01520
	2.5	0.03524
	3.5	0.01652
	4.5	0.01652
	6.0	0.01982
	8.5	0.03304

Temperature	= 65°C
Pressure	= 76 cm Hg
Factor (f)	= 0.5
Number of particles	= 13
Liquid to gas ratio	= 9×10^{-4} m^3/m^3
Gas velocity	= 6.5×10^3 cm/sec
Viscosity	= $1.8 - 10^{-4}$ poise
Liquid density	= 1 g/cm^3
Particle density	= 2.4 g/cm^3

Procedure	Press	Enter	Press	Print
Enter size data				
Press Trace		0.2	STO 25	
		0.4	STO 26	
		0.7	STO 27	
		1.1	STO 28	
		1.6	STO 29	
		2.5	STO 30	
		3.5	STO 31	
		4.5	STO 32	
		6.0	STO 33	
		8.5	STO 34	
		0.00033	STO 41	
		0.00253	STO 42	
		0.0903	STO 43	
		0.0815	STO 44	
		0.0152	STO 45	
		0.03524	STO 46	
		0.01652	STO 47	
		0.01652	STO 48	
		0.01982	STO 49	
		0.03304	STO 50	
Inactivate Trace				

Solution

Procedure	Press	Enter	Press	Print
Enter card 1	1	Side 1		
Enter card 1	2	Side 2		
Enter data			A	
		T (65)	R/S	65
		P (76)	R/S	76
		F (0.5)	R/S	0.5
		N (10)	R/S	10
		L/G (9×10^{-4})	R/S	9. -04
		VG (6.5×10^{3})	R/S	6.5 03
				3.13326 01 = ΔP
		VIS (1.8×10^{-4})	R/S	1.8-04
		RHO L (1)	R/S	1.00
		RHO P (2.4)	R/S	2.400
Particle diameter, μm				2. -01 =D
Pt (d_p)				7.3544066-01 PT
Outlet concentration				2.4269542-04 =O
				4. -01 =D
				3.1897058-01 PT
				8.0699556-04 =O
				7. -01 =D
				8.6663485-02 PT
				7.8257127-03 =O
				1.1 00 =D
				2.6899234-02 PT
				2.1922876-03 =O
				1.6 00 =D
				1.1891733-02 PT
				1.8075435-04 =O
				2.5 00 =D
				5.9545995-03 PT
				2.0984009-04 =O

	Print	
	3.5 00	=D
	4.2499663-03	PT
	7.0209443-05	=D
	4.5 00	=D
	3.5770948-03	PT
	5.9093606-05	=D
	6. 00	=D
	3.1225421-03	PT
	6.1888784-05	=D
	8.5 00	=D
	2.8159444-03	PT
	9.3038803-05	=D
Overall penetration	1.1742516-02	=DPT
Overall efficiency	9.8825748-01	=DE

Uses

This program predicts the collection efficiency of a venturi scrubber and also demonstrates the effect of a scrubber on in-stack opacity. The basic input parameters can be changed so that the effect on particle collection and in-stack opacity can be observed.

REFERENCES

Born, M., and E. Wolf. Principles of Optics. Pergamon Press, Oxford England, 1959.

Deirmendjian, D. Electromagnetic Scattering on Spherical Polydispersions. American Elsevier Publishing Co., Inc., New York, NY, 1969.

Ensor, D.S., and M.J. Pilat. Calculation of Smoke Plume Opacity from Particulate Air Pollutent Properties. J. Air Poll. Contr. Assn. 21: 496, 1971.

Gooch, J.P., J.R. McDonald, and S. Oglesby, Jr. "A Mathematical Model of Electrostatic Precipitation." EPA-650/2-75-037 (NTIS PB 246-188), Southern Research Institute, Birmingham, AL, April 1975.

Hall, H.J. "Trends in Electrical Energization of Electrostatic Precipitators." Presented at Electrostatic Precipitator Symposium, Birmingham, AL, February 23-25, 1971.

McDonald, J.R. A Mathematical Model of Electrostatic Precipitation (Revision 1): Volumes I and II. EPA-600/7-78-111a and b. (NTIS PB 284-614 and -615), Southern Research Institute, Birmingham, AL, June 1978.

Pontius, D.H., L.G. Felix, J.R. McDonald, and W.B. Smith. Fine Particle Charging Development. EPA-600/2-77-173 (NTIS PB 271-727), Southern Research Institute, Birmingham, AL, August 1977.

Sparks, L.E. "A Model of Electrostatic Precipitation for TI-59 Calculator." Presented at the 1979 US/USSR Symposium on Particulate Control Technology, Russia, September 1979.

Sparks, L.E. SR-52 Programmable Calculator Programs for Venturi Scrubbers and Electrostatic Precipitators. EPA-600/7-78-026 (NTIS PB 277-672), USEPA, RTP, NC, March 1978.

van de Hulst, H.C. Light Scattering by Small Particles. John Wiley and Sons, Inc., New York, NY, 1957.

Yung, S.S., S. Calvert, and H. Barbarika. Venturi Scrubber Performance Model. EPA-600/2-77-172 (NTIS PB 271-515), A.P.T., Inc., San Diego, CA, August 1977.

APPENDIX A

Title of Program: PROGRAM NO. 1: Approximate Opacity (Lognormal)

Location	Code	Key
000	76	LBL
001	16	A'
002	61	GTO
003	03	03
004	05	05
005	92	RTN
006	76	LBL
007	17	B'
008	61	GTO
009	03	03
010	46	46
011	92	RTN
012	76	LBL
013	18	C'
014	61	GTO
015	02	02
016	10	10
017	92	RTN
018	76	LBL
019	10	E'
020	53	(
021	01	1
022	85	+
023	04	4
024	65	×
025	43	RCL
026	10	10
027	30	TAN
028	85	+
029	03	3
030	65	×
031	43	RCL
032	10	10
033	30	TAN
034	33	X²
035	54	)
036	92	RTN
037	76	LBL
038	19	D'
039	43	RCL
040	11	11
041	32	X:T
042	53	(
043	05	5
044	65	×
045	43	RCL
046	16	16
047	54	)
048	77	GE
049	01	01
050	15	15
051	53	(
052	04	4
053	93	.
054	00	0
055	08	8
056	55	÷
057	53	(
058	01	1
059	85	+
060	43	RCL
061	10	10
062	30	TAN
063	65	×
064	03	3
065	54	)
066	54	)
067	77	GE
068	01	01
069	58	58

Title of Program: Approximate Opacity (Lognormal)

Location	Code	Key	Location	Code	Key
070	53	(	115	53	(
071	04	4	116	43	RCL
072	93	.	117	16	16
073	00	0	118	33	X^2
074	08	8	119	55	÷
075	55	÷	120	53	(
076	53	(	121	01	1
077	01	1	122	93	.
078	85	+	123	06	6
079	43	RCL	124	03	3
080	10	10	125	02	2
081	30	TAN	126	65	×
082	54	)	127	43	RCL
083	54	)	128	12	12
084	77	GE	129	54	)
085	01	01	130	65	×
086	82	82	131	53	(
087	53	(	132	10	E'
088	53	(	133	85	+
089	02	2	134	01	1
090	93	.	135	54	)
091	00	0	136	85	+
092	04	4	137	53	(
093	65	×	138	93	.
094	43	RCL	139	02	2
095	16	16	140	65	×
096	65	×	141	43	RCL
097	53	(	142	11	11
098	10	E'	143	75	-
099	85	+	144	43	RCL
100	01	1	145	12	12
101	54	)	146	85	+
102	54	)	147	01	1
103	55	÷	148	54	)
104	53	(	149	55	÷
105	43	RCL	150	53	(
106	12	12	151	43	RCL
107	65	×	152	16	16
108	43	RCL	153	65	×
109	11	11	154	10	E'
110	65	×	155	54	)
111	10	E'	156	54	)
112	54	)	157	92	RTN
113	54	)	158	53	(
114	92	RTN	159	43	RCL

Title of Program: Approximate Opacity (Lognormal)

Location	Code	Key
160	16	16
161	55	÷
162	53	(
163	08	8
164	93	.
165	01	1
166	06	6
167	65	×
168	43	RCL
169	12	12
170	54	)
171	65	×
172	43	RCL
173	11	11
174	65	×
175	53	(
176	10	E'
177	85	+
178	01	1
179	54	)
180	54	)
181	92	RTN
182	53	(
183	43	RCL
184	16	16
185	65	×
186	53	(
187	10	E'
188	85	+
189	01	1
190	54	)
191	55	÷
192	53	(
193	02	2
194	65	×
195	43	RCL
196	12	12
197	65	×
198	53	(
199	01	1
200	85	+
201	03	3
202	65	×
203	43	RCL
204	10	10
205	30	TAN

Location	Code	Key
206	54	)
207	54	)
208	54	)
209	92	RTN
210	53	(
211	53	(
212	02	2
213	75	-
214	53	(
215	04	4
216	65	×
217	53	(
218	43	RCL
219	10	10
220	39	COS
221	55	÷
222	43	RCL
223	11	11
224	54	)
225	65	×
226	53	(
227	43	RCL
228	11	11
229	94	+/-
230	65	×
231	43	RCL
232	10	10
233	30	TAN
234	54	)
235	22	INV
236	23	LNX
237	65	×
238	53	(
239	43	RCL
240	11	11
241	75	-
242	43	RCL
243	10	10
244	54	)
245	38	SIN
246	54	)
247	85	+
248	04	4
249	65	×
250	53	(
251	43	RCL

Title of Program: Approximate Opacity (Lognormal)

Location	Code	Key
252	10	10
253	39	COS
254	55	÷
255	43	RCL
256	11	11
257	54	)
258	33	X²
259	65	×
260	53	(
261	53	(
262	02	2
263	65	×
264	43	RCL
265	10	10
266	54	)
267	39	COS
268	75	-
269	53	(
270	43	RCL
271	11	11
272	94	+/-
273	65	×
274	43	RCL
275	10	10
276	30	TAN
277	54	)
278	22	INV
279	23	LNX
280	65	×
281	53	(
282	43	RCL
283	11	11
284	75	-
285	53	(
286	43	RCL
287	10	10
288	65	×
289	02	2
290	54	)
291	54	)
292	39	COS
293	54	)
294	54	)
295	65	×
296	53	(
297	19	D'

Location	Code	Key
298	85	+
299	01	1
300	54	)
301	54	)
302	61	GTO
303	00	00
304	17	17
305	42	STO
306	06	06
307	87	IFF
308	01	01
309	03	03
310	19	19
311	53	(
312	43	RCL
313	06	06
314	33	X²
315	65	×
316	17	B'
317	54	)
318	92	RTN
319	53	(
320	43	RCL
321	06	06
322	65	×
323	04	4
324	65	×
325	89	π
326	55	÷
327	43	RCL
328	20	20
329	65	×
330	43	RCL
331	16	16
332	54	)
333	42	STO
334	11	11
335	53	(
336	43	RCL
337	06	06
338	65	×
339	17	B'
340	65	×
341	18	C'
342	54	)
343	61	GTO

Title of Program: Approximate Opacity (Lognormal)

Location	Code	Key
344	00	00
345	05	05
346	53	(
347	53	(
348	43	RCL
349	06	06
350	55	÷
351	43	RCL
352	07	07
353	54	)
354	23	LNX
355	33	X²
356	55	÷
357	53	(
358	02	2
359	65	×
360	43	RCL
361	08	08
362	23	LNX
363	33	X²
364	54	)
365	54	)
366	94	+/-
367	22	INV
368	23	LNX
369	61	GTO
370	00	00
371	11	11
372	76	LBL
373	11	A
374	03	3
375	69	OP
376	17	17
377	91	R/S
378	70	RAD
379	69	OP
380	00	00
381	03	3
382	06	6
383	02	2
384	04	4
385	02	2
386	02	2
387	03	3
388	00	0
389	01	1

Location	Code	Key
390	03	3
391	69	OP
392	01	01
393	69	OP
394	05	05
395	91	R/S
396	99	PRT
397	42	STO
398	08	08
399	69	OP
400	00	00
401	01	1
402	06	6
403	02	2
404	02	2
405	69	OP
406	02	02
407	69	OP
408	05	05
409	91	R/S
410	99	PRT
411	55	÷
412	02	2
413	95	=
414	23	LNX
415	75	-
416	43	RCL
417	08	08
418	23	LNX
419	33	X²
420	65	×
421	03	3
422	95	=
423	22	INV
424	23	LNX
425	42	STO
426	07	07
427	69	OP
428	00	00
429	03	3
430	00	0
431	69	OP
432	02	02
433	69	OP
434	05	05
435	91	R/S

Title of Program: Approximate Opacity (Lognormal)

Location	Code	Key
436	99	PRT
437	42	STO
438	26	26
439	69	OP
440	00	00
441	03	3
442	06	6
443	69	OP
444	02	02
445	69	OP
446	05	05
447	91	R/S
448	99	PRT
449	42	STO
450	27	27
451	69	OP
452	00	00
453	01	1
454	06	6
455	01	1
456	07	7
457	03	3
458	01	1
459	69	OP
460	02	02
461	69	OP
462	05	05
463	91	R/S
464	99	PRT
465	42	STO
466	28	28
467	69	OP
468	00	00
469	04	4
470	03	3
471	69	OP
472	02	02
473	69	OP
474	05	05
475	91	R/S
476	99	PRT
477	42	STO
478	20	20
479	69	OP
480	00	00
481	01	1
482	03	3

Location	Code	Key
483	69	OP.
484	02	02
485	69	OP
486	05	05
487	91	R/S
488	99	PRT
489	42	STO
490	12	12
491	75	-
492	01	1
493	95	=
494	42	STO
495	16	16
496	69	OP
497	00	00
498	01	1
499	04	4
500	69	OP
501	02	02
502	69	OP
503	05	05
504	91	R/S
505	99	PRT
506	42	STO
507	13	13
508	55	÷
509	43	RCL
510	16	16
511	95	=
512	22	INV
513	30	TAN
514	42	STO
515	10	10
516	93	.
517	00	0
518	01	1
519	42	STO
520	21	21
521	02	2
522	42	STO
523	22	22
524	02	2
525	00	0
526	42	STO
527	23	23
528	00	0
529	42	STO

Title of Program: Approximate Opacity (Lognormal)

Location	Code	Key
530	14	14
531	42	STD
532	15	15
533	02	2
534	42	STD
535	09	09
536	43	RCL
537	21	21
538	15	E
539	43	RCL
540	22	22
541	12	B
542	43	RCL
543	23	23
544	13	C
545	22	INV
546	86	STF
547	01	01
548	36	PGM
549	09	09
550	14	D
551	44	SUM
552	14	14
553	69	OP
554	00	00
555	03	3
556	06	6
557	01	1
558	06	6
559	69	OP
560	04	04
561	25	CLR
562	69	OP
563	06	06
564	86	STF
565	01	01
566	43	RCL
567	21	21
568	15	E
569	43	RCL
570	22	22
571	12	B
572	43	RCL
573	23	23
574	13	C
575	36	PGM
576	09	09
577	14	D
578	44	SUM
579	15	15
580	02	2
581	42	STD
582	21	21
583	02	2
584	00	0
585	42	STD
586	22	22
587	02	2
588	00	0
589	42	STD
590	23	23
591	97	DSZ
592	09	09
593	05	05
594	36	36
595	43	RCL
596	15	15
597	35	1/X
598	65	×
599	43	RCL
600	14	14
601	65	×
602	04	4
603	55	÷
604	03	3
605	95	=
606	35	1/X
607	42	STD
608	25	25
609	69	OP
610	00	00
611	06	6
612	04	4
613	03	3
614	06	6
615	03	3
616	03	3
617	69	OP
618	04	04
619	25	CLR
620	43	RCL
621	25	25

Title of Program: Approximate Opacity (Lognormal)

Location	Code	Key
622	69	OP
623	06	06
624	43	RCL
625	25	25
626	65	×
627	43	RCL
628	26	26
629	65	×
630	43	RCL
631	27	27
632	55	÷
633	43	RCL
634	28	28
635	95	=
636	94	+/-
637	22	INV
638	23	LNX
639	94	+/-
640	85	+
641	01	1
642	95	=
643	65	×
644	01	1
645	00	0
646	00	0
647	95	=
648	42	STO
649	29	29
650	69	OP
651	00	00
652	06	6
653	04	4
654	03	3
655	02	2
656	03	3
657	03	3
658	06	6
659	01	1
660	69	OP
661	04	04
662	25	CLR
663	43	RCL
664	29	29
665	69	OP
666	06	06
667	91	R/S

Location	Code	Key
668	76	LBL
669	15	E
670	42	STO
671	01	01
672	92	RTN
673	76	LBL
674	12	B
675	42	STO
676	02	02
677	92	RTN
678	76	LBL
679	13	C
680	42	STO
681	05	05
682	35	1/X
683	65	×
684	53	(
685	43	RCL
686	02	02
687	75	-
688	43	RCL
689	01	01
690	54	)
691	95	=
692	99	PRT
693	42	STO
694	03	03
695	92	RTN

APPENDIX B

Title of Program: PROGRAM NO. 2: Approximate Opacity (Histogram)
Card 1

Location	Code	Key
000	76	LBL
001	11	A
002	08	8
003	42	STO
004	04	04
005	25	CLR
006	69	OP
007	00	00
008	03	3
009	01	1
010	01	1
011	06	6
012	00	0
013	06	6
014	00	0
015	01	1
016	69	OP
017	01	01
018	69	OP
019	05	05
020	91	R/S
021	99	PRT
022	42	STO
023	06	06
024	42	STO
025	07	07
026	01	1
027	06	6
028	00	0
029	06	6
030	00	0
031	01	1
032	69	OP
033	01	01

Location	Code	Key
034	69	OP
035	05	05
036	53	(
037	91	R/S
038	99	PRT
039	65	×
040	01	1
041	00	0
042	00	0
043	00	0
044	54	)
045	72	ST*
046	04	04
047	01	1
048	44	SUM
049	04	04
050	97	DSZ
051	07	07
052	00	00
053	34	34
054	08	8
055	42	STO
056	04	04
057	43	RCL
058	06	06
059	42	STO
060	07	07
061	02	2
062	01	1
063	69	OP
064	01	01
065	69	OP
066	05	05
067	91	R/S

Title of Program: Approximate Opacity (Histogram) Card 1

Location	Code	Key
068	99	PRT
069	74	SM*
070	04	04
071	01	1
072	44	SUM
073	04	04
074	97	DSZ
075	07	07
076	00	00
077	65	65
078	53	(
079	43	RCL
080	06	06
081	75	-
082	01	1
083	54	)
084	42	STO
085	07	07
086	08	8
087	42	STO
088	04	04
089	09	9
090	42	STO
091	03	03
092	01	1
093	09	9
094	42	STO
095	05	05
096	53	(
097	73	RC*
098	03	03
099	59	INT
100	65	×
101	73	RC*
102	04	04
103	59	INT
104	54	)
105	34	ΓX
106	59	INT
107	72	ST*
108	05	05
109	01	1
110	44	SUM
111	03	03
112	44	SUM
113	04	04
114	44	SUM
115	05	05
116	97	DSZ
117	07	07
118	00	00
119	96	96
120	53	(
121	43	RCL
122	06	06
123	75	-
124	01	1
125	54	)
126	42	STO
127	07	07
128	08	8
129	42	STO
130	03	03
131	09	9
132	42	STO
133	04	04
134	01	1
135	09	9
136	42	STO
137	05	05
138	53	(
139	53	(
140	73	RC*
141	03	03
142	22	INV
143	59	INT
144	55	÷
145	53	(
146	73	RC*
147	04	04
148	59	INT
149	55	÷
150	73	RC*
151	03	03
152	59	INT
153	54	)
154	28	LOG
155	54	)
156	55	÷
157	01	1

Title of Program: Approximate Opacity (Histogram) Card 1

Location	Code	Key
158	00	0
159	54	)
160	74	SM*
161	05	05
162	01	1
163	44	SUM
164	03	03
165	44	SUM
166	04	04
167	44	SUM
168	05	05
169	97	DSZ
170	07	07
171	01	01
172	38	38
173	53	(
174	43	RCL
175	06	06
176	75	-
177	01	1
178	54	)
179	42	STO
180	07	07
181	01	1
182	09	9
183	42	STO
184	05	05
185	08	8
186	42	STO
187	03	03
188	73	RC*
189	05	05
190	72	ST*
191	03	03
192	01	1
193	44	SUM
194	03	03
195	44	SUM
196	05	05
197	97	DSZ
198	07	07
199	01	01
200	88	88
201	03	3

Location	Code	Key
202	01	1
203	01	1
204	07	7
205	04	4
206	04	4
207	03	3
208	07	7
209	69	OP
210	01	01
211	01	1
212	05	5
213	01	1
214	03	3
215	03	3
216	05	5
217	01	1
218	06	6
219	69	OP
220	02	02
221	69	OP
222	05	05
223	25	CLR
224	69	OP
225	00	00
226	91	R/S

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key
000	76	LBL
001	11	A
002	03	3
003	69	OP
004	17	17
005	91	R/S
006	01	1
007	03	3
008	69	OP
009	01	01
010	69	OP
011	05	05
012	91	R/S
013	99	PRT
014	42	STO
015	23	23
016	01	1
017	04	4
018	69	OP
019	01	01
020	69	OP
021	05	05
022	91	R/S
023	99	PRT
024	42	STO
025	24	24
026	04	4
027	03	3
028	69	OP
029	01	01
030	69	OP
031	05	05
032	91	R/S
033	99	PRT
034	42	STO
035	25	25
036	00	0
037	42	STO
038	17	17
039	42	STO
040	18	18
041	93	.
042	00	0
043	02	2
044	42	STO

Location	Code	Key
045	01	01
046	02	2
047	42	STO
048	02	02
049	02	2
050	00	0
051	36	PGM
052	09	09
053	13	C
054	36	PGM
055	09	09
056	14	D
057	43	RCL
058	04	04
059	44	SUM
060	17	17
061	86	STF
062	01	01
063	02	2
064	00	0
065	42	STO
066	05	05
067	36	PGM
068	09	09
069	14	D
070	43	RCL
071	04	04
072	44	SUM
073	18	18
074	22	INV
075	86	STF
076	01	01
077	02	2
078	42	STO
079	01	01
080	04	4
081	00	0
082	42	STO
083	02	02
084	01	1
085	00	0
086	36	PGM
087	09	09
088	13	C

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key
089	36	PGM
090	09	09
091	14	D
092	43	RCL
093	04	04
094	44	SUM
095	17	17
096	86	STF
097	01	01
098	01	1
099	00	0
100	42	STD
101	05	05
102	36	PGM
103	09	09
104	14	D
105	43	RCL
106	04	04
107	44	SUM
108	18	18
109	22	INV
110	86	STF
111	01	01
112	25	CLR
113	69	DP
114	00	00
115	06	6
116	04	4
117	03	3
118	06	6
119	03	3
120	03	3
121	69	DP
122	04	04
123	53	(
124	43	RCL
125	17	17
126	55	÷
127	43	RCL
128	18	18
129	65	×
130	01	1
131	93	.
132	05	5

Location	Code	Key
133	54	)
134	69	DP
135	06	06
136	61	GTD
137	07	07
138	04	04
139	76	LBL
140	16	A'
141	53	(
142	42	STD
143	00	00
144	61	GTD
145	01	01
146	58	58
147	43	RCL
148	00	00
149	33	X²
150	65	×
151	43	RCL
152	20	20
153	65	×
154	43	RCL
155	28	28
156	54	)
157	92	RTN
158	53	(
159	43	RCL
160	06	06
161	75	-
162	01	1
163	54	)
164	42	STD
165	07	07
166	08	8
167	42	STD
168	19	19
169	53	(
170	73	RC*
171	19	19
172	55	÷
173	01	1
174	00	0
175	00	0
176	00	0

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key
177	54	)
178	32	X:T
179	43	RCL
180	00	00
181	22	INV
182	77	GE
183	01	01
184	96	96
185	01	1
186	44	SUM
187	19	19
188	97	DSZ
189	07	07
190	01	01
191	69	69
192	01	1
193	22	INV
194	44	SUM
195	19	19
196	53	(
197	43	RCL
198	08	08
199	59	INT
200	55	÷
201	01	1
202	00	0
203	00	0
204	00	0
205	54	)
206	32	X:T
207	43	RCL
208	00	00
209	22	INV
210	77	GE
211	02	02
212	17	17
213	01	1
214	22	INV
215	44	SUM
216	19	19
217	00	0
218	32	X:T
219	73	RC*
220	19	19
221	22	INV

Location	Code	Key
222	59	INT
223	42	STO
224	07	07
225	53	(
226	73	RC*
227	19	19
228	59	INT
229	42	STO
230	21	21
231	01	1
232	44	SUM
233	19	19
234	53	(
235	73	RC*
236	19	19
237	22	INV
238	59	INT
239	75	-
240	43	RCL
241	07	07
242	54	)
243	65	×
244	01	1
245	00	0
246	55	÷
247	53	(
248	73	RC*
249	19	19
250	59	INT
251	55	÷
252	43	RCL
253	21	21
254	54	)
255	28	LOG
256	65	×
257	53	(
258	43	RCL
259	00	00
260	55	÷
261	43	RCL
262	21	21
263	65	×
264	01	1
265	00	0
266	00	0

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key
267	00	0
268	54	)
269	28	LOG
270	85	+
271	43	RCL
272	07	07
273	65	×
274	01	1
275	00	0
276	54	)
277	68	NOP
278	77	GE
279	02	02
280	95	95
281	55	÷
282	01	1
283	25	CLR
284	42	STO
285	07	07
286	01	1
287	32	X:T
288	43	RCL
289	00	00
290	22	INV
291	77	GE
292	02	02
293	97	97
294	25	CLR
295	42	STO
296	07	07
297	53	(
298	53	(
299	43	RCL
300	07	07
301	65	×
302	06	6
303	55	÷
304	89	π
305	55	÷
306	43	RCL
307	00	00
308	45	Y^X
309	03	3
310	54	)
311	65	×

Location	Code	Key
312	53	(
313	53	(
314	43	RCL
315	00	00
316	85	+
317	43	RCL
318	03	03
319	54	)
320	55	÷
321	43	RCL
322	00	00
323	54	)
324	28	LOG
325	55	÷
326	43	RCL
327	03	03
328	54	)
329	42	STO
330	28	28
331	22	INV
332	87	IFF
333	01	01
334	03	03
335	43	43
336	43	RCL
337	00	00
338	42	STO
339	20	20
340	61	GTO
341	01	01
342	47	47
343	70	RAD
344	53	(
345	53	(
346	43	RCL
347	00	00
348	65	×
349	03	3
350	55	÷
351	43	RCL
352	25	25
353	54	)
354	42	STO
355	26	26

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key
356	65	×
357	02	2
358	65	×
359	53	(
360	43	RCL
361	23	23
362	75	-
363	01	1
364	54	)
365	54	)
366	42	STO
367	27	27
368	32	X:T
369	53	(
370	53	(
371	43	RCL
372	24	24
373	55	÷
374	53	(
375	43	RCL
376	23	23
377	75	-
378	01	1
379	54	)
380	54	)
381	42	STO
382	29	29
383	33	X²
384	65	×
385	03	3
386	85	+
387	04	4
388	65	×
389	43	RCL
390	29	29
391	85	+
392	01	1
393	54	)
394	42	STO
395	19	19
396	53	(
397	05	5
398	65	×
399	53	(
400	43	RCL
401	23	23
402	75	-
403	01	1
404	54	)
405	54	)
406	22	INV
407	77	GE
408	04	04
409	65	65
410	53	(
411	53	(
412	43	RCL
413	23	23
414	75	-
415	01	1
416	54	)
417	33	X²
418	55	÷
419	01	1
420	93	.
421	06	6
422	03	3
423	02	2
424	55	÷
425	43	RCL
426	23	23
427	65	×
428	53	(
429	43	RCL
430	19	19
431	85	+
432	01	1
433	54	)
434	85	+
435	53	(
436	93	.
437	02	2
438	65	×
439	43	RCL
440	27	27
441	75	-
442	43	RCL
443	23	23

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key	Location	Code	Key
444	85	+	489	01	1
445	01	1	490	54	)
446	54	)	491	55	÷
447	55	÷	492	08	8
448	53	(	493	93	.
449	43	RCL	494	01	1
450	23	23	495	06	6
451	75	-	496	55	÷
452	01	1	497	43	RCL
453	54	)	498	23	23
454	55	÷	499	65	×
455	43	RCL	500	53	(
456	19	19	501	43	RCL
457	85	+	502	19	19
458	01	1	503	85	+
459	54	)	504	01	1
460	42	STO	505	54	)
461	21	21	506	65	×
462	61	GTO	507	43	RCL
463	06	06	508	27	27
464	03	03	509	85	+
465	53	(	510	01	1
466	04	4	511	54	)
467	93	.	512	42	STO
468	00	0	513	21	21
469	08	8	514	61	GTO
470	55	÷	515	06	06
471	53	(	516	03	03
472	01	1	517	53	(
473	85	+	518	04	4
474	03	3	519	93	.
475	65	×	520	00	0
476	43	RCL	521	08	8
477	29	29	522	55	÷
478	54	)	523	53	(
479	54	)	524	01	1
480	22	INV	525	85	+
481	77	GE	526	43	RCL
482	05	05	527	29	29
483	17	17	528	54	)
484	53	(	529	54	)
485	53	(	530	22	INV
486	43	RCL	531	77	GE
487	23	23	532	05	05
488	75	-	533	70	70

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key
534	53	(
535	53	(
536	43	RCL
537	23	23
538	75	-
539	01	1
540	54	)
541	65	×
542	53	(
543	43	RCL
544	19	19
545	85	+
546	01	1
547	54	)
548	55	÷
549	02	2
550	55	÷
551	43	RCL
552	23	23
553	55	÷
554	53	(
555	01	1
556	85	+
557	03	3
558	65	×
559	43	RCL
560	29	29
561	54	)
562	85	+
563	01	1
564	54	)
565	42	STO
566	21	21
567	61	GTO
568	06	06
569	03	03
570	53	(
571	02	2
572	93	.
573	00	0
574	.04	4
575	65	×
576	53	(
577	43	RCL
578	23	23

Location	Code	Key
579	75	-
580	01	1
581	54	)
582	65	×
583	53	(
584	43	RCL
585	19	19
586	85	+
587	01	1
588	54	)
589	55	÷
590	43	RCL
591	23	23
592	55	÷
593	43	RCL
594	19	19
595	55	÷
596	43	RCL
597	27	27
598	85	+
599	01	1
600	54	)
601	42	STO
602	21	21
603	53	(
604	53	(
605	02	2
606	75	-
607	53	(
608	04	4
609	65	×
610	43	RCL
611	29	29
612	22	INV
613	30	TAN
614	39	COS
615	42	STO
616	07	07
617	55	÷
618	43	RCL
619	27	27
620	65	×
621	53	(
622	43	RCL
623	27	27

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key
624	94	+/-
625	65	×
626	43	RCL
627	29	29
628	54	)
629	22	INV
630	23	LNX
631	65	×
632	53	(
633	43	RCL
634	27	27
635	75	-
636	43	RCL
637	29	29
638	22	INV
639	30	TAN
640	54	)
641	38	SIN
642	54	)
643	85	+
644	53	(
645	04	4
646	65	×
647	53	(
648	43	RCL
649	07	07
650	55	÷
651	43	RCL
652	27	27
653	54	)
654	33	X^2
655	65	×
656	53	(
657	53	(
658	43	RCL
659	29	29
660	22	INV
661	30	TAN
662	65	×
663	02	2
664	54	)
665	39	COS
666	75	-
667	53	(
668	43	RCL

Location	Code	Key
669	27	27
670	94	+/-
671	65	×
672	43	RCL
673	29	29
674	54	)
675	22	INV
676	23	LNX
677	65	×
678	53	(
679	43	RCL
680	27	27
681	75	-
682	53	(
683	43	RCL
684	29	29
685	22	INV
686	30	TAN
687	65	×
688	02	2
689	54	)
690	54	)
691	39	COS
692	54	)
693	54	)
694	54	)
695	65	×
696	43	RCL
697	21	21
698	54	)
699	42	STO
700	20	20
701	61	GTO
702	01	01
703	47	47
704	25	CLR
705	69	OP
706	00	00
707	03	3
708	01	1
709	04	4
710	04	4
711	03	3
712	07	7
713	00	0

Title of Program: Approximate Opacity (Histogram) Cards 2 and 3

Location	Code	Key
714	02	2
715	69	OP
716	01	01
717	69	OP
718	05	05
719	91	R/S

Title of Program: Approximate Opacity (Histogram) Card 4

Location	Code	Key
000	76	LBL
001	11	A
002	25	CLR
003	69	OP
004	00	00
005	03	3
006	00	0
007	01	1
008	03	3
009	03	3
010	06	6
011	03	3
012	06	6
013	07	7
014	01	1
015	69	OP
016	01	01
017	69	OP
018	05	05
019	91	R/S
020	42	STO
021	01	01
022	99	PRT
023	03	3
024	06	6
025	03	3
026	07	7
027	01	1
028	03	3
029	01	1
030	05	5
031	02	2
032	06	6
033	69	OP
034	01	01
035	00	0
036	00	0
037	01	1
038	06	6
039	02	2
040	04	4
041	01	1
042	03	3
043	03	3
044	00	0

Location	Code	Key
045	69	OP
046	02	02
047	01	1
048	07	7
049	03	3
050	07	7
051	01	1
052	07	7
053	03	3
054	05	5
055	07	7
056	01	1
057	69	OP
058	03	03
059	69	OP
060	05	05
061	91	R/S
062	99	PRT
063	42	STO
064	02	02
065	25	CLR
066	69	OP
067	00	00
068	01	1
069	06	6
070	01	1
071	07	7
072	03	3
073	01	1
074	03	3
075	06	6
076	02	2
077	04	4
078	69	OP
079	01	01
080	03	3
081	07	7
082	04	4
083	05	5
084	07	7
085	01	1
086	00	0
087	00	0
088	00	0
089	00	0

Title of Program: Approximate Opacity (Histogram) Card 4

Location	Code	Key
090	69	OP
091	02	02
092	69	OP
093	05	05
094	91	R/S
095	99	PRT
096	42	STO
097	03	03
098	06	6
099	04	4
100	03	3
101	02	2
102	03	3
103	03	3
104	06	6
105	01	1
106	69	OP
107	04	04
108	43	RCL
109	17	17
110	55	÷
111	43	RCL
112	18	18
113	65	×
114	01	1
115	93	.
116	05	5
117	65	×
118	43	RCL
119	01	01
120	65	×
121	43	RCL
122	02	02
123	55	÷
124	43	RCL
125	03	03
126	95	=
127	94	+/-
128	22	INV
129	23	LNX
130	94	+/-
131	85	+
132	01	1
133	95	=
134	65	×

Location	Code	Key
135	01	1
136	00	0
137	00	0
138	95	=
139	69	OP
140	06	06
141	91	R/S

APPENDIX C

Title of Program: PROGRAM NO. 3: **Extinction Efficiency Approximation**

Location	Code	Key	Location	Code	Key
000	76	LBL	036	05	05
001	11	A	037	91	R/S
002	25	CLR	038	99	PRT
003	69	OP	039	42	STO
004	00	00	040	08	08
005	01	1	041	01	1
006	03	3	042	06	6
007	07	7	043	07	7
008	01	1	044	01	1
009	69	OP	045	69	OP
010	01	01	046	01	01
011	69	OP	047	69	OP
012	05	05	048	05	05
013	91	R/S	049	91	R/S
014	99	PRT	050	99	PRT
015	42	STO	051	42	STO
016	00	00	052	09	09
017	01	1	053	65	×
018	04	4	054	89	π
019	07	7	055	55	÷
020	01	1	056	43	RCL
021	69	OP	057	08	08
022	01	01	058	95	=
023	69	OP	059	42	STO
024	05	05	060	02	02
025	91	R/S	061	70	RAD
026	99	PRT	062	65	×
027	42	STO	063	02	2
028	01	01	064	65	×
029	04	4	065	53	(
030	03	3	066	43	RCL
031	07	7	067	00	00
032	01	1	068	75	-
033	69	OP	069	01	1
034	01	01	070	54	)
035	69	OP	071	95	=

Title of Program: **Extinction Efficiency Approximation**

Location	Code	Key
072	42	STO
073	03	03
074	32	X:T
075	43	RCL
076	01	01
077	55	÷
078	53	(
079	43	RCL
080	00	00
081	75	-
082	01	1
083	54	)
084	95	=
085	42	STO
086	04	04
087	33	X^2
088	65	×
089	03	3
090	85	+
091	04	4
092	65	×
093	43	RCL
094	04	04
095	85	+
096	01	1
097	95	=
098	42	STO
099	05	05
100	05	5
101	65	×
102	53	(
103	43	RCL
104	00	00
105	75	-
106	01	1
107	54	)
108	95	=
109	22	INV
110	77	GE
111	45	Y^X
112	43	RCL
113	00	00
114	75	-

Location	Code	Key
115	01	1
116	95	=
117	33	X^2
118	55	÷
119	01	1
120	93	.
121	06	6
122	03	3
123	02	2
124	55	÷
125	43	RCL
126	00	00
127	65	×
128	53	(
129	43	RCL
130	05	05
131	85	+
132	01	1
133	54	)
134	85	+
135	53	(
136	93	.
137	02	2
138	65	×
139	43	RCL
140	03	03
141	75	-
142	43	RCL
143	00	00
144	85	+
145	01	1
146	54	)
147	55	÷
148	53	(
149	43	RCL
150	00	00
151	75	-
152	01	1
153	54	)
154	55	÷
155	43	RCL
156	05	05
157	85	+

Title of Program: Extinction Efficiency Approximation

Location	Code	Key
158	01	1
159	95	=
160	42	STO
161	06	06
162	13	C
163	76	LBL
164	45	Y^X
165	04	4
166	93	.
167	00	0
168	08	8
169	55	÷
170	53	(
171	01	1
172	85	+
173	03	3
174	65	×
175	43	RCL
176	04	04
177	54	)
178	95	=
179	22	INV
180	77	GE
181	34	$\sqrt{X}$
182	43	RCL
183	00	00
184	75	-
185	01	1
186	95	=
187	55	÷
188	08	8
189	93	.
190	01	1
191	06	6
192	55	÷
193	43	RCL
194	00	00
195	65	×
196	53	(
197	43	RCL
198	05	05
199	85	+
200	01	1
201	54	)
202	65	×

Location	Code	Key
203	43	RCL
204	03	03
205	85	+
206	01	1
207	95	=
208	42	STO
209	06	06
210	13	C
211	76	LBL
212	34	$\sqrt{X}$
213	04	4
214	93	.
215	00	0
216	08	8
217	55	÷
218	53	(
219	01	1
220	85	+
221	43	RCL
222	04	04
223	54	)
224	95	=
225	22	INV
226	77	GE
227	33	X^2
228	43	RCL
229	00	00
230	75	-
231	01	1
232	95	=
233	65	×
234	53	(
235	43	RCL
236	05	05
237	85	+
238	01	1
239	54	)
240	55	÷
241	02	2
242	55	÷
243	43	RCL
244	00	00
245	55	÷
246	53	(
247	01	1

Title of Program: Extinction Efficiency Approximation

Location	Code	Key
248	85	+
249	03	3
250	65	×
251	43	RCL
252	04	04
253	54	)
254	85	+
255	01	1
256	95	=
257	42	STO
258	06	06
259	13	C
260	76	LBL
261	33	X^2
262	02	2
263	93	.
264	00	0
265	04	4
266	65	×
267	53	(
268	43	RCL
269	00	00
270	75	-
271	01	1
272	54	)
273	65	×
274	53	(
275	43	RCL
276	05	05
277	85	+
278	01	1
279	54	)
280	55	÷
281	43	RCL
282	00	00
283	55	÷
284	43	RCL
285	05	05
286	55	÷
287	43	RCL
288	03	03
289	85	+
290	01	1
291	95	=

Location	Code	Key
292	42	STO
293	06	06
294	76	LBL
295	13	C
296	02	2
297	75	-
298	53	(
299	04	4
300	65	×
301	43	RCL
302	04	04
303	22	INV
304	30	TAN
305	39	COS
306	42	STO
307	07	07
308	55	÷
309	43	RCL
310	03	03
311	65	×
312	53	(
313	43	RCL
314	03	03
315	94	+/-
316	65	×
317	43	RCL
318	04	04
319	54	)
320	22	INV
321	23	LNX
322	65	×
323	53	(
324	43	RCL
325	03	03
326	75	-
327	43	RCL
328	04	04
329	22	INV
330	30	TAN
331	54	)
332	38	SIN
333	54	)
334	85	+
335	53	(

Title of Program: **Extinction Efficiency Approximation**

Location	Code	Key
336	04	4
337	65	×
338	53	(
339	43	RCL
340	07	07
341	55	÷
342	43	RCL
343	03	03
344	54	)
345	33	X²
346	65	×
347	53	(
348	53	(
349	43	RCL
350	04	04
351	22	INV
352	30	TAN
353	65	×
354	02	2
355	54	)
356	39	COS
357	75	-
358	53	(
359	43	RCL
360	03	03
361	94	+/-
362	65	×
363	43	RCL
364	04	04
365	54	)
366	22	INV
367	23	LNX
368	65	×
369	53	(
370	43	RCL
371	03	03
372	75	-
373	53	(
374	43	RCL
375	04	04
376	22	INV
377	30	TAN
378	65	×
379	02	2
380	54	)

Location	Code	Key
381	54	)
382	39	COS
383	54	)
384	54	)
385	95	=
386	65	×
387	43	RCL
388	06	06
389	95	=
390	99	PRT
391	91	R/S

APPENDIX D

Title of Program: PROGRAM NO. 4: Mie Extinction Efficiency, Cards 1 and 2, Banks 1, 2, 3

Location	Code	Key
000	76	LBL
001	11	A
002	04	4
003	69	OP
004	17	17
005	91	R/S
006	25	CLR
007	69	OP
008	00	00
009	01	1
010	03	3
011	69	OP
012	01	01
013	69	OP
014	05	05
015	91	R/S
016	99	PRT
017	42	STO
018	20	20
019	01	1
020	04	4
021	69	OP
022	01	01
023	69	OP
024	05	05
025	91	R/S
026	99	PRT
027	42	STO
028	21	21
029	04	4
030	03	3
031	69	OP
032	01	01
033	69	OP

Location	Code	Key
034	05	05
035	91	R/S
036	99	PRT
037	42	STO
038	09	09
039	01	1
040	06	6
041	69	OP
042	01	01
043	69	OP
044	05	05
045	91	R/S
046	99	PRT
047	65	×
048	89	π
049	55	÷
050	43	RCL
051	09	09
052	95	=
053	42	STO
054	05	05
055	76	LBL
056	34	ΓX
057	70	RAD
058	00	0
059	42	STO
060	16	16
061	42	STO
062	34	34
063	42	STO
064	06	06
065	43	RCL
066	09	09
067	43	RCL

Title of Program: **Mie Extinction Efficiency, Cards 1 and 2, Banks 1,2,3**

Location	Code	Key
068	05	05
069	65	×
070	01	1
071	93	.
072	04	4
073	95	=
074	59	INT
075	42	STO
076	08	08
077	04	4
078	32	X⇌T
079	43	RCL
080	08	08
081	77	GE
082	10	E'
083	65	×
084	02	2
085	95	=
086	42	STO
087	08	08
088	76	LBL
089	10	E'
090	43	RCL
091	05	05
092	38	SIN
093	42	STO
094	07	07
095	43	RCL
096	05	05
097	39	COS
098	42	STO
099	18	18
100	42	STO
101	17	17
102	43	RCL
103	07	07
104	94	+/-
105	42	STO
106	10	10
107	76	LBL
108	45	Y^{x}
109	43	RCL
110	08	08
111	01	1
112	44	SUM
113	06	06
114	02	2
115	65	×
116	43	RCL
117	06	06
118	75	-
119	01	1
120	95	=
121	55	÷
122	43	RCL
123	05	05
124	95	=
125	42	STO
126	12	12
127	65	×
128	43	RCL
129	07	07
130	95	=
131	42	STO
132	11	11
133	43	RCL
134	12	12
135	65	×
136	43	RCL
137	18	18
138	95	=
139	42	STO
140	13	13
141	43	RCL
142	11	11
143	75	-
144	43	RCL
145	17	17
146	95	=
147	42	STO
148	11	11
149	43	RCL
150	13	13
151	75	-
152	43	RCL
153	10	10
154	95	=
155	42	STO
156	13	13
157	43	RCL

Title of Program: Mie Extinction Efficiency, Cards 1 and 2, Banks 1,2,3

Location	Code	Key
158	07	07
159	42	STO
160	17	17
161	43	RCL
162	18	18
163	42	STO
164	10	10
165	43	RCL
166	11	11
167	42	STO
168	07	07
169	43	RCL
170	13	13
171	42	STO
172	18	18
173	87	IFF
174	00	00
175	44	SUM
176	86	STF
177	00	00
178	43	RCL
179	20	20
180	65	×
181	43	RCL
182	05	05
183	95	=
184	42	STO
185	22	22
186	38	SIN
187	42	STO
188	23	23
189	43	RCL
190	22	22
191	39	COS
192	65	×
193	43	RCL
194	23	23
195	95	=
196	42	STO
197	24	24
198	43	RCL
199	21	21
200	65	×
201	43	RCL
202	05	05

Location	Code	Key
203	95	=
204	42	STO
205	25	25
206	22	INV
207	23	LNX
208	85	+
209	43	RCL
210	25	25
211	94	+/-
212	22	INV
213	23	LNX
214	95	=
215	55	÷
216	02	2
217	95	=
218	42	STO
219	26	26
220	43	RCL
221	25	25
222	22	INV
223	23	LNX
224	75	-
225	43	RCL
226	25	25
227	94	+/-
228	22	INV
229	23	LNX
230	95	=
231	55	÷
232	02	2
233	95	=
234	42	STO
235	27	27
236	65	×
237	43	RCL
238	26	26
239	95	=
240	42	STO
241	28	28
242	43	RCL
243	23	23
244	33	X²
245	85	+
246	43	RCL
247	27	27

Title of Program: Mie Extinction Efficiency, Cards 1 and 2, Banks 1,2,3

Location	Code	Key
248	33	X^2
249	95	=
250	42	STO
251	29	29
252	43	RCL
253	24	24
254	55	÷
255	43	RCL
256	29	29
257	95	=
258	42	STO
259	24	24
260	43	RCL
261	28	28
262	55	÷
263	43	RCL
264	29	29
265	95	=
266	42	STO
267	28	28
268	76	LBL
269	44	SUM
270	43	RCL
271	22	22
272	36	PGM
273	05	05
274	11	A
275	43	RCL
276	25	25
277	36	PGM
278	05	05
279	11	A
280	36	PGM
281	05	05
282	15	E
283	65	×
284	43	RCL
285	06	06
286	95	=
287	42	STO
288	11	11
289	32	X:T
290	65	×
291	43	RCL
292	06	06
293	95	=
294	42	STO
295	12	12
296	43	RCL
297	11	11
298	36	PGM
299	04	04
300	11	A
301	43	RCL
302	12	12
303	36	PGM
304	04	04
305	11	A
306	43	RCL
307	24	24
308	36	PGM
309	04	04
310	16	A'
311	43	RCL
312	28	28
313	36	PGM
314	04	04
315	16	A'
316	36	PGM
317	04	04
318	17	B'
319	36	PGM
320	05	05
321	15	E
322	43	RCL
323	11	11
324	36	PGM
325	04	04
326	16	A'
327	43	RCL
328	12	12
329	36	PGM
330	04	04
331	16	A'
332	36	PGM
333	04	04
334	17	B'
335	42	STO
336	24	24
337	32	X:T

Title of Program: Mie Extinction Efficiency, Cards 1 and 2, Banks 1,2,3

Location	Code	Key
338	42	STO
339	28	28
340	43	RCL
341	20	20
342	36	PGM
343	04	04
344	16	A'
345	43	RCL
346	21	21
347	94	+/-
348	36	PGM
349	04	04
350	16	A'
351	36	PGM
352	04	04
353	18	C'
354	85	+
355	43	RCL
356	06	06
357	55	÷
358	43	RCL
359	05	05
360	95	=
361	42	STO
362	11	11
363	32	X:T
364	42	STO
365	12	12
366	65	×
367	43	RCL
368	07	07
369	95	=
370	42	STO
371	13	13
372	43	RCL
373	11	11
374	65	×
375	43	RCL
376	07	07
377	95	=
378	42	STO
379	19	19
380	75	-
381	43	RCL

Location	Code	Key
382	17	17
383	95	=
384	42	STO
385	19	19
386	43	RCL
387	11	11
388	36	PGM
389	04	04
390	11	A
391	43	RCL
392	12	12
393	36	PGM
394	04	04
395	11	A
396	43	RCL
397	07	07
398	36	PGM
399	04	04
400	16	A'
401	43	RCL
402	18	18
403	36	PGM
404	04	04
405	16	A'
406	36	PGM
407	04	04
408	13	C
409	42	STO
410	11	11
411	32	X:T
412	42	STO
413	12	12
414	43	RCL
415	17	17
416	36	PGM
417	04	04
418	16	A'
419	43	RCL
420	10	10
421	36	PGM
422	04	04
423	16	A'
424	36	PGM
425	04	04

Title of Program: Mie Extinction Efficiency, Cards 1 and 2, Banks 1,2,3

Location	Code	Key
426	17	B'
427	42	STO
428	11	11
429	32	X:T
430	42	STO
431	12	12
432	43	RCL
433	19	19
434	36	PGM
435	04	04
436	11	A
437	43	RCL
438	13	13
439	36	PGM
440	04	04
441	11	A
442	43	RCL
443	11	11
444	36	PGM
445	04	04
446	16	A'
447	43	RCL
448	12	12
449	36	PGM
450	04	04
451	16	A'
452	36	PGM
453	04	04
454	18	C'
455	42	STO
456	11	11
457	75	-
458	93	.
459	05	5
460	95	=
461	33	X²
462	85	+
463	32	X:T
464	42	STO
465	12	12
466	33	X²
467	95	=
468	43	RCL
469	24	24
470	36	PGM

Location	Code	Key
471	04	04
472	11	A
473	43	RCL
474	28	28
475	36	PGM
476	04	04
477	11	A
478	43	RCL
479	20	20
480	36	PGM
481	04	04
482	16	A'
483	43	RCL
484	21	21
485	94	+/-
486	36	PGM
487	04	04
488	16	A'
489	36	PGM
490	04	04
491	13	C
492	85	+
493	43	RCL
494	06	06
495	55	÷
496	43	RCL
497	05	05
498	95	=
499	42	STO
500	14	14
501	32	X:T
502	42	STO
503	15	15
504	43	RCL
505	14	14
506	65	×
507	43	RCL
508	07	07
509	95	=
510	42	STO
511	13	13
512	43	RCL
513	15	15
514	65	×
515	43	RCL

Title of Program: Mie Extinction Efficiency, Cards 1 and 2, Banks 1,2,3

Location	Code	Key
516	07	07
517	95	=
518	42	STO
519	19	19
520	43	RCL
521	13	13
522	75	-
523	43	RCL
524	17	17
525	95	=
526	42	STO
527	13	13
528	43	RCL
529	14	14
530	36	PGM
531	04	04
532	11	A
533	43	RCL
534	15	15
535	36	PGM
536	04	04
537	11	A
538	43	RCL
539	07	07
540	36	PGM
541	04	04
542	16	A'
543	43	RCL
544	18	18
545	36	PGM
546	04	04
547	16	A'
548	36	PGM
549	04	04
550	13	C
551	42	STO
552	14	14
553	32	X:T
554	42	STO
555	15	15
556	43	RCL
557	17	17
558	36	PGM

Location	Code	Key
559	04	04
560	16	A'
561	43	RCL
562	10	10
563	36	PGM
564	04	04
565	16	A'
566	36	PGM
567	04	04
568	17	B'
569	42	STO
570	14	14
571	32	X:T
572	42	STO
573	15	15
574	43	RCL
575	13	13
576	36	PGM
577	04	04
578	11	A
579	43	RCL
580	19	19
581	36	PGM
582	04	04
583	11	A
584	43	RCL
585	14	14
586	36	PGM
587	04	04
588	16	A'
589	43	RCL
590	15	15
591	36	PGM
592	04	04
593	16	A'
594	36	PGM
595	04	04
596	18	C'
597	42	STO
598	14	14
599	32	X:T
600	42	STO
601	15	15

Title of Program: Mie Extinction Efficiency, Cards 1 and 2, Banks 1,2,3

Location	Code	Key
602	43	RCL
603	11	11
604	85	+
605	43	RCL
606	14	14
607	95	=
608	65	×
609	53	(
610	02	2
611	65	×
612	43	RCL
613	06	06
614	85	+
615	01	1
616	54	)
617	42	STO
618	36	36
619	95	=
620	44	SUM
621	16	16
622	97	DSZ
623	08	08
624	45	Y^x
625	43	RCL
626	16	16
627	65	×
628	02	2
629	55	÷
630	43	RCL
631	05	05
632	33	X^2
633	95	=
634	99	PRT
635	98	ADV
636	22	INV
637	86	STF
638	00	00
639	91	R/S

APPENDIX E

Title of Program: PROGRAM NO. 5: Long Opacity, Card 1, Bank 1

Location	Code	Key
000	76	LBL
001	11	A
002	69	OP
003	00	00
004	03	3
005	06	6
006	02	2
007	04	4
008	02	2
009	02	2
010	03	3
011	00	0
012	01	1
013	03	3
014	69	OP
015	01	01
016	69	OP
017	05	05
018	91	R/S
019	99	PRT
020	42	STO
021	39	39
022	01	1
023	06	6
024	02	2
025	02	2
026	69	OP
027	01	01
028	69	OP
029	05	05
030	91	R/S
031	42	STO
032	19	19
033	99	PRT
034	53	(
035	53	(

Location	Code	Key
036	43	RCL
037	19	19
038	55	÷
039	02	2
040	54	)
041	23	LNX
042	75	-
043	43	RCL
044	39	39
045	23	LNX
046	33	X²
047	65	×
048	03	3
049	54	)
050	22	INV
051	23	LNX
052	42	STO
053	38	38
054	93	.
055	01	1
056	42	STO
057	01	01
058	42	STO
059	35	35
060	02	2
061	00	0
062	42	STO
063	02	02
064	42	STO
065	33	33
066	04	4
067	03	3
068	69	OP
069	01	01
070	69	OP
071	05	05

Title of Program: Long Opacity, Card 1, Bank 1

Location	Code	Key
072	91	R/S
073	99	PRT
074	42	STO
075	09	09
076	01	1
077	03	3
078	69	OP
079	01	01
080	69	OP
081	05	05
082	91	R/S
083	99	PRT
084	42	STO
085	20	20
086	01	1
087	04	4
088	69	OP
089	01	01
090	69	OP
091	05	05
092	91	R/S
093	99	PRT
094	42	STO
095	21	21
096	01	1
097	00	0
098	00	0
099	36	PGM
100	09	09
101	13	C
102	42	STO
103	32	32
104	00	0
105	42	STO
106	04	04
107	42	STO
108	31	31
109	04	4
110	69	OP
111	17	17
112	91	R/S

Title of Program: Long Opacity, Card 1, Bank 3

Location	Code	Key
480	85	+
481	43	RCL
482	06	06
483	55	÷
484	43	RCL
485	34	34
486	54	)
487	42	STD
488	14	14
489	53	(
490	32	X:T
491	65	×
492	43	RCL
493	07	07
494	54	)
495	42	STD
496	19	19
497	53	(
498	43	RCL
499	14	14
500	65	×
501	43	RCL
502	07	07
503	54	)
504	42	STD
505	13	13
506	53	(
507	43	RCL
508	13	13
509	75	-
510	43	RCL
511	17	17
512	54	)
513	42	STD
514	13	13
515	43	RCL
516	14	14
517	42	STD
518	01	01
519	43	RCL
520	07	07
521	36	PGM
522	04	04
523	16	A'
524	43	RCL
525	18	18
526	36	PGM
527	04	04
528	16	A'
529	36	PGM
530	04	04
531	13	C
532	42	STD
533	14	14
534	32	X:T
535	42	STD
536	15	15
537	43	RCL
538	17	17
539	36	PGM
540	04	04
541	16	A'
542	43	RCL
543	10	10
544	36	PGM
545	04	04
546	16	A'
547	36	PGM
548	04	04
549	17	B'
550	42	STD
551	14	14
552	32	X:T
553	42	STD
554	15	15
555	43	RCL
556	13	13
557	42	STD
558	01	01
559	43	RCL
560	19	19
561	42	STD
562	02	.02
563	43	RCL
564	14	14
565	36	PGM
566	04	04
567	16	A'

Title of Program: Long Opacity, Card 1, Bank 3

Location	Code	Key
568	43	RCL
569	15	15
570	36	PGM
571	04	04
572	16	A'
573	36	PGM
574	04	04
575	18	C'
576	42	STO
577	14	14
578	32	X⇄T
579	42	STO
580	15	15
581	53	(
582	53	(
583	43	RCL
584	11	11
585	85	+
586	43	RCL
587	14	14
588	54	)
589	65	×
590	53	(
591	02	2
592	65	×
593	43	RCL
594	06	06
595	85	+
596	01	1
597	54	)
598	42	STO
599	36	36
600	54	)
601	44	SUM
602	16	16
603	97	DSZ
604	08	08
605	45	Y^x
606	53	(
607	43	RCL
608	16	16
609	65	×
610	02	2
611	55	÷
612	43	RCL
613	34	34
614	33	X^2
615	54	)
616	42	STO
617	30	30
618	22	INV
619	86	STF
620	00	00
621	43	RCL
622	35	35
623	42	STO
624	01	01
625	43	RCL
626	33	33
627	42	STO
628	02	02
629	43	RCL
630	32	32
631	42	STO
632	03	03
633	43	RCL
634	31	31
635	42	STO
636	04	04
637	61	GTO
638	00	00
639	20	20

Title of Program: Long Opacity, Card 2, Banks 1 and 2

Location	Code	Key
000	36	PGM
001	09	09
002	14	D
003	99	PRT
004	91	R/S
005	76	LBL
006	16	A'
007	53	(
008	42	STO
009	37	37
010	03	3
011	32	X:T
012	43	RCL
013	37	37
014	22	INV
015	77	GE
016	10	E'
017	02	2
018	42	STO
019	30	30
020	43	RCL
021	37	37
022	68	NOP
023	65	×
024	43	RCL
025	30	30
026	65	×
027	53	(
028	53	(
029	43	RCL
030	37	37
031	55	÷
032	43	RCL
033	38	38
034	54	)
035	23	LNX
036	33	X²
037	55	÷
038	02	2
039	55	÷
040	43	RCL
041	39	39
042	23	LNX
043	33	X²
044	54	)
045	94	+/-
046	22	INV
047	23	LNX
048	54	)
049	92	RTN
050	76	LBL
051	10	E'
052	43	RCL
053	04	04
054	42	STO
055	31	31
056	53	(
057	43	RCL
058	37	37
059	65	×
060	89	π
061	65	×
062	02	2
063	55	÷
064	43	RCL
065	09	09
066	54	)
067	42	STO
068	34	34
069	76	LBL
070	34	ΓX
071	70	RAD
072	00	0
073	42	STO
074	16	16
075	42	STO
076	06	06
077	53	(
078	43	RCL
079	34	34
080	65	×
081	02	2
082	54	)
083	59	INT
084	42	STO
085	08	08
086	43	RCL
087	34	34
088	38	SIN
089	42	STO

Title of Program: Long Opacity, Card 2, Banks 1 and 2

Location	Code	Key
090	07	07
091	43	RCL
092	34	34
093	39	COS
094	42	STO
095	18	18
096	42	STO
097	17	17
098	43	RCL
099	07	07
100	94	+/-
101	42	STO
102	10	10
103	76	LBL
104	45	Y^x
105	01	1
106	44	SUM
107	06	06
108	53	(
109	53	(
110	53	(
111	02	2
112	65	×
113	43	RCL
114	06	06
115	75	-
116	01	1
117	54	)
118	55	÷
119	43	RCL
120	34	34
121	54	)
122	42	STO
123	12	12
124	65	×
125	43	RCL
126	07	07
127	54	)
128	42	STO
129	11	11
130	53	(
131	43	RCL
132	12	12
133	65	×
134	43	RCL

Location	Code	Key
135	18	18
136	54	)
137	42	STO
138	13	13
139	53	(
140	43	RCL
141	11	11
142	75	-
143	43	RCL
144	17	17
145	54	)
146	42	STO
147	11	11
148	53	(
149	43	RCL
150	13	13
151	75	-
152	43	RCL
153	10	10
154	54	)
155	42	STO
156	13	13
157	43	RCL
158	07	07
159	42	STO
160	17	17
161	43	RCL
162	18	18
163	42	STO
164	10	10
165	43	RCL
166	11	11
167	42	STO
168	07	07
169	43	RCL
170	13	13
171	42	STO
172	18	18
173	87	IFF
174	00	00
175	44	SUM
176	86	STF
177	00	00
178	53	(
179	43	RCL

Title of Program: Long Opacity, Card 2, Banks 1 and 2

Location	Code	Key
180	20	20
181	65	×
182	43	RCL
183	34	34
184	54	)
185	42	STO
186	22	22
187	38	SIN
188	42	STO
189	23	23
190	53	(
191	43	RCL
192	22	22
193	39	COS
194	65	×
195	43	RCL
196	23	23
197	54	)
198	42	STO
199	24	24
200	53	(
201	53	(
202	53	(
203	43	RCL
204	21	21
205	65	×
206	43	RCL
207	34	34
208	54	)
209	42	STO
210	25	25
211	22	INV
212	23	LNX
213	85	+
214	43	RCL
215	25	25
216	94	+/-
217	22	INV
218	23	LNX
219	54	)
220	55	÷
221	02	2
222	54	)
223	42	STO
224	26	26

Location	Code	Key
225	53	(
226	53	(
227	53	(
228	43	RCL
229	25	25
230	22	INV
231	23	LNX
232	75	-
233	43	RCL
234	25	25
235	94	+/-
236	22	INV
237	23	LNX
238	54	)
239	55	÷
240	02	2
241	54	)
242	42	STO
243	27	27
244	65	×
245	43	RCL
246	26	26
247	54	)
248	42	STO
249	28	28
250	53	(
251	43	RCL
252	23	23
253	33	X²
254	85	+
255	43	RCL
256	27	27
257	33	X²
258	54	)
259	42	STO
260	29	29
261	53	(
262	43	RCL
263	24	24
264	55	÷
265	43	RCL
266	29	29
267	54	)
268	42	STO
269	24	24

Title of Program: Long Opacity, Card 2, Banks 1 and 2

Location	Code	Key
270	53	(
271	43	RCL
272	28	28
273	55	÷
274	43	RCL
275	29	29
276	54	)
277	42	STO
278	28	28
279	76	LBL
280	44	SUM
281	43	RCL
282	22	22
283	42	STO
284	01	01
285	43	RCL
286	25	25
287	42	STO
288	02	02
289	36	PGM
290	05	05
291	15	E
292	43	RCL
293	06	06
294	36	PGM
295	04	04
296	16	A'
297	00	0
298	36	PGM
299	04	04
300	16	A'
301	36	PGM
302	04	04
303	13	C
304	42	STO
305	11	11
306	32	X⇌T
307	42	STO
308	12	12
309	43	RCL
310	24	24
311	36	PGM
312	04	04
313	16	A'
314	43	RCL
315	28	28
316	36	PGM
317	04	04
318	16	A'
319	36	PGM
320	04	04
321	17	B'
322	36	PGM
323	05	05
324	15	E
325	43	RCL
326	11	11
327	36	PGM
328	04	04
329	16	A'
330	43	RCL
331	12	12
332	36	PGM
333	04	04
334	16	A'
335	36	PGM
336	04	04
337	17	B'
338	42	STO
339	24	24
340	32	X⇌T
341	42	STO
342	28	28
343	43	RCL
344	20	20
345	36	PGM
346	04	04
347	16	A'
348	43	RCL
349	21	21
350	94	+/-
351	36	PGM
352	04	04
353	16	A'
354	53	(
355	36	PGM
356	04	04
357	18	C'
358	85	+

Title of Program: Long Opacity, Card 2, Banks 1 and 2

Location	Code	Key
359	43	RCL
360	06	06
361	55	÷
362	43	RCL
363	34	34
364	54	)
365	42	STO
366	11	11
367	53	(
368	32	X:T
369	65	×
370	43	RCL
371	07	07
372	54	)
373	42	STO
374	13	13
375	53	(
376	53	(
377	43	RCL
378	11	11
379	65	×
380	43	RCL
381	07	07
382	54	)
383	42	STO
384	19	19
385	75	-
386	43	RCL
387	17	17
388	54	)
389	42	STO
390	19	19
391	43	RCL
392	11	11
393	42	STO
394	01	01
395	43	RCL
396	07	07
397	36	PGM
398	04	04
399	16	A'
400	43	RCL
401	18	18
402	36	PGM

Location	Code	Key
403	04	04
404	16	A'
405	36	PGM
406	04	04
407	13	C
408	42	STO
409	11	11
410	32	X:T
411	42	STO
412	12	12
413	43	RCL
414	17	17
415	36	PGM
416	04	04
417	16	A'
418	43	RCL
419	10	10
420	36	PGM
421	04	04
422	16	A'
423	36	PGM
424	04	04
425	17	B'
426	42	STO
427	11	11
428	32	X:T
429	42	STO
430	12	12
431	43	RCL
432	19	19
433	42	STO
434	01	01
435	43	RCL
436	13	13
437	42	STO
438	02	02
439	43	RCL
440	11	11
441	36	PGM
442	04	04
443	16	A'
444	43	RCL
445	12	12
446	36	PGM

Title of Program: Long Opacity, Card 2, Banks 1 and 2

Location	Code	Key
447	04	04
448	16	A'
449	36	PGM
450	04	04
451	18	C'
452	42	STO
453	11	11
454	32	X:T
455	42	STO
456	12	12
457	43	RCL
458	24	24
459	42	STO
460	01	01
461	43	RCL
462	28	28
463	42	STO
464	02	02
465	43	RCL
466	20	20
467	36	PGM
468	04	04
469	16	A'
470	43	RCL
471	21	21
472	94	+/-
473	36	PGM
474	04	04
475	16	A'
476	53	(
477	36	PGM
478	04	04
479	13	C

Title of Program: Long Opacity, Card 3, Bank 1

Location	Code	Key
000	76	LBL
001	11	A
002	25	CLR
003	69	OP
004	00	00
005	03	3
006	00	0
007	01	1
008	03	3
009	03	3
010	06	6
011	03	3
012	06	6
013	07	7
014	01	1
015	69	OP
016	01	01
017	69	OP
018	05	05
019	91	R/S
020	99	PRT
021	42	STO
022	22	22
023	01	1
024	06	6
025	01	1
026	07	7
027	03	3
028	01	1
029	03	3
030	06	6
031	07	7
032	01	1
033	69	OP
034	01	01
035	69	OP
036	05	05
037	91	R/S
038	99	PRT
039	42	STO
040	23	23
041	03	3
042	06	6
043	03	3
044	07	7

Location	Code	Key
045	01	1
046	05	5
047	02	2
048	06	6
049	00	0
050	00	0
051	69	OP
052	01	01
053	01	1
054	06	6
055	02	2
056	04	4
057	01	1
058	03	3
059	03	3
060	00	0
061	07	7
062	01	1
063	69	OP
064	02	02
065	69	OP
066	05	05
067	91	R/S
068	99	PRT
069	42	STO
070	24	24
071	25	CLR
072	69	OP
073	00	00
074	01	1
075	00	0
076	00	0
077	36	PGM
078	09	09
079	13	C
080	25	CLR
081	69	OP
082	00	00
083	06	6
084	04	4
085	00	0
086	00	0
087	02	2
088	06	6
089	03	3

Title of Program: Long Opacity, Card 3, Bank 1

Location	Code	Key
090	06	6
091	03	3
092	03	3
093	69	OP
094	04	04
095	43	RCL
096	04	04
097	42	STO
098	08	08
099	00	0
100	42	STO
101	04	04
102	36	PGM
103	09	09
104	14	D
105	61	GTO
106	01	01
107	38	38
108	76	LBL
109	16	A'
110	53	(
111	42	STO
112	37	37
113	33	X²
114	65	×
115	53	(
116	53	(
117	43	RCL
118	37	37
119	55	÷
120	43	RCL
121	38	38
122	54	)
123	23	LNX
124	33	X²
125	55	÷
126	02	2
127	55	÷
128	43	RCL
129	39	39
130	23	LNX
131	33	X²
132	54	)
133	94	+/-
134	22	INV

Location	Code	Key
135	23	LNX
136	54	)
137	92	RTN
138	53	(
139	43	RCL
140	08	08
141	55	÷
142	43	RCL
143	04	04
144	65	×
145	03	3
146	55	÷
147	04	4
148	54	)
149	42	STO
150	09	09
151	69	OP
152	06	06
153	06	6
154	04	4
155	03	3
156	02	2
157	03	3
158	03	3
159	00	0
160	00	0
161	06	6
162	01	1
163	69	OP
164	04	04
165	53	(
166	53	(
167	53	(
168	43	RCL
169	22	22
170	65	×
171	43	RCL
172	09	09
173	65	×
174	43	RCL
175	24	24
176	55	÷
177	43	RCL
178	23	23
179	54	)

Title of Program: Long Opacity, Card 3, Bank 1

Location	Code	Key
180	94	+/-
181	22	INV
182	23	LNX
183	94	+/-
184	85	+
185	01	1
186	54	)
187	65	X
188	01	1
189	00	0
190	00	0
191	54	)
192	69	OP
193	06	06
194	91	R/S

APPENDIX F

Title of Program: PROGRAM NO. 6: ESP (Histogram) Card 1

Location	Code	Key	Location	Code	Key
000	76	LBL	036	91	R/S
001	11	A	037	99	PRT
002	69	OP	038	42	STO
003	00	00	039	00	00
004	01	1	040	42	STO
005	07	7	041	57	57
006	03	3	042	03	3
007	06	6	043	01	1
008	03	3	044	03	3
009	03	3	045	01	1
010	00	0	046	69	OP
011	00	0	047	01	01
012	69	OP	048	69	OP
013	02	02	049	05	05
014	02	2	050	91	R/S
015	04	4	051	42	STO
016	01	1	052	22	22
017	06	6	053	99	PRT
018	00	0	054	02	2
019	00	0	055	03	3
020	69	OP	056	69	OP
021	03	03	057	01	01
022	69	OP	058	69	OP
023	05	05	059	05	05
024	91	R/S	060	91	R/S
025	99	PRT	061	99	PRT
026	03	3	062	42	STO
027	01	1	063	01	01
028	03	3	064	04	4
029	03	3	065	01	1
030	69	OP	066	69	OP
031	00	00	067	01	01
032	69	OP	068	69	OP
033	01	01	069	05	05
034	69	OP	070	91	R/S
035	05	05	071	99	PRT

Title of Program: ESP (Histogram) Card 1

Location	Code	Key
072	55	÷
073	43	RCL
074	01	01
075	95	=
076	42	STO
077	02	02
078	55	÷
079	01	1
080	93	.
081	07	7
082	05	5
083	95	=
084	42	STO
085	01	01
086	69	OP
087	00	00
088	01	1
089	07	7
090	01	1
091	03	3
092	69	OP
093	04	04
094	43	RCL
095	02	02
096	69	OP
097	06	06
098	01	1
099	07	7
100	03	3
101	03	3
102	69	OP
103	04	04
104	43	RCL
105	01	01
106	69	OP
107	06	06
108	69	OP
109	00	00
110	04	4
111	02	2
112	69	OP
113	02	02
114	69	OP
115	05	05
116	91	R/S

Location	Code	Key
117	99	PRT
118	42	STO
119	08	08
120	01	1
121	04	4
122	69	OP
123	02	02
124	69	OP
125	05	05
126	91	R/S
127	99	PRT
128	42	STO
129	09	09
130	69	OP
131	00	00
132	02	2
133	05	5
134	69	OP
135	01	01
136	69	OP
137	05	05
138	91	R/S
139	99	PRT
140	55	÷
141	01	1
142	93	.
143	06	6
144	52	EE
145	94	+/-
146	01	1
147	09	9
148	55	÷
149	43	RCL
150	02	02
151	55	÷
152	43	RCL
153	09	09
154	95	=
155	42	STO
156	11	11
157	03	3
158	01	1
159	03	3
160	02	2
161	69	OP

Title of Program: ESP (Histogram) Card 1

Location	Code	Key
162	04	04
163	43	RCL
164	11	11
165	69	OP
166	06	06
167	69	OP
168	00	00
169	02	2
170	06	6
171	69	OP
172	01	01
173	69	OP
174	05	05
175	91	R/S
176	22	INV
177	52	EE
178	99	PRT
179	42	STO
180	12	12
181	03	3
182	07	7
183	69	OP
184	01	01
185	69	OP
186	05	05
187	91	R/S
188	99	PRT
189	65	+
190	02	2
191	07	7
192	03	3
193	95	=
194	42	STO
195	05	05
196	04	4
197	02	2
198	02	2
199	04	4
200	03	3
201	06	6
202	69	OP
203	01	01
204	69	OP
205	05	05
206	91	R/S

Location	Code	Key
207	99	PRT
208	65	×
209	93	.
210	01	1
211	95	=
212	42	STO
213	04	04
214	03	3
215	03	3
216	69	OP
217	01	01
218	69	OP
219	05	05
220	91	R/S
221	22	INV
222	52	EE
223	99	PRT
224	35	1/X
225	65	×
226	07	7
227	06	6
228	65	×
229	93	.
230	00	0
231	06	6
232	05	5
233	03	3
234	65	×
235	43	RCL
236	05	05
237	55	÷
238	02	2
239	09	9
240	06	6
241	93	.
242	02	2
243	95	=
244	42	STO
245	07	07
246	03	3
247	06	6
248	01	1
249	05	5
250	01	1
251	03	3

Title of Program: ESP (Histogram) Card 1

Location	Code	Key
252	69	OP
253	01	01
254	69	OP
255	05	05
256	91	R/S
257	99	PRT
258	42	STO
259	03	03
260	02	2
261	07	7
262	01	1
263	07	7
264	03	3
265	01	1
266	02	2
267	02	2
268	03	3
269	07	7
270	69	OP
271	01	01
272	02	2
273	03	3
274	00	0
275	00	0
276	00	0
277	00	0
278	00	0
279	00	0
280	00	0
281	00	0
282	69	OP
283	02	02
284	69	OP
285	05	05
286	91	R/S
287	99	PRT
288	42	STO
289	20	20
290	69	OP
291	00	00
292	04	4
293	02	2
294	01	1
295	07	7

Location	Code	Key
296	02	2
297	07	7
298	69	OP
299	01	01
300	69	OP
301	05	05
302	91	R/S
303	99	PRT
304	35	1/X
305	65	×
306	43	RCL
307	20	20
308	95	=
309	42	STO
310	10	10
311	03	3
312	06	6
313	02	2
314	04	4
315	02	2
316	02	2
317	03	3
318	00	0
319	01	1
320	03	3
321	69	OP
322	01	01
323	69	OP
324	05	05
325	91	R/S
326	99	PRT
327	42	STO
328	06	06
329	03	3
330	01	1
331	03	3
332	06	6
333	69	OP
334	01	01
335	69	OP
336	05	05
337	91	R/S
338	99	PRT
339	42	STO

Title of Program: ESP (Histogram) Card 1

Location	Code	Key
340	13	13
341	03	3
342	06	6
343	69	OP
344	01	01
345	69	OP
346	05	05
347	91	R/S
348	99	PRT
349	42	STO
350	14	14
351	02	2
352	93	.
353	02	2
354	02	2
355	04	4
356	52	EE
357	08	8
358	42	STO
359	15	15
360	08	8
361	93	.
362	06	6
363	07	7
364	01	1
365	52	EE
366	05	5
367	94	+/-
368	42	STO
369	16	16
370	02	2
371	05	5
372	42	STO
373	17	17
374	04	4
375	01	1
376	42	STO
377	18	18
378	42	STO
379	19	19
380	00	0
381	42	STO
382	20	20
383	42	STO

Location	Code	Key
384	21	21
385	91	R/S
386	76	LBL
387	12	B
388	43	RCL
389	00	00
390	42	STO
391	20	20
392	43	RCL
393	17	17
394	42	STO
395	21	21
396	76	LBL
397	13	C
398	01	1
399	06	6
400	69	OP
401	01	01
402	69	OP
403	05	05
404	91	R/S
405	99	PRT
406	72	ST*
407	17	17
408	01	1
409	44	SUM
410	17	17
411	97	DSZ
412	00	00
413	13	C
414	43	RCL
415	20	20
416	42	STO
417	00	00
418	43	RCL
419	21	21
420	42	STO
421	17	17
422	43	RCL
423	18	18
424	42	STO
425	21	21
426	76	LBL
427	14	D

Title of Program: ESP (Histogram) Card 1

Location	Code	Key
428	03	3
429	00	0
430	01	1
431	03	3
432	03	3
433	06	6
434	03	3
435	06	6
436	69	OP
437	01	01
438	69	OP
439	05	05
440	91	R/S
441	99	PRT
442	72	ST*
443	18	18
444	01	1
445	44	SUM
446	18	18
447	97	DSZ
448	00	00
449	14	D
450	43	RCL
451	21	21
452	42	STO
453	18	18
454	43	RCL
455	20	20
456	42	STO
457	00	00
458	00	0
459	42	STO
460	21	21
461	00	0
462	42	STO
463	20	20
464	42	STO
465	21	21
466	91	R/S

Title of Program: ESP (Histogram) Card 2

Location	Code	Key
000	76	LBL
001	12	B
002	01	1
003	52	EE
004	94	+/-
005	06	6
006	32	X:T
007	61	GTO
008	50	I×I
009	76	LBL
010	17	B'
011	43	RCL
012	23	23
013	22	INV
014	77	GE
015	87	IFF
016	61	GTO
017	60	DEG
018	76	LBL
019	10	E'
020	53	(
021	73	RC*
022	17	17
023	77	GE
024	87	IFF
025	23	LNX
026	65	×
027	93	.
028	04	4
029	05	5
030	94	+/-
031	85	+
032	01	1
033	93	.
034	07	7
035	54	)
036	92	RTN
037	76	LBL
038	87	IFF
039	01	1
040	54	)
041	92	RTN
042	76	LBL
043	13	C
044	53	(
045	89	π
046	65	×
047	73	RC*
048	17	17
049	55	÷
050	02	2
051	52	EE
052	06	6
053	65	×
054	43	RCL
055	15	15
056	65	×
057	53	(
058	43	RCL
059	09	09
060	65	×
061	73	RC*
062	17	17
063	55	÷
064	02	2
065	52	EE
066	06	6
067	65	×
068	43	RCL
069	02	02
070	65	×
071	43	RCL
072	58	58
073	65	×
074	43	RCL
075	11	11
076	55	÷
077	53	(
078	43	RCL
079	09	09
080	65	×
081	43	RCL
082	58	58
083	65	×
084	43	RCL
085	11	11
086	85	+
087	43	RCL
088	15	15
089	54	)

Title of Program: ESP (Histogram) Card 2

Location	Code	Key
090	65	×
091	53	(
092	01	1
093	85	+
094	02	2
095	65	×
096	53	(
097	43	RCL
098	12	12
099	75	-
100	01	1
101	54	)
102	55	÷
103	53	(
104	43	RCL
105	12	12
106	85	+
107	02	2
108	54	)
109	54	)
110	85	+
111	43	RCL
112	16	16
113	65	×
114	43	RCL
115	05	05
116	65	×
117	53	(
118	73	RC*
119	17	17
120	55	÷
121	02	2
122	52	EE
123	06	6
124	65	×
125	43	RCL
126	58	58
127	65	×
128	43	RCL
129	11	11
130	65	×
131	43	RCL
132	08	08
133	55	÷
134	53	(

Location	Code	Key
135	43	RCL
136	15	15
137	65	×
138	43	RCL
139	16	16
140	65	×
141	43	RCL
142	05	05
143	54	)
144	85	+
145	01	1
146	54	)
147	23	LNX
148	54	)
149	54	)
150	92	RTN
151	76	LBL
152	18	C'
153	53	(
154	01	1
155	85	+
156	02	2
157	65	×
158	43	RCL
159	07	07
160	55	÷
161	73	RC*
162	17	17
163	65	×
164	53	(
165	01	1
166	93	.
167	02	2
168	06	6
169	85	+
170	93	.
171	04	4
172	02	2
173	65	×
174	53	(
175	01	1
176	93	.
177	00	0
178	08	8
179	65	×

Title of Program: ESP (Histogram) Card 2

Location	Code	Key
180	73	RC*
181	17	17
182	55	÷
183	53	(
184	02	2
185	65	×
186	43	RCL
187	07	07
188	54	)
189	54	)
190	94	+/-
191	22	INV
192	23	LNX
193	54	)
194	54	)
195	24	CE
196	92	RTN
197	76	LBL
198	11	A
199	04	4
200	93	.
201	05	5
202	32	X:T
203	98	ADV
204	69	OP
205	00	00
206	06	6
207	04	4
208	01	1
209	06	6
210	69	OP
211	04	04
212	73	RC*
213	17	17
214	69	OP
215	06	06
216	43	RCL
217	22	22
218	42	STO
219	24	24
220	43	RCL
221	10	10
222	99	PRT
223	55	÷
224	43	RCL
225	22	22
226	95	=
227	42	STO
228	59	59
229	42	STO
230	58	58
231	01	1
232	42	STO
233	23	23
234	76	LBL
235	30	TAN
236	43	RCL
237	58	58
238	13	C
239	65	×
240	01	1
241	93	.
242	06	6
243	52	EE
244	01	1
245	09	9
246	94	+/-
247	65	×
248	43	RCL
249	01	01
250	55	÷
251	53	(
252	06	6
253	65	×
254	89	π
255	65	×
256	53	(
257	73	RC*
258	17	17
259	55	÷
260	02	2
261	52	EE
262	06	6
263	54	)
264	65	×
265	43	RCL
266	04	04
267	54	)
268	65	×
269	18	C'

Title of Program: ESP (Histogram) Card 2

Location	Code	Key
270	65	×
271	10	E'
272	95	=
273	65	×
274	43	RCL
275	03	03
276	55	÷
277	43	RCL
278	22	22
279	94	+/-
280	95	=
281	22	INV
282	23	LNX
283	95	=
284	49	PRD
285	23	23
286	43	RCL
287	59	59
288	44	SUM
289	58	58
290	97	DSZ
291	24	24
292	30	TAN
293	98	ADV
294	43	RCL
295	23	23
296	65	×
297	73	RC*
298	18	18
299	95	=
300	99	PRT
301	44	SUM
302	21	21
303	43	RCL
304	23	23
305	99	PRT
306	23	LNX
307	94	+/-
308	55	÷
309	43	RCL
310	03	03
311	95	=
312	99	PRT
313	55	÷
314	53	(

Location	Code	Key
315	12	B
316	65	×
317	17	B'
318	54	)
319	65	×
320	43	RCL
321	03	03
322	94	+/-
323	95	=
324	22	INV
325	23	LNX
326	95	=
327	99	PRT
328	65	×
329	73	RC*
330	18	18
331	95	=
332	99	PRT
333	72	ST*
334	19	19
335	44	SUM
336	20	20
337	01	1
338	44	SUM
339	17	17
340	44	SUM
341	18	18
342	44	SUM
343	19	19
344	97	DSZ
345	00	00
346	11	A
347	98	ADV
348	43	RCL
349	21	21
350	99	PRT
351	43	RCL
352	20	20
353	99	PRT
354	92	RTN
355	76	LBL
356	50	I×I
357	53	(
358	43	RCL
359	23	23

Title of Program: ESP (Histogram) Card 2

Location	Code	Key
360	22	INV
361	77	GE
362	87	IFF
363	23	LNX
364	55	÷
365	53	(
366	43	RCL
367	13	13
368	65	×
369	53	(
370	43	RCL
371	14	14
372	85	+
373	53	(
374	01	1
375	75	-
376	43	RCL
377	14	14
378	54	)
379	65	×
380	43	RCL
381	23	23
382	45	YX
383	43	RCL
384	13	13
385	35	1/X
386	54	)
387	23	LNX
388	54	)
389	54	)
390	92	RTN
391	76	LBL
392	60	DEG
393	53	(
394	01	1
395	85	+
396	93	.
397	07	7
398	06	6
399	06	6
400	65	×
401	53	(
402	01	1
403	75	-
404	43	RCL
405	23	23
406	54	)
407	65	×
408	43	RCL
409	06	06
410	45	YX
411	01	1
412	93	.
413	07	7
414	08	8
415	06	6
416	85	+
417	93	.
418	00	0
419	07	7
420	05	5
421	05	5
422	65	×
423	43	RCL
424	06	06
425	65	×
426	53	(
427	43	RCL
428	23	23
429	35	1/X
430	54	)
431	23	LNX
432	54	)
433	92	RTN
434	76	LBL
435	14	D
436	69	OP
437	00	00
438	03	3
439	06	6
440	01	1
441	05	5
442	01	1
443	03	3
444	69	OP
445	01	01
446	69	OP
447	05	05
448	91	R/S
449	99	PRT

Title of Program: ESP (Histogram) Card 2

Location	Code	Key
450	42	STO
451	03	03
452	03	3
453	01	1
454	03	3
455	03	3
456	69	OP
457	01	01
458	69	OP
459	05	05
460	91	R/S
461	99	PRT
462	42	STO
463	00	00
464	00	0
465	42	STO
466	20	20
467	42	STO
468	21	21
469	02	2
470	05	5
471	42	STO
472	17	17
473	04	4
474	01	1
475	42	STO
476	18	18
477	11	A
478	92	RTN
479	05	5

APPENDIX G

Title of Program: PROGRAM NO. 7: Venturi Scrubber (Histogram) Card 1

Location	Code	Key
000	76	LBL
001	11	A
002	69	OP
003	00	00
004	03	3
005	07	7
006	07	7
007	01	1
008	69	OP
009	02	02
010	69	OP
011	05	05
012	91	R/S
013	99	PRT
014	42	STO
015	01	01
016	03	3
017	03	3
018	07	7
019	01	1
020	69	OP
021	02	02
022	69	OP
023	05	05
024	91	R/S
025	99	PRT
026	42	STO
027	02	02
028	02	2
029	01	1
030	07	7
031	01	1
032	69	OP
033	02	02
034	69	OP
035	05	05

Location	Code	Key
036	91	R/S
037	99	PRT
038	42	STO
039	03	03
040	03	3
041	01	1
042	07	7
043	01	1
044	69	OP
045	02	02
046	69	OP
047	05	05
048	91	R/S
049	99	PRT
050	42	STO
051	12	12
052	02	2
053	07	7
054	06	6
055	03	3
056	02	2
057	02	2
058	07	7
059	01	1
060	69	OP
061	02	02
062	69	OP
063	05	05
064	91	R/S
065	99	PRT
066	42	STO
067	05	05
068	04	4
069	01	1
070	02	2
071	02	2

Title of Program: Venturi Scrubber (Histogram) Card 1

Location	Code	Key
072	07	7
073	01	1
074	69	OP
075	02	02
076	69	OP
077	05	05
078	91	R/S
079	99	PRT
080	42	STO
081	06	06
082	16	A'
083	04	4
084	02	2
085	02	2
086	04	4
087	03	3
088	06	6
089	07	7
090	01	1
091	69	OP
092	02	02
093	69	OP
094	05	05
095	91	R/S
096	99	PRT
097	42	STO
098	07	07
099	03	3
100	05	5
101	02	2
102	03	3
103	03	3
104	02	2
105	69	OP
106	02	02
107	02	2
108	07	7
109	00	0
110	00	0
111	00	0
112	00	0
113	69	OP
114	03	03
115	69	OP
116	05	05

Location	Code	Key
117	91	R/S
118	99	PRT
119	42	STO
120	04	04
121	03	3
122	03	3
123	00	0
124	00	0
125	00	0
126	00	0
127	69	OP
128	03	03
129	69	OP
130	05	05
131	91	R/S
132	99	PRT
133	42	STO
134	08	08
135	05	5
136	00	0
137	55	÷
138	43	RCL
139	06	06
140	85	+
141	09	9
142	01	1
143	93	.
144	08	8
145	65	×
146	43	RCL
147	05	05
148	45	Y^x
149	01	1
150	93	.
151	05	5
152	95	=
153	42	STO
154	10	10
155	65	×
156	02	2
157	55	÷
158	05	5
159	05	5
160	65	×
161	43	RCL

Title of Program: Venturi Scrubber (Histogram) Card 1

Location	Code	Key
162	05	05
163	65	×
164	43	RCL
165	06	06
166	65	×
167	43	RCL
168	04	04
169	55	÷
170	43	RCL
171	07	07
172	95	=
173	42	STO
174	09	09
175	43	RCL
176	06	06
177	65	×
178	43	RCL
179	08	08
180	55	÷
181	53	(
182	09	9
183	52	EE
184	08	8
185	65	×
186	43	RCL
187	07	07
188	65	×
189	43	RCL
190	10	10
191	95	=
192	42	STO
193	10	10
194	93	.
195	00	0
196	06	6
197	05	5
198	03	3
199	65	×
200	07	7
201	06	6
202	55	÷
203	43	RCL
204	02	02
205	65	×
206	53	(
207	02	2
208	07	7
209	03	3
210	85	+
211	43	RCL
212	01	01
213	54	)
214	55	÷
215	02	2
216	09	9
217	06	6
218	93	.
219	02	2
220	95	=
221	42	STO
222	11	11
223	12	B
224	92	RTN
225	76	LBL
226	16	A'
227	06	6
228	04	4
229	07	7
230	05	5
231	03	3
232	03	3
233	69	OP
234	04	04
235	08	8
236	93	.
237	02	2
238	04	4
239	52	EE
240	04	4
241	94	+/-
242	65	×
243	53	(
244	43	RCL
245	06	06
246	33	X²
247	65	×
248	43	RCL
249	05	05
250	95	=
251	69	OP

Title of Program: Venturi Scrubber (Histogram) Card 1

Location	Code	Key
252	06	06
253	69	OP
254	00	00
255	92	RTN
256	76	LBL
257	12	B
258	43	RCL
259	12	12
260	42	STO
261	00	00
262	02	2
263	05	5
264	42	STO
265	13	13
266	04	4
267	01	1
268	42	STO
269	14	14
270	00	0
271	42	STO
272	15	15
273	98	ADV
274	06	6
275	04	4
276	01	1
277	06	6
278	69	OP
279	04	04
280	73	RC*
281	13	13
282	69	OP
283	06	06
284	18	C'
285	42	STO
286	16	16
287	00	0
288	00	0
289	03	3
290	03	3
291	03	3
292	07	7
293	69	OP
294	04	04
295	15	E
296	69	OP
297	06	06
298	06	6
299	04	4
300	03	3
301	02	2
302	00	0
303	00	0
304	69	OP
305	04	04
306	15	E
307	65	×
308	73	RC*
309	14	14
310	95	=
311	69	OP
312	06	06
313	44	SUM
314	15	15
315	98	ADV
316	01	1
317	44	SUM
318	13	13
319	44	SUM
320	14	14
321	97	DSZ
322	00	00
323	02	02
324	74	74
325	14	D
326	92	RTN
327	76	LBL
328	18	C'
329	53	(
330	01	1
331	85	+
332	02	2
333	65	×
334	43	RCL
335	11	11
336	55	÷
337	73	RC*
338	13	13
339	65	×
340	53	(
341	01	1

Title of Program: Venturi Scrubber (Histogram) Card 1

Location	Code	Key
342	93	.
343	02	2
344	04	4
345	02	2
346	85	+
347	93	.
348	04	4
349	02	2
350	65	×
351	53	(
352	93	.
353	08	8
354	07	7
355	65	×
356	73	RC*
357	13	13
358	55	÷
359	53	(
360	02	2
361	65	×
362	43	RCL
363	11	11
364	54	)
365	94	+/-
366	54	)
367	22	INV
368	23	LNX
369	54	)
370	54	)
371	92	RTN
372	76	LBL
373	13	C
374	53	(
375	73	RC*
376	13	13
377	33	X²
378	65	×
379	43	RCL
380	10	10
381	65	×
382	43	RCL
383	16	16
384	54	)
385	92	RTN
386	76	LBL

Location	Code	Key
387	15	E
388	53	(
389	43	RCL
390	09	09
391	65	×
392	53	(
393	93	.
394	07	7
395	94	+/-
396	75	-
397	13	C
398	65	×
399	43	RCL
400	03	03
401	85	+
402	01	1
403	93	.
404	04	4
405	65	×
406	53	(
407	53	(
408	43	RCL
409	03	03
410	65	×
411	13	C
412	85	+
413	93	.
414	07	7
415	54	)
416	55	÷
417	93	.
418	07	7
419	54	)
420	23	LNX
421	85	+
422	93	.
423	04	4
424	09	9
425	55	÷
426	53	(
427	93	.
428	07	7
429	85	+
430	13	C
431	65	×

Title of Program: Venturi Scrubber (Histogram) Card 1

Location	Code	Key
432	43	RCL
433	03	03
434	54	)
435	54	)
436	55	÷
437	13	C
438	54	)
439	22	INV
440	23	LNX
441	92	RTN
442	76	LBL
443	14	D
444	06	6
445	04	4
446	03	3
447	02	2
448	03	3
449	03	3
450	03	3
451	07	7
452	69	OP
453	04	04
454	43	RCL
455	15	15
456	69	OP
457	06	06
458	06	6
459	04	4
460	03	3
461	02	2
462	01	1
463	07	7
464	69	OP
465	04	04
466	01	1
467	75	-
468	43	RCL
469	15	15
470	95	=
471	69	OP
472	06	06
473	92	RTN

APPENDIX H

Title of Program: PROGRAM NO. 8: Venturi Scrubber (Lognormal)

Location	Code	Key
000	76	LBL
001	16	A'
002	42	STO
003	06	06
004	53	(
005	15	E
006	65	×
007	19	D'
008	54	)
009	92	RTN
010	76	LBL
011	15	E
012	53	(
013	43	RCL
014	06	06
015	33	X^2
016	65	×
017	43	RCL
018	08	08
019	65	×
020	13	C
021	65	×
022	43	RCL
023	16	16
024	54	)
025	42	STO
026	10	10
027	53	(
028	53	(
029	43	RCL
030	19	19
031	65	×
032	53	(
033	93	.
034	07	7
035	94	+/-
036	75	-
037	43	RCL
038	10	10
039	85	+
040	01	1
041	93	.
042	04	4
043	65	×
044	53	(
045	53	(
046	43	RCL
047	10	10
048	85	+
049	93	.
050	07	7
051	54	)
052	55	÷
053	93	.
054	07	7
055	54	)
056	23	LNX
057	85	+
058	53	(
059	93	.
060	04	4
061	09	9
062	55	÷
063	53	(
064	93	.
065	07	7
066	85	+
067	43	RCL
068	10	10
069	54	)
070	54	)
071	54	)

Title of Program: Venturi Scrubber (Lognormal)

Location	Code	Key
072	55	÷
073	43	RCL
074	10	10
075	65	×
076	43	RCL
077	08	08
078	54	)
079	22	INV
080	23	LNX
081	54	)
082	92	RTN
083	76	LBL
084	13	C
085	53	(
086	93	.
087	00	0
088	06	6
089	05	5
090	03	3
091	65	×
092	07	7
093	06	6
094	55	÷
095	43	RCL
096	21	21
097	65	×
098	53	(
099	02	2
100	07	7
101	03	3
102	85	+
103	43	RCL
104	07	07
105	54	)
106	55	÷
107	02	2
108	09	9
109	06	6
110	93	.
111	02	2
112	54	)
113	42	STO
114	22	22
115	53	(
116	01	1

Location	Code	Key
117	85	+
118	02	2
119	65	×
120	43	RCL
121	22	22
122	55	÷
123	43	RCL
124	06	06
125	65	×
126	53	(
127	01	1
128	93	.
129	02	2
130	04	4
131	06	6
132	85	+
133	93	.
134	04	4
135	02	2
136	65	×
137	53	(
138	93	.
139	08	8
140	07	7
141	65	×
142	43	RCL
143	06	06
144	55	÷
145	53	(
146	02	2
147	65	×
148	43	RCL
149	22	22
150	54	)
151	54	)
152	94	+/-
153	22	INV
154	23	LNX
155	54	)
156	54	)
157	92	RTN
158	76	LBL
159	19	D'
160	53	(
161	43	RCL

Title of Program: Venturi Scrubber (Lognormal)

Location	Code	Key
162	18	18
163	35	1/X
164	65	×
165	43	RCL
166	06	06
167	35	1/X
168	65	×
169	53	(
170	53	(
171	43	RCL
172	06	06
173	55	÷
174	43	RCL
175	09	09
176	54	)
177	23	LNX
178	33	X²
179	55	÷
180	43	RCL
181	17	17
182	54	)
183	22	INV
184	23	LNX
185	54	)
186	92	RTN
187	76	LBL
188	17	B'
189	25	CLR
190	93	.
191	01	1
192	42	STO
193	01	01
194	02	2
195	93	.
196	42	STO
197	02	02
198	93	.
199	00	0
200	09	9
201	05	5
202	42	STO
203	03	03
204	02	2
205	00	0
206	42	STO
207	05	05
208	36	PGM
209	09	09
210	14	D
211	42	STO
212	20	20
213	02	2
214	42	STO
215	01	01
216	05	5
217	42	STO
218	02	02
219	02	2
220	00	0
221	42	STO
222	05	05
223	93	.
224	01	1
225	05	5
226	42	STO
227	03	03
228	36	PGM
229	09	09
230	14	D
231	44	SUM
232	20	20
233	05	5
234	42	STO
235	01	01
236	02	2
237	00	0
238	42	STO
239	02	02
240	02	2
241	00	0
242	42	STO
243	05	05
244	93	.
245	07	7
246	05	5
247	42	STO
248	03	03
249	36	PGM
250	09	09
251	14	D

Title of Program: Venturi Scrubber (Lognormal)

Location	Code	Key
252	44	SUM
253	20	20
254	69	OP
255	00	00
256	03	3
257	03	3
258	03	3
259	07	7
260	69	OP
261	04	04
262	43	RCL
263	20	20
264	22	INV
265	52	EE
266	69	OP
267	06	06
268	92	RTN
269	76	LBL
270	11	A
271	47	CMS
272	25	CLR
273	69	OP
274	00	00
275	03	3
276	07	7
277	00	0
278	00	0
279	07	7
280	01	1
281	69	OP
282	02	02
283	69	OP
284	05	05
285	91	R/S
286	99	PRT
287	42	STO
288	07	07
289	03	3
290	03	3
291	00	0
292	00	0
293	07	7
294	01	1
295	69	OP
296	02	02

Location	Code	Key
297	69	OP
298	05	05
299	91	R/S
300	42	STO
301	21	21
302	99	PRT
303	02	2
304	01	1
305	00	0
306	00	0
307	07	7
308	01	1
309	69	OP
310	02	02
311	69	OP
312	05	05
313	91	R/S
314	99	PRT
315	42	STO
316	08	08
317	03	3
318	05	5
319	02	2
320	03	3
321	03	3
322	02	2
323	02	2
324	07	7
325	69	OP
326	02	02
327	69	OP
328	05	05
329	91	R/S
330	99	PRT
331	42	STO
332	11	11
333	69	OP
334	00	00
335	02	2
336	07	7
337	06	6
338	03	3
339	02	2
340	02	2
341	07	7

Title of Program: Venturi Scrubber (Lognormal)

Location	Code	Key
342	01	1
343	69	OP
344	02	02
345	69	OP
346	05	05
347	91	R/S
348	99	PRT
349	22	INV
350	52	EE
351	95	=
352	42	STO
353	12	12
354	69	OP
355	00	00
356	04	4
357	01	1
358	02	2
359	02	2
360	07	7
361	01	1
362	69	OP
363	02	02
364	69	OP
365	05	05
366	91	R/S
367	99	PRT
368	22	INV
369	52	EE
370	95	=
371	42	STO
372	13	13
373	04	4
374	02	2
375	02	2
376	04	4
377	03	3
378	06	6
379	07	7
380	01	1
381	69	OP
382	02	02
383	69	OP
384	05	05
385	91	R/S
386	42	STO

Location	Code	Key
387	14	14
388	99	PRT
389	03	3
390	05	5
391	02	2
392	03	3
393	03	3
394	02	2
395	03	3
396	03	3
397	69	OP
398	02	02
399	69	OP
400	05	05
401	91	R/S
402	22	INV
403	52	EE
404	95	=
405	99	PRT
406	42	STO
407	15	15
408	69	OP
409	00	00
410	03	3
411	06	6
412	02	2
413	04	4
414	02	2
415	02	2
416	03	3
417	00	0
418	01	1
419	03	3
420	69	OP
421	02	02
422	69	OP
423	05	05
424	91	R/S
425	99	PRT
426	23	LNX
427	42	STO
428	10	10
429	33	X²
430	65	×
431	02	2

Title of Program: Venturi Scrubber (Lognormal)

Location	Code	Key
432	94	+/-
433	95	=
434	42	STO
435	17	17
436	43	RCL
437	10	10
438	65	×
439	53	(
440	02	2
441	65	×
442	89	π
443	54	)
444	34	ΓX
445	95	=
446	42	STO
447	18	18
448	69	OP
449	00	00
450	01	1
451	06	6
452	02	2
453	02	2
454	07	7
455	01	1
456	69	OP
457	02	02
458	69	OP
459	05	05
460	91	R/S
461	99	PRT
462	42	STO
463	09	09
464	08	8
465	93	.
466	02	2
467	04	4
468	52	EE
469	04	4
470	94	+/-
471	65	×
472	43	RCL
473	12	12
474	65	×
475	43	RCL
476	13	13
477	33	X²
478	22	INV
479	52	EE
480	95	=
481	42	STO
482	10	10
483	69	OP
484	00	00
485	01	1
486	06	6
487	01	1
488	07	7
489	02	2
490	07	7
491	03	3
492	07	7
493	01	1
494	03	3
495	69	OP
496	01	01
497	03	3
498	03	3
499	00	0
500	00	0
501	00	0
502	00	0
503	00	0
504	00	0
505	69	OP
506	02	02
507	69	OP
508	05	05
509	43	RCL
510	10	10
511	99	PRT
512	25	CLR
513	43	RCL
514	13	13
515	65	×
516	43	RCL
517	15	15
518	55	÷
519	09	9

Title of Program: Venturi Scrubber (Lognormal)

Location	Code	Key
520	55	÷
521	43	RCL
522	14	14
523	55	÷
524	14	D
525	65	×
526	01	1
527	52	EE
528	94	+/-
529	08	8
530	95	=
531	42	STD
532	16	16
533	02	2
534	55	÷
535	05	5
536	05	5
537	65	×
538	43	RCL
539	12	12
540	65	×
541	43	RCL
542	13	13
543	65	×
544	43	RCL
545	11	11
546	65	×
547	14	D
548	55	÷
549	43	RCL
550	14	14
551	95	=
552	42	STD
553	19	19
554	17	B'
555	92	RTN
556	76	LBL
557	14	D
558	53	(
559	05	5
560	00	0
561	55	÷
562	43	RCL
563	13	13
564	85	+
565	09	9
566	01	1
567	93	.
568	08	8
569	65	×
570	53	(
571	43	RCL
572	12	12
573	54	)
574	45	Y^X
575	01	1
576	93	.
577	05	5
578	54	)
579	92	RTN
580	76	LBL
581	12	B
582	69	DP
583	00	00
584	04	4
585	01	1
586	02	2
587	02	2
588	07	7
589	01	1
590	69	DP
591	02	02
592	69	DP
593	05	05
594	91	R/S
595	42	STD
596	13	13
597	99	PRT
598	02	2
599	07	7
600	06	6
601	03	3
602	02	2
603	02	2
604	07	7
605	01	1
606	69	DP
607	02	02

Title of Program: Venturi Scrubber (Lognormal)

Location	Code	Key
608	69	OP
609	05	05
610	91	R/S
611	99	PRT
612	42	STO
613	12	12
614	61	GTO
615	04	04
616	59	59

APPENDIX I

Title of Program: PROGRAM NO. 9: ESP (Lognormal)

Location	Code	Key
000	76	LBL
001	10	E'
002	72	ST*
003	00	00
004	65	×
005	01	1
006	44	SUM
007	00	00
008	95	=
009	92	RTN
010	76	LBL
011	11	A
012	99	PRT
013	65	×
014	02	2
015	42	STO
016	00	00
017	01	1
018	95	=
019	10	E'
020	91	R/S
021	99	PRT
022	23	LNX
023	42	STO
024	19	19
025	33	X²
026	65	×
027	02	2
028	95	=
029	94	+/-
030	10	E'
031	43	RCL
032	19	19
033	65	×
034	53	(
035	02	2
036	65	×
037	89	π
038	54	)
039	34	√X
040	95	=
041	10	E'
042	92	RTN
043	76	LBL
044	12	B
045	99	PRT
046	65	×
047	05	5
048	42	STO
049	00	00
050	01	1
051	95	=
052	10	E'
053	91	R/S
054	99	PRT
055	10	E'
056	91	R/S
057	99	PRT
058	10	E'
059	92	RTN
060	76	LBL
061	13	C
062	99	PRT
063	94	+/-
064	65	×
065	09	9
066	42	STO
067	00	00
068	01	1
069	95	=
070	87	IFF
071	01	01

Title of Program: ESP (Lognormal)

Location	Code	Key	Location	Code	Key
072	88	DMS	116	65	×
073	10	E'	117	93	.
074	92	RTN	118	00	0
075	76	LBL	119	07	7
076	88	DMS	120	05	5
077	65	×	121	05	5
078	01	1	122	95	=
079	93	.	123	10	E'
080	09	9	124	92	RTN
081	06	6	125	76	LBL
082	09	9	126	15	E
083	52	EE	127	99	PRT
084	94	+/-	128	10	E'
085	03	3	129	91	R/S
086	95	=	130	99	PRT
087	10	E'	131	10	E'
088	92	RTN	132	92	RTN
089	76	LBL	133	76	LBL
090	14	D	134	16	A'
091	99	PRT	135	99	PRT
092	42	STO	136	65	×
093	19	19	137	01	1
094	01	1	138	06	6
095	01	1	139	42	STO
096	42	STO	140	00	00
097	00	00	141	01	1
098	43	RCL	142	95	=
099	19	19	143	10	E'
100	45	Y×	144	91	R/S
101	01	1	145	99	PRT
102	93	.	146	10	E'
103	07	7	147	91	R/S
104	08	8	148	99	PRT
105	06	6	149	10	E'
106	95	=	150	87	IFF
107	65	×	151	02	02
108	93	.	152	78	Σ+
109	07	7	153	17	B'
110	06	6	154	76	LBL
111	06	6	155	78	Σ+
112	95	=	156	43	RCL
113	10	E'	157	17	17
114	43	RCL	158	75	-
115	19	19	159	43	RCL

Title of Program: ESP (Lognormal)

Location	Code	Key
160	16	16
161	95	=
162	55	÷
163	43	RCL
164	18	18
165	95	=
166	42	STO
167	18	18
168	99	PRT
169	17	B'
170	76	LBL
171	17	B'
172	00	0
173	42	STO
174	19	19
175	42	STO
176	59	59
177	43	RCL
178	16	16
179	42	STO
180	01	01
181	22	INV
182	86	STF
183	01	01
184	22	INV
185	86	STF
186	02	02
187	22	INV
188	52	EE
189	98	ADV
190	43	RCL
191	09	09
192	94	+/-
193	99	PRT
194	98	ADV
195	91	R/S
196	00	0
197	00	0
198	00	0
199	00	0
200	00	0
201	00	0
202	00	0
203	00	0
204	00	0

Location	Code	Key
205	00	0
206	00	0
207	00	0
208	00	0
209	00	0
210	00	0
211	00	0
212	00	0
213	00	0
214	00	0
215	00	0
216	00	0
217	00	0
218	00	0
219	00	0
220	00	0
221	00	0
222	00	0
223	00	0
224	00	0
225	00	0
226	00	0
227	00	0
228	00	0
229	00	0
230	00	0
231	00	0
232	00	0
233	00	0
234	00	0
235	00	0
236	00	0
237	00	0
238	00	0
239	00	0
240	00	0
241	76	LBL
242	10	E'
243	53	(
244	73	RC*
245	00	00
246	65	×
247	53	(
248	01	1
249	44	SUM

Title of Program: ESP (Lognormal)

Location	Code	Key
250	00	00
251	54	)
252	01	1
253	54	)
254	92	RTN
255	76	LBL
256	19	D'
257	53	(
258	72	ST*
259	00	00
260	65	×
261	53	(
262	01	1
263	44	SUM
264	00	00
265	54	)
266	01	1
267	54	)
268	92	RTN
269	76	LBL
270	18	C'
271	43	RCL
272	01	01
273	92	RTN
274	76	LBL
275	14	D
276	53	(
277	53	(
278	53	(
279	10	E'
280	55	÷
281	10	E'
282	54	)
283	23	LNX
284	33	X²
285	55	÷
286	10	E'
287	54	)
288	22	INV
289	23	LNX
290	55	÷
291	18	C'
292	55	÷
293	10	E'
294	54	)
295	92	RTN
296	76	LBL
297	15	E
298	53	(
299	53	(
300	10	E'
301	85	+
302	18	C'
303	65	×
304	10	E'
305	85	+
306	18	C'
307	33	X²
308	65	×
309	10	E'
310	54	)
311	19	D'
312	65	×
313	10	E'
314	54	)
315	22	INV
316	23	LNX
317	19	D'
318	53	(
319	43	RCL
320	08	08
321	55	÷
322	53	(
323	01	1
324	85	+
325	10	E'
326	65	×
327	53	(
328	01	1
329	75	-
330	17	B'
331	54	)
332	85	+
333	10	E'
334	65	×
335	53	(
336	17	B'
337	35	1/X
338	23	LNX
339	54	)

Title of Program: ESP (Lognormal)

Location	Code	Key
340	54	)
341	55	÷
342	53	(
343	17	B'
344	23	LNX
345	55	÷
346	10	E'
347	55	÷
348	53	(
349	10	E'
350	85	+
351	53	(
352	01	1
353	75	-
354	43	RCL
355	14	14
356	54	)
357	65	×
358	17	B'
359	45	YX
360	10	E'
361	43	RCL
362	13	13
363	35	1/X
364	54	)
365	23	LNX
366	54	)
367	65	×
368	43	RCL
369	09	09
370	54	)
371	22	INV
372	23	LNX
373	92	RTN
374	76	LBL
375	17	B'
376	43	RCL
377	10	10
378	92	RTN
379	76	LBL
380	11	A
381	01	1
382	42	STO
383	00	00
384	53	(
385	53	(
386	14	D
387	65	×
388	15	E
389	54	)
390	65	×
391	53	(
392	18	C'
393	75	-
394	10	E'
395	54	)
396	67	EQ
397	88	DMS
398	53	(
399	18	C'
400	75	-
401	10	E'
402	54	)
403	67	EQ
404	89	π
405	77	GE
406	89	π
407	01	1
408	76	LBL
409	77	GE
410	54	)
411	44	SUM
412	19	19
413	43	RCL
414	18	18
415	44	SUM
416	01	01
417	25	CLR
418	61	GTO
419	11	A
420	76	LBL
421	88	DMS
422	93	.
423	05	5
424	61	GTO
425	77	GE
426	76	LBL
427	89	π
428	93	.
429	05	5

Title of Program: ESP (Lognormal)

Location	Code	Key
430	54	)
431	44	SUM
432	19	19
433	53	(
434	10	E'
435	10	E'
436	65	×
437	43	RCL
438	18	18
439	54	)
440	99	PRT
441	44	SUM
442	59	59
443	18	C'
444	99	PRT
445	91	R/S

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4. TITLE AND SUBTITLE TI-59 Programmable Calculator Programs for In-stack Opacity, Venturi Scrubbers, and Electrostatic Precipitators		5. REPORT DATE May 1980 6. PERFORMING ORGANIZATION CODE
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16. ABSTRACT The report explains the basic concepts of in-stack opacity as measured by in-stack opacity monitors. Also included are calculator programs that model the performance of venturi scrubbers and electrostatic precipitators. The effect of particulate control devices on in-stack opacity can be predicted by using these programs. The size distribution data input can be either in lognormal or histogram format. The opacity is calculated using Deirmendjian's approximation to Mie series to obtain extinction efficiencies. An alternative opacity program employing the exact Mie series solution is also described. The running time for this program is about 8 hours; that for the approximation program is 30 minutes. The accuracy of these programs is as good as the measured data input.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Aerosols	Pollution Control	13B	07D
Approximation	Computer Programs	Stationary Sources	12A	09B
Measurement	Electrostatic Precip-	Particulate	14B	
Flue Gases	itators	TI-59 Calculator	21B	13I
Opacity	Scrubbers	Venturi Scrubbers		07A
Dust			11G	

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