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# SR-52 PROGRAMMABLE CALCULATOR PROGRAMS FOR VENTURI SCRUBBERS AND ELECTROSTATIC PRECIPITATORS

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# SR-52 PROGRAMMABLE CALCULATOR PROGRAMS FOR VENTURI SCRUBBERS AND ELECTROSTATIC PRECIPITATORS

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## ABSTRACT

This report is intended to provide useful tools for estimating particulate removal by venturi scrubbers and electrostatic precipitators. Detailed descriptions are given for programs to predict the penetration (1 minus efficiency) for each device. These programs are written specifically for the Texas Instruments SR-52 programmable calculator. Each program includes a general description of the mathematical model upon which the program is based and the formulas and numerical techniques used in adapting the model to the SR-52. Numerical examples, program listing, and user instructions are included.

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## NOMENCLATURE

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| $a$ | - | First curve fit parameter for $w(d) = a + bd + cd^2$ |
| $B$ | - | Correction factor sneakage and reentrainment in ESP |
| $b$ | - | Second curve fit parameter for $w(d) = a + bd + cd^2$ |
| $C'$ | - | Cunningham correction factor |
| $c$ | - | Third curve fit parameter for $w(d) = a + bd + cd^2$ |
| $D$ | - | Drop diameter |
| $d$ | - | Particle diameter |
| $d_i$ | - | Initial particle diameter for integration |
| $d_f$ | - | Final particle diameter for integration |
| $d_g$ | - | Mass mean particle diameter |
| $E_o$ | - | Overall collection efficiency |
| $E_p$ | - | Electric field at plate |
| $F$ | - | Correction factor for non-uniform gas flow in ESP |
| $f$ | - | Empirical factor in scrubber model |
| $f(d)$ | - | Fraction of particles with diameters between d and d + dd |
| $j$ | - | Current density |
| $K_1$, $K_2$ | - | Constants used in scrubber program |
| $K_{pt}$ | - | Inertial impaction parameter evaluated at throat of venturi scrubber |
| $L/G$ | - | Non-dimensional liquid/gas flow rate ratio for venturi scrubber |
| $N_s$ | - | Number of baffled sections in ESP |
| $h$ | - | Number of steps in numerical integration |
| $Pt(d)$ | - | Penetration (1 minus efficiency) of particles of diameter d |
| $Pt'(d)$ | - | Corrected penetration of particles of diameter d used in ESP model |
| $Pt_o$ | - | Overall particle penetration |

$q$ - Particle electrical charge

$R_{ij}$ - Storage register ij

$S$ - Fraction of particles that are reentrained and that bypass electrified region per section

$T$ - Temperature

$u_G$ - Gas velocity

$V$ - Volumetric flow rate of gas

$w(d)$ - Electrical migration velocity of particles with diameter d

$\Delta d$ - Particle diameter increment for numerical integration

$\Delta p$ - Pressure drop

$\mu$ - Gas viscosity

$\rho$ - Dust electrical resistivity

$\rho_L$ - Liquid density

$\rho_p$ - Particle density

$\sigma$ - Normalized standard deviation of gas flow

$\sigma_g$ - Geometric standard deviation of log normal size distribution

# INTRODUCTION

Computer models for particle collection in venturi scrubbers[1] and electrostatic precipitators[2] have been developed under EPA sponsorship. These models, which are fully described in referenced reports, provide useful tools for the design, specification, selection, and troubleshooting of particulate control devices.

Recent advances in calculator technology make it possible to use these models without a large computer. The scrubber model described by Calvert et al.[1] has been fully programmed for a Texas Instruments SR-52 programmable calculator. Results of calculations made with the ESP computer model described by Gooch et al.[2] have been incorporated in an SR-52 program which has much of the power and usefulness of the full computer model.

These SR-52 programs and examples of their use are presented in this report. These programs are written for the SR-52 and the PC-100A printer. Instructions on how to use the programs without the printer are also presented.

Typical uses of the SR-52 programs are presented in the example problems. Several examples for both the scrubber and the ESP program are presented to enable the user to get a "feel" for the programs before he tries to solve his own problems.

## NOTES ON THE PROGRAMS

In the user instructions and examples, a convention of underline letters or numbers has been adopted to denote the key or keys on the SR-52 keyboard which should be pressed to conduct the operation discussed. For example: in the instruction Press A, the underline indicates that the A button on the keyboard should be pressed. Storage registers are indicated by $R_{ij}$. For example: $R_{01}$ refers to storage register 01.

The programs all make extensive use of the indirect recall and indirect store features of the SR-52. Thus, it is essential that the counter for the indirect recall and indirect store register be set at the proper initial value and advanced at the required times. Anyone who wishes to modify the programs should remember that the programs as written depend on indirect recall and indirect store instructions.

Cards are entered into the SR-52 calculator by:

| Step | Procedure | Press |
|---|---|---|
| 1 | Enter side A | 2nd rst 2nd read |
| 2 | Enter side B | 2nd read |

In the program listing, the use of the 2nd key is denoted by asterisk. Thus, the notation, for example, B'* means press 2nd B'.

VENTURI SCRUBBER

## MATHEMATICAL MODEL

The mathematical model used in the SR-52 program was developed by Calvert and is fully described by Calvert et al.[1] Therefore, only a brief discussion of the model will be given here.

The mathematical model of a venturi scrubber consists of two parts: one to predict scrubber pressure drop; the other to predict scrubber particle collection efficiency.

### Scrubber Pressure Drop

Pressure drop in a venturi scrubber is caused by acceleration and by wall friction. The pressure drop due to acceleration is generally the larger. Therefore, pressure drop due to wall friction will be neglected.

The pressure drop due to acceleration is reasonably insensitive to scrubber geometry and can be predicted from hydrodynamics. Calvert[3] derived the following equation for venturi scrubber pressure drop:

$$\Delta p \ \text{(cm water)} = 1.03 \times 10^{-3} \left[u_G \left(\frac{\text{cm}}{\text{sec}}\right)\right]^2 \frac{L}{G} \qquad (1)$$

where $u_G$ is the gas velocity in the venturi throat, and L/G is the dimensionless liquid to gas flow rate ratio.

Calvert et al.[4] have compared the predictions of equation (1) with experimental data and concluded that the equation consistently overpredicts pressure drop in a venturi scrubber by about 20%. They suggest that equation (2) below gives better agreement with the data.

$$\Delta p \text{ (cm water)} = 8.24 \times 10^{-4} \left[u_G \left(\frac{\text{cm}}{\text{sec}}\right)\right]^2 \frac{L}{G} \qquad (2)$$

Equation (2) is the equation used to predict pressure drop in the SR-52 model.

Particle Penetration

The overall particle penetration (1 minus efficiency) through a venturi scrubber is given by:

$$Pt_o = \int_0^{\infty} Pt(d) f(d) dd \qquad (3)$$

where $Pt_o$ is the overall particle penetration, $Pt(d)$ is the penetration of particles with diameter d, and $f(d)$ the fraction of particles with diameters between d and d + dd.

Calvert et al.[1] derived equation (4) for Pt(d):

$$Pt(d) = \exp\left[\frac{2}{55} \frac{L}{G} \frac{u_G \rho_L D}{\mu} F(K_{pt} f)\right] \qquad (4)$$

where $u_G$ is the velocity of the gas, $\rho_L$ is the density of the liquid, D is the diameter of the collecting drops, $\mu$ is the viscosity of the gas, and $F(K_{pt}f)$ is given by:

$$F(K_{pt}f) = [0.7\,K_{pt}f + 1.4\,\ln\left(\frac{K_{pt}f + 0.7}{0.7}\right) + \frac{0.49}{0.7 + K_{pt}f}]\,\frac{1}{K_{pt}} \qquad (5)$$

where f is an empirical parameter (usually f = 0.5), and $K_{pt}$ is the inertial impaction parameter calculated at conditions in the throat:

$$K_{pt} = \frac{u_G\,\rho_p\,C'\,d^2}{9\mu D} \qquad (6)$$

where $u_G$ is the gas velocity in the throat, $\rho_p$ is the particle density, C' is the Cunningham correction factor, and d is the diameter of the particles.

The diameter of the drops can be calculated from an empirical correlation by Nukiyama and Tanasawa.[1]

$$D\ (\text{cm}) = \frac{50}{u_G(\text{cm/sec})} + 91.8\left(\frac{L}{G}\right)^{1.5} \qquad (7)$$

The assumptions used to derive all these equations are given by Calvert et al.[1] and the interested reader is referred there for additional information.

It should be noted that equation (4) is valid only when inertial impaction is the dominant particle collection mechanism. Inertial impaction is the dominant mechanism for particles with diameters greater than about 0.1 microns. Thus equation (4) is valid in most situations of practical interest.

The parameter "f" in equation (5) is an empirical parameter which includes all unmodelled effects. Experimental data for industrial scale scrubbers indicate that f is essentially a constant with a value of 0.5.

## SR-52 PROGRAM

The SR-52 program is a two card program which provides a numerical solution to equation (3) for a log-normal particle size distribution. Card 1 is used to enter the data, calculate pressure drop, and calculate constants used in calculations performed using Card 2. Card 2 uses a trapezoidal rule numerical integration to solve equation (3) over the limits $d_{initial}$ to $d_{final}$.

### Card 1

The program on Card 1 is used to carry out three activities:

1. Enter and store data on scrubber parameters, gas conditions, and particle size distribution.

2. Calculate constants used in the program contained on Card 2.

3. Calculate pressure drop across the scrubber.

Each of these activities is discussed below.

The data on scrubber parameters, gas conditions, and particle size distribution are entered in a specific order.

| | | |
|---|---|---|
| $T$ | - | Gas temperature (°C) stored in $R_{03}$ |
| $f$ | - | Empirical parameter (usually 0.5) stored in $R_{04}$ |
| $d_g$ | - | Mass mean particle diameter (microns) stored in $R_{08}$ |
| $\sigma_g$ | - | Geometric standard deviation stored in $R_{10}$ |
| $d_i$ | - | Initial particle diameter for integration (micron) stored in $R_{11}$ |
| $d_f$ | - | Final particle diameter for integration (micron) stored in $R_{12}$ |
| $\Delta d$ | - | Particle diameter increment for integration (micron) stored in $R_{13}$ |
| $\rho_L$ | - | Density of liquid ($gm/cm^3$) stored in $R_{14}$ |
| L/G | - | Liquid to gas flow rate ratio ($m^3/m^3$) stored in $R_{15}$ |
| $u_G$ | - | Gas velocity in venturi throat (cm/sec) stored in $R_{16}$ |
| $\mu$ | - | gas viscosity (poise) stored in $R_{17}$ |
| $\rho_p$ | - | Density of the particles ($gm/cm^3$)stored in $R_{18}$ |

Data entry is accomplished by entering gas temperature then pushing A. All other data are entered using RUN key. Each one of the entered data is printed as it is entered.

As soon as the last entry $\rho_p$ is made, the constants for Card 2 are calculated, drop diameter is calculated and printed in cm, and pressure drop is calculated and printed in cm water.

Calculation of Constants for Card 2

As soon as $\rho_p$ is entered the program automatically calculates and stores the following constants for use in the program on Card 2:

$$\frac{u_G p}{9 \mu D}$$

$$- 2 \ln^2 \sigma_g$$

$$\sqrt{2\pi} \ln \sigma_g$$

$$\frac{2}{55} \frac{L}{G} \frac{u_G}{\mu} \rho_L D$$

In order to calculate these constants, the program twice calculates and prints drop diameter, D, in cm.

The calculation routine to calculate constants can be called from the keyboard by pressing C. The calculator will then calculate all the constants, and calculate and print drop diameter and pressure drop. This procedure is especially useful (as is discussed in the section on the use of the program) when it is necessary to perform several calculations where only a few variables, such as gas volocity, are changed from run to run.

NOTE: This procedure cannot be used in cases where the log-normal size distribution parameters are changed.

Calculation of Pressure Drop

After the calculation of constants is complete, the calculator automatically calculates and prints the pressure drop across the venturi in cm of water. The pressure drop calculation routine can be called from the keyboard by pressing 2nd A'. The effects of various combinations of gas velocity and liquid/gas flow rate ratio on pressure drop can be investigated by storing $u_G$ in $R_{16}$ and L/G in $R_{15}$, then pressing 2nd A'.

Card 2

Card 2 is used to calculate the overall penetration for a log-normal particle size distribution. The method of solution is discussed below.

Equation (1) can be approximated by:

$$Pt_o = \int_0^{\infty} Pt(d)f(d)dd \cong \int_{d_i}^{d_f} Pt(d)f(d)dd \qquad (8)$$

where $d_i$ is the initial particle diameter and $d_f$ is the final particle diameter.

The solution to equation (8), for the case where the particle size distribution is log-normal, is accomplished by the program carried on Card 2. Equation (8) is solved using a trapezoidal rule numerical integration:

$$Pt_o = \Delta d \left[\frac{Pt(d_i)f(d_i)}{2} + Pt\ (d_i + \Delta d)f(d_i + \Delta d) + Pt\ (d_i + 2\ \Delta d)f(d + 2\Delta d) + \ldots . \frac{Pt(d_f)f(d_f)}{2}\right] \qquad (9)$$

where Pt(d) is given by:

$$Pt(d) = \exp \{ K_1 [ - 0.7 - K_2C' \; d^2f + 1.4 \ln (\frac{K_2C' \; d^2f + 0.7}{0.7})$$

$$+ \frac{0.49}{0.7 \pm K_2C' \; d^2f} ] \frac{1}{K_2C' \; d^2} \quad (10)$$

where $K_1 = \frac{2}{55} \frac{L}{G} \frac{u_G\rho_L}{\mu} D$ and $K_2 = \frac{u_G\rho_p}{\mu}$

both are calculated using Card 1,

C' is the Cunningham correction factor and is calculated in the program by:

$$C' = 1 + \frac{2T(^oK)}{D(\mu m) \times 10^8} [2.79 + 0.894 \exp (\frac{2.47 \times 10^7 \; d(\; m)}{T(^oK)})] \quad (11)$$

Pt(d) is calculated in subroutine E.

For a log-normal size distribution, f(d) is given by:

$$f(d) = \frac{1}{2\pi \ln\sigma_g d} \exp [\frac{- \ln^2 (^d/d_g)}{2 \ln^2\sigma_g}] \quad (12)$$

where $d_g$ is the geometric mass mean particle diameter ($\mu$m) and $\sigma g$ is the geometric standard deviation.

f(d) is calculated in subroutine D.

At the completion of the numerical solution, the calculator will print $Pt_o$, $d_i$ and $d_f$. $Pt_o$ is stored in $R_{98}$.

Because particle size distributions span several orders of magnitude of particle diameter, it is useful to break equation (8) into increments, each with its own Δd, and sum the solutions to the increments to obtain the overall solution; i.e.,

$$Pt_o = \int_{d_i}^{d_f} Pt(d)f(d)dd = \int_{d_i}^{d_1} Pt(d)f(d)dd + \int_{d_1}^{d_2} Pt(d)f(d)dd \qquad (13)$$

$$+ \; ..... \int_{d_n}^{d_f} Pt(d)f(d)dd$$

The summation is automatically carried out in $R_{98}$. In order to use $R_{98}$ for the summation the user must store 0 in $R_{98}$ when beginning a problem.

The user must determine his own total integration limits, how many increments to divide the total integral into, and the Δd for each increment.

In general overall integration from 0.1 to 20 microns with increments of

0.1 to 1.0 microns (Δd = 0.1)

1.0 to 10 microns (Δd = 0.5)

10 to 20 microns (Δd = 2)

is more than adequate. For particle size distributions with small $d_g$ and large $\sigma_g$, the lower limit should be reduced. For cases where the pressure drop exceeds, say, 40 cm of water, integration past 5 μm is generally not necessary. When the mass mean particle diameter is small, say, less than 2 μm, Δd should not exceed 0.2 until integration is past $d_g$.

Use of the SR-52 Program

The SR-52 program provides a quick way to determine venturi scrubber performance. Three possible uses are:

1. Determine pressure drop and penetration through a given scrubber on a given aerosol. (See Example 1.)

2. Determine pressure drop required to meet a given outlet emission. (See Example 2.)

3. Determine effects of changes in particle size distribution on penetration through a given scrubber. (See Example 3.)

The SR-52 program as written will print all input data, drop diameter, pressure drop, overall penetration, and integration limits using the PC-100A printer.

The printer output is arranged as follows:

T, $^oC$

f

$d_g$, μm

$\sigma_g$

$d_i$, μm

$d_f$, μm

$\Delta d$, μm

$\rho_L$, $gm/cm^3$

L/G, $m^3/m^3$ or $cm^3/cm^3$

$u_G$, cm/sec

$\mu$, poise

$\rho_p$, gm/cc

D, μm

D, μm

Space

$\Delta p$, cm water

Space

$Pt_o$

$d_i$, μm

$d_f$, μm

All the above are automatically printed.

$Pt_o$ for all increments is manually printed by pressing RCL 98 2nd prt and follows $d_f$.

The program can be used without the printer as follows:

1. Card 1

   Pressure drop is displayed at end of calculation.

   Drop diameter can be displayed by pressing D.

2. Card 2

Penetration due to particles between $d_1$ and $d_2$ can be displayed by the following steps:

Press RCL 19

Press X

Press RCL 13

Press =

Penetration will then be displayed.

Overall penetration can be displayed by pressing RCL 98, the same step as required when using the printer.

Example 1

Calculate overall penetration and pressure drop of a scrubber operating under given conditions.

Given:

| | | |
|---|---|---|
| Temperature | = | 65°C |
| Particle size distribution-- | | |
| mass mean diameter, | = | 1.5 μm |
| geometric standard deviation | = | 2.0 |
| Liquid/gas ratio | = | $9 \times 10^{-4}$ cm$^3$/cm$^3$ |
| Gas velocity | = | $100 \times 10^2$ cm/sec |
| Gas viscosity | = | $1.8 \times 10^{-4}$ poise |
| Liquid viscosity | = | 1.0 gm/cm$^3$ |
| Particle density | = | 2.0 gm/cm$^3$ |
| Empirical factor | = | 0.5 |

Solution:

Divide integration into two increments:

$$Pt_o \sim \int_{0.1}^{1.5} Pt(d)f(d)dd + \int_{1.5}^{5} Pt(d)f(d)dd$$

Enter Card 1, sides A and B:

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 10 | | STO 98 | 0 | |
| 2 | Enter data | T (65) | A | 3.38-02 | 65. |
| | | f (.5) | RUN | 5.01 | 5.01 |
| | | $d_g$ | RUN | 1.01 | 1.5 00 |
| | | $\sigma_g$ (2) | RUN | 7.00 | 2. |
| | | $d_i$ (.1) | RUN | 6.00 | 0.1 |
| | | $d_f$ (1.5) | RUN | 5.00 | 1.5 |
| | | $\Delta d$ (.1) | RUN | 4.00 | 0.1 |
| | | $\rho_L$ (1) | RUN | 3.00 | 1. |
| | | L/G (9EE ± 4) | RUN | 2.00 | 9.-04 |
| | | $u_G$ (100EE2) | RUN | 1.00 | 1. 04 |
| | | $\mu$ (1.8EE ± 4) | RUN | 0.00 | 1.8-04 |
| | | $\rho_p$ (2) | RUN | | 2. 00 |
| | | | | | 7.4786-03 |
| | | | | | 7.4786-03 |
| | | | | 7.41601 | 7.416 01 |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 3 | Enter Card 2 | | | | |
| 4 | Calculate $Pt_o$ $0.1< d<1.5$ μm | | A | 1.5 | 1.614021483-02 |
| | | | | | 1. -01 |
| | ($1.614 \times 10^{-2}$ is the penetration of particles | | | | 1.5 00 |
| | with $0.1< d<1.5$ μm) | | | | |
| 5 | Carry integration past 1.5 μm | | | | |
| 6 | Clear $R_{19}$ | 0 | STO 19 | 0 | |
| 7 | Store new $d_i$ | 1.5 | STO 11 | 1.5 | |
| 8 | Store new $d_f$ | 5.0 | STO 12 | 5. | |
| 9 | Store new $\Delta d$ | 0.5 | STO 13 | 0.5 | |
| 10 | Calculate $Pt_o$ $1.5<d<5.0$ μm | | A | | .0012172657 |
| | | | | | 1.5 |
| | | | | | 5. |
| 11 | Recover and print | | RCL 98 | .0173574805 | |
| | $Pt_o$ $0.1<d<5.0$ μm | | 2nd Prt | | .0173574805 |

Figure 1, the Example 1 printer output, shows all printer output from both Cards 1 and 2.

In summary:

$\Delta p = 74$ cm water,

$Pt_o = 0.017$, and

Efficiency, $E_o = 1 - Pt_o = 0.983$.

```
        65.       PRT
         5. -01   PRT
        1.5 00    PRT
         2.       PRT
        0.1       PRT
        1.5       PRT
        0.1       PRT
         1.       PRT
         9. -04   PRT
         1.  04   PRT
        1.8-04    PRT
         2.  00   PRT
     7.4786-03    PRT
     7.4786-03    PRT

      7.416 01    PRT

1.614021483-02    PRT
         1. -01   PRT
        1.5 00    PRT
.0012172657       PRT
        1.5       PRT
         5.       PRT
.0173574805       PRT
```

Figure 1. PC-100A printer output for example 1--overall penetration and scrubber pressure drop.

Example 2

This example shows how to use the program to estimate pressure drop required for a given outlet emission.

Given:

| | | |
|---|---|---|
| Allowable emissions | = | 0.01 mg/dNm$^{3*}$ |
| Inlet loading | = | 1 mg/dNm$^3$ |
| Gas temperature | = | 65°C |
| Particle size distribution-- | | |
| mass mean diameter | = | 3 μm |
| geometric standard deviation | = | 2 |
| Particle density | = | 2 gm/cm$^3$ |

Solution:

Required penetration = 0.01.

(Required efficiency = 1-0.01 = 0.99.)

Assume f = 0.5.

For first guess let L/G = 9 x $10^4$ m$^3$/m$^3$, and

$u_G$ = 1.2 x $10^4$ cm/sec.

Integrate over two intervals:

0.1 to 1 with Δd = 0.1, and

1 to 5 with Δd = 0.2.

*dNm$^3$ is dry normal cubic meters; normal conditions are 1 atm and 20°C

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 1 | | | | |
| 2 | Enter data | T(65) | A | 3.38-02 | 65. |
| | | f (.5) | RUN | 5. -01 | 5. -01 |
| | | $d_g$ (3) | RUN | 1.01 | 3. 00 |
| | | $\sigma_g$ (2) | RUN | 7.00 | 2. 00 |
| | | $d_i$ (.1) | RUN | 6.00 | 1. -01 |
| | | $d_f$ (1) | RUN | 5.00 | 1. 00 |
| | | $\Delta d$ (.1) | RUN | 4.00 | 1. -01 |
| | | $\rho_L$ (1) | RUN | 3.00 | 1. 00 |
| | | L/G(9EE ± 4) | RUN | 2.00 | 9. -04 |
| | | $u_G$ (1.2EE4) | RUN | 1.00 | 1.2 04 |
| | | μ (1.8EE ± 4) | RUN | 0.00 | 1.8 -04 |
| | | | | | 2. 00 |
| | | $_p$ (2) | RUN | | 6.645266667-03 |
| | | | | | 6.645266667-03 |
| | | | | 1.06790402 | Space |
| | | | | | 1.067904 02 |
| | | | | | Space |
| 3 | Clear $R_{98}$ | 0 | STO 98 | 0 | |
| 4 | Enter Card 2 | | | | |
| 5 | Calculate $Pt_o$ $0.1 < d < 1$ μm | | A | 1. | 8.787862447-04 |
| | | | | | 1. -01 |
| | | | | | 1. 00 |
| 6 | Carry integration past 1.0 m | | | | |
| 7 | Clear $R_{19}$ | 0 | STO 19 | 0 | |
| 8 | Store new $d_i$ | 1. | STO 11 | 1. | |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 9 | Store new $d_f$ | 5. | STO 12 | 5. | |
| 10 | Store new $\Delta d$ | 0.2 | STO 13 | 0.2 | |
| 11 | Calculate $Pt_o$ $1.0 < d < 5.0$ μm | | A | 5. | .0010940953 |
| | | | | | 1. |
| | | | | | 5. |
| 12 | Recover and print | | RCL 98 | .0019728815 | |
| | $Pt_o$ $0.1 < d < 5.0$ μm | | 2nd prt | | .0019728815 |
| 13 | Because $Pt_o$ is too low, reduce $\Delta p$ by decreasing $u_G$ | | | | |
| 14 | Enter Card 1 | | | | |
| 15 | Store new $u_G$ $6 \times 10^3$ | | STO 16 | 6.03 | |
| 16 | Store $d_i$ | 0.1 | STO 11 | 01. -01 | |
| 17 | Store $d_f$ | 1. | STO 12 | 1. 00 | |
| 18 | Store $\Delta d$ | 0.1 | STO 13 | 1. -01 | |
| 19 | Clear $R_{98}$ | 0 | STO 98 | 0. | |
| 20 | Calculate new | 2nd stflg 2 C | | 2.66976 01 | 1.081193333-02 |
| | constants and $\Delta p$ | | | (Drop diameter) | 1.081193333-02 |
| | | | | | Space |
| | | | | (New $\Delta p$) | 2.66976 01 |
| | | | | | Space |
| 21 | Enter Card 2 | | | | |
| 22 | Calculate $Pt_o$ | | A | 1. | .0081657664 |
| | $0.1 < d < 1.0$ μm | | | | 0.1 |
| | | | | | 1. |
| 23 | Carry integration past 1.0 μm | | | | |
| 24 | Clear $R_{19}$ | 0 | STO 19 | 0. | |
| 25 | Store new $d_i$ | 1. | STO 11 | 1. | |
| 26 | Store new $d_f$ | 5. | STO 12 | 5. | |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 27 | Store new Δd | 0.1 | STO 13 | 0.1 | |
| 28 | Calculate $Pt_o$ | | A | 5. | 0.008565109 |
| | $1.0 < d < 5.0$ μm | | | | 1. |
| | | | | | 5. |
| 29 | Recover and print | | RCL 98 | .0167308754 | |
| | $Pt_o$ $0.1 < d < 5.0$ μm | | 2nd prt | | .0167308754 |
| 30 | Because this $Pt_o$ is too high increase Δp by increasing $u_G$ to $7.2 \times 10^3$ cm/sec. | | | | |
| 31 | Enter Card 1 | | | | |
| 32 | Store new $u_G$ $7.2 \times 10^3$ | | STO 16 | 7.2 EE3 | |
| 33 | Store new $d_i$ | 0.1 | STO 11 | 1. -01 | |
| 34 | Store new $d_f$ | 1.0 | STO 12 | 1. 00 | |
| 35 | Store new Δd | 0.1 | STO 13 | 1. -01 | |
| 36 | Clear $R_{98}$ | 0. | STO 98 | 0. | |
| 37 | Calculate new | | 2nd stflg 2 | 3.844454401 | 9.423044444-03 |
| | constants and Δp | | C | (new D) | 9.423044444-03 |
| | | | | (new Δp) | 3.8444544 01 |
| 38 | Enter Card 2 | | | | |
| 39 | Calculate $Pt_o$ | | A | 1.0 | .0049534354 |
| | $0.1 < d < 1.0$ μm | | | | 0.1 |
| | | | | | 1. |
| 40 | Carry integration past 1.0 μm | | | | |
| 41 | Clear $R_{19}$ | 0 | STO 19 | 0 | |
| 42 | Store new $d_i$ | 1. | STO 11 | 1. | |
| 43 | Store new $d_f$ | 5. | STO 12 | 5. | |
| 44 | Store new d | 0.2 | STO 13 | 0.2 | |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 45 | Calculate $Pt_o$ | | A | 5.0 | .0051689409 |
| | $1.0 < d < 5.0$ μm | | | | 1. |
| | | | | | 5. |
| 46 | Recover and print | | RCL 98 | .0101223763 | |
| | $Pt_o$ $0.1 < d < 5$ μm | | | | |
| | | | 2nd prt | | .0101223763 |

This is close enough to desired penetration.

In summary:

$$\Delta p = 38.4 \text{ cm water,}$$

$$Pt_o = 0.010, \text{ and}$$

$$E_o = 0.9909.$$

PC-100A printer output for Example 2 is shown in Figure 2.

Example 3

Determine the effects of changing size distribution parameters:

from $d_g = 3,\ \sigma_g = 2$

to $d_g = 3,\ \sigma_g = 3$

on overall penetration for a scrubber operating under given conditions.

Given:

| | |
|---|---|
| Temperature | = 65°C |
| Gas velocity | = $1 \times 10^4$ cm/sec |
| Particle density | = 2 $gm/cm^3$ |

```
          65.       PRT
           5. -01   PRT
           3.  00   PRT
           2.  00   PRT
           1. -01   PRT
           1.  00   PRT
           1. -01   PRT
           1.  00   PRT
           9. -04   PRT
         1.2  04    PRT
         1.8 -04    PRT
           2.  00   PRT
6.645266667-03      PRT
6.645266667-03      PRT

     1.067904 02    PRT

8.787862447-04      PRT
           1. -01   PRT
           1.  00   PRT
.0010940953         PRT
           1.       PRT
           5.       PRT
.0019728815         PRT
1.081193333-02      PRT
1.081193333-02      PRT

      2.66976 01    PRT

.0081657664         PRT
          0.1       PRT
           1.       PRT
0.008565109         PRT
           1.       PRT
           5.       PRT
.0167308754         PRT
9.423044444-03      PRT
9.423044444-03      PRT

    3.8444544 01    PRT

.0049534354         PRT
          0.1       PRT
           1.       PRT
.0051689409         PRT
           1.       PRT
           5.       PRT
.0101223763         PRT
```

Figure 2. PC-100A printer output for example 2--scrubber pressure drop vs. outlet emission.

Liquid density = 1 $gm/cm^3$

Gas viscosity = $1.8 \times 10^{-4}$ poise

Liquid/gas ratio = $1 \times 10^{-3}$ $m^3/m^3$

Solution:

Integrate over two intervals:

$d_i = 0.1$  $d_f = 1.0$  $\Delta d = 0.1$

$d_i = 1.0$  $d_f = 5.0$  $\Delta d = 0.2$

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 1 | | | | |
| 2 | Enter data | T(65) | A | 3.38-02 | 65 |
| | | f(.5) | RUN | 5. -01 | 5. -01 |
| | | $d_g$ | RUN | 1.01 | 3. 00 |
| | | $\sigma_g$ | RUN | 7.00 | 2. 00 |
| | | $d_i$(.1) | RUN | 6.00 | 1. -01 |
| | | $d_f$(1.) | RUN | 5.00 | 1. 00 |
| | | $\Delta$d(.1) | RUN | 4.00 | 1. -01 |
| | | $\rho_L$(1) | RUN | 3.00 | 1. 00 |
| | | L/G(1EE ±3) | RUN | 2.00 | 1. -03 |
| | | $u_G$ (1EE4) | RUN | 1.00 | 1. 04 |
| | | μ (1.8EE ± 4) | RUN | 0.00 | 1.8-04 |
| | | $\rho_p$(2) | RUN | | 2. 00 |
| | | | | | 7.902970892-03 |
| | | | | | 7.902970892-03 |
| 3 | Clear $R_{98}$ | 0 | STO 98 | 8.24 01 | 8.24 01 |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 4 | Enter Card 2 | | | | |
| 5 | Calculate $Pt_o$ | $0.1 < d < 1.0$ μm | A | 1.0 | 1.144198314-03 |
| | | | | | 1. -01 |
| | | | | | 1. 00 |
| 6 | Carry integration past 1.0 μm | | | | |
| 7 | Clear $R_{19}$ | 0 | STO 19 | 0 | |
| 8 | Store new $d_i$ | 1. | STO 11 | 1. | |
| 9 | Store new $d_f$ | 5. | STO 12 | 5. | |
| 10 | Store new Δd | 0.2 | STO 13 | 0.2 | |
| 11 | Calculator $Pt_o$ | $1.0 < d < 5.0$ μm | A | 5.0 | 7.669028639-04 |
| | | | | | 1. 0 |
| | | | | | 5. 0 |
| 12 | Recover and print | | | | |
| | $Pt_o$ $0.1 < d < 5.0$ μm | | RCL 98 | 1.911101177-03 | |
| | | | 2nd prt | | 1.911101177-03 |
| | The above is overall penetration for $d_g = 3$ and $\sigma_g = 2$. | | | | |
| 13 | Determine penetration for $d_g = 3$ and $\sigma_g = 3$ | | | | |
| 14 | Enter Card 1 | | | | |
| 15 | Clear flag 2 | | INV 2nd stflg 2 | | |
| 16 | Clear $R_{98}$ | 0 | STO 98 | 0 | |
| 17 | Store $d_g$ | 3 | STO 08 | 3 | |
| 18 | Store $\sigma_g$ | 3 | STO 10 | 3 | |
| 19 | Store $d_i$ | .1 | STO 11 | .1 | |
| 20 | Store $d_f$ | 1 | STO 12 | 1. | |
| 21 | Calculate constants | | C | | .0079029709 |
| | and Δp | | | | 7.902970892-03 |
| | | | | | space |
| | | | | 8.2401 | 8.24 01 |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 22 | Enter Card 2 | | | | |
| 23 | Calculate $Pt_0$ $0.1 < d < 1$ μm | | A | 1. | .0116402843 |
| | | | | | 0.1 |
| | | | | | 1. |
| 24 | Carry integration past 1.0 μm | | | | |
| 25 | Clear $R_{19}$ | 0 | STO 19 | 0. | |
| 26 | Store new $d_i$ | 1. | STO 11 | 1. | |
| 27 | Store new $d_f$ | 5. | STO 12 | 5. | |
| 28 | Store new Δd | 0.2 | STO 13 | 0.2 | |
| 29 | Calculate $Pt_0$ $1.0 < d < 5.0$ μm | | A | 5. | .0006463882 |
| | | | | | 1. |
| | | | | | 5. |
| 30 | Recover and print | | | | |
| | $Pt_0$ $0.1 < d < 5.0$ μm | | RCL 98 | .0122866724 | |
| | | | 2nd prt | | .0122866724 |

Note the large increase in penetration due to the increase in geometric standard deviation.

Printer output for Example 3 is shown in Figure 3.

## COMPARISON WITH EXPERIMENTAL DATA

The SR-52 program predicts overall penetrations and pressure drops which are in good agreement with experimental data. Comparisons between calculated and measured penetrations and efficiencies are given in Table 1.

```
              65.        PRT
               5. -01    PRT
               3.  00    PRT
               2.  00    PRT
               1. -01    PRT
               1.  00    PRT
               1. -01    PRT
               1.  00    PRT
               1. -03    PRT
               1.  04    PRT
              1.8-04     PRT
               2.  00    PRT
     7.902970892-03      PRT
     7.902970892-03      PRT

            8.24 01      PRT

     1.144198314-03      PRT
               1. -01    PRT
               1.  00    PRT
     7.669028639-04      PRT
               1.  00    PRT
               5.  00    PRT
     1.911101177-03      PRT
     .0079029709         PRT
     7.902970892-03      PRT

            8.24 01      PRT

     .0116402843         PRT
             0.1         PRT
              1.         PRT
     .0006463882         PRT
              1.         PRT
              5.         PRT
     .0122866724         PRT
```

Figure 3. PC-100A printer output for example 3--changing scrubber size distribution parameters.

Table 1. COMPARISON BETWEEN SR-52 SCRUBBER PROGRAM PREDICTED RESULTS AND EXPERIMENTAL DATA

| Plant | Measured | | Calculated | |
|---|---|---|---|---|
| | Δp, cm water | $Pt_o$ | Δp, cm water | $Pt_o$ |
| 1 | 45.7 | 0.015 | 46 | 0.016 |
| 2 | 25 | 0.025 | 25 | 0.028 |
| 3 | 100 | 0.005 | 105 | 0.004 |

## ELECTROSTATIC PRECIPITATOR

### MATHEMATICAL MODEL

The SR-52 program is based on the Environmental Protection Agency/Southern Research Institute (EPA/SoRI) mathematical model of electrostatic precipitation described by Gooch et al.[2] Only a brief discussion of the model will be given here.

The theoretical overall penetration (1 minus efficiency) through an electrostatic precipitator (ESP) is given by:

$$Pt_o = \int_o^{\infty} Pt(d)f(d)dd \qquad (14)$$

where Pt(d) is the penetration of particles with diameter d, and f(d) is the fraction of the particles with diameters between d and d + dd.

The EPA/SoRI model is based on the Deutch-Andersen equation for particle penetration through an ESP:

$$Pt(d) = \exp\,[-w(d)A/V] \qquad (15)$$

where Pt(d) is the theoretical penetration of particles with diameter d, w(d) is the electrical migration velocity of particles with diameter d, A is the collector plate area, and V is the volumetric flow rate of gas.

For the situation where the particle charge, $\underline{q}$, and the electric field at the plate, $E_p$, are known, w(d) can be calculated from:

$$w(d) = (\underline{q}\ E_p C')/(3\pi\ d\mu\ ) \tag{16}$$

where C' is the Cunningham correction factor and $\mu$ is the gas viscosity.

The calculations necessary to determine $\underline{q}$ and $E_p$ are beyond the capabilities of the SR-52. These calculations were carried out in the EPA/SoRI model for a typical ESP collecting fly ash, and the results are incorporated into the SR-52 program.

The penetration predicted by equation (15) is generally less than the penetration measured in industrial ESP because certain non-ideal factors (e.g., non-uniform gas flow, sneakage, and reentrainment) act to increase penetration. Methods for estimating the effects of non-uniform gas flow, sneakage, and reentrainment are described by Gooch et al.[2] whose method is used in the SR-52 program.

Gooch et al. have shown that the effects of these non-ideal factors can be estimated by:

$$Pt'(d) = \exp\left[\frac{-w(d)A}{BF\ V}\right] \tag{17}$$

where Pt'(d) is the corrected penetration, B is the correction factor for sneakage and reentrainment, and F is the correction factor for non-uniform gas flow.

$$B = \frac{\ln Pt(d)}{N_s \ln [S + (1-S)Pt(d)^{1/N_s}]} \quad (18)$$

where $N_s$ = number of baffled sections, and S is the fraction of particles that are reentrained and that bypass the electrified region per section.

$$F = 1.0 + 0.766\,[1-Pt(d)]\sigma^{1.786} + 0.0755\,\sigma \ln\,[1/Pt(d)] \quad (19)$$

where $\sigma$ is 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 is given by:

$$Pt_o = \int_o^{\infty} Pt'(d)f(d)dd \quad (20)$$

It is this equation that is solved by the SR-52 program.

SR-52 PROGRAM

The SR-52 program solves equation (20) over the finite limits of $d_i$ to $d_f$ using a trapezoidal rule numerical integration.

Pt(d) is calculated based on second order polynomial curve fits to W(d) vs d curves given by Gooch et al.[2] These curves are based on typical electrical conditions for an ESP collecting fly ash.

Curves for the following cases were used to develop the least squares curve fit parameters shown in Table 2:

- Cold-side ESP current density 5 $na/cm^2$
- Cold-side ESP current density 20 $na/cm^2$
- Cold-side ESP current density 40 $na/cm^2$
- Hot-side ESP current density 30 $na/cm^2$

Gas temperatures are 150°C and 370°C for cold- and hot-side ESP's, respectively.

The current density that should be used in the calculations depends on the dust resistivity. The relationship between allowable current density (cold-side ESP) and dust resistivity is based on empirical data reported by Hall.[5] Hall's relationship can be written:

$$j = \frac{6.31 \times 10^{11}}{\rho^{0.987}}$$

where j is current density (in $na/cm^2$) and $\rho$ is the dust resistivity (in ohm-cm).

When the current density predicted by the equation above is less than 5 $na/cm^2$, a hot-side ESP should be considered and the hot-side parameters should be used.

This is a two card program: Card 1 is used to enter and store data and to calculate constants; Card 2 is used to perform the numerical integration.

Table 2. MIGRATION VELOCITY VS. PARTICLE DIAMETER CURVE FIT PARAMETERS FOR VARIOUS ESP CURRENT DENSITIES

| Current Density $na/cm^2$ | Temperature °C | Particle Diameter Limits μm | Curve Fit Parameters for Migration Velocity[a] First, a | Second, b | Third, c |
|---|---|---|---|---|---|
| 5 | 150 | $d < 2$ | 1.15987 | 0.3 | 0.21188 |
| 5 | 150 | $d > 2$ | 0.94818 | 0.811698 | -0.0003504 |
| 20 | 150 | $d < 2$ | 2.85176 | 1.06416 | 0.48567 |
| 20 | 150 | $d > 2$ | 2.2525 | 2.3348 | 0.002652 |
| 40 | 150 | $d < 2$ | 4.2029 | 1.5294 | 0.6956 |
| 40 | 150 | $d > 2$ | 2.8475 | 3.6296 | 0.01137 |
| 30 | 370 | $d < 2$ | 3.9943 | -1.2175 | 1.02250 |
| 30 | 370 | $d > 2$ | 2.5917 | 1.5032 | 0.005790 |

[a]Parameters for $w(d) = a + bd + cd^2$ cm/sec

Card 1

The program on Card 1 is used to:

1. Enter and store data on ESP parameters, gas conditions, and particle size distribution.

2. Calculate constants used in Card 2.

The following data are entered and stored by pressing the indicated buttons:

| Enter Data | Press |
|---|---|
| Mass mean particle diameter, $d_g$ (μm) | A |
| Geometric standard deviation, $\sigma_g$ | RUN |
| First curve fit parameter for migration velocity, a | B |
| Second " " " " " " , b | RUN |
| Third " " " " " " , c | RUN |
| Specific collector area, A/V ($cm^2/Acm^3/sec$), or | C |
| Specific collector area, A/V ($ft^2$/1000 ACFM) | stflg 1 C |
| Normalized standard deviation of gas velocity distribution | D |
| Number of baffled sections, $N_s$ | E |
| Sneakage-reentrainment fraction, S | RUN |
| Initial particle diameter, $d_i$ (μm) | 2nd A' |
| Final particle diameter, $d_f$ (μm) | RUN |
| Particle diameter increment, Δd (μm) | RUN |

Each of the input data is printed as it is entered.

Card 2

Card 2 is used to perform the numerical integration of equation (20) for a log-normal size distribution over the finite limits $d_i$ to $d_f$ using the trapezoidal rule numerical integration technique:

$$Pt_o \simeq \int_{d_i}^{d_f} Pt'(d)f(d)dd = \Delta d \; \{ \frac{Pt'(d_i)}{2} + \qquad (21)$$

$$Pt'(d_i + \Delta d) + Pt'(d_i + 2\,\Delta d) + \ldots \frac{Pt'(d_f)}{2} \}$$

where Pt'(d) is given by equation (17) and w(d) is given by:

$$w(d) = a + bd + cd^2. \qquad (22)$$

Data a, b, and c are input using Card 1.

Pt'(d) is calculated in routine E.

For a log-normal size distribution, f(d) is given by:

$$f(d) = \frac{1}{\sqrt{2\pi}\ln\sigma} \exp \left[ \frac{-\ln^2 (d/d_g)}{2 \ln^2 \sigma_g} \right] \qquad (23)$$

where $d_g$ is the mass mean particle diameter, μm, and $\sigma_g$ is the geometric standard deviation.

Fraction of particles with diameter d, f(d), is calculated in subroutine D.

At the completion of the numerical solution, the calculator will print $Pt_o$, $d_i$, and $d_f$. $Pt_o$ is stored in $R_{98}$.

Because particle size distributions span several orders of magnitude of particle diameter, it is useful to break equation (8) into increments (each with its own $\Delta d$) and sum the solutions to the increments to obtain the overall solution; i.e.,

$$Pt_o = \int_{d_i}^{df} Pt(d)f(d)dd = \int_{d_k}^{d_1} Pt(d)f(d)dd + \int_{d_i}^{d_2} Pt(d)f(d)dd + \ldots\ldots \int_{d_n}^{d_f} Pt(d)f(d)dd \qquad (24)$$

The summation is automatically carried out in $R_{98}$. The results of the summation must be manually recalled and printed by pressing RCL 98 2nd prt.

The user must determine: his own total integration limits, the number of increments into which to divide the total integral, and the $\Delta d$ for each integral.

In general, overall integration from 0.1 to 20 microns with increments of

0.1 to 1.0 microns ($\Delta d$ = 0.1)
1.0 to 10 microns ($\Delta d$ = 0.5)
10 to 20 microns ($\Delta d$ = 2)

is more than adequate.

Use of the SR-52 Program

The SR-52 program provides a quick way to estimate ESP performance. Five possible uses of the program are to:

1. Determine penetration of a given aerosol through a given outlet emission standard for a given aerosol. (See Example 4.)

2. Determine specific collector area required to meet a given outlet emission standard for a given aerosol. (See Example 5.)

3. Determine effects of changes in particle size distribution on penetration through a given ESP. (See Example 6.)

4. Determine effects of changes in dust resistivity on penetration through a given ESP. (See Example 7.)

5. Determine effects of changes in non-ideal factors on penetration through a given ESP. (See Example 8.)

The SR-52 program as written will print all input data and penetration through a given increment using the PC-100A printer. The overall penetration summed over all increments must be recovered and printed manually by pressing RCL 98 2nd prt.

The printer output is arranged as follows:

$d_g$, μm

$\sigma_g$

$\left.\begin{matrix} a \\ b \\ c \end{matrix}\right\}$ parameters for $w(d) = a + bd + cd^2$

A/V, $cm^2/Acm^3/sec$ or $ft^2/10^3$KACFM

$\sigma$

$N_s$

S

$d_i$

$d_f$

$\Delta d$

space

A/V, $cm^2/Acm^3/sec$

space

$Pt_o$

The program can be used without the printer with no changes. $Pt_o$ for each increment will be displayed at end of calculation. $Pt_o$ summed over all increments can be displayed by pressing RCL 98.

Steps to follow in using program:

1. Determine dust resistivity, $\rho$, in ohm-cm.
2. Determine allowable current density, j, in $na/cm^2$ from Hall's[5] empirical correlation:

$$j = \frac{6.31 \times 10^{11}}{\rho^{0.987}}$$

3. Determine least squares parameters for $w(d) = a + bd + cd^2$ from Table 2 using current density nearest to but not exceeding that calculated in Step 2.

4. Determine A/V.
5. Enter data using Card 1.
6. Determine $Pt_0$ using Card 2.

Example 4

Calculate overall penetration through an ESP for given conditions.

Given:

| | | |
|---|---|---|
| Cold-side ESP A/V | = | 0.7 $cm^2/Acm^3/sec$ (356 $ft^2/10^3$ ACFM) |
| Dust resistivity | = | $4 \times 10^{10}$ ohm-cm |
| Mass mean particle diameter | = | 15 μm |
| Geometric standard deviation | = | 4 |
| Normalized standard deviation of gas velocity distribution | = | 0.25 |
| Number of baffled sections | = | 4 |
| Fractional sneakage/reentrainment | = | 0.1 |
| Cold-side ESP T | = | 150°C |

Solution:

$$Pt_o = {}_o\int^{\infty} Pt'(d)f(d)dd$$

Divide integration into two increments:

0.1 to 2 μm with Δd = 0.1, and

2.0 to 20 μm with Δd = 1.

Calculate allowable current density:

$$j = \frac{6.31 \times 10^{11}}{(4 \times 10^{10})^{0.987}} = 22 \text{ na/cm}^2$$

Use a, b, c for 20 na/cm².

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 1 | | | | |
| 2 | Enter all data | $d_g$(15) | A | 15 | 15. |
| | | $\sigma_g$(4) | RUN | 3.474924643 | 4. |
| | | a(2.85176) | B | 2.85176 | 2.85176 |
| | | b(1.06416) | RUN | 1.06416 | 1.06416 |
| | | c(0.48567) | RUN | 0.48567 | 0.48567 |
| | | A/V (0.7) | C | -0.7 | 0.7 |
| | | σ(0.25) | D | 0.018875 | 0.25 |
| | | $N_s$(4) | E | 4. | 4. |
| | | S(0.1) | RUN | 0.1 | 0.1 |
| | | $d_i$(0.1) | 2nd A' | 0.1 | 0.1 |
| | | $d_f$(2.0) | RUN | 2.0 | 2. |
| | | Δd(0.1) | RUN | 0.7 | 0.1 |
| | | | | | space |
| | | | | | 0.7 |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 3 | Enter Card 2 | | | | |
| 4 | Calculate $Pt_o$ $0.1 < d < 2.0$ μm | | A | 2. | .0060170031 |
| | (calculation takes about 5 minutes) | | | | 2. |
| 5 | Carry integration past 2.0 μm | | | | |
| 6 | Clear $R_{19}$ | 0. | STO 19 | 0. | |
| 7 | Store new $d_i$ | 2. | STO 16 | 2. | |
| 8 | Store new $d_f$ | 20. | STO 17 | 20. | |
| 9 | Store new $\Delta d$ | 1. | STO 18 | 1. | |
| 10 | Store new a, b, c for $d > 2.0$ μm | | | | |
| | | 2.2525 | STO 05 | 2.2525 | |
| | | 2.3348 | STO 06 | 2.3348 | |
| | | 0.0026252 | STO 07 | 0.0026252 | |
| 11 | Calculate $Pt_o$ for $2 < d < 20$ μm | | A | 20. | 0.002792262 |
| | | | | | 20. |
| 12 | Recover and print | | | | |
| | $Pt_o$ $0.1 < d < 20$ μm | | RCL 98 | .0088092652 | |
| | | | 2nd Prt | | .0088092652 |

It is not useful to carry the integration past 20 μm.

In summary:

$Pt_o = 0.0088,$

$E_o = (1 - Pt_o) - 0.9912,$

$A/V = 0.7\ cm^2/Acm^3/sec,$ and

$T = 150°C.$

Sample printer output for example 4 is shown in Figure 4.

| | |
|---|---|
| 15. | PRT |
| 4. | PRT |
| 2.85176 | PRT |
| 1.06416 | PRT |
| 0.48567 | PRT |
| 0.7 | PRT |
| 0.25 | PRT |
| 4. | PRT |
| 0.1 | PRT |
| 0.1 | PRT |
| 2. | PRT |
| 0.1 | PRT |
| 0.7 | PRT |
| .0060170031 | PRT |
| 2. | PRT |
| 0.002792262 | PRT |
| 20. | PRT |
| .0088092652 | PRT |

Figure 4. PC-100A printer output for example 4--overall penetration through ESP.

Example 5

Determine the required specific collector area, A/V, required for an ESP to meet an emission standard of 0.02 mg/m$^3$ under given conditions.

Given:

| | |
|---|---|
| Inlet loading | = 2 mg/m$^3$ |
| Mass median particle diameter | = 15 μm |
| Geometric standard deviation | = 4 |
| Dust electrical resistivity | = $10^{11}$ ohm-cm |
| Normalized standard deviation of gas velocity distribution | = 0.25 |
| Number of baffled sections | = 4.0 |
| Fraction of particles that are reentrained and that bypass electrified region per section | = 0.1 |
| Cold-side ESP T | = 150°C |

Solution:

Required $Pt_o = \frac{0.02}{\;} = 0.01$.

Allowable current density, $j = \frac{6.31 \times 10^{11}}{\;} = 8.8$ na/cm$^2$.

Use a, b, c for 5 na/cm$^2$.

Divide integration into two increments:

0.1 to 2 μm with $\Delta d = 0.1$, and

2.0 to 20 μm with $\Delta d = 1.0$.

First guess for A/V = 1.0 cm$^2$/cm$^3$/sec (500 ft$^2$/10$^3$ACFM).

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 1 | | | | |
| 2 | Enter all data | $d_g$(15) | A | 15 | 15 |
| | | $\sigma_g$(4) | RUN | 3.474924643 | 4 |
| | | a(1.15987) | B | 1.15987 | 1.15987 |
| | | b(0.3000) | RUN | 0.3 | 0.3 |
| | | c(0.211888) | RUN | 0.211888 | 0.211888 |
| | | A/V(1.0) | C | -1. | 1. |
| | | $\sigma$(0.25) | D | 0.018875 | 0.25 |
| | | $N_s$(4.0) | E | 4. | 4. |
| | | S(.1) | RUN | 0.1 | 0.1 |
| | | $d_i$(0.1) | 2nd A | 0.1 | 0.1 |
| | | $d_f$(2.0) | RUN | 2. | 2. |
| | | $\Delta$d(0.1) | RUN | 1. | 0.1 |
| | | | | | space |
| | | | | | 1. |
| 3 | Enter Card 2 | | | | |
| 4 | Calculate $Pt_o$ | | A | 2. | .0167131954 |
| | $0.1 < d < 2.0$ μm | | | | 2. |
| | Penetration is already too high so there is no benefit in continuing the calculation. | | | | |
| 5 | Increase A/V Enter Card 1 | | | | |
| | New A/V = 2 | 2. | C | -2. | 2. |
| | Calculate constants for Card 2 | | 2nd B' | 2. | space |
| | | | | | 2. |
| 6 | Enter Card 2 | | | | |
| 7 | Calculate $Pt_o$ $0.1 < d < 2.0$ μm | | A | 2. | .0049972136 |
| | | | | | 2. |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 8 | Carry integration past 2.0 μm | | | | |
| 9 | Clear $R_{19}$ | 0. | STO 19 | 0. | |
| 10 | Store new $d_i$ | 2. | STO 16 | 2. | |
| 11 | Store new $d_f$ | 20. | STO 17 | 20. | |
| 12 | Store new Δd | 1. | STO 18 | 1. | |
| 13 | Store new a, b, c for b > 2.0 μm | | | | |
| | | .94818 | STO 05 | .94818 | |
| | | .811698 | STO 06 | .811698 | |
| | | -.0003504 | STO 07 | .0003504 | |
| 14 | Calculate $Pt_o$ 2. < d < 20 μm | | A | 20. | .0025482646 |
| | | | | | 20. |
| 15 | Recover $Pt_o$ 0.1 < d < 20 μm | | RCL 98 2nd Prt | .0075454782 | .0075454781 |
| | This is too low. A/V needs to be decreased. | | | | |
| 16 | Enter Card 1 | | | | |
| 17 | Enter new A/V | 1.78 | C | -1.78 | 1.78 |
| 18 | Enter a, b, c for d < 2.0 μm | | | | |
| | | 1.15987 | B | 1.15987 | 1.15987 |
| | | 0.3 | RUN | 0.3 | 0.3 |
| | | 0.211888 | RUN | 0.211888 | 0.211888 |
| 19 | Enter $d_i$ | 0.1 | 2nd A | 0.1 | 0.1 |
| 20 | Enter $d_f$ | 2.0 | RUN | 2.0 | 2. |
| 21 | Enter Δd | 0.1 | RUN | 1.78 | 0.1 |
| | | | | | space |
| | | | | | 1.78 |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 22 | Enter Card 2 | | | | |
| 23 | Calculate $Pt_o$ $0.1 < d < 2$ μm | | A | 2. | .0064011292 |
| | | | | | 2. |
| 24 | Carry integration past 2.0 μm | | | | |
| 25 | Clear $R_{19}$ | 0 | STO 19 | 0. | |
| 26 | Store new $d_i$ | 2. | STO 16 | 2. | |
| 27 | Store new $d_f$ | 20. | STO 17 | 20. | |
| 28 | Store new Δd | 1. | STO 18 | 1. | |
| 29 | Store a, b, c for d >2.0 μm | | | | |
| | | 0.94818 | STO 05 | 0.94818 | |
| | | 0.811698 | STO 06 | 0.811698 | |
| | | -0.0003504 | STO 07 | -0.0003504 | |
| 30 | Calculate $Pt_o$ $2.0 < d < 20.0$ μm | | A | 20. | .0031990565 |
| | | | | | 20. |
| 31 | Recover and print $Pt_o$ $0.1 < d < 20.0$ μm | | RCL 98 2nd Prt | 0.0096001857 | 0.0096001857 |

This is close enough to the desired penetration.

In Summary

$Pt_o$ = 0.01,

A/V = 1.78 $cm^2/Acm^3/sec$ (∿900 $ft^2/10^3$ACFM),

j = 5 $na/cm^2$, and

T = 150°C.

Printer output for example 5 is shown in Figure 5.

```
         15.      PRT
          4.      PRT
    1.15987       PRT
        0.3       PRT
   0.211888       PRT
          1.      PRT
       0.25       PRT
          4.      PRT
        0.1       PRT
        0.1       PRT
          2.      PRT
        0.1       PRT

          1.      PRT

.0167131954       PRT
          2.      PRT
          2.      PRT

          2.      PRT

.0049972136       PRT
          2.      PRT
.0025482646       PRT
         20.      PRT
.0075454781       PRT
       1.78       PRT
    1.15987       PRT
        0.3       PRT
   0.211888       PRT
        0.1       PRT
          2.      PRT
        0.1       PRT

       1.78       PRT

.0064011292       PRT
          2.      PRT
.0031990565       PRT
         20.      PRT
.0096001857       PRT
```

Figure 5. PC-100A printer output for example 5--specific collector area vs. ESP emission standard.

Example 6

Determine the effects of changing the size distribution parameters from

$d_g = 25\ \mu m,\ \sigma_g = 4$

to $d_g = 25\ \mu m,\ \sigma_g = 3.$

for the given conditions.

Given:

| | | |
|---|---|---|
| A/V (cold-side) | = | 0.7 $cm^2/cm^3/sec$ |
| Current density | = | 20 $na/cm^2$ |
| Normalized standard deviation of gas velocity distribution | = | 0.25 |
| Number of baffled sections | = | 4 |
| Fraction of particles that are reentrained and that bypass electrified region per section | = | 0.1 |

Solution:

Divide integration into two increments:

0.1 to 2 $\mu m$, with $\Delta d$ = 0.1, and

2 to 20 $\mu m$, with $\Delta d$ = 1.0.

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 1 | | | | |
| 2 | Enter all data | 25 | A | 25. | 25. |
| | | 4 | RUN | 3.474924643 | 4. |
| | | 2.85176 | B | 2.85176 | 2.85176 |
| | | 1.06416 | RUN | 1.06416 | 1.06416 |
| | | 0.48567 | RUN | 0.48567 | 0.48567 |
| | | 0.7 | C | -0.7 | 0.7 |
| | | 0.25 | D | 0.018875 | 0.25 |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| | | 4 | E | 4. | 4. |
| | | 0.1 | RUN | .1 | 0.1 |
| | | 0.1 | 2nd A | .1 | 0.1 |
| | | 2.0 | RUN | 2. | 2.0 |
| | | 0.1 | RUN | 0.7 | 0.1 |
| | | | | | space |
| | | | | | 0.7 |
| 3 | Enter Card 2 | | | | |
| 4 | Calculate $Pt_o$ $0.1 < d < 2.0$ μm | | A | 2. | .0026480641 |
| | (calculation requires about 5 minutes) | | | | 2. |
| 5 | Continue integration past 2.0 μm | | | | |
| 6 | Clear $R_{19}$ | 0 | STO 19 | 0 | |
| 7 | Store new $d_i$ | 2. | STO 16 | 2. | |
| 8 | Store new $d_f$ | 20. | STO 17 | 20. | |
| 9 | Store new Δd | 1. | STO 18 | 1. | |
| 10 | Enter new a, b, c for d >2 μm | | | | |
| | | 2.2525 | STO 05 | 2.2525 | |
| | | 2.3348 | STO 06 | 2.3348 | |
| | | 0.002652 | STO 07 | 0.002652 | |
| 11 | Calculate $Pt_o$ $2. < d < 20$ μm | | A | 20 | .0019190628 |
| | | | | | 20. |
| 12 | Recover and print | | RCL 98 2nd | .0045671269 | .0045671269 |
| | $Pt_o$ $0.1 < d < 20$ μm | | Prt | | |

This is the overall penetration for $d_g$ = 25 μm and $\sigma_g$ = 4.

For $d_g$ = 25 μm and $\sigma_g$ = 3:

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 1 | | | | |
| 2 | Enter data | 25 | A | 25 | 25. |
| | | 3 | RUN | 2.753812626 | 3. |
| | | 2.85176 | B | 2.85176 | 2.85176 |
| | | 1.06416 | RUN | 1.06416 | 1.06416 |
| | | 0.48567 | RUN | 0.48567 | 0.48567 |
| | | 0.1 | 2nd A' | 0.1 | 0.1 |
| | | 2.0 | RUN | 2. | 2. |
| | | 0.1 | RUN | 0.7 | 0.1 |
| | | | | | space |
| | | | | | 0.7 |
| 3 | Enter Card 2 | | | | |
| 4 | Calculate $Pt_o$ 0.1 < d < 2.0 μm | | A | 2. | .0006880736 |
| | | | | | 2. |
| 5 | Continue integration past 2.0 μm | | | | |
| 6 | Clear $R_{19}$ | 0. | STO 19 | 0. | |
| 7 | Store new $d_i$ | 2. | STO 16 | 2. | |
| 8 | Store new $d_f$ | 20. | STO 17 | 20. | |
| 9 | Store new Δd | 1. | STO 18 | 1. | |
| 10 | Store new a, b, c for d> 2.0 μm | | | | |
| | | 2.2525 | STO 05 | 2.2525 | |
| | | 2.3348 | STO 06 | 2.3348 | |
| | | 0.002652 | STO 07 | 0.002652 | |
| 11 | Calculate $Pt_o$ | | A | 20. | .001589385 |
| | 2. < d < 20 μm | | | | 20. |
| 12 | Recover and print | | RCL 98 | .0022774587 | .0022774587 |
| | $Pt_o$ 0.1 < d < 20 μm | | 2nd Prt | | |

In summary:

$T = 150°C$,

$A/V = 0.7\ cm^2/Acm^3/sec$,

for $d_g = 25$ and $\sigma_g = 4$, $Pt_o = 0.0046$, and

for $d_g = 25$ and $\sigma_g = 3$, $Pt_o = 0.0023$.

Note the large effect that an increase in $\sigma_g$ has on overall penetration.

Printer output for example 6 is shown in Figure 6.

Example 7

Determine penetration for the ESP in Example 4 for the case where dust resistivity is increased from $4 \times 10^{10}$ ohm-cm to $10^{11}$ ohm-cm.

Given: All conditons, except dust resistivity, are as for example 4.

Solution:

$$\text{Allowable current density, } j = \frac{6.31 \times 10^{11}}{(10^{11})^{.987}} = 8.8\ na/cm^2.$$

Use a, b, c for 5 $na/cm^2$.

Divide integration into two increments:

0.1 to 2.0 μm with $\Delta d = 0.1$, and

2.0 to 20 μm with $\Delta d = 1.0$.

| | |
|---|---|
| 25. | PRT |
| 4. | PRT |
| 2.85176 | PRT |
| 1.06416 | PRT |
| 0.48567 | PRT |
| 0.7 | PRT |
| 0.25 | PRT |
| 4. | PRT |
| 0.1 | PRT |
| 0.1 | PRT |
| 2. | PRT |
| 0.1 | PRT |
| | |
| 0.7 | PRT |
| | |
| .0026480641 | PRT |
| 2. | PRT |
| .0019190628 | PRT |
| 20. | PRT |
| .0045671269 | PRT |
| 25. | PRT |
| 3. | PRT |
| 2.85176 | PRT |
| 1.06416 | PRT |
| 0.48567 | PRT |
| 0.1 | PRT |
| 2. | PRT |
| 0.1 | PRT |
| | |
| 0.7 | PRT |
| | |
| .0006880736 | PRT |
| 2. | PRT |
| 0.001589385 | PRT |
| 20. | PRT |
| .0022774587 | PRT |

Figure 6. PC-100A printer output for example 6--changing ESP size distribution parameters.

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 1 | | | | |
| 2 | Enter all data | 15 | A | 15 | 15. |
| | | 4 | RUN | 3.474924643 | 4. |
| | | 1.15987 | B | 1.15987 | 1.15987 |
| | | 0.3 | RUN | 0.3 | 0.3 |
| | | 0.211888 | RUN | 0.211888 | 0.211888 |
| | | 0.7 | C | -0.7 | 0.7 |
| | | 0.25 | D | 0.018875 | 0.25 |
| | | 4 | E | 4. | 4. |
| | | 0.1 | RUN | 0.1 | 0.1 |
| | | 0.1 | 2nd A | 0.1 | 0.1 |
| | | 2.0 | RUN | 2.0 | 2. |
| | | 0.1 | RUN | 0.7 | 0.1 |
| | | | | | space |
| | | | | | 0.7 |
| 3 | Enter Card 2 | | | | |
| 4 | Calculate $Pt_o$ | A | 2. | | .0251019171 |
| | $0.1 < d < 2.0$ μm | | | | 2. |
| 5 | Continue integration past 2.0 μm | | | | |
| 6 | Clear $R_{19}$ | 0. | STO 19 | 0. | |
| 7 | Store new $d_i$ | 2. | STO 16 | 2. | |
| 8 | Store new $d_f$ | 20. | STO 17 | 20. | |
| 9 | Store new $\Delta d$ | 1. | STO 18 | 1. | |
| 10 | Store new a, b, c for $d > 2.0$ μm | | | | |
| 11 | | 0.94818 | STO 05 | 0.94818 | |
| 12 | | 0.811698 | STO 06 | 0.811698 | |
| 13 | | -0.0003504 | STO 07 | -0.0003504 | |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 14 | Calculate $Pt_o$ | | A | 20. | .0273179683 |
| | 2. < d < 20.0 μm | | | | 20. |
| 15 | Recover and print | | RCL 98 | .0524198854 | .0524198854 |
| | $Pt_o$ 0.1 < d < 20 μm | | 2nd Prt | | |

In summary:

for $\rho = 4 \times 10^{10}$ ohm-cm, $Pt_o = 0.008$, and

for $\rho = 10^{11}$ ohm-cm, $Pt_o = 0.052$.

Printer output for example 7 is shown in Figure 7.

Example 8

Determine the effect of increasing the normalized standard deviation of the gas flow distribution in Example 4 from 0.25 to 0.5.

Given: All conditions, except normalized standard deviation of the gas flow distribution, are as for example 4.

Solution:

Divide integration into two increments:

0.1 to 2.0 μm with $\Delta d = 0.1$ μm, and

2.0 to 20 μm with $\Delta d = 1.0$ μm.

```
       15.      PRT
        4.      PRT
   1.15987      PRT
       0.3      PRT
  0.211888      PRT
       0.7      PRT
      0.25      PRT
        4.      PRT
       0.1      PRT
       0.1      PRT
        2.      PRT
       0.1      PRT

       0.7      PRT

.0251019171     PRT
        2.      PRT
.0273179683     PRT
       20.      PRT
.0524198854     PRT
```

Figure 7. PC-100A printer output for example 7--ESP penetration vs. dust resistivity.

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 1 | Enter Card 1 | | | | |
| 2 | Enter all data | 15 | A | 15 | 15. |
| | | 4 | RUN | 3.474924643 | 4. |
| | | 2.85176 | B | 2.85176 | 2.85176 |
| | | 1.06416 | RUN | 1.06416 | 1.06416 |
| | | 0.48567 | RUN | 0.48567 | 0.48567 |
| | | 0.7 | C | -0.7 | 0.7 |
| | | 0.5 | D | 0.03775 | 0.5 |
| | | 4. | E | 4. | 4. |
| | | 0.1 | RUN | 0.1 | 0.1 |
| | | 0.1 | 2nd A' | 0.1 | 0.1 |
| | | 2.0 | RUN | 2.0 | 2. |
| | | 0.1 | RUN | 0.7 | 0.1 |
| | | | | | space |
| | | | | | 0.7 |
| 3 | Enter Card 2 | | | | |
| 4 | Calculate $Pt_o$ | | A | 2. | .0088151441 |
| | $0.1 < d < 2.0$ μm | | | | 2. |
| 5 | Continue integration past 2.0 μm | | | | |
| 6 | Clear $R_{19}$ | 0. | STO 19 | 0. | |
| 7 | Store new $d_i$ | 2. | STO 16 | 2. | |
| 8 | Store new $d_f$ | 20. | STO 17 | 20. | |
| 9 | Store new $\Delta d$ | 1. | STO 18 | 1. | |
| 10 | Store new a, b, c for $d > 2.0$ μm | | | | |
| | | 2.2525 | STO 05 | 2.2525 | |
| | | 2.3348 | STO 06 | 2.3348 | |
| | | 0.002652 | STO 07 | 0.002652 | |

| Step | Procedure | Enter | Press | Display | Print |
|---|---|---|---|---|---|
| 11 | Calculate $Pt_o$ | | | | |
| | 2. < d < 20 μm | | A | 20. | .0088824589 |
| | | | | | 20. |
| 12 | Recover and print | | RCL 98 | .017697603 | |
| | $Pt_o$ 0.1 < d < 20 μm | | 2nd Prt | | 0.017697603 |

In summary:

for $\sigma$ = 0.5, $Pt_o$ = 0.018, and

for $\sigma$ = 0.25, $Pt_o$ = 0.0088.

This example emphasizes the need for uniform gas velocity distribution in a high efficiency ESP.

Printer output for example 8 is in Figure 8.

```
        15.     PRT
         4.     PRT
    2.85176     PRT
    1.06416     PRT
    0.48567     PRT
        0.7     PRT
        0.5     PRT
         4.     PRT
        0.1     PRT
        0.1     PRT
         2.     PRT
        0.1     PRT

        0.7     PRT

.0088151441     PRT
         2.     PRT
.0088824589     PRT
        20.     PRT
0.017697603     PRT
```

Figure 8. PC-100A printer output for example 8--changing normalized standard deviation of ESP gas flow distribution.

# CAUTIONS ON USING SR-52 PROGRAM RESULTS

The SR-52 program is based on results calculated using the EPA/SoRI ESP computer model for typical ESP used to collect fly ash. Thus, the calculated results are most accurate when the dust concentrations, particle size distributions, and voltage/current relationships are close to those used in the computer model calculations. Even in those cases the SR-52 results will predict values of penetration somewhat higher than those predicted by the computer model for large specific collector area ESP.

The correction factors for non-ideal effects have not been subjected to rigorous experimental evaluation. These correction factors, however, in combination with the rest of the model do give useful results which are in line with available experimental data.

Note that although the absolute accuracy of the SR-52 calculations may not be high when conditions other than those used in the computer model calculations are of interest, the trends predicted by the SR-52 program are still correct and provide useful information.

## REFERENCES


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APPENDIX A

USER INSTRUCTIONS AND PROGRAM LISTING FOR VENTURI SCRUBBER PROGRAM

USER INSTRUCTIONS

Enter Card 1, sides A and B. Enter data as follows:

| Enter | Press | Display |
|---|---|---|
| T °C | A | T°K x $10^{-4}$ |
| f (usually 0.5) | RUN | f |
| $d_g$ μm | RUN | 1.01 |
| $\sigma_g$ | RUN | 7.00 |
| $d_i$ μm | RUN | 6.00 |
| $d_f$ μm | RUN | 5.00 |
| Δd μm (if known) | RUN | 4.00 |
| 2nd stfl 1 (if number n of steps n known) | RUN | 4.00 |
| $\rho_L$ gm/cm$^3$ | RUN | 3.00 |
| L/G m$^3$/m$^3$ | RUN | 2.00 |
| $u_G$ cm/sec | RUN | 1.00 |
| μ poise | RUN | 0.00 |
| $\rho_p$ gm/cm$^3$ | RUN | Δp cm water |
| 0 | RUN | 0 |

Enter Card 2 and press A. Display $d_f$.

Title *Venturi Scrubber Card 1* Page *1* of *2*

Programmer *L. E. Sparks* Date

| Loc | Code | Key | Comments | Loc | Code | Key | Comments | Loc | Code | Key | Comments | Labels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 000 ~~112~~ | 46 | LBL | | | 54 | ) | | | 01 | 1 | | A *Main* |
| | 10 | E'* | | | 54 | ) | | | 08 | 8 | | B |
| | 98 | prt | | 040 ~~152~~ | 98 | prt* | | | 75 | − | | C |
| | 53 | ( | | | 56 | rtn* | | | 43 | RCL | | D *Drop Diam* |
| | 36 | INV | | | 46 | LBL | | 080 ~~192~~ | 00 | 0 | | E |
| 005 ~~117~~ | 42 | STO | | | 11 | A | | | 00 | 0 | | A' |
| | 00 | 0 | | | 99 | pap* | | | 95 | = | | B' |
| | 00 | 0 | | 045 ~~157~~ | 98 | prt* | | | 80 | if pos* | | C' |
| | 65 | X | | | 85 | + | | | 87 | 1'* | | D' |
| | 01 | 1 | | | 02 | 2 | | 085 ~~197~~ | 46 | LBL | | E' |
| 010 ~~122~~ | 44 | SUM | | | 07 | 7 | | | 13 | C | | Registers |
| | 00 | 0 | | | 03 | 3 | | | 14 | D | | 00 |
| | 00 | 0 | | 050 ~~162~~ | 95 | = | | | 65 | X | | 01 |
| | 54 | ) | | | 52 | EE | | | 02 | 2 | | 02 |
| | 56 | rtn* | | | 94 | +/- | | 090 ~~202~~ | 55 | ÷ | | 03 |
| 015 ~~127~~ | 46 | LBL | | | 04 | 4 | | | 05 | 5 | | 04 |
| | 14 | D | | | 42 | STO | | | 05 | 5 | | 05 |
| | 53 | ( | | 055 ~~167~~ | 00 | 0 | | | 65 | X | | 06 |
| | 05 | 5 | | | 03 | 3 | | | 43 | RCL | | 07 |
| | 00 | 0 | | | 81 | HLT | | 095 ~~207~~ | 01 | 1 | | 08 |
| 020 ~~132~~ | 55 | ÷ | | | 98 | prt* | | | 05 | 5 | | 09 |
| | 43 | RCL | | | 42 | STO | | | 65 | X | | 10 |
| | 01 | 1 | | 060 ~~172~~ | 00 | 0 | | | 43 | RCL | | 11 |
| | 06 | 6 | | | 04 | 4 | | | 01 | 1 | | 12 |
| | 85 | + | | | 81 | HLT | | 100 ~~212~~ | 04 | 4 | | 13 |
| 025 ~~137~~ | 09 | 9 | | | 98 | prt* | | | 65 | X | | 14 |
| | 01 | 1 | | | 42 | STO | | | 43 | RCL | | 15 |
| | 93 | . | | 065 ~~177~~ | 00 | 0 | | | 01 | 1 | | 16 |
| | 08 | 8 | | | 08 | 8 | | | 06 | 6 | | 17 |
| | 65 | X | | | 01 | 1 | | 105 ~~217~~ | 55 | ÷ | | 18 |
| 030 ~~142~~ | 53 | ( | | | 00 | 0 | | | 43 | RCL | | 19 |
| | 43 | RCL | | | 42 | STO | | | 01 | 1 | | Flags |
| | 01 | 1 | | 070 ~~182~~ | 00 | 0 | | | 07 | 7 | | 0 |
| | 05 | 5 | | | 00 | 0 | | | 95 | = | | 1 |
| | 45 | $y^x$ | | | 46 | LBL | | 110 ~~222~~ | 42 | STO | | 2 |
| 035 ~~147~~ | 01 | 1 | | | 87 | 1'* | | | 00 | 0 | | 3 |
| | 93 | . | | | 81 | HLT | | | | | | 4 |
| | 05 | 5 | | 075 ~~187~~ | 10 | E'* | | | | | | |

Title Venturi Scrubber Card 1 Page 2 of 2
Programmer L.E. Sparks Date

| Loc | Code | Key | Comments | Loc | Code | Key | Comments | Loc | Code | Key | Comments | Labels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 000 112 | 07 | 7 | | | 01 | 1 | | | 95 | = | | A |
| | 43 | RCL | | | 00 | 0 | | | 94 | +/- | | B |
| | 01 | 1 | | 040 152 | 23 | ln x | | | 55 | ÷ | | C |
| | 06 | 6 | | | 65 | X | | | 43 | RCL | | D |
| | 65 | X | | | 53 | ( | | 080 192 | 01 | 1 | | E |
| 005 117 | 43 | RCL | | | 02 | 2 | | | 03 | 3 | | A' |
| | 01 | 1 | | | 65 | X | | | 95 | = | | B' |
| | 08 | 8 | | 045 157 | 59 | π* | | | 42 | STO | | C' |
| | 55 | ÷ | | | 54 | ) | | | 01 | 1 | | D' |
| | 43 | RCL | | | 30 | √x* | | 085 197 | 03 | 3 | | E' |
| 010 122 | 01 | 1 | | | 95 | = | | | 22 | INV | | Registers |
| | 07 | 7 | | | 42 | STO | | | 50 | st flg* | | 00 |
| | 55 | ÷ | | 050 162 | 01 | 1 | | | 01 | 1 | | 01 |
| | 09 | 9 | | | 00 | 0 | | | 46 | LBL* | | 02 |
| | 52 | EE | | | 50 | st flg* | | 090 202 | 16 | A'* | | 03 |
| 015 127 | 08 | 8 | | | 02 | 2 | | | 08 | 8 | | 04 |
| | 55 | ÷ | | | 46 | LBL* | | | 93 | • | | 05 |
| | 14 | D | | 055 167 | 38 | D.Ms* | | | 02 | 2 | | 06 |
| | 95 | = | | | 00 | 0 | | | 04 | 4 | | 07 |
| | 42 | STO | | | 42 | STO | | 095 207 | 52 | EE | | 08 |
| 020 132 | 00 | 0 | | | 01 | 1 | | | 94 | +/- | | 09 |
| | 02 | 2 | | | 09 | 9 | | | 04 | 4 | | 10 |
| | 60 | if flg* | | 060 172 | 43 | RCL | | | 65 | X | | 11 |
| | 02 | 2 | | | 01 | 1 | | | 43 | RCL | | 12 |
| | 38 | D.Ms* | | | 01 | 1 | | 100 212 | 01 | 1 | | 13 |
| 025 137 | 43 | RCL | | | 42 | STO | | | 06 | 6 | | 14 |
| | 01 | 1 | | | 00 | 0 | | | 40 | $x^2$* | | 15 |
| | 00 | 0 | | 065 177 | 01 | 1 | | | 65 | X | | 16 |
| | 23 | ln x | | | 60 | if flg* | | | 43 | RCL | | 17 |
| | 40 | $x^2$* | | | 01 | 1 | | 105 217 | 01 | 1 | | 18 |
| 030 142 | 65 | X | | | 69 | 9'* | | | 05 | 5 | | 19 |
| | 02 | 2 | | | 16 | A'* | | | 95 | = | | Flags |
| | 94 | +/- | | 070 182 | 46 | LBL* | | | 99 | pap* | | 0 |
| | 95 | = | | | 69 | 9'* | | | 98 | prt* | | 1 |
| | 42 | STO | | | 75 | − | | 110 222 | 99 | pap* | | 2 |
| 035 147 | 00 | 0 | | | 43 | RCL | | | 81 | HLT | | 3 |
| | 09 | 9 | | | 01 | 1 | | | | | | 4 |
| | 43 | RCL | | 075 187 | 02 | 2 | | | | | | |

Title *Venturi Scrubber Card 2* Page *1* of *1*

Programmer *L. E. Sparks* Date

| Loc | Code | Key | Comments |
|---|---|---|---|
| 000 ~~112~~ | 46 | LBL* | |
| | 10 | E'* | |
| | 01 | 1 | |
| | 44 | SUM | |
| | 00 | 0 | |
| 005 ~~117~~ | 00 | 0 | |
| | 36 | IND* | |
| | 43 | RCL | |
| | 00 | 0 | |
| | 00 | 0 | |
| 010 ~~122~~ | 56 | rtn* | |
| | 46 | LBL* | |
| | 11 | A | |
| | 00 | 0 | |
| | 42 | STO | |
| 015 ~~127~~ | 00 | 0 | |
| | 00 | 0 | |
| | 13 | C | |
| | 15 | E | |
| | 65 | X | |
| 020 ~~132~~ | 14 | D | |
| | 65 | X | |
| | 53 | ( | |
| | 10 | E'* | |
| | 75 | − | |
| 025 ~~137~~ | 43 | RCL | |
| | 00 | 0 | |
| | 01 | 1 | |
| | 54 | ) | |
| | 90 | if 0* | |
| 030 ~~142~~ | 88 | 2'* | |
| | 53 | ( | |
| | 43 | RCL | |
| | 00 | 0 | |
| | 01 | 1 | |
| 035 ~~147~~ | 75 | − | |
| | 10 | E'* | |
| | 54 | ) | |
| | 80 | if pos* | |
| | 89 | 3'* | |
| 040 ~~152~~ | 01 | 1 | |
| | 46 | LBL* | |
| | 77 | 4'* | |
| | 95 | = | |
| | 44 | SUM | |
| 045 ~~157~~ | 01 | 1 | |
| | 09 | 9 | |
| | 43 | RCL | |
| | 01 | 1 | |
| | 03 | 3 | |
| 050 ~~162~~ | 44 | SUM | |
| | 00 | 0 | |
| | 01 | 1 | |
| | 41 | GTO | |
| | 11 | A | |
| 055 ~~167~~ | 46 | LBL* | |
| | 88 | 2'* | |
| | 93 | • | |
| | 05 | 5 | |
| | 41 | GTO | |
| 060 ~~172~~ | 77 | 4'* | |
| | 46 | LBL* | |
| | 89 | 3'* | |
| | 93 | • | |
| | 05 | 5 | |
| 065 ~~177~~ | 95 | = | |
| | 44 | SUM | |
| | 01 | 1 | |
| | 09 | 9 | |
| | 43 | RCL | |
| 070 ~~182~~ | 01 | 1 | |
| | 09 | 9 | |
| | 65 | X | |
| | 43 | RCL | |
| | 01 | 1 | |
| 075 ~~187~~ | 03 | 3 | |
| | 95 | = | |
| | 98 | prt* | |
| | 44 | SUM | |
| | 09 | 9 | |
| 080 ~~192~~ | 08 | 8 | |
| | 43 | RCL | |
| | 01 | 1 | |
| | 01 | 1 | |
| | 98 | prt* | |
| 085 ~~197~~ | 43 | RCL | |
| | 01 | 1 | |
| | 02 | 2 | |
| | 98 | prt* | |
| | 81 | HLT | |
| 090 ~~202~~ | 46 | LBL* | |
| | 15 | E | |
| | 53 | ( | |
| | 41 | GTO | |
| | 19 | D'* | |
| 095 ~~207~~ | 46 | LBL* | |
| | 37 | D.MS* | |
| | 65 | X | |
| | 10 | E'* | |
| | 54 | ) | |
| 100 ~~212~~ | 22 | INV | |
| | 23 | ln x | |
| | 56 | rtn* | |
| | 46 | LBL* | |
| | 19 | D'* | |
| 105 ~~217~~ | 53 | ( | |
| | 53 | ( | |
| | 01 | 1 | |
| | 93 | • | |
| | 04 | 4 | |
| 110 ~~222~~ | 65 | X | |
| | 53 | ( | |

| Labels | |
|---|---|
| A | |
| B | |
| C | |
| D | |
| E | |
| A' | |
| B' | |
| C' | |
| D' | |
| E' | |

| Registers | |
|---|---|
| 00 | |
| 01 | |
| 02 | |
| 03 | |
| 04 | |
| 05 | |
| 06 | |
| 07 | |
| 08 | |
| 09 | |
| 10 | |
| 11 | |
| 12 | |
| 13 | |
| 14 | |
| 15 | |
| 16 | |
| 17 | |
| 18 | |
| 19 | |

| Flags | |
|---|---|
| 0 | |
| 1 | |
| 2 | |
| 3 | |
| 4 | |

Title *Venturi Scrubber Card 2* Page *2* of *2*
Programmer *L.E. Sparks* Date

| Loc | Code | Key | Comments | Loc | Code | Key | Comments | Loc | Code | Key | Comments | Labels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ~~000~~ 112 | 10 | E'* | | | 55 | ÷ | | | 06 | 6 | | A |
| | 55 | ÷ | | | 43 | RCL | | | 10 | E'* | | B |
| | 93 | • | | ~~040~~ 152 | 00 | 0 | | | 85 | + | | C |
| | 07 | 7 | | | 01 | 1 | | | 93 | • | | D |
| | 54 | ) | | | 65 | X | | ~~080~~ 192 | 07 | 7 | | E |
| ~~005~~ 117 | 23 | lnx | | | 53 | ( | | | 54 | ) | | A' |
| | 85 | + | | | 02 | 2 | | | 42 | STO | | B' |
| | 93 | • | | ~~045~~ 157 | 93 | • | | | 00 | 0 | | C' |
| | 04 | 4 | | | 07 | 7 | | | 05 | 5 | | D' |
| | 09 | 9 | | | 09 | 9 | | ~~085~~ 197 | 56 | rtn* | | E' |
| ~~010~~ 122 | 55 | ÷ | | | 85 | + | | | 46 | LBL* | | Registers |
| | 43 | RCL | | | 93 | • | | | 14 | D | | 00 |
| | 00 | 0 | | ~~050~~ 162 | 08 | 8 | | | 53 | ( | | 01 |
| | 05 | 5 | | | 09 | 9 | | | 53 | ( | | 02 |
| | 75 | − | | | 04 | 4 | | ~~090~~ 202 | 53 | ( | | 03 |
| ~~015~~ 127 | 43 | RCL | | | 65 | X | | | 43 | RCL | | 04 |
| | 00 | 0 | | | 53 | ( | | | 00 | 0 | | 05 |
| | 05 | 5 | | ~~055~~ 167 | 93 | • | | | 01 | 1 | | 06 |
| | 54 | ) | | | 02 | 2 | | | 55 | ÷ | | 07 |
| | 55 | ÷ | | | 04 | 4 | | ~~095~~ 207 | 10 | E'* | | 08 |
| ~~020~~ 132 | 10 | E'* | | | 07 | 7 | | | 54 | ) | | 09 |
| | 54 | ) | | | 65 | X | | | 23 | lnx | | 10 |
| | 41 | GTO | | ~~060~~ 172 | 43 | RCL | | | 40 | $x^2$* | | 11 |
| | 37 | D.MS* | | | 00 | 0 | | | 55 | ÷ | | 12 |
| | 46 | LBL* | | | 01 | 1 | | ~~100~~ 212 | 10 | E'* | | 13 |
| ~~025~~ 137 | 13 | C | | | 55 | ÷ | | | 54 | ) | | 14 |
| | 53 | ( | | | 43 | RCL | | | 22 | INV | | 15 |
| | 10 | E'* | | ~~065~~ 177 | 00 | 0 | | | 23 | lnx | | 16 |
| | 40 | $x^2$* | | | 03 | 3 | | | 55 | ÷ | | 17 |
| | 65 | X | | | 94 | +/- | | ~~105~~ 217 | 43 | RCL | | 18 |
| ~~030~~ 142 | 10 | E'* | | | 54 | ) | | | 00 | 0 | | 19 |
| | 65 | X | | | 22 | INV | | | 01 | 1 | | Flags |
| | 53 | ( | | ~~070~~ 182 | 23 | lnx | | | 55 | ÷ | | 0 |
| | 01 | 1 | | | 54 | ) | | | 10 | E'* | | 1 |
| | 85 | + | | | 54 | ) | | ~~110~~ 222 | 54 | ) | | 2 |
| ~~035~~ 147 | 02 | 2 | | | 65 | X | | | 56 | rtn* | | 3 |
| | 65 | X | | | 42 | STO | | | | | | 4 |
| | 10 | E'* | | ~~075~~ 187 | 00 | 0 | | | | | | |

APPENDIX B

USER INSTRUCTIONS AND PROGRAM LISTING FOR ESP PROGRAM

USER INSTRUCTIONS

Enter Card 1, sides A and B. Enter data as follows:

| Enter | Press | Display |
|---|---|---|
| $d_g$ μm | A | $d_g$ |
| $\sigma_g$ | RUN | $\sigma_g$ |
| a | B | a |
| b | RUN | b |
| c | RUN | c |
| A/V $cm^2/Acm^3/sec$ | C | -A/V** |
| or A/V $ft^2/10^3$ ACFM | 2nd stfl 1 C | -A/V $cm^2/Acm^3/sec$ |
| $\sigma$ | D | $\sigma$ |
| $N_s$ | E | $N_s$ |
| S | RUN | S |
| $d_i$ μm | 2nd A' | $d_i$ |
| $d_f$ μm | RUN | $d_f$ |
| $\Delta d$ μm | RUN | $\Delta d$ |
| or n (number of steps) | 2nd stflg 2 RUN | $\Delta d$ |

Enter Card 2. Press A. Display $d_f$.

Recover $Pt_o$ by pressing RCL 98.

**A/V in $cm^2/Acm^3/sec$ is displayed because the program uses A/V in the calculations.

Title *E.S.P. Card 1* Page *1* of *1*

Programmer *L. E. Sparks* Date

| Loc | Code | Key | Comments | Loc | Code | Key | Comments | Loc | Code | Key | Comments | Labels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 000 ~~112~~ | 46 | LBL | | | 09 | 9 | | | 01 | 1 | | A |
| | 10 | E'* | | | 65 | X | | | 95 | = | | B |
| | 36 | IND | | 040 ~~152~~ | 53 | ( | | | 60 | ifflg* | | C |
| | 42 | STO | | | 02 | 2 | | | 01 | 1 | | D |
| | 00 | 0 | | | 65 | X | | 080 ~~192~~ | 87 | 1'* | | E |
| 005 ~~117~~ | 00 | 0 | | | 59 | π* | | | 10 | E'* | | A' |
| | 65 | X | | | 54 | ) | | | 56 | rtn* | | B' |
| | 01 | 1 | | 045 ~~157~~ | 30 | √x* | | | 46 | LBL | | C' |
| | 44 | SUM | | | 95 | = | | | 87 | 1'* | | D' |
| | 00 | 0 | | | 10 | E'* | | 085 ~~197~~ | 65 | X | | E' |
| 010 ~~122~~ | 00 | 0 | | | 56 | rtn* | | | 01 | 1 | | Registers |
| | 95 | = | | | 46 | LBL | | | 93 | • | | 00 |
| | 56 | rtn* | | 050 ~~162~~ | 12 | B | | | 09 | 9 | | 01 |
| | 46 | LBL | | | 98 | prt* | | | 06 | 6 | | 02 |
| | 11 | A | | | 65 | X | | 090 ~~202~~ | 09 | 9 | | 03 |
| 015 ~~127~~ | 98 | prt* | | | 05 | 5 | | | 52 | EE | | 04 |
| | 65 | X | | | 42 | STO | | | 94 | +/- | | 05 |
| | 02 | 2 | | 055 ~~167~~ | 00 | 0 | | | 03 | 3 | | 06 |
| | 42 | STO | | | 00 | 0 | | | 95 | = | | 07 |
| | 00 | 0 | | | 01 | 1 | | 095 ~~207~~ | 10 | E'* | | 08 |
| 020 ~~132~~ | 00 | 0 | | | 95 | = | | | 56 | rtn* | | 09 |
| | 01 | 1 | | | 10 | E'* | | | 46 | LBL | | 10 |
| | 95 | = | | 060 ~~172~~ | 81 | HLT | | | 14 | D | | 11 |
| | 10 | E'* | | | 98 | prt* | | | 98 | prt* | | 12 |
| | 81 | HLT | | | 10 | E'* | | 100 ~~212~~ | 42 | STO | | 13 |
| 025 ~~137~~ | 98 | prt* | | | 81 | HLT | | | 01 | 1 | | 14 |
| | 23 | lnx | | | 98 | prt* | | | 09 | 9 | | 15 |
| | 42 | STO | | 065 ~~177~~ | 10 | E'* | | | 01 | 1 | | 16 |
| | 01 | 1 | | | 56 | rtn* | | | 01 | 1 | | 17 |
| | 09 | 9 | | | 46 | LBL | | 105 ~~217~~ | 42 | STO | | 18 |
| 030 ~~142~~ | 40 | x²* | | | 13 | C | | | 00 | 0 | | 19 |
| | 65 | X | | | 98 | prt | | | 00 | 0 | | Flags |
| | 02 | 2 | | 070 ~~182~~ | 94 | +/- | | | 43 | RCL | | 0 |
| | 95 | = | | | 65 | X | | | 01 | 1 | | 1 |
| | 94 | +/- | | | 09 | 9 | | 110 ~~222~~ | 09 | 9 | | 2 |
| 035 ~~147~~ | 10 | E'* | | | 42 | STO | | | 45 | y^x* | | 3 |
| | 43 | RCL | | | 00 | 0 | | | | | | 4 |
| | 01 | 1 | | 075 ~~187~~ | 00 | 0 | | | | | | |

Title ESP Card 1 Page 2 of 2
Programmer L. E. Sparks Date

| Loc | Code | Key | Comments | Loc | Code | Key | Comments | Loc | Code | Key | Comments | Labels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ~~000~~ 112 | 01 | 1 | | | 06 | 6 | | | 17 | B'* | | A |
| | 93 | • | | | 42 | STO | | | 00 | 0 | | B |
| | 07 | 7 | | ~~040~~ 152 | 00 | 0 | | | 42 | STO | | C |
| | 08 | 8 | | | 00 | 0 | | | 01 | 1 | | D |
| | 06 | 6 | | | 01 | 1 | | ~~080~~ 192 | 09 | 9 | | E |
| ~~005~~ 117 | 95 | = | | | 95 | = | | | 42 | STO | | A' |
| | 65 | X | | | 10 | E'* | | | 09 | 9 | | B' |
| | 93 | • | | ~~045~~ 157 | 81 | HLT | | | 08 | 8 | | C' |
| | 07 | 7 | | | 98 | prt* | | | 43 | RCL | | D' |
| | 06 | 6 | | | 10 | E'* | | ~~085~~ 197 | 01 | 1 | | E' |
| ~~010~~ 122 | 06 | 6 | | | 81 | HLT | | | 06 | 6 | | Registers |
| | 95 | = | | | 98 | prt* | | | 42 | STO | | 00 |
| | 10 | E'* | | ~~050~~ 162 | 10 | E'* | | | 00 | 0 | | 01 |
| | 43 | RCL | | | 60 | ifflg* | | | 01 | 1 | | 02 |
| | 01 | 1 | | | 02 | 2 | | ~~090~~ 202 | 22 | INV | | 03 |
| ~~015~~ 127 | 09 | 9 | | | 88 | 2'* | | | 50 | stflg* | | 04 |
| | 65 | X | | | 17 | B'* | | | 01 | 1 | | 05 |
| | 93 | • | | ~~055~~ 167 | 46 | LBL | | | 22 | INV | | 06 |
| | 00 | 0 | | | 88 | 2'* | | | 50 | stflg* | | 07 |
| | 07 | 7 | | | 43 | RCL | | ~~095~~ 207 | 02 | 2 | | 08 |
| ~~020~~ 132 | 05 | 5 | | | 01 | 1 | | | 22 | INV | | 09 |
| | 05 | 5 | | | 07 | 7 | | | 52 | EE | | 10 |
| | 95 | = | | ~~060~~ 172 | 75 | − | | | 99 | pap* | | 11 |
| | 10 | E'* | | | 43 | RCL | | | 43 | RCL | | 12 |
| | 56 | rtn* | | | 01 | 1 | | ~~100~~ 212 | 00 | 0 | | 13 |
| ~~025~~ 137 | 46 | LBL | | | 06 | 6 | | | 09 | 9 | | 14 |
| | 15 | E | | | 95 | = | | | 94 | +/- | | 15 |
| | 98 | prt* | | ~~065~~ 177 | 55 | ÷ | | | 98 | prt* | | 16 |
| | 10 | E'* | | | 43 | RCL | | | 99 | pap* | | 17 |
| | 81 | HLT | | | 01 | 1 | | ~~105~~ 217 | 81 | HLT | | 18 |
| ~~030~~ 142 | 98 | prt* | | | 08 | 8 | | | | | | 19 |
| | 10 | E'* | | | 95 | = | | | | | | Flags |
| | 56 | rtn* | | ~~070~~ 182 | 42 | STO | | | | | | 0 |
| | 46 | LBL | | | 01 | 1 | | | | | | 1 |
| | 16 | A'* | | | 08 | 8 | | ~~110~~ 222 | | | | 2 |
| ~~035~~ 147 | 98 | prt* | | | 98 | prt* | | | | | | 3 |
| | 65 | X | | | 17 | B'* | | | | | | 4 |
| | 01 | 1 | | ~~075~~ 187 | 46 | LBL | | | | | | |

Title ESP Card 2 Page 1 of 2

Programmer L.E. Sparks Date

| Loc | Code | Key | Comments | Loc | Code | Key | Comments | Loc | Code | Key | Comments | Labels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 000 ~~112~~ | 46 | LBL | | | 01 | 1 | | | 54 | ) | | A |
| | 10 | E' * | | | 56 | rtn * | | | 19 | D' * | | B |
| | 53 | ( | | 040 ~~152~~ | 46 | LBL | | | 65 | X | | C |
| | 36 | IND | | | 14 | D | | | 10 | E' * | | D |
| | 43 | RCL | | | 53 | ( | | 080 ~~192~~ | 54 | ) | | E |
| 005 ~~117~~ | 00 | 0 | | | 53 | ( | | | 22 | INV | | A' |
| | 00 | 0 | | | 53 | ( | | | 23 | lnx | | B' |
| | 65 | X | | 045 ~~157~~ | 10 | E' * | | | 19 | D' * | | C' |
| | 53 | ( | | | 55 | ÷ | | | 53 | ( | | D' |
| | 01 | 1 | | | 10 | E' * | | 085 ~~197~~ | 43 | RCL | | E' |
| 010 ~~122~~ | 44 | SUM | | | 54 | ) | | | 00 | 0 | | Registers |
| | 00 | 0 | | | 23 | lnx | | | 08 | 8 | | 00 |
| | 00 | 0 | | 050 ~~162~~ | 40 | $x^2$ * | | | 55 | ÷ | | 01 |
| | 54 | ) | | | 55 | ÷ | | | 53 | ( | | 02 |
| | 01 | 1 | | | 10 | E' * | | 090 ~~202~~ | 01 | 1 | | 03 |
| 015 ~~127~~ | 54 | ) | | | 54 | ) | | | 85 | + | | 04 |
| | 56 | rtn * | | | 22 | INV | | | 10 | E' * | | 05 |
| | 46 | LBL | | 055 ~~167~~ | 23 | lnx | | | 65 | X | | 06 |
| | 19 | D' * | | | 55 | ÷ | | | 53 | ( | | 07 |
| | 53 | ( | | | 18 | C' * | | 095 ~~207~~ | 01 | 1 | | 08 |
| 020 ~~132~~ | 36 | IND | | | 55 | ÷ | | | 75 | − | | 09 |
| | 42 | STO | | | 10 | E' * | | | 17 | B' * | | 10 |
| | 00 | 0 | | 060 ~~172~~ | 54 | ) | | | 54 | ) | | 11 |
| | 00 | 0 | | | 56 | rtn * | | | 85 | + | | 12 |
| | 65 | X | | | 46 | LBL | | 100 ~~212~~ | 10 | E' * | | 13 |
| 025 ~~137~~ | 53 | ( | | | 15 | E | | | 65 | X | | 14 |
| | 01 | 1 | | | 53 | ( | | | 53 | ( | | 15 |
| | 44 | SUM | | 065 ~~177~~ | 53 | ( | | | 17 | B' * | | 16 |
| | 00 | 0 | | | 10 | E' * | | | 20 | 1/x * | | 17 |
| | 00 | 0 | | | 85 | + | | 105 ~~217~~ | 23 | lnx | | 18 |
| 030 ~~142~~ | 54 | ) | | | 18 | C' * | | | 54 | ) | | 19 |
| | 01 | 1 | | | 65 | X | | | 54 | ) | | Flags |
| | 54 | ) | | 070 ~~182~~ | 10 | E' * | | | 55 | ÷ | | 0 |
| | 56 | rtn * | | | 85 | + | | | 53 | ( | | 1 |
| | 46 | LBL | | | 18 | C' * | | 110 ~~222~~ | 17 | B' * | | 2 |
| 035 ~~147~~ | 18 | C' * | | | 40 | $x^2$ * | | | 23 | lnx | | 3 |
| | 43 | RCL | | | 65 | X | | | | | | 4 |
| | 00 | 0 | | 075 ~~187~~ | 10 | E' * | | | | | | |

Title ESP Card 2 Page 2 of 2
Programmer L. E. Sparks Date

| Loc | Code | Key | Comments | Loc | Code | Key | Comments | Loc | Code | Key | Comments | Labels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ~~000~~ 112 | 55 | ÷ | | | 46 | LBL | | | 08 | 8 | | A |
| | 10 | E'* | | | 11 | A | | | 44 | SUM | | B |
| | 55 | ÷ | | ~~040~~ 152 | 01 | 1 | | | 00 | 0 | | C |
| | 53 | ( | | | 42 | STO | | | 01 | 1 | | D |
| | 10 | E'* | | | 00 | 0 | | ~~080~~ 192 | 25 | clr | | E |
| ~~005~~ 117 | 85 | + | | | 00 | 0 | | | 41 | GTO | | A' |
| | 53 | ( | | | 53 | ( | | | 11 | A | | B' |
| | 01 | 1 | | ~~045~~ 157 | 53 | ( | | | 46 | LBL | | C' |
| | 75 | − | | | 14 | D | | | 88 | 2'* | | D' |
| | 43 | RCL | | | 65 | X | | ~~085~~ 197 | 93 | • | | E' |
| ~~010~~ 122 | 01 | 1 | | | 15 | E | | | 05 | 5 | | Registers |
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| | 43 | RCL | | ~~055~~ 167 | 54 | ) | | | 54 | ( | | 06 |
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| | 03 | 3 | | | 88 | 2'* | | ~~095~~ 207 | 01 | 1 | | 08 |
| ~~020~~ 132 | 20 | 1/x* | | | 53 | ( | | | 09 | 9 | | 09 |
| | 54 | ) | | | 18 | C'* | | | 53 | ( | | 10 |
| | 23 | ln x | | ~~060~~ 172 | 75 | − | | | 10 | E'* | | 11 |
| | 54 | ) | | | 10 | E'* | | | 10 | E'* | | 12 |
| | 65 | X | | | 54 | ) | | ~~100~~ 212 | X | X | | 13 |
| ~~025~~ 137 | 43 | RCL | | | 90 | if 0* | | | 43 | RCL | | 14 |
| | 00 | 0 | | | 89 | 3'* | | | 01 | 1 | | 15 |
| | 09 | 9 | | ~~065~~ 177 | 80 | if pos* | | | 08 | 8 | | 16 |
| | 54 | ) | | | 89 | 3'* | | | 54 | ) | | 17 |
| | 22 | INV | | | 01 | 1 | | ~~105~~ 217 | 98 | prt* | | 18 |
| ~~030~~ 142 | 23 | ln x | | | 46 | LBL | | | 44 | SUM | | 19 |
| | 56 | rtn* | | | 77 | 4'* | | | 09 | 9 | | Flags |
| | 46 | LBL | | ~~070~~ 182 | 54 | ) | | | 08 | 8 | | 0 |
| | 17 | B'* | | | 44 | SUM | | | 18 | C'* | | 1 |
| | 43 | RCL | | | 01 | 1 | | ~~110~~ 222 | 98 | prt* | | 2 |
| ~~035~~ 147 | 01 | 1 | | | 09 | 9 | | | 81 | HLT | | 3 |
| | 00 | 0 | | | 43 | RCL | | | | | | 4 |
| | 56 | rtn* | | ~~075~~ 187 | 01 | 1 | | | | | | |

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*(Please read Instructions on the reverse before completing)*

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15. SUPPLEMENTARY NOTES Dr. Sparks' mail drop is 61; his phone is 919/541-2925.

16. ABSTRACT The report provides useful tools for estimating particulate removal by venturi scrubbers and electrostatic precipitators. Detailed descriptions are given for programs to predict the penetration (one minus efficiency) for each device. These programs are written specifically for the Texas Instruments SR-52 programmable calculator. Each program includes a general description of the mathematical model on which the program is based and the formulas and numerical techniques used in adapting the model to the SR-52. Numerical examples, program listing, and user instructions are included.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group | |
|---|---|---|---|---|
| Air Pollution | Programming | Air Pollution Control | 13B | |
| Dust | Manuals | Stationary Sources | 11G | 05B,09B |
| Estimating | Calculators | Particulate | 14B | |
| Scrubbers | Mathematical | Venturi Scrubbers | 07A | |
| Venturi Tubes | Models | SR-52 Calculator | | 12A |
| Electrostatic Precipitators | | | | |

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