Report

SMOKE CURVE CALIBRATION

March 1969

New York University
School of Engineering and Science
University Heights, New York, N.Y. 10453

Research Division

Report

Smoke Curve Calibration

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Prepared by

William T. Ingram
Project Director

Research Division
New York University
School of Engineering and Science

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REPORT

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Objective

The original goals of this project were to establish the shape of a smoke curve for fine suspended particulates in New York City comparable to the International Smoke Curve used in British and other European practice, and to relate two commonly used reporting units of surface concentration, μg/m^3 (European practice) and Coh/1000 lineal feet (United States practice), to each other. An additional goal was developed during the project which was to examine the possible relationship between size of particle and particulate density as measured in United States practice. While not directly a goal of the project, it was essential in the course of work to study the relationship between particulate density readings taken for one hour and two hour sampling periods. Progress toward achievement of these goals is presented in the following pages.

Summary

This report reviews briefly the background and development of particulate density measurement systems in the United States and Great Britain and discusses the difference in reporting units which has made it impossible, from routine reporting, to make comparisons of particulate density concentrations in the atmosphere between locations in the United States, using either gravimetric measurement or light reflection or transmission techniques, and locations in Great Britain or other European countries using the International Smoke Curve for estimating concentration. Procedures for the establishment of a relationship between United States reporting units (Coh/1000 ft.) and British equivalent units (μg/m^3), each expressing

a unit measure of concentration of particulates in atmosphere but neither expressing a true unit weight concentration of suspended particles, have been developed and described in detail.

A smoke curve for New York City has been developed at two locations, one representing a heavily populated area with industrial, commercial and vehicular influence on particle emissions, the other representing urban residential living with less obvious industrial, vehicular and commercial contributions. The relationship between curves for these sites and between curves derived for New York and the International Smoke Curve is shown to be of basically the same form between 0 and 45 darkness index. It is further shown that the New York City curve can be normalized to 30 $\mu g/cm^2$ at a darkness index of 25. This positioning compares with 17 $\mu g/cm^2$ (England) and 20 $\mu g/cm^2$ (International Smoke Curve). In effect then the surface concentration of particulates required to produce the same darkness index is higher in New York than in either England, France or Holland, but in other regards the New York curve is one of the family of curves common to all. The final form of the New York City Standard Smoke Curve has been taken as:

$$\mu g/cm^2 = 1.00 \text{ (Darkness Index)} + .0079 \text{ (DI)}^2 \qquad (13)$$

That expression has been converted into a concentration equation standardized at an air volume of 2 M^3 passing through the filter as follows:

$$\mu g/m^3 = \frac{5.06 \times \mu g/cm^2}{V} \qquad (15)$$

Data are presented that show that a one hour Coh/1000' reading alone cannot be representative of a two hour Coh/1000' reading. The calculated line of best fit is:

$$Y = - 0.14 + 1.31 X \qquad (23)$$

where Y = average of two one hour values, Coh/1000'

X = one two hour value, Coh/1000'

Data are presented to show that the relationship of transmittance value as measured by RAC spot evaluation, and the reflectance value measured on a Photovolt Reflectometer was

$$y = 2.71 + 1.008 X \tag{21}$$

where y = % Transmittance
X = % Reflectance

A graphical presentation is shown that will permit the conversion of either United States or European data by entering with a measured darkness index and reading the equivalent concentration in $\mu g/m^3$. A standard curve is also provided for New York City whereby entry can be made in Coh/1000 ft. and read as $\mu g/m^3$, thus providing an easy and direct reading that can be used in comparison of particulate density concentrations measured in the European system.

An exploratory study was made for the purpose of investigating possible relationships between particle count differentiated by size range and particulate density in terms of light transmittance and/or light reflectance. A series of curves is presented to show that relationship. The concentration is greatest and most significant when the Coh/1000' value is related to total particle count in the size range 1.0-2.0 μ. The relationship appears to be most stable for ambient air relative humidities between 31% and 47%, however further work on this relationship is needed to be definitive in either humidity effects or controls.

Obviously more work on calibration curves for places elsewhere than New York City is necessary. However, it is believed that with relatively small error, the New York City curve could be used for making relative comparisons of small size suspended particulates in the atmosphere based on Coh/1000' readings as they are routinely taken. Likewise, with the procedures offered a calibration curve index for other locations could be established quickly for curve positioning.

It would not be necessary for practical and routine measurement to undertake the more rigorous and exacting work required to revalidate the form of curve for each locality, since both in New York, Great Britain, France and Holland the studies have uniformly confirmed that curve form, within the normal measurement limits, is consistent and needs only to be positioned at the standardized index point.

Particulate Measurement Systems

United States Practice

Although there are several methods for measuring particulates in air, it has been somewhat routine practice in the United States to measure suspended particulates in atmosphere by two basic systems. One is a gravimetric process the other is related to measurement of optical density of filtered deposit.

The gravimetric system requires the collection of particulates taken from a large volume of air on fairly large size filter paper (usually 4" diameter or 8" x 10"). The method has been known as the Hi-Vol method. The filter paper is weighed before and after the sample, and the air volume producing the quantity of particulate is measured by rate of flow and time of run. Results are reported as μg/cubic meter of air.

A commonly used method in the United States employing the optical density relationship is described fully in ASTM-D1704-61 (Standard Method of Test for Particulate Matter in the Atmosphere). The system is applicable to fine particles (usually less than 40 μ in diameter). Air is passed through a definite circular area of filter paper at a measured sampling rate for a one or two hour period and is repeated on a new area in sequence so that in the selected increments of time it is possible to obtain a series of spots or stains that can be compared by measuring either reflectance or transmission of light as compared with clean paper. The optical density relationship measured by transmission thus obtained is then converted into a relationship with the volume of air producing the stain and has commonly been reported as Coh/1000 linear feet. A variant in reporting is introduced by using the reflection value converted to a relationship known as the rud, or a deposit which produces an optical reflectance of 0.01 due to 10,000 lineal feet of air. The rud then equals 0.1 Coh/1000 ft.

European Practice

Practice in Europe stems from early work of Harris, and Owens and Clark. In 1936 Hill[1] used transmitted light to assess the stain produced on a filter paper after a known volume of air had been passed through it. A relation was established between the optical density and the mass concentration of smoke. Calibration curves were established to show relationships between % reflectance and weight in $\mu g/cm^2$ filter paper surface.

Waller[2] has reviewed the historical development of British Smoke Curves that are based on optical density relationships and not on mass concentration.

The importance of differentiating between weight and darkness was examined by the Working Party on Methods of Measuring Air Pollution and Survey Techniques, Organization for Economic Cooperation and Development and reported in 1964.[3] That group pointed out that darkness of the stain cannot be proportional to the total weight of suspended matter in the volume samples and should be considered simply as an indication of the dark material in the air. However, experimental work of the group has shown that the shape of the calibration curve does not vary beyond reasonable limits, so that it is possible to have a workable index of dark smoke concentration related to standard smoke from a reflectometer reading. And, in fact, the form of curve between darkness index of 10 and 60 was sufficiently reliable that it could be referred to as the

Generalized International Standard Calibration Curve. By normalizing the curve at an equal point (in this case 20 $\mu g/cm^2$ at darkness index of 25) the curve could then be used to define the proposed equivalent international standard smoke scale. It has been reasoned therefore that the adaptation of an established universal form of smoke calibration curve would allow results of air pollution surveys made all over the world to be compared directly.

The British form of that curve has been taken by the British Standards Institution as a basis for the measurement of smoke and is now used in the National Survey. The Warren Spring Laboratory carried out an experimental program that stemmed from a basic assumption that the deduced (from curve) surface concentration on the filter is linearly proportional to the volume of the sample passed through it.[4] It was established that properties of the proposed curve held good for a variety of smokes in England, France and Holland as presented in the OECD report[3] and since 1964 the curve has been used in England for the estimate of smoke concentrations in equivalent standard smoke units. The surface concentration determined by standard curve was transferred into smoke concentrations by calculations according to equations derived for the purpose and this calculation permitted the expression of a darkness index measurement in equivalent units of $\mu g/m^3$ for reporting purposes, valid for a darkness index ranging from 0 to 60.

Reporting Units of Both Practices

Thus British data on particulate density are now reported as $\mu g/m^3$, and it should be clear that though this unit is related to a gravimetric reading of surface concentration in its original derivation, it is not and cannot be a reporting of actual weight of material trapped on filter paper per unit volume of air passed through the paper.

It is also quite apparent that if particulate density as measured nationally in the United States by the ASTM Standard

Method (D1704-61) is to be compared to particulate density as measured in England or the European countries such as France and Holland, there must be a relationship established between Coh/1000' and $\mu g/m^3$ the reporting units of the two light index measurement systems.

This project has been directed to the major task of establishing that relationship for at least one city of the United States, New York City. If, as has been found in the European studies, the curve form is the same between acceptable limits, and an index point placement of the curve is possible, then procedures for the transfer of United States reporting units into English units and vice versa become a reality. The experimental procedures and the results obtained are presented in the following pages.

Correlation of Particle Size and Particulate Density

In the latter stages of project work it became apparent that size of particle trapped on the filter might influence the index. Exploratory work related to the establishment of those relationships that might exist has been performed and is also reported here.

Experimental Procedure

It was the intent of the procedure to duplicate as closely as possible the calibration procedures used by the Warren Spring Laboratory. Both before the start of the project and during the project, personal visits and correspondence were employed to check out the procedures and findings. Several items of equipment and, for portions of the work, the same filter paper used in England were borrowed so that any differences attributable to the equipment or paper could be reduced or eliminated.

Relationship Between Units of Surface Concentration

The equations used in Great Britain for determining smoke concentrations in the air are calculated by the use of the British Standard Smoke Calibration Curve. For reflectometer reading of 99 to 40, equation (1) is used:

$$C = \frac{F}{V}(91{,}679.22 - 3{,}332.0460\ R + 49.618884\ R^2 - 0.35329778\ R^3 + 0.0009863435\ R^4) \qquad (1)$$

where C = concentration, $\mu g/m^3$

V = volume of sample in cubic feet

F = constant equal to 1.00 for 1 inch filter

For reflectometer readings between 40 and 20, equation (2) is used:

$$C = \frac{F}{V}(214{,}245.1 - 15{,}130.512\ R + 508.181\ R^2 - 8.831144\ R^3 + 0.0628057\ R^4) \qquad (2)$$

where the key is as above.

In the United States smoke concentration is expressed as soiling index where the Coh unit is used. The Coh unit is defined by equation (3):

$$\text{Coh/1000 linear feet} = \frac{\text{O.D. X area of spot x } 10^5}{\text{volume of air sample}} \qquad (3)$$

where O.D. = optical density determined by light transmission

The solution of equation (1) for sample volumes of 30 ft^3* and 70.62 ft^3** (2 M^3) is plotted in Figure 1.

The solution of equation (3), plotted in Figure 2, was solved for a 1" diameter spot and a sample of 30 ft^3.

It is noted that light reflection is used to determine $\mu g/m^3$ whereas light transmission is used to determine Coh

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*Represents volume for two hour sampling period on AISI.

**Represents volume for typical sampling period in Great Britain.

Surface Concentration
$\mu g/m^3$ vs. % Reflection

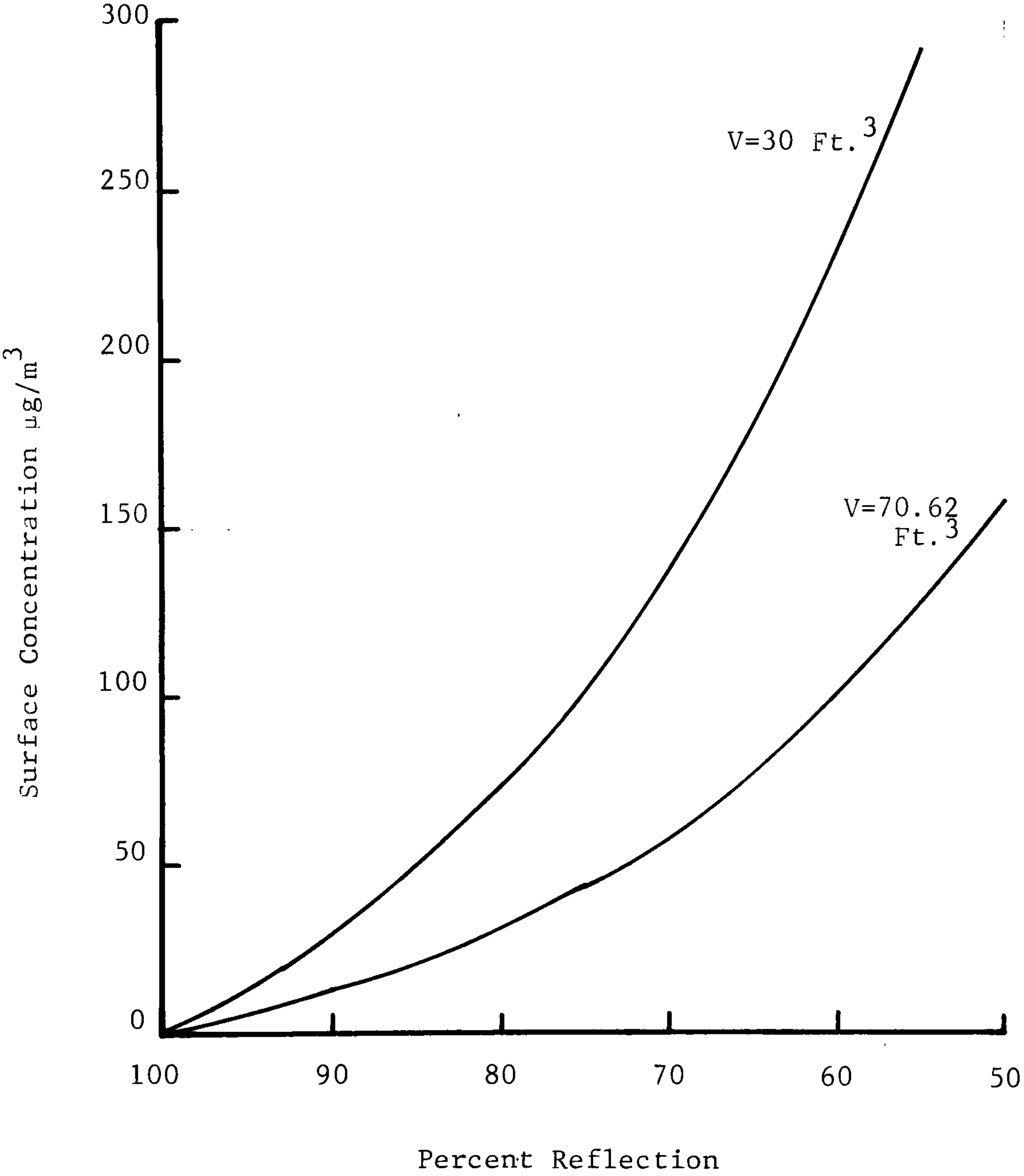


Figure 1

Surface Concentration
Coh/1000' vs. % Transmission

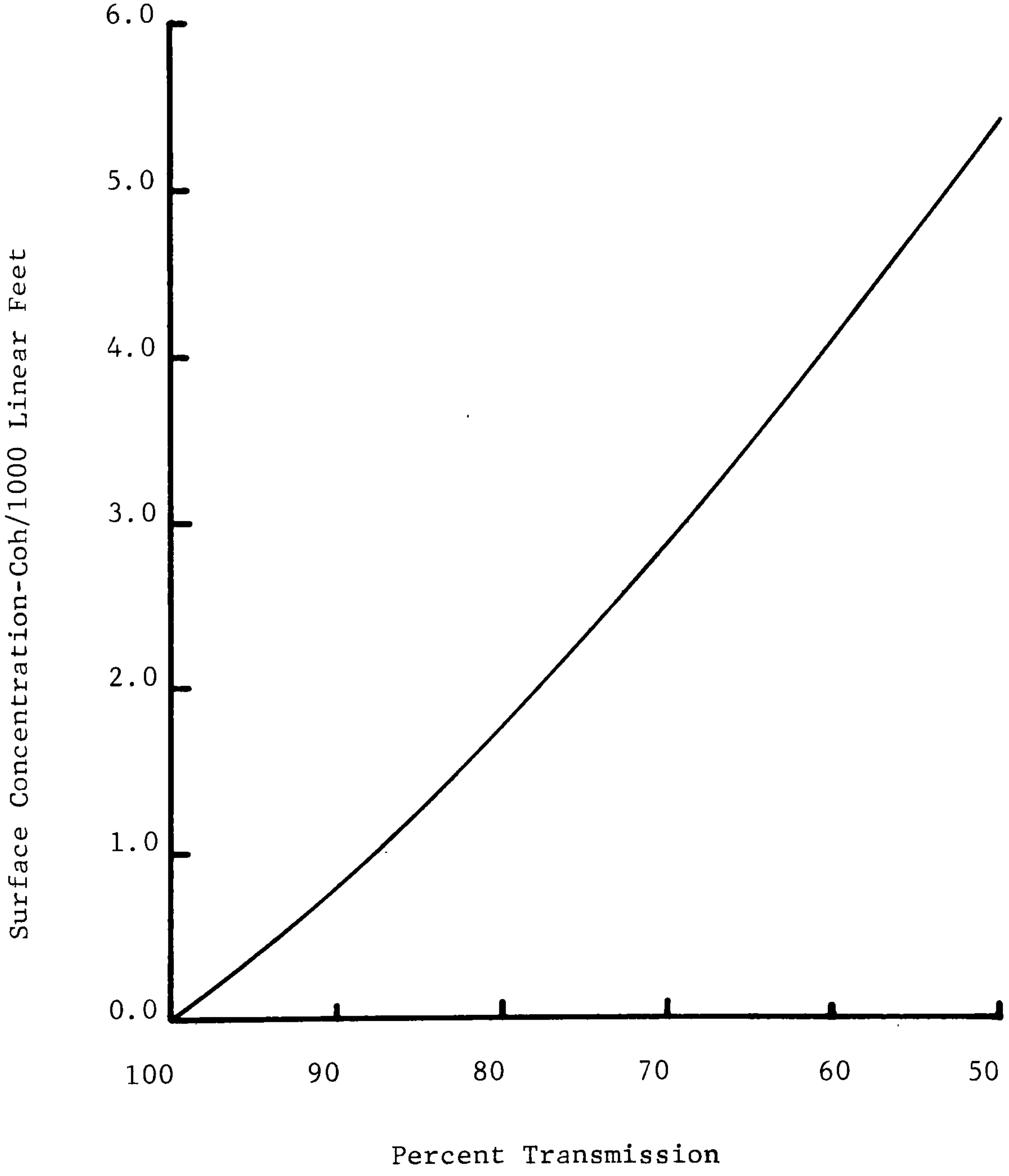


Figure 2

values. Due to the nature of the instruments, there is almost a 1:1 relationship between these two quantities.

Rationale of Comparison

The ultimate goal required a method of comparison between $\mu g/m^3$ and Coh/1000 LF. If, for example, 100 $\mu g/m^3$ is reported, what would be the comparable Coh value? From Figure 1 we note that a surface concentration of 100 $\mu g/m^3$ is obtained when the resultant spot produces a reflectance of 60%, when sampling at the normal flow rate in Great Britain and sampling a volume of 70.62 cubic feet. If we now assume that an AISI instrument was sampling the same atmosphere, it would require a percent transmission (or reflection) reading, after a sample of 30 cubic feet, of 75%. This 75% value would be equivalent to a Coh reading of 2.3.

The British curve is based on a standard curve where a darkness index of 25 equals 17 $\mu g/cm^2$. For the international form, a darkness index of 25 equals 20 $\mu g/cm^2$.

The sub-goals then became:

1. the comparison of curve form to determine that a curve for New York did or did not fit into the European family of curves, and
2. the determination of the value for New York data that would normalize at a darkness index of 25.

Description of Sampling Sites

The New York University Bronx Station is located in the northwest section of the Bronx, on the NYU Campus, at 1911 Osborne Place. The surrounding land usage includes a steam power plant, several thousand feet to the north, operated by Consolidated Edison Company of New York; five-story apartment buildings to the south and east; and the Major Deegan Highway and the Harlem River to the west. Two sampling probes were placed on the outside of the building facing toward the north-west. These probes were three feet from the building at a height of about seven feet above the ground. This site was used for runs covering the periods March 1966 to October 1966, and January 1968 to February 1968.

The station designated as Christodora Station (Manhattan) is located at 601 East 9th Street on the lower east side of Manhattan. Immediate surroundings include a park, five-story apartment buildings, and eighteen-story buildings to the north and east about 2,000 feet on the periphery. A steam power plant, operated by Consolidated Edison Company of New York is northeast of the area. The two sampling probes extended three feet beyond the building and about 189 feet above the ground, facing in a southwesterly direction. Sampling was conducted at this station from February 1968 to August 1968.

The stations are located as shown in Figure 3. The approximate distance separating the New York University Bronx Station and Christodora Station is ten miles.

Determination of the Form of the Calibration Curve

In this first phase of the investigation, proportional sampling of the air provided a series of smoke stains with increasing values of darkness index (darkness index equals 100 - %R) for corresponding increasing volumes of air sampled. This was accomplished by using several fractional timers, arranged so that the flow to each individual filter was operating either 11.1%, 16.6%, 33.3%, 50%, 66.6% or 100% (continuous flow) of the time. The actual on time percentage was slightly less, as shown in Table 1.

Basically, air was drawn through an inverted funnel four inches in diameter and fed into a wide mouthed cylindrical mixing bottle by means of a one-half inch I.D. glass tubing. The tubing entered the stopper centrally and dropped to one inch above the base. Seven symetrically placed one-quarter inch I.D. glass tubes were placed one-half inch into the bottle and each tube led to a one inch diameter filter clamp containing Whatman No. 1 filter paper and then to a dry gas meter

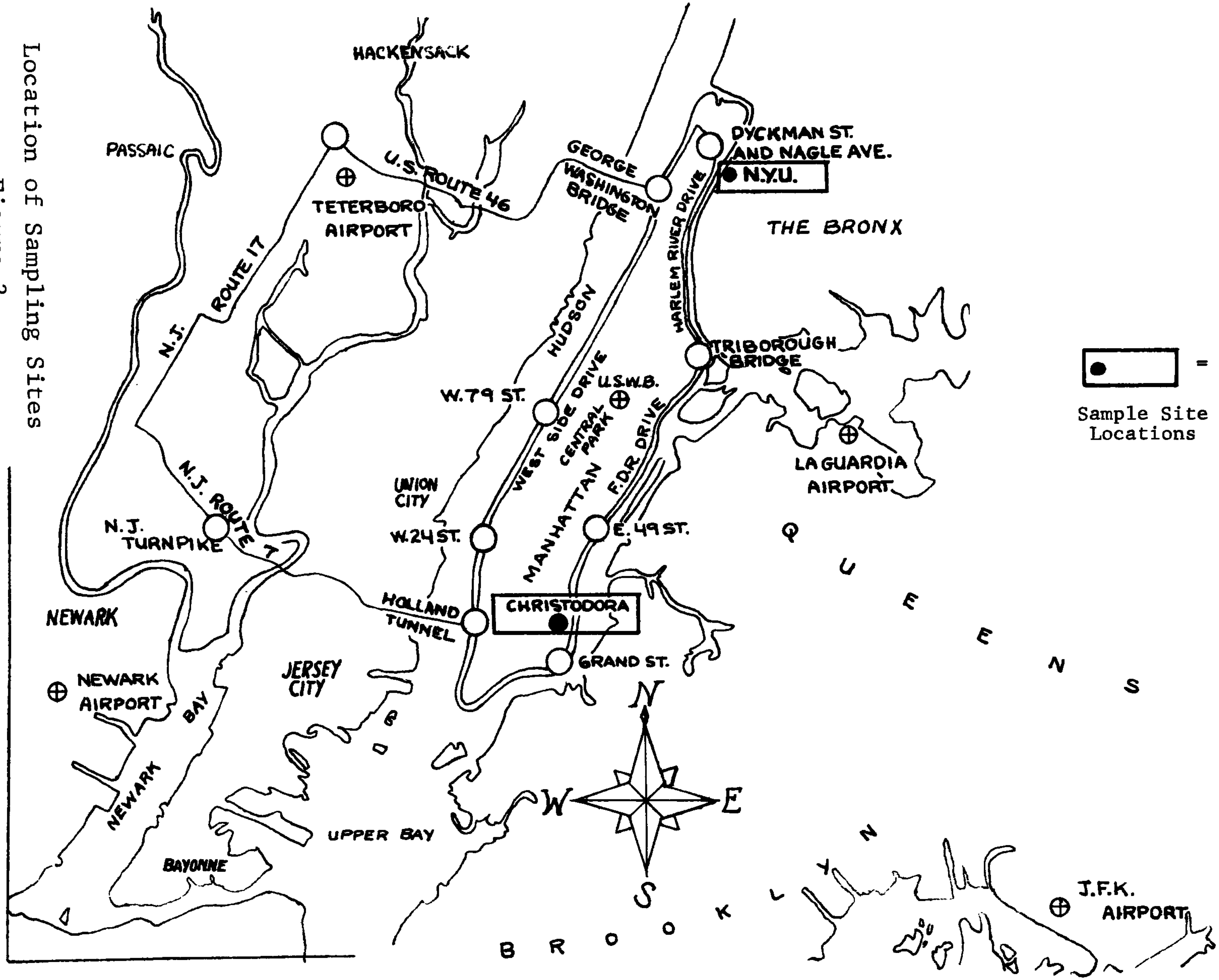


Figure 3
Location of Sampling Sites

Table 1

Pump Operation During 15 Minute Cycle

Pump No.	Theoretical On Time (Minutes)	Actual On Time (Minutes)	Actual On Time (%)
1	15.0	15	100
2	10.0	10.03	66.91
3	7.5	7.22	48.1
4	5.0	5.0	33.3
5	2.5	2.57	17.1
6	1.7	1.64	10.9

capable of reading 0.1 ft^3. One filter was used as a control and the remaining were used as test filters. Each meter was connected to a 1.3 cfm pump which had been orificed to produce a flow of approximately .073 ft^3/min.

The fractional timers were arranged to operate the pumps for different periods of time over a 15 minute cycle. The number of cycles that the test was run was set so that there was an approximate darkness index of less than 60 on a second continuously operated control filter. This filter was used only to check the progress of the test and, therefore, was removed from the filter clamp periodically to check the darkness index.

Table 1 gives the actual time each pump was running during a 15 minute cycle. The apparatus for the test program is diagrammed in Figure 4 and listed in Appendix A.

A general view of the test apparatus is shown in Exhibit 1. Exhibit 2 illustrates pictorially the sequence of flow diagrammed in Figure 4.

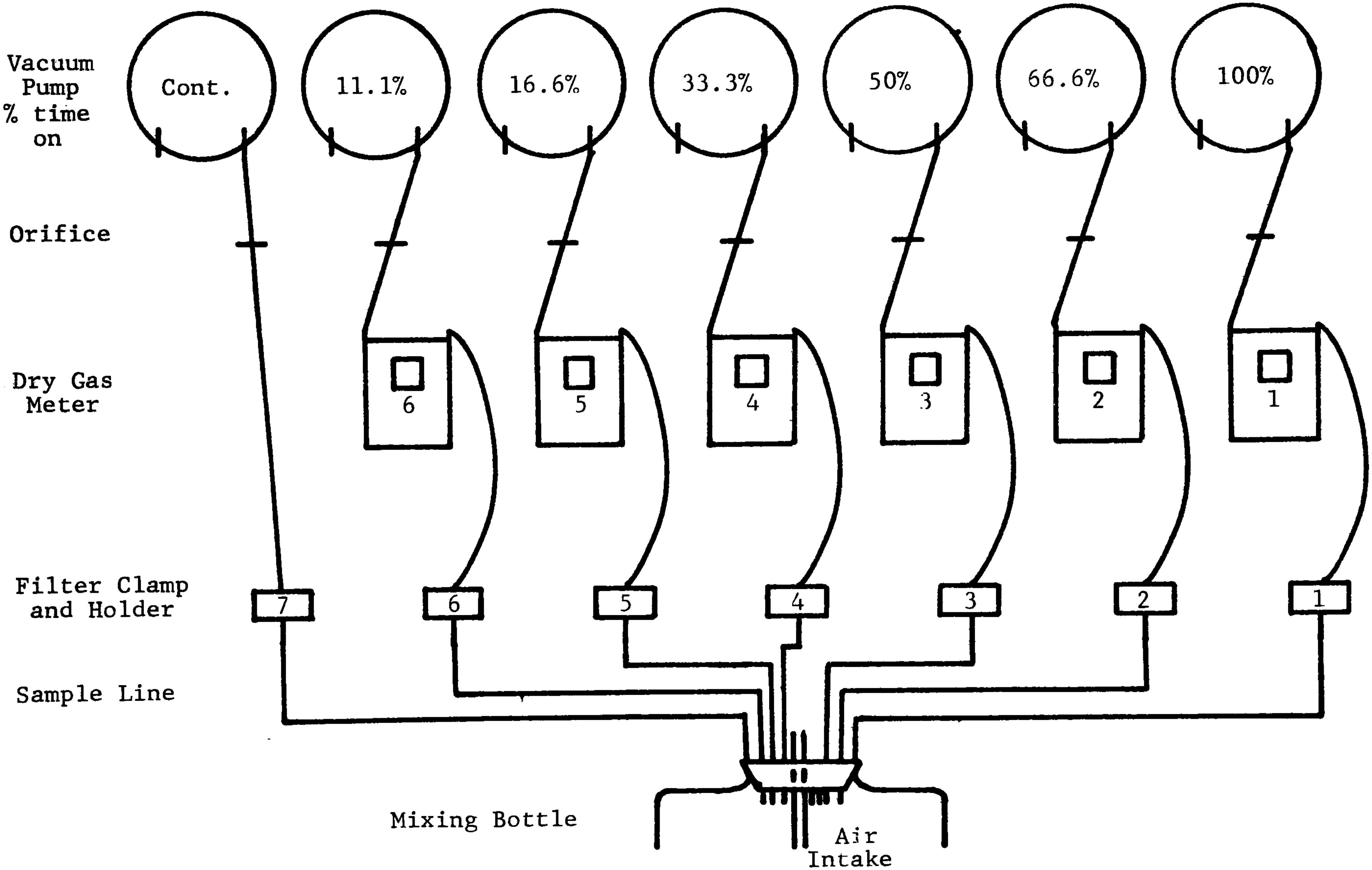
At the end of the test period, usually 24 hours, the volume of air passed through each filter was read on dry gas meters and the darkness index of each stain was read with a Photovolt Reflectometer using a green tristimulus filter (see Appendix B).

This procedure was repeated several times and each individual test was graphed, volume of air vs. darkness index. As each curve was plotted, the values at darkness indexes of 5, 10, 15, 20, 25 through 50 were summed. Each individual value of "volume of air" was then divided by the summation and multiplied by 100. This new unit was now an "arbitrary unit" which brought the curves into coincidence over a normal working range.

Determination of Weight of Total Suspended Matter in the Air

For the determination of smoke concentrations in

Figure 4



Apparatus for Test Program

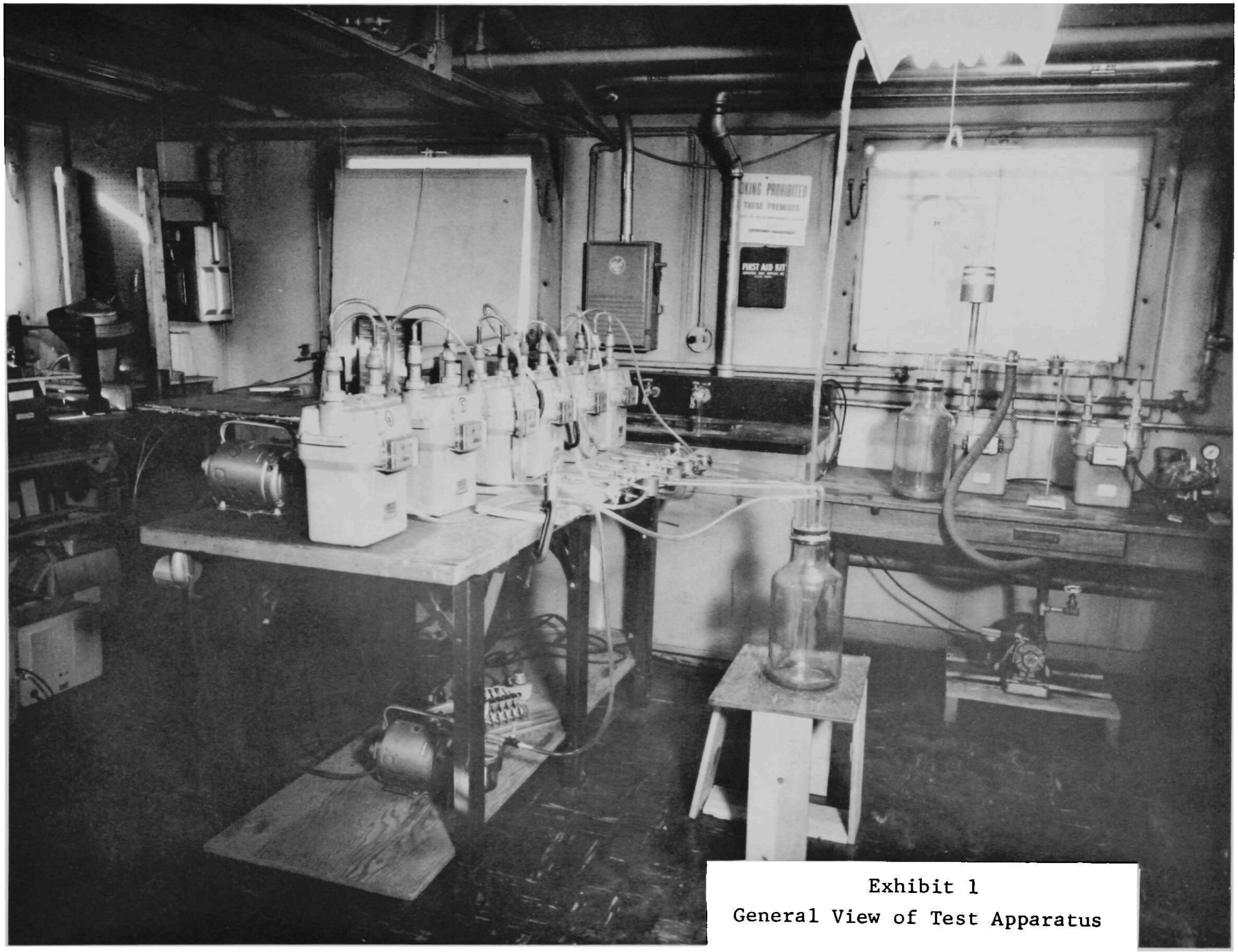


Exhibit 1
General View of Test Apparatus

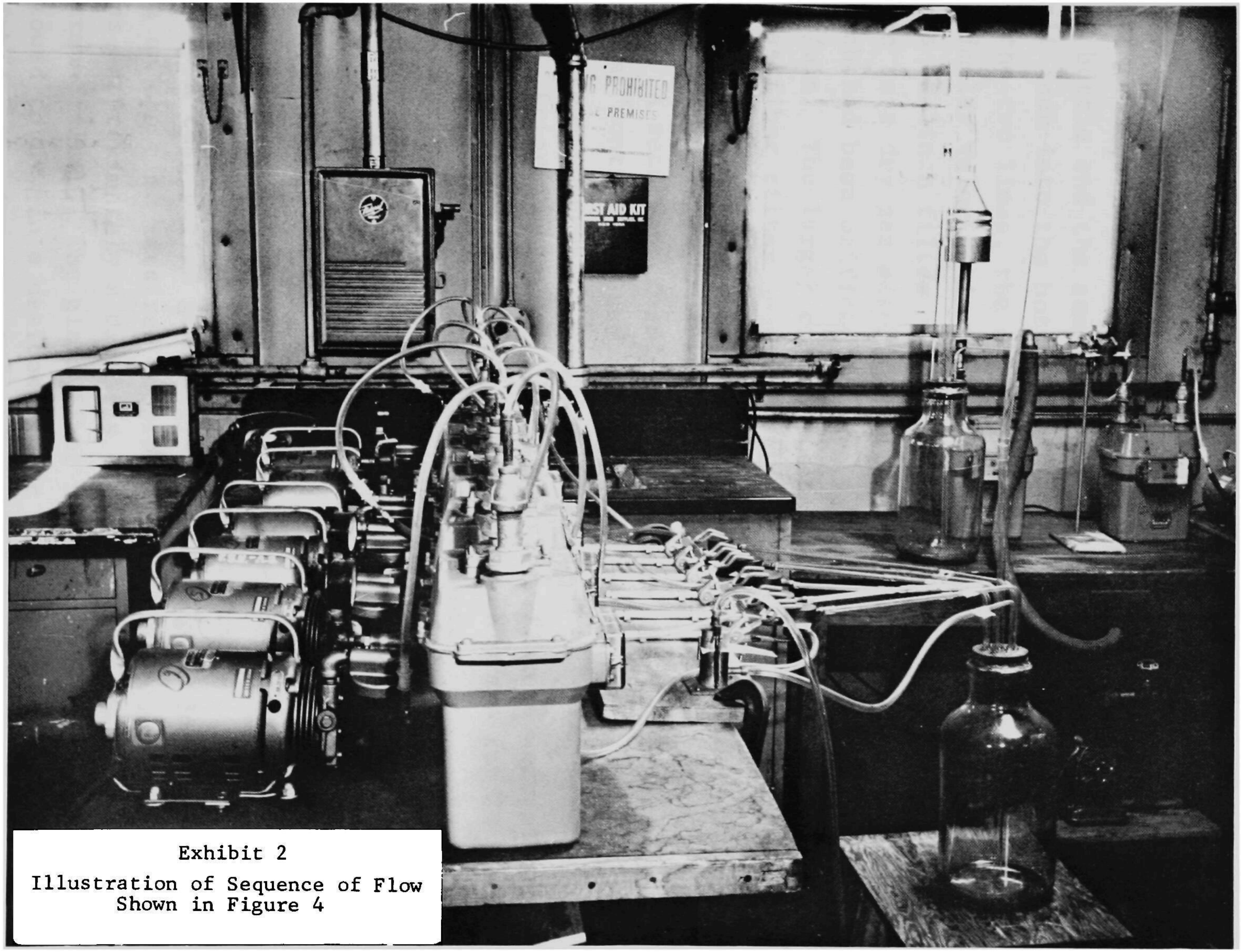


Exhibit 2

Illustration of Sequence of Flow Shown in Figure 4 absolute gravimetric units, the procedure illustrated in Figure 5 was used.

The air sample was initially drawn through an inverted 60°, 8.5 inch diameter glass funnel into a wide mouthed mixing bottle. The intake line was within one inch of the bottom of the bottle and the sample lines leaving it were placed one-half inch into the bottle. Since the volume flow was different in the two lines, the diameter of the lines were varied to give a similar velocity in each line. The smaller diameter line led to a one inch filter clamp, housing Whatman No. 1 filter paper, then to a dry gas meter, and finally to a 1.3 cfm vacuum pump which had been orificed to give a flow of approximately 0.073 ft^3/min. The larger diameter line was connected to a four inch glass fiber filter housed in line with a dry gas meter and attached to a high vacuum pump orificed to deliver a flow of 1.5 ft^3/min. (see Exhibit 3).

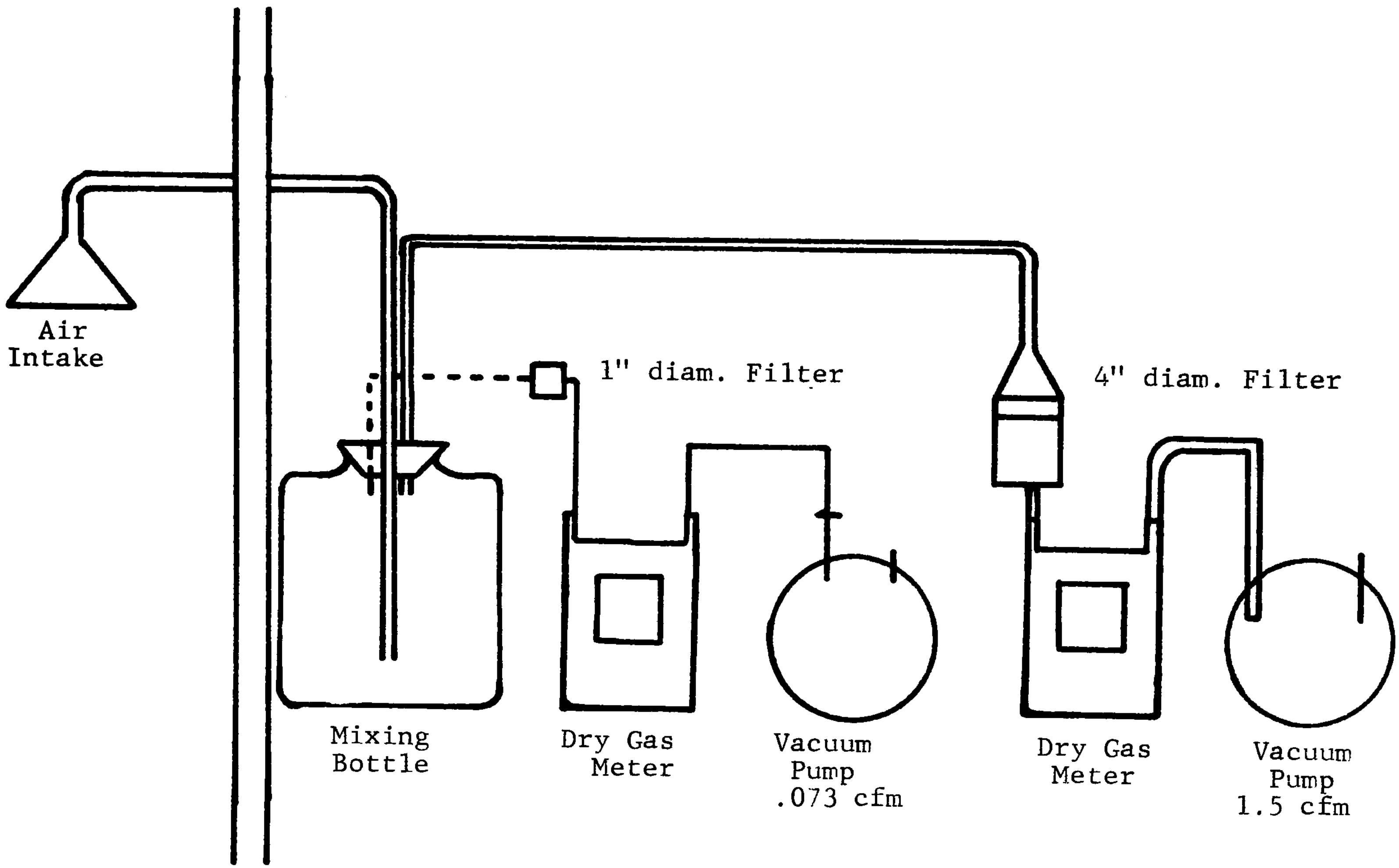
A secondary four inch glass fiber filter was required as the "control" filter and was used in the test to determine extraneous changes in weight arising from handling procedures.

Prior to testing, the glass fiber filters were placed in a desiccator containing magnesium perchlorate for 24 hours and weighed on a Mettler electronic balance. One glass filter was placed in a four inch diameter filter unit in the high volume sampling line, and the other four inch filter was placed in the control unit. Apparatus used in this procedure is listed in Appendix C.

The one inch Whatman No. 1 filter paper was placed in its filter clamp and the testing was started.

A test period generally continued 24 to 36 hours depending on the time required to produce a stain of suitable darkness, approximately a darkness index of 50 on the one inch Whatman filter. The glass fiber filters were removed and allowed to dry in a desiccator for 24 hours before being weighed. The increase in weight on the test filter was a measure of the dry deposited material or smoke and any change

Figure 5



Apparatus to Determine Scale of Smoke Curve

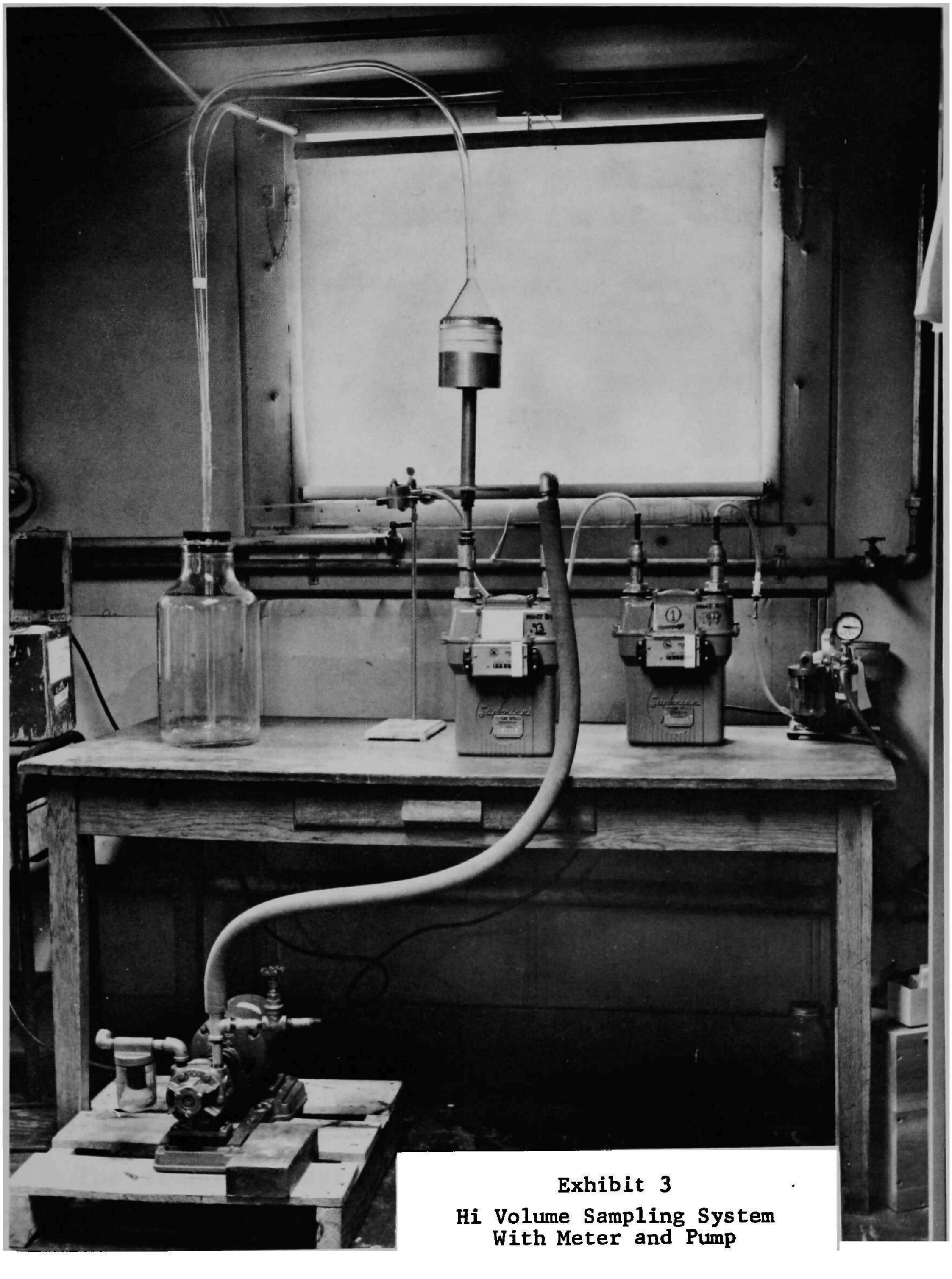


Exhibit 3

Hi Volume Sampling System With Meter and Pump

in weight arising from the handling procedure. A correction factor for the error due to handling was made by either adding or subtracting the difference between the initial and final weights of the control filter.

If:

W = weight of dry deposited matter, μg

V_M = volume of air passed by the high volume sampler, M^3

then the mean concentration of suspended matter, C, is equal to:

$$C = \frac{W}{V_M} \quad \text{or} \quad \frac{\mu g}{M^3} \qquad (4)$$

As the same concentration of suspended matter is sampled in the normal sampling line, the surface concentration of suspended matter present on the one inch diameter filter can be calculated from the corresponding volume of air passed in this line and the area of the filter.

If:

V = volume of air sampled by the normal sampler, M^3

D = diameter of the filter, cm

then the surface concentration of suspended matter on the filter, S, is given by:

$$S = \left(\frac{4W}{D^2}\right)\left(\frac{V}{V_M}\right) \quad \text{or} \quad \left(\frac{\mu g}{cm^2}\right) \qquad (5)$$

Surface concentrations computed in this manner are seen in Table 2.

Determination of Relationship Between % Reflectance and % Transmission

The standard instrument used to sample particulate matter in Coh/1000' is an AISI Model No. F2, manufactured by the Research Appliance Company of Pennsylvania. This instrument had an adjustable timer so that samples could be taken for any time period between one minute and three hours. The

Table 2

Normalization of Arbitrary Units

Darkness Index	Average Arbitrary Unit-NYU	Normalized Surface Concentration µg/cm², NYU	Normalized* Surface Concentration µg/cm² International
5	0.7	1.9	-
10	1.7	4.8	5.7
15	3.1	8.7	9.5
20	4.9	13.8	14.5
25	7.1	20.0	20.0
30	9.8	27.6	26.9
35	12.8	36.0	34.8
40	16.2	45.6	45.2
45	19.8	55.8	57.7
50	24.8	69.8	73.1

*Data from private communication from DSIR, Warren Spring Laboratory.

instrument is also equipped with an adjustable flowmeter varying from 2 ft^3/hr to 20 ft^3/hr. Calibration of the instrument was done by using a Precision Dry Gas Meter with varying flow rates on the flowrater. The standard filter paper used was Whatman #4.

Percent transmission was measured by a Research Appliance Company Spot Evaluator, Model No. 363. This instrument is capable of measuring optical density between 0-100 percent transmission. Standardization is made by adjusting the built-in rheostat to 100% T on a clean section of Whatman #4 filter paper before and after samples are recorded.

Percent reflection was measured by a Photovolt Reflection Meter, Model No. 610, capable of measuring percent reflectance between 0-100. One clean sheet of Whatman No. 1 filter paper placed on a white enamel plaque was used in the standardization procedure. The galvanometer was then adjusted to read 100% R.

One Hour vs. Two Hour Coh/1000' Values

In order to determine whether one hour Coh/1000' values would be the same as two hour Coh/1000' values (i.e., the average of two one-hour Coh values equaling a two-hour Coh value), the following procedure was used.

Two Research Appliance Company AISI Model F2 Samplers were attached to a common mixing jug. One AISI sampled for one hour periods while the other sampled for two hour periods. The flowraters were set at 15 cfh or .25 cfm and were kept at constant flow.

Each sample was measured on a RAC Model 363 Spot Evaluator in % T and then converted to Coh/1000'. The one hour Coh values were then averaged into two hour sampling periods corresponding to the two hour Coh values. The results of these comparisons are discussed in a later section of this report.

Results

Shape or Form of Smoke Calibration Curve

Two series of data (1966, 1968) were used in determining the shape of the NYU Bronx Station curve in arbitrary units. These arbitrary units were computed by plotting the volume of air sampled in cubic feet vs. the darkness index (DI = 100 - % R) for each run. After each curve was plotted, the values at darkness indexes 5, 10, 15 through 50 were summed. Each volume of air was then divided by the sum and multiplied by 100. This new unit was the arbitrary unit for the different darkness indexes

$$\text{arbitrary unit} = \frac{ft^3}{\Sigma\, ft^3} \times 100 \qquad (6)$$

The values in arbitrary units for each series of runs were tabulated in Table 3. These values were averaged for each darkness index and the NYU Bronx Station curve in arbitrary units is shown in Figure 6.

Manhattan Curve

In order to determine whether the shape of the smoke curve would vary according to geographic location, the smoke curve apparatus was moved to Christodora Station in Manhattan. The same procedure for calculating arbitrary units in the Bronx curve was used in the Manhattan curve. Data obtained from the Christodora runs are given in Table 4. Each run was then averaged for the varying darkness indexes and the Manhattan curve constructed from the data is given in Figure 7.

Comparison of International-Bronx-Manhattan Curves in Arbitrary Units

The proposed generalized International Standard Calibration Curve as reported in the OECD report[3] is the average of natural curves found in France, Holland and Great Britain. An

Table 3

NYU (Bronx) Station
1966 and 1968 Values in Arbitrary Units

Date	Darkness Index 5	10	15	20	25	30	35	40	45	50
3/29/66	0.6	1.5	3.1	5.1	7.4	9.9	12.8	16.0	19.7	23.6
3/30/66	0.5	1.6	3.1	5.0	7.2	9.8	12.0	16.0	19.8	23.9
3/31/66	0.6	1.7	3.2	5.2	7.4	10.0	12.8	16.1	19.5	23.4
4/05/66	0.8	1.9	3.3	5.2	7.4	9.8	12.6	15.7	19.7	23.6
4/07/66	0.5	1.5	2.7	4.7	6.6	9.3	12.5	16.2	20.5	25.3
4/18/66	0.5	1.4	2.6	4.3	6.2	8.7	12.2	16.2	21.2	26.7
6/14/66	0.6	1.7	3.1	5.0	7.1	9.7	12.5	16.0	19.9	24.3
6/20/66	0.9	2.2	3.6	5.3	7.4	9.7	12.4	15.8	19.3	23.7
6/27/66	0.8	2.0	3.6	5.3	7.3	9.8	12.3	15.6	18.9	22.4
9/28/66	0.7	1.8	3.2	5.0	7.2	9.9	13.0	16.2	19.6	23.3
10/03/66	0.7	1.1	2.5	4.3	6.5	9.4	12.7	16.7	20.3	25.7
1/03/68	0.8	1.5	3.3	5.1	7.3	9.7	12.5	16.0	19.6	24.2
1/18/68	0.5	1.6	3.0	4.9	6.8	9.5	12.2	15.8	20.1	25.5
1/22/68	0.6	1.9	3.3	5.0	7.1	9.5	12.4	15.8	19.5	24.9
1/25/68	0.7	1.8	3.2	4.7	6.7	9.4	12.4	15.9	20.1	25.0
1/30/68	0.8	1.7	3.0	4.5	6.7	9.4	12.2	16.0	20.2	25.5
2/05/68	0.8	1.8	3.2	5.0	7.3	9.8	12.8	15.9	19.6	23.8
2/12/68	0.6	1.6	3.0	4.8	6.8	9.2	12.2	16.0	20.4	25.1
Average	0.7	1.7	3.1	4.9	7.0	9.6	12.5	16.0	19.9	24.4

NYU Bronx Station Smoke Curve
in Arbitrary Units

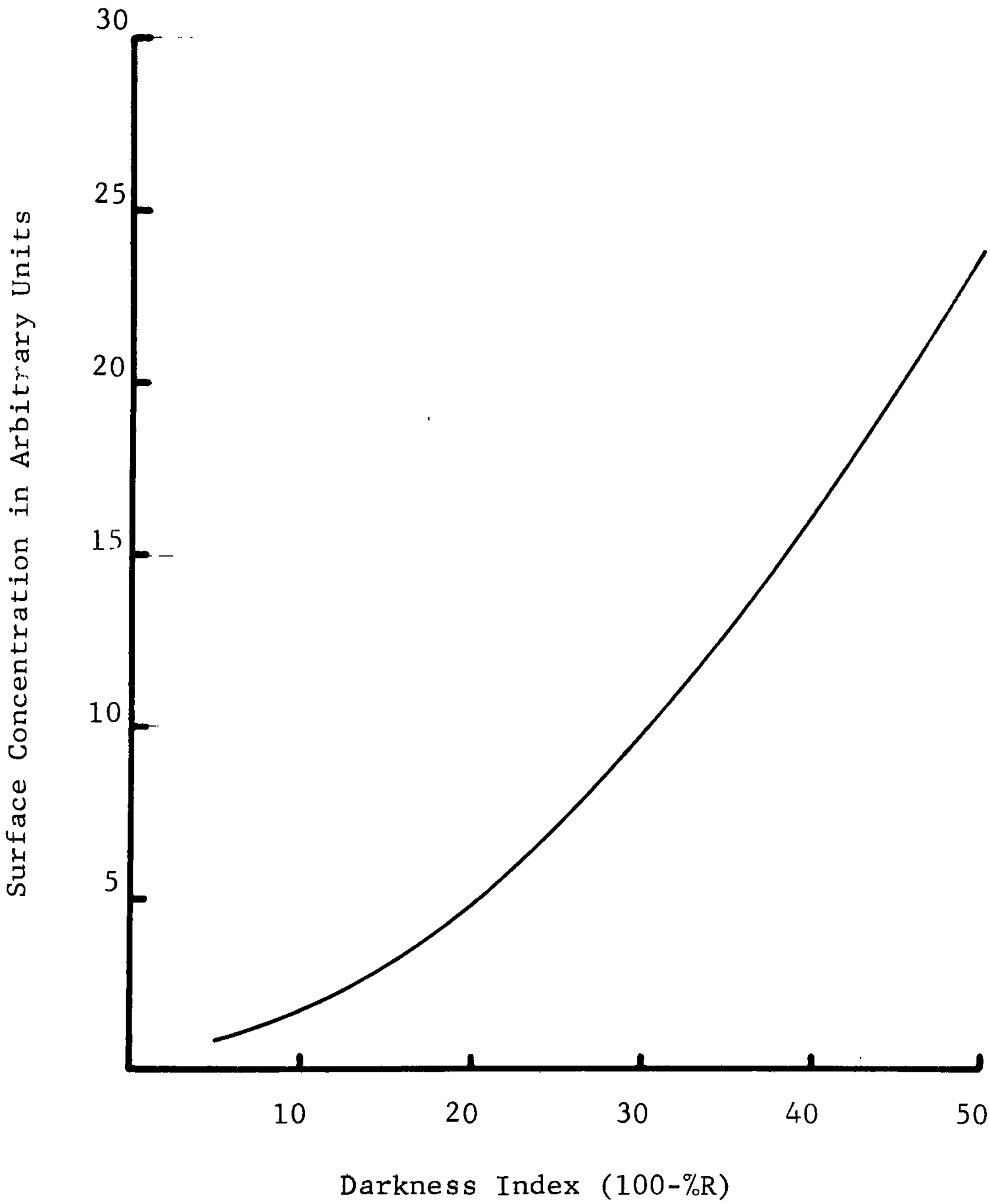


Figure 6

Table 4

Christodora (Manhattan) Station
1968 Values in Arbitrary Units

Date	Darkness Index 5	10	15	20	25	30	35	40	45	50
2/27/68	1.0	2.0	3.3	5.0	7.0	8.7	12.0	15.3	20.0	25.6
3/05/68	1.0	1.9	3.4	4.9	6.9	8.9	11.8	15.5	20.1	25.5
3/12/68	0.6	1.7	3.0	4.7	6.7	9.2	12.3	16.0	20.0	25.8
3/26/68	0.4	0.9	2.2	4.0	5.8	8.9	12.1	16.5	21.5	27.3
4/02/68	0.7	1.7	3.2	5.0	7.0	9.2	11.5	14.3	19.1	28.2
4/23/68	0.5	1.5	2.9	4.9	7.2	9.6	12.4	15.3	19.5	26.1
4/30/68	0.7	1.8	3.3	5.0	7.0	9.1	12.0	15.0	20.0	26.5
5/09/68	0.7	1.7	3.1	4.8	6.9	8.9	11.7	15.6	20.2	26.4
5/14/68	0.3	1.2	2.6	4.3	6.6	9.3	12.2	16.0	20.7	26.7
6/10/68	0.5	1.2	2.5	4.3	6.5	9.1	10.6	15.7	21.1	28.2
6/17/68	0.7	1.8	3.1	4.7	6.5	8.7	11.6	15.5	20.6	26.7
6/24/68	0.5	1.4	2.8	4.7	6.8	9.5	12.2	15.3	19.7	27.1
7/01/68	0.7	1.9	3.3	5.1	7.3	9.8	12.7	16.0	19.6	23.5
Average	0.6	1.6	2.9	4.7	6.8	9.2	11.9	15.5	20.2	26.4

NYU Christodora Station Smoke Curve
in Arbitrary Units

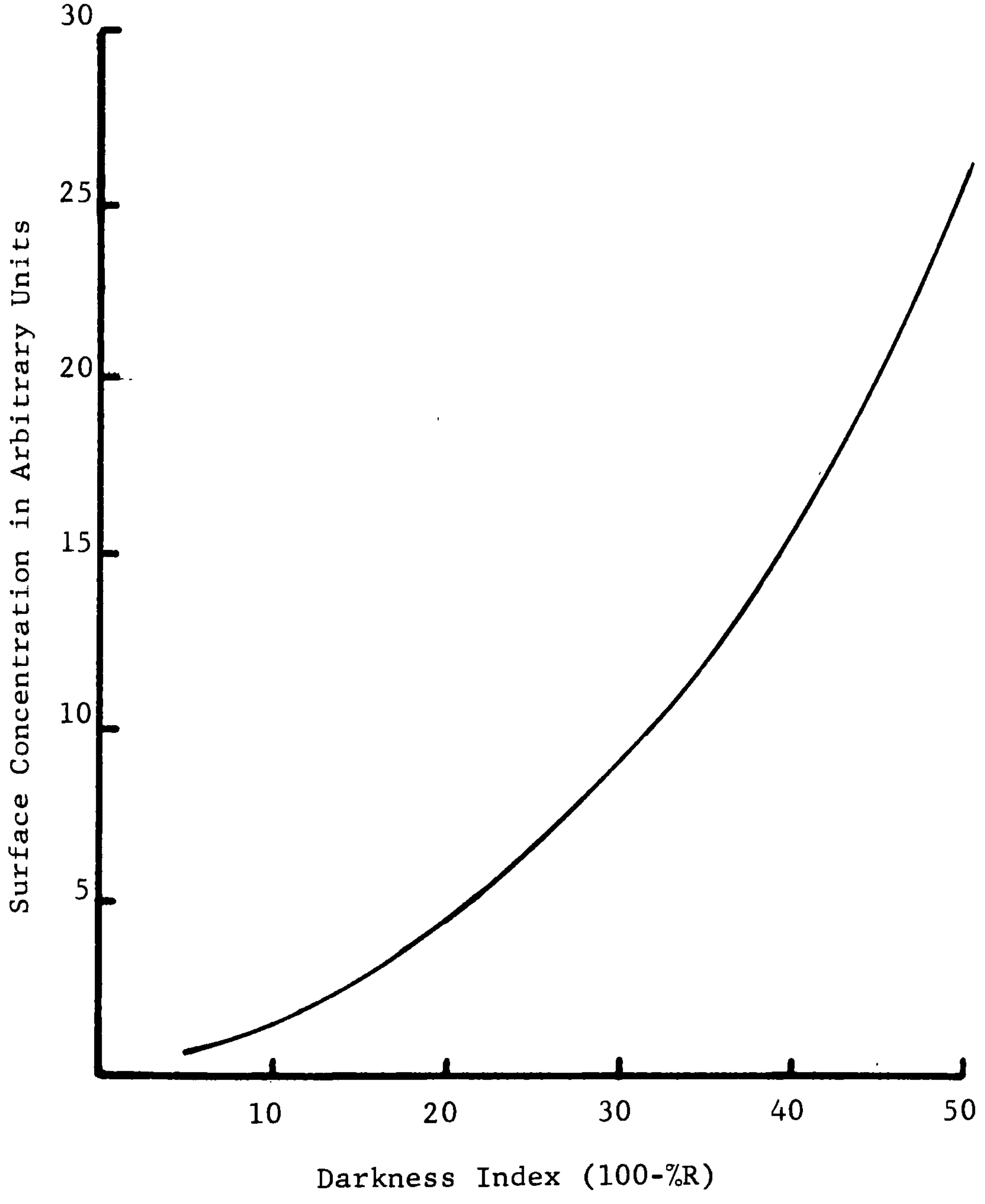


Figure 7

Eel Reflectometer was used in determining the form of the international calibration curve, but data obtained from private correspondence with the DSIR in England* indicated that readings obtained with a Photovolt Reflectometer are almost identical with those taken with an Eel Reflectometer (see Table 5).

A comparison of the NYU Bronx Station, Christodora (Manhattan) Station and the International Curves in arbitrary units (Figure 8) shows that these curves are almost identical. This relationship established that the form of the smoke curve for New York City stations is relatively the same and in turn, the New York City curve is relatively the same as the International curve within the limits of darkness index normally measured.

Determination of the Scale to be Attached to the Smoke Calibration Curve

An absolute, constant scale cannot be attached to a calibration curve as the weight of material deposited depends upon the nature of the material forming the smoke and this varies from place to place and with time at any one location. The International Standard Calibration Curve now in use, therefore, is in terms of surface concentration of a hypothetical equivalent standard smoke established by arbitrary definition, but based on extensive experimental data.[3]

To determine the absolute scale of surface concentrations to be assigned to the ordinate of a calibration curve at any particular place and time, it is necessary to determine the absolute weight of total suspended matter or smoke in the air. The procedure and apparatus used for this determination have been discussed previously.

It is recommended by the OECD that for Whatman No. 1 filter paper and the Eel Reflectometer, the Generalized

*These data obtained by sending papers read with Photovolt Reflectometer to Warren Spring Laboratory for independent reading with Eel Reflectometer.

Table 5

Comparison of Reflection Readings
Eel and Photovolt Reflectometers
Using 1" Whatman No. 1 Filter Paper

Eel	Photovolt
80.0	79.5
79.0	78.5
73.0	75.5
65.5	65.0
64.5	64.5
57.5	55.5
54.5	53.5

Mean - International - Bronx - Manhattan
Smoke Calibration Curves
in Arbitrary Units

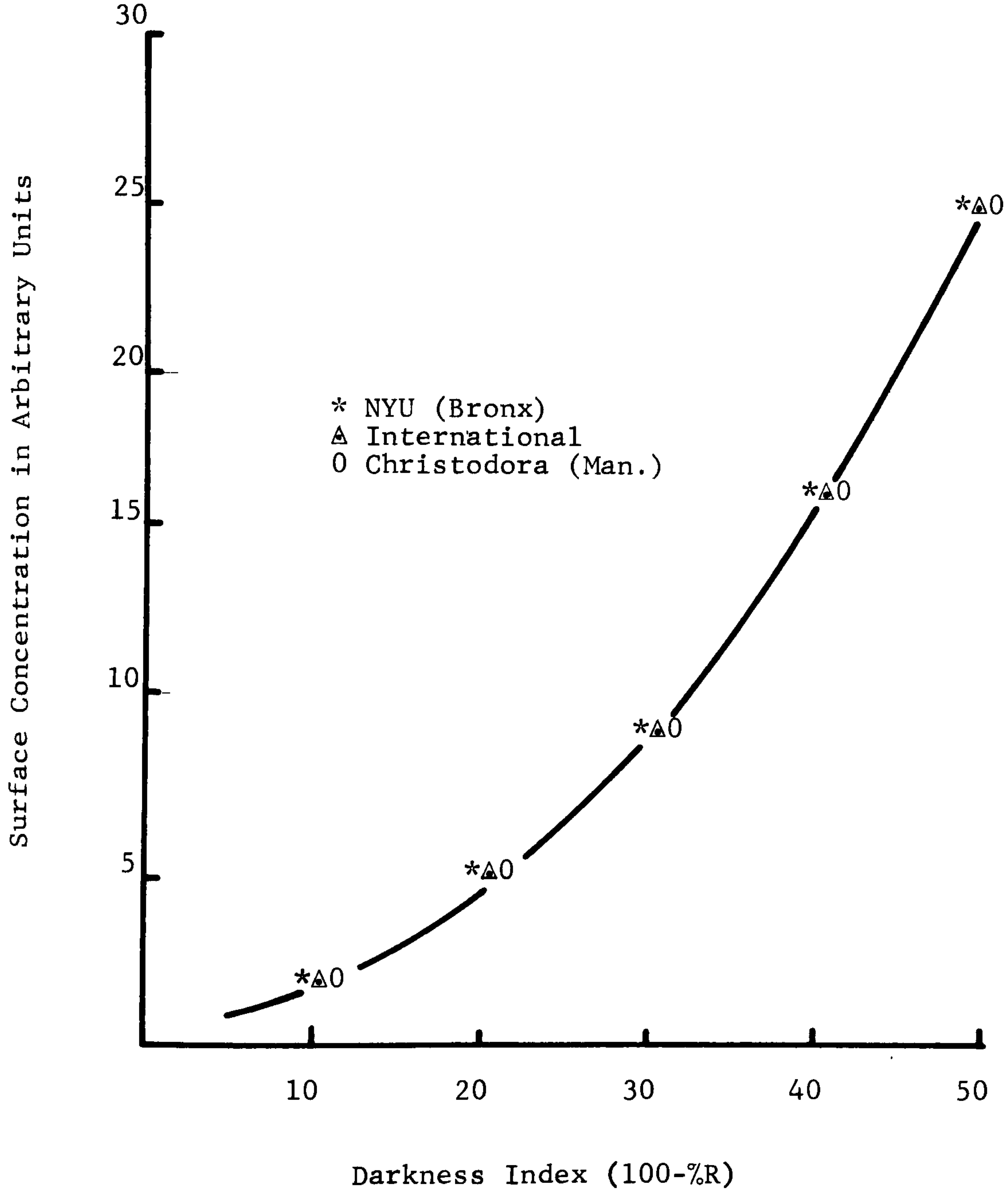


Figure 8

International Calibration Curve, the form of which has been defined above, should be normalized so that a darkness index of 25 (DI = 100 - % R) corresponds to a value of 20 $\mu g/cm^2$ for the surface concentration of an equivalent international standard smoke. By using 20 $\mu g/cm^2$ at a darkness index of 25, the normalization formula becomes:

$$\frac{20\ \mu g/cm^2\ (\text{Arbitrary Unit at X})}{\text{Arbitrary Unit at DI} = 25} = \text{Normalized}\ \mu g/cm^2\ \text{at X} \qquad (7)$$

NYU Bronx and Christodora (Manhattan) Station Results

In order to determine the surface concentration scale to be assigned to the ordinate of the New York City Smoke Calibration Curve, three series of runs, during two different years (1966 and 1968) at two different locations (NYU Bronx and Christodora Manhattan) were made. For each set of data a two variable non-linear correlation was used

where $a = 0$, $X = DI$, $Y = \mu g/cm^2$

$$Y = b \Sigma X + c \Sigma X^2 \qquad (8)$$

$$XY = b \Sigma X^2 + c \Sigma X^3 \qquad (9)$$

and was substituted in

$$Y = a + b X + c X^2 \qquad (10)$$

for the equation of the line. The following equations were calculated:

NYU Bronx 1966 Series

$$Y = .4871 X + .02375 X^2 \qquad (11)$$

Christodora (Manhattan) 1968 Series

$$Y = .89 X + .011 X^2 \qquad (12)$$

By combining these two similar series of data with additional data taken at our NYU Station in 1968, the proposed New York City curve equation becomes:

$$y = 1.00\ X + .0079\ X^2 \tag{13}$$

where X = darkness index
y = $\mu g/cm^2$

Proposed New York City Standard Calibration Curve

From these results it was calculated that the standard value for Christodora (Manhattan) Station is 29 $\mu g/cm^2$ at a darkness index of 25 and the NYU Bronx Station yields a result of 28 $\mu g/cm^2$ at a darkness index of 25. The combined data of these two curves (equations 11 and 12) plus additional data from our NYU Station in 1968, produced the proposed New York City Standard Calibration Curve in $\mu g/cm^2$.

The value of 30 $\mu g/cm^2$ at a darkness index of 25 was selected as the representative positioning value and the equation for normalizing the data was:

$$\frac{30\ \mu g/cm^2\ (\text{Arbitrary Unit at X})}{\text{Arbitrary Unit at DI} = 25} = \text{Normalized } \mu g/cm^2 \text{ at X} \tag{14}$$

These data would shift the curve $\frac{30}{20}$ from the International curve and $\frac{30}{17}$ from the British curve, and would introduce a 17.6% correction in the conversion using the British curve.

The results of normalization process calculations then yielded the proposed New York City Standard Calibration Curve presented in Figure 9.

A tabulated comparison of the relation between darkness index, the Internation Smoke Curve, and the proposed New York City curve is given in Table 6.

Conversion of that curve into the reporting unit $\mu g/m^3$ is then accomplished by calculating values using the relationship of equations (4) and (5) expressed as

$$\mu g/m^3 = \frac{5.06 \times \mu g/cm^2}{V} \tag{15}$$

The curve of equivalent standard smoke units with $V = 2\ M^3$ (70.62 ft^3) derived for New York City is shown in

Proposed New York City Calibration Curve
in $\mu g/cm^2$
Photovolt Reflectometer-Whatman No. 1 Filter Paper
Normalized to DI = 25 $\mu g/cm^2$ = 30

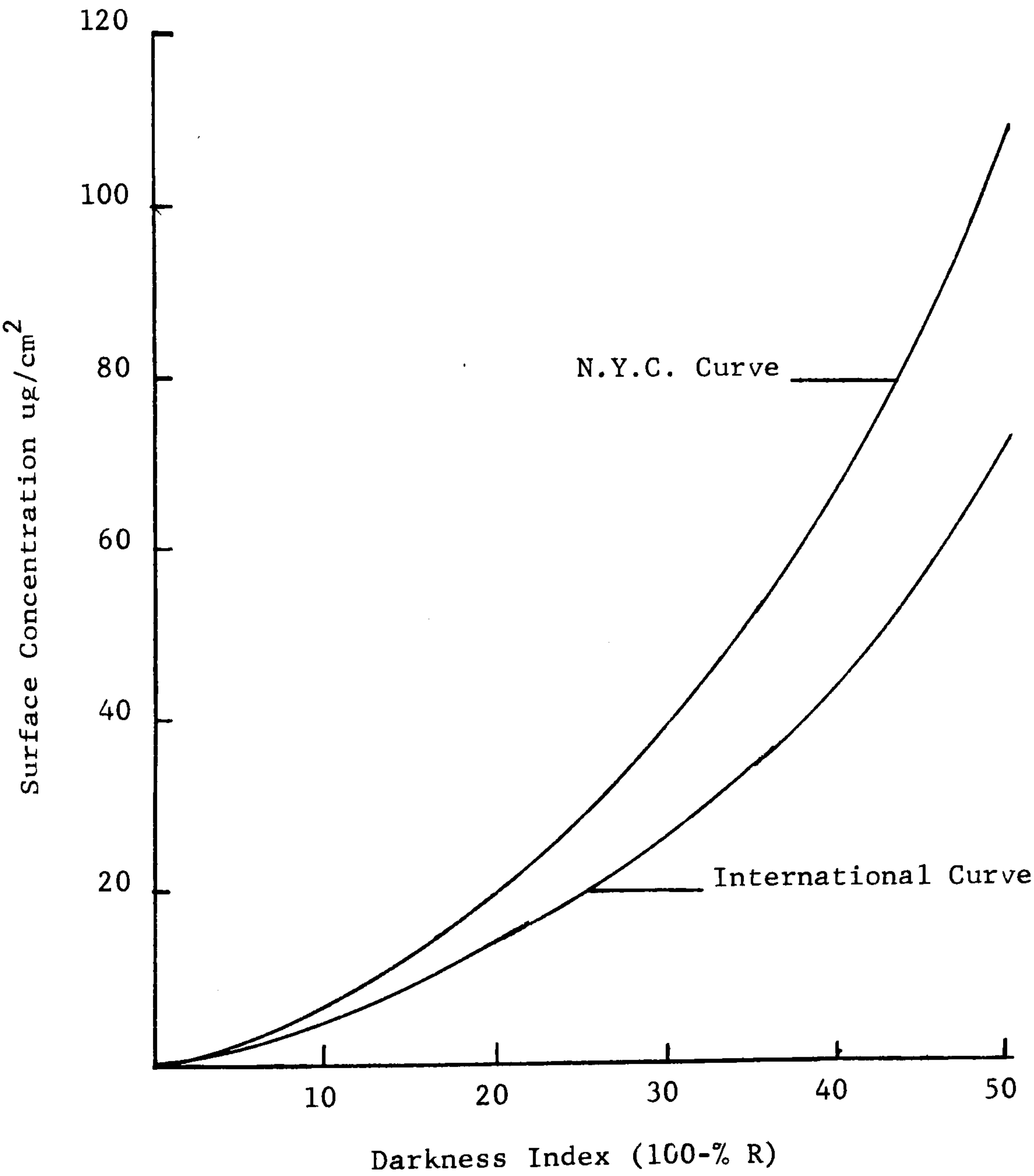


Figure 9

Table 6

Comparison
International Smoke Calibration Curve
and
Proposed New York City Smoke Calibration Curve
in $\mu g/cm^2$

Darkness Index	International Curve	New York City Curve
10	5.7	7.1
15	9.5	13.2
20	14.5	21.2
25	20.0	30.0
30	26.9	40.8
35	34.8	53.3
40	45.2	68.7
45	57.7	87.1
50	73.1	110.1

Figure 10 and comparison data are tabulated in Table 7.

Figure 10 is now in a form that can be used to translate the equivalent unit values for comparison that might be made between United States cities and those of Great Britain and other European countries. However, there remains one further step applied to United States practice where the reporting unit is Coh/1000' rather than $\mu g/m^3$.

Development of European vs. United States Reporting Unit Relationship

The development of Figure 10 was accomplished according to the Warren Spring and OECD procedure and utilized darkness index as measured by photovolt meter.

As soon as it became necessary to convert Coh/1000' based on light transmittance into $\mu g/m^3$ based on light reflectance, questions arose concerning

1. the validity of using % T or % R, and
2. the comparability of readings taken at one hour or two hour intervals on particulate spots developed by passing air through the filter paper of the AISI sampler.

Accordingly, these two issues were investigated.

Validity of Using % T or % R

If a light beam is placed on a piece of paper the light will either be reflected, R; transmitted, T; absorbed by the dirt, A; or absorbed by the paper and scattered, E. This can be represented by:

$$T + R + A + E = 100 \qquad (16)$$

Therefore the equations for transmittance and reflectance are:

$$T = 100 - R - E - A \qquad (17)$$

$$R = 100 - T - E - A \qquad (18)$$

Proposed Standard Calibration Curve
in $\mu g/m^3$
DI = 25, $\mu g/cm^2$ = 30, V = 2 M^3

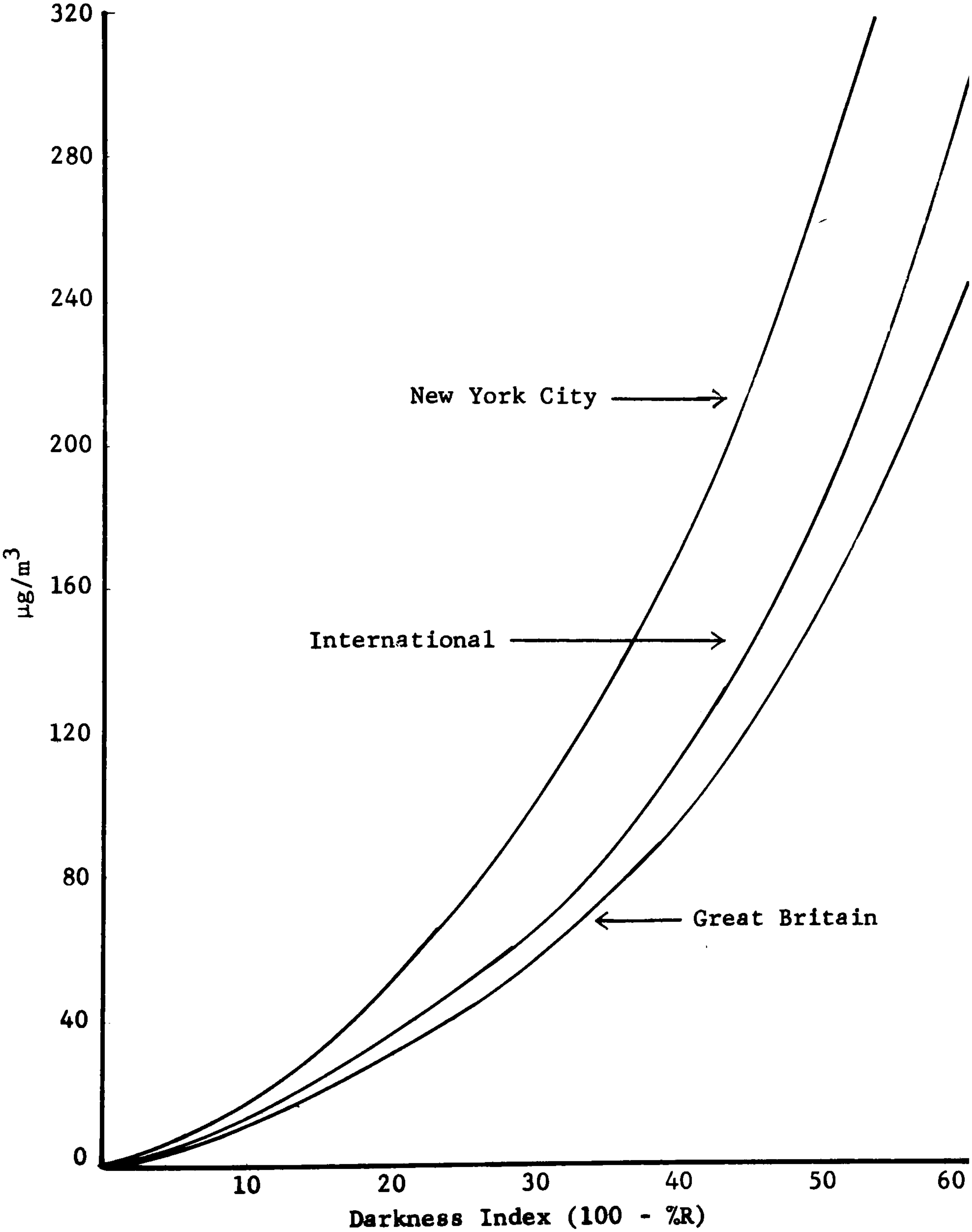


Figure 10

Table 7

Comparison
International-Great Britain Smoke Calibration Curve
and
Proposed New York City Smoke Calibration Curve
in
$\mu g/m^3$ at $V = 2\ M^3$

Darkness Index	International	Great Britain	New York City
10	14.4	12.4	18.0
15	24.0	21.0	33.4
20	36.7	30.9	53.6
25	50.6	43.1	75.9
30	68.1	57.7	103.2
35	88.0	75.4	134.8
40	114.5	97.2	173.8
45	146.0	124.0	220.3
50	185.0	157.1	278.5

When the light transmission of a sample is read, clean paper is inserted and the light transmittance is adjusted to 100%. The sample spot is then inserted and a reading is obtained. Initially we have:

$$\text{For} \quad A = 0$$
$$T = 100\%$$

which says

$$R + E = 0$$

and the equation for transmittance becomes

$$T = 100 - A \tag{19}$$

When reflectometer readings are made the reflectance is set at 100% on a clean sheet of filter paper. Therefore initially:

$$\text{For} \quad A = 0$$
$$R = 100$$

which says

$$T + E = 0$$

and the equation for reflectance is

$$R = 100 - A \tag{20}$$

Since the equations for transmittance and reflectance are the same, a given sample spot should give identical readings for both methods of evaluation.

Procedure

A clean roll of Whatman No. 4, 1-inch filter paper was placed in a spot evaluator (reading percent transmission) with the initial reading set to 90%. The roll was continuously passed through the light beam and % transmission was noted.

The results are as follows:

% Transmission Interval	No. of values In Interval	
77-79	0	
80-82	9	
83-85	44	
86-88	247	
89-91	130	Initial Setting
92-94	20	
95-97	0	

It is noted that while these values can be reset to an initial reading on a clean portion of the paper proceeding the dirt spot, one is never sure that the portion where the spot appears would not have the same initial setting. It is obvious that the paper is not uniform. The most nearly acceptable procedure for determining initial setting appears to be the average of a reading immediately preceding and one immediately following the actual spot. There is no assurance that that is the correct reading, however the errors so introduced may be no greater than errors due to humidity, and other factors influencing either light transmission or reflectance values.

Table 8 indicates the data used in the comparison between transmittance and reflectance, and Figure 11 compares the data with the theoretical 1:1 relationship. Procedures and instruments for making this comparison are described in Appendix D.

The 1:1 relationship is therefore not absolutely true. The difference introduced at 50% reflection is in the relationship of the curve as shown by the equation:

$$y = 2.71 + 1.008\ X \qquad (21)$$

where y = % Transmission

X = % Reflection

The relationship is apparently linear and therefore in the normal range of measurement (say 90 to 50% transmittance) can easily be converted by using Figure 11 (i.e., 50% R = 53.11% T;

Table 8

Percent Transmission vs. Percent Reflection Values
1966 and 1968 Data

%T	%R	%T	%R	%T	%R	%T	%R
71	70	90	93.5	85	85	46	40
72	73.5	62	58	93	88.5	48	50
75	78.5	74	66	91	93.5	64	57
66	64.5	76	61	98	94	70	63
70	69.5	84	77.5	54	52	80	75
64	61.5	87	86	66	61	81	82
64	59	95	90.5	67	67	52	47.5
69	65	76	74	72	74.5	57	58.5
76	73.5	86	81	79	84	66	66
80	79	82	84.5	86	88	78	72.5
94	85.5	89	89	43	42	84	80.5
97	89.5	94	92.5	51	50.5	88	87
62	63.5	98	95	53	57.5	74	68.5
70	70	50	53	63	66	54	52.5
74	75	63	58.5	72	77	63	66.5
81	82	62	56	82	83.5	38	39.5
88	89	62	57	45	39.5	64	64
97	92.5	72	63.5	58	48	56	53.5
66	60	78	72	59	54	52	52.5
67	67.5	83	81	64	63.5	50	50
74	74	84	88	79	74	62	61
82	79.5	42	41	84	81.5	71	70
93	86	50	49.5	38	28.5	80	75.5
90	91	57	55.5	46	38	42	36.5
65	64.5	71	63.5	60	46	54	51.5
74	71	78	73.5	62	54	64	60
78	78.5	86	78.5	76	74	77	78.5
84	82.5	67	73.5	72	68	78	79.5
92	89	80	80	80	75	70	75.5
55	53.5	55	55.5	67	65	63	58
82	78.5	65	64.5	68	68.5	76	72
						60	61

Comparison
% Transmission vs. % Reflection

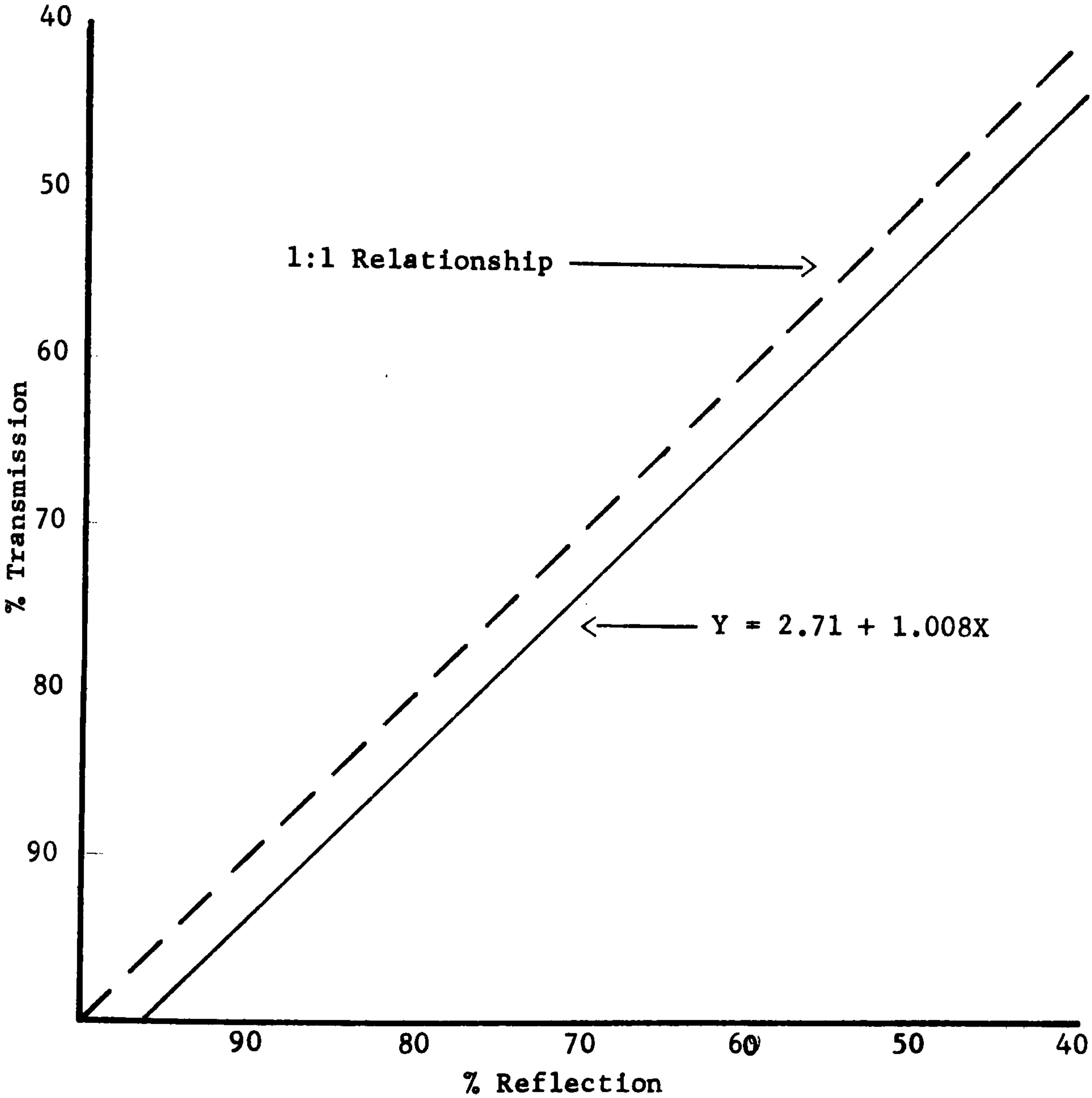


Figure 11

90% R = 93.43% T). If % T were used directly in calculating darkness index (100% - % R), the difference in equivalent smoke units would be 47 $\mu g/m^3$ less at 50% R than at 53.11% T. This is about as large an error as would normally be introduced by that practice. On the other hand, the minimum error in using the 1:1 relationship at 90% R would be 8 $\mu g/m^3$. The routine field observer might then at some point wish to correct for this by calculating darkness index using % R calculated for % T according to equation (21), whereas research work of greater refinement would probably require the correction on all % T readings.

Relationship Between Coh/1000 LF Values Obtained from 1 and 2 Hour Sampling Periods

When the ambient air is passed through filter paper, the dirt in that air will be retained on the paper. The resultant "spot" can be reported in terms of soiling index or Coh/1000 LF. This term combines into a quantitative expression, the Coh, which is an arbitrary unit of measurement describing light scattering potential and the volume of air from which the particulates producing that potential have been trapped.

The Coh unit is defined as that value of light scattering particulates that produces an optical density of 0.01 when measured by light transmission. This is the term Log $\frac{I_o}{I}$ in the Beers Law equation

$$\text{Log } \frac{I_o}{I} = KQ \qquad (22)$$

where K = constant of proportionality

Q = quantity of sample in air

Plots of that optical density are proportional to the air volume and the plot of one against the other results in a straight line when light transmission values are above 50% (i.e., low optical densities). There is also in practicality an upper limit (about 90%) at which ability to read the light transmission value accurately is impaired and error is introduced.

A 100% transmission value is taken on a piece of clean filter paper and then the transmission value of the spot created on a given area of paper passing air at a given flow rate through that area is read as a percent of the original optical transmission. Dimensional analysis shows that the quantitation of

$$\frac{ft^3}{ft^2} = \frac{(Q)}{(A)} = \text{linear feet}$$

Thus if the number of Cohs of particulate potential is in proportion to the air flow, the expression Coh/1000 linear feet expresses the light scattering potential in relation to the air sample volume and the area of entrapment.

The measurement can be illustrated by the following example:

Given Q = 0.250 ft^3/min
Time of sampling = 120 minutes
Sample volume = 30.00 ft^3
Given area of filter paper 1" diameter = $5.45 \times 10^{-3}\ ft^2$

$$\text{Air Sample} = \frac{30.00\ ft^3}{5.45 \times 10^{-3}\ ft^2} = 5504.5\ ft$$

$$= 5.5045 \quad 1000\ ft$$

If the resultant spot gives a light transmission value of 87%

$$\log \frac{100}{87} = 0.0603 = 6.03\ \text{Coh}$$

$$\frac{6.03}{5.5045} = 1.10\ \text{Coh/1000 ft}$$

A question that arises concerns the influence of a change in sample volume on the resultant transmission reading.

That is, if, as in the above example, the sample volume is changed to 15 ft^3 (60 min @ .25 ft^3/min), will the light transmission of the spot vary to the degree that Coh/1000 LF will indeed be 1.1? The problem is further complicated by the fact that if the concentration of particles in the air changes during the sampling period, the result would not be expected to be the same. However, each one hour sampling period in a given two hour density determination would be correct. This assumption can be demonstrated readily by averaging two 1 hour Coh readings taken simultaneously with one 2 hour determination. The following example illustrates this point:

	60 min cycle	120 min cycle
% transmission after 1 hour	87	not read
% transmission after 2 hours	100*	87
Coh end of first hour	2.2	not read
Coh for end of second hour	0.0	1.1
Average for 2 hour period	1.1	1.1

It is seen by this example that time and therefore sample volume should not affect the final answer, and that each segment, i.e., one hour particulate density value, is correct unto itself.

Two main additional items also require consideration. The quality of the filter paper fluctuates. In a roll of Whatman No. 4, for example, as used on the AISI instrument, the percent transmission can vary as much as 9% (see page 41). In the low ranges this is quite significant and a larger sampling volume would be needed to provide a darker spot, and thereby minimize the initial error. At high Coh/1000' values, the filtering action may be more efficient than at low values, so that lower sampling volumes might be required.

---

*Assume clean air during second one hour sampling period.

Results of 1 Hour and 2 Hour Coh/1000' Testing

Two Research Appliance Corporation AISI Instruments were placed into operation sampling the same atmosphere. One instrument was set to cycle every 60 minutes and the other every 120 minutes. The flow rates were identical at 15 cfh.

For each two hour sampling period, two 1 hour readings and one 2 hour reading were obtained. An average of the two 1 hour readings was made and these average values were compared to the one 2 hour value (see Tables 9 and 10). A line of best fit was calculated and a correlation between the two values was obtained. The equation relating the two 1 hour Coh/1000' averages and the one 2 hour Coh/1000' is

$$Y = -0.14 + 1.31 X \qquad (23)$$

where Y = average of two 1 hour values, Coh/1000'

X = one 2 hour value, Coh/1000'

The correlation coefficient was 0.9434.

Figure 12 represents 2 hour Coh/1000' readings vs. 1 hour Coh/1000' readings and shows that a one hour reading <u>alone</u> cannot be directly representative of a two hour reading.

Relationship Between Equivalent Units

The final steps in completing a relationship between United States reporting units and European reporting units required that all normalized data be averaged thereby obtaining final values at varying darkness index values.

When that had been done, the values could be used in equation (15) with the air volume $V = 0.8496\ M^3$ (the AISI sampling flow for two hours at 0.25 cfm), thus:

$$\mu g/m^3 = \frac{5.06 \times \mu g/cm^2}{0.8496} \qquad (24)$$

The curve so calculated is given in Figure 13 and can be used for the AISI sampling unit set to pass 0.25 cfm through the

Table 9

Frequency Distribution Coh/1000'
Average of Two 1 Hour Readings
February 15, 1968 to March 13, 1968

Interval (Coh/1000')	No. of Cases in Given Interval	% Total	
0.0-0.4	91	28.9	58.1
0.5-0.9	92	29.2	
1.0-1.4	55	17.5	28.0
1.5-1.9	33	10.5	
2.0-2.4	12	3.8	6.3
2.5-2.9	8	2.5	
3.0-3.4	4	1.3	
3.5-3.9	2	.6	
4.0-4.4	7	2.2	
4.5-4.9	5	1.6	
5.0-5.4	2	.6	
5.5-5.9	1	.3	
6.0-6.4	--	--	
6.5-6.9	3	1.0	
	315	100.0%	

Table 10

Frequency Distribution Coh/1000'
One 2 Hour Reading
February 15, 1968 to March 13, 1968

Interval (Coh/1000')	No. of Cases in Given Interval	% Total	
0.0-0.4	76	24.1	62.8
0.5-0.9	122	38.7	
1.0-1.4	62	19.7	26.7
1.5-1.9	22	7.0	
2.0-2.4	9	2.9	5.0
2.5-2.9	7	2.1	
3.0-3.4	9	2.9	
3.5-3.9	4	1.3	
4.0-4.4	4	1.3	
4.5-4.9	--	--	
5.0-5.4	--	--	
5.5-5.9	--	--	
6.0-6.4	--	--	
6.5-6.9	--	--	
	315	100.0%	

Relationship
2 Hour Readings vs. 1 Hour Readings
Coh/1000'

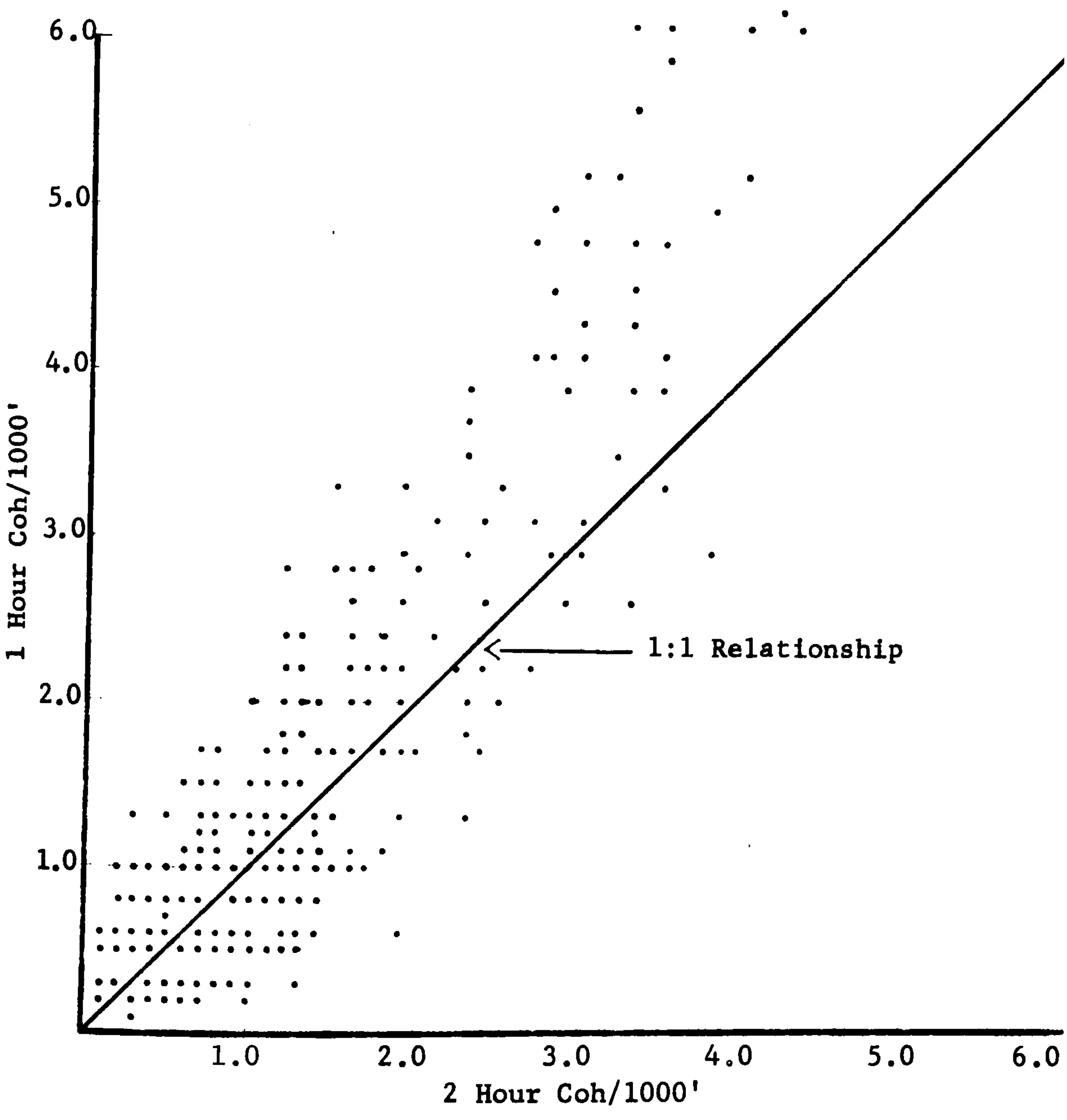


Figure 12

Conversion Curve

$\mu g/m^3$ to Coh/1000 Linear Feet

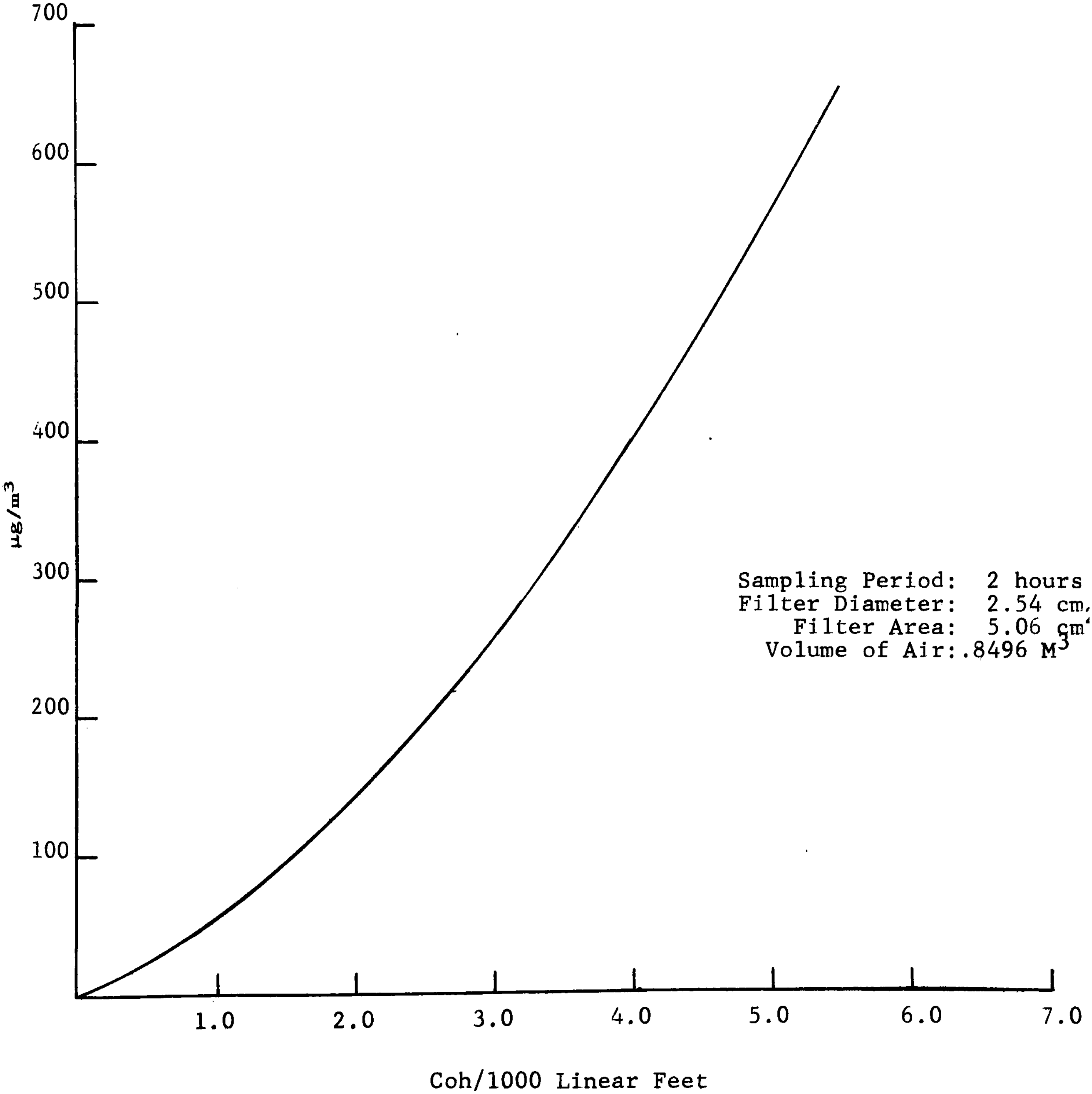


Figure 13

filter paper tape for two hours. It should not be used for any other set of conditions without running check tests. Under the conditions stated it is now possible to take United States reporting units and convert them directly to European units. That is, a Coh/1000' value of 3.0 in New York City represents 260 $\mu g/m^3$ in equivalent standard smoke units. A tabulation of Coh/1000' values by 0.1 intervals is given in Table 11 with its equivalent in $\mu g/m^3$.

Relationship Between Particulate Density and Particle Count

Late in the study it became possible to obtain on loan a particle counting instrument that could be used to explore briefly the number of particles counted in size ranges related to the Coh/1000' value obtained by standard particulate density measurements.

It was then the purpose of this short study to investigate the relationship between air borne particulate density defined in terms of light transmittance (and/or light reflectance) and the airstream particle count differentiated by size ranges.

The work was made feasible by Particle Technology, Inc. who supplied, on loan, their Model 140 Airborne Particle Sensor equipped with two Model 3116 counter racks.

Instrumentation

The filter tape samples were collected by a Research Appliance Corporation Model F2SE AISI Tape Sampler. This unit was modified so that its pump could be shut down independent of the remainder of its electrical system. The sampler is equipped with a R.A.C. Spot Evaluator meter (% T or O.D.) to provide a continuous readout of the transmittance. In addition to the meter readout, transmittance values were read on a Research Appliance Company Spot Evaluator, Model No. 363.

Table 11

Conversion Table Coh/1000' vs. μg/m^3

Coh/1000'	μg/m^3	Coh/1000'	μg/m^3	Coh/1000'	μg/m^3
.1	5	2.6	212	5.1	585
.2	7	2.7	223	5.2	600
.3	13	2.8	243	5.3	620
.4	20	2.9	250	5.4	638
.5	25	3.0	260	5.5	650
.6	30	3.1	275	5.6	675
.7	37	3.2	288	5.7	690
.8	42	3.3	300	5.8	710
.9	50	3.4	317	5.9	728
1.0	57	3.5	330	6.0	745
1.1	65	3.6	345	6.1	755
1.2	73	3.7	358	6.2	775
1.3	79	3.8	370	6.3	790
1.4	90	3.9	385	6.4	810
1.5	100	4.0	400	6.5	835
1.6	108	4.1	418	6.6	850
1.7	117	4.2	433	6.7	865
1.8	126	4.3	450	6.8	890
1.9	135	4.4	465	6.9	905
2.0	145	4.5	480	7.0	925
2.1	155	4.6	500	7.1	945
2.2	168	4.7	519	7.2	965
2.3	179	4.8	530	7.3	985
2.4	190	4.9	550	7.4	1005
2.5	200	5.0	568	7.5	1025

(Reflectance values were read on a Photovolt Reflectometer Model No. 610.)

The particle counts were made using a Particle Technology, Inc. Model 140 Airborne Particle Sensor/Photometer equipped with two Model 3116 counter racks. Each counter rack was capable of providing the particle counts in two adjacent size ranges, thus the particles were counted in four different size ranges simultaneously. The P.T.I. Model 140 Airborne Particle Sensor/Photometer is a near forward scatter (30°-71° half-angle) electro-optical system. This optical system minimizes the effect of particle coloration influencing the size determination of each particle and maximizes the intensity of light scattered by each particle.

Definitions

The following definitions have been used (in accordance with ASTM Standards, Industrial Water: Atmospheric Analysis, D1704, Part 23, 1965):

1. Optical Density (O.D.) = $\log_{10} \frac{I_o}{I}$

   where I_o = the intensity of transmitted light through the clean paper,

   and I = the intensity of transmitted light through the sample.

2. 1 Coh Unit = that quantity of particulate matter which produces an optical density of 0.01 on filter paper.

3. Smoke concentration = Coh Units per 1000 linear feet of air drawn through filter paper.

   $$\text{Coh}/1000 \text{ ft} = \frac{(\text{O.D.})(10^5)}{L}$$

   where L is the total linear feet of air drawn through the filter paper.

4. Optical Reflectance (O.R.) = $\log_{10} \frac{R_o}{R}$

   where R_o = the intensity of the light reflected from the clean paper, and

   R = the intensity of the light reflected from the sample.

5. 1 RUD Unit = that quantity of particulate matter which produces an optical reflectance of 0.01 due to 10,000 linear feet of air.

6. RUD = 0.1 Coh/1000 ft.

Program and Procedure

The particle counter racks were set to discriminate and count all particles in the following four ranges:

0.3 to 1.0 μ
1.0 to 2.0 μ
2.0 to 6.0 μ
6.0 to 30.0 μ

Because of time limitations, all particle size ranges on the digital counters were set in accordance with the "Signal in Volts vs. Particle Size" calibration curve supplied by Particle Technology, Inc. No attempt was made to size calibrate with an aerosol generator according to the manufacturer's prescribed procedures. The precise technique involving the use of a pulse generator and oscilloscope was not employed to set the discriminator voltages at the low end of the scale (0.3-1.0 μ).

Outside air was drawn to the instruments through a common mixing vessel using the pumps of the respective instruments. The P.T.I. Sensor sampled at the rate of 1.0 cfm and the R.A.C., AISI at the rate of 0.20 cfm. The total sample period was two hours (1 hour sample periods were tried but they did not produce filter stains dark enough to be in the range of reliable measurement).

Operational Procedure

Both instruments were turned on and allowed to warm up. The pump of the AISI was turned off and filter tape advanced to a fresh spot. The "initial" % T (after a 15 minute aging period--see discussion) was noted on the readout meter. The P.T.I. counter panels were set at zero and then the AISI pump and the P.T.I. counters were turned on simultaneously. After an elapsed time of 10 minutes, the AISI pump and the P.T.I.

counters were turned off simultaneously. The % T and the indicated particle counts were then transcribed. The counters were reset to zero and the entire process repeated until two hours of running time had been achieved. At the end of the two hour period, the AISI tape was removed and read according to standard procedure on the R.A.C. Spot Evaluator for % Transmission, and on the Photovolt Reflectometer for % Reflectance.

Results

The summary of observed and measured results is presented in Table 12. Runs 1 and 2 are omitted since they were for a different time base (one hour) and their spots were so light as to be considered unreliable particularly in view of the overall sparsity of data.

The results of the regression analysis are presented in Table 13 with selected regressions lines shown in Figures 14 and 15. It is noted that the total counts have been reduced by a factor of 5 to make the volume sampled equivalent to that which produced the Coh/1000'. The correlation coefficients are all significantly non-zero with 99% confidence except for those obtained for Coh/1000 feet vs. 1/5 (Particle count: 6-30 μ).

Discussion of Results

Variations in % T Readings

For the purpose of analysis of results, the values of % T used to determine Coh/1000' are restricted to those measured on the R.A.C. Model 363 Spot Evaluator. This became necessary when, in three cases (Runs 8, 9 and 12), the initial % T was such that the final transmission value on the attached Spot Evaluator meter fell below the 50% level thereby introducing inaccuracies. The calculated values of Coh/1000' on the basis of % T measurement technique are given in Table 14 and shown in the scatter diagram of Figure 16.

Table 12

Related Spot Evaluation and Particle Count
(2 Hour Sample Period)

Run No.	Date	Time	Spot Evaluation @ 0.20 cfm		Particle Counts (Np) 1 cfm				USWB @ Central Park	
			%T*	(%R)	0.3-1.0µ	1.0-2.0µ	2.0-6.0µ	6.0-30µ	Wind Velocity	Relative Humidity (Average)
3	3/10/69	1405-1605	94	95.5	14,141	71,386	21,388	2,736	NW @ 18 MPH	40%
4	3/12/69	0925-1125	92	93.5	18,200	75,887	20,030	2,306	NW @ 18 MPH	47%
5	3/14/69	0925-1125	95	95.0	12,436	45,526	9,439	960	NW @ 12 MPH	47%
6	3/17/69	0915-1115	78	83.0	58,576	185,942	24,977	2,137	SW @ 9 MPH	31%
7	3/17/69	1335-1535	88	90.5	30,540	146,458	32,550	2,336	SW @ 11 MPH	23%
8	3/18/69	0600-0800	55	67.0	95,576	353,027	44,167	2,033	SW @ 6 MPH	45%
9	3/18/69	0815-1015	56	69.5	96,791	367,747	49,928	2,377	SW @ 5 MPH	32%
10	3/19/69	1206-1406	84	86.5	35,724	150,986	29,470	1,745	NE @ 13 MPH	40%
11	3/20/69	1135-1335	82	84.5	69,047	154,071	23,970	1,442	SSE @ 5 MPH	68%
12	3/20/69	1900-2100	71	77.5	24,365	98,949	21,532	1,313	SE @ 11 MPH	86%
13	3/21/69	1720-1920	95	95.5	12,579	65,832	22,309	1,031	W @ 12 MPH	42%
14	3/22/69	1520-1720	94	94.5	13,856	73,154	26,045	1,389	NW @ 14 MPH	43%

*Values from R.A.C. Spot Evaluator Model 363.

Table 13

Linear Regression Analysis
Coh/1000 Ft. vs. Particle Count (Np/5)

Particle Size Range	No. of Cases	Average		Standard Deviation		Correlation Coeficent	Scatter*	Regression Equation $y = mx + b$
		Coh	Np/5	σ Coh	σ Np/5			
0.3-1.0 μ	12	2.13	8,030	1.86	6,109	0.887	0.86	Coh = 0.270×10^{-3} Np - .043
	10**	2.08	8,538	1.98	6,569	0.950	0.61	Coh = 0.286×10^{-3} Np - .362
1.0-2.0 μ	12	2.13	29,816	1.86	20,866	0.929	0.69	Coh = 0.834×10^{-4} Np - .362
	10**	2.08	30,871	1.98	22,390	0.995	0.20	Coh = 0.879×10^{-4} Np - .634
2.0-6.0 μ	12	2.13	5,430	1.86	2,091	0.905	0.79	Coh = 0.804×10^{-3} Np - 2.24
	10**	2.08	5,435	1.98	2,236	0.910	0.82	Coh = 0.804×10^{-3} Np - 2.29
6.0-30 μ	12	2.13	363	1.86	112	0.259	1.79	Coh = 0.430×10^{-2} Np + .563
	10**	2.08	363	1.98	118	0.368	1.84	Coh = 0.617×10^{-2} Np - .160

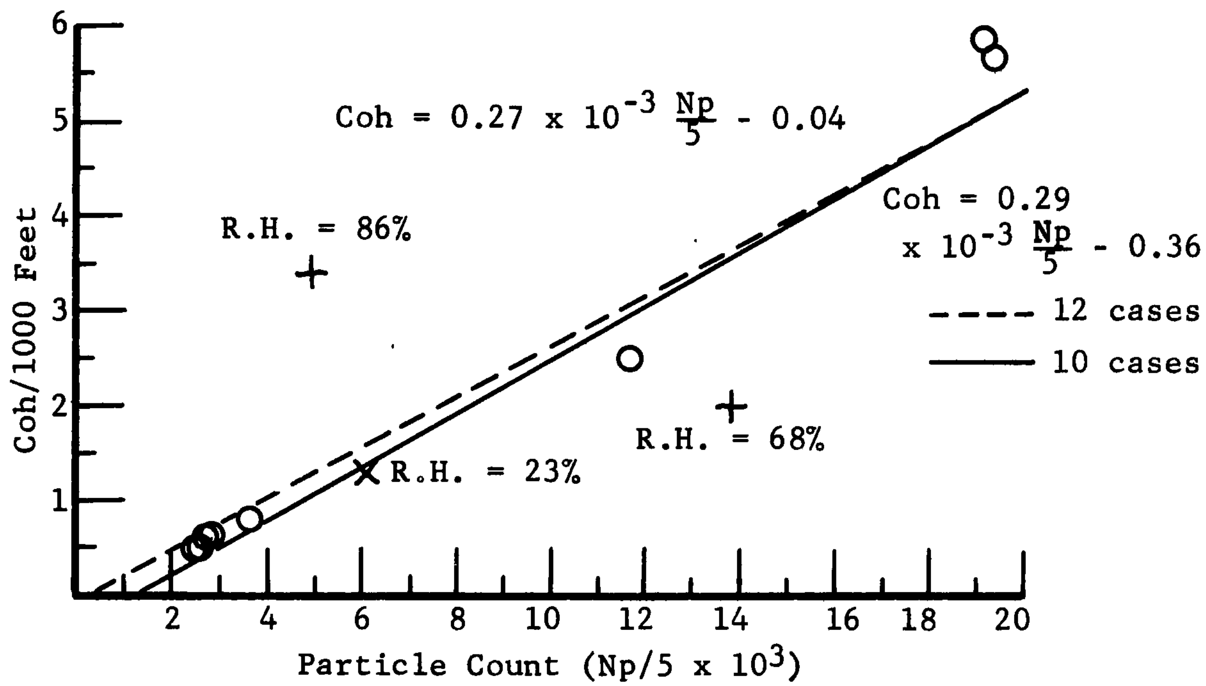
*Scatter = $\sigma_{Coh} \sqrt{1 - r^2}$.

**Runs 7 and 12 omitted.

Figure 14

Regression Lines for Coh/1000 Feet and Particle Count (Np/5)
For Selected Particle Size Ranges

a. Particle Size Range: 0.3-1.0 μ



b. Particle Size Range: 1.0-2.0 μ

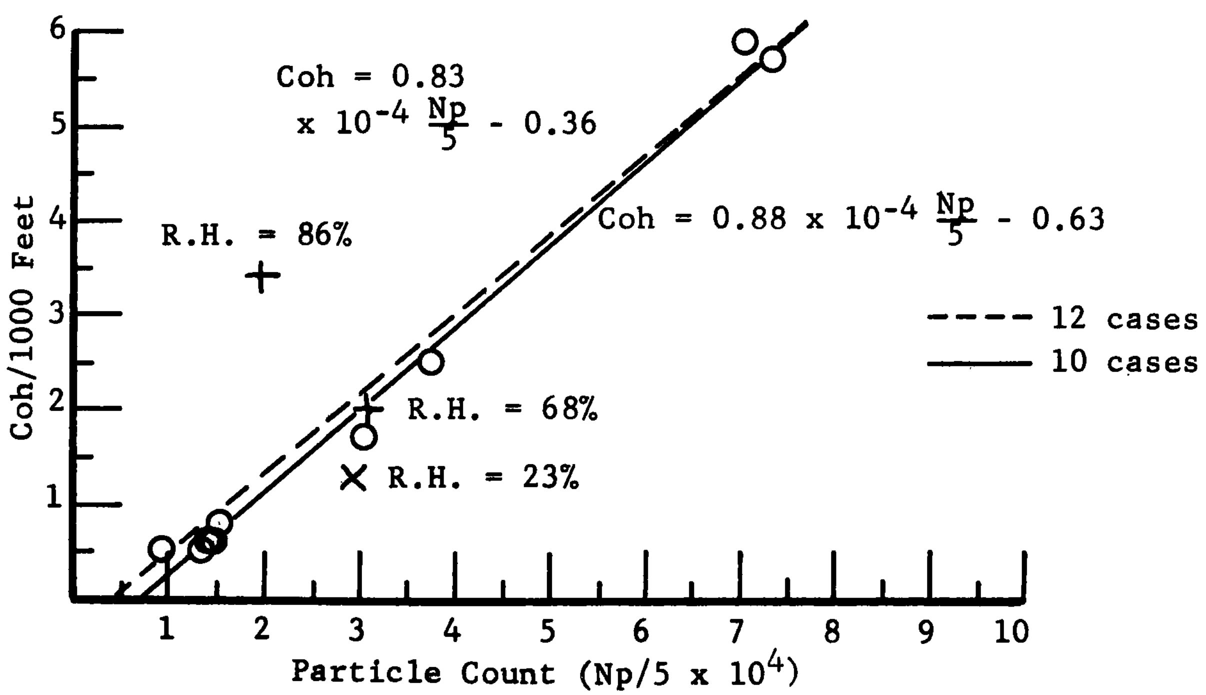
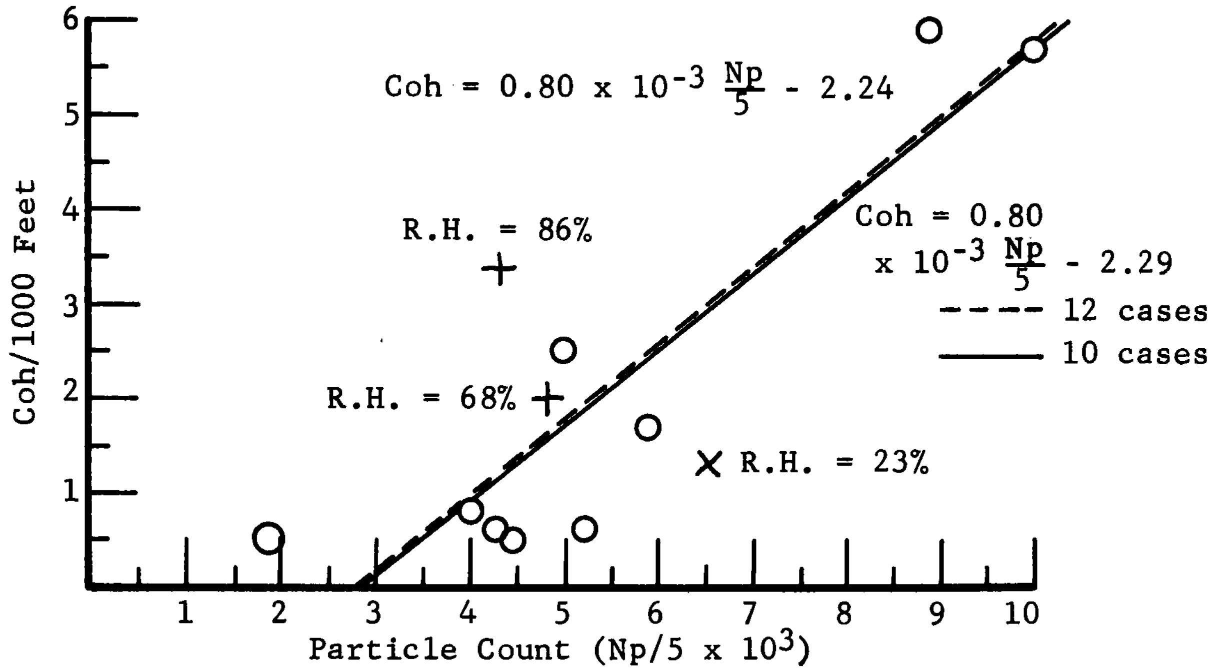


Figure 15

Regression Lines for Coh/1000 Feet and Particle Count (Np/5)
For Selected Particle Size Ranges

a. Particle Size Range: 2.0-6.0 μ



b. Particle Size Range: 6.0-30.0 μ

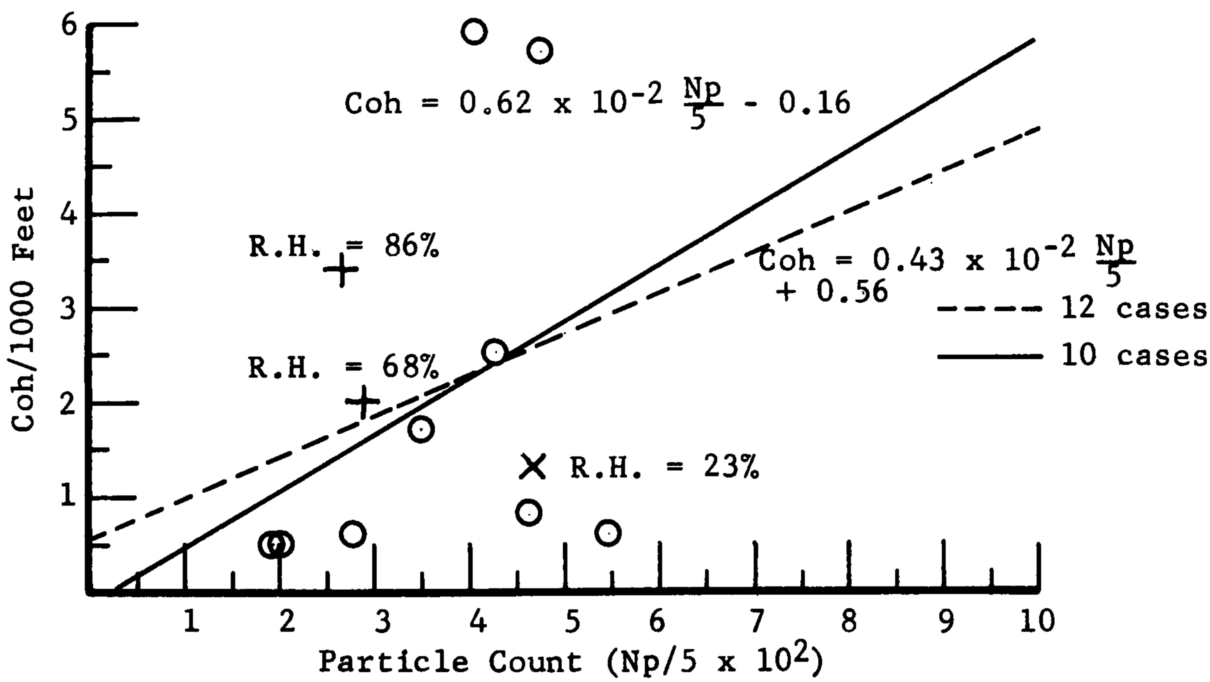


Table 14

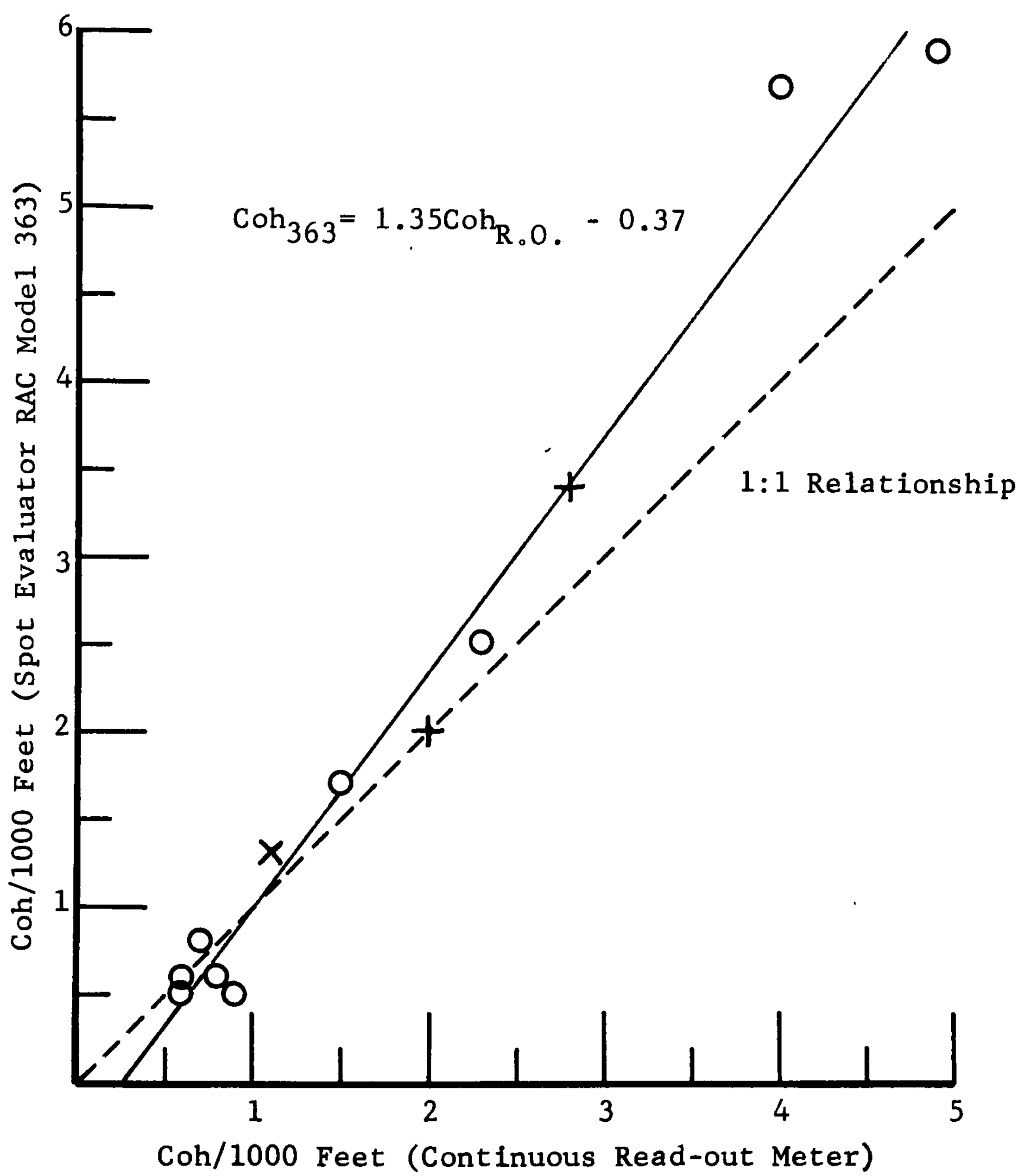
Calculated Values
Coh/1000' and RUD

Run No.	Coh/1000'*	RUD	Coh/1000'**
3	0.6	4.5	0.6
4	0.8	6.5	0.7
5	0.5	5.0	0.9
6	2.5	18.0	2.3
7	1.3	9.6	1.1
8	5.9	39.0	4.9
9	5.7	36.0	4.0
10	1.7	14.0	1.5
11	2.0	16.0	2.0
12	3.4	25.0	2.8
13	0.5	4.5	0.6
14	0.6	5.5	0.8

*Values from R.A.C. Spot Evaluator, Model 363.
**Values from attached readout meter.

Figure 16

Comparison of Values of Coh/1000 Feet
As a Function of Evaluation Technique



It was noted earlier that the AISI tapes were aged under the light source incorporated in the AISI Sampler for 15 minutes prior to the start of the air flow pump. This practice was begun when it was observed that there was invariably an initial drop of up to 4-5% T that bore no apparent relationship to the particulate loading of the incoming air stream. Were this initial drop in % T not discounted, the calculated values of the Coh/1000 feet would have been disportionately high. It is not at all clear at this stage as to the cause of this phenomena. Separate tests conducted with a tape alternately humidified and desiccated suggest that the "initial drop" may be, at least in part, due to realignment of filter fibers due to the heat generated by light source as a result of desiccation and/or fiber roasting. It is of further interest to note that once the filter spot was obtained by two hours of sampling, there were only random, insignificant variations in the value of the final % T when evaluated on the Model 363 Spot Evaluator immediately after the test completion, one hour later, 24 hours later and after 24 hours of desiccation (all sections of record filter tapes were stored in plastic "Baggies" to minimize external contamination).

Apparent Effect of Humidity

It was obvious, even as the tests were being conducted, from preliminary scatter diagrams maintained for the values of Coh/1000 feet versus particle counts that excellent relationships were developing. Except for Runs 7, 11 and 12, there was a strong linear relationship particularly evident in the size ranges 0.3 to 1.0 μ and 1.0 to 2.0 μ (see Figure 14). In all instances (disregarding size range 6-30 μ) Run 11 showed a very high Coh/1000 feet value for a markedly low particle count. Except in the 0.3 to 1.0 μ size range, Run 7 showed a high particle count for a comparatively low Coh/1000 feet value. This latter feature was also true of Run 11 in the

0.3 to 1.0 μ size range. The only immediately common denominator between these anomalous points seems to be the value of the relative humidity. From Table 12 it is found that Run 7 had an extremely low relative humidity average, 23%, while Runs 11 and 12 had high relative humidity averages, 68% and 86% respectively. The relative humidity for all other runs averaged between 32% and 47%.

Junge[5] notes that "as the relative humidity increases, the aerosol particles gradually change both in size and physical properties, and finally become cloud and fog droplets ... They pick up other material from the surrounding air by a variety of processes and thus their composition and physical structure changes continually." He further notes that below 70% relative humidity a noticeable fraction of particles behaved as though they were dry, but above 70% they soon assumed the properties of droplets. Similar observations of effects of relative humidity on light scattering properties of particles have been recently reported by Lundgren, et al.[6]

It can be surmised in the case of Run 11, where the relative humidity is 86%, that "large" droplets have been formed which have swept up and coalesced and/or agglomerated smaller particles thereby producing a relatively low total particle count in all size ranges on the P.T.I. instrument. However, when these aggregates are trapped on the AISI tape their moisture is evaporated and the smaller individual particles return to reduce the light transmission. Similar reasoning can also be applied to Run 11. The relative humidity has begun to increase the size of the submicron particles substantially increasing the count in the 0.3 to 1.0 μ size range (but not as yet in the 1.0-2.0 μ range); however when impinged on the filter paper and dried out, they return to their former smaller size, apparently ineffective in reducing light transmission.

The case of Run 7, where the relative humidity was obviously low, cannot be explained by any of the above reasoning. If one assumes, however, that trapping of particles on filter paper is a process of polymerization which is related to cohesive properties of the particle surface, then one can speculate that the low relative humidity results in a low cohesive force thereby retarding the polymerization process and effectively producing a low value of Coh/1000 feet for a relatively high particle count. As has been observed, this phenomena would be most active in the larger particle size ranges where the surface area is greatest and least effective in the smallest size range.

Particle Size Range Responsible for Coh/1000 Feet

From Table 13 and Figure 14 the highest correlation and least scatter of data points is observed, without question, for particles in the size range from 1.0-2.0 μ. In a separate sequence of tests 25 readings were taken at one minute intervals with the P.T.I. counter. Ten readings were taken with the counter racks set to read in the following ranges:

0.3 - 0.8 μ
0.8 - 2.0 μ
2 - 6 μ
6 - 30 μ

These were followed immediately by twelve readings in the standard ranges:

0.3 - 1.0 μ
1.0 - 2.0 μ
2 - 6 μ
6 - 30 μ

After the above, three additional readings were taken in the ranges:

0.3 - 0.8 μ, etc.

The average counts/cubic foot/minute are tabulated below:

Size Range	$\bar{N}p$/min	Size Range	$\bar{N}p$/min
0.3 - 0.8 μ	18	0.3 - 1.0 μ	204
0.8 - 2.0 μ	1114	1.0 - 2.0 μ	980
2 - 6 μ	150	2 - 6 μ	166
6 - 30 μ	8	6 - 30 μ	11

It is observed that the particle count in the range from 0.3 - 1.0 μ is over 100 times that of the count of 0.3 - 0.8 μ. Furthermore it is noted that when the difference between these two counts is subtracted from the count in the 0.8 - 2.0 μ range, the new count is consistent with the actual count measured in the 1.0 - 2.0 μ range. This may imply that the strong correlation between Coh/1000 feet and particle count earlier observed in the 0.3 - 1.0 μ size range may in fact be generated by those particles in the 0.8 - 1.0 μ range. Unfortunately a similar study was not conducted between the 1.0 - 2.0 μ and 2.0 - 6.0 μ range bands. It is quite possible that one would find the dominate correlation results from those particles close to 2.0 μ in size.

Comment

On the basis of limited data, there is a very strong and significant correlation between the actual count of particles in various size ranges and the commonly used parameter Coh/1000 feet.

The correlation is greatest and most significant when the Coh/1000 feet value is related to total particle count in the size range from 1.0 - 2.0 μ. There is strong evidence to believe that the relationship can be still more firmly established if the lower limit of the size range is reduced to 0.8 μ and the upper limit increased to some value between 2 - 6 μ.

It appears that this relationship between Coh/1000 feet and particle count is most stable for ambient air relative humidities between 31% and 47%. Aberrations occur at higher and lower values of humidity, but it is suggested that this relationship too, could be firmly established with sufficient controlled experiments. It is quite possible that the problem may be alleviated simply by establishing a standard humidity control value on the incoming air stream.

Summary Discussion

This project has reported a series of operations that have worked sequentially from a basic concept of reporting equivalent smoke concentration based on light reflectance techniques adapted by OECD and Great Britain to the ultimate conversion of United States reporting units of particulate density into the same equivalent reporting units. In brief, using techniques, methodologies, curves and equations presented in this report it is now possible for New York City (and probable with only minor error for any United States reporting unit) to take routine readings of particulate density in Coh/1000 feet and convert these to $\mu g/m^3$ as used in European practice. The reverse is also true. That is, those in Great Britain or other European countries who wish to make comparisons of particulate concentration in the respective atmospheres of United States and European locations may use the curve presented here for converting levels of particulate concentration and comparing them in epidemiological studies of the effects of particulate concentration. It has been established that the New York City curve is, in form, practically identical to the International Smoke Calibration Curve and to the British Standard Smoke Calibration Curve. Positioning of the curve is accomplished according to procedures proposed by OECD in 1964 with the index point established at 25% darkness index. The postioning value for the International curve is 20 $\mu g/cm^2$, for Great Britain 17 $\mu g/cm^2$, and for New York City 30 $\mu g/cm^2$.

For New York City major points of conversion include:

1.0 Coh/1000 feet	=	57 $\mu g/m^3$
2.0	=	145
3.0	=	260

4.0 Coh/1000 feet = 400 $\mu g/m^3$
5.0 = 568
6.0 = 745
7.0 = 925

Curve divergence does not permit carrying the comparison to higher Coh/1000 feet levels, or greater particulate concentration in the atmosphere, without special calculations. It has also been established in this study that there is a slight divergence from a 1:1 relationship between % light transmission and % light reflection.

Likewise it has been shown that one hour particulate density readings are not directly representative of two hour readings and can not be extrapolated in the comparison of readings taken with a substantially different total flow passing through a spot on a tape sampler.

It has been established on the basis of limited data that there is a strong and significant correlation between the actual particle count of particles in various size ranges and the parameter of concentration, Coh/1000'.

It is believed that for preliminary estimating purposes, at least, the New York Calibration Curve may be applied in the interpretation of AISI data from other United States cities. This belief is based on the established similarity of smoke curve data from various cities in Great Britain. For more precise comparison it is necessary only to establish with relatively few measurements the proper index point for a calibration curve for any city, and the procedure for establishing that index point has been presented in this report.

Acknowledgments

The staff of the Research Division, New York University, School of Engineering and Science has devoted an unusual amount of time (not always compensated) in pursuing the work of this project. The staff included, in addition to the Project

Director, Jack Golden, Research Scientist, Edward J. Kaplin, Research Scientist, and Raymond Broglie, Research Technician. They are all to be commended for the interest they have shown.

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The particle size studies could not have been undertaken without the cooperation of Particle Technology, Inc. The loan of essential equipment by that company is greatly appreciated.

Needless to say, the efforts of the project secretary, Miss Patricia Twomey, have been invaluable. Her services are greatly appreciated.

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APPENDIX A

Apparatus Used to Determine the Form of the Smoke Calibration Curve

In order to determine the shape or form of the smoke calibration curve, the following equipment was used:

a) Seven 1" diameter brass filter holders.

b) Seven filter holder clamps.

c) Seven "Superior" dry gas meters adjusted to read to 0.1 ft^3.

d) Seven 1.3 cfm vacuum pumps.

e) Fractional timer unit with sampling time ratios (over a 15 minute cycle) of 1/9, 1/6, 1/3, 1/2 and 1 (i.e., continuous operation).

f) Yale Regular Point Hypodermic Needles (20 gauge).

g) Wide-mouth glass mixing jug--capacity 5 liters.

h) Glass funnel--4" diameter inlet and a 1/2" bore glass outlet.

i) Whatman No. 1 filter paper.

APPENDIX B

Standard Operating Procedure for Photovolt Reflectometer Model 610

1. Insert plug of search unit into instrument panel.
2. Insert plug of instrument into 110 volt AC outlet.
3. Insert green TRISTIMULUS filter into search unit.
4. Place 1 clean sheet of Whatman No. 1 filter paper on enamel plaque.
5. Place search unit on top of Whatman No. 1 filter paper.
6. Switch "On" knob on the instrument panel.
7. Allow 15 minutes for instrument to warm up.
8. Set reading to 100% R by adjusting course and fine dials.

9a. After each sample (for small numbers of samples) check 100% R by inserting original clean Whatman No. 1 filter paper. Adjust if necessary with fine adjustment dial.

b. For numerous samples, check arbitrarily and adjust, if necessary, with fine adjustment dial.

10. After completing all samples, disassemble unit in reverse of steps 1 through 6 and clean components.

APPENDIX C

Apparatus Used to Determine Scale To be Attached to the Calibration Curve

a) One 1.3 cfm vacuum pump orificed to produce approximately .073 ft^3/min.

b) High volume suction pump, of normal rating 50-200 ft^3/hr., capable of drawing the air through the apparatus at 1100-4400 ft^3/day.

c) Two "Superior" dry gas meters adjusted to read to 0.1 ft^3.

d) Two filter clamps 4" I.D.

e) Hard glass funnel 8.5" I.D. (to produce inlet velocity of approximately 2 cm/sec).

f) Glass tubing of 1/2" I.D. with all bends having an 8" radius.

g) One 1" brass filter clamp.

h) Desiccator containing magnesium perchlorate for drying filter medium.

i) Electronic balance capable of measuring 0.1 mg.

j) Filter Medium - Glass Fiber Filter (Type E--Gelman Instrument Company).

APPENDIX D

Instruments and Procedures for Comparison of Light Transmission and Reflection

Reflectance values were read on a Photovolt Reflectometer, Model Number 610. The instrument was checked against a standard after each reading. The standard was one clean sheet of Whatman No. 1 paper placed on a white enamel plaque supplied by the manufacturer. In all cases a green tristimulus filter was used in the search unit. The initial reading produced by the standard was 100%.

Transmittance vlaues were read on a Research Appliance Company Spot Evaluator, Model Number 363. The instrument is reset, if necessary, to 100% before each sample is read. This is done on a clean piece of Whatman No. 4 paper.