OBJECTIVE MEASUREMENT OF SMOKE FROM COMBUSTION SOURCES

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INTRODUCTION

Interest in fine particle pollution began a long time ago. In England, the Owens Pollution Recorder has been used for many years to determine atmospheric concentrations of smoke. Early in the 1950's Hemeon developed the AISI automatic smoke sampler and demonstrated the logic of drawing a relatively small sample of air through a white filter paper strip with automatic indexing and evaluating the residue retained on the paper by optical means. (1). The unit of measurement of the resultant sample suggested by Hemeon is called the Coh Unit and is defined as that quantity of light scattering solids producing an optical density of .01 when measured by light transmission.

The City of Cincinnati, Division of Air Pollution Control, early recognized the value of making continuous measurements of the non-settling particulates in the general atmosphere and has maintained several such monitoring stations since 1952. (2) It was considered that the soiling of light-colored surfaces is of particular interest and that the evaluation of the stain by light reflectance is preferable to transmission. In order to differentiate the results obtained by reflectance, the unit of soil was christened the Rud (Reflectance Unit of Dirt), the Rud value being that quantity of light scattering solids producing an optical density of 0.01 when measured by light reflectance.

Rud or Coh values are further standardized to a unit volume of air filtered through a unit area of filter. The resultant values have become known as the Soiling Index (3) of the atmosphere, and are generally reported as Ruds or Cohs per 1000 linear feet of air, equivalent to filtering 1000 cubic feet of air through one square foot of filter area.

NEED FOR A METHOD OF QUANTITATING SMOKE EMISSION

The smoke plume from the incomplete combustion of the volatile matter in fossil fuels is an important source of fine particles in many urban atmospheres. Most black smoke plumes from combustion sources contain only an infinitesimal weight of particulate matter even though at times such plumes appear to be solid black. The opacity is due to the presence in the smoke plume of a tremendous number of sub-micron carbon particles which have a highly effective light scattering effect but contribute little to the mass of the emission. Therefore, quantification in mass emission units or weight concentration is not a practical measurement and authorities rely almost universally on subjective evaluation such as the Ringelmann Chart.

THE SOILING POTENTIAL METHOD APPLIED TO SMOKE PLUME MEASUREMENT

In view of the success in quantitating the build-up of fine particles in community atmospheres by the soiling index method it appears only logical that this same method could be applied to evaluating the source strength of smoke plumes in objective units. Such objective units could then be used in the development of emission inventories, in cause and effect studies, and in setting objective performance criteria for combustion equipment.

The analogy between weight units and optical units is illustrated in Table I. It can be seen that for every mass unit there is a corresponding optical unit.

TABLE I COMPARISON BETWEEN COMMON WEIGHT UNITS AND OPTICAL SOILING UNITS (4)

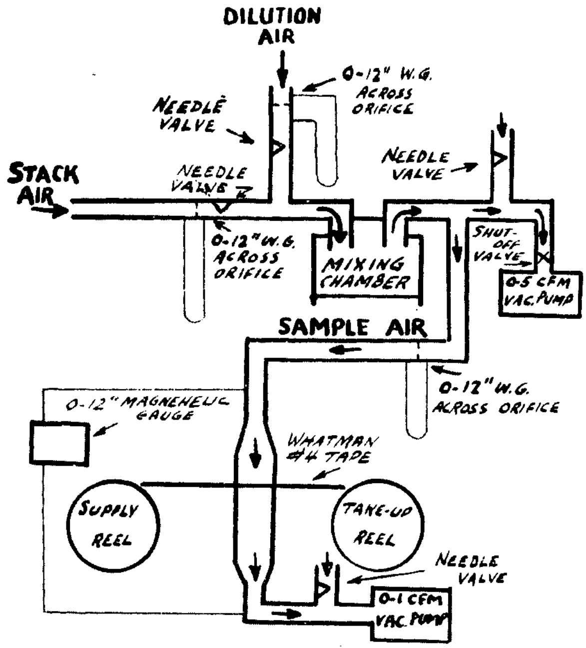
	Weight Units		Optical Units	
	Metric	English	By Trans.	By Ref.
Quantity	Gms	Pounds	Coh-ft^2	Rud-ft^2
Concentration	gms/cc	lbs/1000# gas	Coh-ft^2/ft^3	Rud-ft^2
		grains/scf	Also: Coh-ft^2/1000 ft^3 (Coh/1000 ft)	Also: Rud-ft^2/1000 ft^3 Rud/1000 ft)
Rate (time)	gms/min.	lbs/min.	Coh-ft^2/min.	Rud-ft^2/min.
Rate (fuel)	gms/kg coal	lbs/# coal	Coh-ft^2/# coal	Rud-ft^2/# coal

THE SOILING POTENTIAL SAMPLER

In 1953, Hemeon (1) applied the automatic tape sampler to a stoker-fired coal burning boiler plant and reported the smoke emissions in terms of Coh-ft^2/min. When such information is obtained, it is necessary to know only the total gas flow and by simpl[e] arithmetic calculation the total quantity of smoke in Coh-ft^2/unit of time can be obtained.

In 1964, the authors, using a sampling train similar to that arranged by Hemeon, constructed the Soiling Potential Sampler (SOPOS). Figure 1 shows the sampling trai[n] and Figure 2 is a photograph of SOPOS, Model 4. Essentially the instrument is arran[ged] to draw a variable sample of the combustion gases from the breeching either directly through the filter tape or through a circuit which first dilutes the sample from the source. From the direct extraction or from the diluted sample, a portion is taken through the filter tape at a rate of approxiately 1/4 cfm. Isokinetic sampling is n[ot] considered necessary because of the sub-micron size of the smoke particles. Samplin[g] time must be adjusted according to the concentration of the smoke in the source so that a combination of sampling rate and time will produce a spot having a reflectanc[e] of greater than 50%. The spots are moved, or indexed, manually as they are complete[d]. Data are recorded on a log sheet as the test progresses. The spots are evaluated by means of a reflectance meter, and the soiling potential in terms of Rud-ft^2/cu.ft. [of] gas sampled is calculated.

A sample calculation is shown in Appendix 1.



SCHEMATIC DIAGRAM OF SOILING POTENTIAL SAMPLER (MODEL #4)

Figure 1

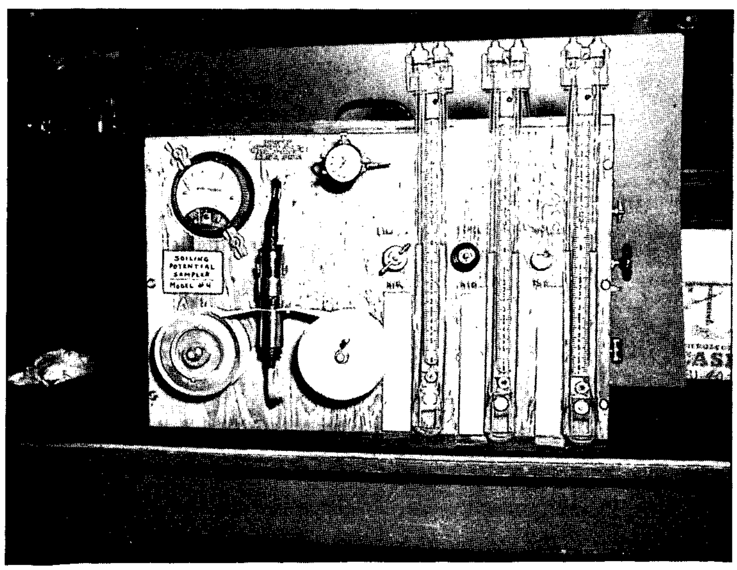


Figure 2

FIELD TESTING

To date 17 tests have been made on 9 different plants ranging from a small 70 H.P. steel fire tube boiler, fired by a single retort underfeed stoker, serving a school heating load to a 225,000 lb. water tube boiler, fired by pulverized fuel burner, serving an industrial steam processing load. One test on one plant taken during start-up of a newly installed boiler was discarded because the operating conditions were not considered typical.

The average value of soiling potential per cubic foot of stack gas for 16 tests was 1.10 Ruds-ft^2/cu.ft. with a maximum of 7.4 and a minimum of .05. The soiling potential per pound of coal burned was an average of 134 with 1250 maximum and 9 minimum. Figure 3 shows the average soiling potential for the 9 different plants tested while Table II summarizes the results of the 16 tests.

SOILING POTENTIAL VS VISIBLE SMOKE

There appears to be good correlation between the soiling potential and opacity of plume for any one plant.

Plant No. 9 contains a newly installed 85,000 lb. steam/hr. water tube boiler fired by a traveling grate spreader stoker. The plant is equipped with a moderate draft loss collector with decanting re-injection and a good over-fire-air smoke consuming system. The combustion controls include a Bailey recording smoke meter.

During the test 300 samples were taken one each minute or less for 4½ hours. Readings were made from the smoke meter chart once each minute and periodic observations of the visible plume were made and recorded as Ringelmann Numbers.

Figure 4 shows a plot soiling potential values in Rud-ft^2/cu.ft. of stack gas versus time. Directly above is the plot of the smoke recorder values as percent of chart. The individual observations are indicated by circles. Visual comparison shows excellent and sensitive correlation while statistical analysis shows a correlation coefficient of .90 (5).

Another type of test was run on Plant 4. A city air pollution inspector made smoke observations from a post about 1/4 mile from the stack. Using conventional procedures he recorded the opacity of the plume in Ringelmann numbers on 1/4 minute intervals. The observed smoke is plotted against SOPO values in Rud-ft^2/cu.ft. in Figure 5 and again it can be seen that a general correlation between soiling potential and observed opacity exists for this one plant.

SOILING POTENTIAL FOR EMISSION INVENTORY FOR COMBUSTION SMOKE PLUMES

Soiling potential per pound of fuel burned will lend itself readily to an emission inventory of smoke particles from incomplete combustion of the volatiles in the fuel burned in any given area. It is only necessary to make sufficient numbers of tests of representative equipment under all operating conditions to obtain a statistical average. Then, by knowing the total fuel burned in any significant unit of time the total contribution of incomplete combustion of this fuel to the dark particle soiling index of the general atmosphere can be calculated.

The Cincinnati Division of Air Pollution Control in cooperation with the Meteorological Section of PHS, Division of Air Pollution at Taft Center in Cincinnati, explored this procedure which produced encouraging results. A rather accurate estimate was made of

Figure 3

SOILING POTENTIAL OF NINE BOILER PLANTS

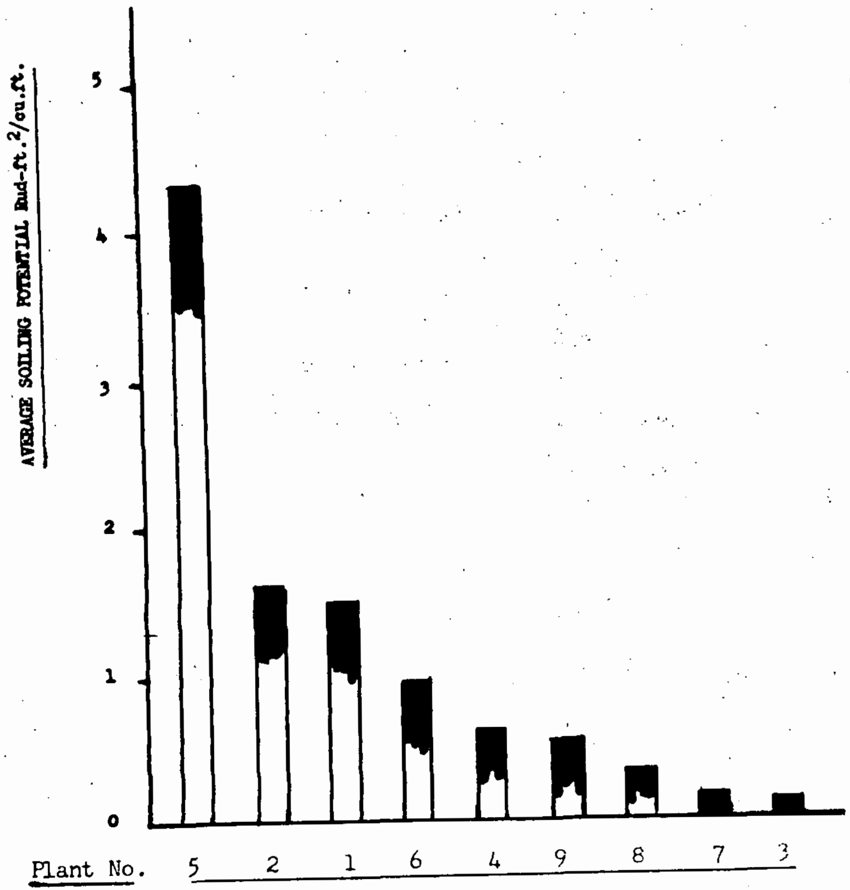


FIGURE 4

SOILING POTENTIAL VS. RECORDED AND OBSERVED SMOKE

PLANT # 9 - 85,000 lb BOILER w/ SPR STOKER

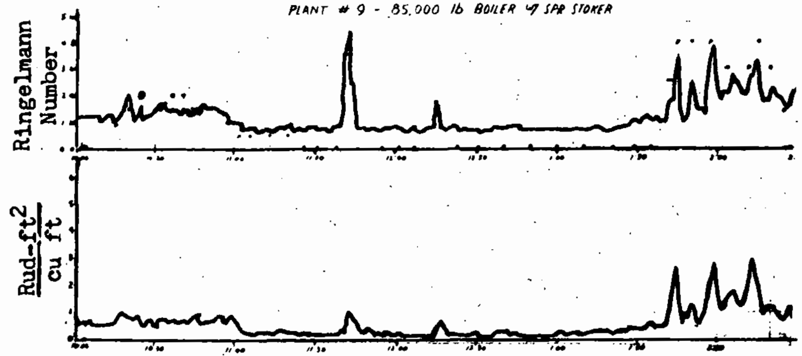


FIGURE 5

SOILING POTENTIAL VS. OBSERVED SMOKE

PLANT # 4 65,000 lb. BOILER w/ VIB. GRATE STOKER

5-MIN. AVERAGE VALUES

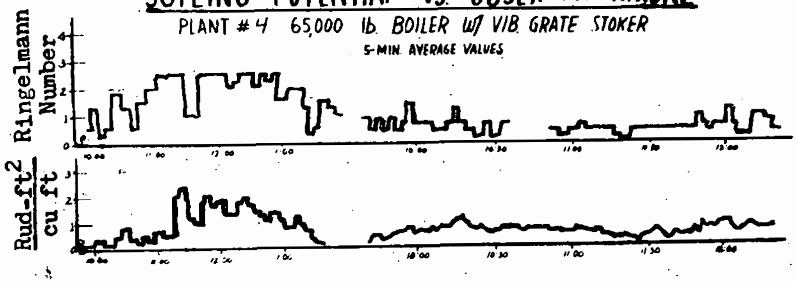


TABLE II

PLANT	BOILER	METHOD OF FIRING	NO. OF TESTS	SOILING POTENTIAL RUD-FT2/CU.FT. STACK GAS AV.	Max.	Min.	RUD-FT^2/# COAL AV.	Max.	Min.
1.	38,000# W. T.	Spreader Sta. Grate	3	1.43	4.6	.11			
2.	189 H.P. St.. F.B.	U.F. Stoker Single Retort	3	1.53	7.4	.06			
3.	200,000# W. T.	Pulv. Fuel	1	.07	.09	.05	11	15	9
4.	65,000# W. T.	Vibrating Grate	4	.60	2.54	.06	190	1250	12
5.	71.5 H.P. St. F.B.	U.F. Stoker Single Retort	1	4.3	5.6	2.9			
6.	26,800# W. T.	U.F. Stoker Single Retort	1	.9	1.9	.19			
7.	225,000# W. T.	Pulv. Fuel	1	.20	.28	.14	40	56	28
8.	65,000# W. T.	7 Retort Underfeed	1	.32	.82	.12			
9.	85,000# W. T.	Spreader Trav. Grate	1	.57	2.88	.15	125	750	30
	SUMMATION OF ALL TESTS			1.10	7.4	.05	134	1,250	9

oal consumed in one segment of the city between 8:00 and 9:00 a.m. on a cold day. A OPO value of 500 Rud-ft^2/lb. coal burned was used and the total emission in Rud-ft^2 etween 8:00 and 9:00 a.m. from all coal burning sources was calculated. Then using ie working equation reported by Clarke (6) in his development of a simple diffusion odel for calculating point concentrations from multiple sources, the expected smoke article concentration (Soiling Index) in the general atmosphere was determined.

ie calculated values of soiling index for the Downtown Cincinnati Station with light W winds and slightly stable atmosphere was 1.4 Rud-ft^2/1000 cu.ft. (Rud/1000 ft) id for moderate WNW winds with neutral condition was .4 Rud-ft^2/1000 cu.ft. Those amiliar with soiling index measurements in the general atmosphere will recognize such alues as being representative of levels measured in many communities.

SUMMARY - USES & ADVANTAGES OF THE SOPO METHOD OF SMOKE MEASUREMENT

n summary there is strong indication that the soiling potential method of quantitaing smoke plume values will produce reliable information which can be used in a number f different fields related to the soiling of light colored surfaces by dark colored ib-micron smoke particles.

. It produces sensitive, reproducible, objective quantity measurements of smoke particles resulting from incomplete combustion of the volatile matter in fossil fuels.

The resultant measurements are in terms of concentration: soiling potential per cubic foot of combustion gas (Rud-ft^2/cu.ft.) or rate soiling potential per unit of fuel input (Rud-ft^2/lb. coal).

. The resulting value of soiling potential per unit of fuel lends itself to quantitating the emission per unit of time from single or multiple sources within an area by simple arithmetic calculations. The summation of source strengths, in the same terms as the measurement of the resultant soiling index of the atmosphere, provides a ready means of estimating the contribution of various combustion sources to the total build-up of fine particles in the atmosphere. Such information is invaluable in estimating the corrective action within an area in order to reduce the fine particle pollution in any air pollution control effort.

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APPENDIX 1

CALCULATING SOILING POTENTIAL VALUES - EXAMPLE

SAMPLE DATA:

Duration of Sample	Air Flow Data Sample Air	Stack Air	Dilution Air	% CO_2	Density of Spot, % Reflectance
5 min.	.23 cfm	.11 cfm	3.1 cfm	11.5	80

CALCULATING VOLUME OF STACK GASES SAMPLED:

Dilution Ratio: $\frac{.11}{.11 + 3.1} = \frac{.11}{3.21} = .034$

Volume of stack gases sampled: .23 cfm x 5 min. x .034 = .039 cu.ft. (Q)

CALCULATING SOILING POTENTIAL:

$\text{Rud-ft}^2/\text{ft}^3 = \frac{\text{O.D. x 100}}{Q/A}$ A = .0054 sq.ft. (area of spot)

$\text{O.D.} = \log_{10} \frac{100}{\% R} = \log_{10} \frac{100}{80} = .097$

$\text{Rud-ft}_2/\ \text{ft}_3 = \frac{.097 \times 100}{7.2} = \frac{9.7}{7.2} = 1.3$

CALCULATING Rud-ft_2/lb. of COAL BURNED:

Theoretical: 143 cu.ft. of air required to burn 1 pound of coal. (for coal at 14,550 Btu/lb.)

11.5 % CO_2 = 58% Excess Air = 83 cu.ft. of Excess Air

Total air per pound of coal = 143 + 83 = 226 cu.ft.

Then, 1.3 $\text{Rud-ft}^2/\text{ft}^3$ x 226 cu.ft. = 294 Rud-ft^2/lb. of coal