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MEASUREMENT OF THE OPACITY AND MASS CONCENTRATION OF PARTICULATE EMISSIONS BY TRANSMISSOMETRY

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MEASUREMENT OF THE OPACITY AND MASS CONCENTRATION OF PARTICULATE EMISSIONS BY TRANSMISSOMETRY

by

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INTRODUCTION

Evaluation of smoke emissions on the basis of appearance began near the end of the nineteenth century when a number of different methods and scales for visual estimation of smoke were proposed. It was during this period that Maximilian Ringelmann developed a series of charts of graduated shades of gray for use as visual comparators for the evaluation of gray or black smoke.[1] Ringelmann Charts are still considered the reference standard of smoke regulations for visible emissions in most industrial nations.

Although the Ringelmann Chart generally remains the reference standard for regulation of visible emissions, its method of application has changed,[2] and other measurement methods have been applied.[3-5] One of the most common methods is transmissometry, which has become an accepted instrumental method for measuring the opacity of visible emissions. An equivalency has been accepted between the opacity readings and Ringelmann number values of "black" plumes. By the use of opacity measurements, visible emissions regulations have been extended to plumes that are not gray or black,[2] have limited the effect of the environment on the method, and have made the regulation better represent the concentration of the particulate emissions.[6] Today, smoke inspectors are commonly trained to read visible emissions at a plume evaluation school; they qualify when they learn to read black and white training plumes with acceptable accuracies relative to transmissometer measurements of the opacity of the emissions.

Opacity and/or mass standards are, or will be, placed on the particulate emissions from new and existing sources. Emission controls at these sources are required for implementation, maintenance, and enforcement of emission standards and ambient air quality standards promulgated by the Environmental Protection Agency as required by the Clean Air Act of 1970. Standards of performance for new stationary sources also require the monitoring of smoke emissions from a number of sources, and the requirement is expected to be extended to additional new and existing sources.

This paper discusses the relationship between the opacity, light transmittance, visual effects, and mass concentration of particulate emissions. It also discusses some optical-design factors of transmissometers that can affect their measurement of the opacity of visible emissions.

OPACITY AND VISUAL EFFECTS OF SMOKE PLUMES

Two different visual effects may be attributed to plumes containing particles that scatter and/or absorb light: (1) the plumes become visible, and (2) they obscure the visibility of objects behind them. These visual effects have been analyzed in this laboratory in terms of the luminance contrast between objects (or plumes) and their surroundings.[6] The work indicated that both effects are dependent not only on opacity but on the amount of light scattered by plumes into the viewer's eyes and, consequently, are dependent upon the environmental lighting conditions of the plumes. In the case of obscuration of visibility by plumes, however, the ambient lighting conditions have been shown to be less important.[2]

It is the obscuration of visibility by plumes that represents the basis for regulating plumes by a visual effect. The term opacity has been defined as "the degree to which emissions reduce the transmission of light and obscure the view of an object in the background."[7] A theoretical hypothesis of vision obscuration by a plume in terms of the reduction in luminance contrast of an object viewed through the plume can be presented to illustrate the opacity concept.

VISIBILITY OBSCURATION BY PLUMES

The luminance contrast (C_t) between an object of luminance (B_t) viewed against an extended background such as the sky with luminance (B_s) is:

$$C_t = \frac{B_t - B_s}{B_s} \qquad (1)$$

If the object is viewed through a plume, its apparent luminance (B_t^1) and the apparent luminance of the sky behind the plume (B_s^1) will depend on the amount of light that the plume scatters from the surroundings and sun into the viewer's eyes (B_a), and on the amount of light transmitted through the plume from the background and object. The apparent contrast of the object (C_t^1) may be written as:

$$C_t^1 = \frac{B_t^1 - B_s^1}{B_s} \qquad (2)$$

The denominator of equation (2) remains, as in equation (1), the intrinsic luminance of the sky (B_s) since it remains the dominant luminance of the scene. Dividing by the intrinsic luminance of the sky simplifies the analysis by removing the light scattering term (B_a) from the final results. This differs from a more complicated earlier analysis from this laboratory in which the reduction in contrast between two contrasting targets located behind the plume was discussed.[6] Dividing by the intrinsic luminance of the sky would not be realistic for atmospheric pollution or for extended sources where the scatter and absorption of light by the particulates would affect the luminance of the entire scene. For these cases, the denominator of equation (2) should be the apparent luminance of the sky (B_s^1).

If the plume has a transmittance (T) and the amount of light scattered by the plume toward the observer is B_a, then $B_t^1 = B_tT + B_a$ and $B_s^1 = B_sT + B_a$ and equation (2) may be written:

$$C_t^1 = \frac{(B_t - B_s)\,T}{B_s} \qquad (3)$$

The reduction in object to background contrast due to the plume may be defined as:

$$C_R = \frac{C_t - C_t^1}{C_t} \qquad (4)$$

which, after substitution of equations (1) and (3) and rearrangement, becomes:

$$C_R = 1 - T \qquad (5)$$

Equation (5) indicates that the reduction in luminance contrast and visibility of an object behind a plume viewed against an extended background is equivalent to one minus the transmittance (1-T) of the plume. 1-T is commonly called the opacity of the plume. The relationship also indicates that the visibility reduction is independent of the environmental illumination, and that there is an equivalency between the opacity of plumes and their reduction of visibility.

The equivalent opacity concept was studied by the Bay Area Air Pollution Control District in the mid-1960's.[2] In that study, a group of observers was used to determine the light transmittances (opacities) of black (carbon) and white (oil) experimental plumes with equivalent vision obscurations. Because the observers had no previous experience in reading smoke, they were screened to establish a statistically consistent group. After instruction in the use of the Ringelmann Charts for evaluating black plumes, the observers were asked to assign Ringelmann number values to black plumes of various densities and to observe how much the black plumes obscured the visibility of a target located behind them. They were then asked to view a similar target behind white plumes of various densities and assign "equivalent Ringelmann numbers" to the plumes by equating their visibility reduction to the black plumes. During the tests, the opacity of both plumes was monitored by identical photoelectric transmissometers. The Bay Area APCD used the results of the tests to calibrate the transmissometers on the black and white smoke generators in terms of Ringelmann numbers and "equivalent Ringelmann numbers," respectively. These curves represented the average of 14,400 observer estimates of the Ringelmann number values of the black plumes (9 observers, 80 series of 20 readings), and 8,120 observer estimates of the "equivalent Ringelmann number" values of white plumes (7 observers, 58 series of 20 readings).

Since the two Ringelmann number scales reported by the Bay Area APCD are related through the equivalency in the vision obscuration produced by the plumes, the two curves may be combined to show a general equivalency in the transmissometer-measured opacity and the reduction in visibility by the two plumes (Figure 1). The averaged data shown in Figure 1 indicate that, in the important opacity region below 35 percent, black plumes have slightly greater vision obscuration than white plumes with equivalent opacities. In the opacity region above 35 percent, white plumes were judged to have greater vision obscuration than black plumes with equivalent opacities. Since standard deviations of up to 12 percent opacity are reported for the data, the averaged curve shown in Figure 1 is within one standard deviation of the theoretical one-to-one relationship.

Although the opacity of plumes represents a measure of how much they obscure visibility, the plumes are generally located where they are observable only against the sky, and their obscuration of visibility (obscuration of objects behind them) is not observable. Consequently, it is the visual

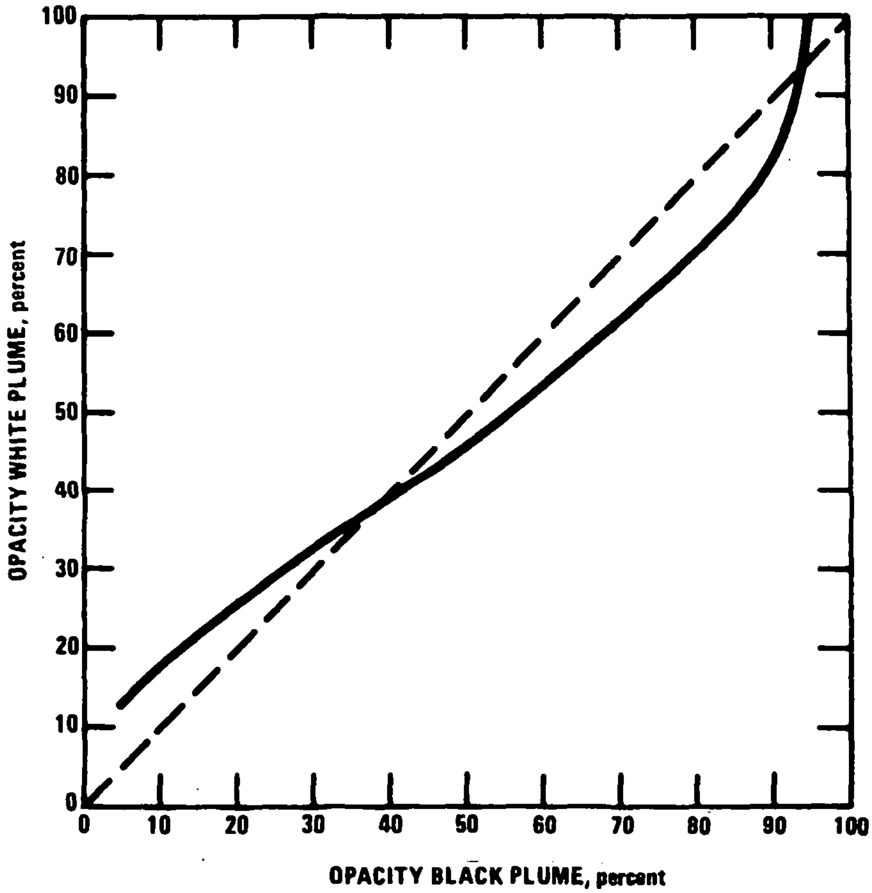

Figure 1. Observer estimates of the opacity of black and white experimental plumes with equivalent vision obscuration.

appearance of plumes that is usually observed by both the casual observer and by the trained observer assessing their opacity.

VISIBILITY OF SMOKE PLUMES

Analysis of the visibility of plumes[6] in terms of their luminance contrast with their background (C_p) has shown that:

$$C_p = \frac{B_a}{B_s} - (1 - T) \qquad (6)$$

where: B_a = the amount of light scattered by the plume toward the observer

B_s = the luminance of the background (usually the sky)

T = the light transmittance of the plume

$(1-T)$ = the opacity of the plume

Equation (6) indicates that the visibility of a plume depends on the amount of light scattered by the plume from the sun and its surroundings into the viewers eyes (B_a) relative to the luminance of the plume's background (B_s) and the opacity of the plume (1 - T).

The dependency of the appearance of plumes on their environmental lighting, background, and general viewing conditions makes plume visibility or simple telephotometric contrast measurements undesirable for regulating particulate emissions. Consequently, visible emissions regulations are based on the opacity (visibility obscuration) of the plumes, which is an intrinsic property of the plume and a better indicator of the particulate emissions. It may be measured instrumentally by transmissometry or estimated by trained observers.

OBSERVER EVALUATION OF OPACITY

The smoke inspector or trained observer receives training at a smoke inspector training school where he is taught to evaluate the opacity of black and white training plumes with prescribed accuracies relative to transmissometer measurement of their opacities. Upon passing the course, he becomes certified by the school as capable of evaluating the opacity of smoke plumes from their appearance. This procedure requires the inspector to evaluate an intrinsic optical property of the plumes (their opacity) by observing their visibility, which is dependent not only on their opacity, but also on their illumination and background viewing conditions.

Clearly, the trained-observer method of evaluating opacity has limitations; e.g., at night when a plume cannot be seen, the method is not generally applicable. Halow and Zeek[8] have analyzed the visibility of white plumes in daylight and have shown that observer evaluations depend upon the background and environmental lighting conditions of the plumes. A white plume viewed against a white overcast sky is often invisible because the amount of light it scatters toward the viewer equals the amount of light that it attenuates from the background. The visibility of a white plume viewed on a clear day is particularly sensitive to the viewing direction relative to the sun. The plume appears much brighter when the sun is illuminating it from behind. Tests with trained observers[6] have shown that the evaluation of such plumes should be limited to times when they may be seen with the sun illuminating them from the front. There are many plume background and illuminating conditions confronting the smoke inspector in the field that may impose limitations on the visual evaluation of the plumes; consequently, it is important that the inspectors be trained under viewing conditions that generally prevail in the field, and that the inspectors know of any limitations that may result because of deviations from these conditions.

MEASUREMENT OF SMOKE OPACITY BY TRANSMISSOMETRY

The measurement of the light transmittance or opacity of aerosols by transmissometry requires the standardization of two important optical characteristics of the transmissometer to obtain similar performance between instruments. The need for standardizing the wavelength and collimation characteristics of the transmissometer can best be illustrated by examining the light-scattering characteristics of fine particles.

LIGHT TRANSMITTANCE OF AEROSOLS

A part of a parallel beam of incident light upon an aerosol such as a smoke plume will always be removed from the beam by scattering and also by absorption if the smoke is composed of absorbing particles. A measure of the amount of light that passes through the smoke relative to the amount of incident light is the transmittance of the smoke. The transmitted light has not interacted with the particulates and will emerge from the smoke still parallel to the incident beam.

The transmittance of light through an aerosol of monodisperse spherical particles is defined by Bouguer's law:[9]

$$T = \frac{F}{F_o} = e^{-naQL} \qquad (7)$$

where:

T = transmittance of the aerosol

F_o = light flux incident on the aerosol

F = light flux transmitted through aerosol

L = light path length through the aerosol

n = number concentration of the particles

a = projected area of one of the particles

Q = particle extinction coefficient

The particle extinction coefficient (Q) is defined as the total flux scattered and absorbed by a particle divided by the flux geometrically incident on the particle. It is, in general, a function of the particle size and shape, the refractive index, and the wavelength of the incident light. The product $naQ=\sigma$ is sometimes called the turbidity coefficient or the attenuation coefficient of the aerosol and has the dimensions ($length^{-1}$).

WAVELENGTH CONSIDERATION

The effect of wavelength on the transmittance of smoke depends primarily on the size of the particulates in the smoke and their associated extinction coefficients. The particle size-extinction relationship can usually be divided into three different light-scattering regions that describe the scatter by particles much smaller than, larger than, and comparable to the illuminating wavelength.

Particles that are much smaller than the illuminating wavelength ($d<0.05$ micron in white light) are in the dipole or Rayleigh scattering region. Particles in this region contribute little to the opacity of smoke emissions since their extinction coefficients seldom exceed 10^{-2}. The extinction coefficients in this region are proportional to λ^{-4} if the particles are transparent, and proportional to λ^{-1} if the particles are absorbing.

Particles that are large compared to the illuminating wavelength ($d>2$ micron in white light) are in the geometrical scattering region. In this region, the extinction coefficient will have the value of 2 for absorbing and irregularly shaped particles, but will oscillate around the value of 2 for spherical transparent particles (Figure 2). For monodisperse spherical transparent particles in air, the oscillations in the

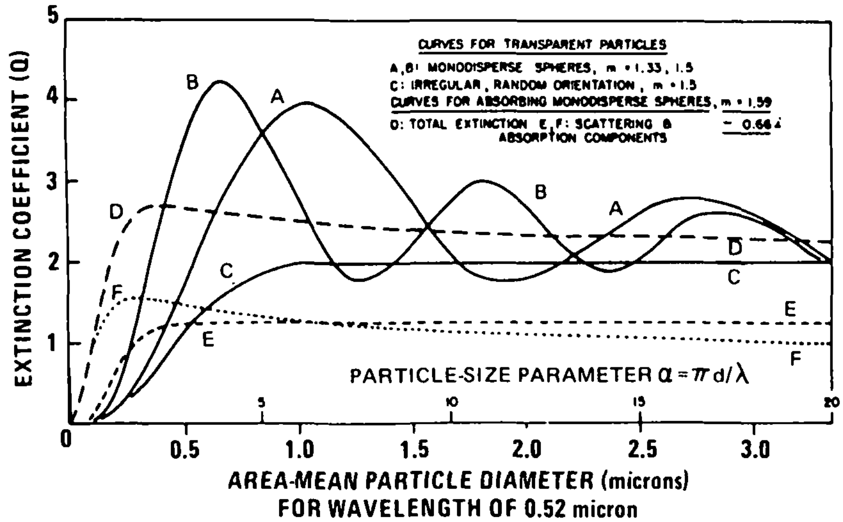

Figure 2. Particle extinction coefficients for various aerosols calculated from the Mie theory (except curve C).

extinction coefficient can result in extinction coefficient values in this region being as high as 1.5 times the value of 2, to which it converges at large particle sizes. If the particles are absorbing or irregular in shape (randomly oriented), the limiting extinction coefficient value of 2 can be obtained at particle sizes as small as 0.3 micron with little or no oscillation. In practice, the particulates in smoke emissions are polydisperse and the oscillatory behavior of the individual particle extinction coefficients is smoothed. Further smoothing results when the particles vary in composition and the measurements are made with polychromatic (white) light; consequently, smoke emissions with mean particle sizes above 2 microns will generally have a mean particle extinction coefficient of 2 and a transmittance that is not a function of wavelength.

The intermediate size region (0.05 <d<2 micron in white light) in which the particle sizes are comparable to the illuminating wavelength is the Mie scattering region. In this region, the value of the particle extinction coefficient increases with particle size from the Rayleigh region value of 10^{-2} to the plateau of 2 for absorbing and irregularly shaped particles, and sometimes to a maximum value of 3 or 4 if the particles are spherical, transparent, and monodisperse.

As indicated above, the extinction coefficient of highly absorbing and irregularly shaped particles will reach the value of 2 between 0.3 and 0.7 micron. The maximum extinction coefficient value for transparent, spherical particles is obtained between 0.67 and 1 micron in visible light before oscillating around the value of 2. Again, the oscillations are smoothed toward the value of 2 for smoke emissions that are polydisperse and of varying composition. Smoke emissions in this size region generally have an extinction coefficient proportional to λ^{-n} $(0<n<4)$ and a transmittance that is a function of wavelength. Data generated in this laboratory[6] with experimental white (oil) and black (carbon) plumes have illustrated the effect of wavelength on the opacity of fine particulates (Figures 3 and 4).

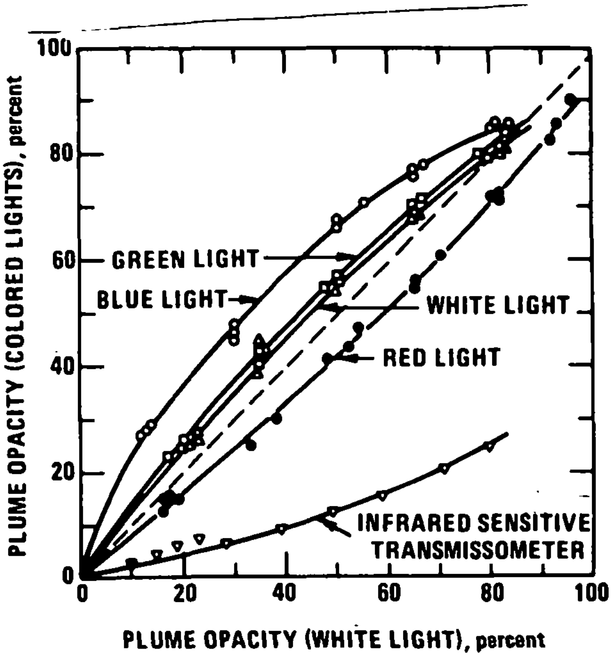

Figure 3. Opacity of an experimental white (oil) plume to light of various colors.

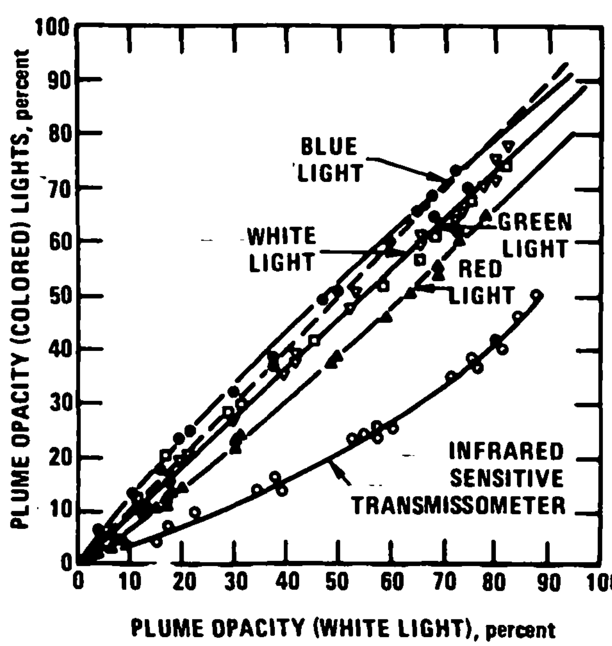

Figure 4. Opacity of an experimental black (carbon) plume to light of various colors.

COLLIMATION CONSIDERATIONS

To measure the amount of light transmitted by an aerosol, the transmissometer must be designed to exclude the light scattered by the aerosol from the measurement. The poorly collimated transmissometer detects an excessive amount of scattered light along with the transmitted light and gives an erroneously high transmittance (low opacity) measurement of the aerosol. Collimation of the in-stack transmissometer is obtained by restricting the light projection and detection angles of the instrument (Figure 5).

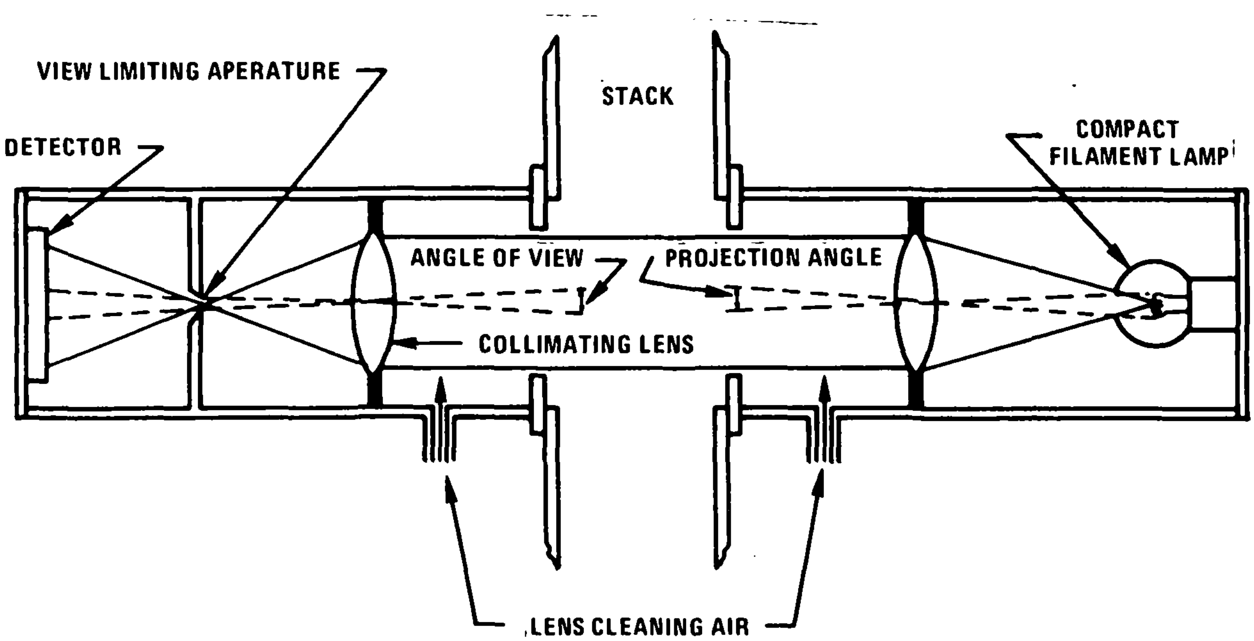

Figure 5. Schematic of transmissometer with collimating optics.

The error in the transmittance measurement due to the use of transmissometers with different light detection angles has been analyzed theoretically by Ensor and Pilat[10] and shown to be a function of detection angle and aerosol particle size. They show that, in general, the error associated with a given detector viewing angle increases with increased particle mean diameter and, at a given particle mean diameter, decreases with increasing particle size geometric standard deviation (increasing polydispersity of the particle size). These results were used to calculate the apparent opacity of a 10-micron aerosol when measured with detection angles of 0.2°, 2°, and 20° (Figure 6), and the apparent opacity of 2-, 5-, 10-, and 20-micron-sized aerosols when measured with a detection angle of 20° (Figure 7). Figure 6 shows that, for a given aerosol size, increased error in the measurement of opacity results with increased detector angles of view; Figure 7 shows that, for a given angle of view, increased error in the measurement of opacity results with increased aerosol size.

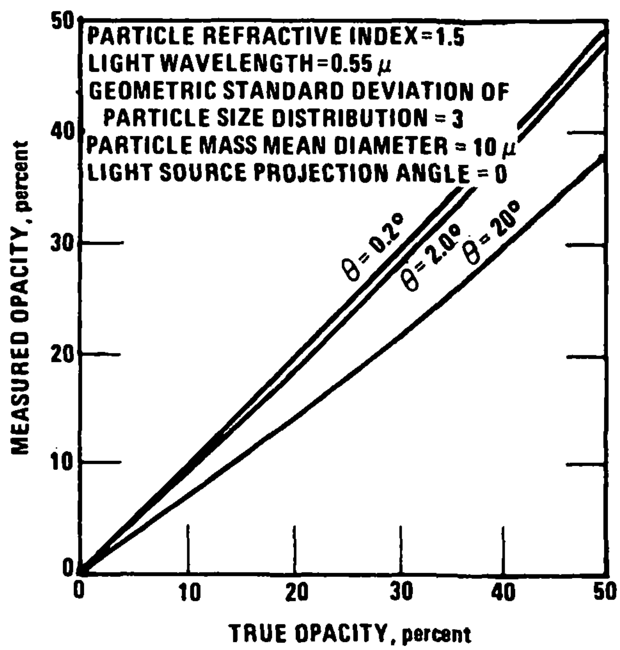

Figure 6. Opacity of an aerosol as measured with transmissometers with different light detection angles as a function of the true opacity of the aerosol.

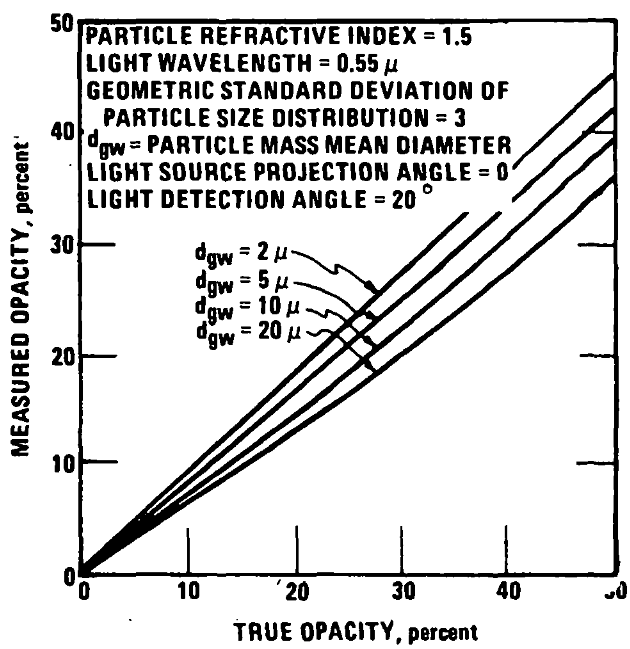

Figure 7. Opacity of aerosols containing particles of different sizes as measured with a transmissometer with a 20 degree light detection angle as a function of the true opacity of the aerosol.

An experimental study of the effect of the collimating angles of the detector and light source of a transmissometer on the measurement of the opacity of emissions from a coal-fired steam generator was conducted by Peterson and Tomaides.[11] They show that the size of the collimating angles of the detector and light source produces similar errors, and both must be restricted to minimize the error in the measured transmittance or opacity. Detailed design and performance specifications for transmissometer opacity measurement systems have been reported.[12]

MEASUREMENT OF MASS CONCENTRATION BY TRANSMISSOMETRY

The value of the transmissometer for monitoring the mass concentration of particulate emissions from pollution sources has not been resolved. Several investigators have reported the observation of good empirical correlations between the mass concentration and light transmittance of specific sources, whereas others have pointed out that the usefulness of such relationships is too dependent on invariable particulate characteristics of the sources. To understand the effect of various aerosol characteristics on the relationship, it is useful to express Bouguer's transmittance law in terms of the mass concentration of the aerosol.

For a polydisperse aerosol, Bouguer's law, shown in equation (7), may be written as:

$$T = \exp \frac{\pi L}{-4} \Sigma\, n_i d_i^2 Q_i \qquad (8)$$

and the mass concentration (C_m) of the aerosol may be written as:

$$C_m = \frac{\pi \rho}{6} n_i d_i^{\,3} \qquad (9)$$

where: T = transmittance of the aerosol

L = light path length through the aerosol

d_i = diameter of the particles within the size increment i

n_i = number of particles of size d_i

Q_i = particle extinction coefficient of the particles of size d_i

ρ = density of the particles in the aerosol

Dividing equations (8) and (9) and solving for C_m gives:

$$C_m = \frac{2 \Sigma n_i d_i^{\,3}}{3 \Sigma n_i d_i^{\,2} Q_i} \cdot \frac{\rho}{L} \ln \frac{1}{T} \qquad (10)$$

By defining a mean extinction coefficient, $\overline{Q} = \Sigma n_i d_i^2 Q_i / \Sigma n_i d_i^2$, and a mean particle diameter, $\overline{d} = \Sigma n_i d_i^3 / \Sigma n_i d_i^2$, for the aerosol, equation (10) may be written:

$$C_m = \frac{2\overline{d}\rho}{3\overline{Q}L} \ln \frac{1}{T} \qquad (11)$$

$\overline{d}$ is often referred to as the volume-to-surface mean diameter of the aerosol (sometimes called Sauter diameter).

Pilot and Ensor[13] express equation (10) as:

$$C_m = \frac{K\rho}{L} \ln \frac{1}{T} \qquad (12)$$

and define K as the specific particulate volume (cm^3 particles/m^3 air) divided by the aerosol attenuation coefficient (m^{-1}). They show theoretical values of K as a function of particle size for several aerosols with different characteristics. These values of K were used in equation (12) to calculate the effect of particle size and composition on the relationship between the opacity and mass concentration of aerosols (Figure 8).

Figure 8 shows that particle size is the primary characteristic of the aerosol affecting the opacity-mass concentration relationship when the particle size of the aerosol is larger than 3 or 4 microns. However, at particle sizes below 3 or 4 microns, the refractive index of the particulates also has a pronounced effect on the relationship. This results in the white particles in Figure 8 showing a maximum opacity per unit mass concentration at about 0.6 micron particle size, whereas the black particles show the maximum at about 0.15 micron.

Pilot and Ensor[13] also show that the width of the size distribution will usually affect the opacity-mass concentration relation. In addition, irregular transparent particles smaller than 2 microns generally attenuate

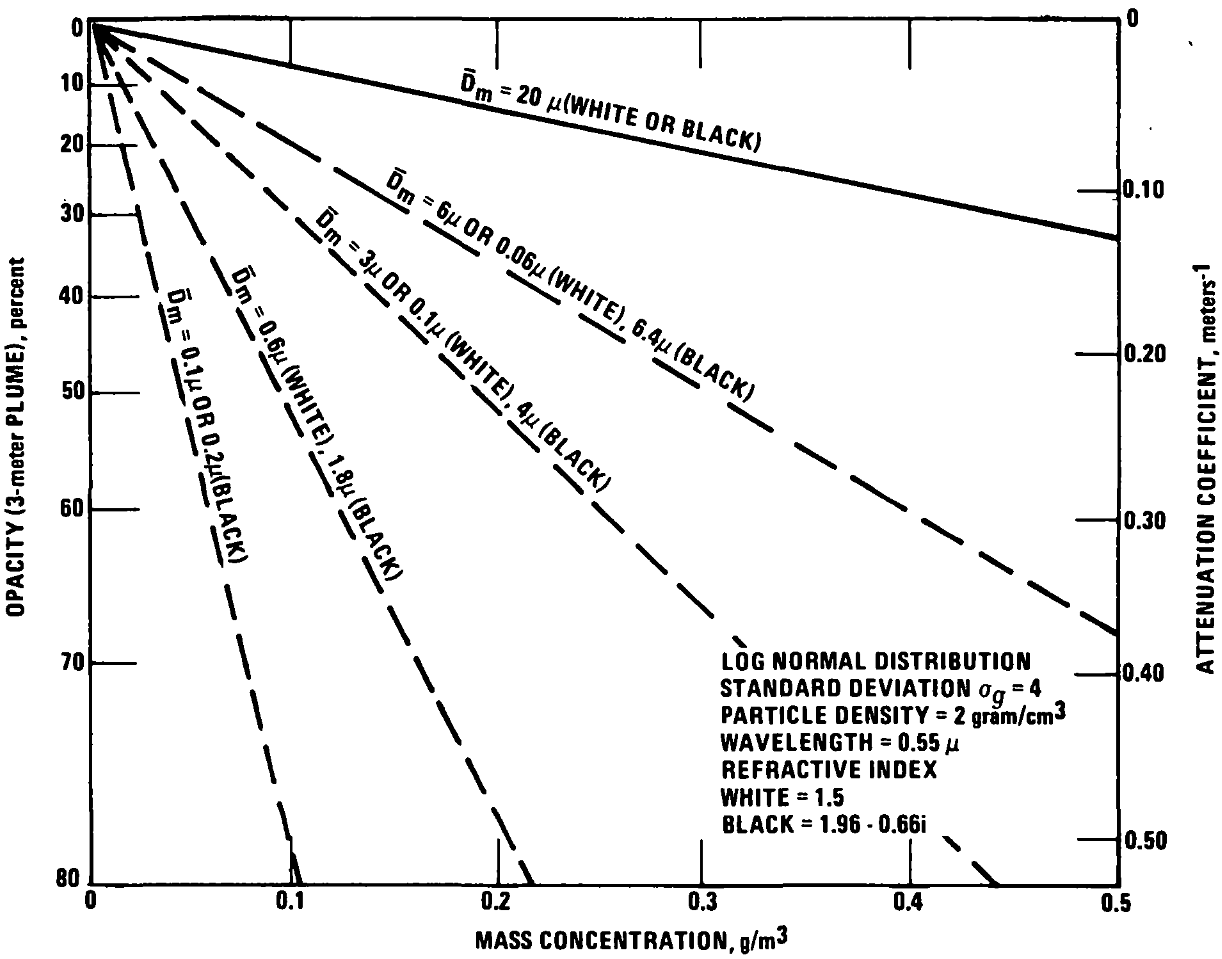

Figure 8. Opacity of smoke plumes containing particles of different sizes and refractive indexes as a function of their mass concentration.

less light than spherical particles of the same projected area.[14] consequently, the observed mass concentration indicated in Figure 8 for small transparent particles will be two to three times too low for irregular particles, but not appreciably different for absorbing particles.

The effect of particle size on the opacity-mass concentration relationship has been studied experimentally in the laboratory by Uthe and Lapple.[15] They collected fly ash from a bituminous coal-fired power plant and classified it into a series of size fractions. The various size fractions were then pneumatically injected into an aerosol chamber at controlled concentrations where the opacity was measured with a transmissometer.

Figure 9 is the opacity-mass concentration relationship observed by Uthe and Lapple for aerosols with four different mean sizes. Each point shown in the figure generally represents an average of two to six runs. The mass concentrations were calculated from aerosol generation rates.

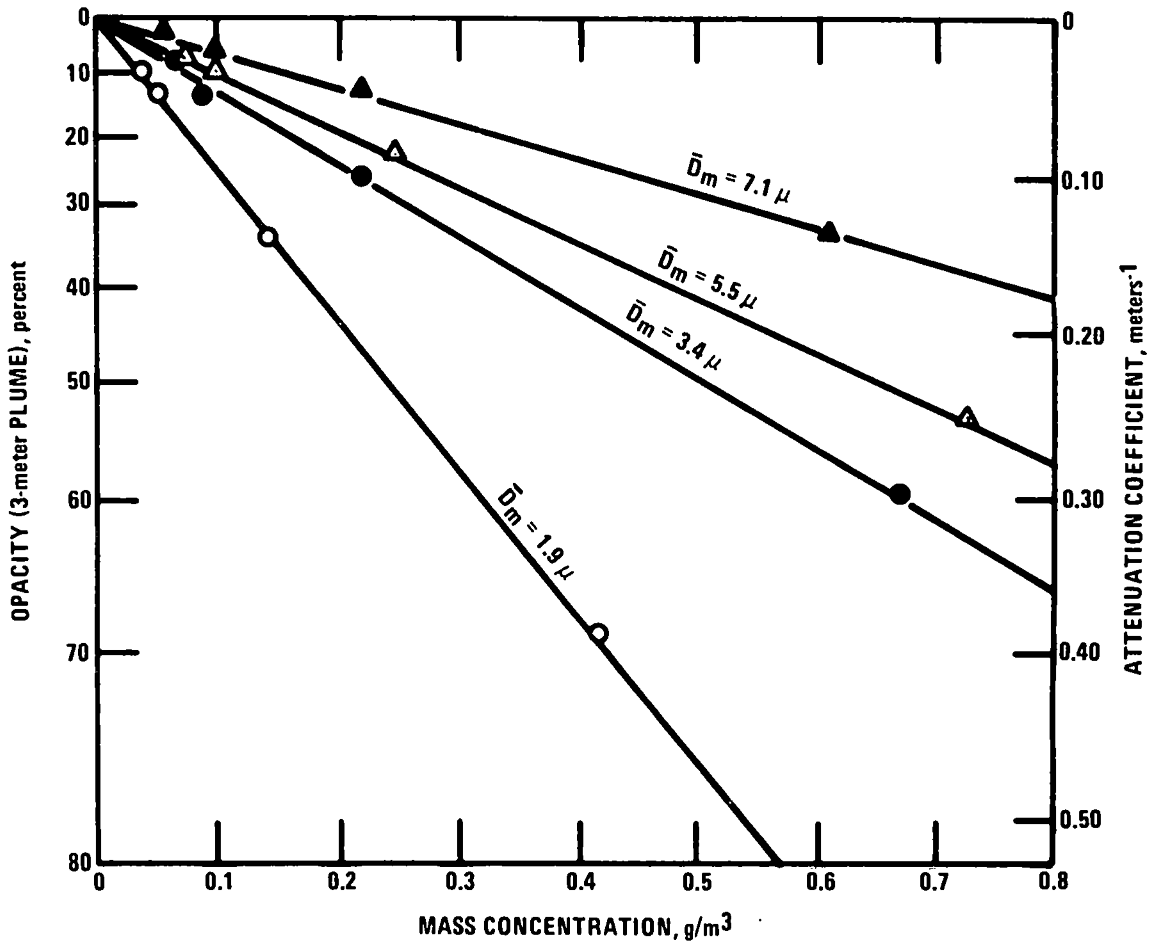

Figure 9. Opacity - mass concentration relationship of laboratory generated coal-fired power plant emissions with different particle sizes.

These results were as expected and show the particle size dependence indicated from theoretical considerations. Comparison of Figure 9 with the theoretical calculations of Figure 8 for spherical particles with a refractive index of 1.5 and a specific gravity of 2 indicates that the coal-fired power plant fly ash attenuated around 50 percent as much light for similar particle sizes and mass concentrations. Considering the differences in aerosol characteristics, better agreement was not to be expected. The ash used for the aerosol generation was reported to have size distributions of σ_g=1.5 and contained a good number of particulates with absorption characteristics; additionally, the specific gravity of 2 used for the theoretical calculations may be somewhat low for fly ash.

It is clear that for a useful relationship to exist between the opacity and mass concentration of the particulate emissions from a pollution source, the characteristics of the particulates (size, shape, and composition) must be sufficiently constant, and for a conventional transmissometer to be useful as a monitor of the mass concentration, the particulate characteristics must remain constant over a useful period of time. Some experimental data are available that show good empirical opacity-mass concentration calibrations can be obtained for transmissometers on some sources (Figures 10, 11, and 12). Although these data indicate the particle characteristics were sufficiently constant during the time of calibration, no data on the long-term usefulness of the calibrations seem to be available. Considering the simplicity of the transmissometer, the collection of such data seems to be highly desirable in order to evaluate its potential as a mass monitor for specific sources. It is likely that particulate emission control equipment will also control the characteristic of the aerosol that most affects the relationship (particle size) and improve the potential of the transmissometer as a mass monitor.

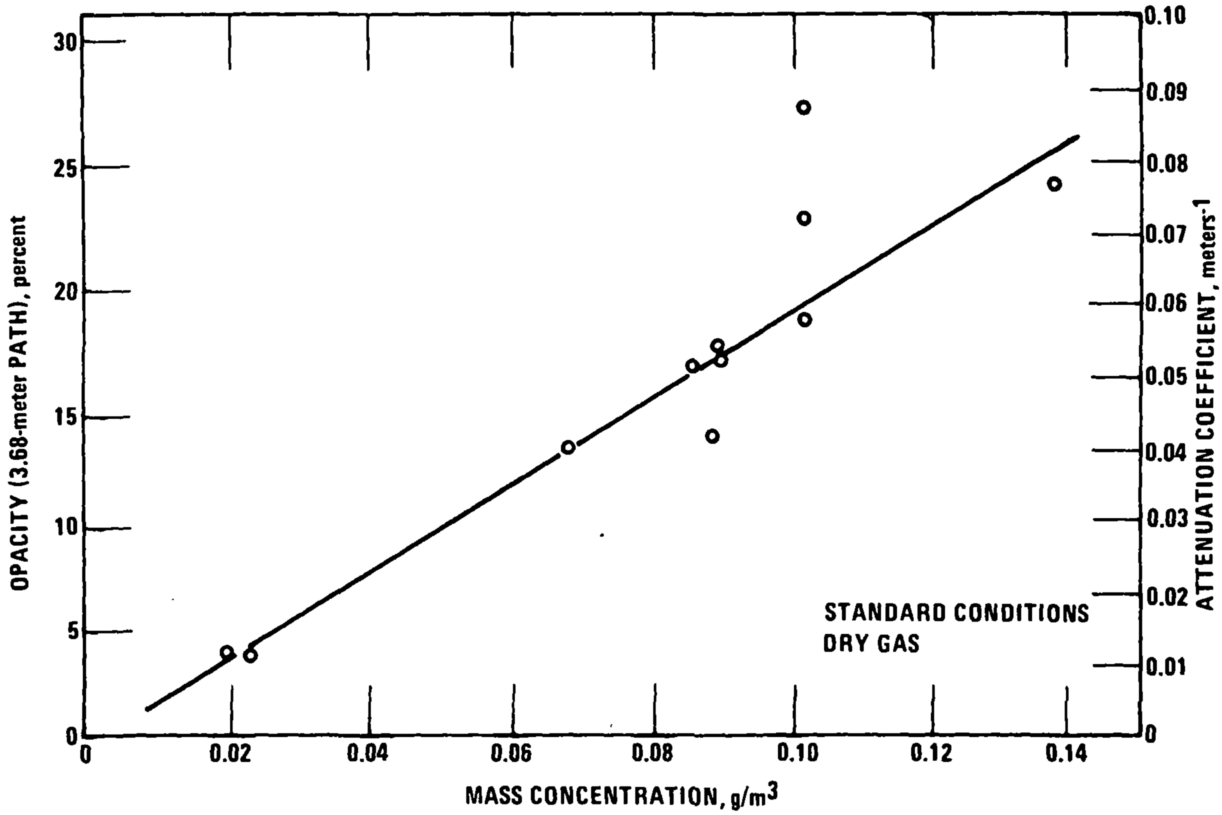

Figure 10. Opacity-mass concentration relationship for particulate emissions from a kraft recovery furnace.[16]

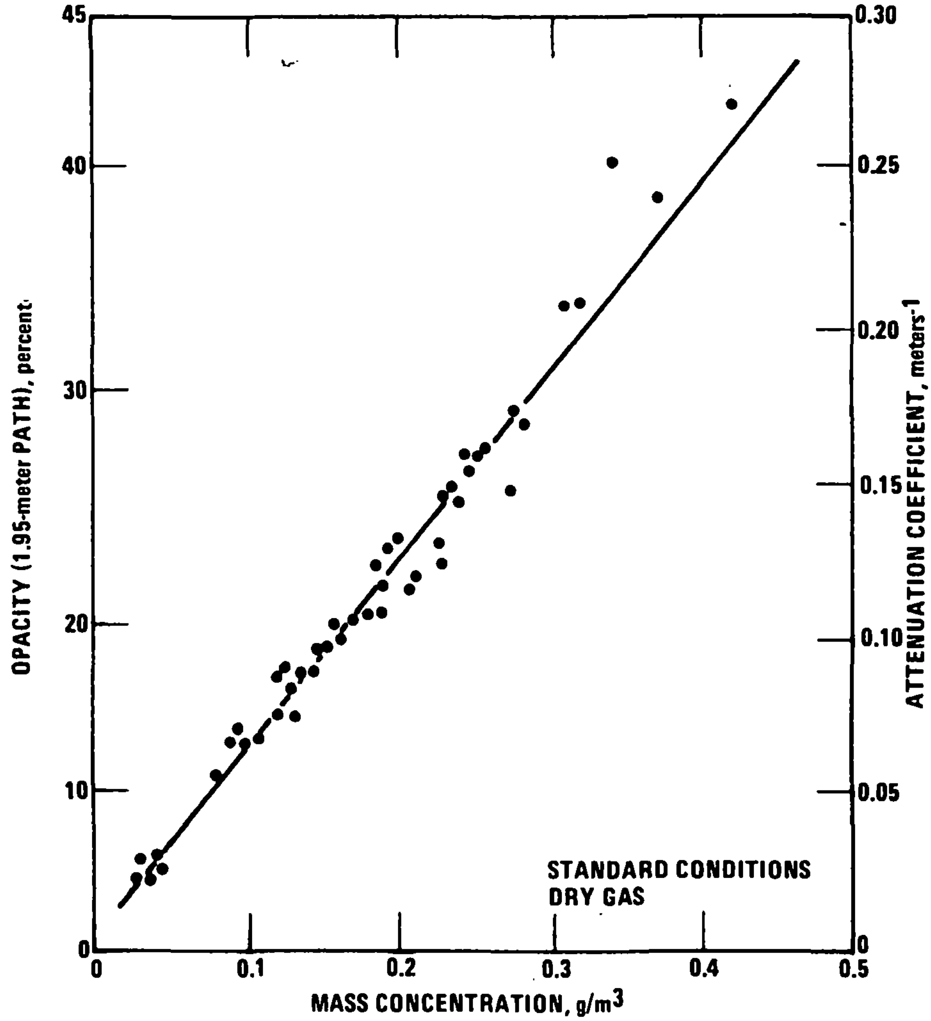

Figure 11. Opacity-mass concentration relationship for particulate emissions from a cement plant kiln.[17]

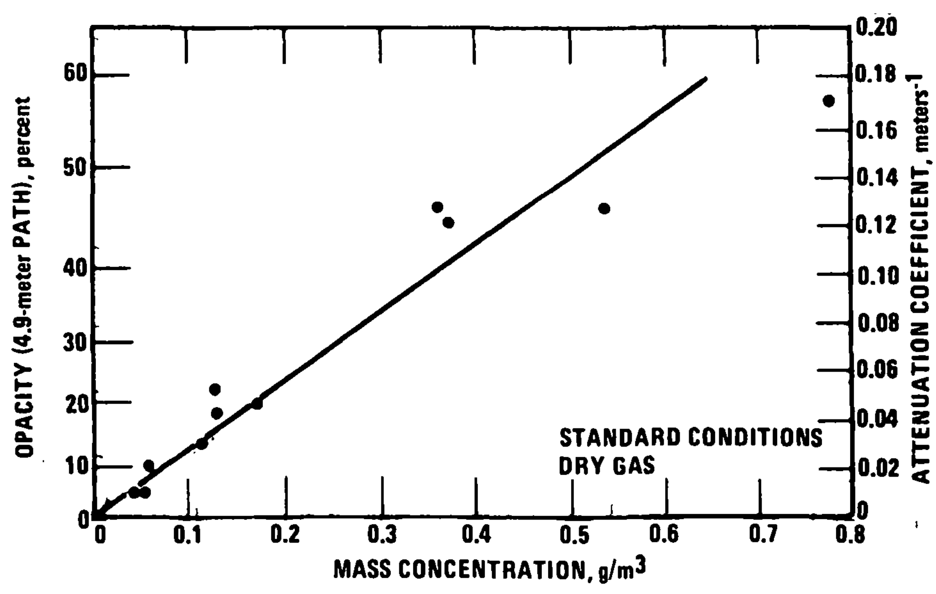

Figure 12. Opacity-mass concentration relationship for particulate emissions from a bituminous coal-fired boiler.[18]

REMOTE MEASUREMENT OF PLUME OPACITY

There are three instrumental methods that have been described for remote measurement of plume opacity. Two of the methods use photometry of the sun or of contrasting targets through the plumes for the measurements.[6] These methods are considered methods of opportunity since they are applicable only under certain conditions. The third method is more general and uses a laser radar (lidar) technique. With this method, the plume opacity is determined by shooting a pulse of light through the plume and measuring the ratio of the light backscattered from the pulse by the atmosphere before and after the plume.

SUN PHOTOMETRY

Measurement of plume opacity by sun photometry is restricted to times when the sun is unobstructed by clouds and may be viewed through a discrete cross section of the plume at the stack exit. Conditions for the measurement are usually best on clear days when the sun is relatively low in the sky, the sun can be viewed through the plume at the stack exit, and the direction of flow of the dispersing plume in the atmosphere is away from the sun. A sun photometer specifically designed for plume opacity measurements is available from the Shell Development Company. The measurement can also be made with a standard sun photometer, e.g., the Volz sun photometer.[19] However, it may be necessary to modify the spectral response of the standard sun photometer to obtain good sensitivity to visible light. A Volz sun photometer modified for plume opacity measurements has been described.[6]

CONTRASTING TARGET TELEPHOTOMETRY

Measurement of plume opacity by contrasting target telephotometry is restricted to times when contrasting targets can be viewed through the plume at the stack exit and to times when the ambient illumination of the plume is stable during the measurement. The contrasting targets may be distant hills, tall buildings, or towers and the sky adjacent to them. For the plume illumination to be sufficiently stable during the measurement normally requires that the sky be clear or uniformly overcast. The plume opacity is determined by using a narrow-angle-view (less than 1/2 degree) telephotometer to measure the ratio of the luminance difference between targets when viewed through and beside the plume. Narrow-angle telephotometers suitable for the measurement are commercially available.

It is also feasible to determine the opacity of a plume by photographing the contrasting targets through them, e.g., from a helicopter. The ratio of the luminance differences between the targets is then measured from the film images with a laboratory densitometer. Plume opacity measurements by telephotometry and photography of contrasting targets have been described in detail.[6,20]

LIDAR

The technique of determining plume opacity by lidar was first proposed to the Edison Electric Institute and the U. S. Public Health Service by the late M.G.H. Ligda of Stanford Research Institute (SRI) during the middle 1960's. EEI and PHS pursued the development of the technique as part of a cooperative research study in the measurement of the opacity of plumes from stacks of steam electric power plants. They contracted SRI to conduct a laboratory and field study of the method using existing SRI lidar equipment designed for atmospheric studies. The results indicated the method was feasible and defined many of the design parameters needed for a lidar system for plume opacity measurements.[21] The General Electric Company was then contracted to develop a mobile lidar system specifically designed for remote measurement of plume opacity.[20,22] The performance of the lidar is presently being evaluated by the Environmental Protection Agency in conjunction with studies to develop and evaluate opacity measurement methods for various sources.

Application of the pulsed lidar system described above is primarily for opacity research studies and for further development of the method. In its present form the instrument would have little application for surveillance work by a control agency because of cost, operating power, and complexity. For the development of a smaller, low-powered, and less expensive instrument for remote measurement of plume opacity, a lidar technique using a frequency modulated, continuous wave (CW) laser is being investigated. The initial investigation of the CW lidar indicates that the method is feasible, and further development is planned.[23]

SUMMARY AND CONCLUSIONS

Visible emission standards have been used for regulating the particulate emissions of stationary sources for more than 75 years. During most of this period, the regulations applied only to emissions that appeared gray or black, and the primary method of measuring the blackness of the emissions was the Ringelmann Chart comparators. However, during the past 20 years, visible emissions regulations have been extended to any emission affecting visibility regardless of color. This general application of the visible emissions regulations has been accomplished by defining the emission standards in terms of the opacity of the plumes emitted by the sources. Plume opacity is an intrinsic optical property of the emissions that is measured instrumentally by light transmission methods. To permit the older Ringelmann number standards to also be measured by light transmission methods, a Ringelmann number 1, 2, 3, 4,-opacity 20, 40, 60, 80 equivalency is normally accepted.

Opacity of plumes is also measured by trained smoke observers who attend a smoke-reading course where they are taught to assign opacity values to plumes based on their appearance. The inspectors become certified smoke readers when they learn to assign opacity values to a range of black and white training plumes with a specified accuracy relative to a calibrated in-stack transmission meter. It should be noted that the trained observer is not actually evaluating the visibility of plumes but is evaluating the opacity of plumes by observing their visibility. The actual visibility of plumes is generally too dependent upon ambient illumination and background viewing conditions to be well regulated by opacity standards. The plume visual effect best regulated by the opacity standards is the obscuration of visibility.

The transmissometer used to measure the opacity of particulates must have two essential design features. The spectral response of the instrument should be limited to visible light and, moreover, should be mostly sensitive to green light. The instrument should also be designed with light collimating optics to exclude light scattered by the particulates from the measurement. A properly designed and installed in-stack transmissometer should be capable of monitoring the opacity of the plume emitted from the stack provided water in condensed form is not present and the characteristics of the aerosols in the effluent are maintained between the in-stack measurement point and the plume.

In considering the relationship between opacity and mass concentration of a particulate emission, it should be recognized that the opacity of the emission is a stack-size dependent measurement, whereas its mass concentration is not. In addition, the relationship between the opacity or light transmittance and mass concentration of particulate emissions is complicated due to its dependence upon the characteristics of the particulates, e.g., size, shape, composition, etc. Nevertheless, as the opacity of the particulate emissions approaches zero, their mass concentrations also approach zero; consequently, limiting the opacity of the emissions has the effect of limiting their mass concentration.

Although only a limited opacity-mass concentration relationship can be expected between sources of different sizes and particulate characteristics, or for sources with fluctuating particulate characteristics, a good opacity-mass concentration relationship can be expected for sources with particulate characteristics that are stable. Development of such relationships is usually done by empirical calibration of a transmissometer on the source with an accepted manual gravimetric sampling method. Good empirical opacity-mass concentration calibrations have been obtained for transmissometers on a number of stationary sources; however, the precision of the calibrations for long-term mass monitoring of the sources by transmissometry has not been determined nor has the precision of the calibration within a source category been determined. Clearly, the usefulness of the calibration depends on the stability of the particulate characteristics of the source and the similarity of the particulate characteristics between sources within a source category.

Remote instrumental measurement of plume opacity is complicated by the ambient light scattered by the plume in the direction of the viewer. This scattered light generally prevents opacity measurement by simple plume-to-background contrast measurements by direct telephotometry or by photometry of plume photographs although such methods may at times give reasonable estimates of plume opacity if the plume consists of light-absorbing particles such that the amount of light scattered by the plume toward the viewer is small when compared to the brightness of the plume background.

Two relatively simple methods exist for remote instrumental measurement of opacity, but both are methods of opportunity. They are through-the-plume photometry of the sun and telephotometry of contrasting targets. The sun photometer method is most applicable in those areas with a large number of clear days. It is also limited to those sources whose plumes can be viewed with the sun behind them. The telephotometry-of-contrasting-target method is limited to those sources whose plumes can be viewed with contrasting scenes behind them, e.g., a hill or building and the adjacent sky. The method is difficult to apply if the environmental or background lighting conditions of the plumes or the opacity of the plumes is fluctuating.

A more general laser radar (lidar) method for remote measurement of plume opacity is being developed, but at present the instrumentation is complicated and expensive. Development of simpler instrumentation for the method is being pursued.

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16. ABSTRACT

This report is a review of particulate opacity measurement techniques. The relationship between the opacity of plumes and their visual effects, and the relationship between the opacity of plumes and their particulate mass concentration are discussed. The report also discusses optical design characteristics of transmissometers that are necessary for measurement of the opacity of particulate emissions. Various methods for remote measurement of plume opacity are reviewed including the visible emission observer.

17. KEY WORDS AND DOCUMENT ANALYSIS

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