FEATURE

# Factors influencing plume opacity

Previously unrecognized uncontrollable variables such as the angle of the sun, the time of day and the geographic location of the power plant greatly influence smoke plume opacity


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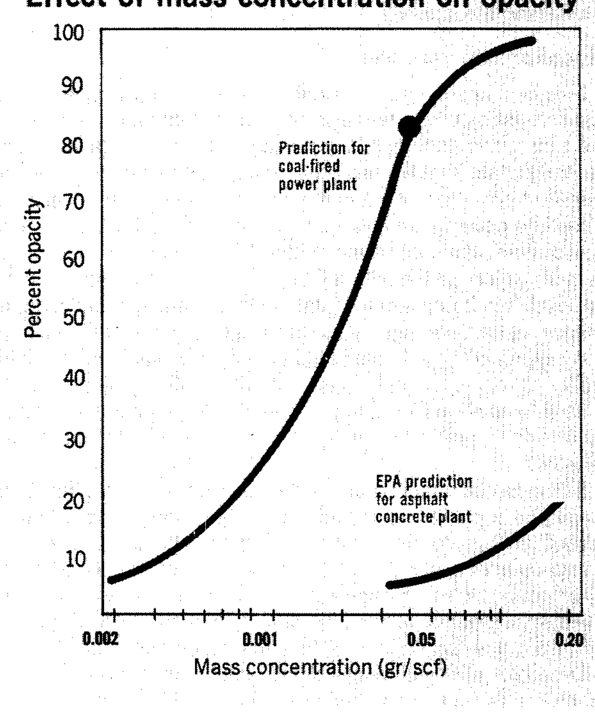
Numerous experiments on the removal of particulate matter with electrostatic precipitators and wet scrubbers have been conducted at the 1580 MW coal-fired Mohave Generating Station at South Point, Nev. It was established that opacity is not a function of particulate grain loading alone, but is influenced by a number of other independent variables, some of which are beyond the control of the operator of the stationary source. Thus, mass emissions cannot be determined by opacity measurements alone.

The experimental data, including plume opacity observations by trained smoke observers, were obtained in conjunction with 11-ft and 32.5-ft diameter stacks and fly ash particles of similar shape having 0.95 and 2.5 $\mu$ mean diameters. Mass emissions of particulate matter ranged from 0.004–0.40 gr/scf. The data indicate that it is possible for opacity to vary from 14–87% with a 32.5-ft diameter stack at a constant mean particle diameter of 2.5 $\mu$ and a constant mass emission rate of 0.05 gr/scf.

This paper presents the quantitative effect of a number of independent variables on opacity. It also shows that the use of opacity measurements by regulatory agencies to determine the degree of particulate emissions is contrary to the laws of nature, regardless of the laws of man.

FIGURE 1

**Effect of mass concentration on opacity**




### Variables affecting opacity

There are a number of variables that affect opacity other than the mass emissions of particulate matter. These variables can be divided into two categories: Those variables that are a function of the control equipment and can be "controlled" by the operator or the designer; and those variables beyond the control of the operator (see box).

Control equipment could be installed to influence plume opacity as a result of controllable variables, but opacity standards would still reflect the influence of five other "controllable" variables in addition to mass emissions.

Light-scattering theory (see Reference 1 Additional reading) predicts opacity values within a reasonable degree of accuracy over a range of mass emissions (from 0.004–0.4 gr/scf) and large variations in mean particle sizes compared with the observations of trained observers.

In this paper the theory is used to quantitatively determine the effects of changes in a single parameter on opacity, while all other factors are held constant. Several arbitrarily selected conditions were used as a basis for conducting this parametric study. In the figures that follow, the opacity that corresponds to this nominal set of conditions is indicated as a black dot on a curve generated by variations in a single parameter. By using the Halow-Zeek equation and making certain assumptions, the opacity corresponding to the arbitrarily selected conditions (see Table 2 for "black dot" values) is 85%.

### Controllable variables

Mass concentration of particulate emissions was the first parameter considered. A Functional Opacity-Mass Relationship for an Asphalt Concrete Plant was recently reported by the EPA in the *Federal Register*. These EPA data have been replotted in Figure 1, which also shows the predicted opacity-mass relationship beginning with the "black dot" conditions typical at the Mohave Generating Station. Note that for the coal-fired power plant, as the grain loading approaches a large value, the opacity

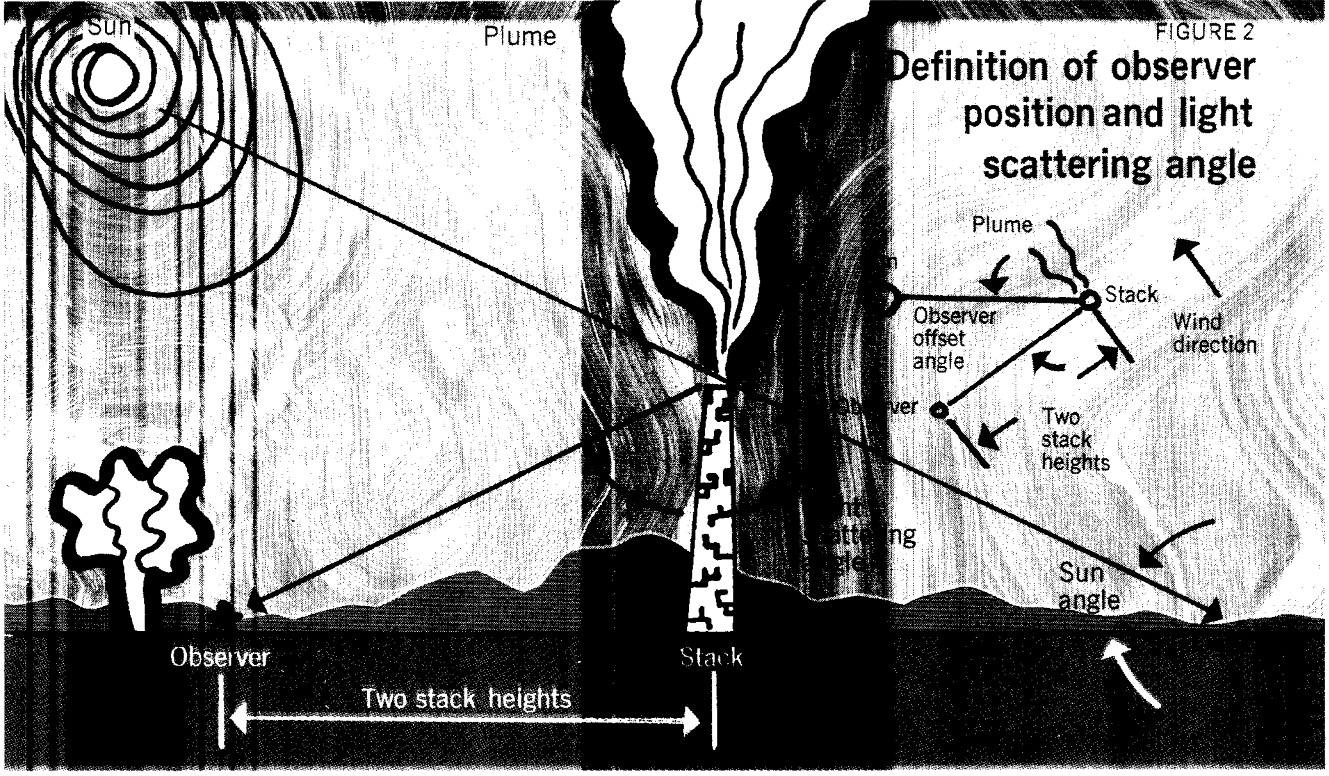



FIGURE 2
**Definition of observer position and light scattering angle**

asymptotically approaches 100%. Conversely, as the grain loading approaches zero, the opacity asymptotically approaches zero. In coal-fired power plants, opacity is thus not a simple linear function of mass emissions as EPA published for asphalt-concrete plants.

Figure 1 indicates that at a grain loading of 0.05 gr/scf, the EPA data suggest an opacity of 6%, while at the same grain loading the opacity at the coal-fired power plant would be 85%, as indicated by the black dot. This large difference is accounted for by the influence of variables other than the concentration of mass emissions.

One important independent variable is the diameter of the stack, which fixes the path length that light traverses during penetration of a smoke plume. The larger the diameter, the greater the path length over which light is scattered by smoke particles, and the greater the apparent plume opacity.

The size of the particulate matter in the smoke plume is another variable that has a pronounced effect on opacity. If 50% of the particles by weight are larger than a given size (and the remaining 50% by weight smaller than a given size), then the characteristic size is called the mean particle size. At a given grain loading, the smaller the mean particle size, the greater the number of particles in a given volume of gas and the greater the degree of light scattering and resultant opacity.

Deviation from the mean size is another important variable. Particle size distribution can be measured with a sampling device called a cascade impactor that separates the particles into different sizes. By weighing the amount of particles collected for each size range, the weight fraction of particles can be determined as a function of particle size. Most particle size distributions for coal-fired power plants can be plotted as a straight line on log probability paper, corresponding to a gaussian distribution of the ratio of particle diameter to the mean particle diameter. Thus, the geometric standard deviation from the mean particle size can be defined as the ratio of the particle size at 84 wt % to the mean size, or also the ratio of the mean size to the particle size at 16 wt %. If all the particles are the same size, the geometric standard deviation is one, but increases as more particles are found in size categories different from the mean size.

For mean particle diameters of 2.5 $\mu$ and larger, the smoke plume opacity is minimum at a geometric standard deviation of one, and increases as the deviation increases. This is because of a larger percentage of small particles fall between 0.2–2.0 $\mu$ (the most effective size range for light scattering). For a mean particle diameter of about one micron, the converse is true. The opacity is a maximum at a geometric standard deviation of one since all the particles are within the optimum light-scattering size range. As the deviation increases, an increasing fraction of particles fall outside the optimum light-scattering size range, and the opacity decreases. Therefore, for the small particles (0.95 $\mu$) opacity *decreases* as the deviation from the mean particle size is *increased,* while for large particles (2.6 $\mu$) the converse is true.

Stack gas temperature is also an important factor. One convenient measure for mass emissions of particulate matter, which is reported in the literature and frequently used for comparisons between different coal-fired power plants, is grain loading, or grains of particulate matter per standard cubic foot. If such a measure is used, then variations in the temperature of the stack gas will influence the relationship between standard cubic feet and actual cubic feet of stack gas. The higher the stack gas temperature, the higher the ratio of actual to standard cubic feet, and the lower the particle concentration per cubic foot, thus decreasing the opacity.

**Uncontrollable variables**

One of the important variables that is determined by the characteristics of the fuel and not controllable by a power plant operator is the density of the particles emitted. The less dense the particulate matter, the greater the number of particles at a specified grain loading and the greater the opacity. Variations in particle density between 2.0–4.0 g/cm$^3$ can occur for coal-fired power plants because of the different chemical nature of the ash, which varies with the geologic location where the coal is mined. It is important to point out that standard techniques of measuring particle density by displacement may not be valid for many types of fly ash particles because of surface inclusions and/or formation of hollow ash spheroids during the combustion of coal. Variations in opacity from 60–90%, owing to normal variations in particle density alone, would not be considered unusual.

Still another uncontrollable particle property that influences opacity at a given mass emission rate is the particle index of refraction. Typical power plant fly ash particles have an index of refraction of about 1.5. Mohave fly ash particles have an index of refraction of 1.6 (measured by microscopic examination with selected immersion oils). A range in refractive index from 1.4–1.6 corresponds to a difference in opacity from 77–95%.

The color of the plume and the color contrast ratio between the plume and the sky is another uncontrollable variable related

Mass emission of particulate matter
Mean particle size
Deviation from the mean size
Stack diameter
Stack gas temperature
Stack velocity and other factors influencing plume dispersion

*(Related to type of fuel burned or process involved)*
Particle density
Particle index of refraction
Water vapor
"Color" of the plume
*(Related to human observer, ambient weather conditions and movement of earth about the sun)*
Wind speed
Wind direction
Wind turbulence
Ambient air temperature and humidity
"Color" of the sky
Distance of observer from stack
Non-level terrain
Observer offset angle
Time of day
Day of year
Longitude of stack
Latitude of stack
"EPA allowable" human error
Sun angle

TABLE 1
**Effects of geographic location and calendar date on opacity**

| | Kauna Point, Hawaii | Key West, Florida | Grantley Harbor, Alaska |
|---|---|---|---|
| **Latitude** | 19° 02′N | 24° 33′N | 65° 16′N |
| **Angle of Sun at time of maximum opacity** | | | |
| June 21 | 85.5° | 89.0° | 48.0° |
| Dec. 21 | 47.5° | 42.0° | 1.0° |
| **Percent opacity under "black dot" conditions at maximum opacity** | | | |
| June 21 | 86.4% | 86.8% | 68.5% |
| Dec. 21 | 67.5% | 64.5% | 14.5% |

Note: The opacity at sunrise or sunset is 14.0% at all three locations.

to the type of fuel burned. Even if all factors such as mass emissions and particle size are the same, the opacity of a "black" plume against an overcast background will be different from the opacity of a "white" plume against an overcast background. If the overcast is white, the "black" plume will have a higher apparent opacity than the "white" plume. If the overcast is black or dark grey, the opposite situation will prevail.

Plume color is caused by the nature of the particulate matter in the plume. Silica or glass-like particles produce "white" plumes while carbon or light-absorbing particles produce "black" plumes. Because of combustion temperatures achieved in coal-fired power plant boilers, the particles in the plume are generally glass-like in nature, and the plume is generally "white" in color.

Data have been obtained for a white plume viewed against a blue sky background. If the sky were a white overcast color, a white plume would tend to disappear and could only be seen by a brightness difference between the plume and the overcast. There are no data upon which to base a prediction of the opacity of a white plume on an overcast day. Similarly, a white plume on a clear day viewed against a dark background (such as a forest-covered mountain) will produce a different opacity than the same white plume viewed against a blue sky. The color of the background thus has a significant effect on the opacity of a white plume.

Seasonal variations in ambient airborne particulate matter (caused by wind or other factors) tend to change the color of the sky. Daily variations in sky color resulting from sunrise/sunset effects, photochemical smog or changes in weather conditions all influence the opacity of a white plume without any change in the mass emissions of the plume itself. Such factors are difficult to quantify since no data for white plumes are available for correlating Ringelmann number to color contrast ratio as a function of background color.

Another uncontrollable factor related to the type of fuel burned is the water vapor content of the flue gas. While it is generally recognized that water is one of the products of combustion emitted by oil-fired power plants, it is not always recognized that large quantities of water also result from the combustion of coal. Specifically, the combustion of a coal containing 10% ash would result in over five times (by weight) as much water as ash being formed. If a wet scrubber were used to remove the ash, additional water would be introduced in the gas so that the gas would be saturated with water vapor at 120–130 °F leaving the scrubber. While not adding water, an electrostatic precipitator will not remove any water vapor from the gas.

Ambient temperature and humidity conditions can result in the condensation of some of this water vapor and there are no presently available scientific methods with which an observer can distinguish between the degree of opacity caused by the presence of the condensed water vapor and the opacity caused by the presence of fly ash. This factor is interrelated with the variables of wind direction, velocity, and turbulence and no attempt has been made to quantify it in this report.

Unlike previously discussed variables that were quantitatively related to opacity, variables such as stack and wind velocity are more difficult to quantify. Although it is not difficult to measure either stack or wind velocity or wind direction, plume opacity is measured by a human observer, and the appearance of the plume in the atmosphere is subject to atmospheric conditions such as turbulence and velocity. Haythorne and Rankin, describing the effects of these variables, said: "The velocity of the exhaust gas and the external wind conditions also will have obvious effects. In a still atmosphere the particulates may build up increasing opacity. In a high wind particles may be dispersed so that there may be no opacity at all even though the same volume of particulates is emitted." It is also obvious that the wind direction will have an influence on the opacity with observations parallel with the flow of the plume giving higher values than observations made perpendicular to the flow. This "path length effect" is similar to the effect of stack diameter presented previously.

Because of the many combinations of stack velocity, wind velocity, wind direction, and atmospheric turbulence that exist, no attempt has been made to quantify these interrelated variables.

### The position of the sun

An important category of uncontrollable factors that influences plume opacity is the position of the sun and the observer with respect to the plume.

The degree of plume opacity seen by an observer depends critically on the scattering angle through which incident light is reflected and refracted from the particles in the smoke plume. This "scattering angle" and other geometric relationships are presented in Figure 2. The maximum opacity would be seen when looking at the sun through the plume and the minimum opacity would be seen when the plume is observed with the sun directly behind the observer. The closer to the stack that the observer stands, the more he must tilt his head upward toward the sky and the greater the opacity (because of the decreased light-scattering angle). A remote observation, on the other hand, gives a low reading and is another reason why an opacity measurement is not a reliable indicator of mass emissions.

Another variable affecting plume opacity is non-level terrain. Occasionally, the sun is in such a position relative to the stack that power plant equipment obscures a view of the plume at a distance of two stack heights from the base of the stack. Alternatively, coal-fired power plants are sometimes located near the edge of a cliff or near elevated terrain. In these cases, an observer must usually make an observation at a location elevated or depressed with respect to the base of the stack. This influence on the light-scattering angle has been calculated for an observer at two stack heights from the base of the stack.

The variation in opacity with changes in the elevation of the observer are more pronounced at low sun angles in the winter than at high sun angles in the summer. Also, the opacity increases as the observer position is depressed with respect to the base of the stack. Depending on sun angle, aircraft observations would normally indicate a lower opacity than would be seen on the ground. The effects of distance from the stack would be a severe problem, however, in making airborne observations.

If opacity changes when an observer moves closer to the stack at a fixed sun angle, then the opacity obviously must also change when the sun angle changes as the sun moves across the sky relative to a fixed observer position. If all opacity readings are made with the sun directly behind an observer who is two stack heights from the stack, then on June 21st at latitude 35°, the sun angle varies between 0° at sunrise or sunset and 79° at the time of maximum opacity. The opacity correspondingly varies between 18% at sunrise or sunset and 85% at the maximum sun angle when all other variables are held constant.

This sun angle effect is illustrated in greater detail in Figure 3, where the variation in opacity, as seen by a perfect observer, is plotted as a function of the time of day. Figure 3 is computed from data presented in the Nautical Almanac and Sight Reduction Tables for Air Navigation to obtain the angle of the sun as a function of the time of day. Knowledge of the latitude, longitude, and time zone in which the power plant is located was also required to obtain the sun angle data. Figure 3 is plotted for the location of the Mohave Generating Station at South Point, Nev.

Since a perfect observer always has the sun directly behind him, he would thus begin the day east of the stack and traverse a circular path at two stack heights from the stack before ending his day west of the stack. Note that this assumes no obstructions within the circular path around the stack, which probably never occurs at an actual power plant.

If the perfect observer returned to the Mohave site every day of the year, and only made an observation at the time of maximum opacity (the highest sun angle), and if all other variables were held constant for the entire year, the records of the perfect observer would be such that the opacity would vary between 54% on December 21st and 85% on June 21st. Naturally, the daily variations in opacity between sunrise and sunset would occur throughout the year, with the opacity at sunrise/sunset being 14%. The wintertime daily variation in opacity would be less than the summertime daily variation.

Obstructions between the observer and the stack (for example, the power plant boilers) might require that observations be made when the sun is not directly behind the observer (see Figure 2). By using solid geometry to calculate the scattering angle when the sun angle and observer offset angles are known, the effects of making an observation when the sun is not directly behind the observer can be calculated.

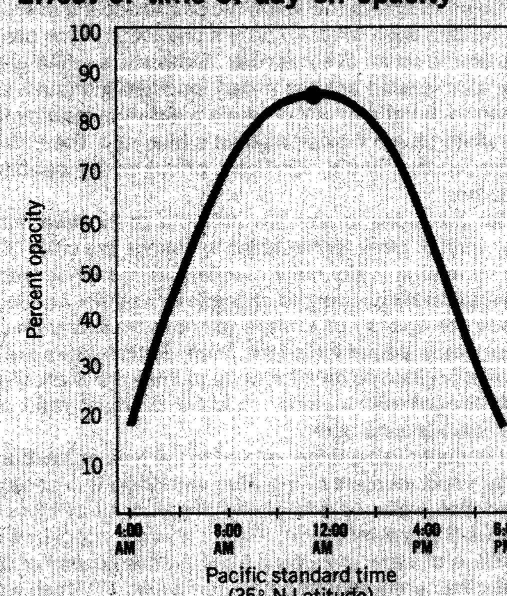
The lower the sun angle, the more pronounced the effects of observer offset angle. If an observer looks at the smoke plume when he is in the wrong position with respect to the stack and the sun, the impression received would always indicate an opacity that is greater than the correct value. This is especially pronounced when the sun angle is low and is more likely to occur in the winter than in the summer.

It was previously indicated that observations should be made with the wind at right angles to the direction of observation, since the EPA has established that the observation point should be "perpendicular to the plume." However, it also should be noted that this set of circumstances—wind at right angles, sun at observer's back—will only occur under certain specific conditions.

A smoke inspector who wished to make visual measurements when the opacity of the plume was at its maximum value would chose the time when the angle of the sun was at its maximum value for that day. This time occurs when the sun crosses the meridian of longitude of the observer and is referred to as "Local Apparent Noon" by navigators and astronomers. However, the time of "Local Apparent Noon" seldom coincides with twelve o'clock on the observer's watch. For an observer who is located in the exact center of the time zone, this coincidence only occurs four times a year (on April 15, June 15, September 1, and Christmas Day). On the other 361 days of the year, maximum opacity occurs either before or after twelve noon "Local Standard Time" on the observer's watch.

This irregular variation of the time of occurrence of maximum opacity throughout the year at any given location is caused by differences in the speed of rotation of the earth around the sun, tidal action and other factors. However, the time of maximum opacity occurrence can be calculated for any given day by use of information presented in the Nautical Almanac and knowledge of the local longitude.

FIGURE 3
**Effect of time of day on opacity**



### The effects of latitude

The angle of the sun at the time of maximum opacity is a function of the latitude of the power plant or other source of smoke plume, with greater angles (and greater opacity) occurring at the lower latitudes.

If a power plant is located at different areas within the continental U.S.—all other factors remaining constant—the opacity values for a power plant in the south will always be higher than those seen by the same observer under identical conditions and at an identical power plant in the north. This effect is the result of higher sun angles in the southern latitudes. If national opacity standards were applicable, a power plant in Alaska would obviously have less difficulty meeting the regulations than an identical power plant in Florida.

Figure 4 indicates quite clearly that visual opacity is not an indication of the amount of pollutants being emitted from a stationary source. With all other variables being constant (grain loading, particle size and density, and stack diameter) opacity can vary from 14–87% depending on the geographic location and time of day. If power plants located in Hawaii and Alaska are considered, these effects are even greater.

Table 1 presents the opacities that would exist if power plants were located at Kauna Point, Hawaii; Key West, Fla.; and Grantley Harbor, Alaska. The opacity at the time of maximum opacity on June 21st in Alaska is almost the same as the opacity on December 21st in Hawaii (68.5% vs. 67.5%). However, the opacity in Hawaii increases to a maximum of 86.4% in the summer, while in Alaska the opacity decreases to 14.5% in the winter. The winter opacity in Alaska, even at the maximum daily opacity, is just slightly greater (14.5% to 14.0%) than the opacity at sunrise or sunset.

The opacity in summer at Key West would be slightly greater (86.8–86.4%) than in Hawaii even though the latitude is greater. This is because the maximum sun angle in summertime occurs when the latitude is equal to the declination of the sun (23° 26.5′N in 1975). The latitude of Key West (24° 33′N) is closer to this value than the latitude of Kauna Point (19° 02′N).

FIGURE 4

**Effect of geographic location and time of day on opacity**

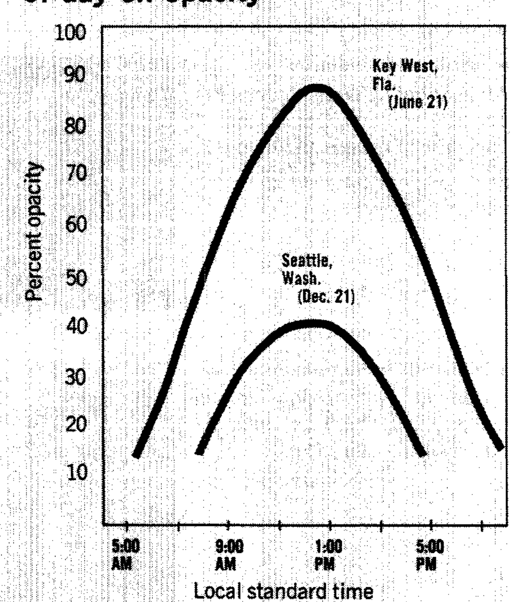



TABLE 2

**Relative effects of variables on opacity**

| Independent variable | "Black dot" value | Typical range of variation | Resultant change in opacity with all other variables held constant |
|---|---|---|---|
| Particulate grain loading | 0.05 gr/scf | 0.01–0.20 gr/scf | 25–98% |
| Stack diameter | 32.5 ft | 10–35 ft | 37–87% |
| Mean particle size | 2.6 $\mu$ | 0.9–10 $\mu$ | 96–34% |
| Deviation from the mean size | 3.0 | 1.5–5.0 | 70–80% |
| Particle index of refraction | 1.5 | 1.4–1.6 | 77–95% |
| Particle density | 2.2 g/cc | 1.5–5.0 g/cc | 93–51% |
| Stack gas temperature | 270 °F | 130 °–350 °F | 91–82% |
| Stack velocity | 90 ft/s | 70–130 ft/s | — |
| Water vapor content of stack gas | 10% | 6–14% | — |
| Color of the plume | White | White to black | — |
| Wind speed | Zero | Zero to 70 mph | — |
| Wind direction | Perpendicular to observation direction | ±180° | — |
| Wind turbulence | Zero | Zero to ±30% | — |
| Ambient air temperature and humidity | 70 °F, 15% R.H. | −10 °F to 130 °F 0–100% R.H. | — |
| Color of the sky | Blue | Blue to overcast | — |
| Distance of observer from stack | 2 $H_s$ | 0.5–50 $H_s$ | 92–74% |
| Effect of nonlevel terrain | Level | ±20% $H_s$ | 84–86% |
| Sun angle | 79° | 0–90° | 18–87% |
| Time of day | 11:30 AM (PST) | 4 AM to 7 PM | 18–85% |
| Day of year | June 21 at maximum sun angle | January 1 to December 1 at maximum sun angle | 55–85% |
| Geographic location—longitude | 114° W. Long. time of max. sun angle | ±15° of Lat.. time of maximum sun angle | 83–85% |
| Observer offset angle | 0° | 0–60° | 85–88% |
| Geographic location—latitude | 35° N. Lat. at max. sun angle | 25° N. Lat. to 48% N. Lat. max sun angle | 79–88% |
| Allowable human error | Zero | Zero to ±15% opacity | 70–100% |

### Summing up

The prediction of plume opacity by using light-scattering theory and measurements in the stack gas at Mohave were in agreement with the observations made by trained observers. A parametric study of the effects of independent variables on plume opacity by using the same light-scattering theory has shown that plume opacity can vary from 14–87% depending only on the geographic location of the source and the time of day, with all other factors such as particulate matter emissions remaining the same. This implies that the EPA New Source Performance Standard for plume opacity (20%) is not consistent with the particulate matter emissions standard (0.1 lb/$10^6$ Btu) for all power plant locations or times of day and days of the year.

The relative effects of the 24 variables are tabulated in Table 2. As can be seen, there is an extremely wide variation in possible values of opacity, even when the mass emission of particulate matter remains unchanged. It is concluded that opacity measurements are not indicative of the mass emissions of particulate matter, and that mass emissions cannot be accurately determined from opacity observations. The use of an opacity standard to enforce a mass emission limitation is therefore difficult to justify on a technical basis.

### Additional reading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