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VISUAL IMPACT OF PLUMES FROM POWER PLANTS: A THEORETICAL MODEL

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Abstract – Theoretical relationships have been derived and transformed into a computer model to describe plume visual impact at various observer vantage points resulting from power plant boiler operation. Plume visual impact results from a reduction in visual range (visibility) and plume coloration. The model considers plume transport and diffusion, light scattering and absorption by aerosols and gases, and chemical transformation in the plume of nitric oxide to nitrogen dioxide, sulfur dioxide to sulfates, and nitrogen oxides to nitrates.

The model is applied in a parametric study to explore the effect of emissions and environmental conditions on plume visual impact. The case selected is a hypothetical 1500 Mwe coal-fired power plant equipped with efficient particulate abatement equipment. The results establish that visual range is not significantly affected unless the observer is viewing along the plume axis or unless significant amounts of secondary particles are formed in the plume. Yellow–brown plume coloration is shown to result from the net production of nitrogen dioxide gas in the plume. The coloration is most apparent during stable and clear atmospheric conditions and effectively masked for elevated concentrations of background or plume aerosol.

NOMENCLATURE

$B(\lambda, r)$	Luminance at wavelength of light λ and at sight path distance r (candle m^{-2}).
$B_h(\lambda)$	Luminance of horizon at wavelength λ (candle m^{-2}).
$B_h'(\lambda)$	Luminance of horizon at wavelength λ, as affected by plume (candle m^{-2}).
$b_s(\lambda)$	Mie scattering coefficient at wavelength λ (m^{-1}).
$b_R(\lambda)$	Rayleigh scattering coefficient at wavelength λ (m^{-1}).
$b_{abs}(\lambda)$	Absorption coefficient at wavelength λ (m^{-1}).
$E(\lambda)$	Illuminance of wavelength λ (lumen m^{-2}).
I_y, I_z	Integrated plume concentration in horizontal and vertical directions (s m^{-2}).
$I(\alpha, \beta)$	Integrated plume concentration for sight path azimuth angle α and elevation angle β (s m^{-2}).
$K_s(\lambda, \phi)$	Phase function for Mie scattering at scattering angle ϕ and wavelength λ.
$K_R(\phi)$	Phase function for Rayleigh scattering at scattering angle ϕ.
r	Sight path distance (m).
r_0	Distance from observer to viewed object (m).
r_p	Distance from observer to plume (m).
r_v	Visual range or visibility (m).
t	Time after emission from top of stack (s).
u	Wind speed (m s^{-1}).
x	Distance downwind from stacks (m).

Greek letters

α	Sight path azimuthal angle relative to plume centerline.
β	Sight path elevation angle relative to horizontal.
$\beta'(\lambda, \phi)$	Volume scattering coefficient for wavelength λ and scattering angle ϕ.
γ	Aerosol power law size distribution parameter.
λ	Wavelength of light (millimicrons).
ϕ	Scattering angle.
$\sigma(\lambda)$	Total extinction coefficient for wavelength of light (m^{-1}).

1. INTRODUCTION

A. *Importance of visual impact*

An important issue in the evaluation of environmental impact of power plants is the impact of emissions on the visibility and esthetic qualities of the existing environment. In this regard, plumes from coal-fired power plants are of interest, particularly in the western United States where spectacular scenery is enhanced by generally excellent visibility.

In the past, many of the older coal-fired power plants generated conspicuous, visible plumes as a result of high emission rates of particulate matter. Old plants still in operation and newer plants have benefited from more efficient particulate abatement equipment and a state-of-the-art for which particulate removal efficiencies in excess of 99% are commonly specified and achieved. The installation of flue gas desulfurization systems (scrubbers) and boiler combustion modifications have led to a reduction of sulfur dioxide and nitrogen oxides emissions. This has brought about a sharp reduction in the visual impact of power plant plumes as evidenced by modern coal-fired power plants which frequently produce nearly invisible plumes. As a result, an evaluation of impact based on experiences from older power plants may be misleading.

The purpose of this paper is to present and to illustrate the use of a mathematical model for predicting the visual impact of emissions from a power plant based on a knowledge of expected pollutant emission rates and the visual effects of the pollutants. To achieve this purpose, the following two questions are ad-

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dressed: (1) Will plumes from the power plant be visible? (If so, how often and where?) (2) Will emissions adversely affect the visual range and esthetic qualities of the local environment? (If so, how often and where?)

B. *Causes of visual impact*

The following constituents of plumes may produce visual effects: primary particles, secondary particles (sulfates, nitrates), water particles and gaseous nitrogen dioxide.

Primary particles. A coal-fired power plant emits *primary particles* of fly ash and combustion-generated particulates to the atmosphere. The emission rate of primary particles may be very small if the power plant is equipped with an efficient precipitator or other abatement equipment. However, the emission which escapes the control equipment will contribute to the ambient particulate concentration, scatter and absorb light, and thereby affect the general visibility. If the emission rate of primary particulates is sufficiently high, the plume itself may be visible.

Secondary particles. Gaseous emissions (sulfur dioxide and nitrogen oxides) may react in the atmosphere to form *secondary particles* that also scatter and absorb light and affect the general visibility.

Water particles. Water vapor contained in the flue gas emitted to the atmosphere may also produce a visual impact if conditions are such that condensation occurs. When a plume is cooled by mixing with ambient air, it may become supersaturated. Water will then condense and form small particle droplets of water. These *water particles* scatter light and produce a white "steam" plume. Generally, the "steam" plume disappears at some distance from the stack after additional mixing has reduced the moisture content below the saturation point.

Gaseous nitrogen dioxide. Gaseous *nitrogen dioxide* (NO_2) absorbs light selectively and may discolor the atmosphere. Nitrogen dioxide is a reddish-brown gas that produces a yellow or brown colored plume if present in sufficient concentrations. Almost all of the nitrogen oxide (NO_x) emitted from power plant stacks is nitric oxide (NO), a colorless gas. Chemical reactions in the atmosphere, however, may oxidize a substantial portion of the colorless NO to NO_2.

C. *Previous work*

Plume opacity. Plume opacity at the stack is an indicator of the emission rate of particulate matter and serves as a standard in the air pollution regulations of regulatory bodies (e.g. Federal Register, 1976). As a result, a large body of literature exists regarding the optical effects of particulate matter in flue gas from power plants. For example, Pilat and Ensor (1970, 1971) presented a theoretical relationship between plume opacity and properties of the particulate matter in the plume. From experiments with white and black smoke plumes, Conner and Hodkinson (1972) found visual effects to be related to the viewing background and illumination as well as the properties of the plume.

Plume visibility. Some work has been undertaken to determine the visual effects of particulate matter in a plume distant from the stack. Jarman and DeTurville (1969) presented theoretical relationships for the contrast of a power plant plume downwind of a stack against the background sky based on the properties of the particulate matter in the plume and on meteorological conditions. Ensor *et al.* (1973) presented a calculational method to determine light transmittance horizontally through a plume distant from the source.

Visual range. The influence of suspended particulates (aerosols) on visual range has been studied extensively. Middleton's book *Vision through the Atmosphere*, is a classic treatment of the subject. Charlson (1969) has summarized more recent advances in this area. However, the effect of power plant plumes on visual range has been only recently addressed. For example, studies conducted for the *Southwest Energy Study* explored the impact of power plant plumes on visual range by combining the Gaussian plume dispersion model with visibility–particulate concentration relationships (USEPA, 1971a, b; Nicholson and White, 1971).

D. *Present work*

This paper presents and illustrates the use of a model that predicts the visual impact (visual range and coloration) of power plant plumes. The model is based on the physics of light scattering and absorption, but differs from the previous models in two key aspects. First, the present model predicts both (1) the impact of the plume on visual range and (2) the color and appearance of the plume. Second, the present work takes into account wavelength-dependent light scattering, scattering and absorption, size distribution and density of fly ash, chemical conversion of nitric oxide to nitrogen dioxide, formation of sulfates and nitrates, and observer-plume geometry.

2. SUMMARY OF THEORETICAL MODEL

The present model consists of the following three elements: light interactions, chemical conversion of plume constituents and plume diffusion. A detailed treatise of the model is available (Latimer and Samuelsen, 1975).

A. *Light interactions*

Middleton (1952) has shown that the wavelength-dependent effect of an atmosphere on the transmission of light can be evaluated by the following expression:

$$dB(\lambda, r) = [E(\lambda)\beta'(\lambda, \phi) - \sigma(\lambda)B(\lambda, r)]\,dr \quad (1)$$

where $\sigma(\lambda)$ is the total extinction coefficient:

$$\sigma(\lambda) = b_s(\lambda) + b_R(\lambda) + b_{abs}(\lambda) \quad (2)$$

and $\beta'(\lambda, \phi)$ is the volume scattering function:

$$\beta'(\lambda, \phi) = K_s(\lambda, \phi)b_s(\lambda) + K_R(\phi)b_R(\lambda) \quad (3)$$

For a power law size distribution K_s is independent of wavelength (Husar and White, 1976).

The present model is founded on the case shown in Fig. 1, namely a plume with non-uniform concentrations of light scattering and absorbing constituents in an otherwise uniform atmosphere. Application of the conditions shown in Fig. 1 to Equation (1) results in the following solution:

$$\begin{aligned} B(\lambda, r_o) = {} & B_h(\lambda)[1 - \exp(-\sigma(\lambda) r_p)] \\ & + \frac{E(\lambda) K_s(\lambda, \phi) \int^{\text{plume}} b_s \, \mathrm{d}r}{\int^{\text{plume}} (b_s + b_{\text{abs}}) \mathrm{d}r} \\ & \times [1 - \exp(-\textstyle\int^{\text{plume}} (b_s + b_{\text{abs}}) \mathrm{d}r)] \\ & \times [\exp(-\sigma(\lambda) r_p)] + B_h(\lambda)[1 - \exp(-\sigma(\lambda) r_q)] \\ & \times [\exp(-\textstyle\int^{\text{plume}} (b_s + b_{\text{abs}}) \mathrm{d}r)] \\ & \times [\exp(-\sigma(\lambda) r_p)] + B(\lambda, 0)[\exp(-\sigma(\lambda) r_q)] \\ & \times [\exp(-\textstyle\int^{\text{plume}} (b_s + b_{\text{abs}}) \mathrm{d}r)] \\ & \times [\exp(-\sigma(\lambda) r_p)]. \end{aligned} \tag{4}$$

The effect of a plume on the apparent color and visibility of objects can be calculated by evaluating Equation (4). An indicator of plume coloration is the "luminance ratio", defined by B at $\lambda = 400$ millimicrons (the blue end of the visible spectrum) divided by B at $\lambda = 700$ millimicrons (the red end). One can infer from the work of Hodkinson (1966) and Horvath (1971) that the object being viewed will appear yellow or brown in colour when the luminance ratio is less than 0.9.

It can be shown that the visual range as affected by an optically thin plume is:

$$r_v = \frac{1}{\sigma(\lambda)} \left[3.912 - \ln \left[\frac{B_h'(\lambda)}{B_h(\lambda)} \right] - \int^{\text{plume}} (b_s + b_{\text{abs}}) \mathrm{d}r \right]. \tag{5}$$

The values of b_s and b_{abs} in the above equations are wavelength-dependent and can be evaluated if the concentration of nitrogen dioxide gas and the concentration, size distribution, and density of aerosol are known (Pilat and Ensor, 1971; Schulz *et al.*, 1975; Charlson and Ahlquist, 1969; Waggoner and Charlson, 1971; Thielke *et al.*, 1972; State of California, 1966).

B. *Chemical conversion*

Nitric oxide to nitrogen dioxide. Nitric oxide (NO) is produced as a product of combustion of any fuel with air. It is formed by the thermal oxidation of atmospheric nitrogen at the high temperature experienced in the combustion zone (the boiler in a power plant) and the oxidation of nitrogen that may be present in the fuel. By modifying the combustion process so that excess air and peak temperatures are kept relatively low, the amount of nitric oxide produced can be reduced. Nitric oxide concentrations in flue gas can be maintained at levels below 400 ppm in well-controlled boilers. The nitrogen dioxide present in the flue gas is typically assumed to be approximately five percent of the total nitrogen oxides emitted. However, chemical reactions in the atmosphere can form sufficient NO_2 from NO to cause coloration.

The following reactions are used in the present model to describe the chemical conversion of NO to NO_2 within the plume:

$$2NO + O_2 \rightarrow 2NO_2 \tag{6}$$

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{7}$$

$$NO_2 + (\text{photon of ultraviolet light}) \rightarrow NO + O \tag{8}$$

The rates of these reactions (Leighton, 1961; Niki, 1974; Baulch *et al.*, 1973) were evaluated and incorporated in the theoretical model.

Gas to particles. Although sulfur dioxide and nitrogen oxides do not scatter light appreciably, these gases react in the atmosphere to form sulfate and nitrate particles which do scatter light and affect visibility. Recognizing that secondary particles may be a significant fraction of the total particulate concentration in a plume, especially at large distances from the source (i.e. long reaction times), the formation of sulfates and nitrates are considered in the present model by introducing first-order rate constants for the chemical conversion of SO_2 and NO_x. (Features worthy of consideration in a refined gas to particle model include a detailed reaction mechanism, size distribution of particles, density of particles and the effect of water condensation on particle size and mass.)

C. *Plume diffusion*

The transport and diffusion of plume material must be calculated in order to evaluate the rate of nitrogen dioxide formation, which is dependent on concentrations of NO, NO_2 and O_3, and to determine the spatial and temporal distribution of plume material. Accordingly, standard Gaussian plume dispersion and

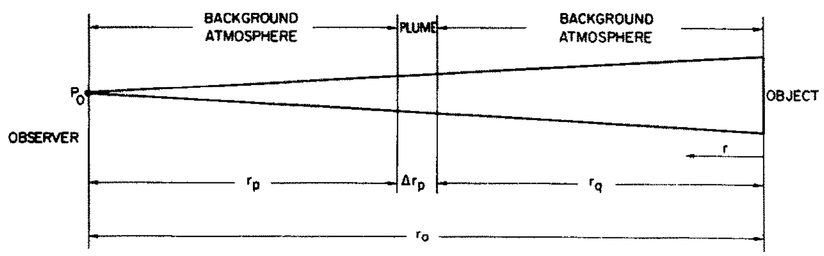

Fig. 1. Object–observer geometry with plume.

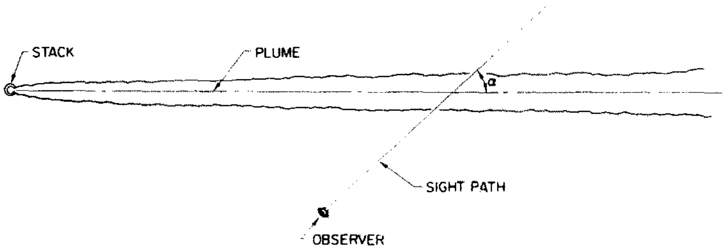

Fig. 2. Plan view of observer–plume geometry.

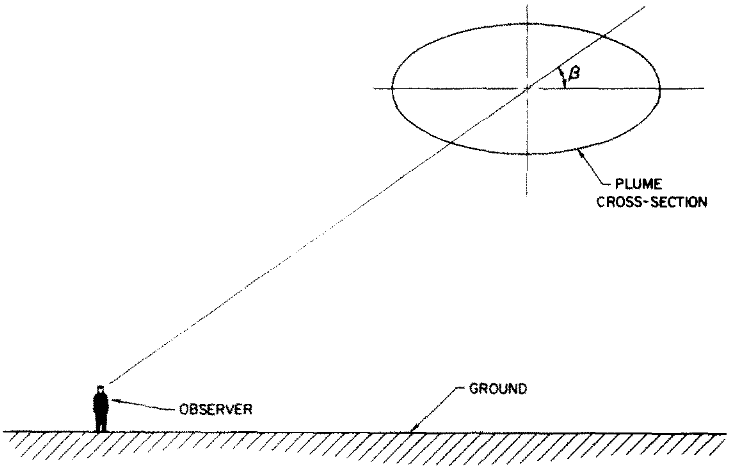

Fig. 3. Elevation view of observer–plume geometry.

plume rise models were incorporated in the theoretical model (Slade, 1968; Carpenter *et al.*, 1971; Briggs, 1969). As indicated in Equation (4), the integral of the light scattering and absorption coefficients along horizontal and vertical cross-plume lines of sight are necessary to evaluate visual effects. The integrals are evaluated in the present model following the method of Ensor *et al.* (1973).

The magnitude of visual impact of a power plant plume depends on the orientation of the observer to the plume because the sight path distance through the plume will vary depending on this orientation, as illustrated in Figs. 2 and 3. The sight path integral of plume constituent concentrations is a function of sight path angles α and β:

$$I(\alpha,\beta) = \frac{1}{\sin\alpha}\left[(I_y\cos\beta)^2 + (I_z\sin\beta)^2\right]^{1/2} \qquad (9)$$

For the purposes of calculating visual range it is appropriate to consider horizontal or nearly horizontal sight paths. In a rugged terrain area, several types of sight paths deserve attention. Figure 4 illustrates two possible sight paths across a plume. One is a sight path at ground level that crosses underneath the plume. The other is a sight path that passes through the plume center.

The case where the plume is being transported directly toward the observer results in the greatest potential impact on the visual range. Figure 5 illustrates the situation. If the observer looks either toward or away from the plant, the sight path distance affected by the plume is greatest, hence the impact on visual range is greatest. If the observer is situated on elevated terrain such that one possible sight path could be down the plume centerline, a still greater potential visual impact could result. It should be pointed out that a plume directly overhead would be an extremely rare occurrence. Even rarer would be the case of an observer located on elevated terrain with a plume centerline at eye level. Thus, this situation represents a worst case that would virtually never be experienced. Also, it should be pointed out that plume meander will tend to reduce the visual impact for sight paths along the plume axis.

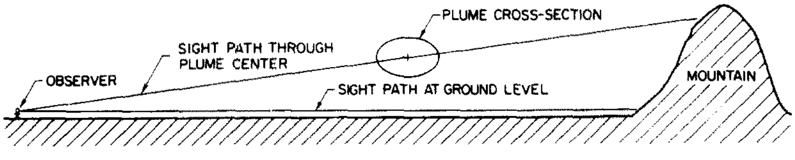

Fig. 4. Two possible sight paths for viewing distant scenery across plume.

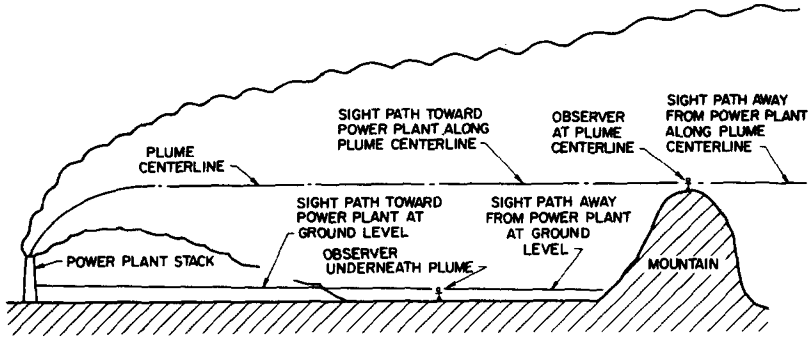

Fig. 5. Four possible sight paths for viewing distant scenery with plume overhead.

3. APPLICATION OF THEORETICAL MODEL

A. *Computer program and input*

A computer program, based on the theory described in the preceding section, has been written and applied to the assessment of cause–effect relationships between plume visual impact and power plant boiler emissions, background pollutant levels, atmospheric stability, observer location and background visual range. The case study is based on a 1500 Mwe coal-fired power plant that is designed to meet the United States Environmental Protection Agency New Source Performance Standards (Federal Register, 1976).

The values of the input variables used in the computer runs are given in Table 1. Parameters varied to assess select cause–effect relationships are indicated by asterisks. Only one parameter was varied at a time from the base value.

For this study it is assumed that the plume and background aerosol phase functions (K_s) are independent of wavelength (as would be the case with a power law size distribution, as noted by Husar and White (1976)). Thus, a horizon sky would appear white for all scattering angles (i.e. $B_h(\lambda) = E(\lambda)K_s(\phi)$).

B. *Visual range*

Figures 6 and 7 illustrate the impact on visual range of the hypothetical 1500 Mwe coal-fired power plant for two TVA stability categories (Carpenter *et al.*, 1971). In each figure, the visual range is illustrated for a

Table 1. Input values used in application of computer program

Coal-fired power plant emission conditions	
Number of boilers	3
Number of stacks	3
Power (total)	1500 Mwe
Stack height	152 m
Flue gas temperature	121°C
Flue gas flow rate (per stack)	727 $m^3 s^{-1}$
Particulate emission rate (total)	161 $g s^{-1}$
Sulfur dioxide emission rate (total)	1974 $g s^{-1}$
NO_x emission rate (total, as NO_2)	1159 $g s^{-1}$
Fly ash density	2.5 $g cm^{-3}$
Fly ash aerosol parameter	0.36 $cm^3 m^{-2}$
* Fly ash size distribution parameter γ	[2], 3, [4] (power law size distribution)
Environmental conditions	
Wind speed	4.5 $m s^{-1}$
* Stability category (TVA)	[neutral], [stable], isothermal, [strong inversion]
* Background visual range	[5], [10], [20], [40], 80 km
Background NO_x concentration	0 ppm
* Background O_3 concentration	[0], [0.02], 0.04, [0.08], [0.16], [0.32] ppm
Ambient temperature	25°C
Ambient pressure	1.0 atmosphere
* Plume-observer distance r_p	[0], 1, [5] km
Assumed sulfate formation rate	0.5% h^{-1} (appropriate only for clean background)
Assumed nitrate formation rate	0.0% h^{-1}
Background viewing color	white (caused by Mie scatter)

* Parameters.

[ ] Values of parameters when varied from base value.

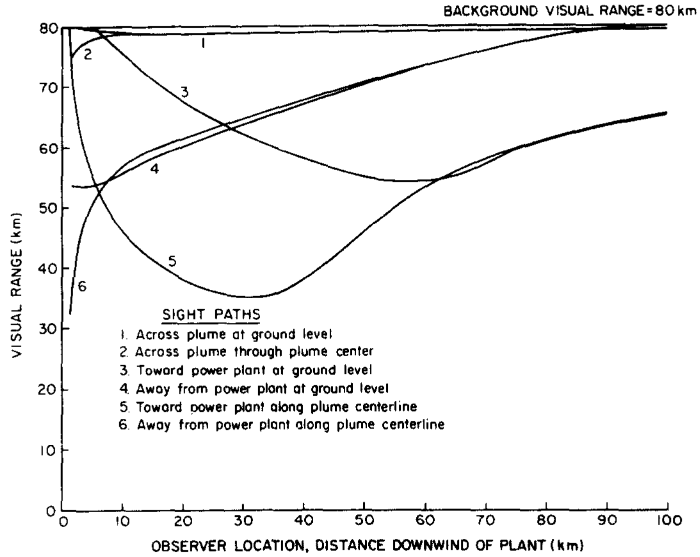

Fig. 6. Impact on visual range (neutral case).

number of possible sight paths as a function of the observer location downwind of the power plant. The background visual range (80 kilometers) assumed in these calculations is identified in these figures for comparison.

It is assumed that the plume extends in a perfect straight line out to 100 kilometers downwind from the power plant, but does not extend beyond this distance because of wind direction change.

The figures show that visual range is significantly reduced only when the observer is viewing along the plume axis such that the plume material extends a significant distance along the observer's sight path. When the observer views across the plume, such that the sight path is perpendicular to the plume axis, only a small reduction in visual range results. The impact on visual range increases with increasing atmospheric stability (decreasing plume dilution) when the sight path is along the plume axis.

C. *Plume appearance*

Atmospheric stability. Figure 8 illustrates the effect of atmospheric stability (or the effect of plume dilution rate) on the NO_2/NO_x mole ratio as a function of downwind distance (or time $t = x/u$). Nitric oxide is more rapidly transformed to NO_2 in the well-mixed neutral stability case than in the stable cases. This results because a greater amount of background ozone (assumed to be 0.04 ppm) is mixed into the plume and is available for reaction with the NO (Equation 7). If the background ozone concentration were zero, the NO_2/NO_x ratios would be smaller and the NO_2/NO_x ratio would increase with increasing stability (decreasing plume dilution), because increased concentration of NO_x causes the termolecular reaction (Equation 6) to proceed faster.

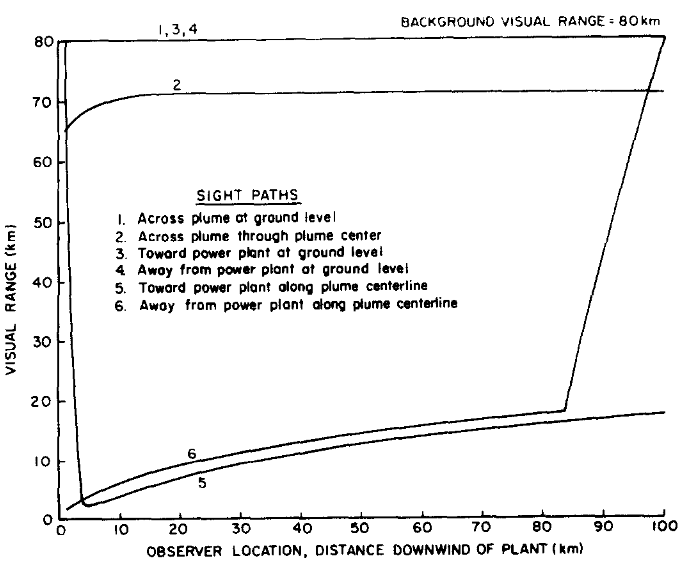

Fig. 7. Impact on visual range (isothermal case).

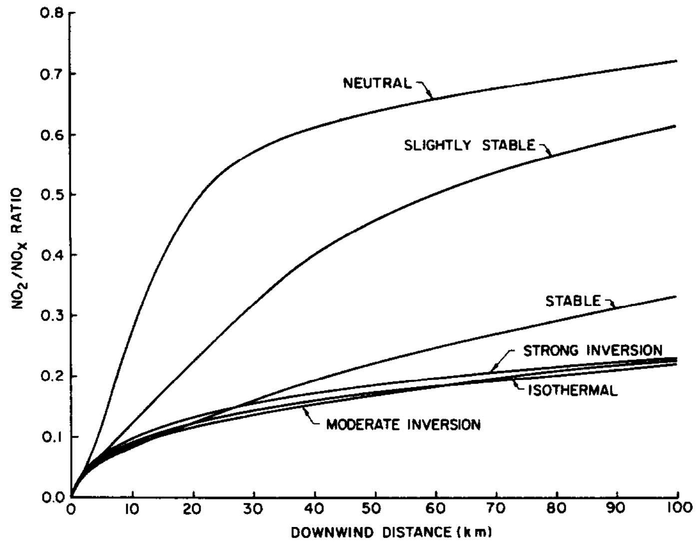

Fig. 8. Effect of atmospheric stability on NO_2/NO_x mole ratio as a function of downwind distance (background ozone concentration = 0.040 ppm).

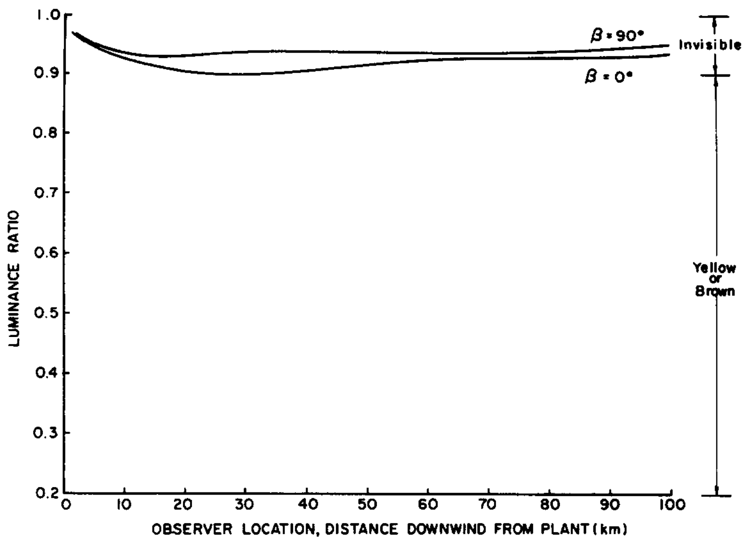

Fig. 9. Luminance ratios for sight paths perpendicular to plume through plume center as a function of observer location and sight path elevation angle (neutral case).

The impact of the particulate matter and nitrogen dioxide on the appearance of the plume is illustrated in Figs 9 and 10 for two TVA stability categories. Each figure is a plot of the luminance ratio (the ratio of the luminance at 400 millimicrons to that at 700 millimicrons) seen by the observer looking perpendicular to the plume axis through the plume center, as a function of the observer location downwind of the power plant. The effect of sight path angle β is shown in each figure. Elevation angles from 0° (horizontal) to 90° (vertical) are assumed.

Even though the NO_2/NO_x ratio decreases with increasing stability, Figs 9 and 10 show that the coloration of the plume becomes more apparent as stability increases. This can be explained by the fact that the plume NO_2 concentration increases with increasing stability even though the NO_2/NO_x ratio decreases.

The dramatic effect of the observer's sight path elevation angle is also evident from Fig. 10. The plume appears more colored with the nearly horizontal sight paths compared with the vertical ones. This effect can be explained by the fact that the plume's cross-section is somewhat flattened, as shown in Fig. 3, particularly for the more stable cases, so that the observer is looking through more plume material when his sight path is more nearly horizontal. For the neutral stability case, the plume appearance does not vary considerably with elevation angle because of the more nearly circular cross-section of the neutral, coning plume.

Background ozone. Figure 11 shows the pronounced effect of background ozone concentration on the formation of NO_2. Without any background ozone the NO_2/NO_x ratio will be approximately 0.10; however,

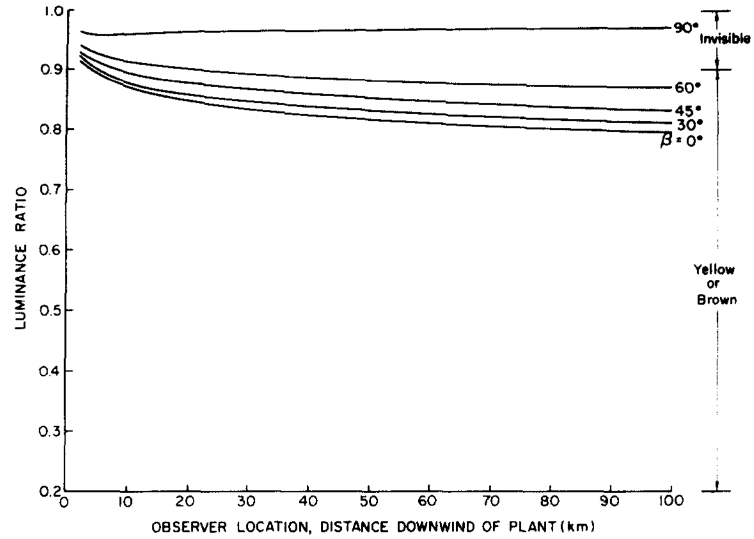

Fig. 10. Luminance ratios for sight paths perpendicular to plume through plume center as a function of observer location and sight path elevation angle (isothermal case).

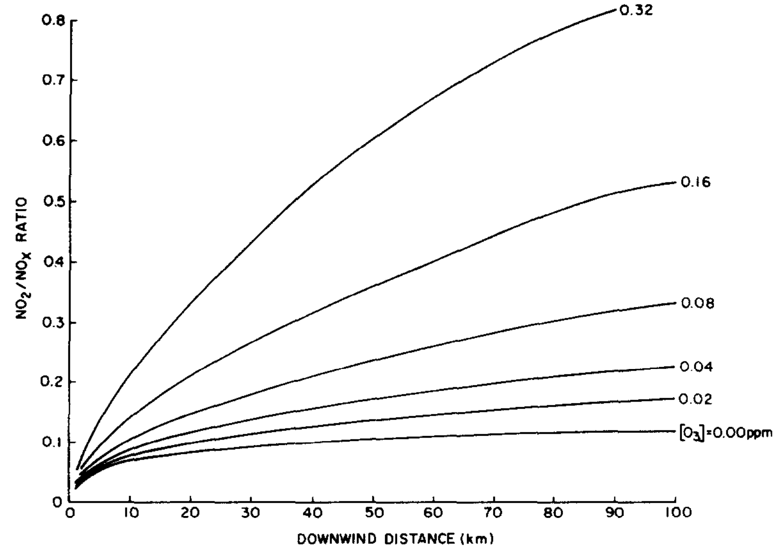

Fig. 11. Effect of background ozone concentration on NO_2/NO_x mole ratio as a function of downwind distance (isothermal case).

if the background ozone concentration is high, the NO_2/NO_x ratio can be 0.50 or higher for otherwise identical ambient conditions.

Light scatter. Aerosol in the sight path of the observer will scatter light into, as well as out of, the sight path. Light scattered into the sight path (airlight) will tend to mask the coloration of the plume because the scattered light from the blue end of the visible spectrum will increase the luminance ratio (the ratio of luminance of 400 millimicron light to that of 700 millimicron light), making the plume less colored. However, it can be shown that for $B(\lambda, r) > E(\lambda)K_s(\lambda, \phi)$, aerosol will contribute to the coloration caused by NO_2.

Thus the masking of the colored plume will increase with increasing distance between the plume and the observer for a given background visual range (a given background aerosol concentration). Figure 12 illustrates this effect by showing the luminance ratio for two plume-observer distances $r_p = 0$ and $r_p = 5$ kilometers. Also, for a fixed plume-observer distance the masking will increase with decreasing visual range as shown in Fig. 13.

The wavelength dependence of the light scattering coefficient (a function of particle size distribution) will also affect the plume coloration. Figure 14 illustrates the effect on luminance ratio of three different wavelength dependencies of the light scattering coefficient

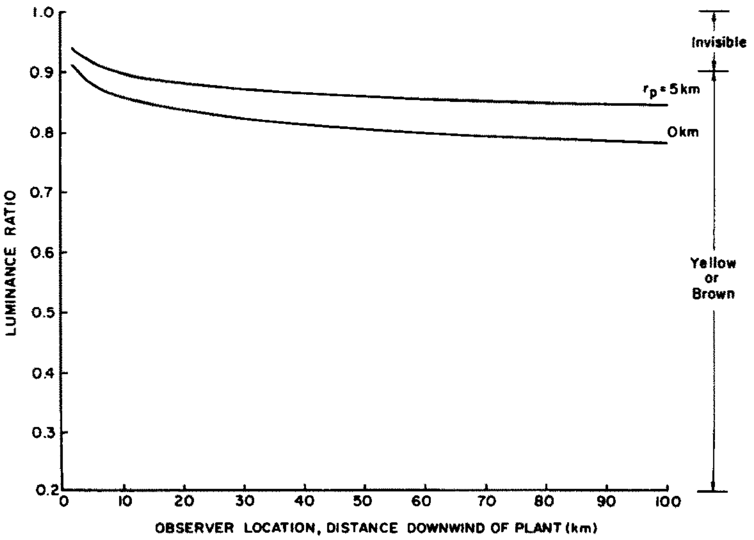

Fig. 12. Effect of plume–observer distance (r_p) on plume appearance for fixed background visual range of 80 km (isothermal case).

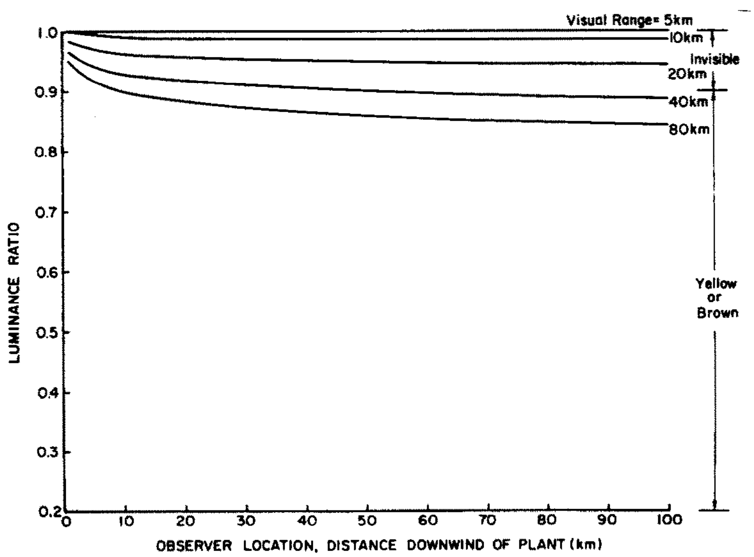

Fig. 13. Effect of background visual range on plume appearance for fixed plume observer distance of 5 km (isothermal case).

for an aerosol with a power law size distribution. If the light scattering is independent of wavelength ($\gamma = 2$; see Fig. 14 for definition), the plume will appear more colored than the cases where the scattering coefficient is inversely proportional to the wavelength of light ($\gamma = 3, 4$). This may be explained by the fact that with $\gamma = 3$ or 4, more light from the blue end of the visible spectrum is scattered toward the observer than is the case with $\gamma = 2$, and a greater masking results.

It may be concluded from the above discussion that high particulate emission rates from power plants will tend to mask the color of the plume caused by light-absorbing nitrogen dioxide.

4. CONCLUSIONS

The following conslusions have been made based on the development of a theoretical model for plume visual impact and on an application of this model to a case study of a 1500 Mwe coal-fired power plant:

(1) Nitrogen dioxide formation in a power plant plume is strongly affected by the atmospheric background ozone concentration and the atmospheric turbulence that mixes the background ozone into the plume.

(2) Emissions from a coal-fired power plant with efficient particulate abatement equipment have a very

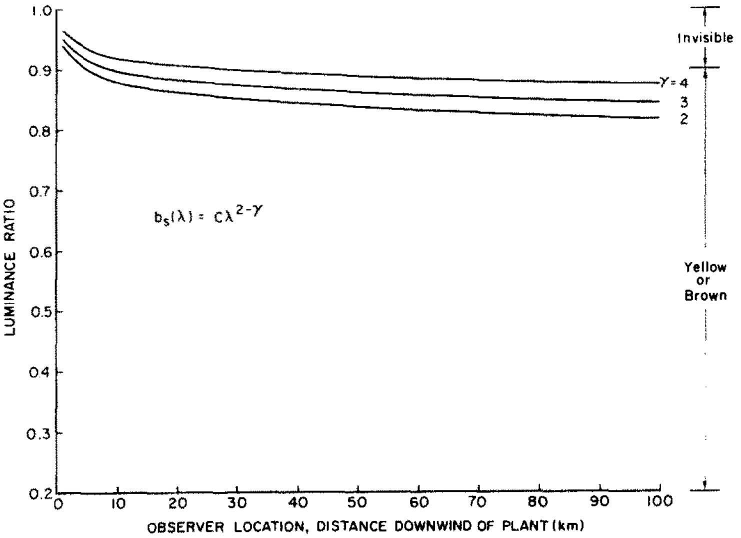

Fig. 14. Effect of aerosol size distribution on luminance ratio as a function of downwind distance for observer looking horizontally through plume center perpendicular to plume axis ($r_p = 5$ km).

small effect on visual range within 100 km of the plant except when the observer is viewing along the plume axis or conditions are such that significant amounts of secondary particles (e.g. sulfate and nitrates) are formed.

(3) Power plant plumes may appear yellow or brown due to wavelength-dependent, light-absorbing nitrogen dioxide gas in the plume.

(4) Background aerosol and aerosol from a power plant may mask the color of a power plant plume. The yellow or brown color of a plume will become more apparent with decreasing particulate emission rate (relative to the NO_x emission rate) and with increasing background visual range.

(5) A power plant plume will appear most colored during stable atmospheric conditions.

(6) A power plant plume will appear more colored when viewed with a horizontal sight path than with a vertical sight path, especially during stable atmospheric conditions.

Tests of the mathematical model against field measurement are appropriate to identify directions for refinement and are presently in progress. The rate of formation of particulate sulfates and nitrates from SO_2 and NO_x and the effect of the size distribution and light scattering characteristics of these secondary particles should be further defined and incorporated in future applications of the model. In addition, the present application of the model is based on the assumption that the plume is observed against the horizon sky whose luminance is determined by the light scattering of the background aerosol. Application of the model to consider a variety of typically encountered backgrounds, such as very blue sky or a bright white cloud, is appropriate.

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