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**TITLE:** COMPUTER SIMULATION OF THE VISUAL EFFECTS OF SMOKE PLUMES

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## COMPUTER SIMULATION OF THE VISUAL EFFECTS OF SMOKE PLUMES

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### Abstract

With recent changes provided by the Clean Air Act Amendment of 1977, the effect of industrial smoke plumes on scenic landscapes assumes heightened importance. The impact of large coal-fired power plants is most easily understood through the use of before-and-after photographs. A technique has been developed to modify a clean "before" scene as dictated by solutions to the radiation transfer problem in a polluted atmosphere. This allows one to produce simulated "after" scenes, which can illustrate the visual effects of pollutants emitted under a variety of circumstances. Application of this technique to very large coal-fired power plants suggests that such facilities may impair scenic vistas under some circumstances, unless stricter pollution controls and standards are enforced.

### Introduction

Existing and projected coal-fired power plants in the West have sparked considerable controversy about their possible impacts on the environment. One of the principal areas of concern has been the effect on the individual's enjoyment of scenic vistas. A National Park Service study<sup>1</sup> identified this problem as a major area of concern over the ill-fated Kaiparowits plant. Furthermore, a multi-agency study<sup>2</sup> on impacts of power plants in the Southwest also identified loss of visibility as a major concern.

Recently, the Clean Air Act was amended to address these concerns. Section 169A<sup>3</sup> states "Congress hereby declares as a national goal the prevention of any future, and the remedying of any existing impairment of visibility in mandatory class I federal areas which impairment results from man made air pollution." In this context, visibility impairment is defined as "reduction in visual range and atmospheric discoloration." Mandatory Class I areas include national parks and wilderness areas larger than a specified minimum size. The goal is to be achieved through a clean-up program for existing plants and stricter control of future plants and other pollution sources. These changes in the Act make it more important to develop techniques that can be used to predict visibility effects. A technique that permits visualization of the effects of smoke plumes, therefore, would be most useful.

Coal-fired power plants emit particulates (primarily fly ash) and gases (e.g., oxides of nitrogen and sulfur). At the stack top, fly ash and perhaps nitrogen dioxide will be the only visible components. Sulfur oxides convert to visible particulate sulfates, however, and nitric oxide converts to nitrogen dioxide and particulate nitrate. This results in a faint white plume, which may become an obvious brown one downwind under conditions of restricted dispersion. The appearance of the plume will depend upon the changes in light transmission and scattering produced by the materials as a function of wavelength. It will also depend upon the background against which the plume appears.

At large distances downwind, the contribution of several sources may be important and the role of any single source may be difficult to determine. While this regional haze may be treated with techniques used herein, this paper will not deal with that aspect of the problem. Instead, this paper will focus on the effects of coherent plumes on areas within 60 miles of the source. This circumstance is frequently known as "plume blight."

### Problem Approach

The simulation of plumes is accomplished through a multi-step process. First, a color slide is processed to produce information about the background scene. This scene is then modified to provide the view as observed with the smoke plume. The second major step requires the computer simulation of the background atmosphere in terms of its brightness in each of three wavelengths representative of the colors red, blue, and green. Third, a calculation of concentrations of light scattering and/or absorbing materials along each line of sight is performed. In the fourth step, a solution is constructed to the radiative transfer problem for a series of infinite planes oriented normal to the line of sight. The boundary

conditions are derived from the background atmosphere. The solution provides plume light scattering (TRAD) and light transmission (TR) for each line of sight. Next, the transmission and scattering values are interpolated over the entire photographic field of vision. This is followed by modification of film densities to provide revised film densities for the simulated scene. Finally, the densities are converted to equivalent brightnesses and displayed on a TV console. The screen is photographed to provide the picture of the simulated scene.

### Original Slide Processing

The original 35-mm color slide of Canyonlands National Monument was scanned on a flatbed microdensitometer using a 40-micron aperture. Three separate images were digitized, scanning 512 lines of 825 picture elements through standard red, blue, and green filters. The digitized pictures were expressed in photographic densities of 0 to 5.12.

### Radiative Transfer for the Background Atmosphere

The background atmosphere is idealized as a 30-layer, semi-infinite plane, parallel atmosphere. Both Rayleigh and Mie scattering are considered. The radiative transfer equation is written as:

$$\mu \frac{dI(\tau; \mu, \phi)}{d\tau} = I(\tau; \mu, \phi) - w(\tau) J(\tau; \mu, \phi) \quad (1)$$

where  $I(\tau; \mu, \phi)$  is the intensity of radiation emerging at a level in the atmosphere corresponding to a normal optical thickness  $\tau$  in the direction  $\mu, \phi$ , and  $\mu$  is  $\cos\theta$ ;  $\theta$  is the angle that the direction makes with the local zenith;  $\phi$  is the azimuth angle referred to an arbitrary meridian plane.  $w(\tau)$  is the albedo of single scattering, which is given by:

$$w(\tau) = \left[ \Delta\tau^{(s,m)} + \Delta\tau^{(s,r)} \right] / \Delta\tau \quad (2)$$

where  $\Delta\tau^{(s,m)}$  refers to change in optical depth in traversing unit volume associated with Mie scattering and  $\Delta\tau^{(s,r)}$  is the change in optical depth in traversing unit volume associated with Rayleigh scattering. The source term  $J(\tau; \mu, \phi)$  is given by:

$$J(\tau; \mu, \phi) = \frac{1}{4\pi} e^{-\tau/\mu_0} P(\tau; \mu, \phi; -\mu_0, \phi_0) F + \frac{1}{4\pi} \int_{-1}^{+1} \int_0^{2\pi} P(\tau; \mu, \phi; \mu', \phi') I(\mu', \phi') d\mu' d\phi' \quad (3)$$

when it is assumed that  $F$  is the solar radiation flux per unit area at  $\tau = 0$  at right angles to the incident direction represented by  $-\mu_0, \phi_0$ . The boundary conditions are:

$$I(0; -\mu, \phi) = 0 \quad (4)$$

and

$$I(\tau_b; +\mu, \phi) = 0 \quad (5)$$

The contribution due to ground reflection is treated separately through a technique developed by Chandrasekhar.<sup>4</sup> Solution involves expansion of the phase function in Legendre polynomials of the cosine of the angle between incident and emerging radiation. The resulting expression can be written in terms of associated Legendre polynomials of  $\mu$  and  $\mu'$  and Fourier coefficients of  $\phi$  and  $\phi'$ . Fourier expansion of the intensities permits transformation of the radiative transfer equation into a set of uncoupled first order integro-differential equations for the Fourier coefficients  $I_n(\tau; \mu)$ . These equations are solved by an iterative technique as used by Braslau and Dave.<sup>5</sup> Initially the intensities are all zero, and non-zero fluxes are produced by the contribution of the direct solar radiation. These intensities are substituted into the source term, and new intensities are calculated. This procedure continues until successive approximations differ by less than 0.1%.

### Contaminant Concentration Calculations

Contaminant concentrations are estimated via a Gaussian plume formulation. In this formulation, the concentration at a point downwind distance  $x$  and a crosswind distance  $y$  and height  $z$  is given by:<sup>6</sup>

$$X(x, y, z, H) = \frac{Qe^{-\frac{y^2}{2\sigma_y^2}}}{2\pi u \sigma_y \sigma_z} \left\{ e^{-\frac{1}{2} \left( \frac{H-z}{\sigma_z} \right)^2} + e^{-\frac{1}{2} \left( \frac{H+z}{\sigma_z} \right)^2} \right\} \quad (6)$$

where  $H$  is the effective height of the centerline of the smoke plume above terrain.  $u$  is the wind speed,  $Q$  is the source emission rate,  $\sigma_y$  is the horizontal dispersion parameter, and  $\sigma_z$  is the vertical dispersion parameter. The parameters  $\sigma_y$  and  $\sigma_z$  are dependent upon the downwind distance and the stability.<sup>7</sup> The effective plume height is the sum of the stack height and the plume rise, which is calculated via Briggs' plume rise equations.<sup>8</sup> Equation (6) is valid for conservative pollutants. For pollutants that are converted from other pollutants, an exponential conversion rate is assumed. For nitrogen dioxide, however, it is assumed that the  $\text{NO}_2$  concentration cannot exceed a value equal to 25% of the  $\text{NO}$  concentration plus an amount equivalent to the background ozone in parts per million. With equation (6), the concentration of pollutants can be calculated at each point along a line of sight. The concentrations are then multiplied by extinction coefficients per unit mass concentration to determine the differential extinction coefficient along the line of sight. Integration along the line of sight gives the optical thickness along the path.

### Plume Radiative Transfer Solution

Once the total optical thickness and the absorption optical thickness are calculated, the radiative transfer problem for the plume can be solved. The total optical thickness is divided into a number of segments. Each segment represents the value associated with an infinite plane normal to the line of sight. A new coordinate system with the  $z$  axis along the line of sight is defined. The light intensities incident upon the outermost layer are given by:

$$I(0; -\mu_\ell) = I_0(\tau_b; -\mu_\ell) e^{-\sigma_b D_{\max}}$$

while the light intensities incident upon the innermost layer are

$$I(\tau_{\max}; +\mu_\ell) = I_0(\tau_b; \mu_\ell) e^{-\sigma_b d_{\min}}$$

where  $I_0(\tau_b; \mu')$  is the zero<sup>th</sup> Fourier coefficient of the intensity for radiation traveling outward.  $D_{\max}$  is the physical distance to the far edge of the plume from the observer, while  $d_{\min}$  is the distance to the near edge.  $\sigma_b$  is the background extinction coefficient.

The values  $I_0(\tau_b; \mu')$  are obtained from the intensities found for the background atmosphere through a coordinate transformation and expansion in a Fourier series about the transformed azimuthal coordinate. Only the zeroth order term is needed to determine the intensity along the line of sight.

The radiative transfer equations are solved by an iteration technique similar to that used for the background atmosphere. This solution is provided by the code PVISN. The output of this step is a plume transmission (TR) and total radiance (TRAD), which are used to modify the original picture.

### Picture Element Manipulation

The digitized images were processed on a CDC 7600 computer using the Los Alamos Digital Image Enhancement System (LADIES), a user-oriented subroutine package for image processing. The computer program POLLUT used the LADIES package to superimpose the power plant plume on the original clean scene. The light transmittance through the plume and the total radiance from plume particles were calculated by code PVISN for 10 elevation angles from the horizon and 10 bearing angles from an assumed observer. The minimum bearing angle of the calculated transmittance and radiance data correspond to the left side of the clean scene; the maximum

bearing angle to the right side. The code POLLUT was given the image line numbers that corresponded to the elevation range of the data. For each picture element where the power plant plume was to be added to the original clean scene, an elevation and a bearing angle were determined by a simple rectangular approximation. Given an elevation and bearing angle for each picture element, the transmittance and total radiance of the plume at that element were calculated using a two-dimensional, linear interpolation.

The basic equation defining the new picture brightness for each picture element with superimposed pollutant data is:

$$B_{new} = TR \times B_{old} + Trad$$

where

$B_{old}$  = picture brightness from  
the clean scene.

The corresponding film densities are obtained through the relation:

$$D = -\gamma \log (a B_{new})$$

where  $a$  is the factor representing the equivalent exposure.  $a$  is given by:

$$a = \frac{1}{B_{ref}} 10^{-\frac{D_{ref}}{\gamma}}$$

where  $D_{ref}$  is obtained from the original slide.  $B_{ref}$  is the brightness calculated for the background atmosphere for the same portion of the sky. The value of " $a$ " is taken for the blue wavelength only; values of " $a$ " for red and green are drawn from film characteristics. This is necessary because the actual aerosol concentration in the background sky is not precisely known, and the intensities for green and red light are sensitive to this value.

The new film density is given by:

$$D = -\gamma \log (a Tr B_{old} + a Trad)$$

where  $B_{old}$  is given by:

$$B_{old} = \frac{1}{a} 10^{-\frac{D_{old}}{\gamma}}$$

and  $D_{old}$  is the original slide density.

#### Image Display System

The Digital Image and Analysis Display System (DIADS) is the LASL image processing system. DIADS consists of a PDP-11 computer, a COMTAL image processor, control and display devices, and the computer software required to provide a user with interactive capability to analyze and enhance image data.

The new images of the pollutant-contaminated scene produced on the CDC 7600 computer are written on magnetic tape for subsequent processing on the DIADS system. The DIADS PDP-11 computer transfers the image data from magnetic to the refresh memory of the COMTAL image processor. Since the original image was  $512 \times 825$  pixels and the resolution of the image processor is  $512 \times 512$ , the DIADS software halved the polluted scene image to  $256 \times 412$  picture elements before displaying the image on the COMTAL video CRT.

### Case Studies

Four separate cases were examined using this system. Case 1 is representative of a 3000-MW, coal-fired power plant during low-wind stable conditions with a Venturi scrubber for particulate control. The background ozone concentration was 0.05 ppm. SO<sub>2</sub> was assumed to convert to particulate sulfate with a 96-hour life, while NO<sub>x</sub> converted to particulate nitrate with a 46-hour half life. Nitric oxide is assumed to convert to nitrogen dioxide with a 2-hour half life until 25% has been converted. The source is assumed to have 90% control of SO<sub>2</sub> and 99.5% control of fly ash, while NO<sub>x</sub> is released at a rate slightly below New Source Performance Standards. The resulting emission rates are: 120 grams per second for fly ash, 1750 grams per second for nitrogen oxides, and 500 grams per second for sulfur dioxide. Case 2 represents the same source except a precipitator is used instead of a scrubber for particulate control. Case 3 represents the situation of Case 1 except that neutral stability is assumed instead of stable conditions. For Case 4, we examined the situation when a single 3000-MW plant is replaced by three 1000-MW plants. All plants are assumed to have scrubbers.

The geometry of Case 1 is depicted in Figure 1, while the geometry of Case 4 is shown in Figure 2.

Figure 3 is a computer rendition of the original scene. Figure 4 depicts the situation for Case 1 with a 3000-MW plant with a scrubber during stable conditions. One notes the marked change of brightness along the plume that results from small angle scattering as the scattering angle is decreased. The view of the plume passing in front of the bluff on the left is an artifice of the code which assumes that the distance to terrain only depends upon the elevation angle. The code is currently being modified to properly consider irregular terrain.

Figure 5 illustrates the effect of replacing a scrubber by a precipitator. The slightly deeper brown color of the plume is the result of increasing the role of nitrogen dioxide as compared with that of light scattering materials. Near the plant, the precipitator-equipped plant would probably appear much cleaner because the relatively larger particles released by the precipitators would scatter light much less effectively.

Figure 6 shows the situation of Case 3 with a single plant whose emissions are released in a neutral atmosphere instead of a stable one. Figure 7 portrays the results of Case 4 with three 1000-MW plants emitting into a stable atmosphere. The plume from the more distant plant is almost below the horizon while the third plant is not in the field of view.

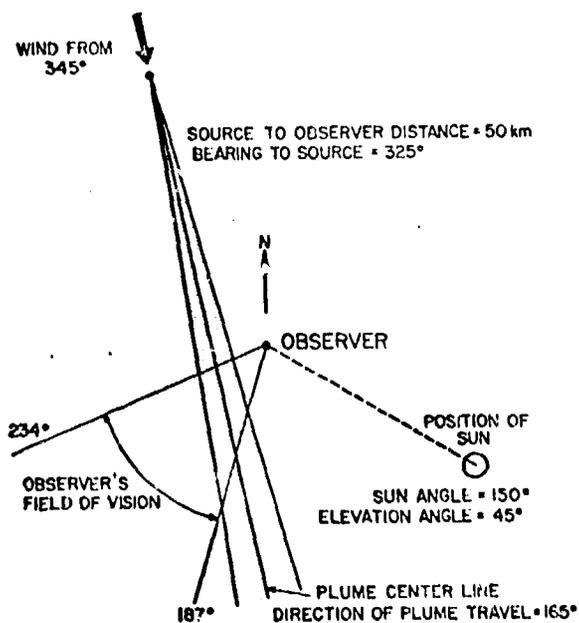


Figure 1. Source-observer geometry for cases one through three.

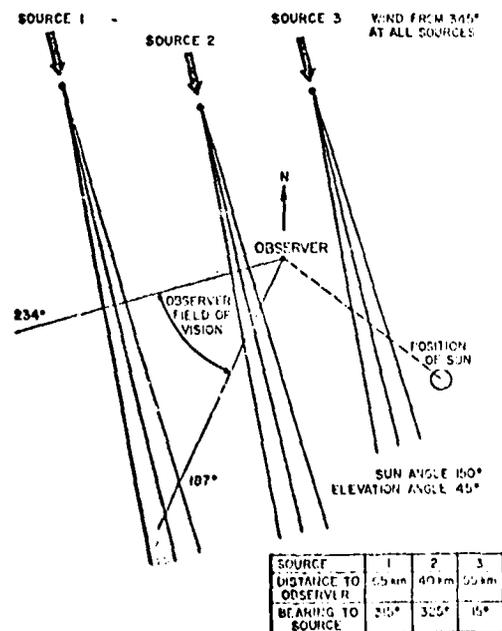


Figure 2. Source-observer geometry for case four.

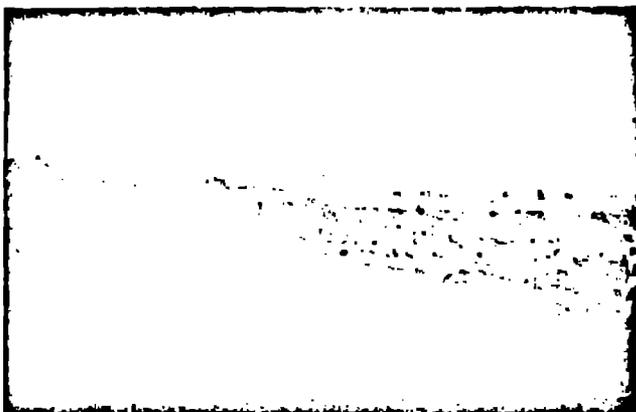


Figure 3. Computer rendition of original clean slide.



Figure 4. Computer-simulated picture of a smoke plume from a 3000-MW plant.



Figure 5. Computer-simulated picture of a smoke plume from a 3000-MW plant fitted with a precipitator.



Figure 6. Computer-simulated picture of a smoke plume from a 3000-MW plant emitting into a neutral atmosphere.



Figure 7. Computer-simulated picture of the smoke plumes from three 1000-MW power plants.

### Conclusions

A technique has been developed for simulating the visual effects of smoke plumes on a scenic vista. The technique involves digitizing information on a color slide and modifying the digitized densities as indicated by the solution of radiative transfer codes. The modified densities are displayed on a color TV console. The picture is then photographed to provide a picture of the simulated scene.

Application of the technique to large coal-fired power plants suggests that these plants may impair scenic values under some circumstances when further control devices are installed.

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### References

1. US Department of Interior, National Park Service, Denver Service Center, Analysis of Kaiparowits Power Plant Impacts on National Recreation Resources (March 1976).
2. US Environmental Protection Agency, Southwest Energy Study Air Pollution Aspects - Appendix C-1 (March 1972).
3. 95th Congress - US House of Representatives, Clean Air Act Amendments of 1977, Report No. 95-564 (August 1977).
4. Chandrasekhar, S., Radiative Transfer (Dover Publications, 1960).
5. Braslau, Norman and J. V. Dave, Effect of Aerosols on the Transfer of Solar Energy Through Realistic Model Atmospheres, IBM Research Report #RC-4114, Palo Alto, California (1972).
6. Turner, D. F., Workbook of Atmospheric Dispersion Estimates, US Dept. of Health, Education, and Welfare (1969).
7. Carpenter, S. B., T. L. Montgomery, J. M. Leavitt, W. C. Colbaugh, and F. W. Thomas, "Principal Plume Dispersion Models - TVA Power Plants," Journal of the Air Pollution Control Association, 21, pp. 491-493 (1971).
8. Briggs, Gary A., "Some Recent Analyses of Plume Rise Observation." In Proceedings of the Second International Clean Air Congress edited by H. M. Englund and W. T. Beery, pp. 1029-1032 (1971).