United States
Environmental Protection
Agency
Air

Office of Air Quality
Planning and Standards
Research Triangle Park, NC 27711

EPA-454/B-95-001
June 1996

EPA

Addendum to the User's Manual for the Plume Visibility Model, PLUVUE II (Revised)

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Addendum to the

User's Manual for the Plume Visibility Model,

PLUVUE II (Revised)

U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Emissions, Monitoring, and Analysis Division
Research Triangle Park, North Carolina 27711
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PREFACE

The User's Manual for the Plume Visibility Model, PLUVUE II (Revised), EPA-454/B-92-008 (NTIS PB93-18223) is the primary source of documentation for the PLUVUE II model. This Addendum documents revisions made to the PLUVUE II model (dated 96170). The PLUVUE II model was revised to correct several errors found in the previous version of the model and to make some minor refinements. The user should replace the related items in the user's manual with the pages provided herein. Note that the Appendix A, Comparison of the Original Version of PLUVUE II with the Revised Version for Different Stability Classes, in the user's manual is deleted.

ACKNOWLEDGMENTS

This addendum has been prepared by L. Willard Richards, Sonoma Technology, Santa Rosa, California. This effort was funded by the Environmental Protection Agency under Contract No.68D30020, with Jawad S. Touma as Work Assignment Manager. Considerable assistance was obtained from John Vimont, National Park Service.

1.0 INTRODUCTION

1.1 Overview

Sources of air pollution located near Class I areas such as national parks and wilderness areas are required by the United States Environmental Protection Agency's (EPA) Prevention of Significant Deterioration (PSD) and Visibility regulations to evaluate the impact of their facility on such Class I areas. The *Workbook for Plume Visual Impact Screening and Analysis (Revised)* (EPA, 1992) recommends the use of a plume visual impact screening model (VISCREEN) for two successive levels of screening (Levels 1 and 2). A detailed plume visual impact analysis (Level 3) is conducted using the more sophisticated plume visibility model, PLUVUE II.

The PLUVUE II model described in this document refers to a restructured and revised version of the original PLUVUE II model described in the *User's Manual for the Plume Visibility Model (PLUVUE II)* (EPA, 1984a and EPA, 1984b). The model was restructured in order to improve the user interface and computing requirements and revised to remove several errors in the original PLUVUE II code. The PLUVUE II algorithm is basically the same algorithm as developed in 1984, except for some changes to correct computer coding errors and to use "lookup" tables for the calculation of the phase functions, which describe the intensity of the scattered light as a function of the scattering angle. (For example, the intensity of the sunlight scattered to the earth by the moon depends on the phase of the moon.) Also, a program has been designed to assist the user with the application of the PLUVUE II visibility model on a personal computer by allowing the user to prepare an input file, select or create a library of Mie calculations to reduce computational time, and run the PLUVUE II model. This program is referred to as the RUNPLUVU visibility modeling system. In addition, this user's guide, which duplicates many of the sections contained in the original (EPA, 1984a) user's guide, has been transferred to WordPerfect 5.1 for easy downloading from the EPA's Technology Transfer SCRAM bulletin board.

The objective of the PLUVUE II model is to calculate visual range reduction and atmospheric discoloration caused by plumes consisting of primary particles (e.g., fly ash), nitrogen oxides, and sulfur oxides emitted by a single emission source. Primary emissions of sulfur dioxide (SO_2) and nitric oxide (NO) do not scatter or absorb light and therefore do not cause visibility impairment. However, these emissions are converted in the atmosphere to secondary species that do scatter or absorb light and thus have the potential to cause visibility impairment. SO_2 emissions are converted to sulfate ($SO_4^=$) aerosols. These aerosols are generally formed or grow to a size (0.1 to 1.0 μm) that is effective in scattering light. NO emissions are converted to nitrogen dioxide (NO_2) gas, which is effective in absorbing light. In turn, NO_2 is converted to nitric acid vapor (HNO_3), which in turn neither absorbs nor scatters light. In some situations, nitric acid may form ammonium nitrate or organic nitrate aerosol, which scatters light. However, in many nonurban plumes, nitrate probably remains as HNO_3 vapor without visual effects. Eventually, all primary particles, secondary aerosols, and gases in a plume are removed from the atmosphere as a result of surface deposition and precipitation scavenging. PLUVUE II is designed to predict the transport, atmospheric diffusion, chemical conversion, optical effects, and surface deposition of point and area source emissions.

The PLUVUE II model uses a Gaussian formulation for transport and dispersion. The spectral radiance $I(\lambda)$ (i.e., the intensity of light) at 39 visible wavelengths ($0.36 < \lambda < 0.75$ μm) is calculated for views with and without the plume. The changes in the spectrum are used to calculate various parameters that predict the perceptibility of the plume and contrast reduction caused by the plume (Latimer et al., 1978). The four key perception parameters for predicting visual impact are:

- reduction in visual range;
- contrast of the plume against a viewing background at the 0.55 μm wavelength;
- blue-red ratio of the plume; and
- color change perception parameter $\Delta E(L^*a^*b^*)$.

1.2 Limitations of the System

The plume visibility model PLUVUE II was evaluated with the 1981 VISTTA data base which was collected in the vicinity of the Kincaid Generating Station near Springfield, Illinois, and the Magma Copper Smelter near San Manuel, Arizona. Details of the model evaluation results are given in Seigneur et al. (1983).

For applications to distant Class I areas (more than 50 km from the emission source), the model is less accurate because of mesoscale wind speed, wind direction, and stability variations. Thus, the use of a Gaussian-based model for downwind distances greater than 50 km to predict visual effects is probably a conservative approach; however, this has not yet been demonstrated conclusively. Visual impacts for horizontal lines of sight are inversely proportional to the vertical extent of plume mixing. This vertical extent of plume mixing is defined by the vertical plume dispersion parameter (σ_z) and, at farther distances downwind, by the mixing depth. Thus, errors in predicting vertical plume dimensions will carry throughout the calculations of plume visibility impacts. However, until field measurements of mesoscale plume transport and diffusion are carried out, and until better models based on these data are developed and verified, the EPA does not know of a better approach to model plume dispersion for the purposes of plume visual impact analysis.

Other limitations are basic to the chemical mechanism used in PLUVUE II to predict the conversion of sulfur and nitrogen oxides. Although this mechanism is a reasonable approximation for most applications in nonurban areas, it is not valid for applications in photochemical (urban) atmospheres or for sources of significant quantities of reactive hydrocarbons. For such applications, photochemical plume models or regional models should be used.

Other approximations are used in the atmospheric optics calculations and are discussed in Latimer et al. (1978). These approximations probably do not introduce significant errors in most situations; however, this has not yet been demonstrated. Terrain viewing backgrounds are idealized as white, gray, and black objects. The background atmosphere is treated as two layers; a homogeneous, surface mixed layer and a relatively clean upper-atmosphere layer. Diffusion radiation is calculated by integrating an angle-dependent radiance field according to the algorithm of Isaacs (1981). Errors in predicting diffuse-radiation intensities may adversely affect the accuracy of spectral radiance calculations, but not necessarily the accuracy of calculations of plume contrast, color differences, and reduction in visual range. In PLUVUE II, the calculated visual impact of a plume is quantified using coloration, color difference, and contrast parameters that are related to human visual perception.

1.3 User's Guide Organization

A technical overview of PLUVUE II, PLUIN2 (algorithm which allows the user to edit PLUVUE II input files), and MIETBL (algorithm which allows the user to create Mie library files as input to PLUVUE II) is presented in Section 2.0. Detailed RUNPLUVU user instructions including the basic computer requirements, detailed operating instructions, and a Level-3 plume visibility example are presented in Section 3.0. The references are given in Section 4.0.

- Light scattering and absorption characteristics of the resultant aerosol; and
- Radiative transfer through the aerosol along different lines of sight.

2.1.1 Pollutant Transport, Diffusion, and Removal

There are two scales that are of interest in visibility impairment calculations. They require two different types of models:

- A near-source plume model designed to predict the incremental impact of one emission source (such as a power plant or smelter).
- A regional model designed to predict, over time periods of several days, the impacts of several emissions sources within a region whose spatial scale is in the range of 1000 km.

Calculation of near-source visual impacts, which is the design objective of PLUVUE II, requires a basic model that accurately predicts the spatial distribution of pollutants and the chemical conversion of NO to NO_2 and SO_x and NO_x to sulfates and nitrates. The plume model must be capable of handling the spatial scale from emissions at the source to at least 100 km downwind. Because the regional-scale problem may be caused by the long-range transport of pollutants over a spatial scale of 1000 km, an air quality model is needed that can account for multiple sources and for temporal variations in mixing heights, dispersion parameters, emission rates, reaction rates, and wind speed and direction. This second type of model, a regional visibility model, is beyond the scope of this user's manual. PLUVUE II is a near-source plume visibility model.

Initial Dilution in a Buoyant Plume

Modeling of the initial dilution of a plume from the top of the stack to the point of final plume rise is important when modeling the conversion of nitric oxide (NO) to nitrogen dioxide (NO_2) in a power plant plume because of the quick quenching of the thermal oxidation of NO. The rate of this reaction is second order with respect to NO concentrations; therefore, the rate is fastest in the initial stages of plume dilution. It is also important to account for the initial dilution of buoyant releases because the rate of dilution caused by the turbulent entrainment of ambient air by a rising plume parcel can be considerably greater than that indicated by diffusion coefficients based on measurements for nonbuoyant releases (e.g., Pasquill-Gifford σ_y, σ_z). Thus, initial plume dilution during plume rise should be taken into account to calculate accurately both plume dilution and atmospheric chemistry.

Briggs (1969) suggested that the characteristic plume radius (R_p) increases linearly with the height of the plume above the stack and can be represented as follows:

Gaussian Plume Diffusion

After the plume has achieved its final height (about 1 km downwind), plume concentrations for uniform wind fields can be predicted using a Gaussian model if the wind speed u at plume height H (or $h_s + \Delta h$, where h_s is the stack height) and the rate of diffusion are known for the particular situation so that diffusion coefficients (σ_y, σ_z) can be selected:

$$\chi = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right]\right\} . \tag{1}$$

Equation (12) is appropriate for a conservative species and can be modified to be appropriate for a nonconservative species by changing the source term Q.

It is necessary for calculating plume visual impact to integrate, along the line of sight, the plume extinction coefficient, the magnitude of which depends on primary and secondary particulate and nitrogen dioxide concentrations. Equation (12) can be integrated (Ensor et al., 1973) in the cross-wind direction y, from $y = -\infty$ to $y = +\infty$, to obtain the optical thickness of the plume:

$$\tau_{py} = \int_{-\infty}^{+\infty} b_{ext}\, dy = \frac{Q'(x)}{(2\pi)^{1/2}\sigma_z u}\left\{\exp\left[-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right]\right\} , \tag{2}$$

where b_{ext} is the incremental increase in extinction coefficient in the plume and Q' is the flux of the plume extinction coefficient over the entire plume cross section at downwind distance x. In the vertical direction z, from $z = 0$ to $z = +\infty$, the plume optical thickness is

$$\tau_{pz} = \int_{0}^{\infty} b_{ext}\, dz = \frac{Q'(x)}{(2\pi)^{1/2}\sigma_y u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] . \tag{3}$$

Observer-Plume Orientation

The magnitude of the visual impact of a plume depends on the orientation of the observer with respect to the plume because the plume optical thickness will vary depending on this orientation. Figure 1 shows plan and elevation views of an observer and a plume and indicates that the sight path distance through the constituents of the plume is a function of angles α and β. The optical thickness for most combinations of angles α and β can be approximated as follows:

- Background accumulation mode (submicron) aerosol (typically having a mass median diameter of about 0.3 μm and a geometric standard deviation of 2).

- Background coarse mode (> 1 μm) aerosol (typically having a mass median diameter of about 6 μm and a geometric standard deviation of 2).

- Plume and background carbonaceous aerosol (typically having a mass median diameter of about 0.1 μm and a geometric standard deviation of 2).

- Plume primary particulate aerosol (e.g., fly ash emissions).

- Plume secondary sulfate ($SO_4^=$) aerosol (typically having a mass median diameter of 0.1 to 0.3 μm and a geometric standard deviation of 2).

The expression developed by Winkler (1973) is used to calculate the amount of liquid water associated with submicron background and plume sulfate aerosol as a function of relative humidity.

Secondary aerosol is assumed to form in the submicron plume secondary aerosol mode. A time delay equal to the time between successive downwind distances is introduced to account for coagulation and condensation time delays.

2.1.4 Atmospheric Optics

In the atmospheric optics component of the plume visibility model, the light scattering and absorption properties of the aerosol and the resultant light intensity (spectral radiance) for various illumination and viewing situations are computed.

Calculation of the Scattering and Absorption Properties

After the concentrations of the pollutants are specified by the transport and chemistry subroutines, their radiative properties must be determined. For NO_2, the absorption at a particular wavelength is a tabulated function (Nixon, 1940) multiplied by the concentration. For aerosols, however, the procedure is more complicated.

In general, a particle's ability to scatter and absorb radiation at a particular frequency is a function of size, composition, and shape, which depend on the relative humidity. The flexibility to specify the size distribution of both primary and secondary particles was desired. The effect of these parameters on the wavelength dependence of the extinction coefficient and the angular distribution of the light scattered by particles is calculated by the Mie equations. These calculations are performed by the MIETBL algorithm and the results saved in tables as described in Section 2.3. This eliminates the need to repeat the Mie calculations with each execution of the PLUVUE II model.

Calculation of Light Intensity

The light intensity, or radiance (watts/m^2/steradian/μm) at a particular location in the atmosphere is a function of the direction of observation Ω and the wavelength λ. Calculation of the light intensity in a medium follows from the radiative transfer equation. This equation is a conservation of energy statement that accounts for the light added to the line of sight by scattering and the light lost because of absorption and scattering. Approximations and solution techniques applicable to planetary atmospheres have been discussed by Hansen and Travis (1974) and Irvine (1975).

To compute the spectral light intensity at the observer, we sum (integrate) the scattered and absorbed light over the path, r, associated with the line of sight Ω. The resultant general expression for the background sky intensity at a particular wavelength is

$$I_b(\Omega) = \int_0^{\tau_\infty} \frac{\omega(\tau)}{4\pi} \int_{\Omega'=4\pi} I(\Omega',\tau') \, p(\Omega' - \Omega,\tau') \, d\Omega' \, e^{-\tau'} \, d\tau' \quad , \tag{4}$$

where
τ = the optical depth ($\tau \equiv \int_0^r b_{ext}\,dr$, where b_{ext} is the extinction coefficient),
ω = the albedo for single scattering ($\omega \equiv b_{scat}/b_{ext}$ where b_{scat} is the scattering coefficient),
$p(\Omega' \rightarrow \Omega)$ = the scattering distribution function for the angle $\Omega' \rightarrow \Omega$, and
I = the spectral intensity at τ' from direct and diffuse solar radiation.

The intensity seen by an observer in direction Ω of a background viewing object of intensity I_o at distance R is

$$I_{obj}(\Omega) = I_o(\Omega)e^{-\tau_R} + \int_0^{\tau_R} \frac{\omega(\tau')}{4\pi} \int_{\Omega'=4\pi} I(\Omega',\tau) \, p(\Omega' + \Omega,\tau') \, d\Omega' \, e^{-\tau'} \, d\tau' \quad . \tag{5}$$

Equations (36) and (37) then completely describe the spectral intensity of the sky and a background object. Once these two quantities are known, the visual effects of the intervening atmosphere can be quantified. In evaluating Equations (36) and (37), we encounter two main

- Plume Contrast

  This parameter indicates the relative brightness of a plume compared to a viewing background. For a sight path through the plume centerline, it is equal to the radiance with the plume present minus the radiance with the plume absent, all divided by the radiance with the plume absent. A contrast that is positive indicates a relatively bright plume and a negative contrast indicates a dark plume. Plumes that subtend angles between roughly 0.1 and 1 degree and have contrasts with absolute values greater than 0.02 are generally perceptible. A two percent contrast is used to define visual range. Appendix A of the Workbook for Plume Visual Impact Screening and Analysis (Revised) should be consulted to determine the dependence of the threshold contrast on the angle subtended by the plume (EPA, 1992). Plume contrast calculations in PLUVUE II are done at one wavelength, 0.55 μm, which is a green color in the middle of the visible spectrum, which extends from 0.4 μm (violet) to 0.7 μm (red).

- Blue-Red Ratio

  This parameter indicates the relative coloration of a plume relative to its viewing background. Blue-red ratios less than one indicate relatively yellow, red, or brown plumes. Blue-red ratios greater than one indicate plumes that are whiter, grayer, or bluer than the viewing background. Blue-red ratios less than 0.9 or greater than 1.1 would be indicative of perceptible plumes.

- Color Contrast Parameter (ΔE)

  The color contrast parameter ΔE is probably the best single indicator of the perceptibility of a plume due both to its contrast and its color with respect to a viewing background. ΔE is calculated for the entire visible spectrum and indicates the difference between the brightness and color of a plume and its background. The larger the value of ΔE, the greater the perceptibility of the plume. Under ideal viewing conditions, when the viewing background is uniform and the plume is sharp-edged, a just perceptible ΔE would be equal to one. For cases of plumes with diffuse edges that subtend angles between roughly 0.1 and 1 degree, a just perceptible ΔE threshold would be greater than one, perhaps two (EPA, 1992).

2.1.7 1992 Code Modifications

In 1989 (SAI, 1989), the PLUVUE II model was revised to include an interpolated scheme to calculate the phase functions which significantly decreased the execution time of the PLUVUE II computer code. The development of an interpolation procedure to calculate phase functions needed in the visibility model was performed by Richards and Hammarstrand (1988). The phase function calculation uses "lookup" tables which contain the phase functions for different particle size distributions. Further details concerning the phase function calculations are given in Section 2.3.

Details concerning the most recent modifications to the PLUVUE II algorithm are as follows:

- Under Pasquill-Gifford stability class A conditions, PLUVUE II was found to produce numerical overflows. Diagnostic checks indicated that the interpolation formula based on a series of logarithms to calculate σ_y and σ_z in PLUVUE II have a relatively large degree of error (especially for values of σ_z). In order to avoid the numerical overflows caused by the logarithmic equations, the subroutines used to calculate σ_y and σ_z in ISC2 (EPA, 1992) were substituted for the original PLUVUE II subroutines.

- The optical depth TAUP3 in subroutine PLMOBJ becomes negative and produces light amplification rather than attenuation along a line of sight when the observer and the object are close to the plume. This was caused by a trigonometric error, which made the plume-observer distance (RP) exceed the observer-object distance (RO). The trigonometric error was corrected.

- When the scattering angle approaches the solar zenith angle near 45°, a PLUVUE II code check to avoid an inverse cosine argument outside the range (-1, 1) terminated many of the optical computations. Due to the conversion from radians to degrees plus other numerical manipulations, the distance calculations produce slight numerical arguments greater than 1.0 to the inverse cosine function. The numerical excesses were found to be of the order of less than one percent (-1.01, 1.01). As a result, for excesses less than two percent (1.000000 to 1.020000), the argument is now truncated to 1.00000 so that the estimates continue to be made. For excesses greater than two percent, should they occur, the optical estimations are stopped.

- The stability class supplied for intermediate distances seemed to be ignored by PLUVUE II. It was decided that the ability to change stability class with downwind distance should not be allowed; therefore, the option was disabled in PLUVUE II by setting NXSTAB to NX2+1 and INEW to I. NXSTAB (the index for downwind distance where stability changes from I (stability index) to INEW (secondary stability index)) and INEW are no longer input to PLUVUE II.

- The PLUVUE II model incorrectly predicted impacts for lines of sight with terrain background. It was discovered that there were errors in the PLUVUE II model when calculating the effects of multiple scattering because two of the three multiple scattering integral terms were missing from the algorithm. The corrected integral terms have been incorporated in the revised version of PLUVUE II.

In addition to the code modifications listed above, a number of cosmetic changes have been made to the code. Headers have been added to all subroutines. Unused variables and arrays, along with commented out statements, have been eliminated.

2.1.8 1995 Code Modifications

Additional modifications were made in the PLUVUE II code at the end of 1994 to remove known errors and to improve the realism of the model simulations. The reasons for modifying the code and the approach used to implement the modifications are described in this section.

- Correct an Error in Subroutine BACKOBJ

  Line BAC00620 of the subroutine BACOBJ was changed from

  ```
  SPECO(I) = SPECO(I) + G(I)
  ```

  to

  ```
  SPECO(I) = SPECO(I) + G(I)*(1.0 - TRO)
  ```

  to remove an error. Here G(I) is the source function (or equilibrium radiance), and G(I)*(1.0 - TRO) is the contribution of the path radiance (or air light) to the apparent radiance SPECO(I).

- Provide Realistic Reflectances for Black and White Terrain Backgrounds

  The reflectance of the black terrain background was changed from 0.0 to 0.1 and the reflectance of the white background from 1.0 to 0.9 to more accurately simulate the reflectances of dark, shaded forests and snow. This refinement has the greatest effect on the simulation of plumes viewed against a nearby, black background, where even the slightest scattering of light by the plume can cause large calculated contrasts if it is assumed that no light is reflected from the background. Data for the radiances of typical terrain backgrounds compared to the radiance of the horizon sky have been published by Malm et al. (1982).

- Calculate the Contrast of a Plume Against a Black Terrain Background Assuming that the Eye is Accommodated to the Radiance of the Horizon Sky

  Before this modification, the contrast of the plume against a background was calculated using the assumption that the eye was accommodated to the radiance of the background. Warren White has pointed out in unpublished correspondence that for black terrain backgrounds, it is more likely that the eye is accommodated to the radiance of the horizon sky just above the terrain than to the radiance of the black background. The PLUVUE II code was modified to calculate the contrast of a plume against a black background assuming that the eye is accommodated to the radiance of the horizon sky and to add this value to the output file.

An example from common experience provides an illustration of the need for this refinement. When a person is in a relatively dark room, his eyes are accommodated to the darkness, and objects in the room can be clearly seen. However, if that person goes outside and looks into the dark room through an open window, his eyes become accommodated to the outside light and objects in the room become difficult to perceive. In the same way, a plume against a black background that would be perceptible if the eye were accommodated to the radiance of the black background could be imperceptible if the eye is accommodated to the radiance of the horizon sky.

- Add Diffuse Skylight to the Illumination of the Reference White

The human visual system has the property that the lightest and brightest object in a scene is typically perceived as white (MacAdam, 1981). The colors of other objects are then referred to the color of this object. White clouds in the sky often provide the reference white in scenes that may include perceptible plumes.

The color difference calculations in PLUVUE II require calculating the spectral radiance of a reference white. Before this refinement, the reference white was a diffuse reflector with 100 percent reflectance that was normal to the solar rays and was illuminated only by the direct solar rays. As a result, the illumination of the reference white became too small as the sun approached the horizon. This caused the calculated color differences to become unrealistically large as the sun approached the horizon.

The code was modified so that diffuse skylight was added to the illumination of the reference white. This was accomplished by calculating the downward flux of both direct sunlight and diffuse skylight at 39 wavelengths in Subroutine BACCLI, and then subtracting the contribution of direct sunlight to the downward flux in Subroutine BACOBJ. This gave a value for the downward flux of diffuse skylight, which was added to the previously used illumination of the reference white by the direct solar rays. The contribution of the direct sunlight to the downward flux calculated in Subroutine BACCLI is calculated as the flux on a horizontal surface. Therefore, this flux cannot replace the direct solar flux calculated in Subroutine BACOBJ, which is the flux on a surface normal to the solar rays.

The same subroutine, BACOBJ, is used to both calculate the spectral radiance of the white, gray and black terrain backgrounds as well as the spectral radiance of the reference white. Thus, this code modification also increases the illumination of the terrain backgrounds, especially at low sun angles.

- Correct Errors in the Calculation of the Fraction of the Primary Particle Emissions that are Carbon and Non-carbon

  The capability of simulating the optical effects of soot in the primary particle emissions and in the background air was added to the model when PLUVUE I was converted to PLUVUE II. On review of the code, it was found that some parts of the code had not been modified to incorporate this refinement. The code was modified so the correct emission rates of carbon and non-carbon primary particles were used in all calculations.

- Define Some Variables as Characters Instead of Integers to Avoid Errors with Some Compilers

  FORTRAN 90 is replacing FORTRAN 77 as the standard. It was found that the existing code caused errors with FORTRAN 90 compilers that could be eliminated by defining some variables as characters instead of integers.

2.1.9 Input Data

The input data needed to run PLUVUE II are contained in one file of 80 byte, card-image records. As is discussed in Sections 2.2 and 3.2, the RUNPLUVU visibility modeling system allows the user to interactively edit the PLUVUE II input file. The PLUVUE II input data include the following parameters:

- Wind speed aloft or at the 10-m level
- Stability category
- Lapse rate
- Height of the planetary boundary layer (mixing depth)
- Relative humidity
- SO_2, NO_x, and particulate emissions rates
- Flue gas flow rate, exit velocity, and exit temperature
- Flue gas oxygen content
- Ambient air temperature at stack height
- Ambient background NO_x NO_2, O_3, and SO_2 concentrations
- Properties (including density, mass median radius, and geometric standard deviation) of background and emitted aerosols in accumulation (0.1-1.0 μm), coarse (1.0-10.0 μm), and carbonaceous aerosol size modes
- Coarse mode background aerosol concentration
- Background visual range or background sulfate and nitrate concentration
- Deposition velocities for SO_2, NO_x, coarse mode aerosol, and accumulation mode aerosol
- UTM coordinates of the source location
- Elevation of the source location
- UTM coordinates and elevation of the observer location for an observer-based analysis
- UTM zone for the site and observer locations
- Time, day, month, year, and time zone for the time and date of the simulation
- For an observer-based run, terrain elevation at the points along the plume trajectory at which the analysis will be performed
- For an observer-based run with white, gray, and black viewing backgrounds, the distances from the observer to the terrain that will be observed behind the plume
- For an observer-based run, the wind direction

The input data file also has numerous switches or flags to allow the user to select the particular subset of the complete model that is required. Table 1 lists the input parameters with formats, summary descriptions, and suggested values for some of the input parameters.

TABLE 1 (Continued)

DATA REQUIREMENTS FOR PLUVUE II

Card No.	Format	Variables	Description
	F10.2	QPART	Total primary particulate emissions rates from all stacks in tons per day
16	F10.1	FLOW	Flue gas flow rate (cfm) per stack
	F10.1	FGTEMP	Flue gas exit temperature (°F)
	F10.1	FGO2	Flue gas oxygen concentration (mole percent) [3]***
	F10.2	WMAX	Flue gas stack exit velocity (m/s)
17	F5.1	UNITS	Number of stacks
	F5.1	HSTACK	Stack height (feet)
18	F10.1	TAMB	Ambient temperature (°F)
19	F10.3	AMBNOX	Ambient [NO_x] in ppm [0]
	F10.3	AMBNO2	Ambient [NO_2] in ppm [0]
	F10.3	03AMB	Ambient [0_3] in ppm [0.04]
	F10.3	AMBSO2	Ambient [SO_2] in ppm [0]
20	F10.3	ROVA	Mass median radius (μm) for background accumulation mode aerosol [0.15]
	F10.3	ROVC	Mass median radius (μm) for background coarse mode aerosol [3.0]
	F10.3	ROVS	Mass median radius (μm) for plume secondary aerosol [0.10]
	F10.3	ROVP	Mass median radius (μm) of emitted primary particulate [1.0]

In MIETBL, the strength of the aerosol light scattering at the desired angles is determined by linear interpolation using data tabulated every 2°.

To calculate the light scattering properties of a log-normal size distribution of aerosol particles, it is necessary to perform Mie calculations for a number of different particle sizes in the size range of interest. These results are then averaged using weighting factors derived from the relative numbers of particles of each size in the log-normal particle size distribution.

For large particles, averaging over particle sizes is important because the angular distribution of light scattered by a single size of particles shows many peaks and valleys. When results for only a few sizes of particles are averaged, some of these peaks and valleys persist. However, when calculated results for many different particle sizes are weighted according to a log-normal distribution and averaged, the angular distribution of scattered light becomes quite smooth.

The default aerosol properties for PLUVUE II which are contained in the Mie default library are listed in Table 2. The data were obtained from a listing of input parameters presented in an earlier version of the PLUVUE II User's Manual (Seigneur et al., 1983). These six aerosol size distributions provide a compact data set that may be used when no better aerosol size distribution data are available. When using this default library, the only choice to be made is aerosol diameter (D) = 0.2 μm for the plume secondary aerosol in polluted or humid areas (e.g., east of the Mississippi) or D = 0.1 μm in clean or dry areas (e.g., the clean areas in the west or Alaska).

Hampson, R.F. Jr. and D. Garvin, 1978: Reaction Rate and Photochemical Data for Atmospheric Chemistry-1977. NBS Special Pub. 513, National Bureau of Standards, Washington,D.C.

Hanson, J.E. and L.D. Travis, 1974: Light Scattering in Planetary Atmospheres. *Space Science Reviews*, 16:527-610.

Irvine, W.M., 1975: Multiple Scattering in Planetary Atmospheres *Icarus*, 25:175-204.

Isaacs, R.G., 1981: The Role of Radiative Transfer Theory in Visibility Modeling: Efficient Approximate Techniques. *Atmos. Environ.*, 15:1827-1833.

Isaksen, I., A., Hesstredt, and O. Hov, 1978: A Chemical Model for Urban Plumes: Test for Ozone and Particulate Sulfur Formation in St. Louis Urban Plume. *Atmos. Environ.*, 12:599-604.

Kerker, M., 1969: *The Scattering of Light and Other Electromagnetic Radiation.* Academic Press, New York, NY.

Latimer, D.A. and G.S. Samuelsen, 1975: Visual Impact of Plumes from Power Plants. UCI-ARTR-75-3. UCI Air Quality Laboratory, School of Engineering, University of California, Irvine, CA.

Latimer, D.A. and G.S. Samuelsen, 1978: Visual Impact of Plumes from Power Plants. *Atmos. Environ.*, 12:1455-1465.

Latimer, D.A., R.W. Bergstrom, S.R. Hayes, M.K. Liu, J.H. Seinfeld, G.Z. Whitten, M.A. Wojcik, and M.J. Hillyer, 1978: The Development of Mathematical Models for the Prediction of Anthropogenic Visibility Impairment. EPA-450/3-78-110a,b,c. U.S. Environmental Protection Agency, Research Triangle Park, NC.

Leighton, P.A., 1961: *Photochemistry of Air Pollution.* Academic Press, New York, NY.

Malm, W.C., Pitchford M., and Pitchford A., 1982: Site Specific Factors Influencing the Visual Range Calculated from Teleradiometer Measurements. *Atmos. Environ.* 16:2323-2333.

Miller, D.F., 1978: Precursor Effects on SO_2 Oxidation. *Atmos. Environ.*, 12:273-280.

Niki, H., 1974: Reaction Kinetics Involving O and N Compounds. *Can. J. Chem.*, 52:1397-1404.

Nixon, J.K., 1940: Absorption Coefficient of Nitrogen Dioxide in the Visible Spectrum. *J. Chem. Phys.*, 8:157-160.

Richards, L.W. and R.G.M. Hammarstrand, 1988: User's Manual for Running PLUVUE and Performing Mie Calculations on a Personal Computer. Sonoma Technology Inc., Santa Rosa, CA.

SAI, 1989: Addenda User's Manual for the Plume Visibility Model (PLUVUE II). SYSAPP-89/045. Systems Applications, Inc., San Rafael, CA.

Schere, K.L. and K.L Demerjian, 1977: Calculation of Selected Photolytic Rate Constants over a Diurnal Range. EPA-600/4-77-015. U.S. Environmental Protection Agency, Research Triangle Park, NC.

Seigneur, C., R.W. Bergstrom, C.D. Johnson, and L.W. Richards, 1983: Measurements and Simulations of the Visual Effects of Particulate Plumes. Systems Applications, Inc., San Rafael, CA.

van de Hulst, H.C., 1957: *Light Scattering by Small Particles.* John Wiley & Sons, New York, NY.

Wallace, J.M. and P.V. Hobbs, 1977: *Atmospheric Science.* Academic Press, New York, NY.

White, W.H., 1977: NO_x-O_3 Photochemistry in Power Plant Plumes: Comparison of Theory with Observation. *Environ. Sci. Technol.*, 11:995-1000.

Winkler, P., 1973: The Growth of Atmospheric Aerosol Particles as a Function of the Relative Humidity--II. An Improved Concept of Mixed Nuclei. *Aerosol Sci.*, 4:373-387.

TECHNICAL REPORT DATA
(Please read Instructions on reverse before completing)

1 REPORT NO EPA-454/B-95-001	2	3 RECIPIENT'S ACCESSION NO
4 TITLE AND SUBTITLE Addendum to the User's Manual for the Plume Visibility Model, PLUVUE II (Revised)		5 REPORT DATE June 1996 6 PERFORMING ORGANIZATION CODE
7 AUTHOR(S)		8 PERFORMING ORGANIZATION REPORT NO
9 PERFORMING ORGANIZATION NAME AND ADDRESS Sonoma Technology Inc. 5510 Skylane Blvd., Suite 101 Santa Rosa, CA 95403		10. PROGRAM ELEMENT NO 11. CONTRACT/GRANT NO. EPA Contract No. 68D30020
12 SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Emissions, Monitoring & Analysis Division Research Triangle Park, NC 27711		13 TYPE OF REPORT AND PERIOD COVERED Final Report 14 SPONSORING AGENCY CODE

15 SUPPLEMENTARY NOTES

EPA Work Assignment Manager: *Jawad S. Touma*

16 ABSTRACT

This addendum documents revisions made to the PLUVUE II model to correct several errors and make some minor refinements. The user should replace the related items in the user's manual with the pages in this addendum.

17 KEY WORDS AND DOCUMENT ANALYSIS

a DESCRIPTORS	b IDENTIFIERS/OPEN ENDED TERMS	c COSATI Field/Group
Air Pollution Air Quality Dispersion Models Meteorology Visibility Aerosols		
18 DISTRIBUTION STATEMENT Release Unlimited	19 SECURITY CLASS *(Report)* Unclassified	21 NO OF PAGES 22
	20 SECURITY CLASS *(Page)* Unclassified	22 PRICE

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