Draft Final Report

POWER PLANT IMPACTS ON AIR QUALITY AND VISIBILITY: SITING AND EMISSION CONTROL IMPLICATIONS

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PREPARED BY

SYSTEMS APPLICATIONS, INC.

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I INTRODUCTION

On 19 September 1978, the Environmental Protection Agency (EPA) published in the Federal Register proposed standards of performance for new electric utility steam generating units (power plants) to revise current emission standards. In addition to making the standards for nitrogen oxide and particulate emissions more stringent, the proposed standards would require that uncontrolled SO_2 emissions be reduced by 85 percent. The intent of these proposed regulations is to require new power plants "to use the best demonstrated systems of continuous emission reduction," namely, flue gas desulfurization (SO_2 scrubbers).

In proposing these regulations, the EPA has stated (Federal Register, 1978a, p. 42154):

> The principal issue associated with this [emission standard] proposal is whether electric utility steam generating units firing low-sulfur-content coal should be required to achieve the same percentage reduction in potential SO_2 emissions as those burning higher sulfur content coal. Resolving this question of full versus partial control is difficult because of the significant environmental, energy, and economic implications associated with each alternative [emission standard].

In November 1978, the EPA's Office of Planning and Evaluation contracted with Systems Applications, Incorporated (SAI) to study the air quality and visibility implications of alternative New Source Performance Standards (NSPS) for SO_2. This report describes that study and the conclusions reached regarding the impacts on air quality, visual range, and atmospheric discoloration and the constraints on power plant siting resulting from alternate SO_2 emission control requirements.

We studied three alternate SO_2 emission floors (i.e., maximum required control levels): 0.2, 0.5, and 0.8 pounds of SO_2 per million Btu heat input ($lb/10^6$ Btu). In addition, we investigated the emission ceiling for coal (or lignite) of 1.2 $lb/10^6$ Btu.

In this study, we attempted to answer the following questions:

> What will be the air quality impacts associated with new power plants meeting alternate emission standards?

> Will these impacts cause exceedances of Prevention of Significant Deterioration (PSD) Regulations?

> What will be the impact of alternate emission regulations on visibility impairment (including reductions in visual range and atmospheric discoloration)?

> What are the implications of alternate SO_2 emission regulations on power plant siting?

> What is the maximum regional power plant siting capacity?

> How close can a power plant be sited to a Class I (pristine) area without causing significant visibility impairment or exceedances of PSD increments?

> How close can a power plant be sited to elevated terrain without causing violations of PSD Class I, II, or III increments or National Ambient Air Quality Standards (NAAQS)?

> What are the implications for power plant siting in the regions of the western United States where the terrain is complex and the number of Class I areas is large?

Chapter II of this report summarizes the conclusions of our study. Chapter III outlines the basis for our air quality and visibility calculations. Chapter IV describes the impacts of individual power plants, and Chapter V outlines estimated cumulative regional impacts resulting from regional power plant development. In conclusion, Chapter VI presents recommendations for future studies.

II SUMMARY AND CONCLUSIONS

We have analyzed the impact of various sizes of power plants, which emit SO_2 and NO_x at various rates, using EPA-recommended air quality models and SAI models to estimate air quality impacts and visibility impairment caused by power plant plumes over the long range ($>$ 100 km downwind) and on a regional scale. On the basis of these analyses, we have drawn tentative conclusions of profound significance to air quality planning in the following areas:

- Air quality impacts caused by individual power plants.
- Visibility impairment.
- Constraints on power plant siting.
- Cumulative regional impacts.
- Implications for emission control.
- Needs for further research.

Each of these is discussed below.

A. AIR QUALITY IMPACTS CAUSED BY INDIVIDUAL POWER PLANTS

Our conclusions about the air quality impacts of individual power plants are as follows:

- The Prevention of Significant Deterioration Regulations, which limit increases in 3-hour- and 24-hour-average SO_2 concentrations, impose the most restrictive limitations on power plant emissions and siting.
- Maximum 3-hour- and 24-hour-average SO_2 Class I area increments will restrict the siting of and SO_2 emissions from coal-fired power plants located in Class II areas as far as 100 to 200 km away from Class I areas.

- Limited mixing conditions, during which vertical mixing of emissions is restricted by stable layers 500 to 1000 m above the ground, are likely to be associated with the highest 3-hour- and 24-hour-average SO_2 ground-level concentrations; however, in complex terrain areas even higher ground-level concentrations are likely to occur as a result of plume impingement on elevated terrain.
- Surface deposition of SO_2 and conversion of SO_2 to sulfate must be considered in models that are designed to calculate impacts beyond 100 km from a power plant. More than half of the initially emitted SO_2 will be lost by surface deposition at distances greater than 200 km during light-wind, limited mixing conditions.
- The wind speed that maximizes the impact of power plant emissions on ground-level SO_2 concentrations increases linearly with the downwind distance of the receptor of concern. Thus, maximum concentrations at 100 km downwind are likely to occur with light winds (1 to 2 m/sec), whereas those at 200 to 500 km are likely to occur with moderate winds (3 to 6 m/sec).
- Maximum ground-level surface concentrations are not likely to occur less than 100 km downwind; however, plume centerline concentrations of sulfate are likely to remain relatively constant with downwind distance since plume dilution is counterbalanced by additional sulfate formation.
- Sulfate mass fluxes tend to increase monotonically with downwind distance, whereas NO_2 fluxes appear to reach maxima between 20 and 100 km downwind of the power plant, depending on atmospheric stability.
- The fraction of initial SO_x or NO_x emissions that has been deposited by the time a plume parcel is transported to a given downwind distance depends on the travel time, the rate of plume mixing, ground-level concentrations, and the deposition velocity.

B. VISIBILITY IMPAIRMENT

With regard to visibility impairment caused by power plant emissions, we have concluded that:

> Reductions in visual range caused by power plant emissions depend on the SO_2 emission rate and the rate at which gaseous emissions are converted to aerosol. Assuming a 0.5 percent per hour SO_2-to-$SO_4^=$ conversion rate and a typical western U.S. background visual range of 130 km, a 2000 Mwe (megawatts of electric output) power plant, during worst-case dispersion conditions, will cause maximum visual range reductions of 11, 28, 40, and 51 percent as a result of SO_2 emission rates of 0.2, 0.5, 0.8, and 1.2 lb/10^6 Btu, respectively. The same plant would cause visual range reductions of 2, 4, 7, and 11 percent, respectively, if it were located in an area with a background visual range of 15 km (a value typical of the eastern United States). These estimates correspond to maximum ground-level sulfate concentrations of 1, 3, 5, and 8 $\mu g/m^3$ for SO_2 emission rates of 0.2, 0.5, 0.8, and 1.2 lb/10^6, respectively.

> These estimates of maximum visual range reduction are based on the assumptions of worst-case meteorological conditions, location of the observer at ground level within the plume 350 km from the power plant, and an observer's line of sight along the plume axis. If the observer's line of sight is perpendicular to the plume axis, visual range reductions are smaller: 4, 9, 14, and 21 percent, respectively, for the case assuming a background visual range of 130 km.

> Visual range reduction during worst-case meteorological conditions is at least a factor of 5 larger than what it would be during average meteorological conditions (with higher wind speeds and mixing depths).

> Yellow-brown plumes are expected to be visible only when the background visual range is great--for example, in the nonurban areas of the western United States--and only during stable, light-wind conditions. Since such wind conditions are expected to persist for 11 to 17 hours at a time, yellow-brown plumes could be transported to 100 to 150 km downwind from a coal-fired power plant located in the western United States.

> During typical well-mixed and ventilated atmospheric conditions, plumes from power plants meeting the proposed New Source Performance Standards would not be visible, regardless of the SO_2 emission rate floor.

C. AIR QUALITY CONSTRAINTS ON POWER PLANT SITING

We have reached the following conclusions about air quality constraints on power plant siting:

> Power plants that are 1000 Mwe or larger emitting 0.8 lb $SO_2/10^6$ Btu, or 2000 Mwe or larger emitting 0.5 lb $SO_2/10^6$ Btu, may cause maximum 24-hour-average ground-level SO_2 concentrations in excess of the PSD Class II increment of 91 $\mu g/m^3$, according to calculations using air quality models recommended by the EPA.

> According to calculations using the EPA's Valley Model, 2000 Mwe power plants will have to be sited at least 18 km away from elevated terrain if SO_2 emissions are well controlled (0.2 lb/10^6 Btu) and at least 50 km away if SO_2 emissions are 0.8 lb/10^6 Btu in order to meet Class II PSD increments. Even small (500 Mwe), well-controlled (0.2 lb $SO_2/10^6$ Btu) power plants will have to be sited at least 50 km from elevated terrain in Class I areas.

> On the basis of calculations using EPA air quality models, power plants having capacities of 2000 Mwe or larger, even with SO_2 emission rates as low as 0.2 lb/10^6 Btu, will have to be sited

at least 100 km from Class I areas to meet the Class I 24-hour-average SO_2 PSD increment of 5 $\mu g/m^3$. Large power plants (2000 to 3000 Mwe) that burn high-sulfur coal or that have only partial SO_2 control (0.8 to 1.2 $lb/10^6$ Btu) may have to be sited as far as 200 km from Class I areas.

> In the western United States, which has excellent background visual range, large coal-fired power plants may have to be sited at least 100 to 150 km from Class I areas to prevent the occurrence of yellow-brown haze in scenic areas during periods of poor atmospheric dispersion.

> Since maximum reductions in visual range occur more than 200 km downwind of a power plant, the protection of visual range in Class I areas cannot be achieved practically through constraints on siting alone.

> From 60 to 90 percent of the land area of the western United States (the states of and westward of Montana, Wyoming, Colorado, and New Mexico) may have to be excluded as sites for large coal-fired power plants to prevent significant deterioration of air quality and visibility in Class I areas.

D. CUMULATIVE REGIONAL IMPACTS

Our conclusions about the cumulative regional impacts of power plant emissions are:

> As a result of PSD Regulations, it may be necessary to limit increases in regional SO_2 emission density to 0.08 to 0.11 $g/km^2/sec$.

> With the above increases in regional SO_2 emission density, regional average sulfate concentrations will be increased by 1 or 2 $\mu g/m^3$, and visual range will be reduced 18 percent in the western United States and 4 percent in the eastern United States on worst-case days.

- On typical days with good ventilation, reductions in visual range will be much less--about 4 percent in the western United States and 1 percent in the eastern United States.

E. IMPLICATIONS FOR POWER PLANT EMISSION CONTROL

We have concluded that the implications of our findings for power plant emission control are:

- According to calculations using air quality models recommended by the EPA, it may be necessary to limit SO_2 emissions from power plants to less than 1 kg/sec, or about 100 tons per day, to meet Class II PSD Standards in level terrain. Even greater control may be necessary to meet those standards in complex terrain. This emission rate is the equivalent of about 0.8 lb/10^6 Btu for a 1000 Mwe plant and 0.4 lb/10^6 Btu for a 2000 Mwe plant.
- If SO_2 emissions from power plants located in the western United States that burn low-sulfur coal are not well controlled (resulting in SO_2 emission rates less than 0.2 lb/10^6 Btu), then siting alternatives will be restricted by the required minimum separation distance between the site and elevated terrain or Class I areas. This outcome will occur regardless of the SO_2 emission floor that is selected for New Source Performance Standards.
- With less stringent SO_2 control (increased SO_2 emissions), limitations become more severe on power plant size, power plant siting relative to elevated terrain and Class I areas, and the number of power plants that can be built in a region.
- It appears that with any of the anticipated SO_2 emission floors considered (0.2, 0.5, and 0.8 lb/10^6 Btu), PSD increments will not be used up within regions in the eastern United States as a result of planned power plant development in the next 20 years, assuming judicious and well-planned siting. However, as noted above, power plants located in the western United States will require full SO_2 control, regardless of emission standards, to meet stringent PSD Class I Regulations.

- It appears that the siting and SO_2 emission constraints imposed by effective enforcement of PSD Class I SO_2 increments may be sufficient to prevent significant visibility impairment in Class I areas during most atmospheric dispersion conditions. However, during limited mixing or stable, light-wind conditions, visual range may be reduced by as much as 20 to 50 percent, and yellow-brown haze may be visible in Class I areas in the western United States as a result of power plant emissions more than 200 km away. The meteorological conditions that would cause such impairment are expected to occur only a few days each year in the western United States. The incremental impact of power plant emissions on visibility in the eastern United States will be much smaller because of the relatively poor background visual range in that region.
- Control of SO_2 emissions from power plants will reduce impacts on visual range at locations several hundred kilometers downwind but will increase the yellow-brown plume coloration caused by NO_x emissions. Control of NO_x emissions from power plants will reduce atmospheric discoloration but will not significantly reduce impacts on visual range.
- Long term air quality and visibility goals may require both SO_2 and NO_x emission control, particularly for large power plants located in the western United States.

F. RESEARCH NEEDS

From the results of our study, we have determined the following needs for further research:

- Air quality simulation models that provide realistic estimates of the transport, diffusion, chemical transformation, and visual effects of power plant emissions at distances more than 50 km downwind must be developed, tested, refined, and validated.

- The frequency of occurrence and persistence of meteorological conditions that cause potential exceedances of PSD increments must be quantified for different regions of the country.
- Cumulative impacts resulting from proposed new sources should be analyzed in detail. In particular, the impacts of planned regional energy development in the western United States on air quality and visibility in scenic Class I areas should be evaluated.
- Tentative conclusions based on this short study should be critically examined in future, more detailed analyses because of their significant siting and control implications.

III BASES FOR CALCULATIONS

This chapter outlines the methodology, assumptions, and techniques used in our study. These bases for calculations can be categorized as follows:

> Power plant emission conditions.
> Air quality and PSD Regulations.
> Meteorological scenarios and air quality modeling.
> Visibility modeling.

A. EMISSION CONDITIONS

We evaluated air quality and visibility impacts for several sizes of power plants: 500, 1000, 2000, and 3000 Mwe. The power plants of larger capacity were assumed to consist of multiple 500 Mwe units, an average size for new coal-fired boilers. The 3000 Mwe size is believed to be the largest capacity likely to be installed at a given site. The 1000 Mwe size is probably representative of a small power station, and the 2000 Mwe size (consisting of four 500 Mwe boilers) is believed to be most typical of developments at a single site.

Power plant emission conditions for this study were selected by the EPA based on the assumption that the power plant would be equipped with SO_2 (wet) scrubbers and stack heights representing "good engineering practice." Power plant emission conditions were assumed as follows:

Variable	Value
Stack height	500 ft
Number of stacks per boiler	1
Flue gas temperature	175°F (scrubbed temperature of 125°F plus 50°F reheat)
Flue gas flow rate	2540 acfm/Mwe at 175°F (1,270,000 acfm per stack)
Overall power plant heat rate	9000 Btu/kwh (equivalent to a thermal efficiency of 38%

SO_2 emission rates of 0, 0.2, 0.5, 0.8, and 1.2 pounds per million Btu and NO_x emission rates of 0, 0.2, 0.5, 0.6, and 0.8 pounds (as NO_2) per million Btu were evaluated. Although the particulate (fly ash) emission standard is 0.03 $lb/10^6$ Btu, we found that the 20 percent opacity standard is the most restrictive on the particulate emission rate. (The opacity requirement limits particulate emissions to 70 percent of 0.03, or 0.02 $lb/10^6$ Btu.)

A simple formula can be used to express the overall mass emission rates as a function of emission standards and power plant size:

$$\begin{aligned} Q_0 &= (E\ lb/10^6\ Btu)\ (P\ Mwe) \\ &\quad \times (9000\ Btu/kwe\text{-}hr)\ (1000\ kwe/Mwe) \\ &\quad \times (453.6\ g/lb)\ (1\ hr/3600\ sec) \\ &= 1.134\ (E)(P)\ (g/sec) \end{aligned}$$

It is instructive to compare the SO_2 emission rates evaluated ($0 < E < 1.2$ $lb/10^6$ Btu) to the rates that would result from the combustion of various types of coal. Table 1 indicates the sulfur content, heating value, and resulting uncontrolled and controlled SO_2 emission rates in pounds per million Btu for several typical U.S. coals. Note that several low-sulfur coals, after 85 percent SO_2 control, result in emissions of less than 0.2 $lb/10^6$ Btu; however, use of a Midwest (Illinois) coal would cause SO_2 emissions to be almost at the emission ceiling of 1.2 $lb/10^6$ Btu. Thus, the various SO_2 emissions considered in our study could result from the imposition of alternative floors (0.2, 0,5, and 0.8 $lb/10^6$ Btu) or from 85 percent control of a high-sulfur coal, irrespective of the SO_2 floor.

TABLE 1. SUMMARY OF TYPICAL U.S. COALS AND RESULTING SO_2 EMISSIONS

Type of Coal	Sulfur Content* (percent)	Heating Value* (Btu/lbm)	SO_2 Emission Rate ($lb/10^6$ Btu) Uncontrolled	85% Control
Anthracite (Pennsylvania)	0.8	12,880	1.24	0.19
Semi-anthracite (Arkansas)	1.7	13,880	2.45	0.37
Bitiminous				
Pensylvania	1.0	14,310	1.40	0.21
Kentucky	2.8	11,680	4.79	0.72
Illinois	3.8	10,810	7.03	1.05
Subbituminous				
Wyoming	0.5	9,610	1.04	0.16
Colorado	0.3	8,560	0.70	0.11
Lignite (North Dakota)	0.9	7,000	2.57	0.39

* Source: Ode (1967).

B. AIR QUALITY AND PSD STANDARDS

To evaluate power plant impacts on ambient air quality, we compared calculated ground-level SO_2 concentrations with the following National Ambient Air Quality Standards and PSD increments:

Standard	SO_2 Concentrations ($\mu g/m^3$) 3-Hour Average	24-Hour Average
PSD Class I	25	5
PSD Class II	512	91
PSD Class III	700	182
NAAQS	1300	365

It can easily be shown that for power plants the SO_2 PSD increments and air quality standards, not those for particulate and NO_2, are most controlling. Furthermore, as shown in the next section, the 24-hour-average SO_2 PSD increments, rather than the 3-hour-average or annual average, are most restrictive based on EPA-recommended modeling procedures.

C. METEOROLOGICAL SCENARIOS AND MODELING APPROACHES

In the 19 June 1978 Federal Register, the EPA referenced two documents that provide guidance on air quality modeling approaches to be used in evaluating power plant compliance with PSD Regulations (EPA, 1978; Budney, 1977). The EPA recommends Gaussian modeling approaches and various (somewhat conservative) screening techniques to determine whether there is a possibility of an exceedance of an ambient air quality standard. These EPA-recommended models were used in this study.

The EPA stated (Federal Register, 1978b):

> . . . EPA's assessment of the air quality impacts of new major sources and modifications will be based on EPA's "Guidelines on Air Quality Models," OAQPS 1.2-080, U.S. Environmental Protection Agency, Research Triangle Park, N.C. 27711, April, 1978. This guideline is incorporated by reference into the regulations. Sources may request approval from the Administrator to use air quality dispersion models other than those noted in the "Guideline." If the Administrator determines that the model recommended in the "Guideline" and the model proposed by a source are comparable, the proposed model may be used. . . .
>
> EPA intends to retain the screening procedures set forth in "Guidelines for Air Quality Maintenance Planning and Analysis, Vol. 10 (Revised), Procedures for Evaluating Air Quality Impact of New Stationary Sources," (October 1977, U.S. EPA, Office of Air Quality Planning and Standards, Research Triangle Park, N.C. 27711). . . .
>
> [EPA] intends to limit generally the application of air quality models to a downwind distance of no more than 50 kilometers. This is because dispersion parameters commonly in use are based on experiments relatively close to sources, and extending these parameters to long downwind distances results in great uncertainty as to the accuracy of the model estimates at such distances. . . .
>
> However, since the 1977 Amendments provide special concern for Class I areas, any reasonably expected impacts for these areas must be considered irrespective of the 50 kilometer limitation or the above significance levels.

In our study, we used modeling approaches outlined in the EPA's "Guidelines for Air Quality Maintenance Planning and Analysis, Volume 10" (Budney, 1977). These Gaussian models have the following formulation:

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

where

χ = pollutant concentration ($\mu g/m^3$),
Q_o = pollutant emission rate (g/sec),
f = concentration ratio factors of 0.9 and 0.4 for 3- and 24-hour averages, respectively,
σ_y, σ_z = Pasquill-Gifford dispersion coefficients, which are functions of atmospheric stability and downwind distance x,
u = wind speed (m/sec),
y = crosswind distance of receptor point from plume centerline (m),
z = elevation difference between receptor point and the power plant site (m),
H = effective plume height (m), equal to the stack height plus plume rise.

Using EPA-recommended plume rise models based on Briggs' formulation, we calculated effective plume heights ranging from 300 m for stable, light-wind or neutral, strong-wind conditions to 640 m for neutral, light-wind conditions.

One of the worst-case meteorological conditions occurs when plume mixing is limited by a stable layer at elevation H_m. In such a situation, the plume eventually becomes uniformly mixed vertically for $0 < z < H_m$:

$$\chi = \frac{fQ_o}{(2\pi)^{1/2}\sigma_y H_m} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (2)$$

Using the EPA guidelines documents, we selected the following meteorological conditions to analyze worst-case atmospheric dispersion conditions:

> Limited mixing conditions, Pasquill C stability, $u = 2.5$ m/sec ($0 < x < 50$ km).
> Limited mixing conditions, Pasquill D stability, $u = 7.5$ m/sec ($0 < x < 100$ km).
> Stable conditions, Pasquill E stability, $u = 4$ m/sec ($0 < x < 100$ km).
> Plume impingement conditions, Pasquill F stability, $u = 2.5$ m/sec, EPA Valley Model (Burt, 1977)--appropriate for elevated terrain only ($0 < x < 50$ km).

Although the EPA plans "to limit generally the application of air quality models to a distance of no more than 50 km" (Federal Register, 1978b), the Volume 10 guidelines document (Budney, 1977) provides guidance for estimating impacts at distances up to 100 km downwind. We have used these recommended models in this study. In addition, we found that evaluation of potential air quality impacts in Class I areas required estimation of the power plant impacts at distances more than 100 km from a plant site. Therefore, in addition to the EPA-recommended approaches for downwind distances up to 100 km, we used a model with the following characteristics to estimate impacts at distances greater than 100 km:

> Uniform concentration within a sector subtending 11.25°.
> Uniform concentrations in the vertical direction within the mixed layer ($0 < z < H_m$).
> Mixing depth H_m of 1000 m.
> Wind speed u_c so as to maximize the concentration at each downwind distance (see below).

> Depletion of the initial SO_2 flux Q_o as a function of downwind distance (travel time) resulting from sulfate formation and SO_2 surface deposition.
> SO_2-to-$SO_4^=$ conversion rate k of 0.5 percent per hour.
> SO_2 surface deposition velocity v_d of 1 cm/sec.
> EPA-recommended 3-hour- and 24-hour-average concentration ratio factors f of 0.9 and 0.4, respectively.

This model can be stated mathematically as follows:

$$\chi = \frac{fQ_o e^{-[k+(v_d/H_m)]x/u}}{\left(2 \tan \frac{11.25°}{2}\right) u_c H_m} \qquad (3)$$

We can find the wind speed u_c at each downwind distance that maximizes χ by taking the derivative of χ with respect to u at each given downwind distance, setting the derivative equal to zero, and solving for u_c as follows:

$$\frac{d\chi}{du} = C_1 \left[\frac{\left(k + \frac{v_d}{H_m}\right) x}{u_c^3} - \frac{1}{u_2^2} \right] = 0 \qquad (4)$$

Thus, at any given distance x, the wind speed u_c that maximizes the concentration is simply:

$$u_c = \left(k + \frac{v_d}{H_m}\right) x \qquad (5)$$

Substituting Eq. (5) into Eq. (3) and simplifying, we have:

$$\chi = fQ_o \left[\left(0.535\right) \left(k + \frac{v_d}{H_m}\right) x^2 H_m \right]^{-1} \qquad (6)$$

Using the selected values for k, v_d, and H_m, we have the following formula for estimating power plant impacts at downwind distances x greater than 100 km:

$$\frac{\chi}{Q_o} = f\left(\frac{1.64 \cdot 10^{-4}}{x^2}\right) \sec/m^3 \qquad \text{when x is in km.} \qquad (7)$$

When one evaluates Eq. (5) for the values of parameters selected, he obtains:

$$u_c = (1.14 \cdot 10^{-2}) \text{ m/sec} \qquad \text{when x is in km.}$$

Thus, maximum concentrations at 200 km are predicted to occur with a wind speed of 2.3 m/sec; such winds would transport emissions from the power plant to the receptor location in 24 hours. Also note from Eq. (7) that concentrations fall off with the square of the distance downwind. This relationship results for two reasons: With increasing downwind distance, (1) the plume width is assumed to increase linearly, and (2) the pollutant flux is decreasing owing to surface deposition and conversion to sulfate.

The model used to estimate regional air quality impacts and visual range reduction due to several power plants sited throughout a region is described in Chapter IV.

D. VISIBILITY IMPAIRMENT

The impacts of different rates of power plant SO_2 and NO_x emissions on visual range and atmospheric coloration were evaluated using a plume visibility model recently developed for the EPA by SAI (Latimer et al., 1978). The reader is referred, in particular, to Volumes I and III of that report for a complete description of the model and the parameters used to characterize visibility. In this section, we briefly describe the four parameters that have been used to characterize visibility impairment and the assumptions made in the model calculations.

1. Parameters That Characterize Visibility Impairment

We used four parameters to characterize visibility impairment caused by power plant plumes:

> Percentage reduction in visual range
> Blue-red ratio
> Plume contrast
> ΔE.

Each is discussed below.

Visual range is defined as the farthest distance at which a black object can be perceived against the clear horizon sky. The percentage reduction in visual range is calculated as follows:

$$\left(1 - \frac{r_v}{r_{v0}}\right) \times 100 \text{ percent}$$

where r_v is the visual range for views through the plume center and r_{v0} is the visual range without the plume (ambient background visual range). In most situations, the percentage reduction in visual range is directly proportional to the integral of the plume light scattering and absorption coefficients along the line of sight and is independent of the background visual range. The percentage reduction in visual range is indicative of the "haziness" of objects observed through the plume. Until it is diffused, the plume will affect only a few of the observer's lines of sight; therefore, calculated visual range reduction pertains only to specific lines of sight through the plume center (perpendicular to the plume centerline), not to prevailing visibility. The magnitude of visual range reduction is not necessarily related to the perceptibility of the plume or to atmospheric discoloration. A significant reduction in visual range could occur without a perceptible plume or atmospheric discoloration.

The blue-red ratio indicates the coloration of the plume relative to the unaffected background sky. It is the ratio of the plume light intensity at the blue end of the visible spectrum (λ = 0.4 μm) to that at the red end (λ = 0.7 μm) divided by the same ratio for the background:

$$R = \frac{I_{plume}(blue)/I_{back}(blue)}{I_{plume}(red)/I_{back}(red)}$$

A ratio of 1 indicates that the plume is the same color as the background sky, though not necessarily of the same brightness. Ratios greater than 1 indicate bluish discoloration relative to the background, and ratios of less than 1 indicate yellowish discoloration. If the background sky is blue, the plume could be white or gray with a ratio of less than 1 because the ratio is a relative discoloration index. The plume color will be a more saturated yellow with decreasing values of this ratio (<0.9).

Plume contrast is the normalized difference in light intensity of the plume relative to the background:

$$C_p = \frac{I_p(0.55\ \mu m) - I_b(0.55\ \mu m)}{I_b(0.55\ \mu m)}$$

Contrast is evaluated at a wavelength λ of 0.55 μm, which is the midpoint of the visible spectrum where the human eye is most sensitive. With no color shifts (that is, with a blue-red ratio = 1), a plume will be visible only if it is sufficiently brighter ($C_p > 0$) or darker ($C_p < 0$) than the background sky. There are no experimental data concerning the perceptibility threshold contrast for plumes. A threshold contrast of 0.02 is used in defining the perceptibility of a dark object against the horizon sky in the calculation of visual range; however, it is likely that the threshold contrast for plumes is greater than 0.02 because, in many cases, the boundary between a plume and the background is not distinct owing to the nature of plume dilution. The use of the blue-red ratio in conjunction with the plume contrast at 0.55 μm is a simple way of characterizing plume color. When $R > 1$, the plume is more blue than the background; when $R < 1$, the plume is redder (or more yellow-brown); when $R = 1$, with $C_p(0.55\ \mu m) > 0$, the plume is a brighter white than the horizon, and with $C_p(0.55\ \mu m) < 0$, the plume is a darker gray.

The final step in the quantification of plume perceptibility is the specification of color differences--differences both in color and brightness. In 1976 the Commission Internationale de l'Eclairage (CIE) adopted two color difference formulae by which the perceived magnitude of color differences can be calculated. Color differences are specified by a parameter ΔE, which is a function of the change in light intensity or value (ΔL^*) and the change in chromaticity ($\Delta x, \Delta y$). ΔE can be considered as a distance between two colors in a color space. The color space is defined such that equal distances (ΔE) between any two colors correspond to equally perceived color changes. This suggests that a threshold (ΔE_0) can be found to determine whether a given color change is perceptible.

Since the CIE could not decide between two different proposed formulae for ΔE, both were adopted in 1976 as standard means by which color differences can be specified. These color differences, which are labeled $\Delta E(L^*U^*V^*)$ and $\Delta E(L^*a^*b^*)$, are calculated by the plume visibility code. We have elected to plot $E(l^*a^*b^*)$. ΔE's greater than 20 indicate a strong discoloration, ΔE's between 5 and 20 represent weak discoloration, and those less than 5 indicate that a plume would probably not be perceptible. It is currently uncertain as to what the thresholds of perceptibility are in terms of values of blue-red ratio, plume contrast, and ΔE.

Figure 1 summarizes these qualitative interpretations of the quantitative specifications of visibility impairment. This figure provides a key to Figures 8 and 9 presented in Chapter III.

2. Assumptions Used in the Model Calculations

Visibility impairment was calculated for ambient conditions typical of the western United States for the following reasons:

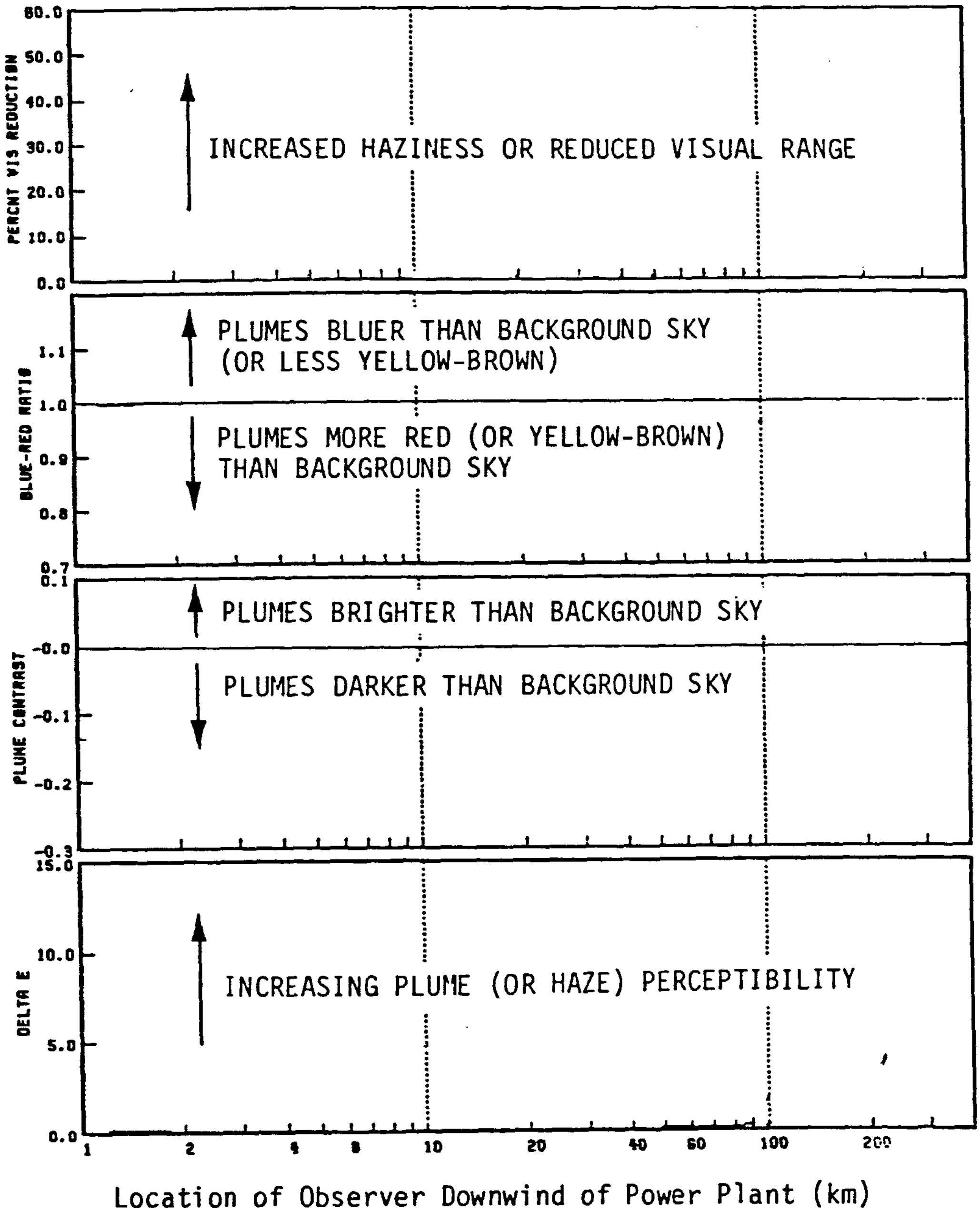

FIGURE 1. KEY TO PARAMETERS USED TO CHARACTERIZE VISIBILITY IMPAIRMENT

> The greatest atmospheric discoloration was found by previous studies (Latimer et al., 1978) to occur in the western United States, where excellent visibility makes plume discoloration easily observable. Indeed, because of the relatively poor background visual range in the eastern United States, plume discoloration would rarely be seen there.
> Calculations of the percentage reduction in visual range caused by power plant plumes based on an assumed background visual range typical of the western United States will be valid for the eastern United States, assuming that all of the plume aerosol flux is within the visual range of the observer (10 to 30 km) and that sulfate formation rates and relative humidity are equal. However, at large downwind distances (>200 km), percentage reductions in visual range calculated for the western United States will overestimate impairment in the eastern United States because some of the plume sulfate will have dispersed beyond the visual range.

The following conditions were assumed in our visibility calculations:

> The observer looks horizontally across the plume at a given downwind distance.
> The sun zenith angle is 45°.
> The scattering angle (between direct solar radiation and the observer's line of sight) is 90°.
> The observer is located 5 km from the plume centerline.
> The background visual range is 130 km.
> The background ozone concentration is 40 ppb.
> The SO_2-to-$SO_4^=$ aerosol conversion rate is 0.5 percent per hour.
> The NO_x-to-NO_3^- aerosol conversion rate is 0 percent per hour.
> The mixing depth (H_m) is 1000 m (for Pasquill C and D stabilities).
> The Pasquill stability categories are C, D, E, and F.
> The surface deposition velocities for gases and aerosols are 1 and 0.1 cm/sec, respectively.

IV IMPACTS OF INDIVIDUAL POWER PLANTS AND THEIR IMPLICATIONS FOR EMISSION CONTROL AND SITING

This chapter discusses the impacts of individual power plants ranging in size from 500 to 3000 Mwe on ambient air quality and visibility. The impacts of alternative SO_2 and NO_x emission rates are also described, along with the implications of PSD Regulations and visibility protection for Class I areas, particularly those related to power plant siting and SO_2 and NO_x emission control.

A. IMPACTS ON GROUND-LEVEL AIR QUALITY

EPA-recommended air quality models and meteorological scenarios were used to calculate ground-level concentrations as a function of distance downwind of a power plant. EPA-recommended models for plume impingement on elevated terrain and for limited-mixing, light-wind conditions in flat terrain were used for downwind distances $0 < x < 50$ km. For distances $0 < x < 100$ km, EPA-recommended models were used to model ground-level concentrations in flat terrain resulting from stable conditions and from moderate-wind, limited-mixing conditions. These calculations were supplemented with long range transport model calculations for distances beyond 100 km downwind. The transport model developed for this study assumes uniform mixing within a 11.25° sector between ground level and 1000 m aloft and reductions in SO_2 flux resulting from surface deposition and sulfate formation.

To make tractable the calculation of both 3-hour- and 24-hour-average SO_2 concentrations due to emissions from hypothetical power plants of different sizes (Mwe) and SO_2 emission rates (lb/10^6 Btu), we calculated the maximum short-term-average (less than 1 hour) SO_2 concentrations χ_{peak} normalized by SO_2 emission rate Q_o. Thus, with this normalized χ/Q_o, we can compute 3-hour or 24-hour concentrations using a simple ratio:

$$\chi_{ave} = f_{ave/peak}\, Q_o \left(\frac{\chi_{peak}}{Q_o} \right) \qquad (8)$$

Figure 2 shows these short-term-average (χ/Q)'s as a function of downwind distance and meteorological/atmospheric dispersion condition. Note that the units of χ/Q are seconds per cubic meter.

We have provided clear plastic overlays so that the procedure for obtaining the ratios described above can be performed graphically by the reader. For this task, select the clear plastic overlay corresponding to the averaging period desired (3 or 24 hour), and align the overlay on the χ/Q figure by placing the "x" on the overlay sheet directly on top of the "x" corresponding to the desired power plant size (500, 1000, 2000, or 3000 Mwe) and SO_2 emission rate (0.2, 0.5, 0.8, or 1.2 $lb/10^6$ Btu). Note that these plastic overlays show the values of the NAAQS and the Class I, II, and III PSD increments. Thus, the reader can determine the maximum 3-hour- and 24-hour-average SO_2 concentrations resulting from power plants of given SO_2 emissions and can immediately find out whether the power plant would be in compliance with PSD increments and air quality standards.

B. IMPLICATIONS OF PSD AND ALTERNATE SO_2 EMISSION CONTROLS ON POWER PLANT SITING

We used the graphical technique described above to determine the minimum separation distances between power plants and different PSD areas necessary to meet the 3-hour- and 24-hour-average SO_2 PSD increments. Tables 2 through 9 display the minimum separation distances for power plants of different sizes with different SO_2 emission rates located in the following types of areas:

> Class I areas.
> Elevated terrain in Class II areas [where the EPA Valley Model (Burt, 1977) is applicable].
> Low terrain in Class II areas.
> Elevated terrain in Class III areas.

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TABLE 2. MINIMUM SEPARATION DISTANCES (km) BETWEEN COAL-FIRED POWER PLANTS AND CLASS I AREAS (LOW TERRAIN) NECESSARY TO MEET THE CLASS I 3-HOUR-AVERAGE SO_2 PSD INCREMENT

SO_2 Emission Rate ($lb/10^6$ Btu)	Power Plant Size (Mwe)			
	500	1000	2000	3000
0.2	13	29	50	100
0.5	40	50	100	100
0.8	50	100	100	130
1.2	100	100	130	160

TABLE 3. MINIMUM SEPARATION DISTANCES (km) BETWEEN COAL-FIRED POWER PLANTS AND CLASS II AREAS (HIGH TERRAIN) NECESSARY TO MEET THE CLASS II 3-HOUR-AVERAGE SO_2 PSD INCREMENT

SO_2 Emission Rate ($lb/10^6$ Btu)	Power Plant Size (Mwe)			
	500	1000	2000	3000
0.2	4	6	10	13
0.5	7	11	19	24
0.8	10	16	26	35
1.2	13	21	35	47

TABLE 4. MINIMUM SEPARATION DISTANCES (km) BETWEEN COAL-FIRED POWER PLANTS AND CLASS II AREAS (LOW TERRAIN) NECESSARY TO MEET THE CLASS II 3-HOUR-AVERAGE SO_2 PSD INCREMENT

SO_2 Emission Rate ($lb/10^6$ Btu)	Power Plant Size (Mwe)			
	500	1000	2000	3000
0.2	0	0	0	0
0.5	0	0	0	0
0.8	0	0	10	16
1.2	0	0	16	26

TABLE 5. MINIMUM SEPARATION DISTANCES (km) BETWEEN COAL-FIRED POWER PLANTS AND CLASS III AREAS (HIGH TERRAIN) NECESSARY TO MEET THE CLASS III 3-HOUR-AVERAGE SO_2 PSD INCREMENT

SO_2 Emission Rate ($lb/10^6$ Btu)	Power Plant Size (Mwe)			
	500	1000	2000	3000
0.2	3	5	8	10
0.5	6	9	15	20
0.8	8	13	21	28
1.2	10	17	28	37

TABLE 6. MINIMUM SEPARATION DISTANCES (km) BETWEEN COAL-FIRED POWER PLANTS AND CLASS I AREAS (LOW TERRAIN) NECESSARY TO MEET THE CLASS I 24-HOUR-AVERAGE SO_2 PSD INCREMENT

SO_2 Emission Rate ($lb/10^6$ Btu)	Power Plant Size (Mwe)			
	500	1000	2000	3000
0.2	33	50	100	100
0.5	80	100	120	150
0.8	100	110	160	190
1.2	100	130	190	230

TABLE 7. MINIMUM SEPARATION DISTANCES (km) BETWEEN COAL-FIRED POWER PLANTS AND CLASS II AREAS (HIGH TERRAIN) NECESSARY TO MEET THE CLASS II 24-HOUR-AVERAGE SO_2 PSD INCREMENT

SO_2 Emission Rate ($lb/10^6$ Btu)	Power Plant Size (Mwe)			
	500	1000	2000	3000
0.2	6	11	18	25
0.5	13	21	36	48
0.8	18	30	50	50
1.2	25	41	50	50

TABLE 8. MINIMUM SEPARATION DISTANCES (km) BETWEEN COAL-FIRED POWER PLANTS AND CLASS II AREAS (LOW TERRAIN) NECESSARY TO MEET THE CLASS II 24-HOUR-AVERAGE SO_2 PSD INCREMENT

SO_2 Emission Rate ($lb/10^6$ Btu)	Power Plant Size (Mwe)			
	500	1000	2000	3000
0.2	0	0	0	0
0.5	0	0	17	27
0.8	0	13	30	47
1.2	0	21	47	50

TABLE 9. MINIMUM SEPARATION DISTANCES (km) BETWEEN COAL-FIRED POWER PLANTS AND CLASS III AREAS (HIGH TERRAIN) NECESSARY TO MEET THE CLASS III 24-HOUR-AVERAGE SO_2 PSD INCREMENT

SO_2 Emission Rate ($lb/10^6$ Btu)	Power Plant Size (Mwe)			
	500	1000	2000	3000
0.2	4	6	11	15
0.5	8	13	22	29
0.8	11	19	31	41
1.2	15	25	41	50

Tables 2 through 5 show separation distances necessary to meet the 3-hour-average SO_2 PSD increment, and Tables 6 through 9 present the separation distances necessary to meet the 24-hour-average SO_2 PSD increment.

As shown by these tables, the 24-hour-average SO_2 PSD increments are more restrictive than the 3-hour-average increments. For example, Table 8 indicates that a 2000 Mwe plant emitting SO_2 at a rate of 0.5 $lb/10^6$ Btu or a 1000 Mwe plant emitting at a rate of 0.8 $lb/10^6$ Btu would violate the 24-hour-average SO_2 PSD Class II increment according to the EPA models under the assumption of a 500 foot stack.

We should point out that the minimum separation distance between any of the power plants considered and elevated terrain features in Class I areas is at least 50 km, the farthest downwind distance at which the EPA Valley Model should be applied. However, Table 6 indicates that, except for the smallest SO_2 emission rate considered (0.2 $lb/10^6$ Btu from a 500 Mwe plant), the minimum separation distance between a power plant and a Class I area would be more than 50 km, simply to prevent exceedances of Class I PSD increments in low-terrain areas.

Figure 3 summarizes the implications of Table 6. Note that with larger SO_2 emission rates resulting from less stringent SO_2 control the separation distance between a plant site and a Class I area must increase. For example, Figure 3 indicates that a well-controlled 2000 Mwe plant burning low-sulfur coal (0.2 $lbm/10^6$ Btu) would have to be sited at least 100 km from a Class I area to ensure that 24-hour-average SO_2 PSD Class I increments were not exceeded (assuming EPA air quality model guidelines are correct). However, the same plant without controls would have to be sited almost 200 km from a Class I area. If an SO_2 emission floor of 0.8 $lb/10^6$ Btu were adopted, the same plant would have to be sited at least 160 km away from a Class I area.

Another constraint on power plant siting that is particularly significant in the western United States derives from the relatively high SO_2

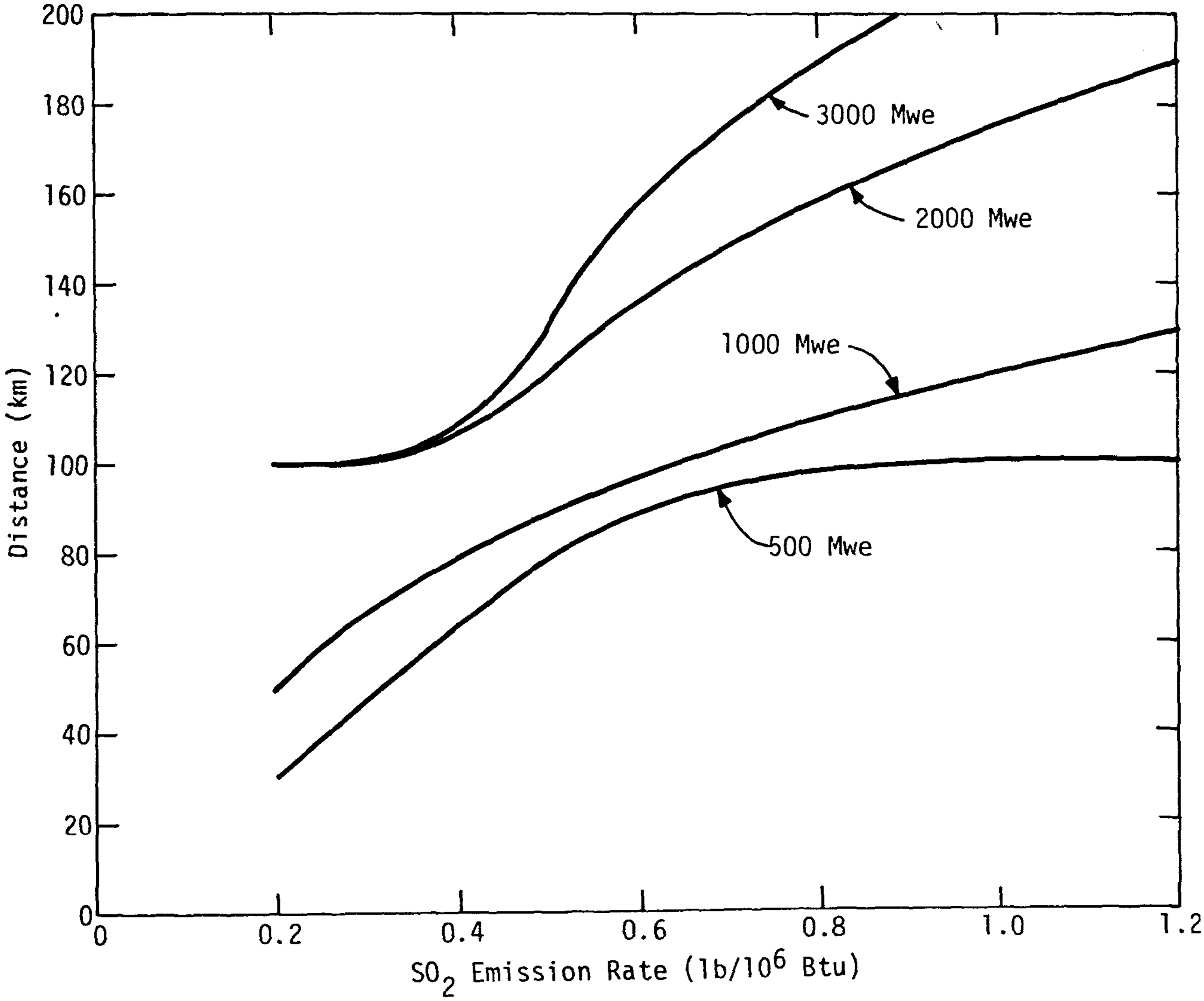


FIGURE 3. ESTIMATED MINIMUM SEPARATION DISTANCES BETWEEN COAL-FIRED POWER PLANTS AND CLASS I AREAS

concentrations that can occur in elevated terrain areas. As Figure 2 illustrates, if there is elevated terrain near the power plant site equal to or higher than the effective stack height H, the EPA Valley Model calculations predict significantly higher concentrations than would be predicted in low-terrain areas. Figures 4 and 5 illustrate the minimum separation distances between power plants and elevated terrain in Class II and Class III areas, respectively.

Figure 4 illustrates that a well-controlled 2000 Mwe coal-fired power plant (0.2 $lb/10^6$ Btu) would have to be sited 18 km away from elevated terrain in Class II areas. If the same plant were not as well controlled and its SO_2 emissions were greater than 0.8 $lb/10^6$ Btu, the plant would have to be sited more than 50 km from elevated terrain. Since many potential siting areas in the western United States are located in the vicinity of elevated terrain, it would be more difficult to find a suitable site for a power plant emitting more than 0.2 $lb/10^6$ Btu. The many valleys in Nevada, Utah, Colorado, Arizona, and New Mexico have widths ranging from 30 to 50 km and are surrounded by mountains, ridges, or plateaus. With a plant site in the middle of such a valley, elevated terrain would be 15 to 25 km away. Thus, on the basis of EPA Valley Model calculations, full SO_2 control may be required simply to meet PSD Class II increments in complex terrain. Of course, this does not imply that full SO_2 control, with a 0.2 $lb/10^6$ Btu floor, is necessary throughout the country, but it does suggest that full SO_2 control may be needed in the western United States, regardless of the SO_2 emission floor that is selected for the New Source Performance Standards.

In summary, with less stringent SO_2 control, siting constraints become more severe relative to Class I areas and elevated terrain. Since large portions of the western United States are near either elevated terrain or Class I areas, stringent SO_2 control may be necessary, regardless of New Source Performance Standards, to meet PSD Regulations.

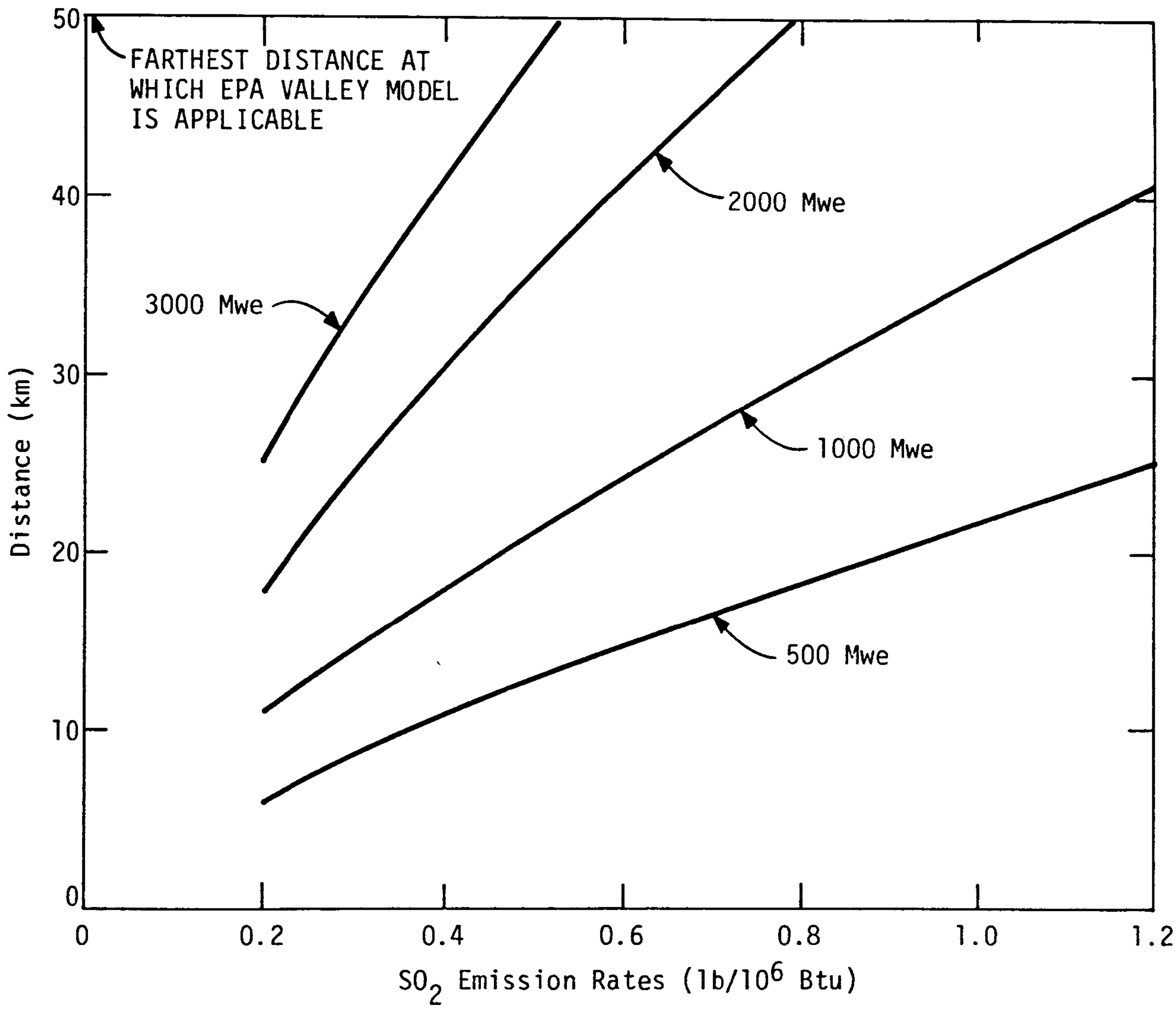


FIGURE 4. MINIMUM SEPARATION DISTANCES BETWEEN COAL-FIRED POWER PLANTS AND ELEVATED TERRAIN IN PSD CLASS II AREAS BASED ON EPA VALLEY MODEL CALCULATIONS

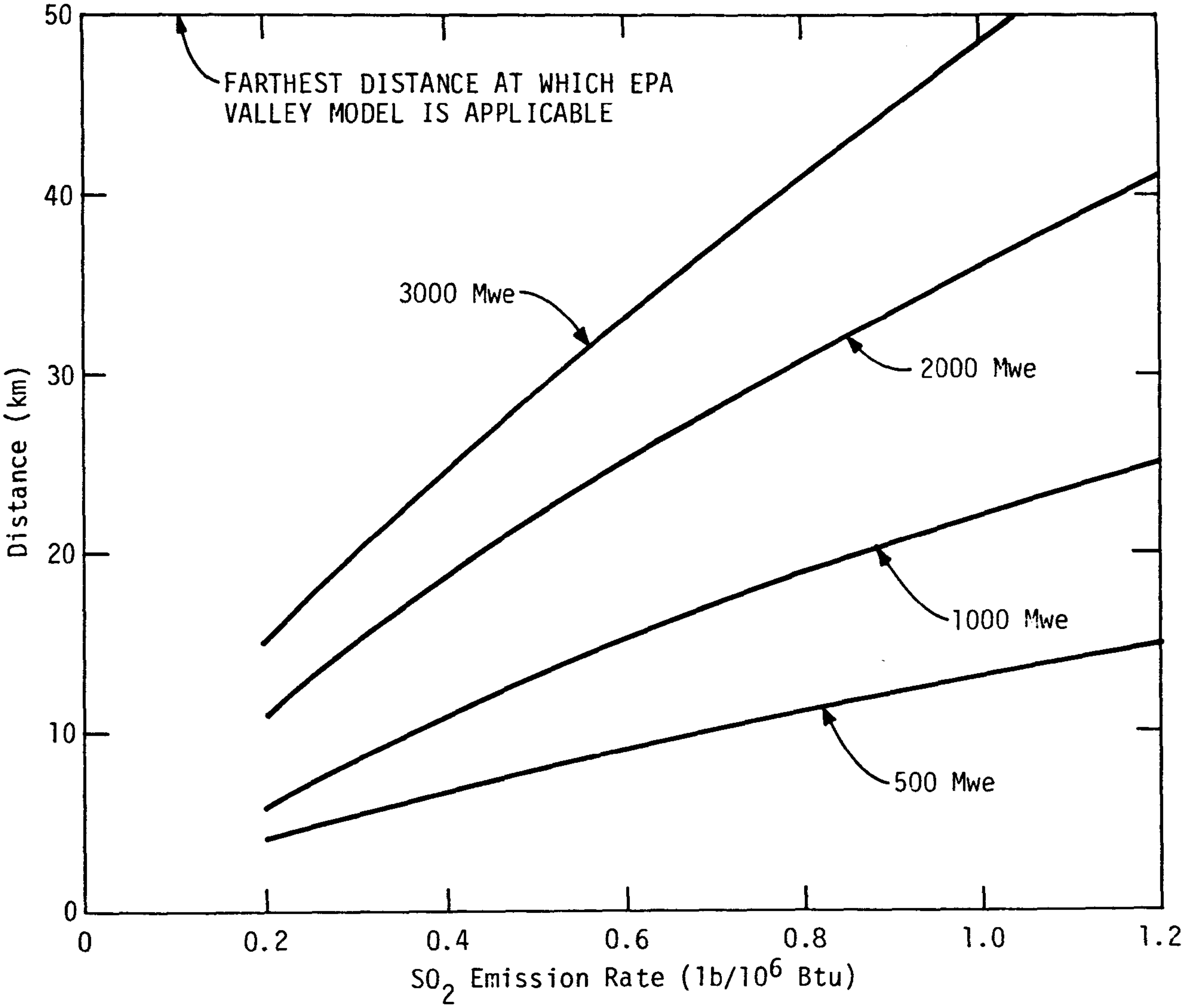


FIGURE 5. MINIMUM SEPARATION DISTANCES BETWEEN COAL-FIRED POWER PLANTS AND ELEVATED TERRAIN IN PSD CLASS III AREAS BASED ON EPA VALLEY MODEL CALCULATIONS

C. VISIBILITY IMPAIRMENT

We applied SAI's plume visibility model to calculate not only visual impacts (reductions in visual range and plume discoloration, contrast, and perceptibility), but also SO_x and NO_x fluxes and concentrations as a function of downwind distance for a variety of meteorological conditions. We selected a range of meteorological conditions for analysis to document the effect of atmospheric stability on:

- Plume centerline SO_x and NO_x concentrations.
- Ground-level SO_x and NO_x concentrations.
- The fraction of SO_x and NO_x flux that is deposited on the ground.
- The fractions of initial SO_2 and NO emissions that are converted to sulfate and NO_2.
- Visual range.
- Plume coloration, contrast, and perceptibility.

We selected a light, 2.5 m/sec (5.6 mph) wind speed as the basis for the analysis. The impacts during limited-mixing conditions, assuming a 1000 m mixing depth, were analyzed using Pasquill C and D dispersion coefficients, which correspond to slightly unstable and neutral atmospheric conditions. Pasquill D conditions are likely to persist for more than 24 hours, whereas Pasquill C conditions are likely to persist for only 6 to 12 hours (Budney, 1977). The impacts were also analyzed during stable conditions; Pasquill E and F dispersion coefficients were selected, with no vertical limit on mixing. Stable conditions will persist for periods ranging from 11 to 17 hours (Budney, 1977).

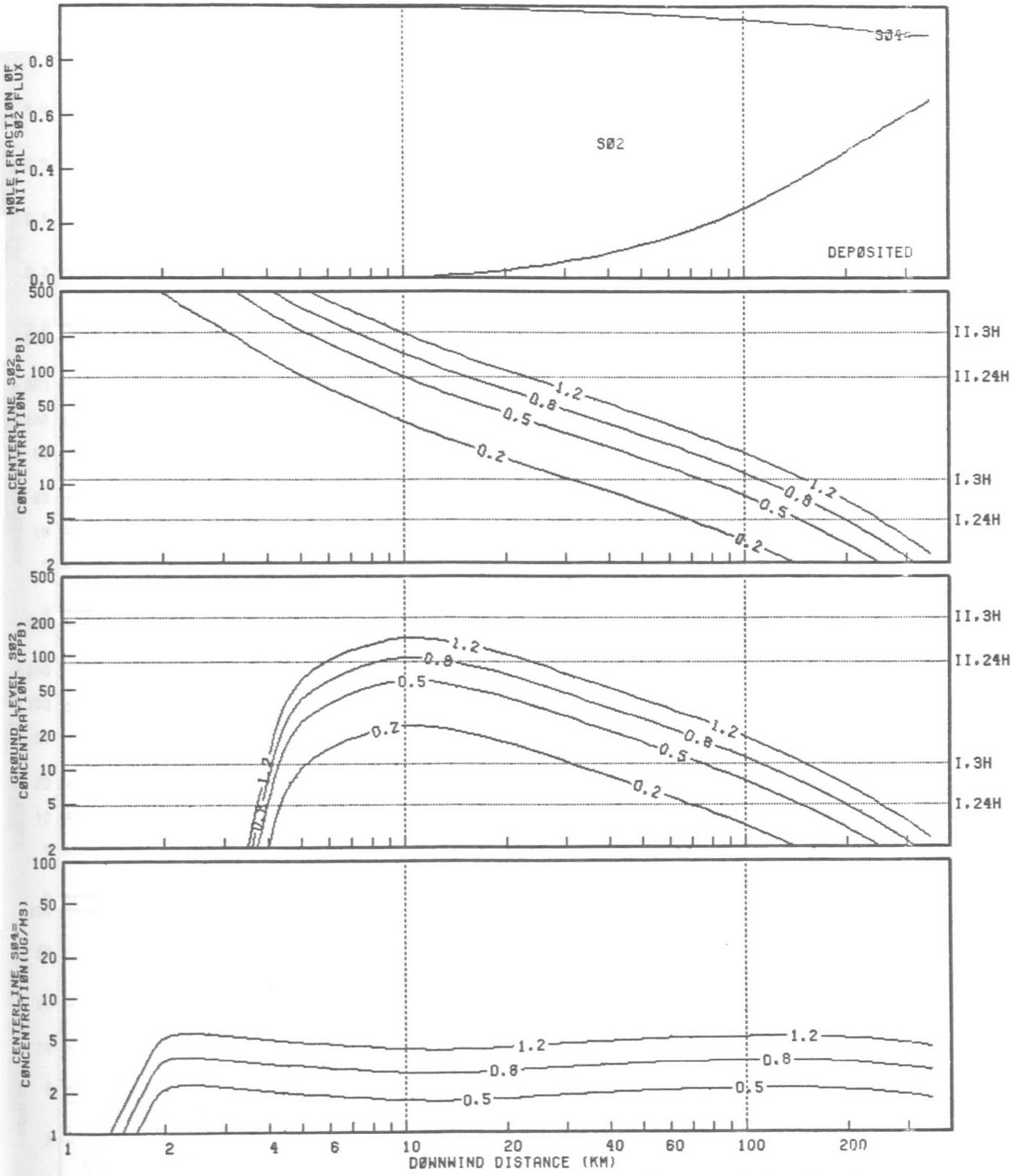
A word about the persistence of meteorological conditions is in order here. We can calculate the travel time necessary for a plume parcel to be transported a given distance: Assuming a 2.5 m/sec wind speed, a plume parcel will travel 216 km in 24 hours. Thus, since Pasquill C conditions are expected to persist for 6 to 12 hours, we should consider impacts associated with these conditions out to distances of 50 to 100 km. Similarly, Pasquill E or F conditions persisting 11 to 17 hours will carry emissions to distances of 100 to 150 km. Thus, only the Pasquill D conditions should be used to evaluate impacts beyond 100 to 150 km from a power plant for the assumed 2.5 m/sec wind speed. As pointed out by Holzworth (1972), in many regions of the continental United States, limited mixing conditions with mixing depths ranging from 1000 to 2000 m, persisting for periods of two to five days without precipitation, occur more than once per year.

1. Effect of SO_2 Emission Rates on SO_x Fluxes and Concentrations

Figures 6(a) through 6(d) show for Pasquill C, D, E, and F stability conditions, respectively, the effect of SO_2 emission rates on SO_x fluxes and concentrations as a function of distance downwind from a 2000 Mwe power plant. (Similar plots for 500, 1000, and 3000 Mwe plants are presented in Appendices A, B, and C.)

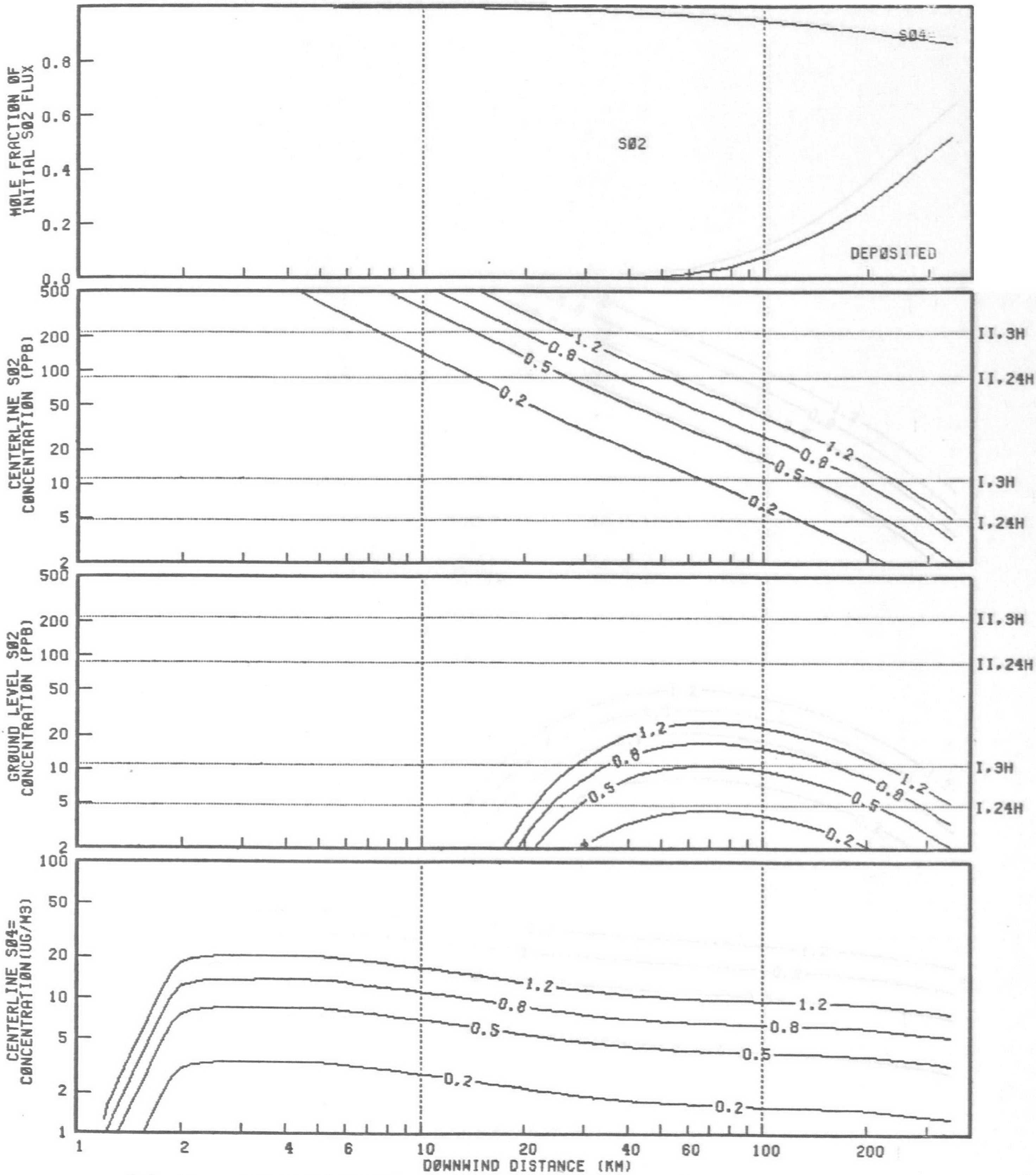
The top plot in each of these figures shows the distribution of sulfur between SO_2 and sulfate in the atmosphere and the amount deposited on the ground as a function of downwind distance. From these plots, one can see that the SO_2 flux at large downwind distances decreases as a result of sulfate ($SO_4^=$) formation and surface deposition. (Note that the $SO_4^=$ and SO_2 fluxes and the fraction deposited on the ground are represented by the areas above, between, and below the curves in this plot.) Within 100 km of the power plant, only a small fraction of the initial SO_2 emissions is converted to sulfate or is deposited. However, at distances of 200 to 350 km downwind, 15 to 20 percent of the initial sulfur flux (power plant emissions) has been converted to sulfate, and up to 65 percent has been deposited. Note that surface deposition is a function of stability because it is linearly proportional to ground-level concentrations; thus, during the stable Pasquill F conditions [Figure 6(d)], surface deposition is negligible because the plume has not mixed to the ground.

The second and third plots in Figures 6(a) through 6(d) show the short-term-average centerline and ground-level SO_2 concentrations on log-log plots.



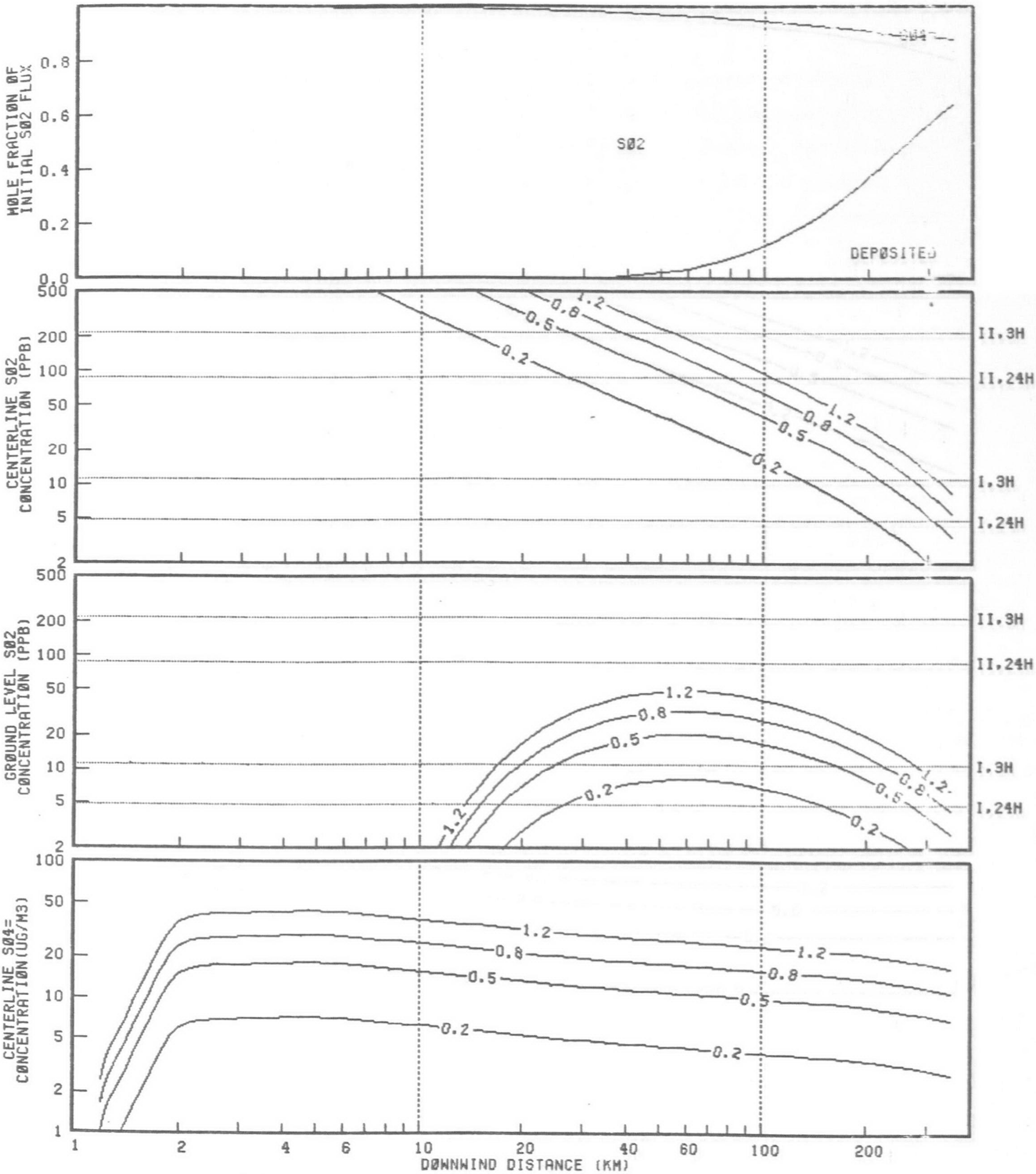
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE 6. EFFECT OF SO_2 EMISSION RATES ON SO_x FLUXES AND CONCENTRATIONS DOWNWIND OF A 2000 Mwe COAL-FIRED POWER PLANT. SO_2 emission rates in pounds per million Btu are indicated.



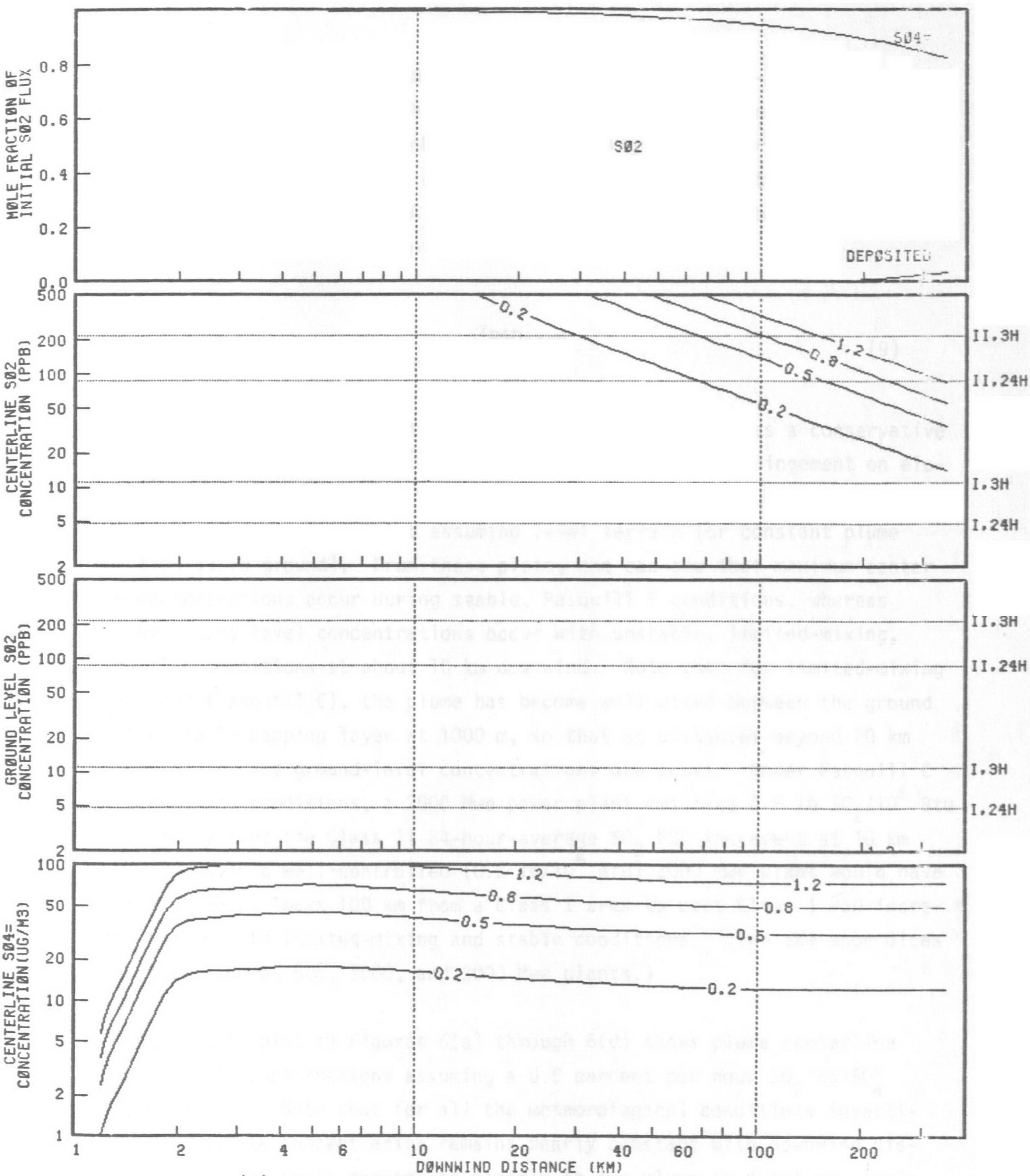
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE 6 (Continued)



(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE 6 (Continued)



(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE 6 (Concluded)

For reference, the Class I and Class II 3-hour- and 24-hour-average SO_2 PSD increments are indicated by the horizontal lines. These are equivalent short-term-average standards obtained by dividing the 3-hour- and 24-hour-average PSD increments by the appropriate average concentration ratio factors recommended by the EPA (Budney, 1977) of 0.9 for 3-hour-average and 0.4 for 24-hour-average concentrations, respectively:

$$\chi_{PSD\text{-}peak} = \frac{\chi_{PSD\text{-}ave}}{\chi_{ave/peak}} \qquad (9)$$

The centerline concentrations can also be interpreted as a conservative estimate of maximum ground-level concentrations if plume impingement on elevated terrain were to occur. The ground-level concentrations displayed in the third plot were calculated assuming level terrain (or constant plume elevation above ground). From these plots, one can see that maximum centerline concentrations occur during stable, Pasquill F conditions, whereas maximum ground-level concentrations occur with unstable, limited-mixing, Pasquill C conditions at about 10 km downwind. Note that for limited-mixing conditions (Pasquill C), the plume has become well mixed between the ground and the stable capping layer at 1000 m, so that at distances beyond 20 km the centerline and ground-level concentrations are equal. Under Pasquill C limited-mixing conditions, a 2000 Mwe power plant emitting 0.8 lb $SO_2/10^6$ Btu would barely meet the Class II 24-hour-average SO_2 PSD increment at 10 km downwind. Even a well-controlled (0.2 lb/10^6 Btu) 2000 Mwe plant would have to be located at least 100 km from a Class I area to meet Class I PSD increments during both limited-mixing and stable conditions. (See the appendices for information on 500, 1000, and 3000 Mwe plants.)

The fourth plot in Figures 6(a) through 6(d) shows plume centerline sulfate ($SO_4^=$) concentrations assuming a 0.5 percent per hour SO_2-to-$SO_4^=$ conversion rate. Note that for all the meteorological conditions investigated the sulfate concentration remains nearly constant with downwind distance, since sulfate is forming as rapidly as the plume is diluting. Calculated centerline $SO_4^=$ concentrations depend on the SO_2 emission rate and the stability. At the 0.2 $lb/10^6$ Btu emission rate, centerline sulfate concentrations range from 1 to 15 $\mu g/m^3$. For Pasquill C and D, at large downwind distances, ground-level $SO_4^=$ concentrations will equal centerline concentrations because emissions are well mixed. Thus, we see that ground-level sulfate concentrations can be as high as 1, 3, 5, and 8 $\mu g/m^3$ for the SO_2 emission rates of 0.2, 0.5, 0.8, and 1.2 $lb/10^6$ Btu, respectively, from a 2000 Mwe power plant.

2. Effect of NO_x Emission Rates on NO_x Fluxes and Concentrations

Figures 7(a) through 7(d) show plots of NO_x fluxes and concentrations as a function of NO_x emission rates of 0.2, 0.5, 0.6, and 0.8 $lb/10^6$ Btu. Note that the NO-to-NO_2 conversion rate, as evidenced by the top plot in each of these figures, depends on the rate of plume dilution (atmospheric stability). Figure 7(a) shows the limiting effect of the background ozone concentration (assumed to be 40 ppb) on ground-level NO_2 concentrations. Both of these effects occur because the reaction responsible for most of the NO_2 formation requires background ozone to be mixed into the plume:

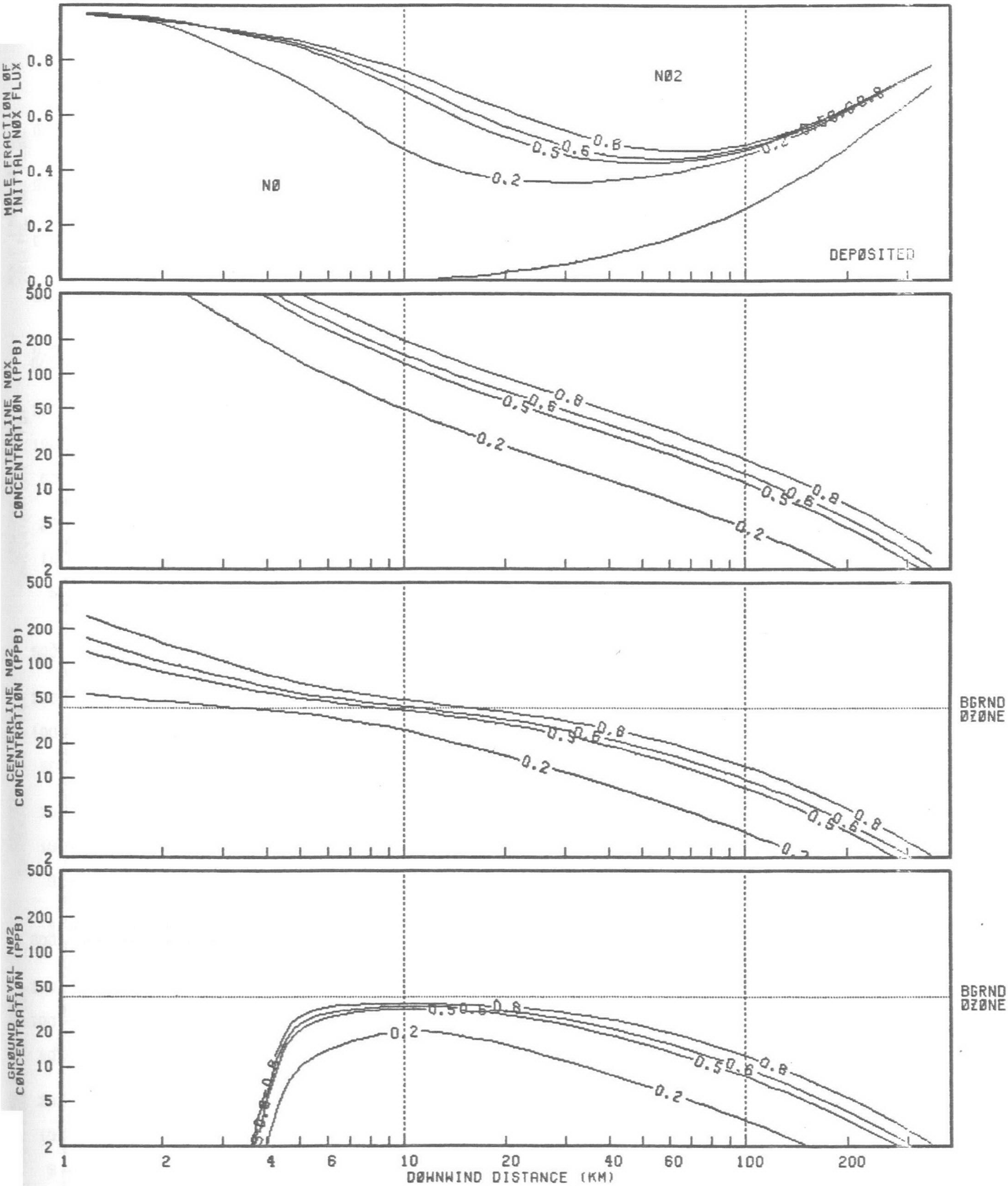
$$NO + O_3 \rightarrow NO_2 + O_2 \quad . \qquad (10)$$

Plots similar to Figures 7(a) through 7(d) are shown in the appendices for other power plant sizes (500, 1000, and 3000 Mwe).

3. Effect of SO_2 Emission Rates on Visibility Impairment

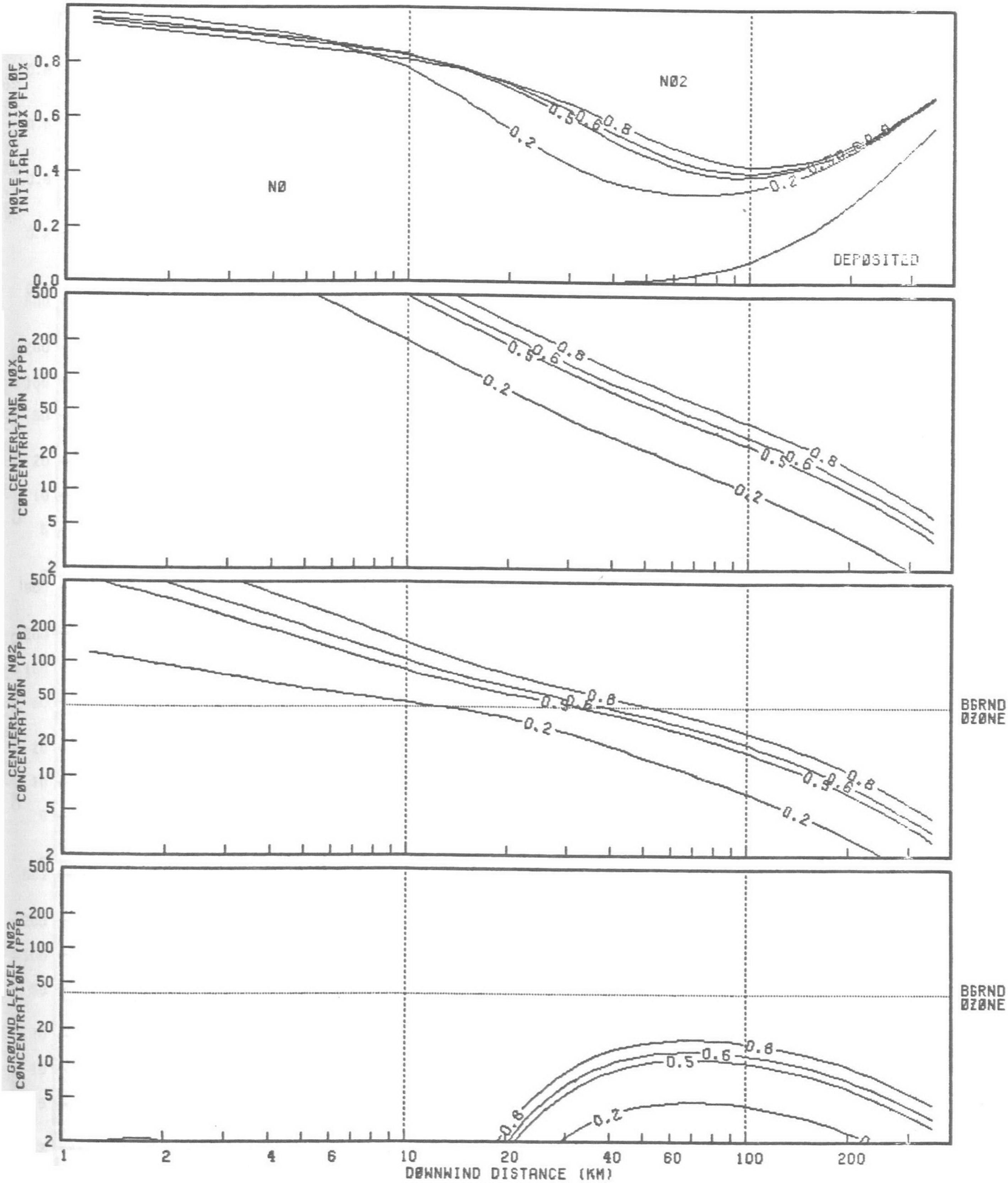
Keeping the NO_x emission rate fixed at 0.6 $lb/10^6$ Btu, we evaluated the effect of various SO_2 emission rates (0, 0.2, 0.5, 0.8, and 1.2 $lb/10^6$ Btu) on visibility impairment. Figures 8(a) through 8(d) show the calculated impairment due to a 2000 Mwe power plant for the four meteorological conditions: Pasquill C and D limited-mixing conditions and Pasquill E and F stable conditions.

The most striking effect of less stringent SO_2 control (increased SO_2 emission rates) is the reduction in visual range at distances more than



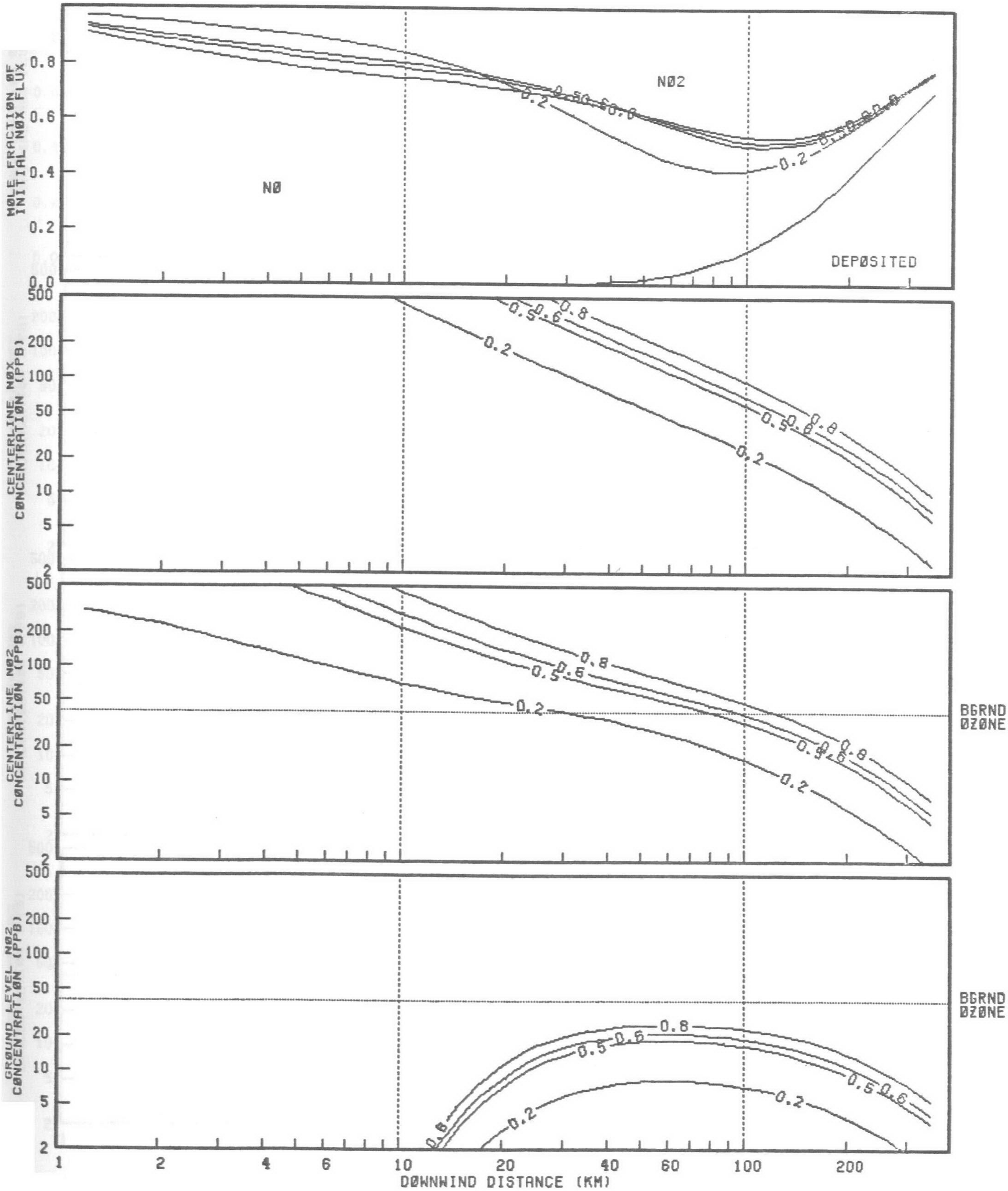
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE 7. EFFECT OF NO_X EMISSION RATES ON NO_X FLUXES AND CONCENTRATIONS DOWNWIND OF A 2000 Mwe COAL-FIRED POWER PLANT. NO_X emissions rates in pounds per million Btu are indicated.



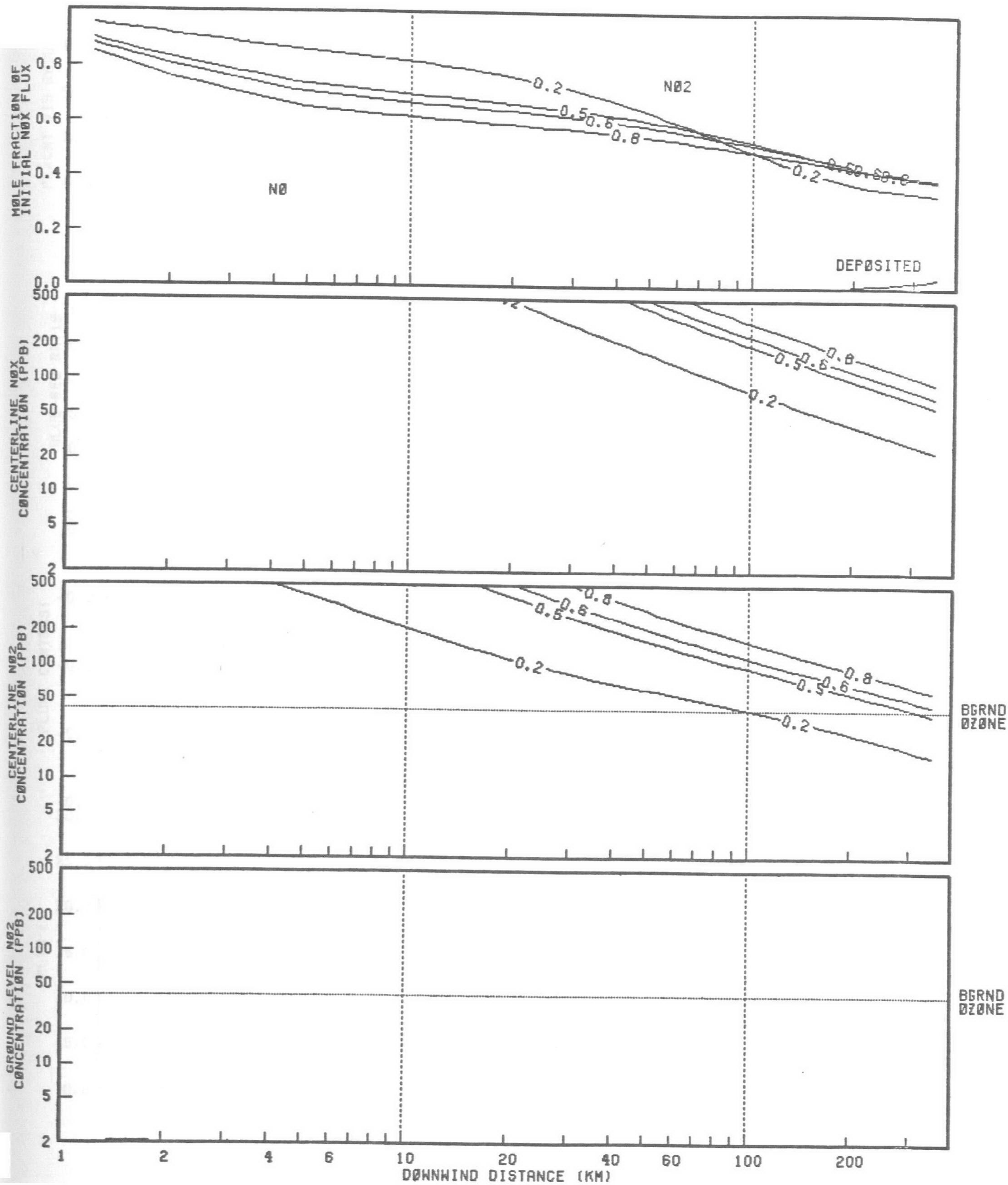
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE 7 (Continued)



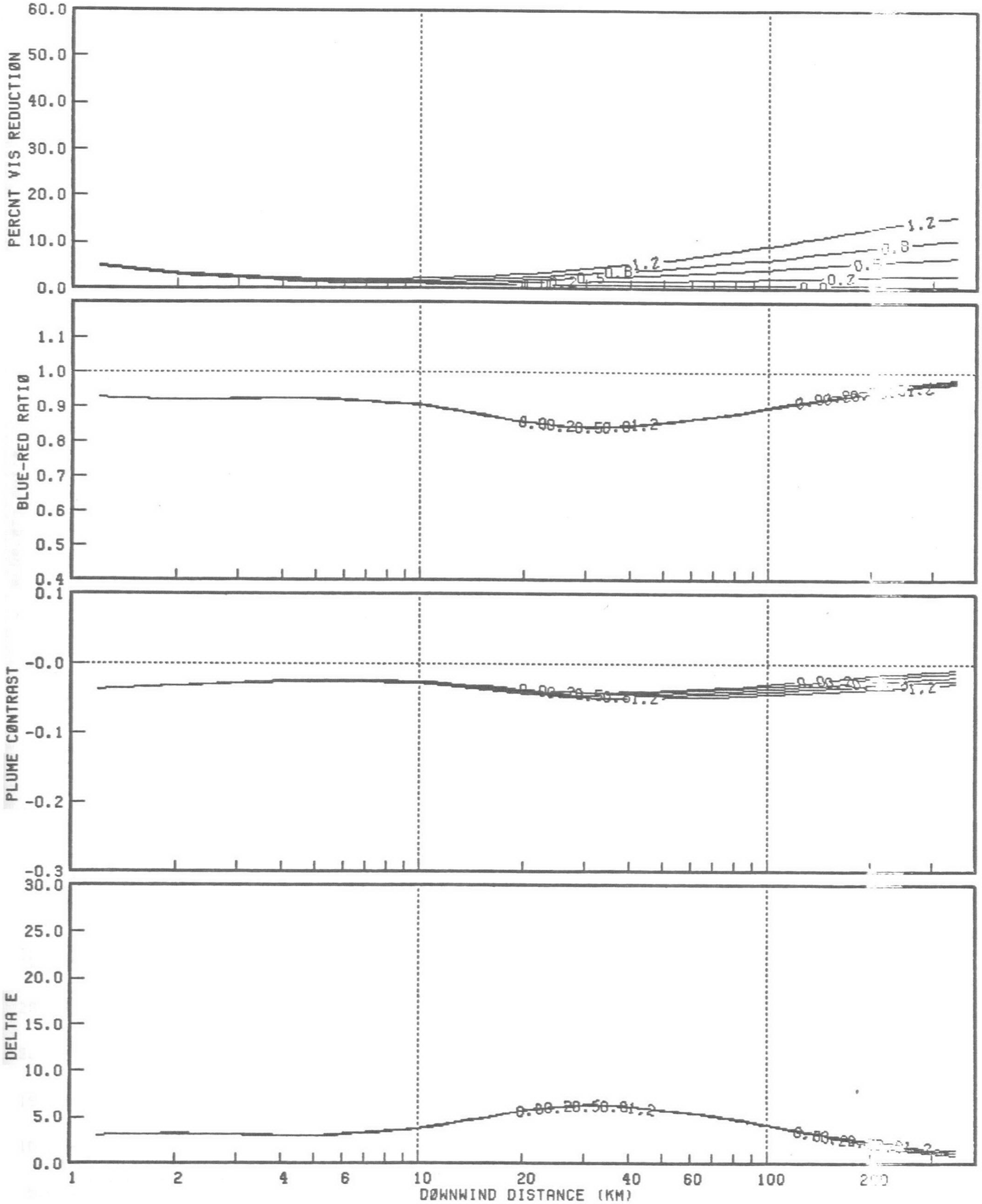
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE 7 (Continued)



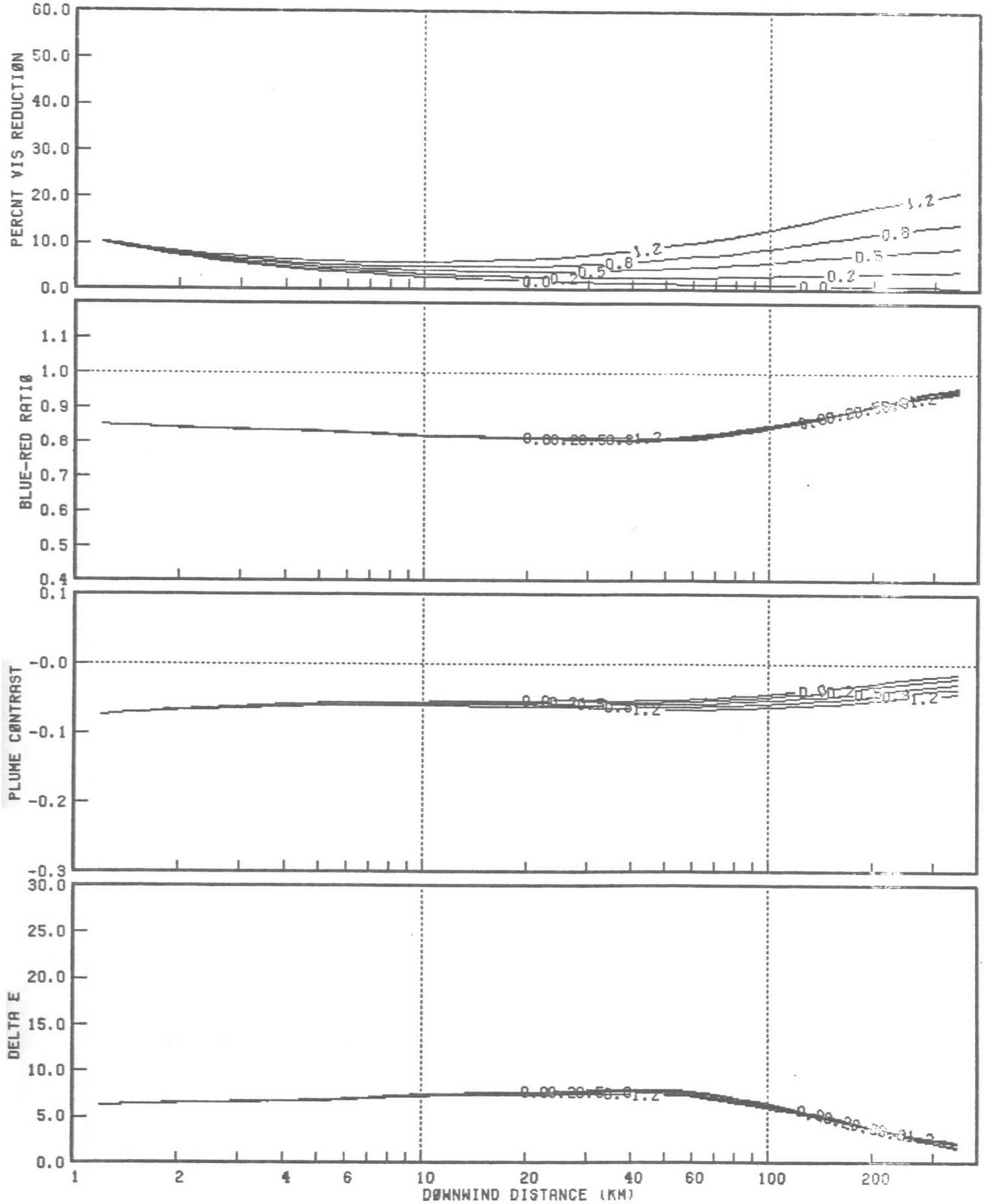
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE 7 (Concluded)



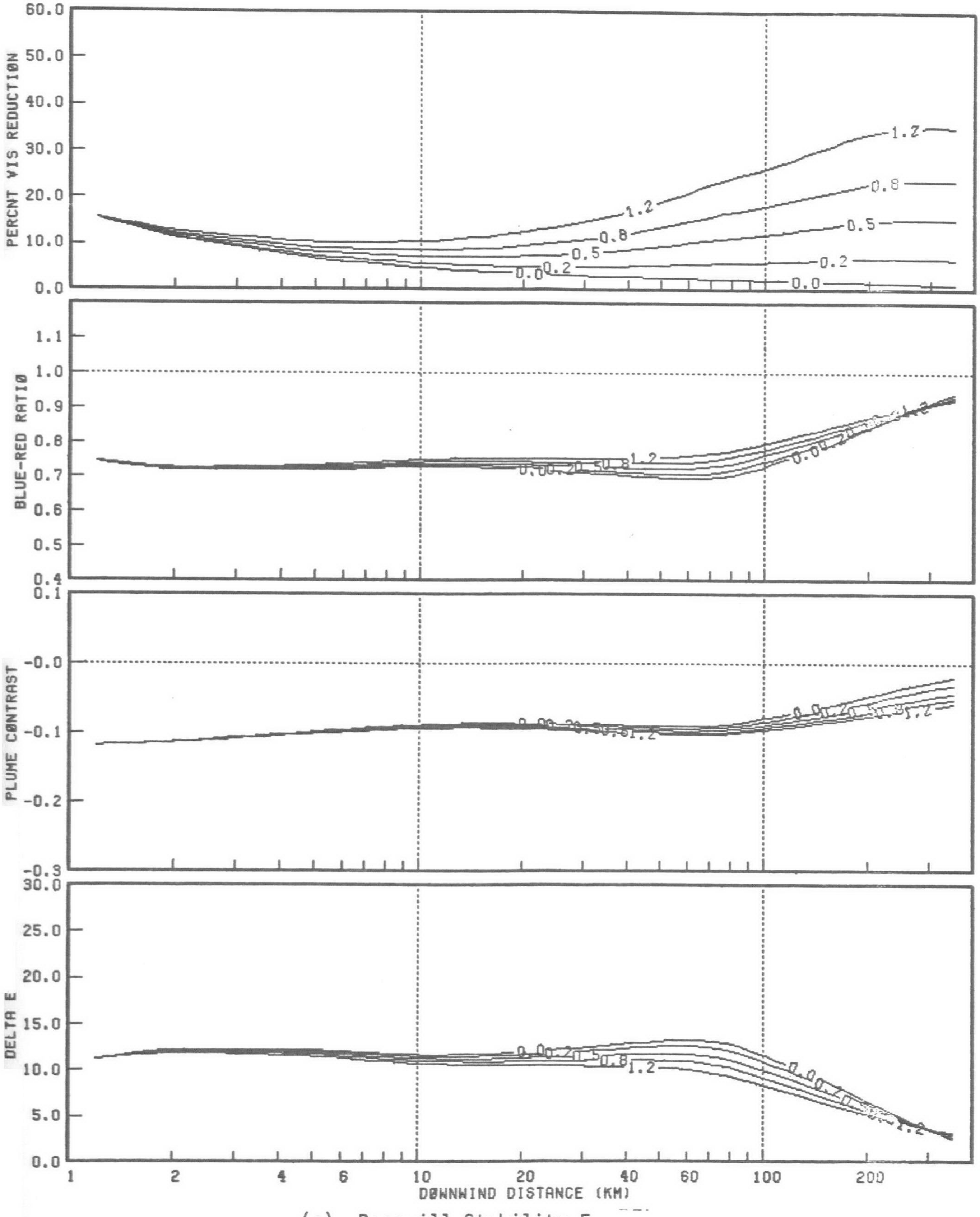
(a) Pasquill Stability C

FIGURE 8. EFFECT OF SO_2 EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 2000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. SO_2 emission rates in pounds per million Btu are indicated.



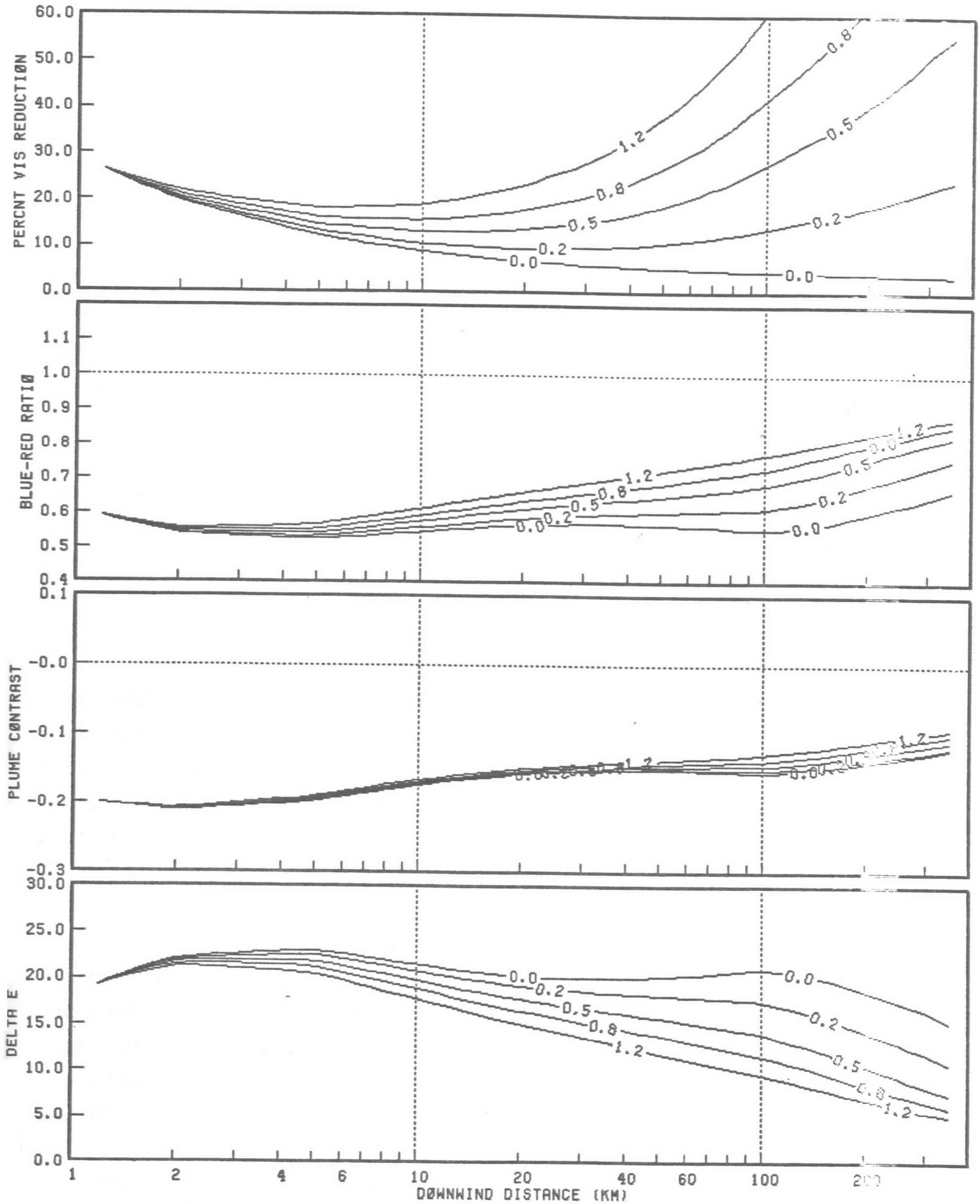
(b) Pasquill Stability D

FIGURE 8 (Continued)



(c) Pasquill Stability E

FIGURE 8 (Continued)



(d) Pasquill Stability F

FIGURE 8 (Concluded)

100 km downwind. As we noted previously, it is appropriate to consider only the Pasquill D meteorological conditions for distances beyond 100 to 150 km. Therefore, from Figure 8(b) we see that at 200 km downwind (approximately one day's plume travel time) the reduction in visual range is 1, 3, 8, 12, and 18 percent for the SO_2 emission rates of 0, 0.2, 0.5, 0.8, and 1.2 $lb/10^6$ Btu, respectively. At 350 km downwind, the visual range reduction is 0, 4, 9, 14, and 21 percent, respectively. These values are based on the assumptions that the background visual range is 130 km (typical for nonurban areas of the western United States) and that the observer is viewing with a line of sight perpendicular to the plume axis.

Greater reductions in visual range would be detected if the observer looked along the plume. We used the incremental increases of sulfate concentrations in the plume calculated previously of 1, 3, 5, and 8 $\mu g/m^3$, corresponding to SO_2 emission rates of 0.2, 0.5, 0.8, and 1.2 $lb/10^6$ Btu, respectively, from a 2000 Mwe power plant to calculate the maximum reductions in visual range when viewing along the plume. With a background visual range typical of the western United States (130 km), the visual range would be reduced 11, 28, 40, and 51 percent, respectively. For a background visual range typical of the eastern United States (15 km), the visual range would be reduced 2, 4, 7, and 11 percent, respectively. Thus, greater incremental impacts will result from the same sulfate fluxes in the western United States, where the visual range is excellent, than will occur in the eastern United States.

Visual range reduction will be greater in stable, ribbon-like plumes, but these plumes affect only a few lines of sight and do not affect prevailing visibility (in many different directions). Visual impacts caused by stable plumes are better characterized by the appearance of dark, yellow-brown haze, which can be quantified using blue-red ratios, plume contrast, and ΔE.

Thus, if a 2000 Mwe plant located in the western United States burns low-sulfur coal with 85 percent SO_2 control, a 4 to 11 percent reduction in visual range, during worst-case meteorological conditions, will occur 200 to 400 km downwind. During typical meteorological conditions, this impact is likely to drop by a factor of 5, producing impacts of 1 to 2 percent. However, without SO_2 control, sulfate concentrations would cause a 20 to 50 percent reduction in visual range during poor dispersion conditions and a 5 to 10 percent reduction during typical dispersion conditions.

Another striking observation can be made from Figures 8(a) through 8(d): Increased SO_2 emissions cause a decrease in plume coloration, contrast, and perceptibility during stable atmospheric conditions. As shown previously (Latimer et al., 1978), plume NO_2 is the principal cause of the dark, yellow-brown discoloration caused by plumes when viewed against a cloudless horizon sky. Increases in the ratio of sulfate to NO_2 concentration under these viewing conditions have the effect of masking the yellow-brown coloration with a white-gray haze caused by light scattered by sulfate aerosol. Thus, we see from Figures 8(c) and 8(d) that as SO_2 emission rates increase:

- The plume's yellow-brown coloration is diminished (indicated by blue-red ratios closer to 1).
- The plume becomes less dark (indicated by plume contrasts closer to 0).
- The plume becomes less perceptible (indicated by ΔE's closer to 0).

The conditions under which plume discoloration would be observed downwind of a power plant were indicated in previous reports (Latimer et al., 1978, Volume III) and in Figures 8(a) through 8(d). Plume discoloration is not likely to be visible in areas where the background visual range is relatively poor, such as the eastern United States. Plume discoloration is most pronounced in areas with good visibility, such as the western United States. Figures 8(a) through 8(d) indicate that meteorological conditions have a strong effect on plume discoloration. During well-mixed conditions [see Figures 8(a) and (b)], plumes would be barely visible ($\Delta E < 10$) assuming a light, 2.5 m/sec wind but would be invisible ($\Delta E < 5$) during well-ventilated conditions with deeper mixed layers and stronger winds than those assumed here. However, during stable, light-wind conditions [as evidenced by Figures 8(c) and 8(d)], yellow-brown plumes ($10 < E < 25$) would be visible as far as 100 to 150 km downwind (assuming that stable, light-wind conditions persist long enough).

As noted previously, SO_2 emission control will increase yellow-brown plume coloration, not reduce it. As we show in the next section, NO_x control is necessary to ameliorate plume discoloration.

4. Effect of NO_x Emission Rates on Visibility Impairment

Figures 9(a) through 9(d) show the effect of various NO_x emission rates of 0, 0.2, 0.5, 0.6, and 0.8 lb/10^6 Btu on visibility impairment assuming a fixed SO_2 emission rate of 0.5 lb/10^6 Btu. These figures show the effects for a 2000 Mwe power plant; impairment calculations for 500, 1000, and 3000 Mwe power plants are shown in the figures in the appendices.

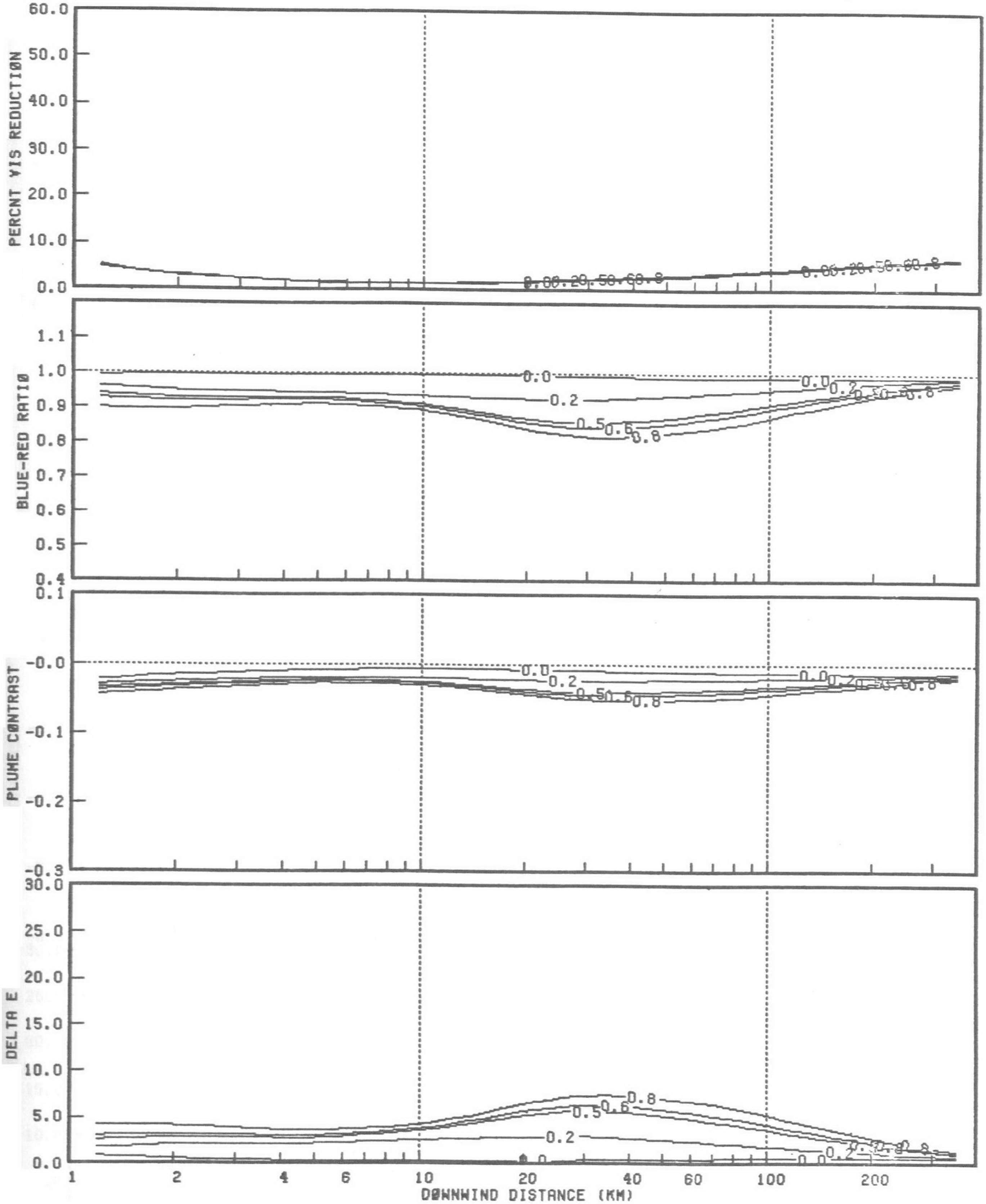
Varying the NO_x emission rate has a negligible effect on visual range because it is assumed that nitrate aerosol is not formed. (This assumption should be checked in future plume measurement programs.) However, the NO_x emission rate has a strong effect on plume discoloration. On the basis of Figures 9(c) and 9(d), plume discoloration could be virtually eliminated with efficient NO_x control by reducing NO_x emission rates to less than 0.2 lb/10^6 Btu.

D. POWER PLANT SITING CONSTRAINT MAPS

We have identified three significant constraints on power plant siting related to air quality:

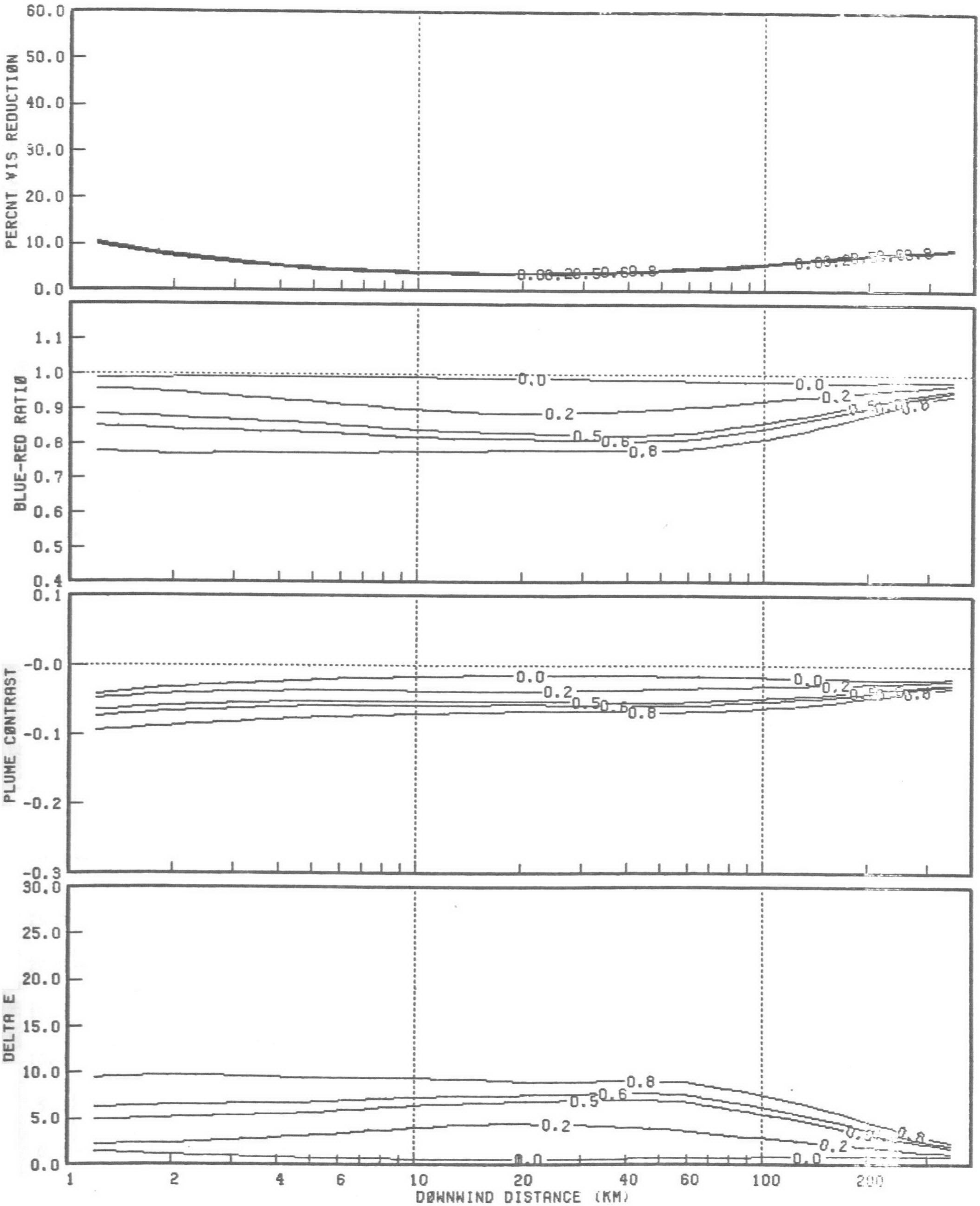
> Exceedances of PSD increments in elevated terrain areas due to excessive 3-hour- and 24-hour-average SO_2 concentrations resulting from plume impingement.

> Exceedances of PSD increments in Class I areas due to excessive 3-hour- and 24-hour-average SO_2 concentrations during limited-mixing conditions.



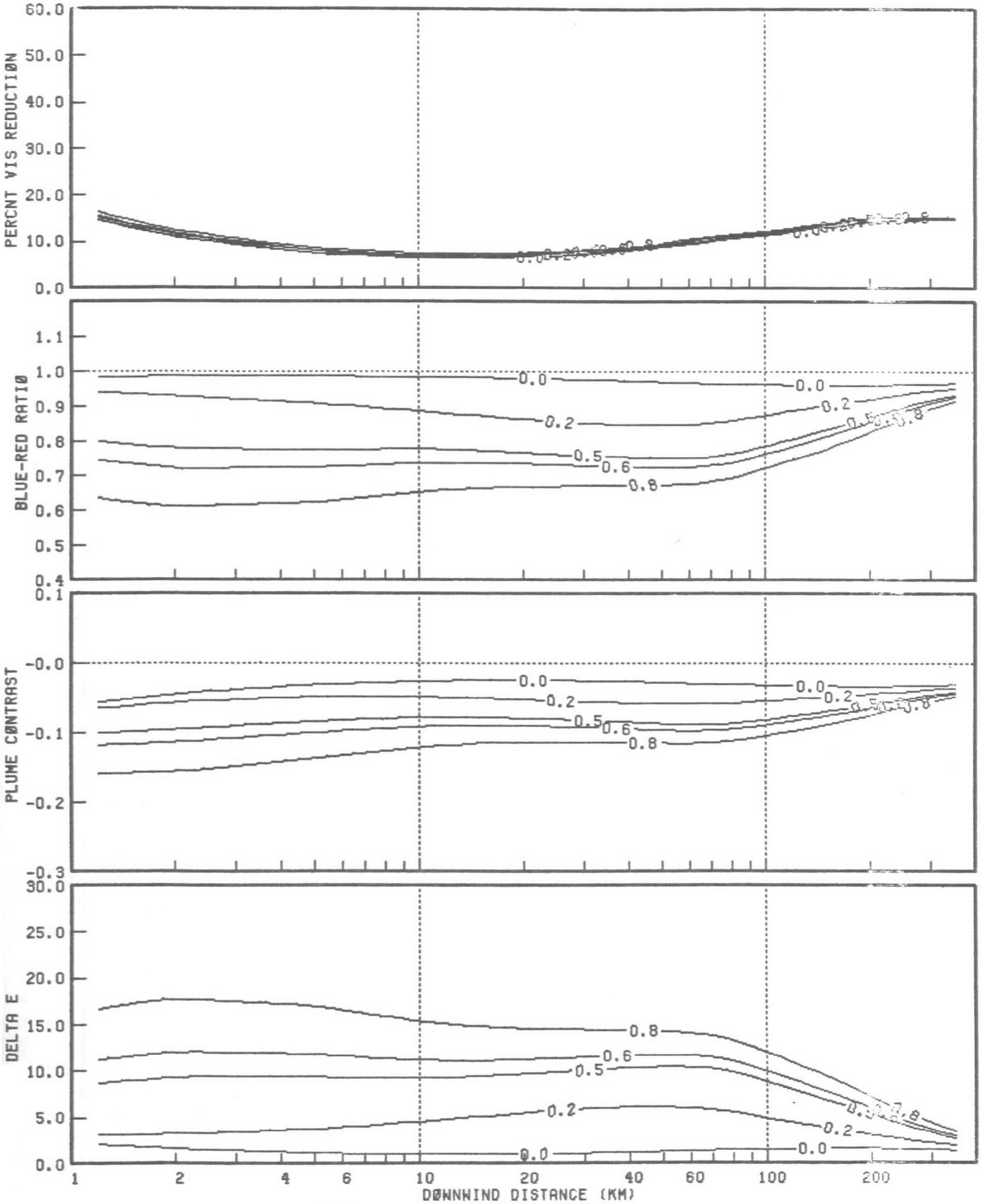
(a) Pasquill Stability C

FIGURE 9. EFFECT OF NO_x EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 2000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. NO_x emissions rates in pounds per million Btu are indicated.



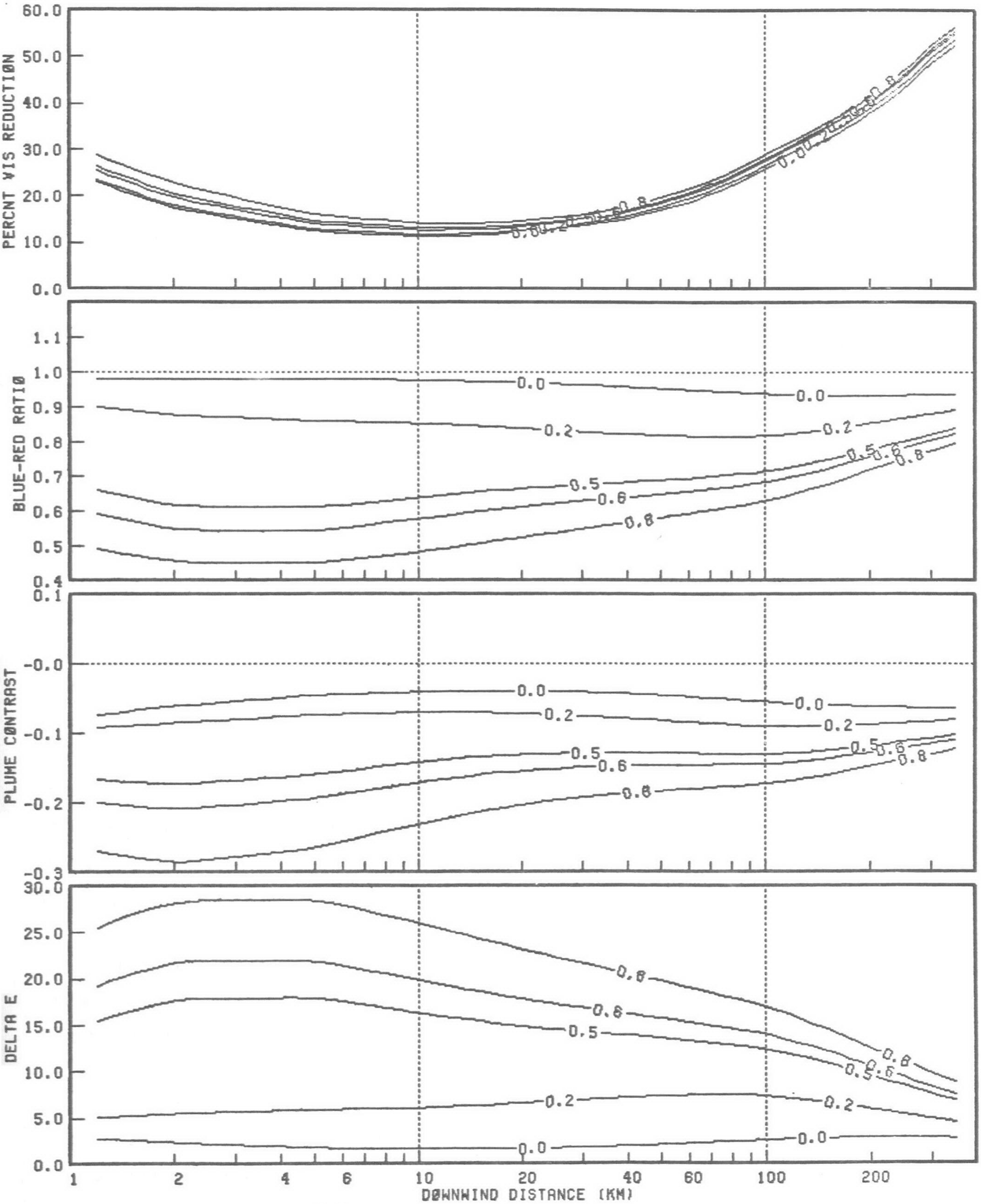
(b) Pasquill Stability D

FIGURE 9 (Continued)



(c) Pasquill Stability E

FIGURE 9 (Continued)



(d) Pasquill Stability F

FIGURE 9 (Concluded)

> Impairment of visibility in Class I areas caused by increases in haziness due to SO_x emissions and the appearance of dark yellow or brown haze from NO_x emissions.

The first constraint potentially limits siting alternatives in complex terrain; the others limit siting near Class I areas.

Figure 10 shows the locations of mandatory Class I areas in the United States; many additional areas are expected to be redesignated Class I in the near future.

The calculations presented in this report suggest that, regardless of which of the alternate SO_2 emission floors for the New Source Performance Standards are selected, large coal-fired power plants may have to be sited at least 100 km, and possibly as far as 200 km, from Class I areas. To illustrate the profound effect this constraint might have on power plant siting, we drew exclusion area circles with radii of 100 and 200 km around mandatory Class I areas in the continental United States, as shown in Figures 11(a) and 11(b). With 200 km circles, virtually all of the western United States is affected, but even with the 100 km circles most of the states of California, Oregon, Idaho, Colorado, Arizona, and New Mexico are affected. With these Class I area constraints, siting alternatives in the western United States will be limited principally to eastern Montana and Wyoming, northern Utah, and Nevada.

These results suggest potentially profound siting constraints in the western United States, and therefore, they deserve careful scrutiny in future studies. Furthermore, we emphasize that these results are based on:

> Possibly conservative calculations using air quality models recommended by the EPA.

> Generally conservative, average concentration ratios recommended by the EPA.

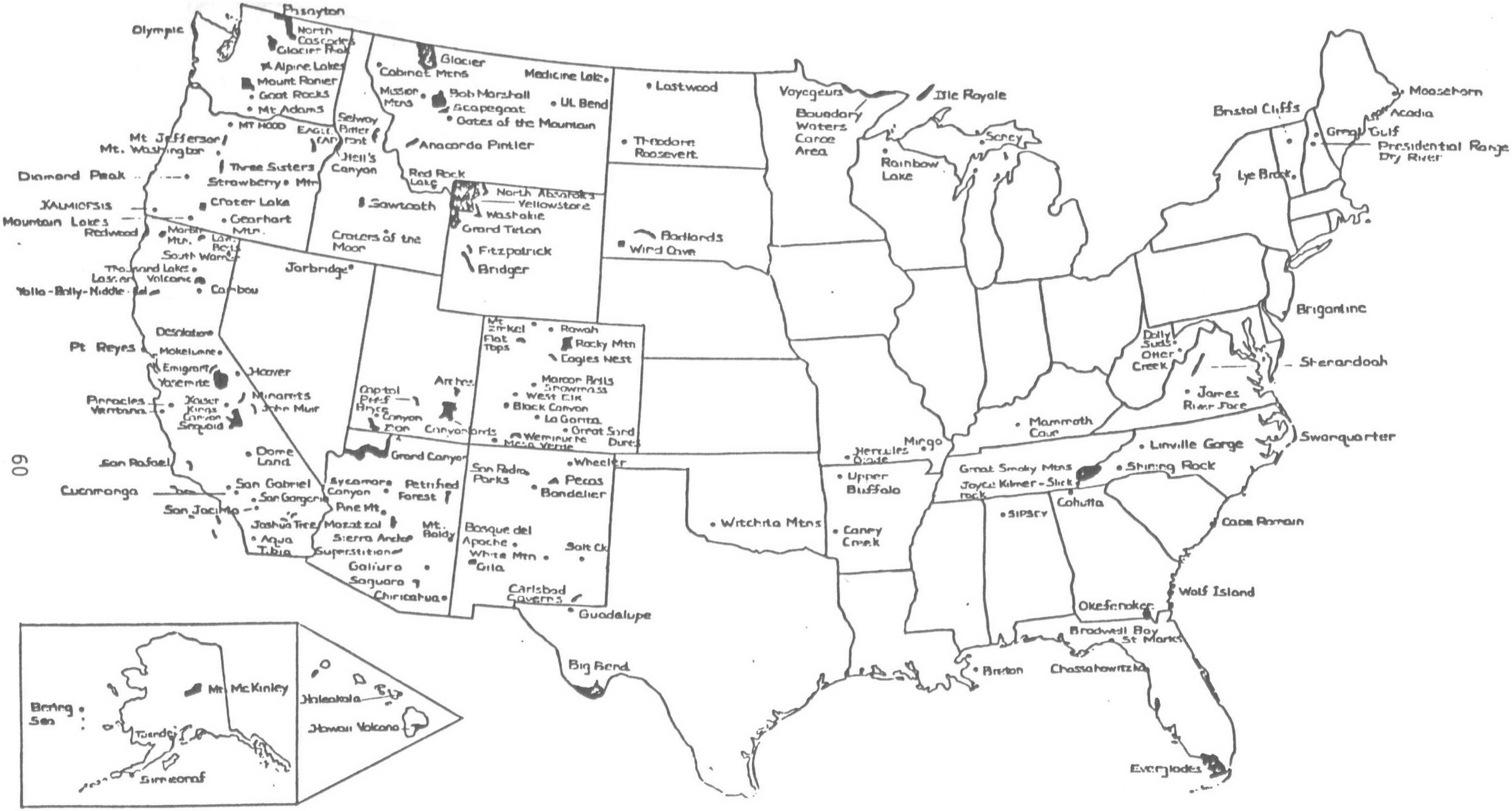
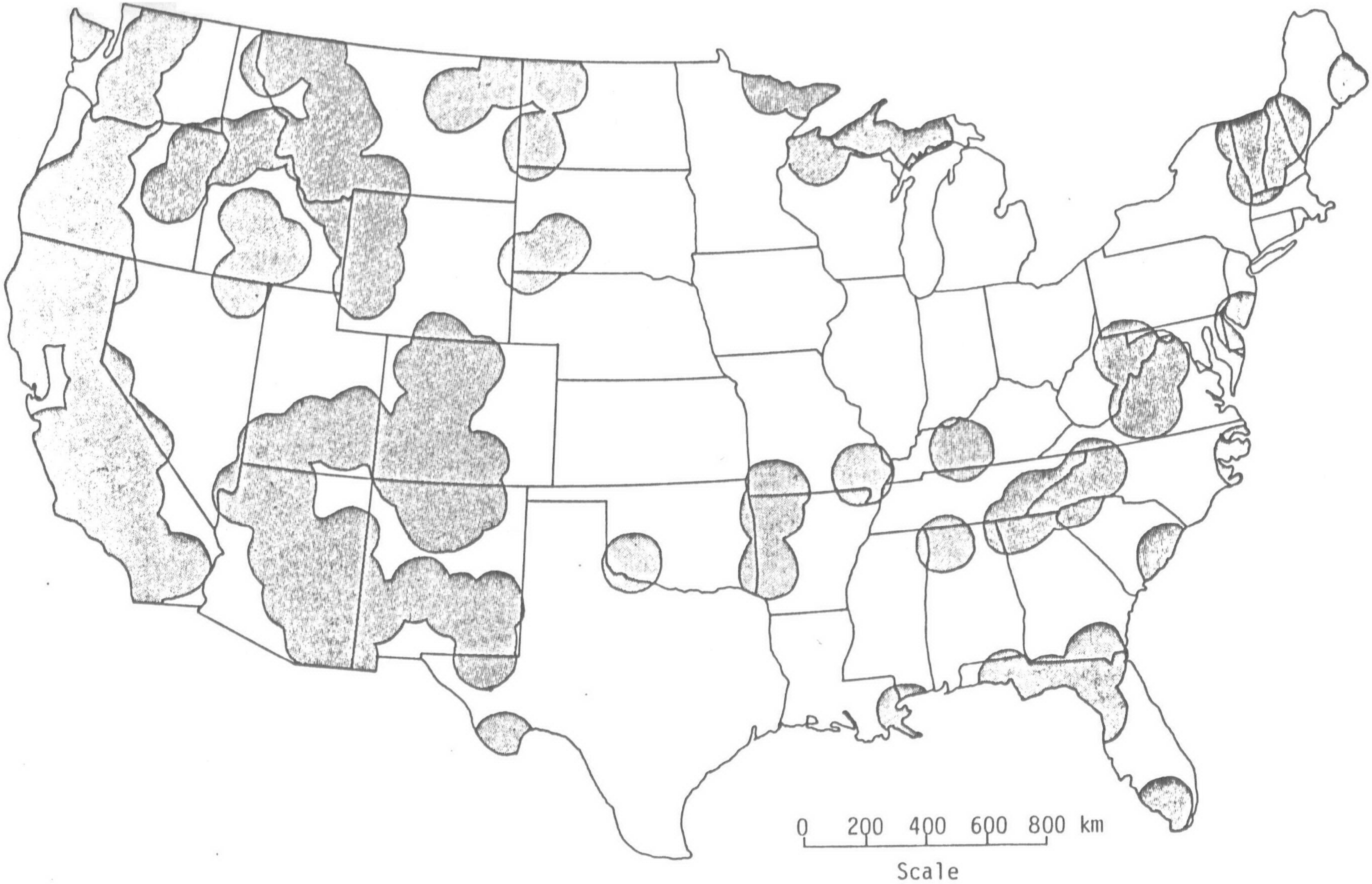
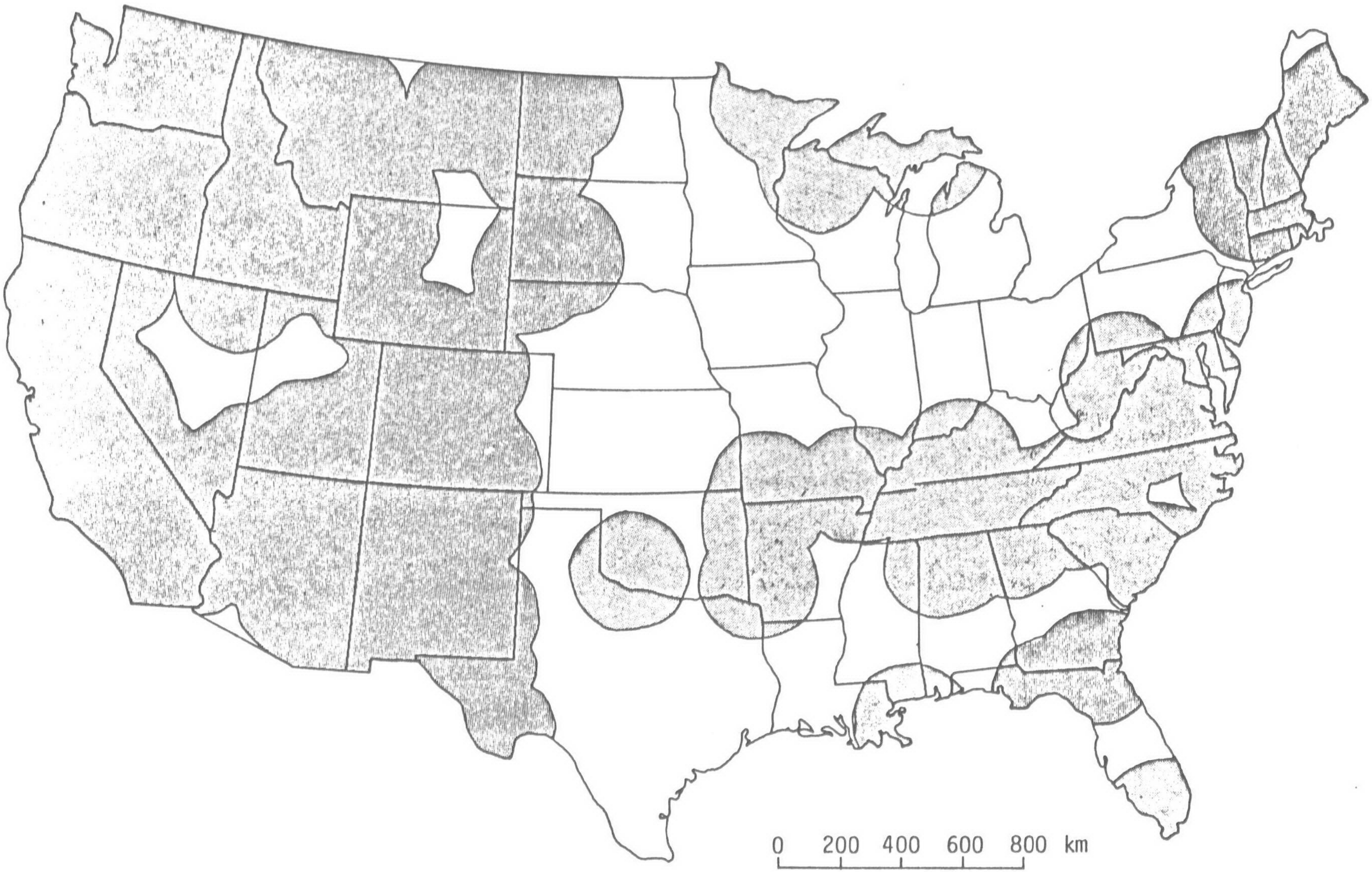


FIGURE 10. MANDATORY CLASS I AREAS



(a) Assumption of a 100 km Separation Distance

FIGURE 11. POWER PLANT SITING EXCLUSION AREAS POTENTIALLY NECESSARY TO PROTECT VISIBILITY AND TO PREVENT SIGNIFICANT DETERIORATION OF AIR QUALITY IN MANDATORY CLASS I FEDERAL AREAS



(b) Assumption of a 200 km Separation Distance

FIGURE 11 (Concluded)

> Assumptions regarding the persistence of worst-case meteorological conditions.

These models and assumptions should be evaluated in future work.

V CUMULATIVE IMPACTS OF POWER PLANTS WITHIN A REGION

Another consideration in evaluating the implications of alternative New Source Performance Standards for power plants is the maximum number of power plants that can be sited in a given region without causing exceedances of PSD increments.

A. A GENERIC REGIONAL MODEL

As a first step in estimating these maximum siting capacities, we developed a simple regional air quality model that can be used to calculate the cumulative impacts of many power plants. The basic assumption used in formulating this model is that the distribution of new power plant sites throughout a region is such that emissions are uniformly mixed between the ground and an elevated stable layer at some downwind distance. Under this assumption of distributed emissions sources and uniformly mixed emissions, we do not have to account for rates of vertical and horizontal atmospheric dispersion.

Figure 12 illustrates the conceptual basis for the regional siting capacity calculations. The objective of the calculations is to determine the concentrations of emissions from several power plants sited throughout a region having dimensions X_R and Y_R at a receptor location such as the shaded vertical plane shown in Figure 12. In these calculations, it is assumed that concentrations are uniformly mixed between the ground and the top of the mixed layer, which has a height H_m. Emissions are transported in this mixed layer by a wind of velocity $\bar{u}$. The regional SO_2 concentrations may be increased as a function of the downwind distance x as a result of emissions from additional sources, or they may be decreased as a result of surface deposition, precipitation scavenging, and conversion to sulfate.

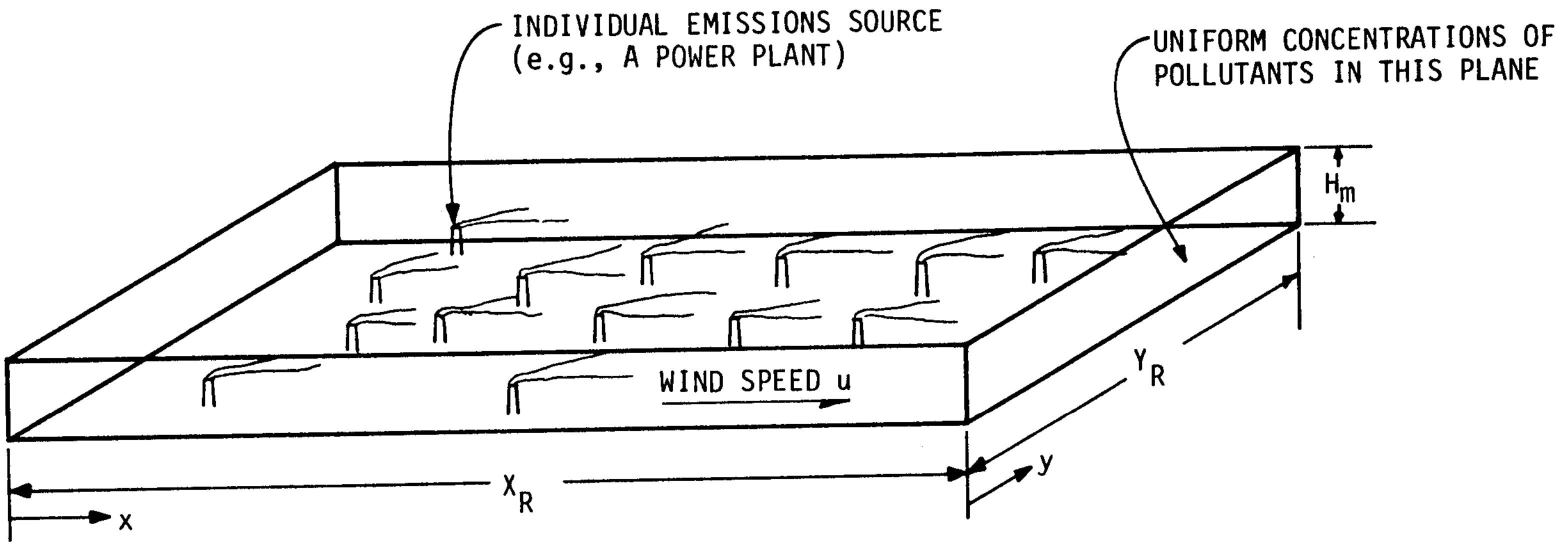


FIGURE 12. CONCEPTUAL BASIS FOR REGIONAL SITING CAPACITY CALCULATIONS

We can calculate the concentration at any given downwind distance x (or transit time t) using a simple box model formula:

$$\chi = \frac{Q(t)}{uH_m} \tag{11}$$

The pollutant flux Q per unit crosswind distance y may be increased if the air parcel is transported over emissions sources Q_o or may be decreased as a result of surface deposition, precipitation scavenging, and chemical conversion to sulfate. For convenience, we treat the contributions of individual sources Q_o as distributed sources of emission density q:

$$q = \frac{Q_o}{x_s^2} \tag{12}$$

where

q = emission density ($g/m^2/sec$),

Q_o = individual source emission rate (g/sec),

x_s = average source spacing (m).

Ignoring periods of precipitation, we can write a mass balance for regional SO_2 mass flux as follows:

$$dQ = qu\ dt - \left(\frac{Q}{uH_m}\right)v_d u\ dt - kQ\ dt \tag{13}$$

where v_d = deposition velocity of SO_2 (m/sec) and k = SO_2 to $SO_4^=$ rate constant (per sec). Thus, the resulting equation is:

$$\frac{dQ}{dt} + \left(k + \frac{v_d}{H_m}\right)Q = qu \tag{14}$$

The solution to Eq. (14) as a function of air parcel travel time is:

$$Q(t) = \frac{qu}{k'}\left(1 - e^{-k't}\right) \tag{15}$$

where $k' = k + (v_d/H_m)$.

By combining Eqs. (11) and (15), we obtain:

$$\chi = \frac{q\left(1 - e^{-k't}\right)}{k'H_m} = \frac{q\left(1 - e^{-k'x/u}\right)}{k'H_m} \tag{16}$$

Thus, the SO_2 concentration χ downwind of a region of emission density q is directly proportional to q and indirectly proportional to the mixing depth H_m. If the air parcel travel time is large over the region of emission density q, the resultant SO_2 concentration is simply:

$$\chi = \frac{q}{k'H_m} \tag{17}$$

Equation (16) is appropriate for estimating concentrations immediately downwind of an area with emission density q. However, as previously shown, new power plants cannot be sited within some particular distance of a Class I area because of the need to ensure that individual sources do not violate Class I PSD increments. Consequently, over a distance on the order of 50 to 200 km, an air parcel will be transported over areas with zero incremental emission densities Δq (above levels existing when PSD legislation was enacted). Thus, SO_2 flux is decreased somewhat by conversion to sulfate and by surface deposition within these exclusion areas around Class I areas. Equation (16) can be modified as follows to account for this effect of exclusion areas around Class I areas:

$$\chi = \frac{q\left(1 - e^{-k'T_R}\right)e^{-k'T_0}}{k'H_m} \tag{18}$$

where T_0 is the air parcel transit time over the area surrounding the Class I region where power plants cannot be sited and T_R is the transit time over the region in which emissions sources are located.

Similar equations can be derived for sulfur fluxes Q' and concentrations χ' if we ignore surface deposition of sulfate (an appropriate assumption since a negligible amount of sulfate is deposited during periods without precipitation) and precipitation scavenging (an appropriate assumption only for periods without precipitation). Thus, we have:

$$\frac{dQ'}{dt} = 1.5\ kQ \tag{19}$$

$$\chi' = \frac{1.5\ kq}{k'H_m}\left[T_R - \frac{1}{k'}\left(1 - e^{-k'T_R}\right)e^{-k'T_0}\right] \quad . \tag{20}$$

Note from Eq. (20) that, unlike SO_2 concentrations, sulfate concentrations continue to increase with transit time over a region unless precipitation occurs and scavenges the aerosol [see, for example, the plot of sulfate flux in Figure 6(a)].

We can use Eq. (16) to estimate the maximum increment in emission density Δq allowed by PSD increments $\Delta\chi_{PSD}$. The value of Δq can be used to calculate the siting capacity in megawatts of coal-fired power plants in a region of known area.

B. MAXIMUM REGIONAL SO_2 EMISSION DENSITIES AND POWER PLANT SITING CAPACITIES

It can be shown that the Class I 24-hour-average SO_2 increment of 5 $\mu g/m^3$ is the most limiting PSD increment for the regional siting capacity. A limited-mixing situation with a stable capping layer persisting over a period of three to five days without precipitation appears to be the meteorological condition most likely to cause exceedances of the 24-hour SO_2 PSD increment in Class I areas due to regional emissions. According to an analysis by Holzworth (1972), this condition occurs more than once per year in most areas of the United States. In the East, this condition is associated with mixing depths up to 2000 m, whereas in the West the associated mixing depths are less than 1000 m.

With these mixing depths, we calculated the maximum regional emission densities necessary to meet Class I PSD increments using Eq. (18) modified as follows:

$$\Delta q = \frac{\Delta \chi_{PSD}\, k' H_m}{\left(1 - e^{-k' T_R}\right) e^{-k' T_0}} \quad . \tag{21}$$

Maximum emission densities of 0.081 $g/km^2/sec$ for the western United States (H_m = 1000 m) and 0.107 $g/km^2/sec$ for the eastern United States (H_m = 2000 m) were computed using Eq. (21) and the following values of parameters:

$\Delta \chi_{PSD}$ = 5 $\mu g/m^3$ (Class I 24-hour-average SO_2 increment),

$k' = k + (v_d/H_m)$,

k = 0.005 per hour (SO_2-to-sulfate conversion pseudo-first-order rate constant),

v_d = 1 cm/sec (SO_2 deposition velocity),

T_R = 2 days (air parcel travel time over the emissions areas),

T_0 = 5 hours (air parcel travel time over the exclusion area between the emissions area and the Class I area).

We can translate these maximum SO_2 emission densities into maximum power plant regional siting capacities in terms of megawatts of coal-fired generating capacity per square kilometer if we know the SO_2 emission rates. ICF Incorporated (1978) has calculated average regional SO_2 emission rates corresponding to each of the alternative NSPS SO_2 emission floors of 0.2, 0.5, and 0.8 $lb/10^6$ Btu, as well as the current NSPS limit of 1.2 $lb/10^6$ Btu, for the eastern and western United States. These emission rates are shown in Table 10, which also presents the maximum power plant regional siting capacities for each of these cases.

Using the results shown in Figure 11(a) and Table 10, we estimated the maximum power plant siting capacity in the contiguous United States from the standpoint of air quality (PSD) considerations. From estimates of power plant siting constraints imposed by Class I areas, we estimated that approximately 40 percent of the land area of the western United States (the states of and westward of Montana, Wyoming, Colorado, and New Mexico) could be used for power plant siting. That area totals 1.3 million km^2. In the eastern United States, more than 90 percent of the land area would be left unrestricted for power plant siting from the standpoint of Class I area protection. That area totals 3.8 million km^2. By multiplying the siting capacities shown in Table 10 by these areas, we determined the maximum coal-fired power plant capacity that can be installed in the United States, assuming different NSPS limitations. The results of this calculation are displayed in Table 11.

TABLE 10. REGIONAL AVERAGE SO_2 EMISSION RATES AND MAXIMUM POWER PLANT SITING CAPACITIES

NSPS SO_2 Emission Floor ($lb/10^6$ Btu)	Eastern United States		Western United States	
	SO_2 Emissions ($lb/10^6$ Btu)	Siting Capacity (Mwe/km^2)	SO_2 Emissions ($lb/10^6$ Btu)	Siting Capacity (Mwe/km^2)
0.2	0.42	0.22	0.18	0.40
0.5	0.42	0.22	0.28	0.25
0.8	0.52	0.18	0.48	0.15
1.2	0.96	0.10	0.80	0.09

The maximum power plant siting capacities for each of the proposed NSPS SO_2 floors are well above the 400 gigawatt electric (Gwe) output of coal-fired generating capacity that was predicted by ICF Incorporated (1978) to be installed during the period 1975 to 1995. However, with the current NSPS limit of 1.2 $lb/10^6$ Btu, planned capacity additions over the period 1975 to 1995 would use up 80 percent of the estimated U.S. power plant siting capacity. It appears that any of the floors studied for the proposed

NSPS SO_2 standard will be adequate to ensure that a sufficient number of coal-fired power plants can be built to meet growing energy needs while air quality goals are being met. Obviously, a greater number of power plants can be built in a given region and more area will be available for power plant siting with the implementation of more restrictive SO_2 emission controls.

TABLE 11. MAXIMUM POWER PLANT SITING CAPACITIES IN THE CONTIGUOUS UNITED STATES

(gigawatts of electric output*)

NSPS SO_2 Emission ($lb/10^6$ Btu)	Eastern United States†	Western United States§	Total
0.2	836	520	1356
0.5	836	325	1161
0.8	684	195	879
1.2	380	117	497

* 1 Gwe = 1000 Mwe.

† Maximum regional SO_2 emissions
= (3.8×10^6 km^2)(0.107 $g/km^2/sec$) = 39,000 tons per day.

§ Maximum regional SO_2 emission rate
= (1.3×10^6 km^2)(0.081 $g/km^2/sec$) = 10,000 tons per day.

C. IMPACT OF MAXIMUM SO_2 EMISSION DENSITY ON REGIONAL VISUAL RANGE

We evaluated the impact of the maximum regional SO_2 emission density calculated in the previous section on regional sulfate concentrations and the resulting impacts on visibility (visual range) as described below.

Using Eq. (20), we calculated the maximum increase in 24-hour-average sulfate concentration resulting from the calculated maximum allowable incremental increases in regional SO_2 emission density of 0.081 and 0.107 $g/km^2/sec$ for the western and eastern United States, respectively. These maximum sulfate increments were calculated to be approximately 1.7 $\mu g/m^3$ for the western United States and 1.4 $\mu g/m^3$ for the eastern United States.

Using appropriate values of scattering efficiency (b_{scat}-to-mass ratios) for the eastern and western United States [0.08 and 0.04 x $10^{-4}/m/(\mu g/m^3)$, respectively], we calculated the incremental increases in scattering coefficient corresponding to these increases in sulfate concentration and the resultant reductions in visual range. Assuming an average background visual range of 130 and 15 km, respectively, for the western and eastern United States, these increases in sulfate concentration would cause the following reductions in visual range in Class I areas during worst-case limited-mixing conditions:

- 18 percent in the western United States.
- 4 percent in the eastern United States.

During more typical, well-ventilated conditions, visual range would be reduced about 4 percent in the western United States and 1 percent in the eastern United States. Thus, it appears that limits to growth in regional SO_2 emission density imposed by effective enforcement of Class I area PSD increments will be effective in limiting the reductions in visual range in Class I areas.

VI RECOMMENDATIONS FOR FUTURE WORK

On the basis of our one-month study, we have concluded that significant constraints will likely be placed on the siting of coal-fired power plants, particularly in the western United States, to meet air quality goals. We believe that this tentative conclusion deserves further, immediate analysis by testing the assumptions about the frequency of occurrence and persistence of worst-case meteorological conditions.

The following characteristics of the West will limit power plant siting:

> The large number of federal Class I areas and areas that are likely to be redesignated Class I, with their associated stringent regulations on SO_2 concentrations to prevent significant deterioration.
> The excellent background visual range, which makes plume discoloration much more noticeable.
> The possibility of plume impingement on elevated terrain, thereby causing relatively large ground-level concentrations.

This and other studies performed thus far by SAI suggest that atmospheric discoloration, not reduction in visual range, may be the most significant visual impact caused by new coal-fired power plants meeting the recently proposed New Source Performance Standards. If the proposed NSPS limits are adopted, particulate and SO_2 emissions from new plants will be well controlled, and their impact on visual range and atmospheric discoloration can be expected to be insignificant. However, even with the more stringent NO_x emissions standards recently proposed, large quantities of NO_x will still be emitted from new power plants. Our studies have led us to postulate that NO_2 is the cause of yellow-brown plume discoloration in power plant plumes and that this discoloration may be visible during periods of poor atmospheric dispersion more than 100 km downwind from a large coal-fired power plant.

Until large-scale efficient NO_x emissions control technology for the coal-fired power plants is developed, the visual impact caused by yellow-brown power plant plumes may become a limiting factor in power plant siting near Class I areas in the West. It may be necessary to exclude significant land areas around Class I areas from power plant siting to protect scenic values and to ensure that PSD SO_2 increments within Class I areas are not exceeded. The implications of these air quality constraints on power plant siting could be quite significant, as evidenced by Figures 11(a) and 11(b).

We recommend that a more detailed study be performed to assess the constraints imposed by PSD and visibility protection goals on power plant siting throughout the United States using actual upper atmospheric meteorological data to estimate frequencies of occurrence and persistence of worst-case dispersion conditions. Since the EPA has not yet promulgated visibility regulations, the nature of such future regulations is unknown. However, we have used several quantitative measures of visibility (visual range and atmospheric discoloration) in our model development that could become the basis of future regulations and could be used to assess the impact of power plant emissions on Class I area visibility.

In the proposed study, representative National Weather Service upper atmospheric data could be used to develop a diffusion climatology for the West (or the entire country if desirable). Such a diffusion climatology, along with the application of the SAI plume visibility model for various power plant sizes and emissions controls, would enable production of isopleth maps showing the spatial extent--relative to a power plant site--of various impact measures (e.g., SO_2 concentration increments or plume perceptibility ΔE) and the frequency with which each measure would be exceeded in an average year. Overlaying these isopleths onto maps indicating the Class I areas would produce a final set of maps indicating where power plant construction (for each plant design) cannot be allowed.

To achieve this objective, the proposed study would need to include the following tasks:

(1) Obtain upper air meteorological data from representative National Weather Service rawinsonde stations in the West (or throughout the United States, if desired).

(2) Produce joint frequency distributions of upper air wind speed, wind direction, and vertical temperature gradients (indicative of atmospheric stability) for each of these upper air stations to represent the diffusion climatology of each region of the country.

(3) Calculate the plume centerline and ground-level SO_2 concentrations and visibility impairment increments as a function of downwind distance for a variety of power plant sizes, emissions conditions, and diffusion conditions using SAI's plume visibility model.

(4) Produce isopleth maps, using the results of Tasks 2 and 3, illustrating the spatial and temporal extent of air quality impacts, including visibility, in the vicinity of a power plant of a given size (see Figure 13). Each isopleth in such a map would show, as a function of direction from a hypothetical power plant site, the distance at which an air quality or visibility impact would occur with the stated frequency. For example, Figure 13 illustrates isopleths showing frequencies of occurrence of 1, 10, and 18 times per year at which a given air quality parameter is exceeded. Air quality parameters of interest might be the plume perceptibility parameter ΔE or SO_2 concentrations (e.g., the 3-hour and 24-hour Class I PSD increments). These maps could be produced for various power plant sizes and emissions conditions. Thus, one would have a map like Figure 13 for each combination of power plant size, emission condition, air quality parameter, and region that was chosen for evaluation. The value of such maps would be their provision of

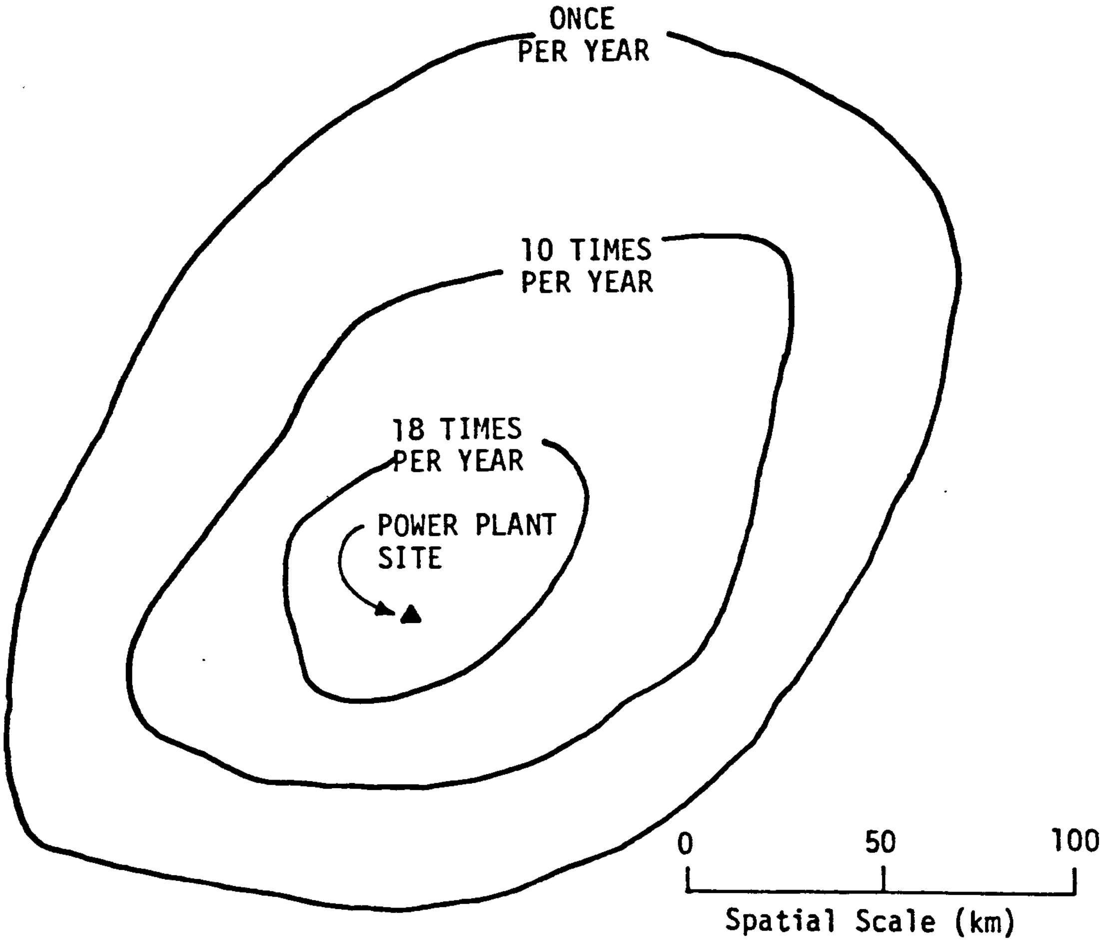


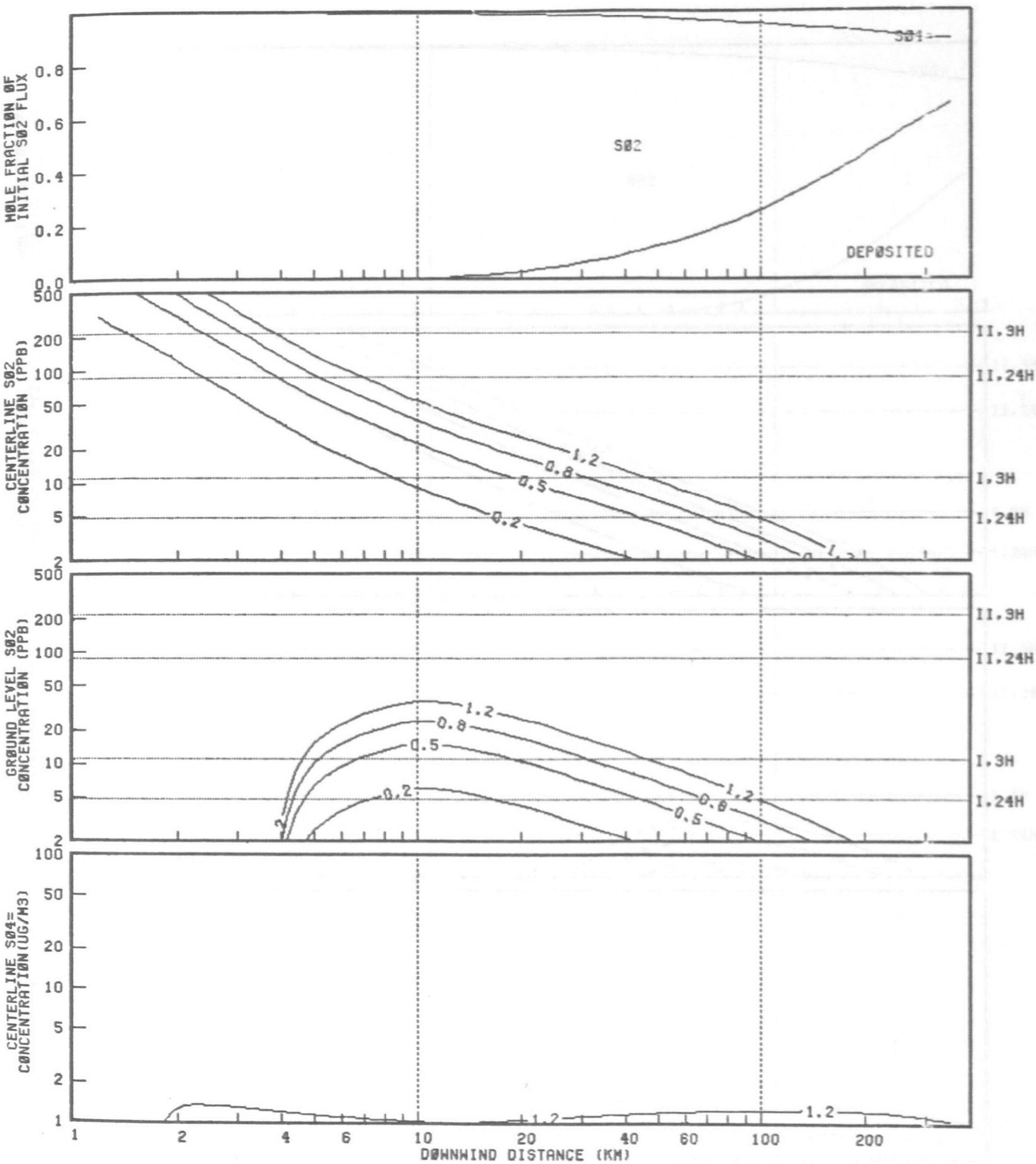
FIGURE 13. EXAMPLE OF AN ISOPLETH MAP SHOWING AREAS AROUND A HYPOTHETICAL POWER PLANT IN WHICH ITS AIR QUALITY IMPACT (e.g., SO_2 CONCENTRATION OR PLUME PERCEPTIBILITY) IS GREATER THAN A GIVEN VALUE

information about the magnitude, spatial extent, and frequency of occurrence of the given air quality impact in a single figure. Also, these maps could be used as overlays to identify specific areas that should be restricted for siting (Task 5).

(5) Produce maps of the United States showing Class I areas (and regions that may be so redesignated) and the areas surrounding them where the results of Task 4 indicate that the air quality impact of a power plant of a given size would be too large (from the standpoint of either PSD Class I SO_2 increments or visibility). Such maps, together with appropriate overlays, could be used by both government and industry to identify air quality constraints on power plant siting and to direct future research and regulatory efforts.

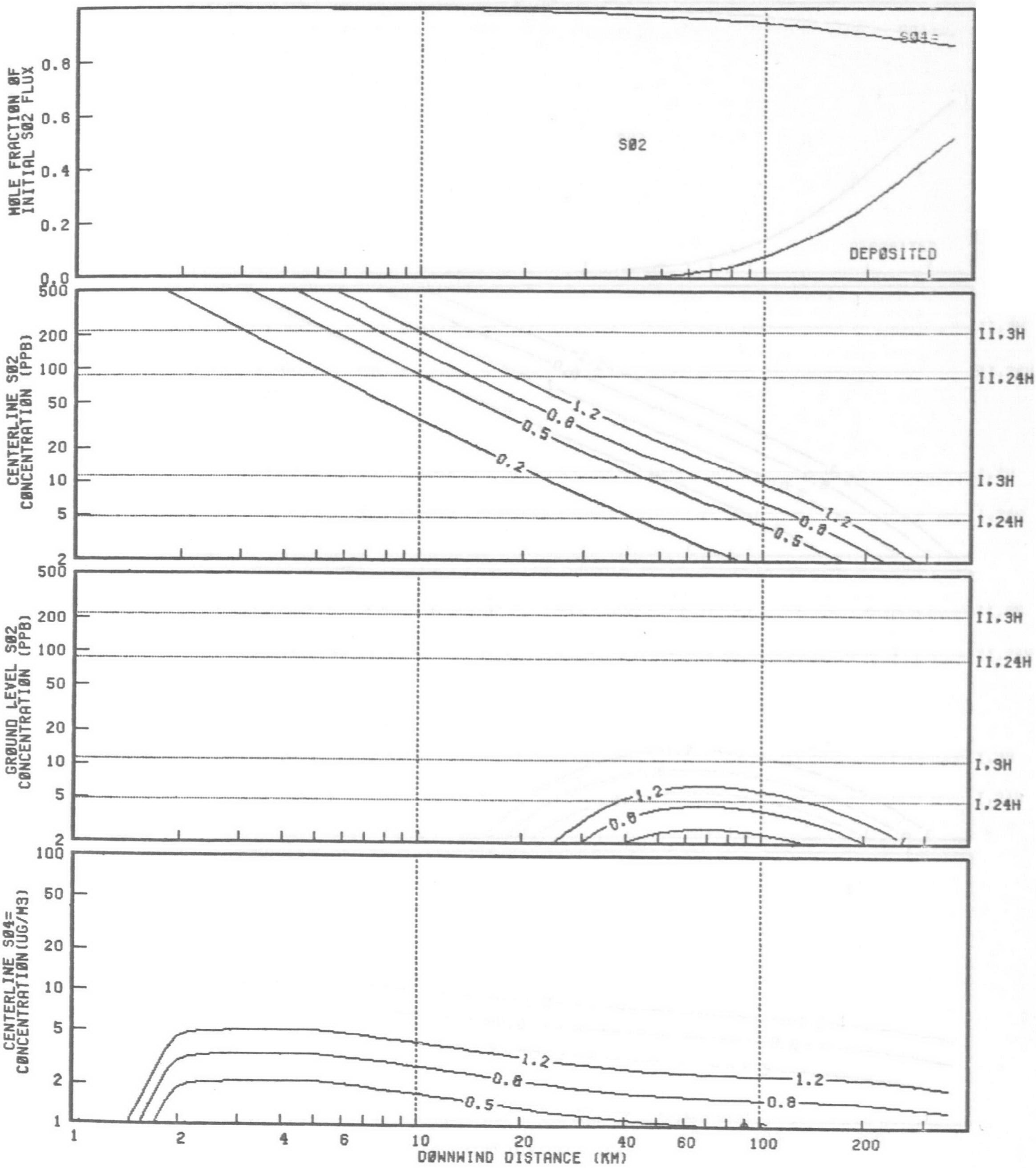
APPENDIX A

500 MWE POWER PLANT IMPACTS



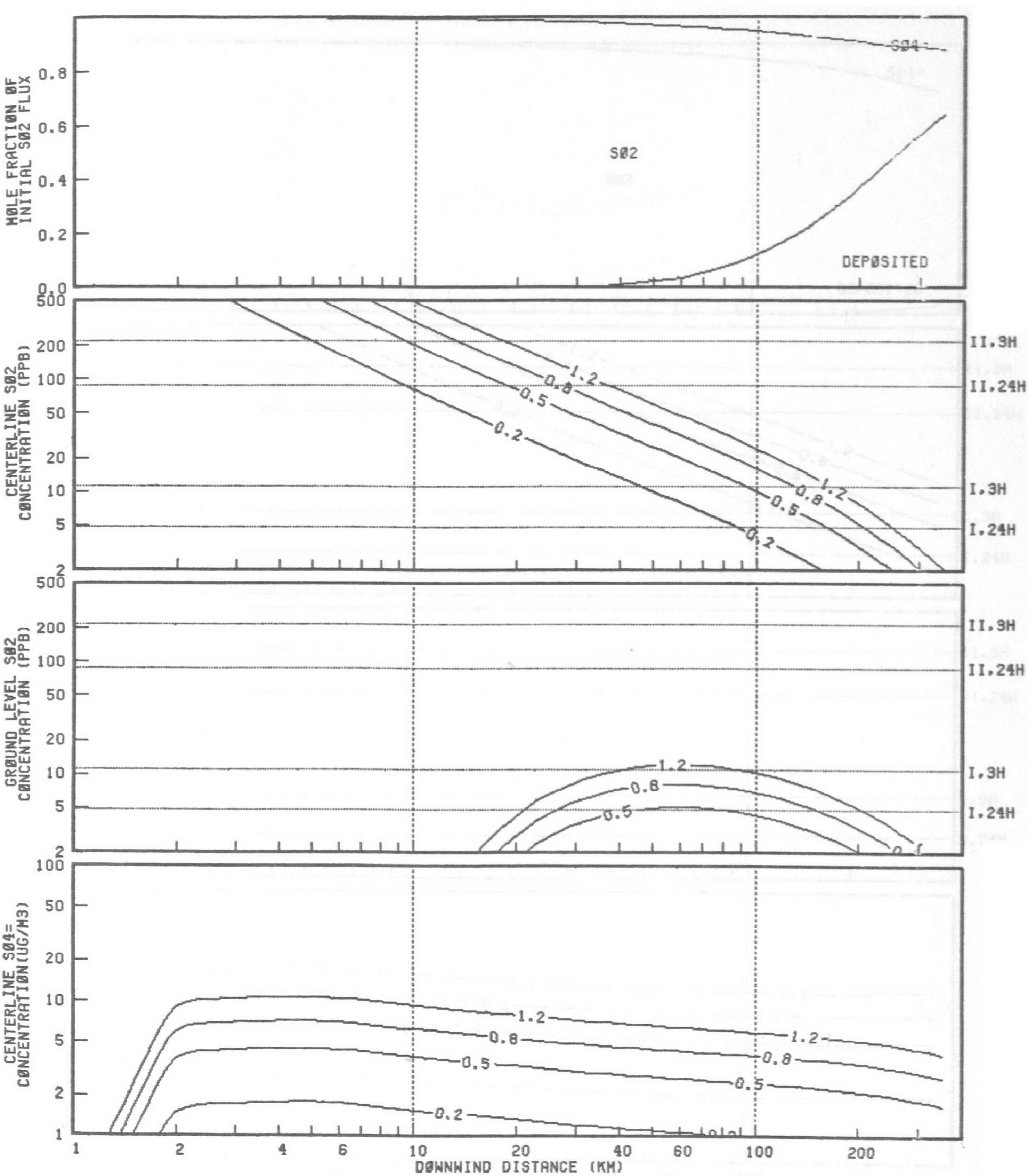
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE A-1. EFFECT OF SO_2 EMISSION RATES ON SO_x FLUXES AND CONCENTRATIONS DOWNWIND OF A 500 Mwe COAL-FIRED POWER PLANT. SO_2 emission rates in pounds per million Btu are indicated.



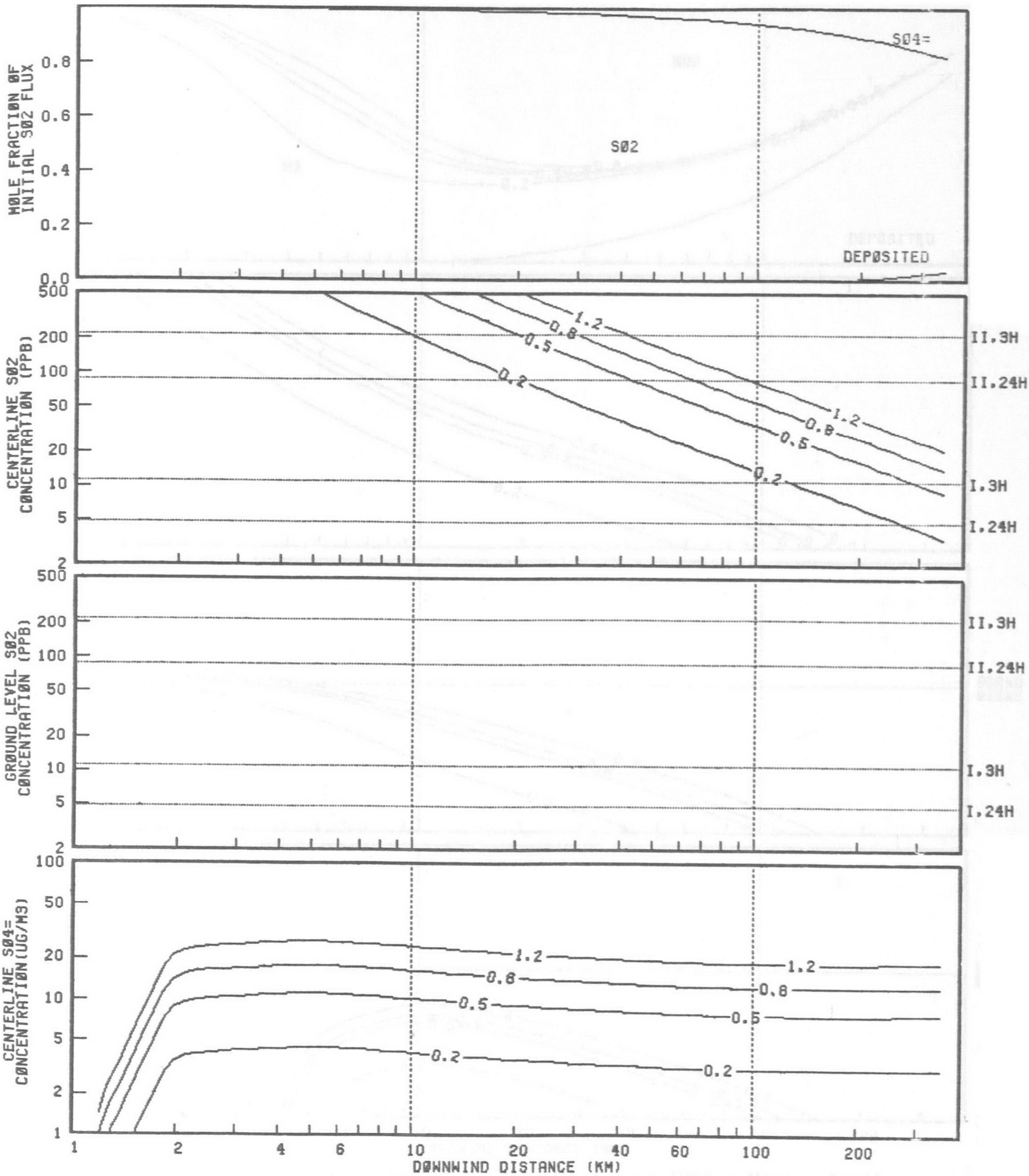
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE A-1 (Continued)



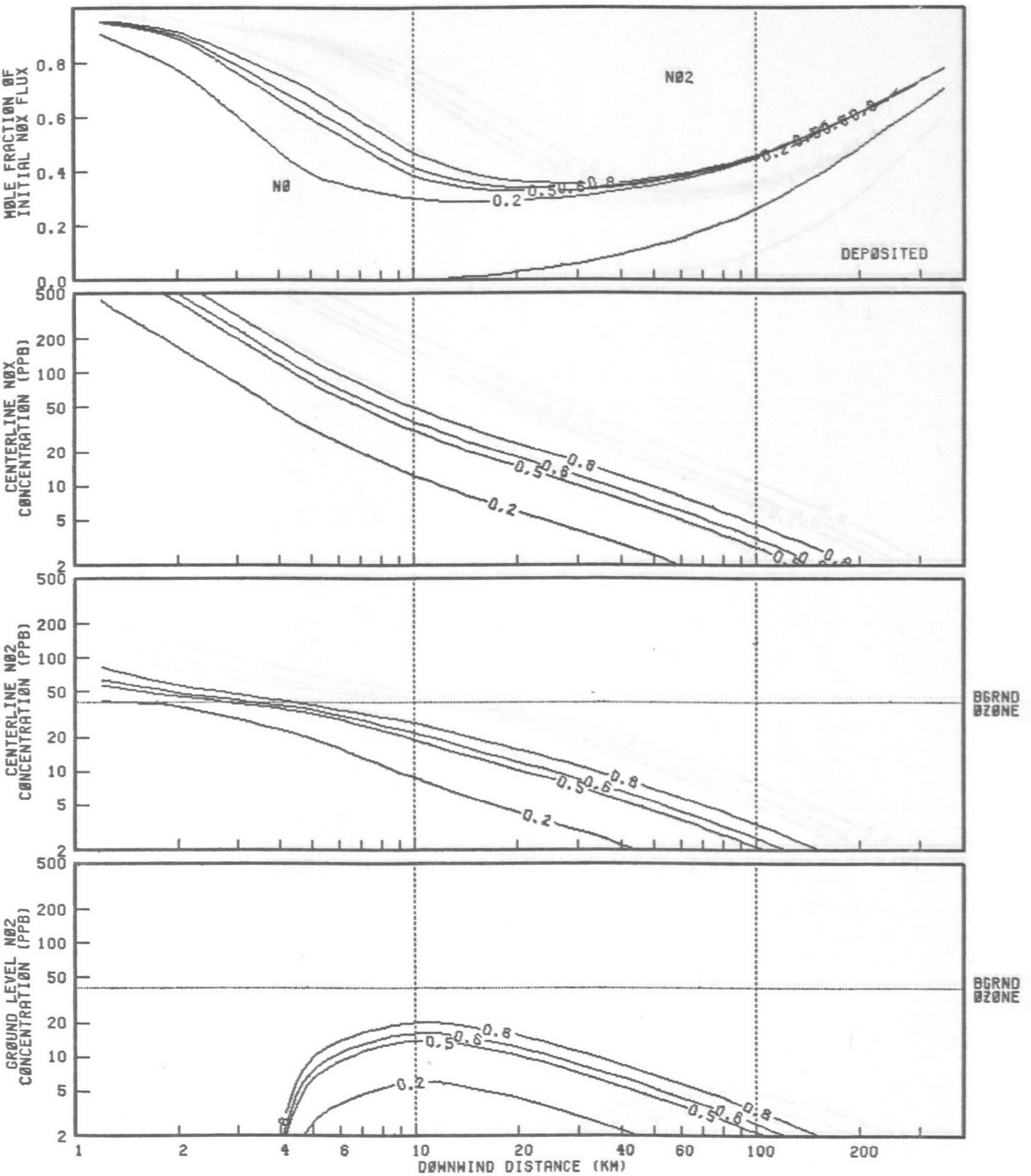
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE A-1 (Continued)



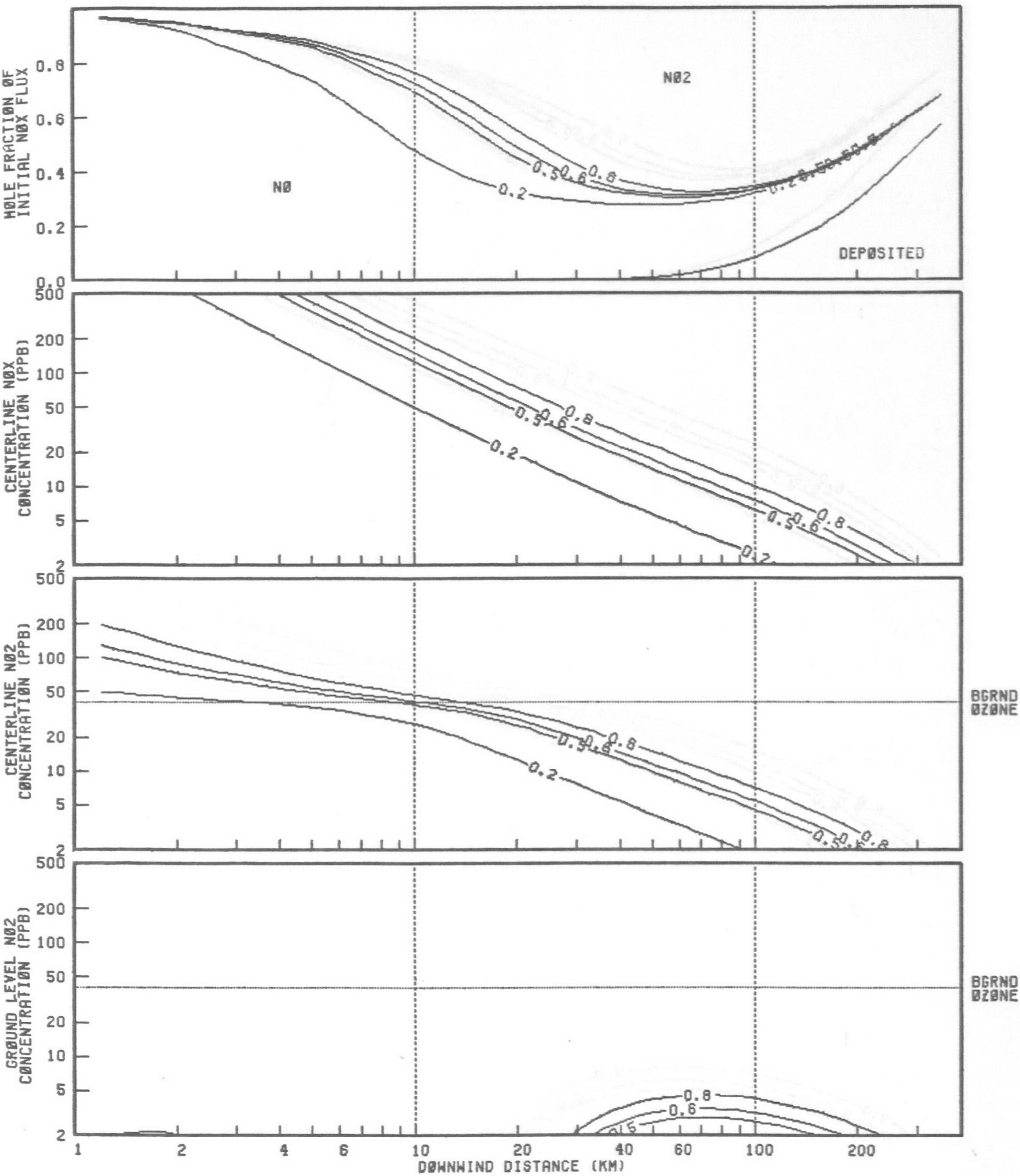
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE A-1 (Concluded)



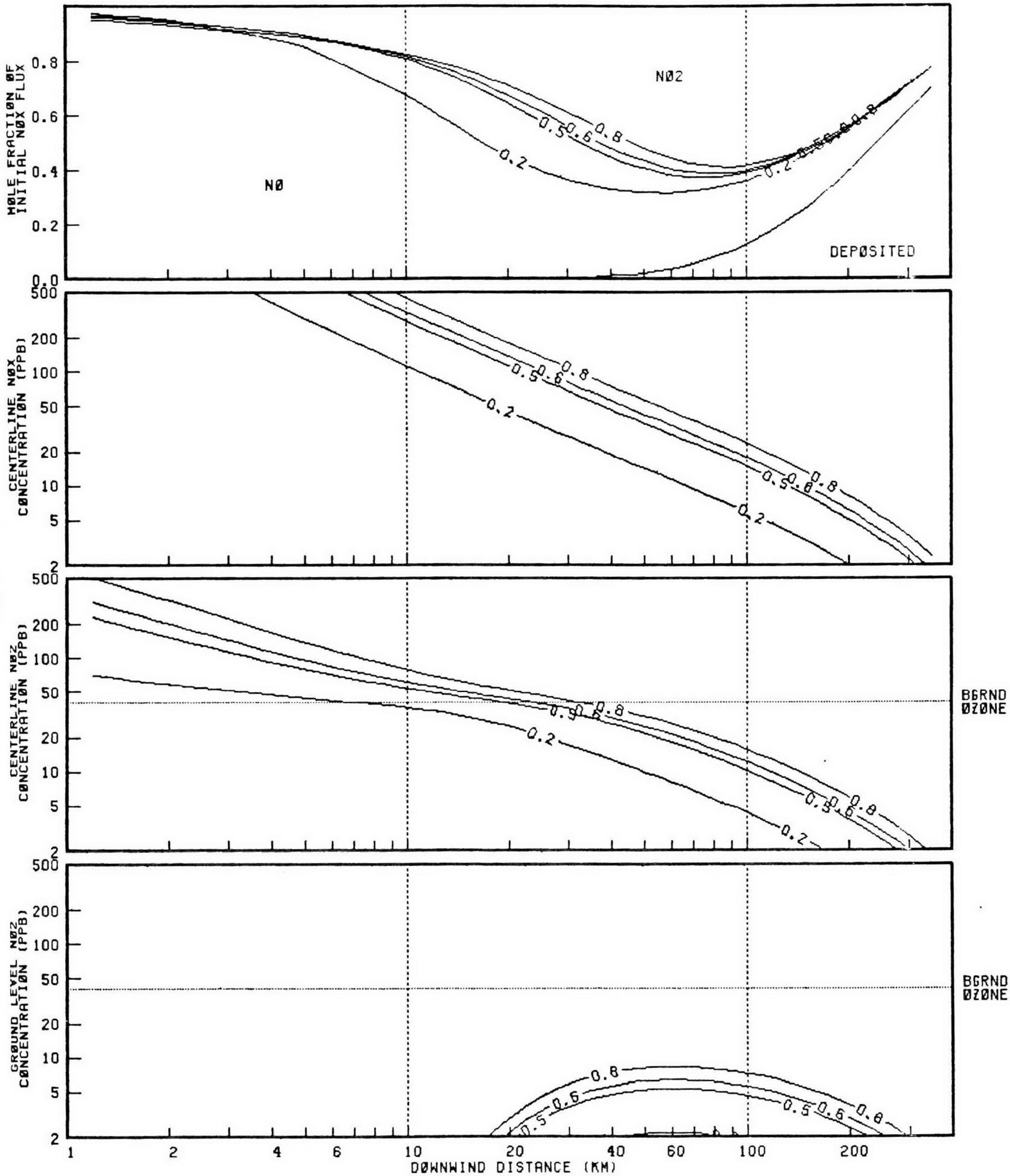
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE A-2. EFFECT OF NO_x EMISSION RATES ON NO_x FLUXES AND CONCENTRATIONS DOWNWIND OF A 500 Mwe COAL-FIRED POWER PLANT. NO_x emission rates in pounds per million Btu are indicated.



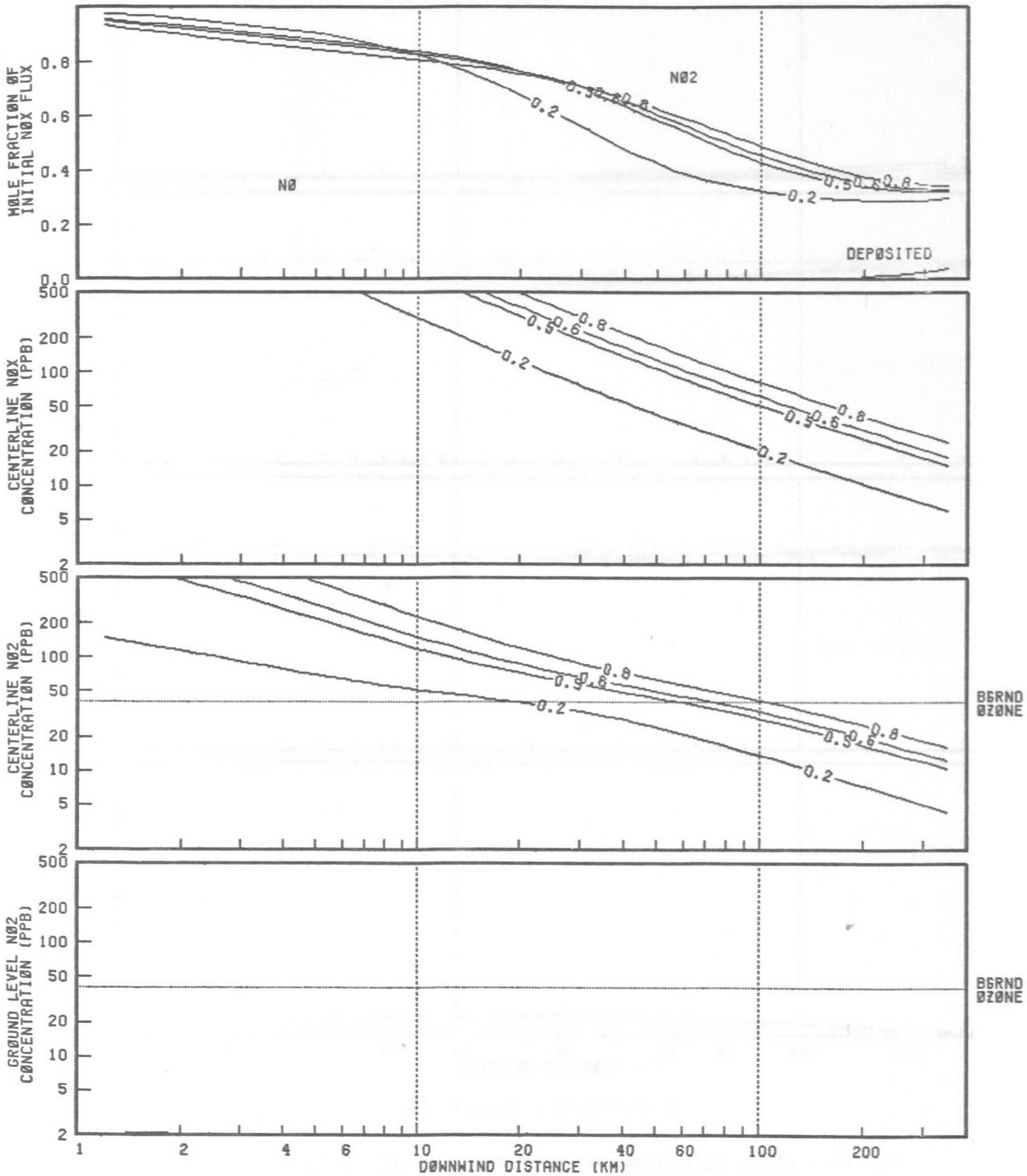
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE A-2 (Continued)



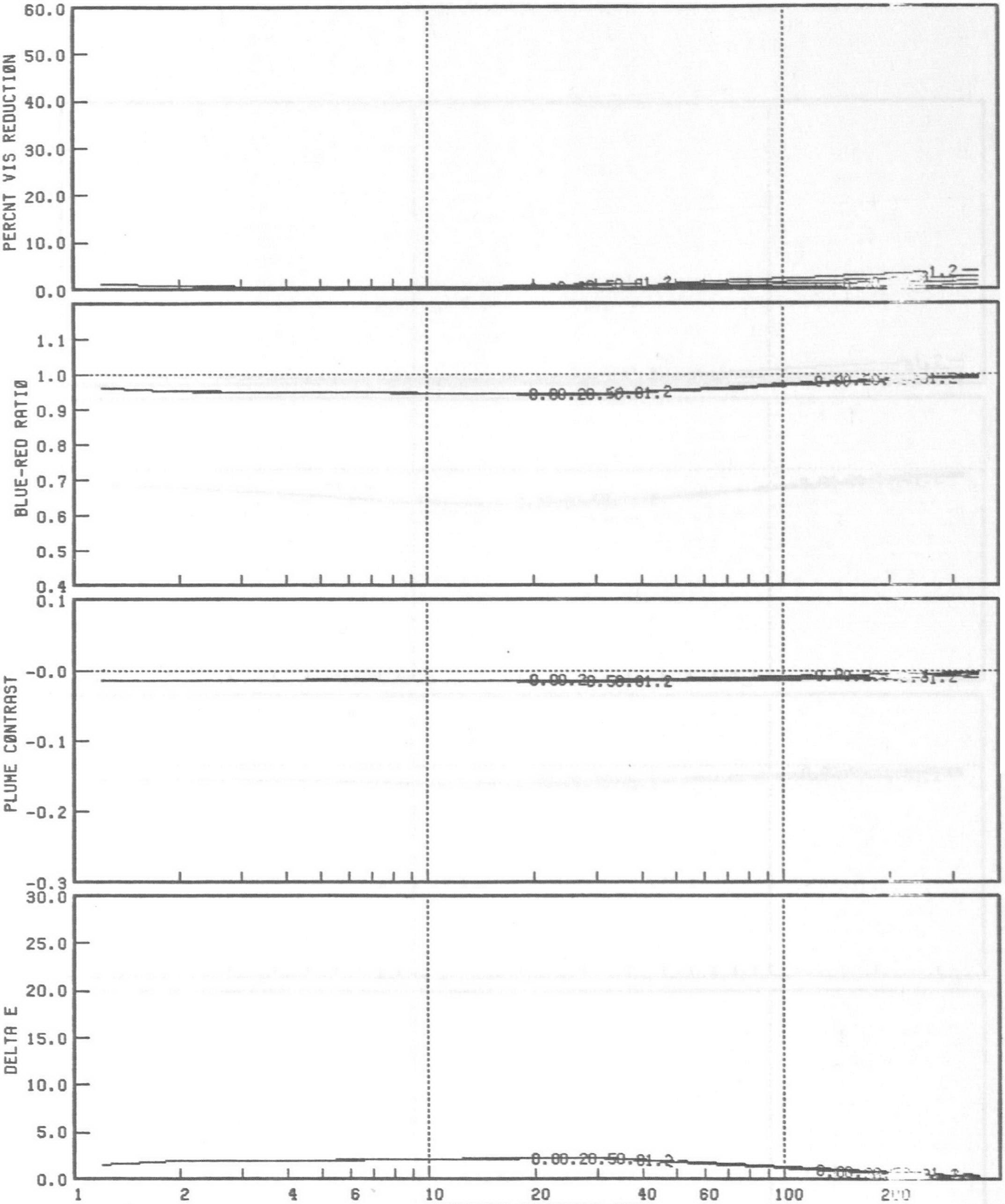
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE A-2 (Continued)



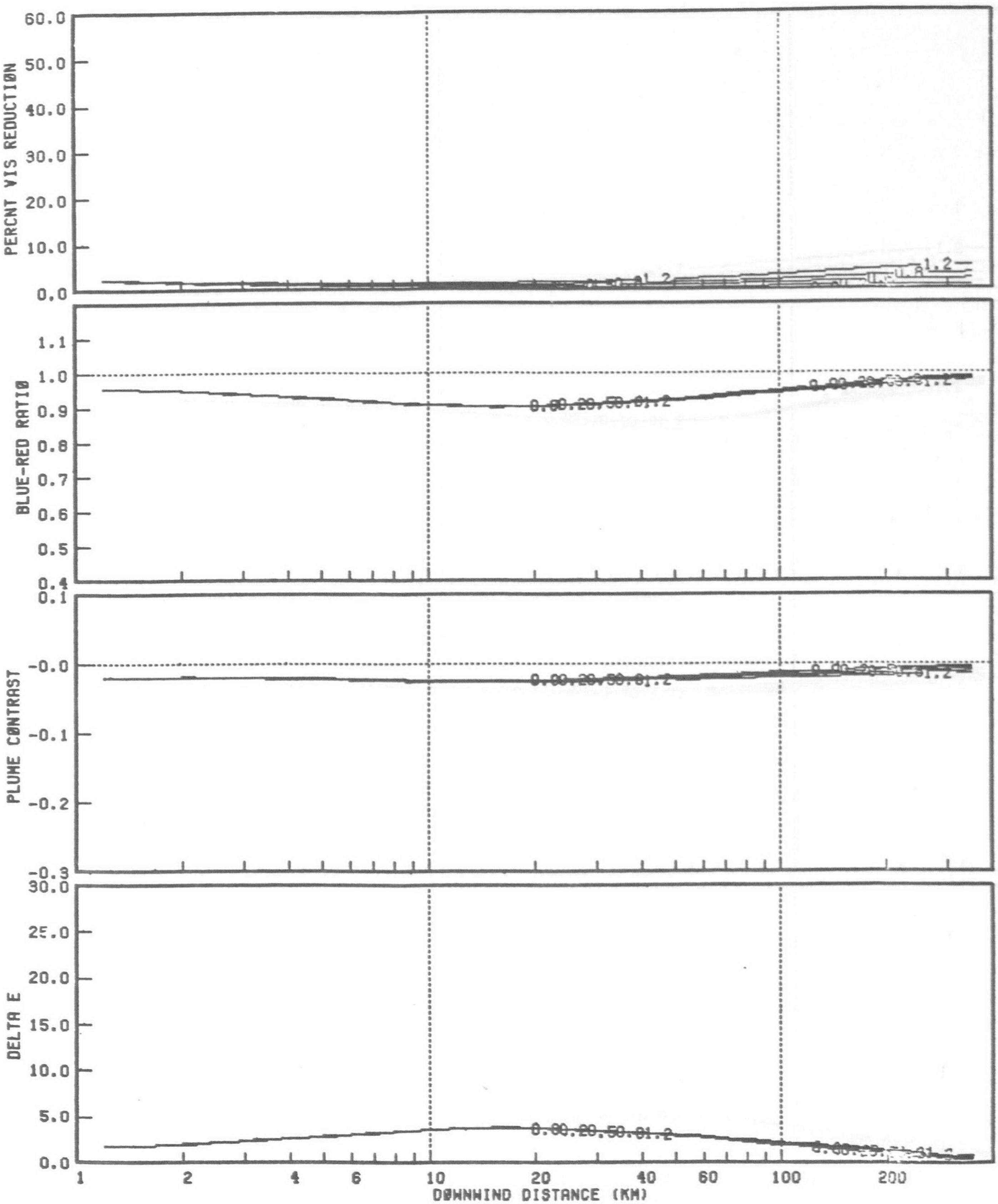
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE A-2 (Concluded)



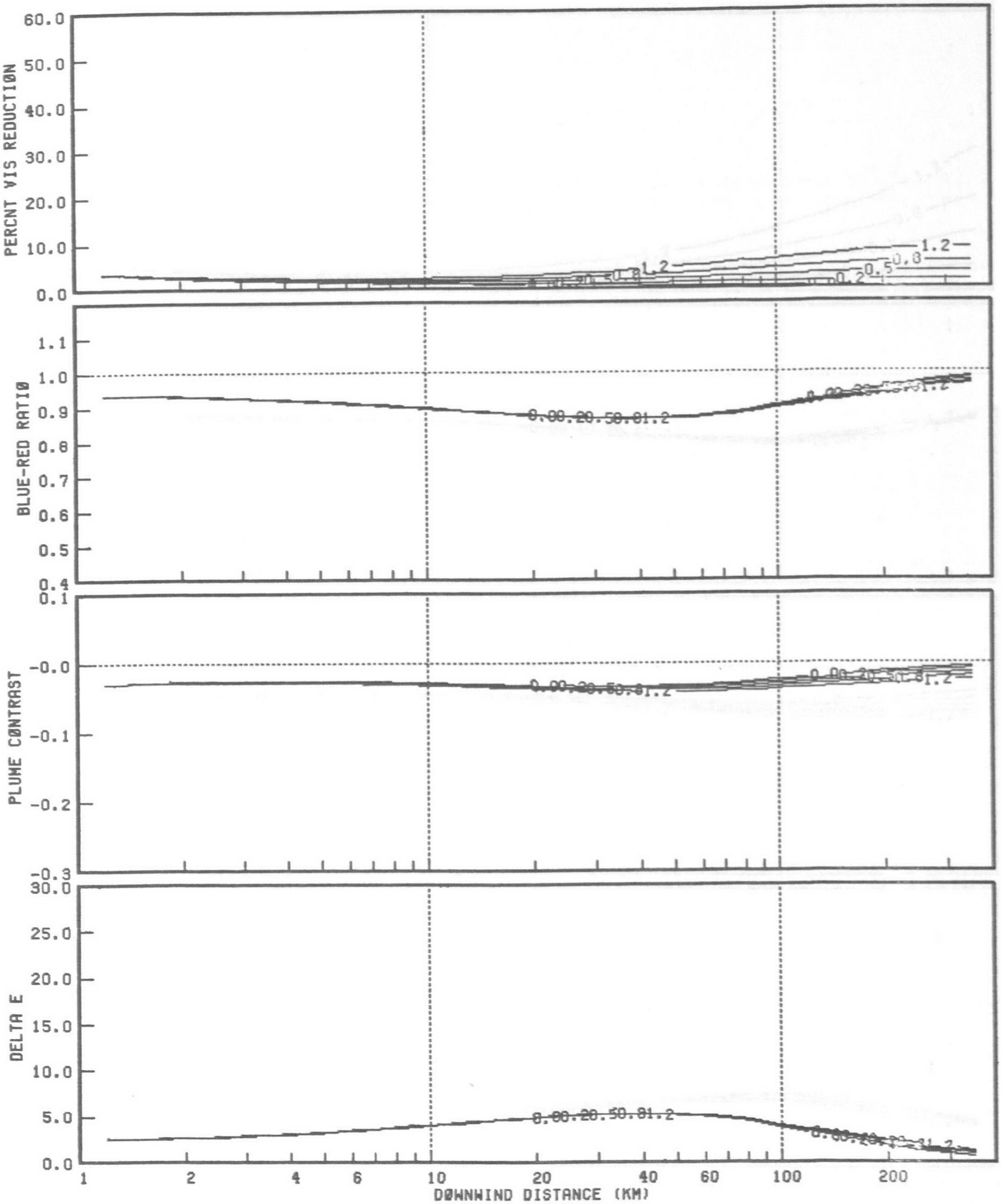
(a) Pasquill Stability C

FIGURE A-3. EFFECT OF SO_2 EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 500 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. SO_2 emission rates in pounds per million Btu are indicated.



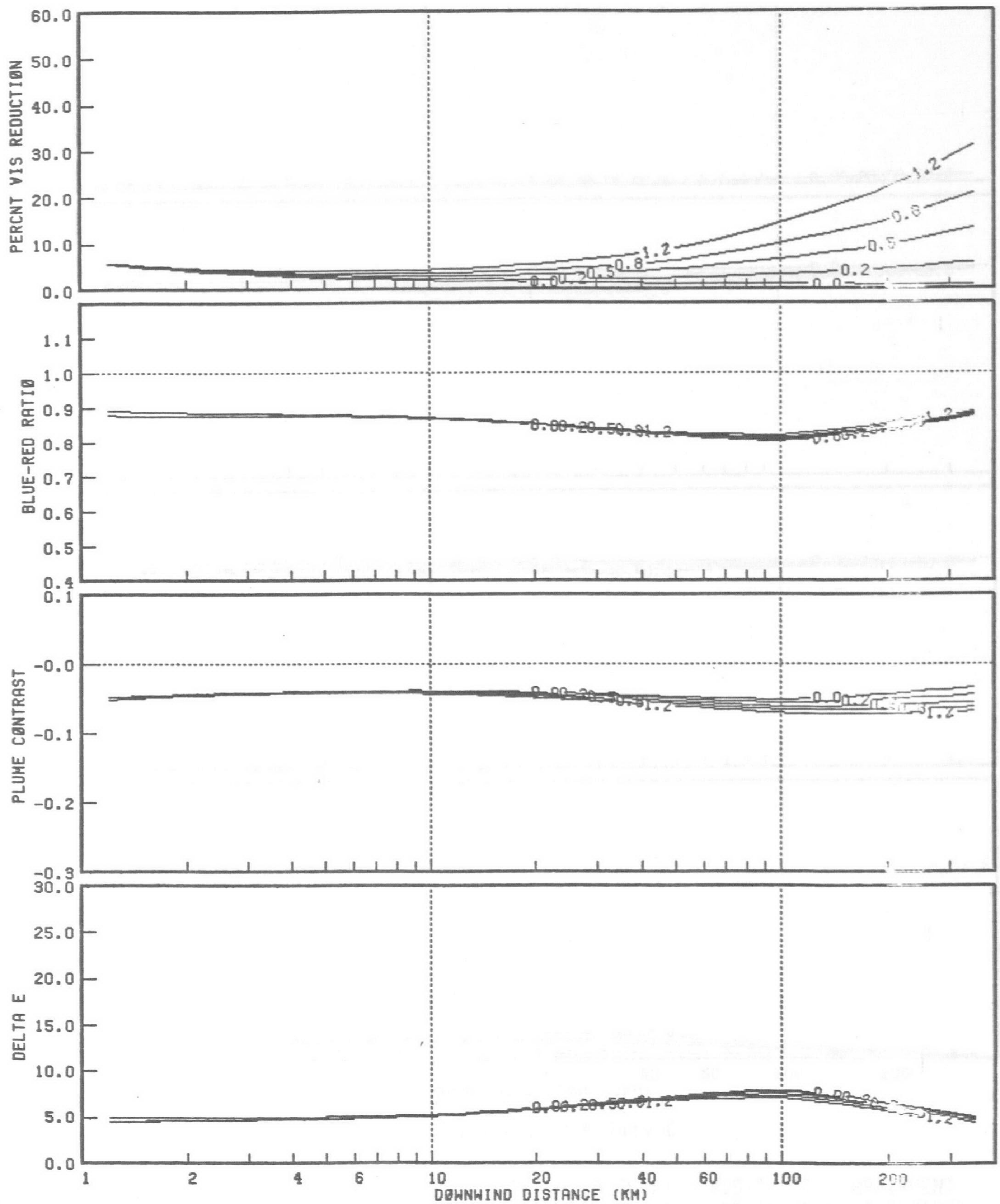
(b) Pasquill Stability D

FIGURE A-3 (Continued)



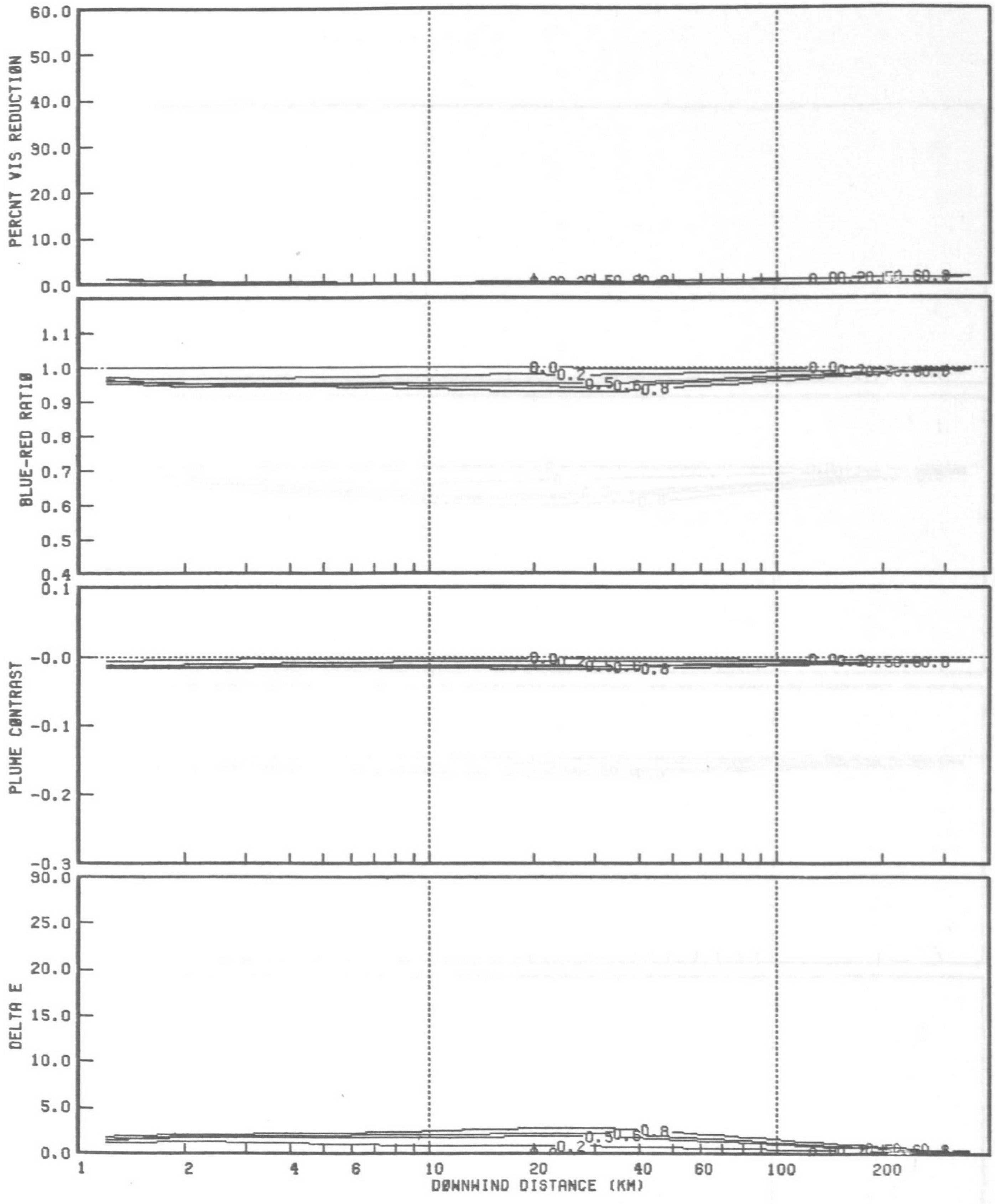
(c) Pasquill Stability E

FIGURE A-3 (Continued)



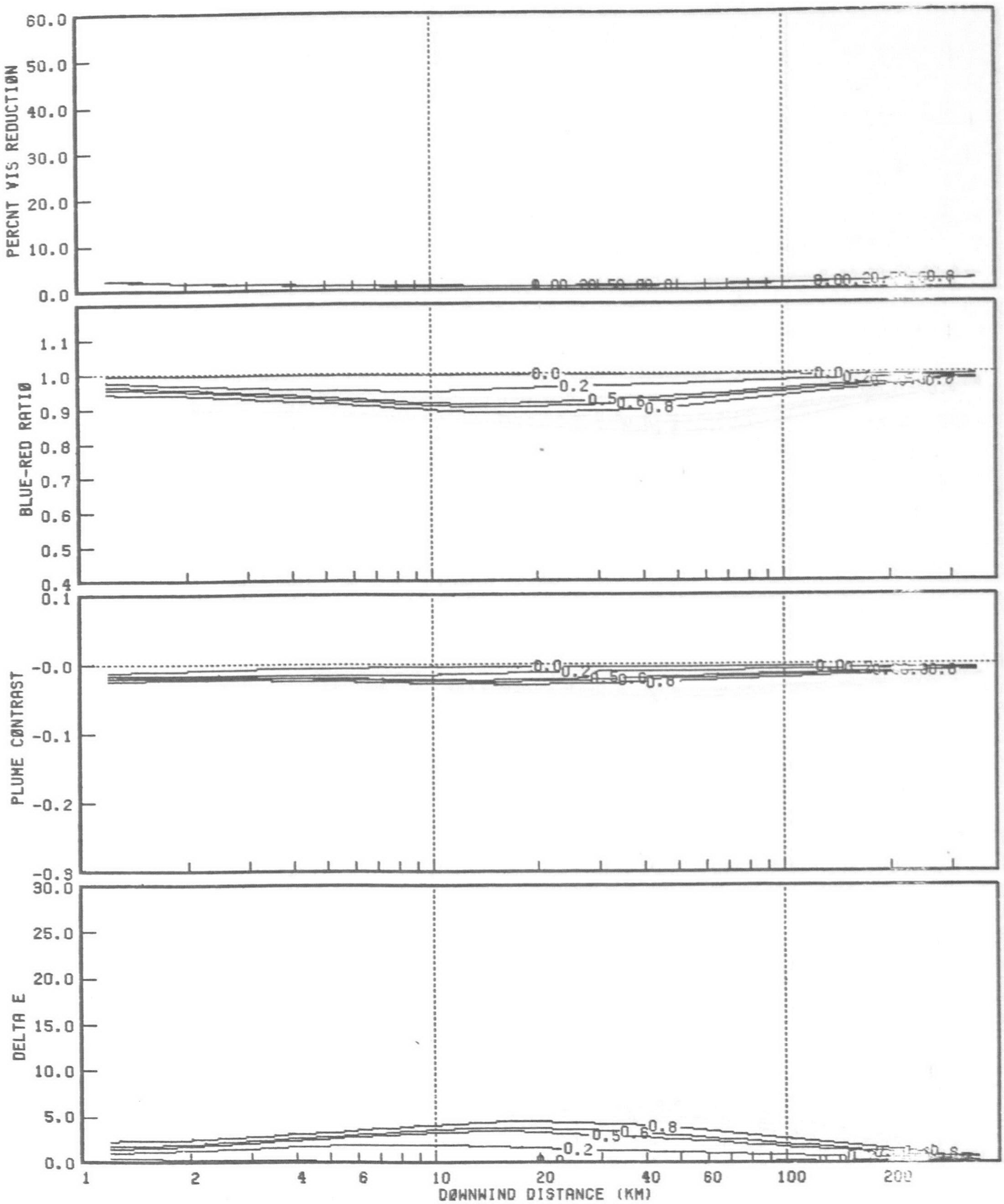
(d) Pasquill Stability F

FIGURE A-3 (Concluded)



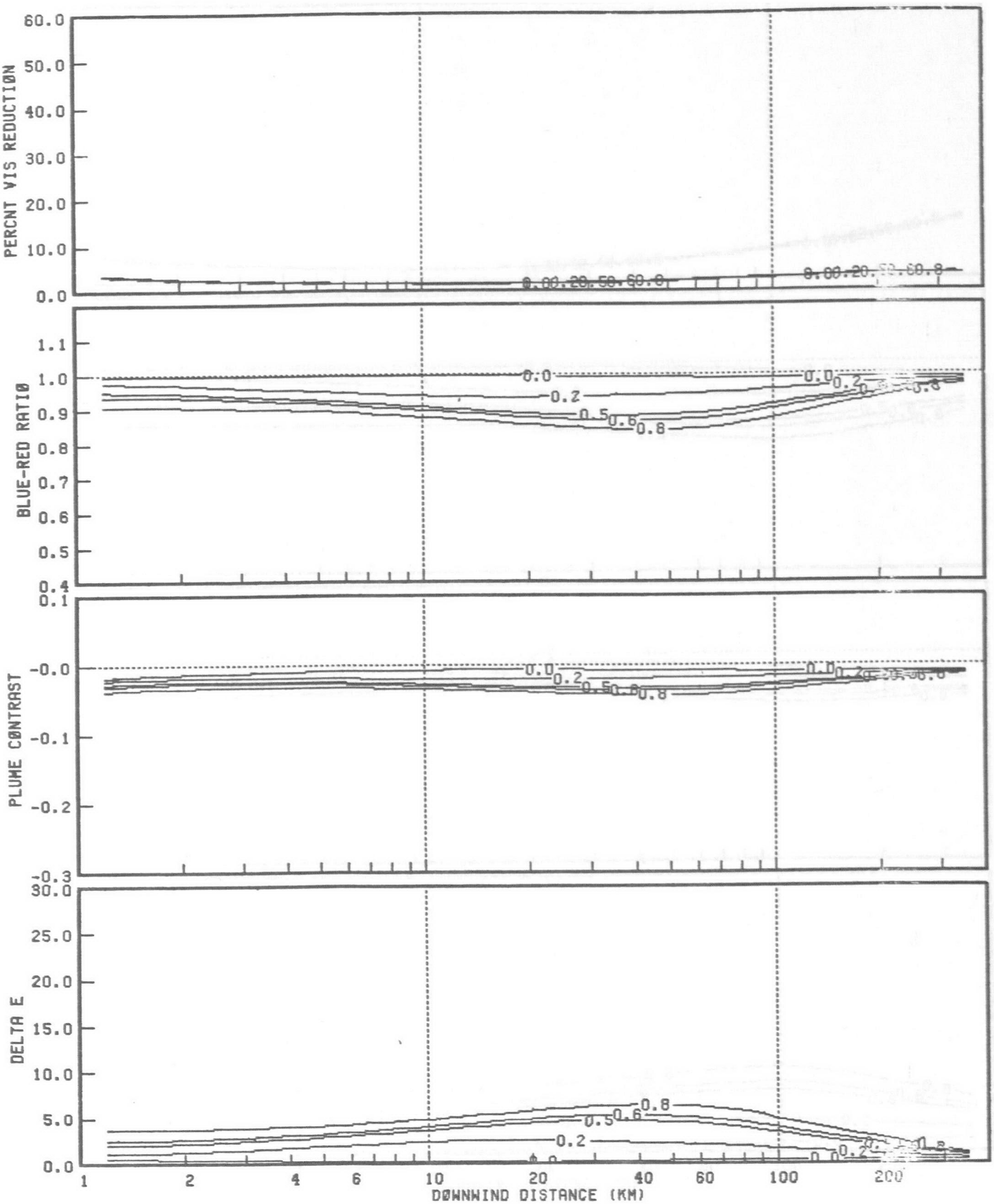
(a) Pasquill Stability C

FIGURE A-4. EFFECT OF NO_x EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 500 MWe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. NO_x emission rates in pounds per million Btu are indicated.



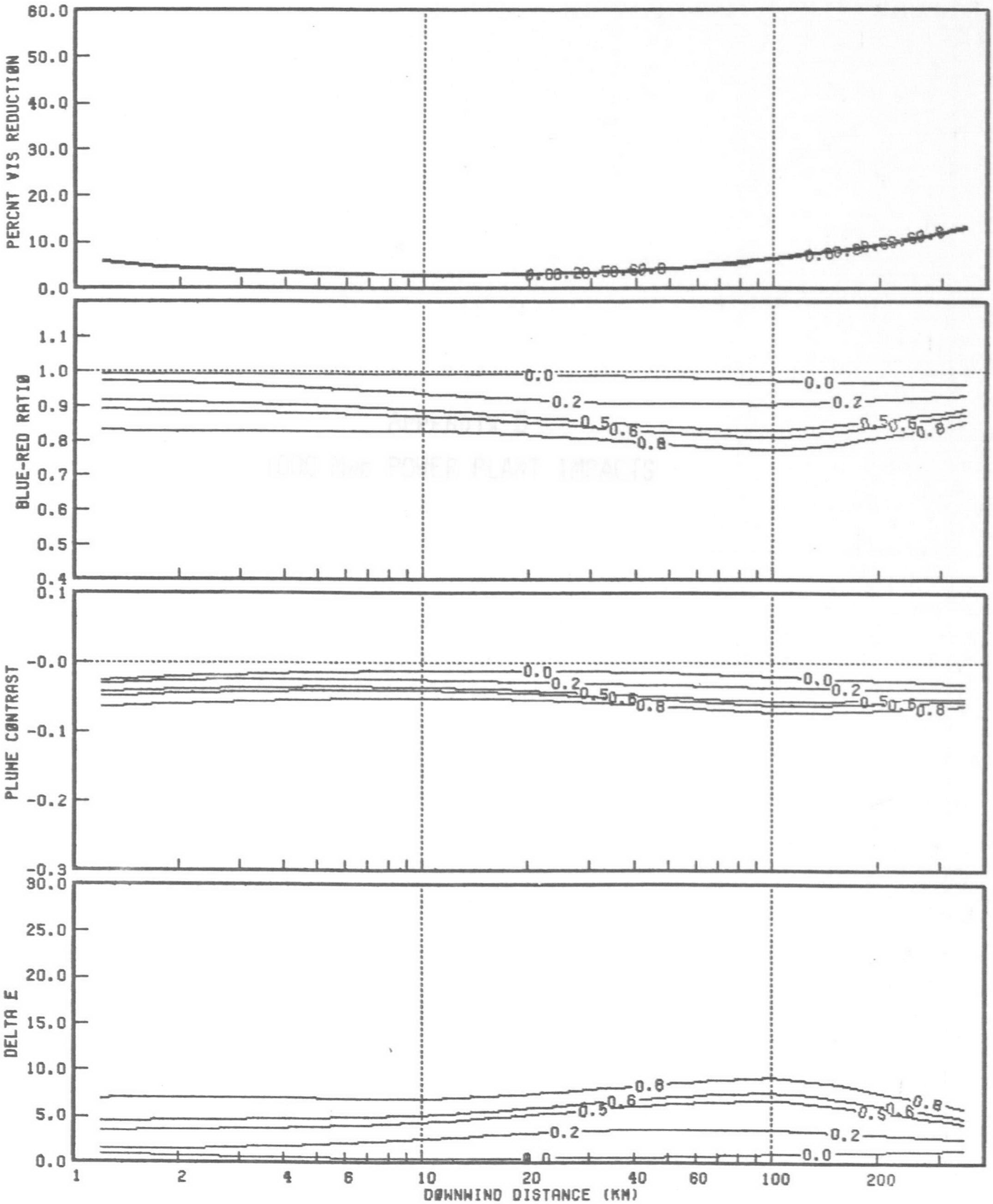
(b) Pasquill Stability D

FIGURE A-4 (Continued)



(c) Pasquill Stability E

FIGURE A-4 (Continued)

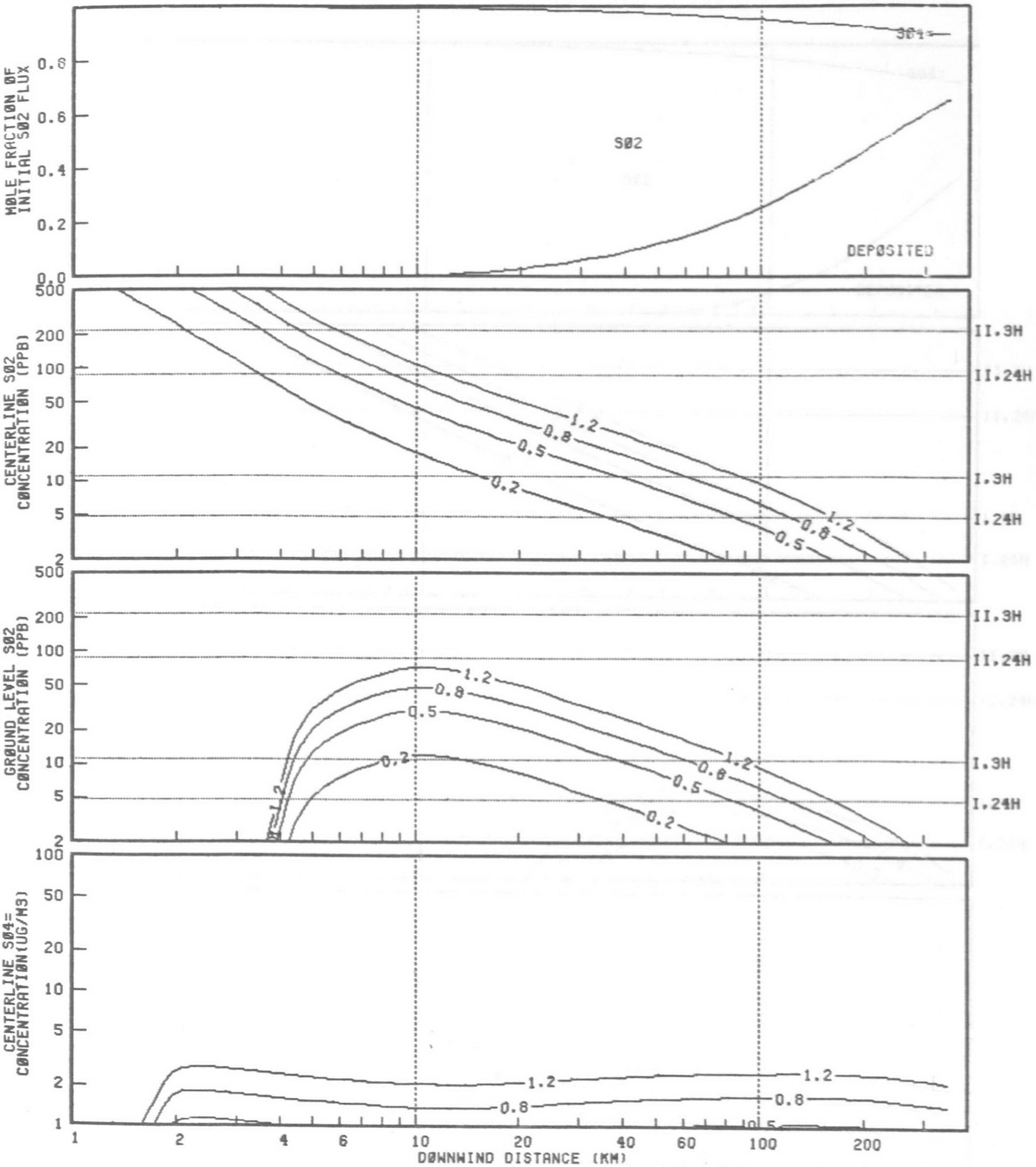


(d) Pasquill Stability F

FIGURE A-4 (Concluded)

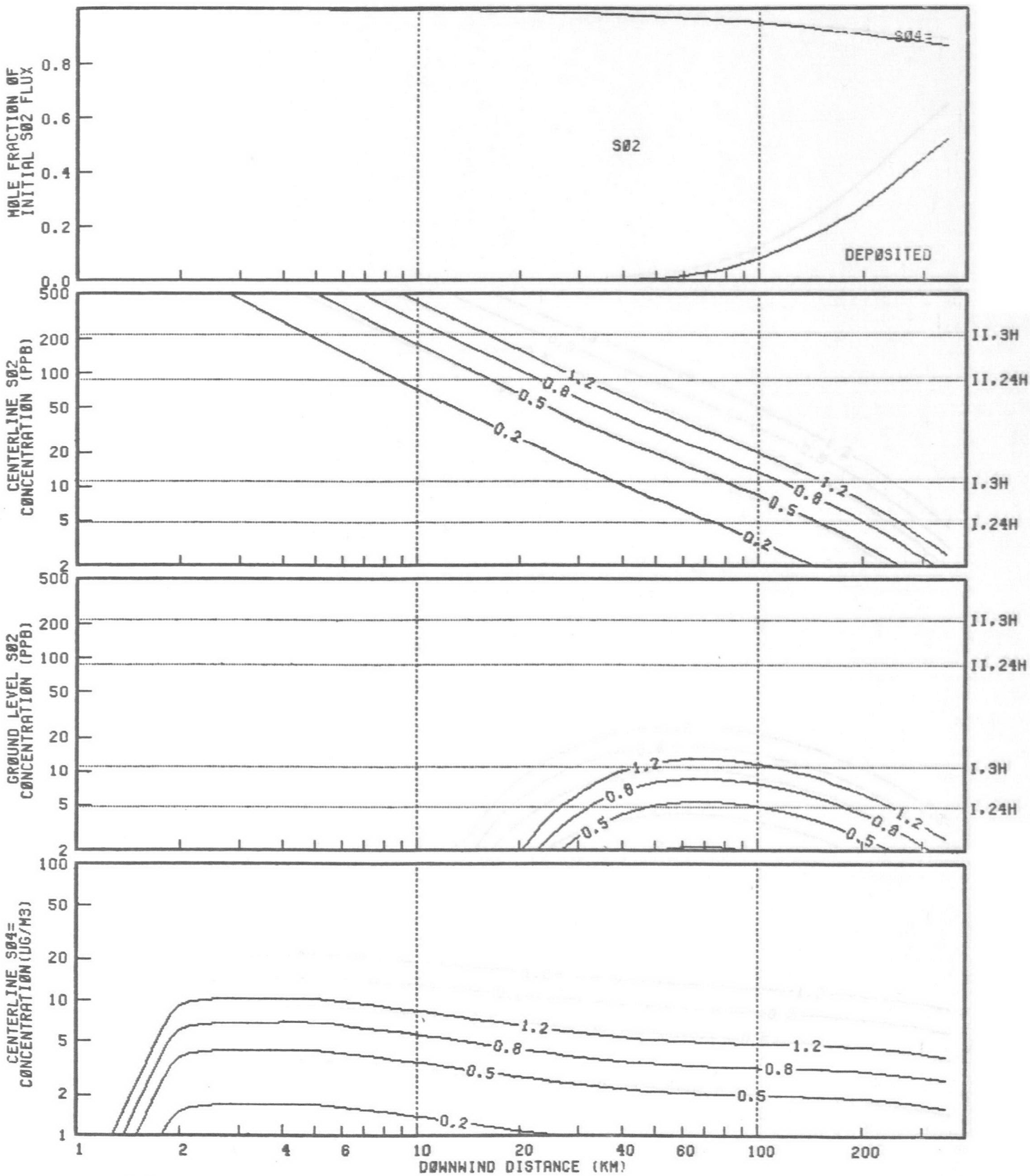
Appendix B

1000 MWe POWER PLANT IMPACTS



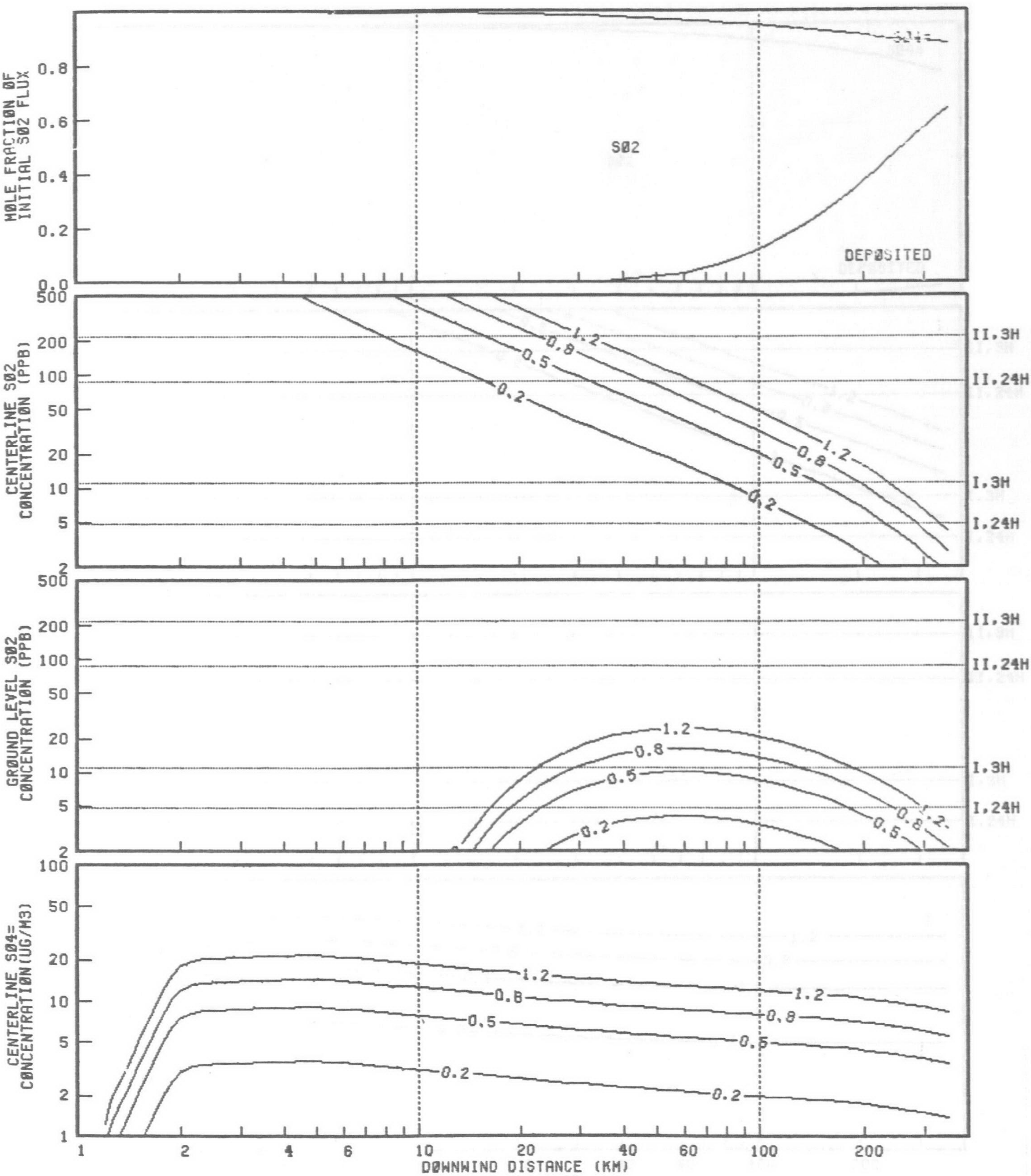
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE B-1. EFFECT OF SO_2 EMISSION RATES ON SO_x FLUXES AND CONCENTRATIONS DOWNWIND OF A 1000 Mwe COAL-FIRED POWER PLANT. SO_2 emission rates in pounds per million Btu are indicated.



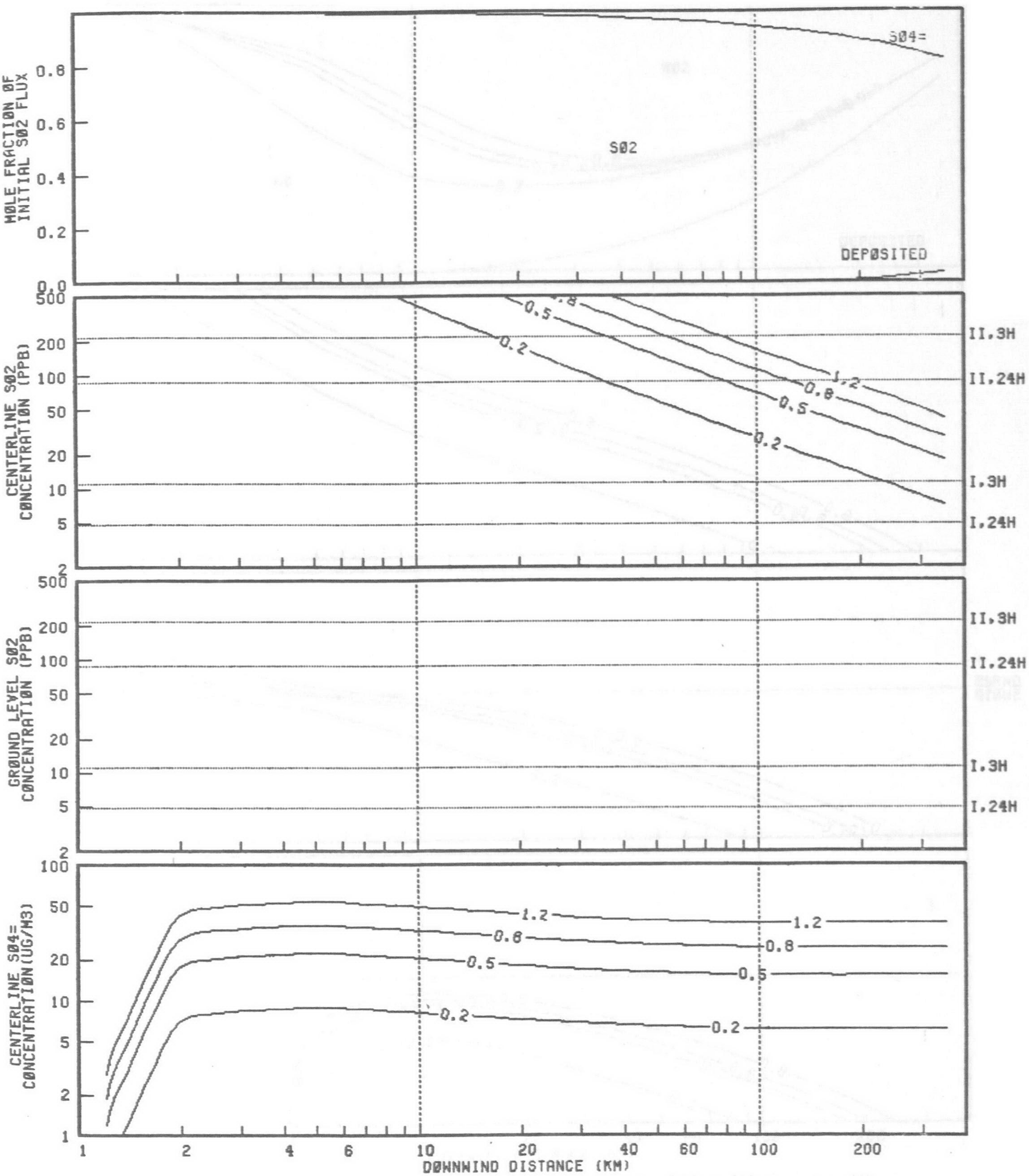
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE B-1 (Continued)



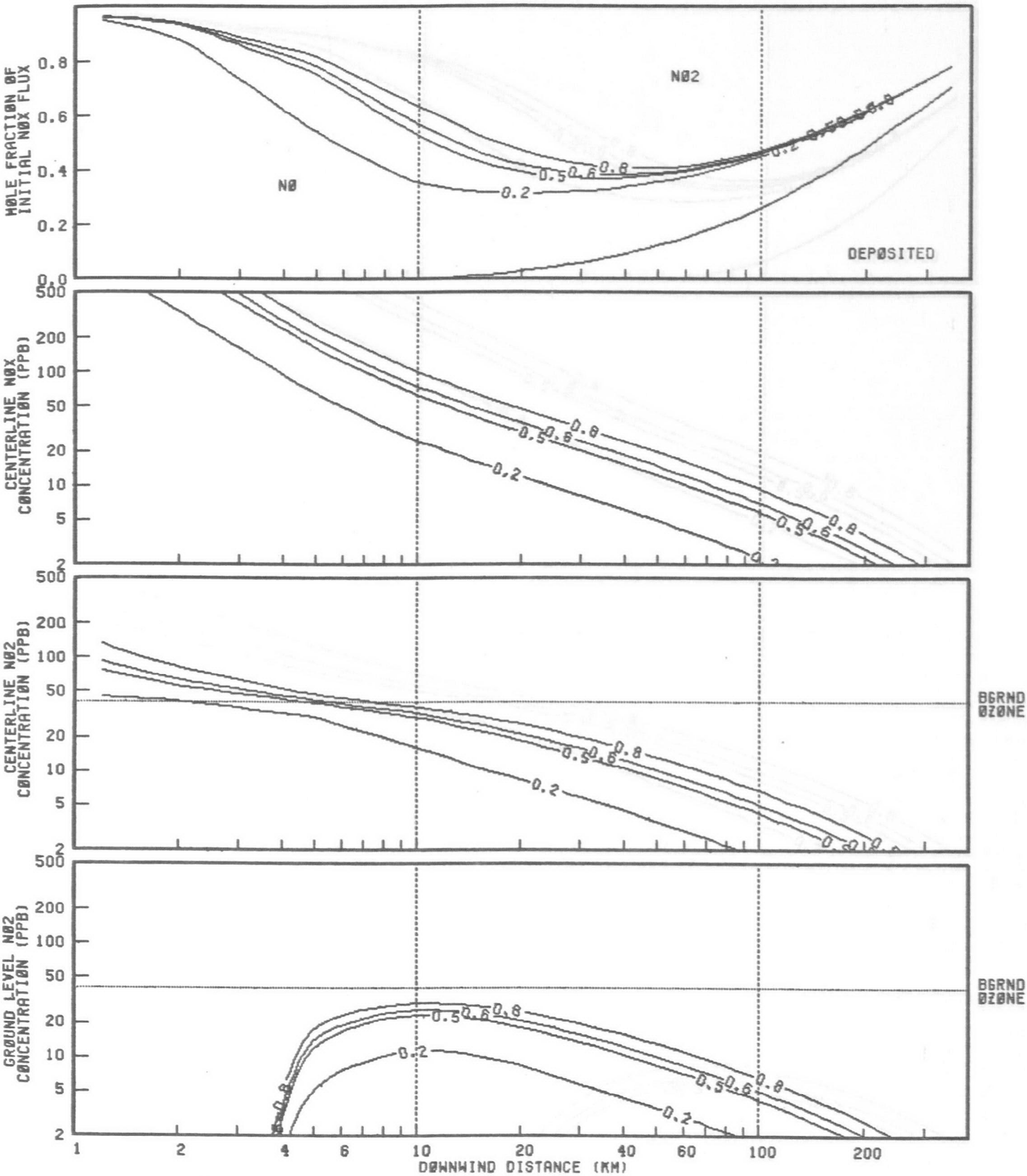
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE B-1 (Continued)



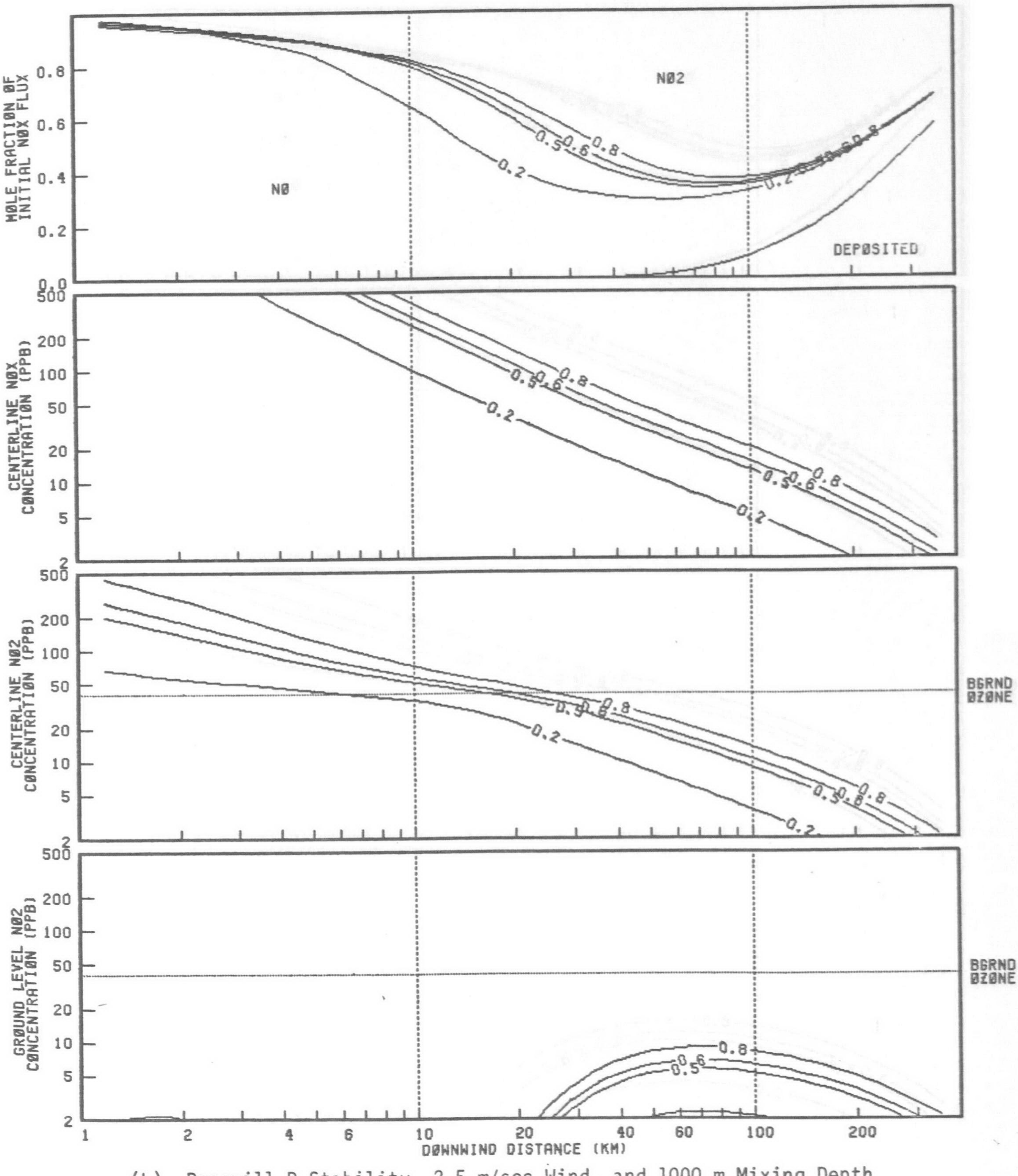
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE B-1 (Concluded)



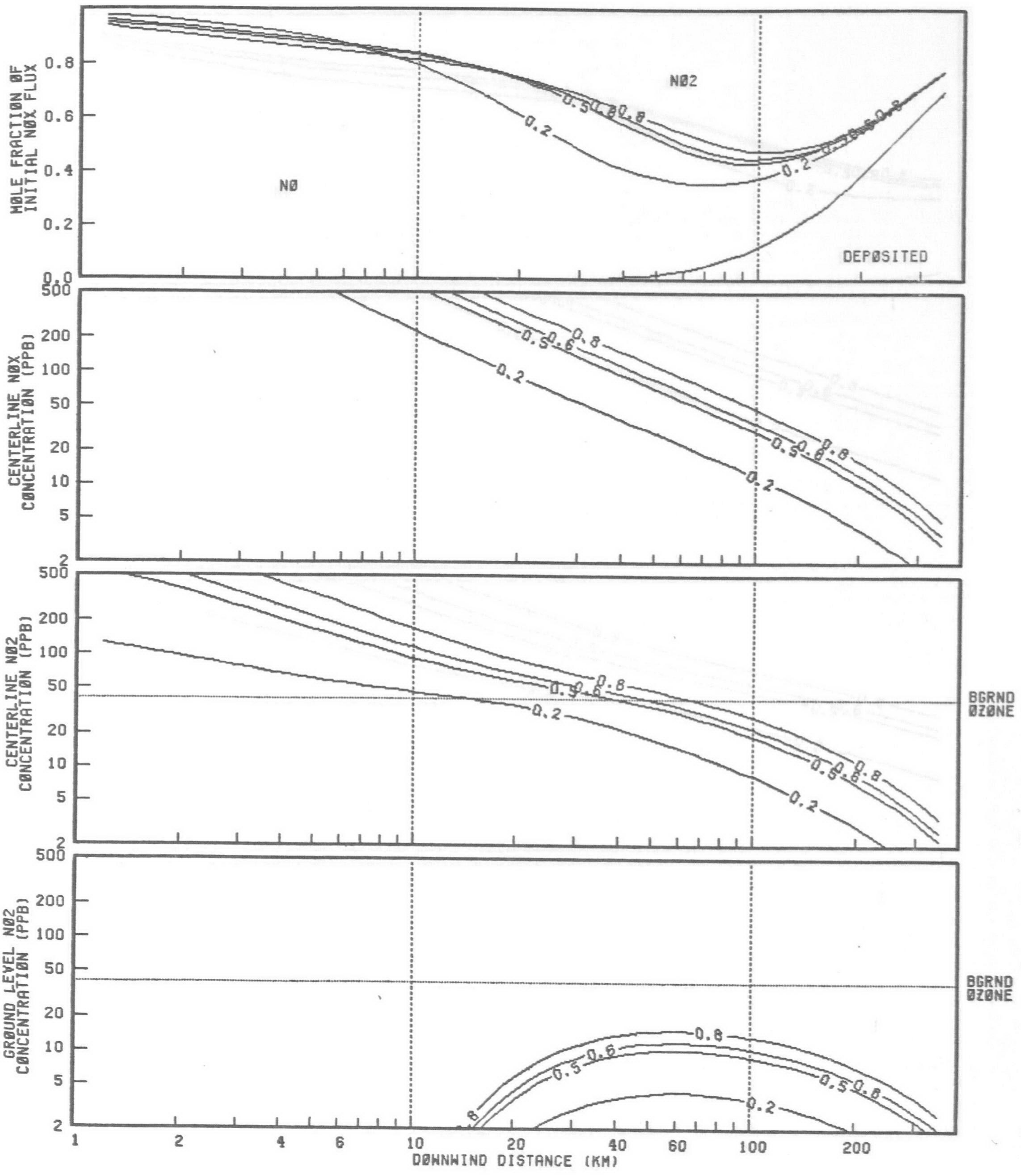
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE B-2. EFFECT OF NO_x EMISSION RATES ON NO_x FLUXES AND CONCENTRATIONS DOWNWIND OF A 1000 Mwe COAL-FIRED POWER PLANT. NO_x emission rates in pounds per million Btu are indicated.



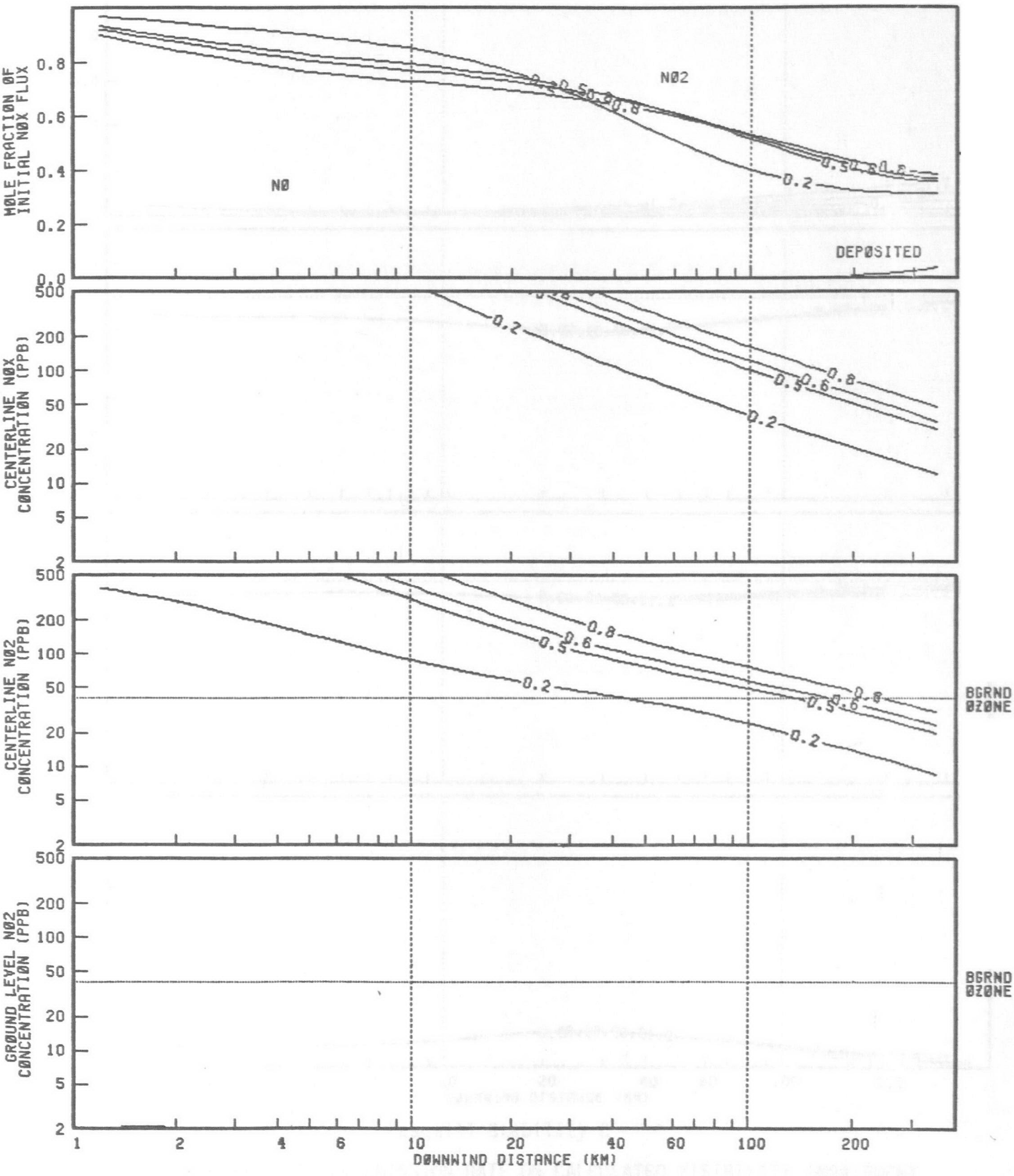
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE B-2 (Continued)



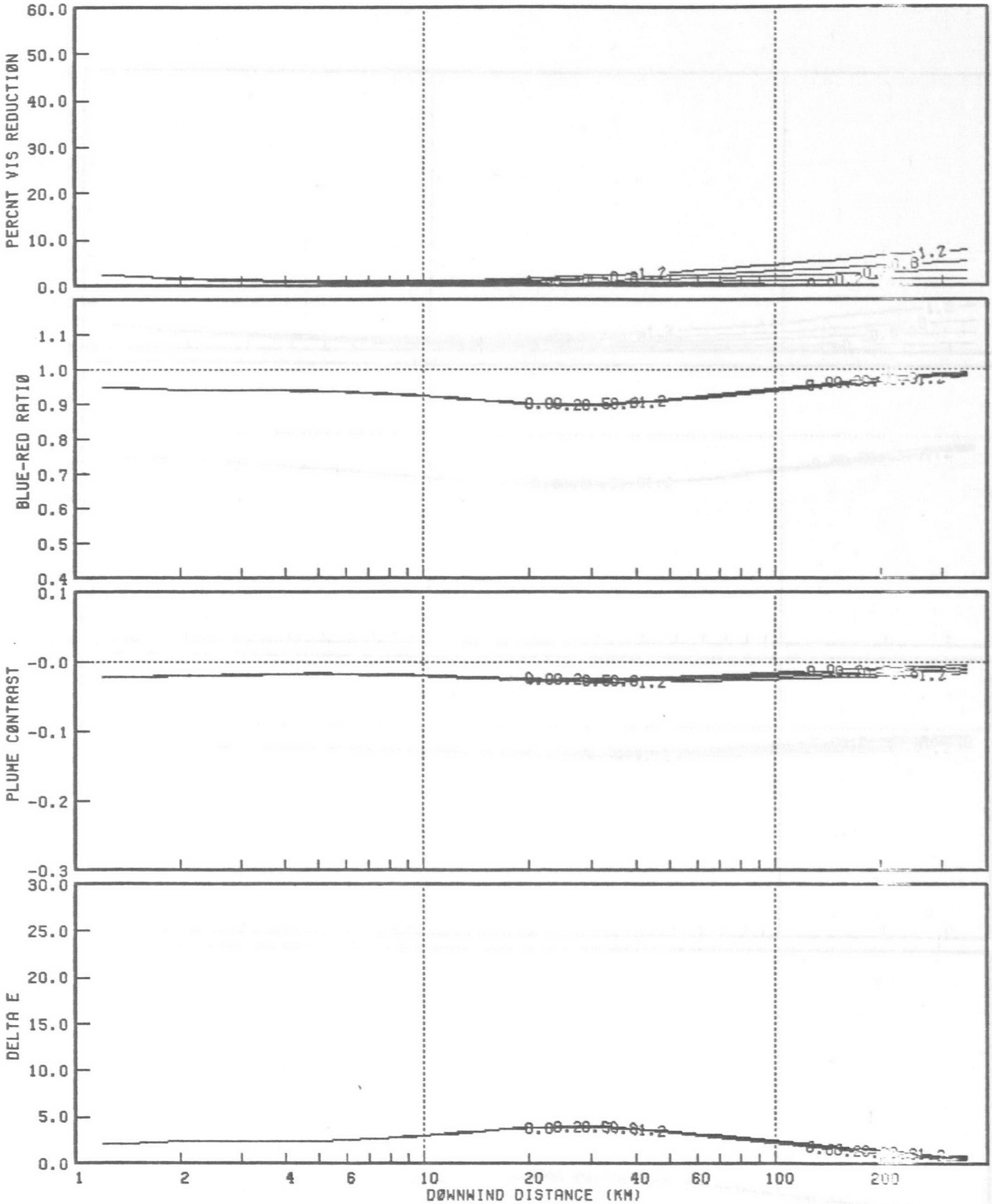
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE B-2 (Continued)



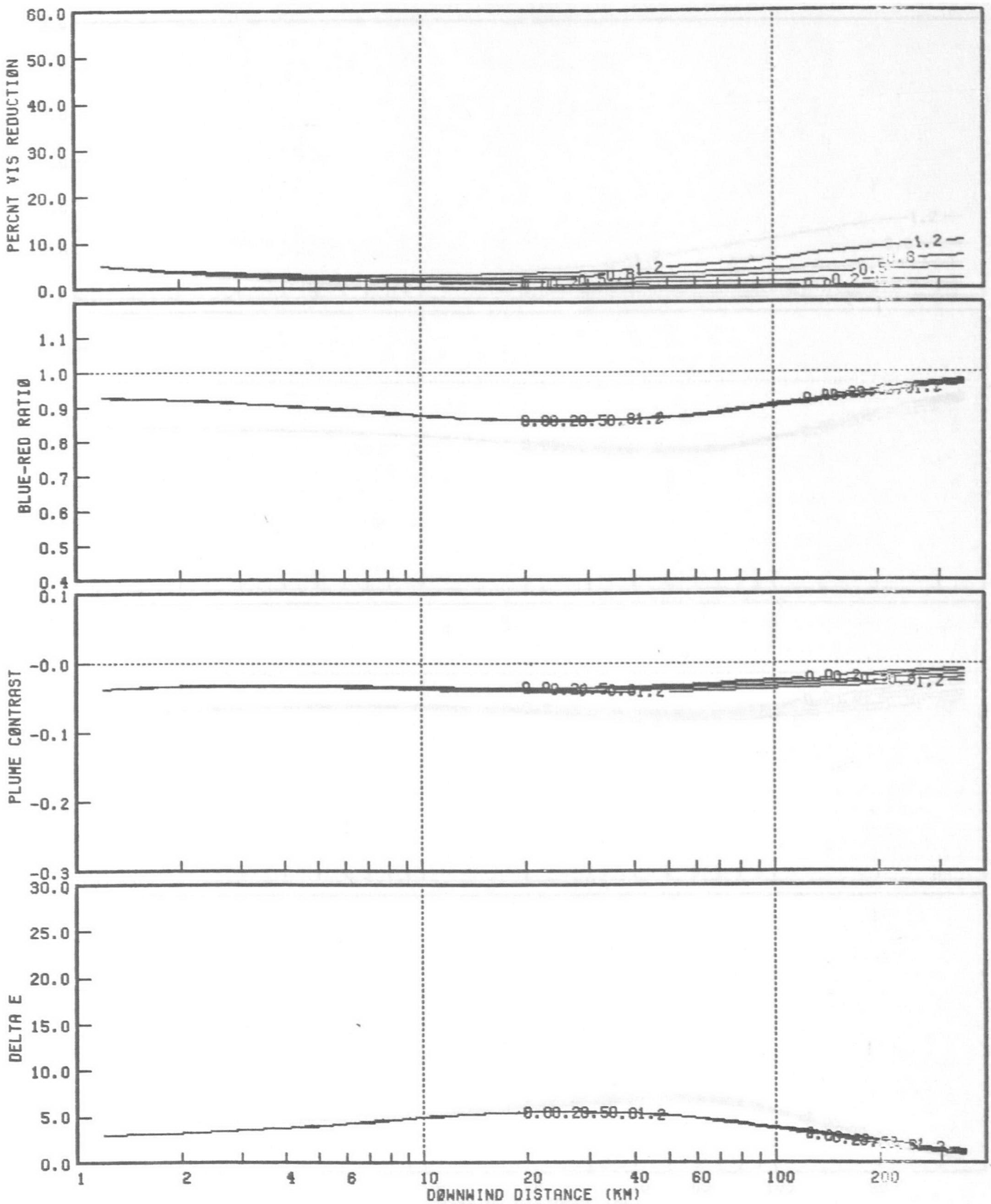
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE B-2 (Concluded)



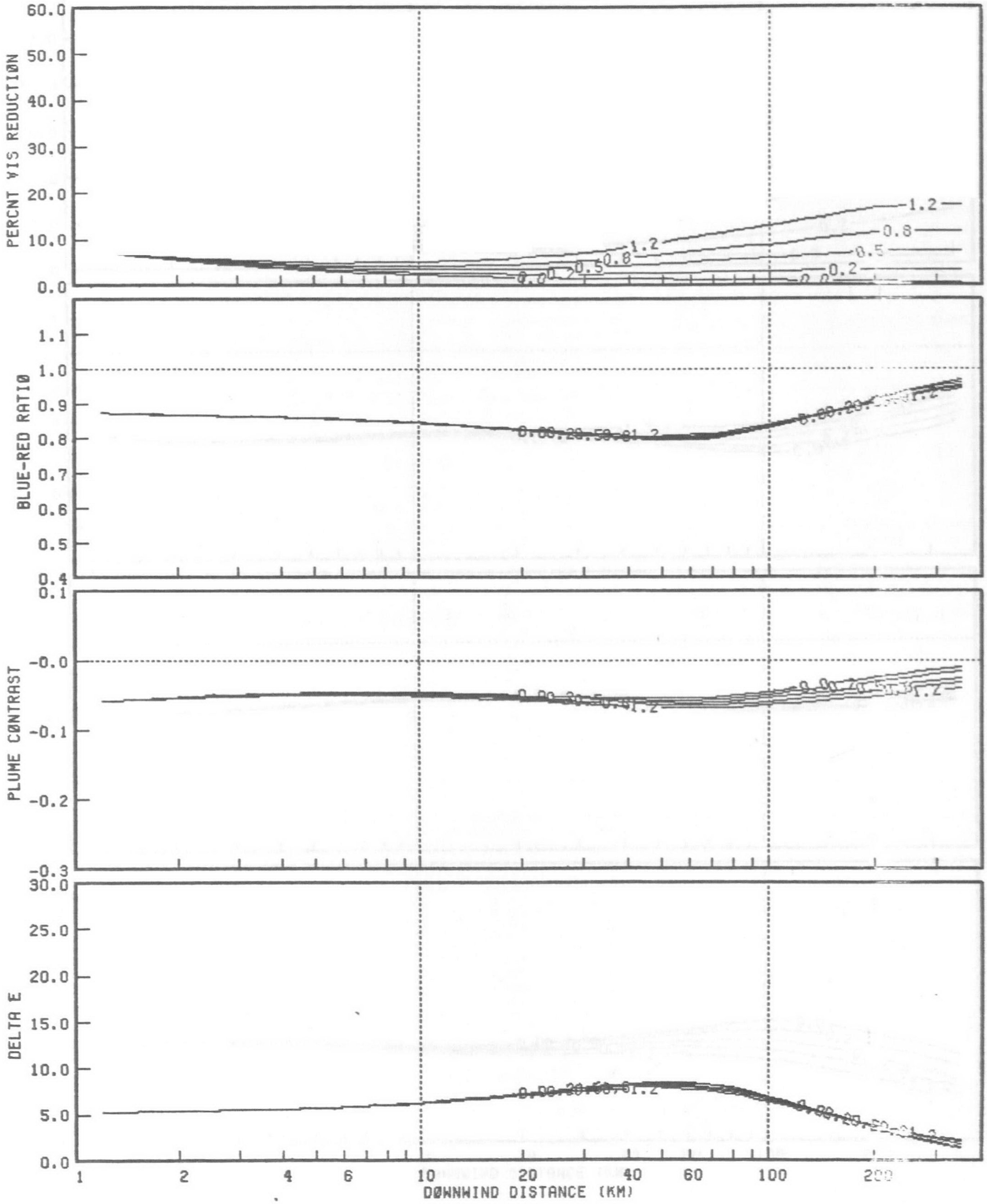
(a) Pasquill Stability C

FIGURE B-3. EFFECT OF SO_2 EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 1000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. SO_2 emission rates in pounds per million Btu are indicated.



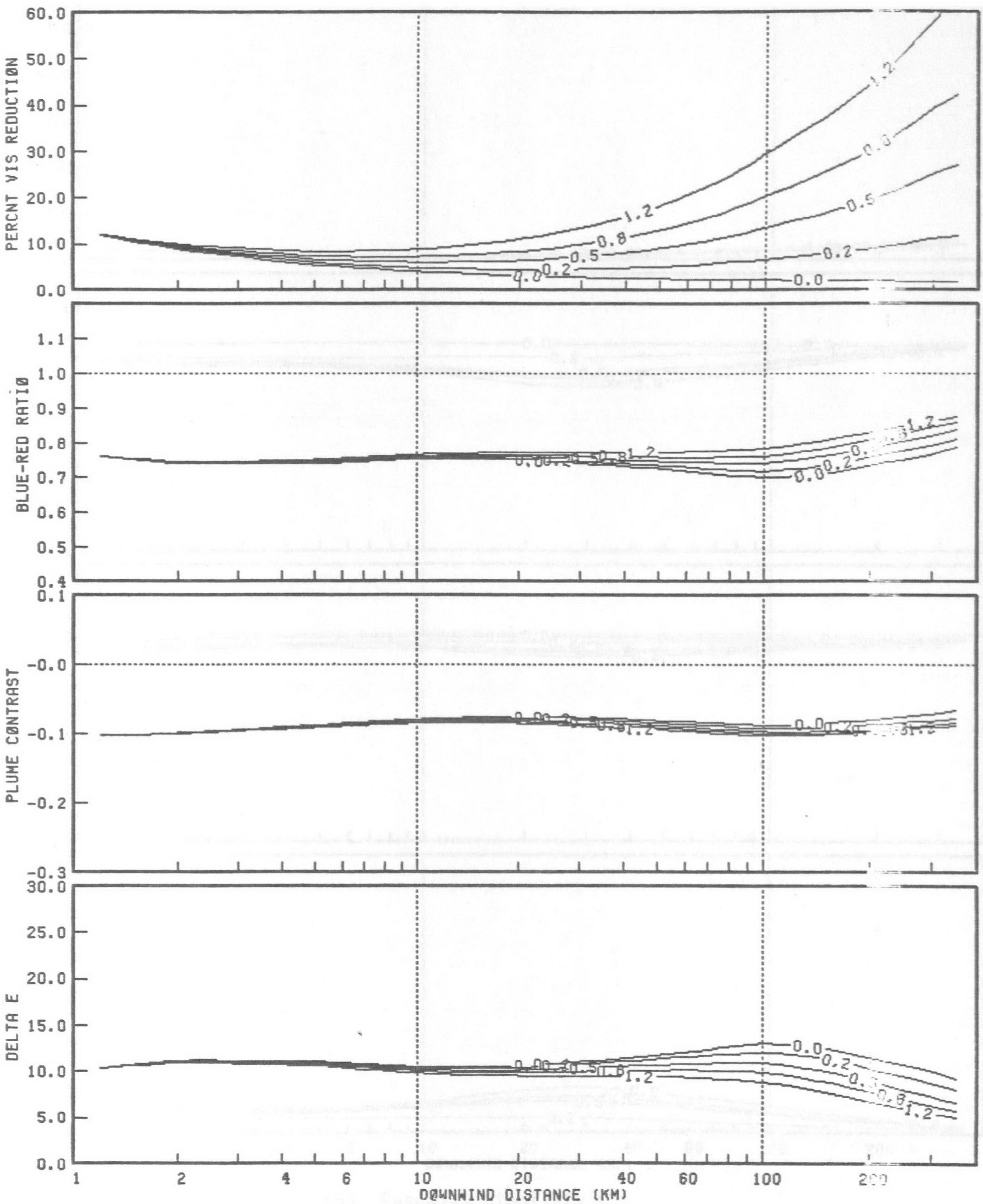
(b) Pasquill Stability D

FIGURE B-3 (Continued)



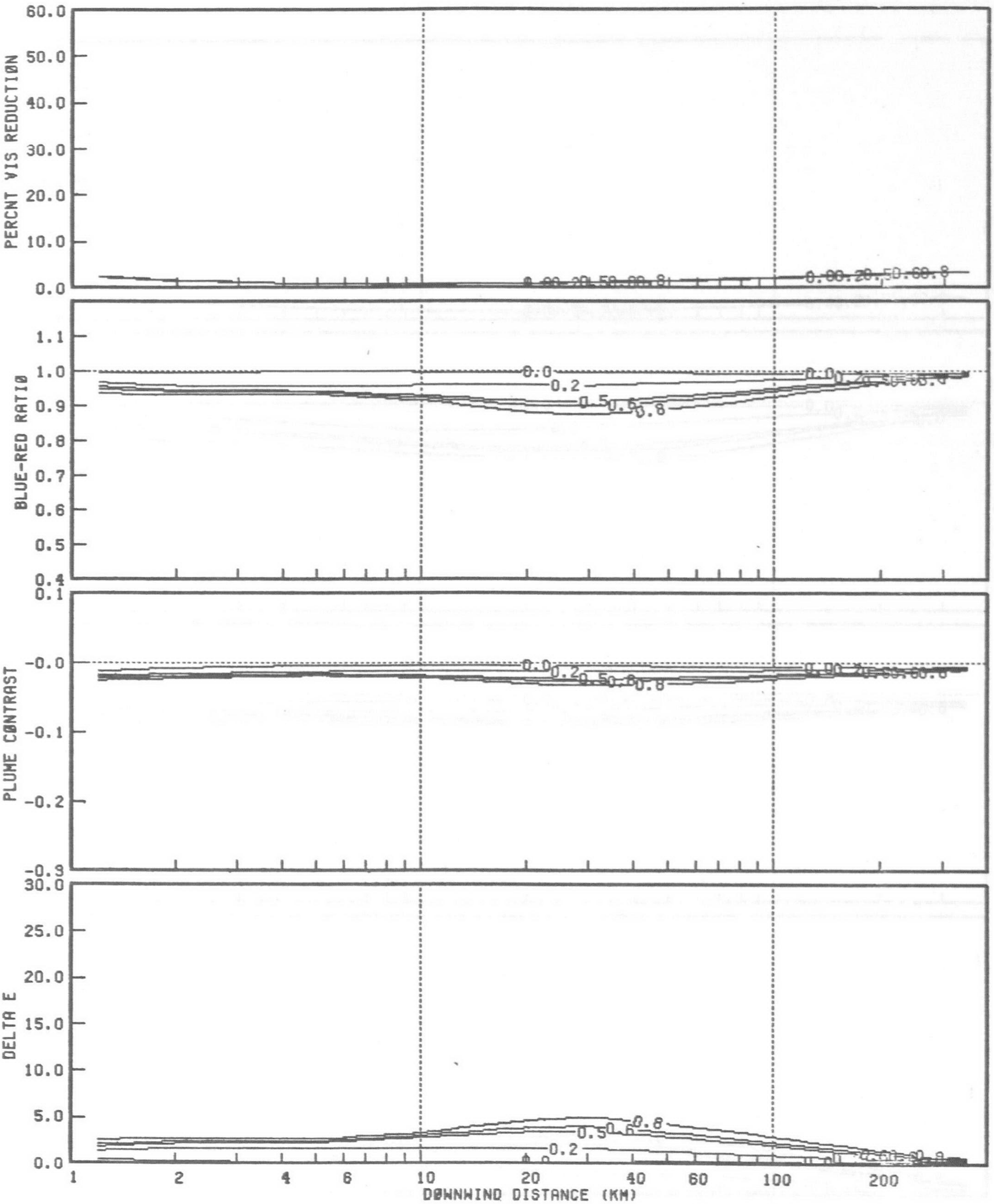
(c) Pasquill Stability E

FIGURE B-3 (Continued)



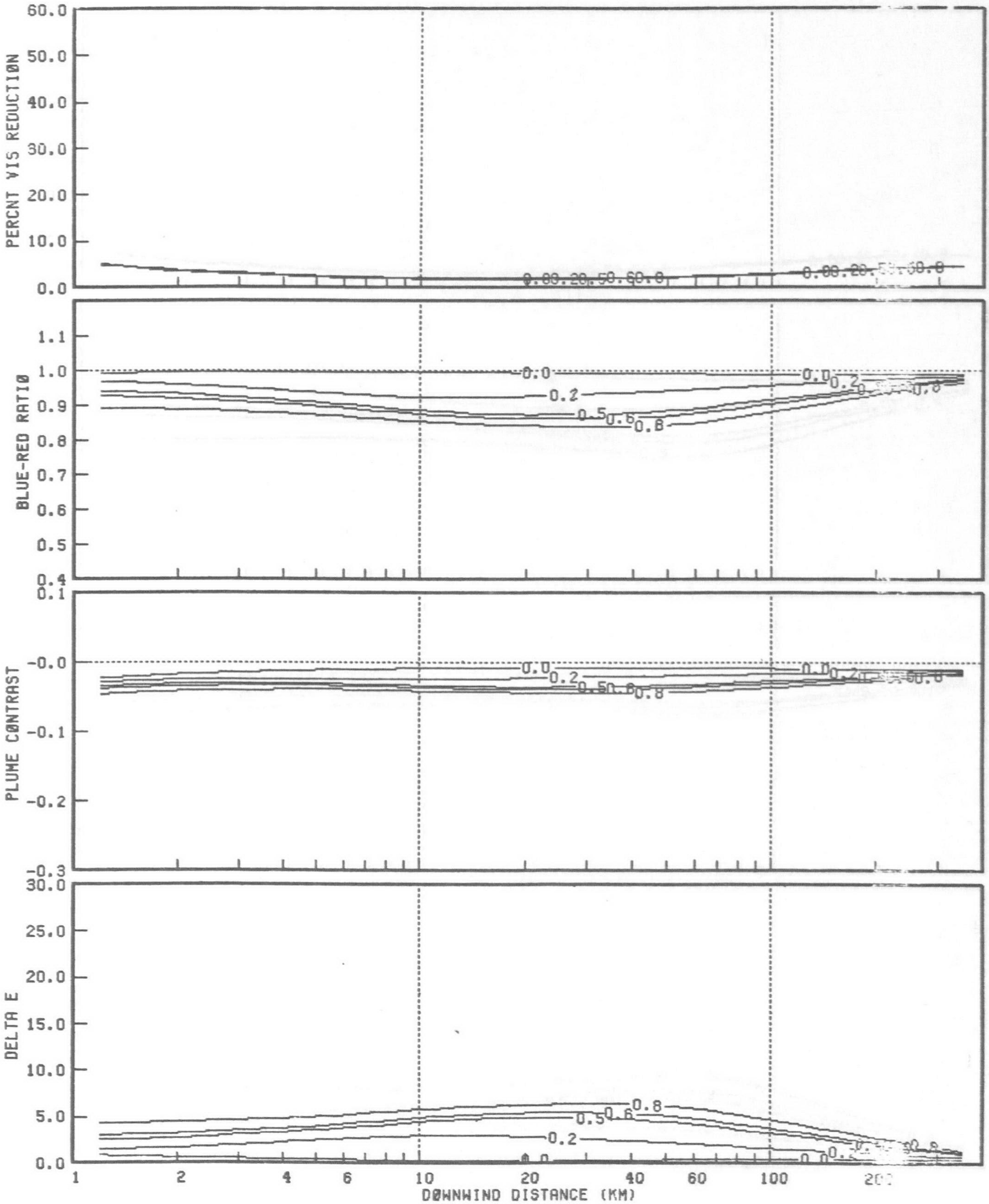
(d) Pasquill Stability F

FIGURE B-3 (Concluded)



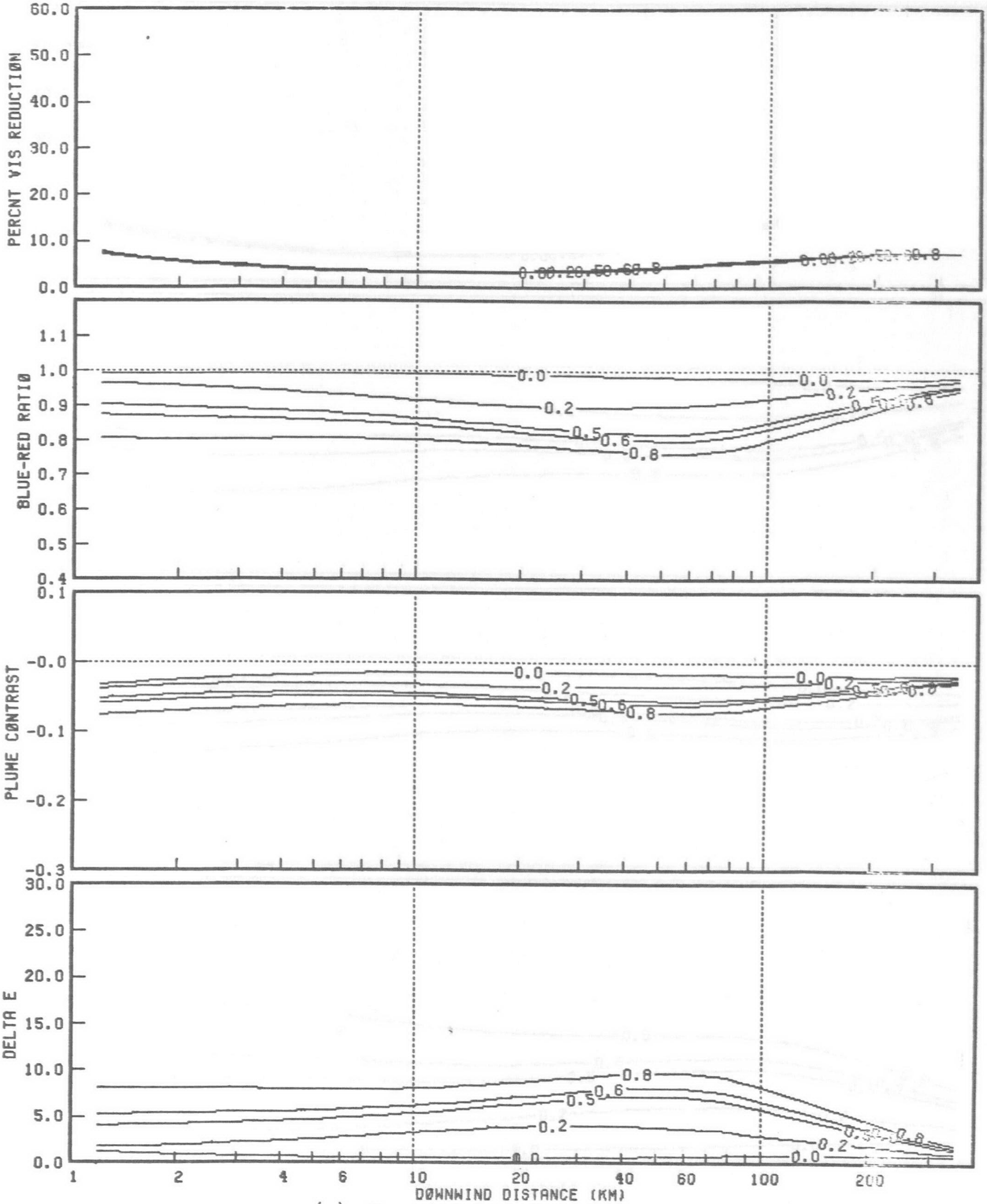
(a) Pasquill Stability C

FIGURE B-4. EFFECT OF NO_x EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 1000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. NO_x emission rates in pounds per million Btu are indicated.



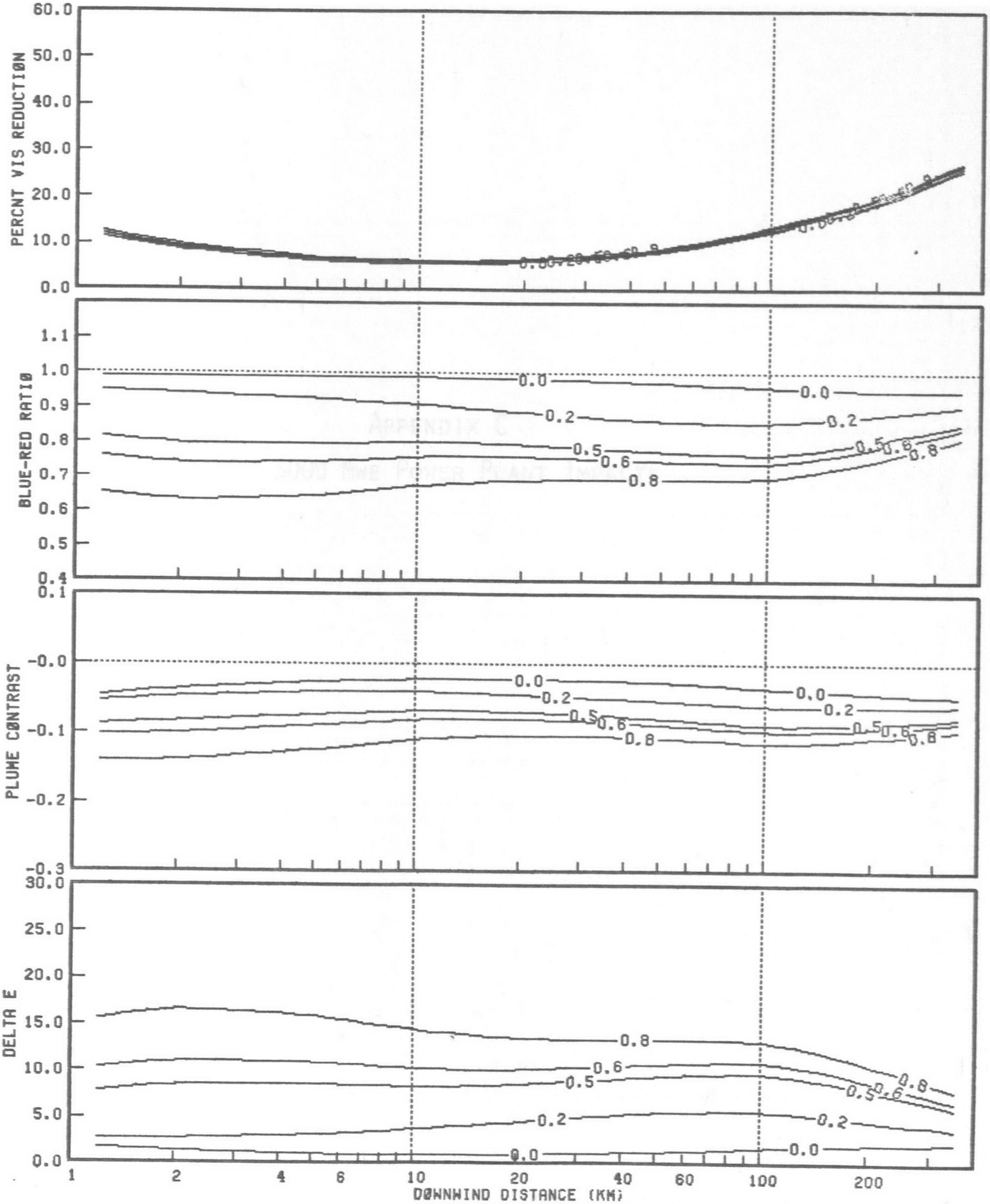
(b) Pasquill Stability D

FIGURE B-4 (Continued)



(c) Pasquill Stability E

FIGURE B-4 (Continued)

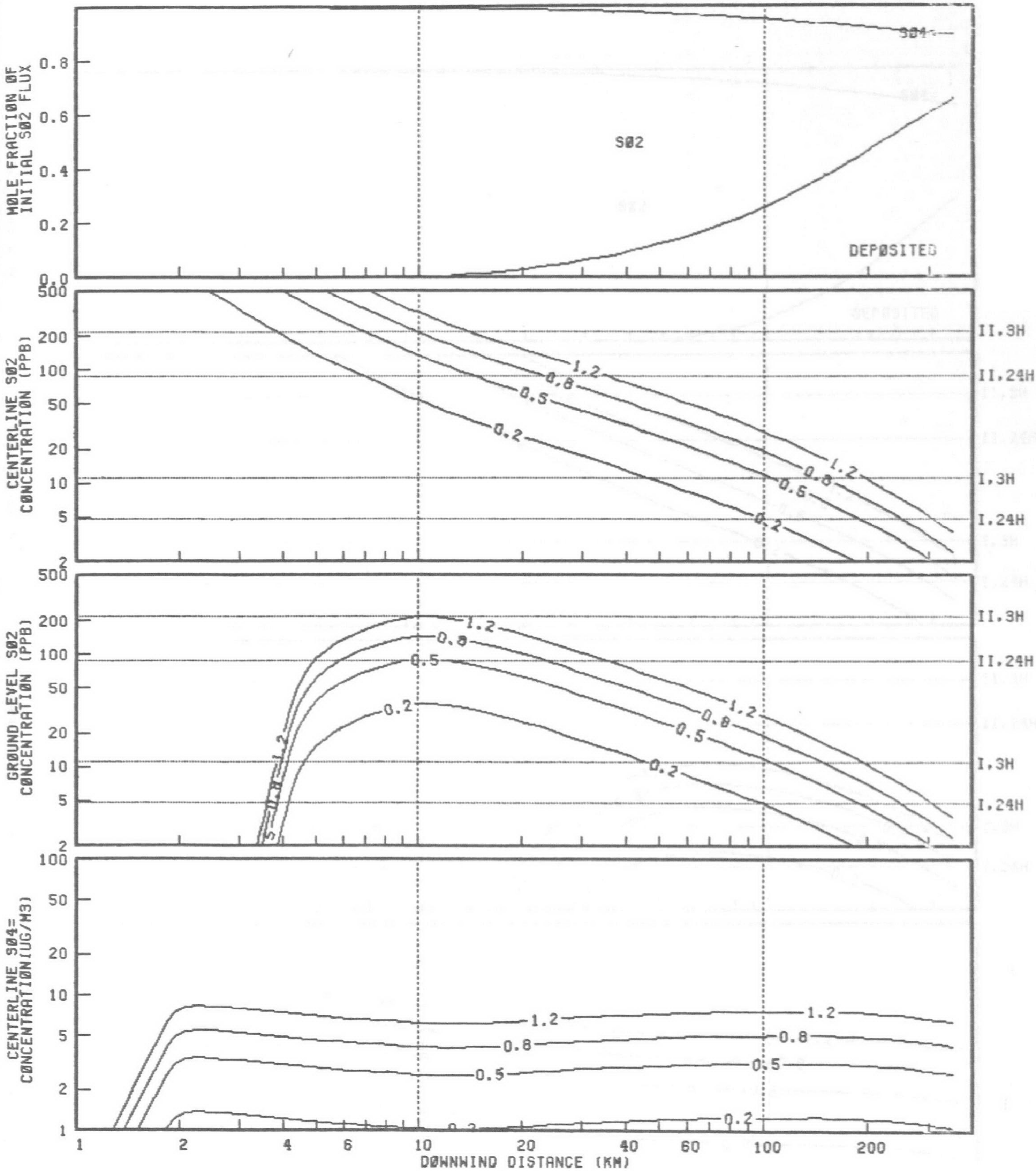


(d) Pasquill Stability F

FIGURE B-4 (Concluded)

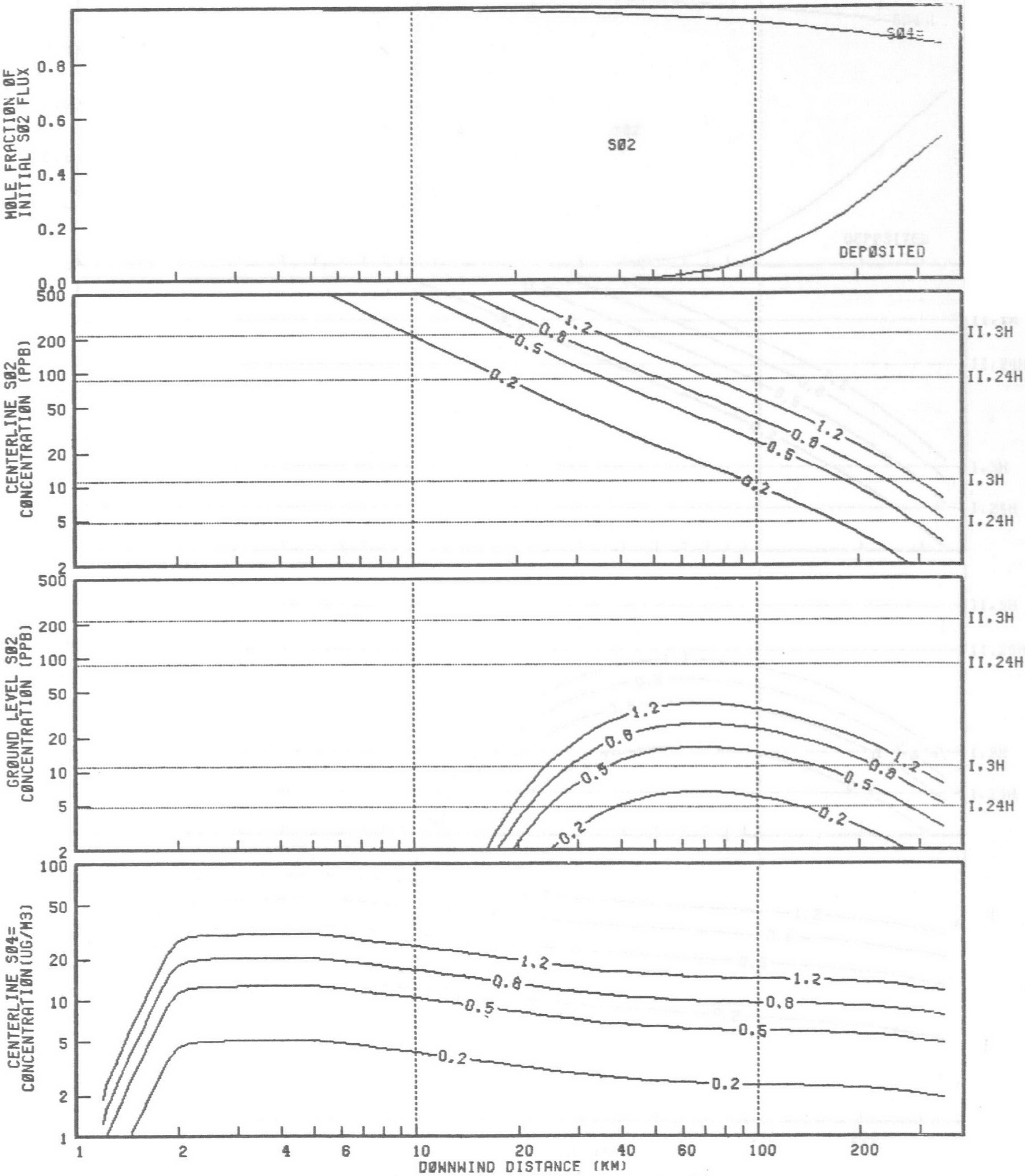
Appendix C

3000 MWe Power Plant Impacts



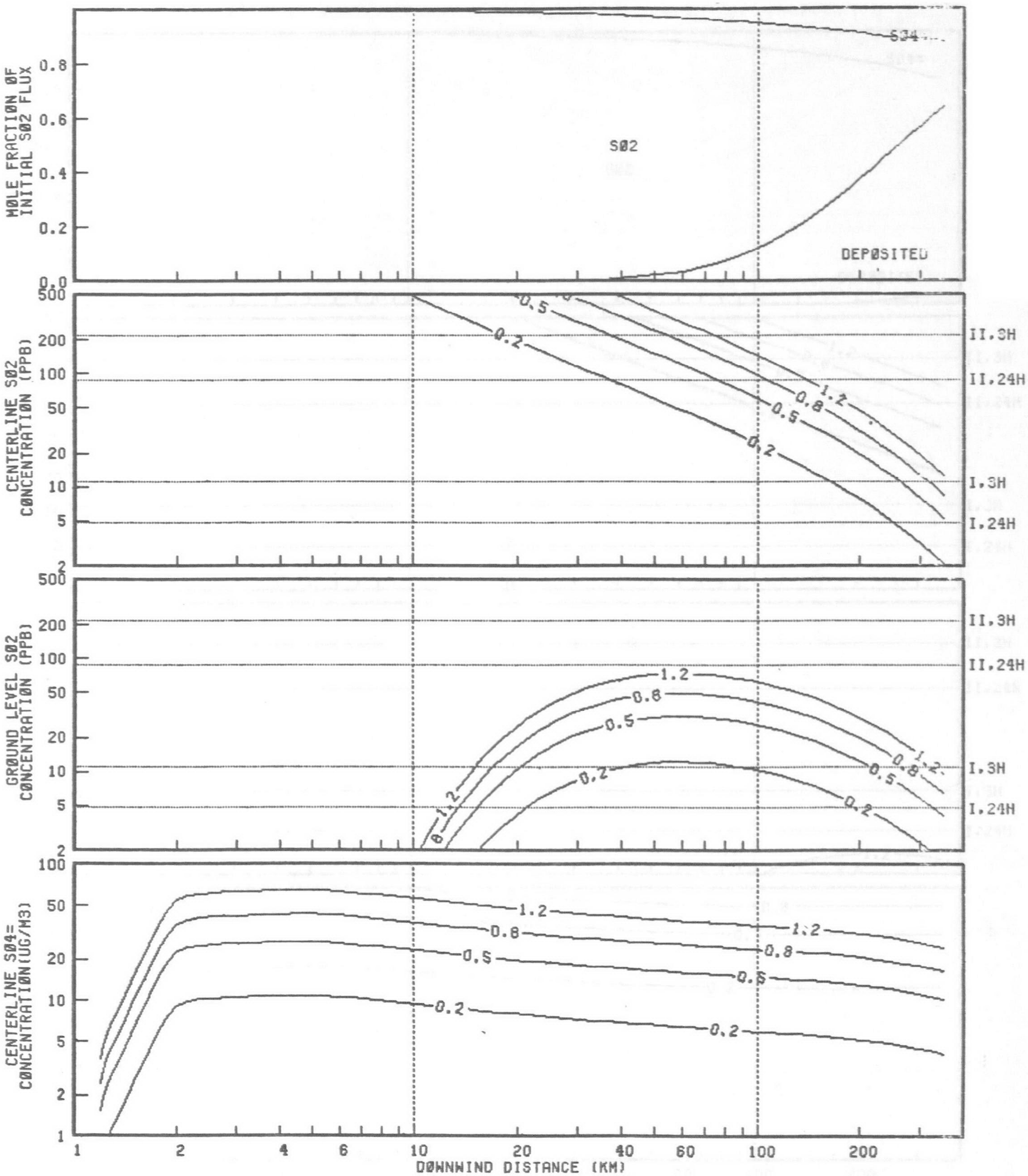
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE C-1. EFFECT OF SO_2 EMISSION RATES ON SO_x FLUXES AND CONCENTRATIONS DOWNWIND OF A 3000 Mwe COAL-FIRED POWER PLANT. SO_2 emission rates in pounds per million Btu are indicated.



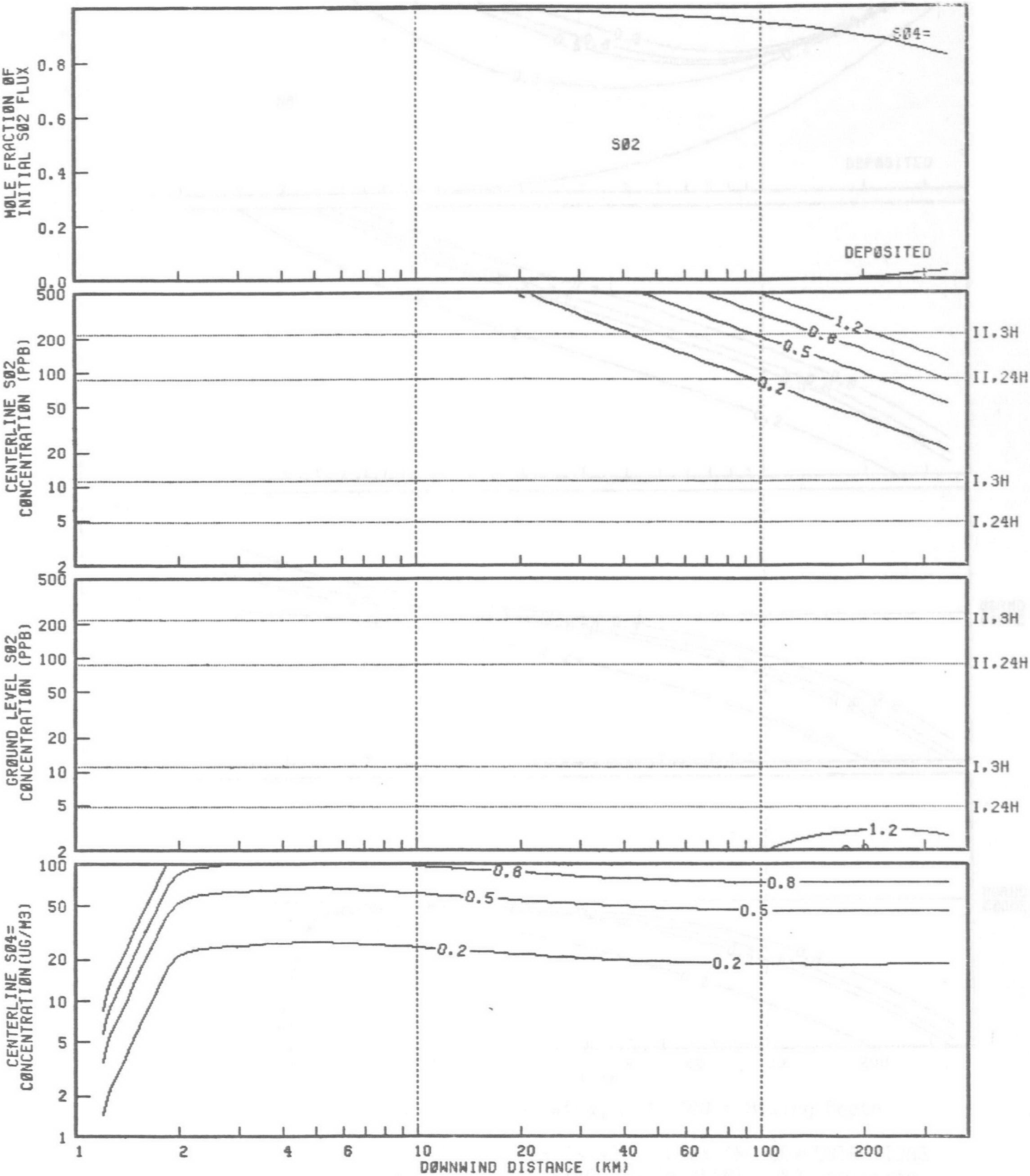
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE C-1 (Continued)



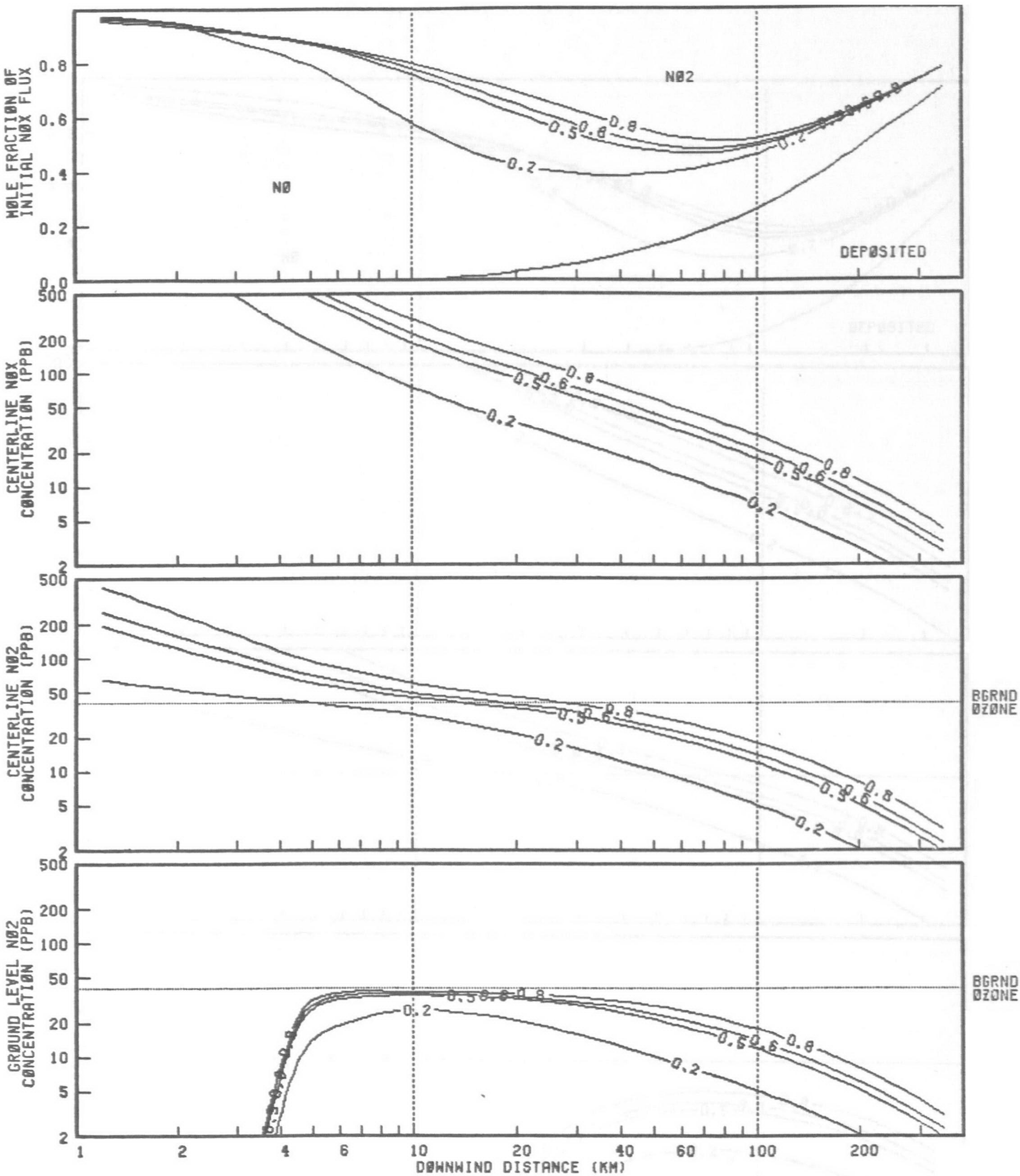
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE C-1 (Continued)



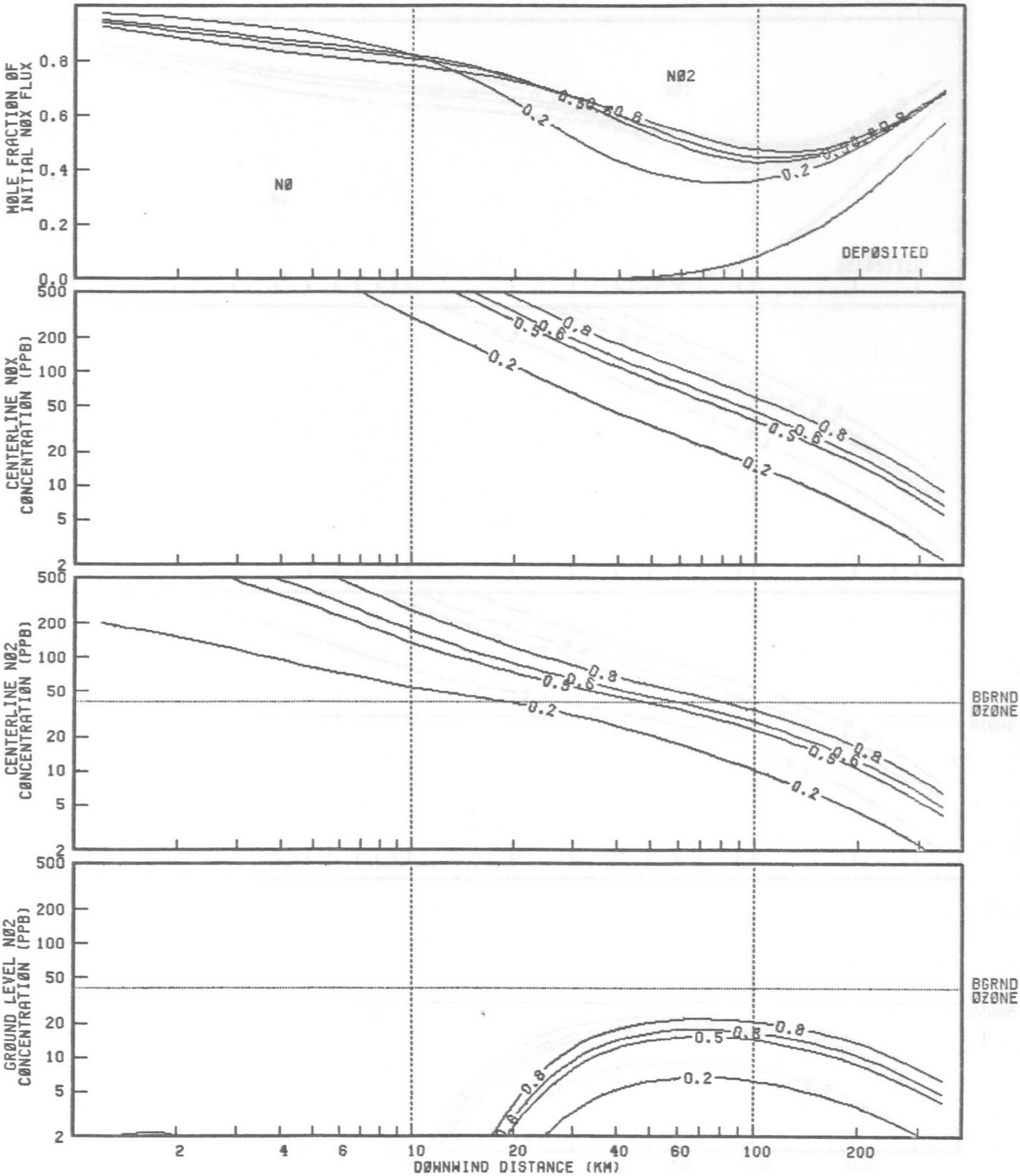
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE C-1 (Concluded)



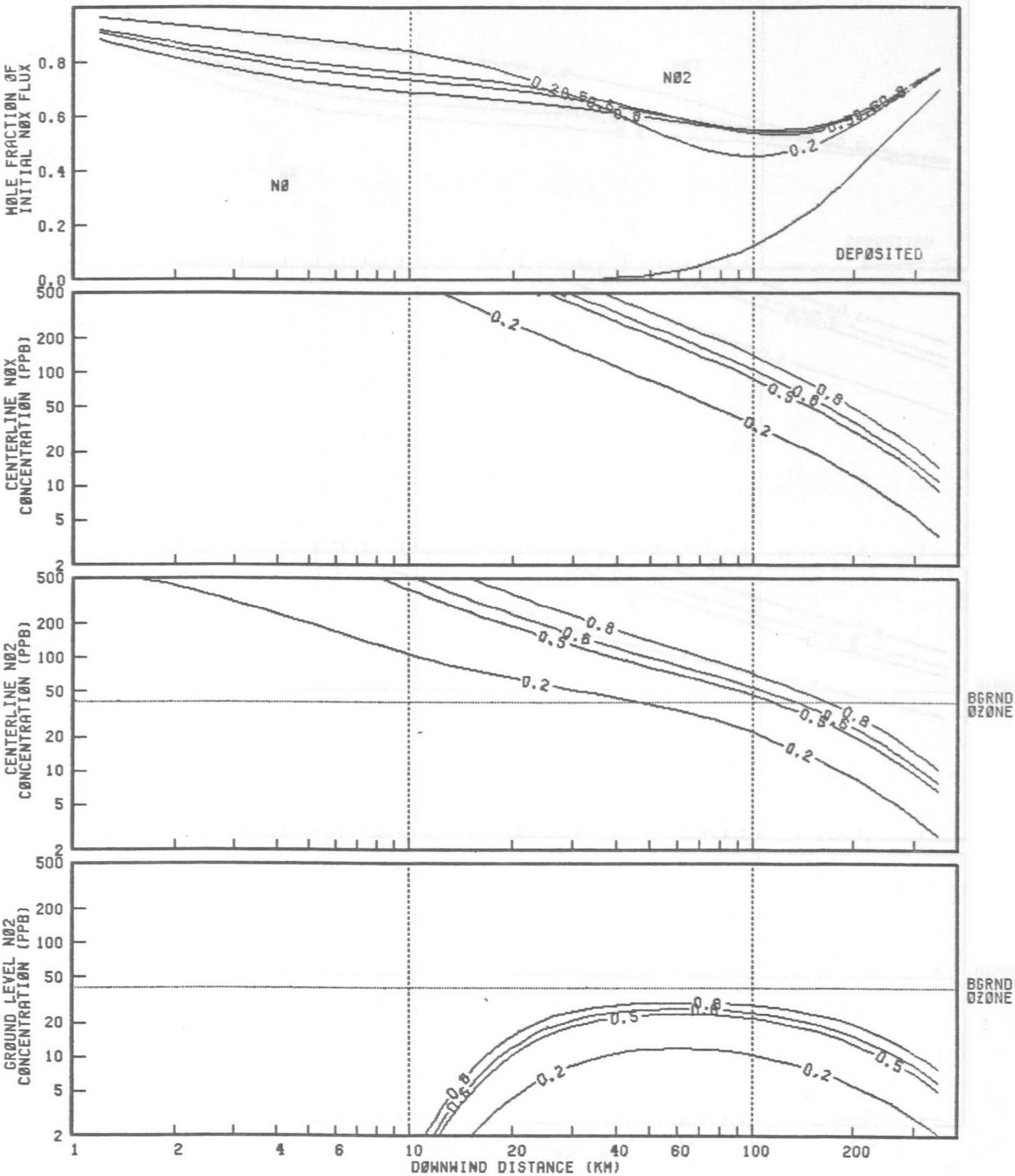
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE C-2. EFFECT OF NO_x EMISSION RATES ON NO_x FLUXES AND CONCENTRATIONS DOWNWIND OF A 3000 Mwe COAL-FIRED POWER PLANT. NO_x emission rates in pounds per million Btu are indicated.



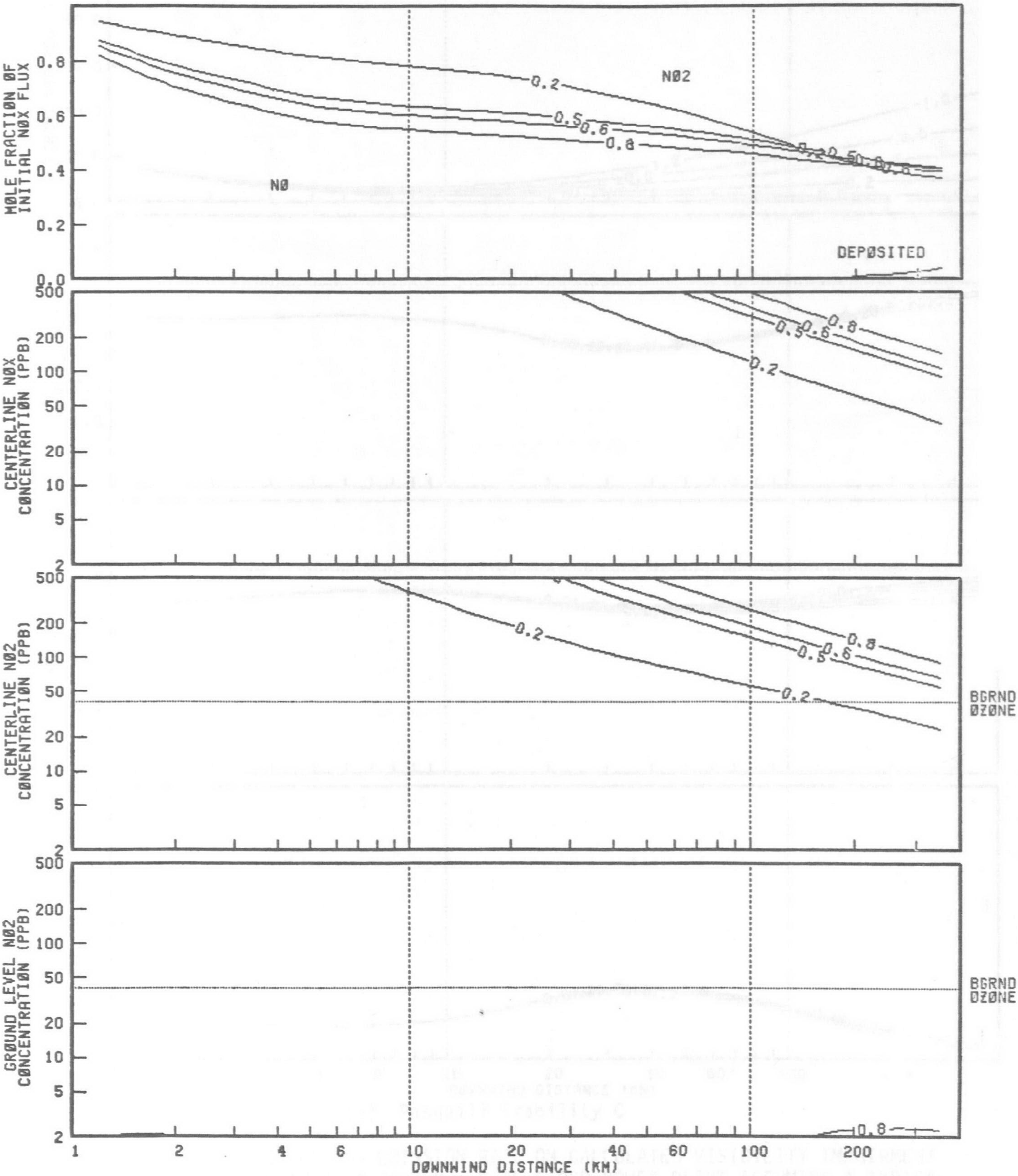
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE C-2 (Continued)



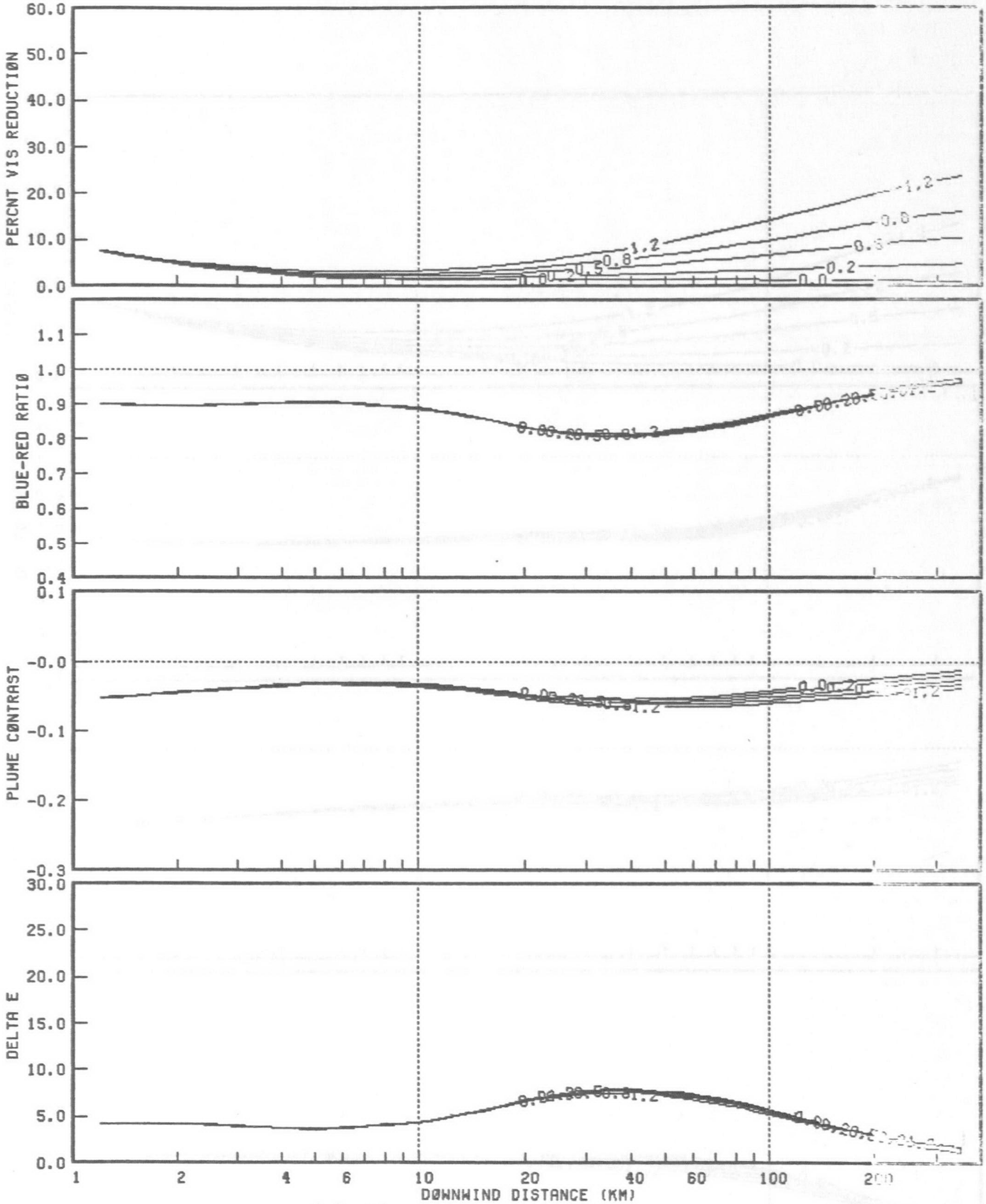
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE C-2 (Continued)



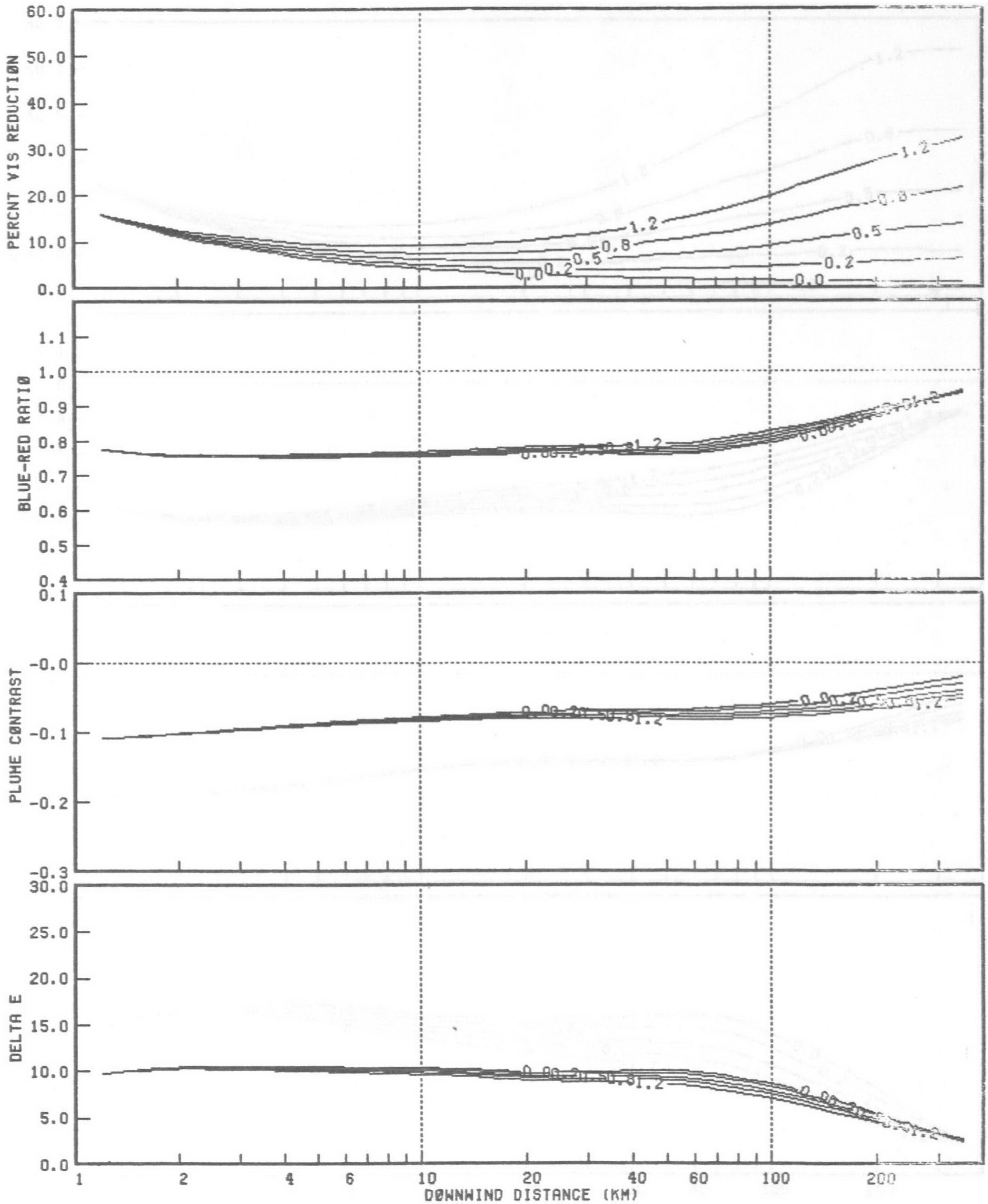
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE C-2 (Concluded)



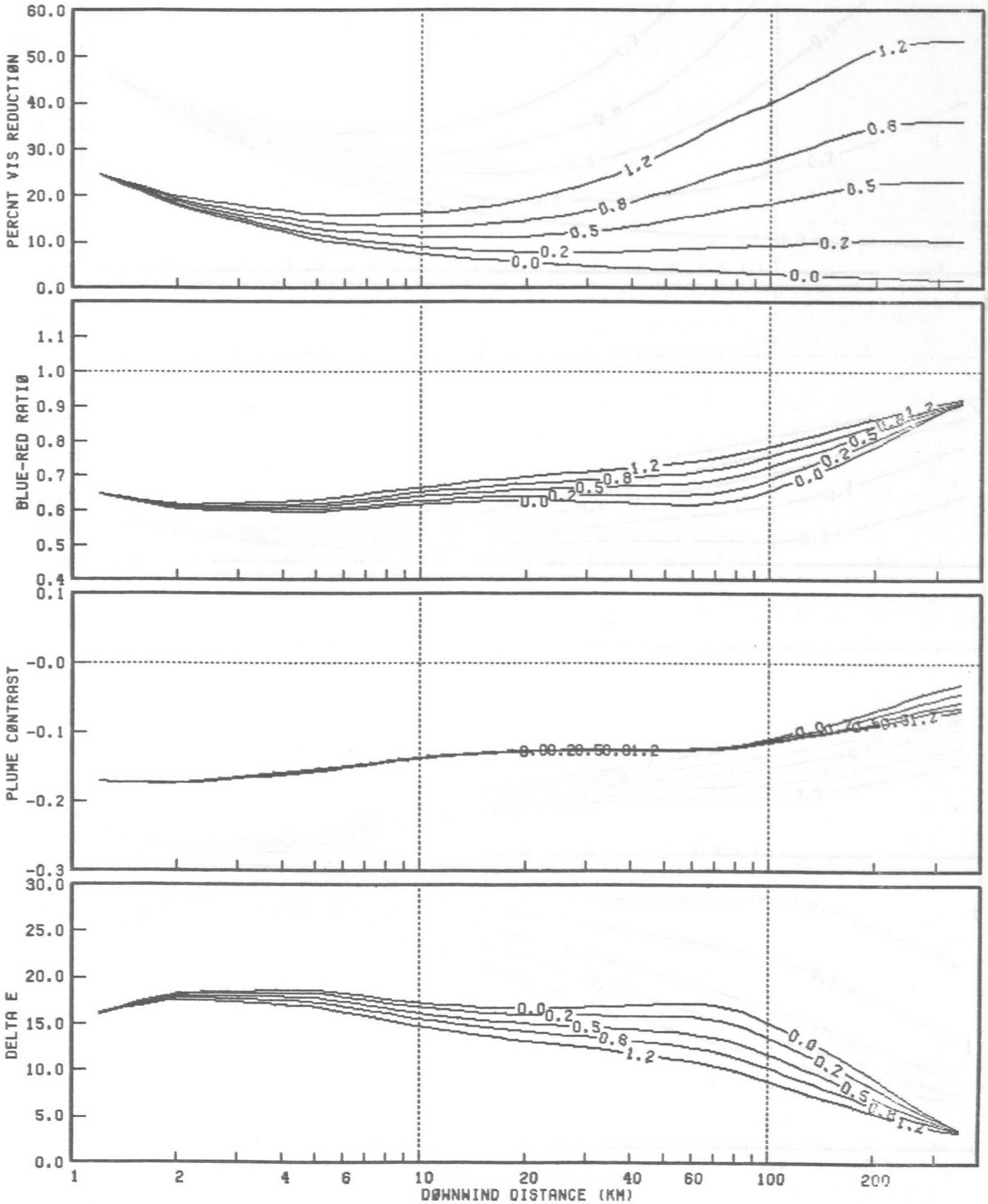
(a) Pasquill Stability C

FIGURE C-3. EFFECT OF SO_2 EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 3000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. SO_2 emission rates in pounds per million Btu are indicated.



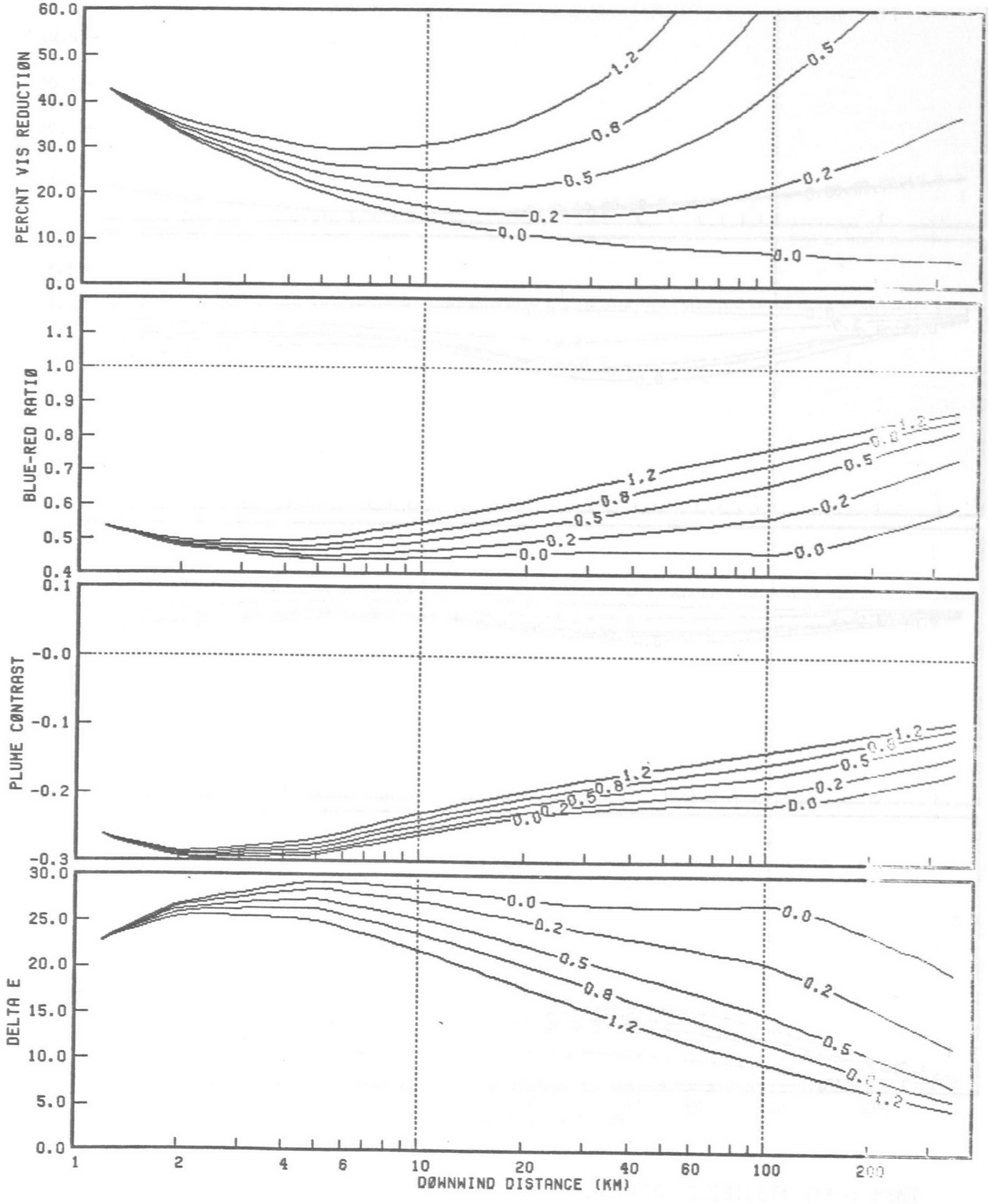
(b) Pasquill Stability D

FIGURE C-3 (Continued)



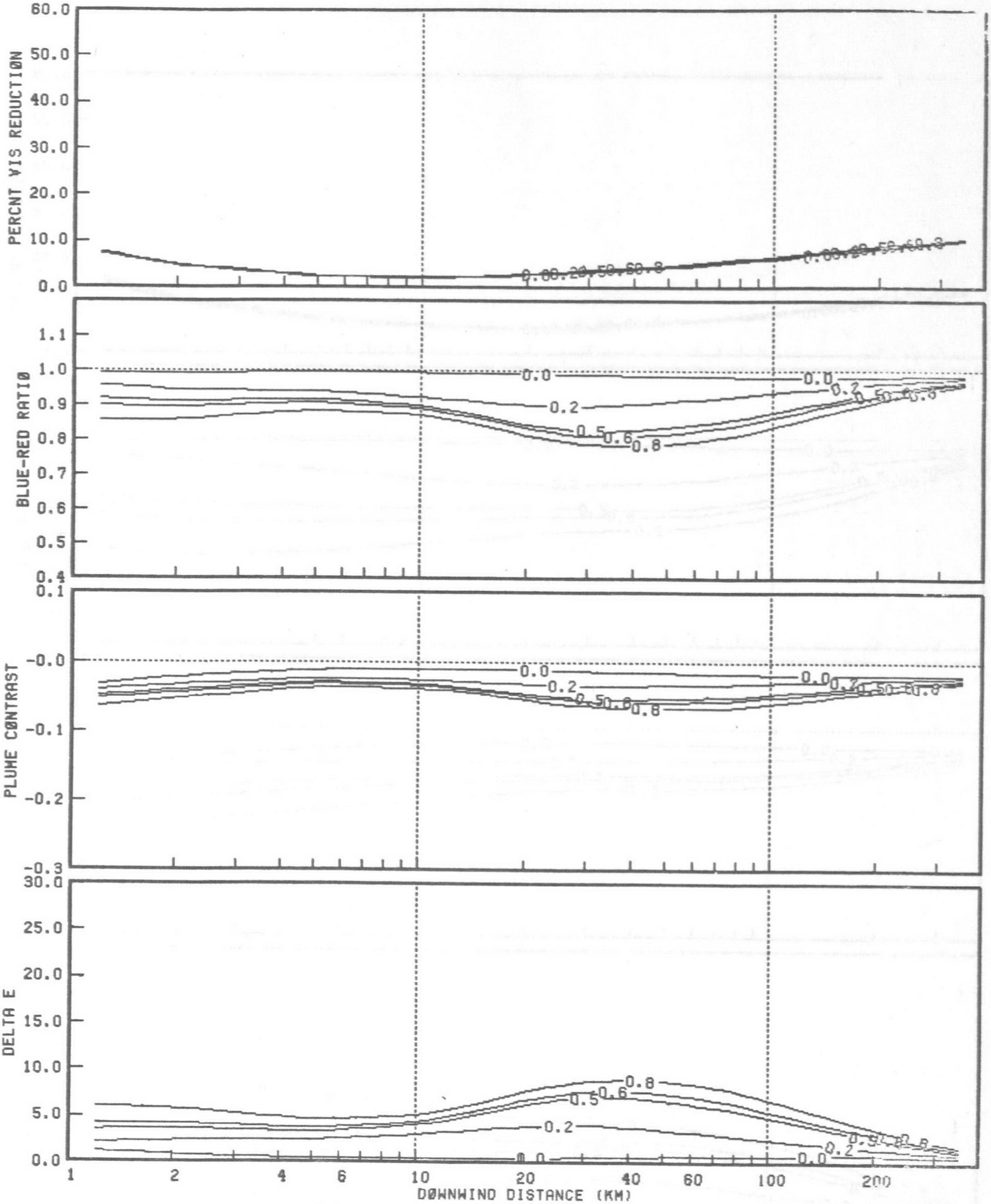
(c) Pasquill Stability E

FIGURE C-3 (Continued)



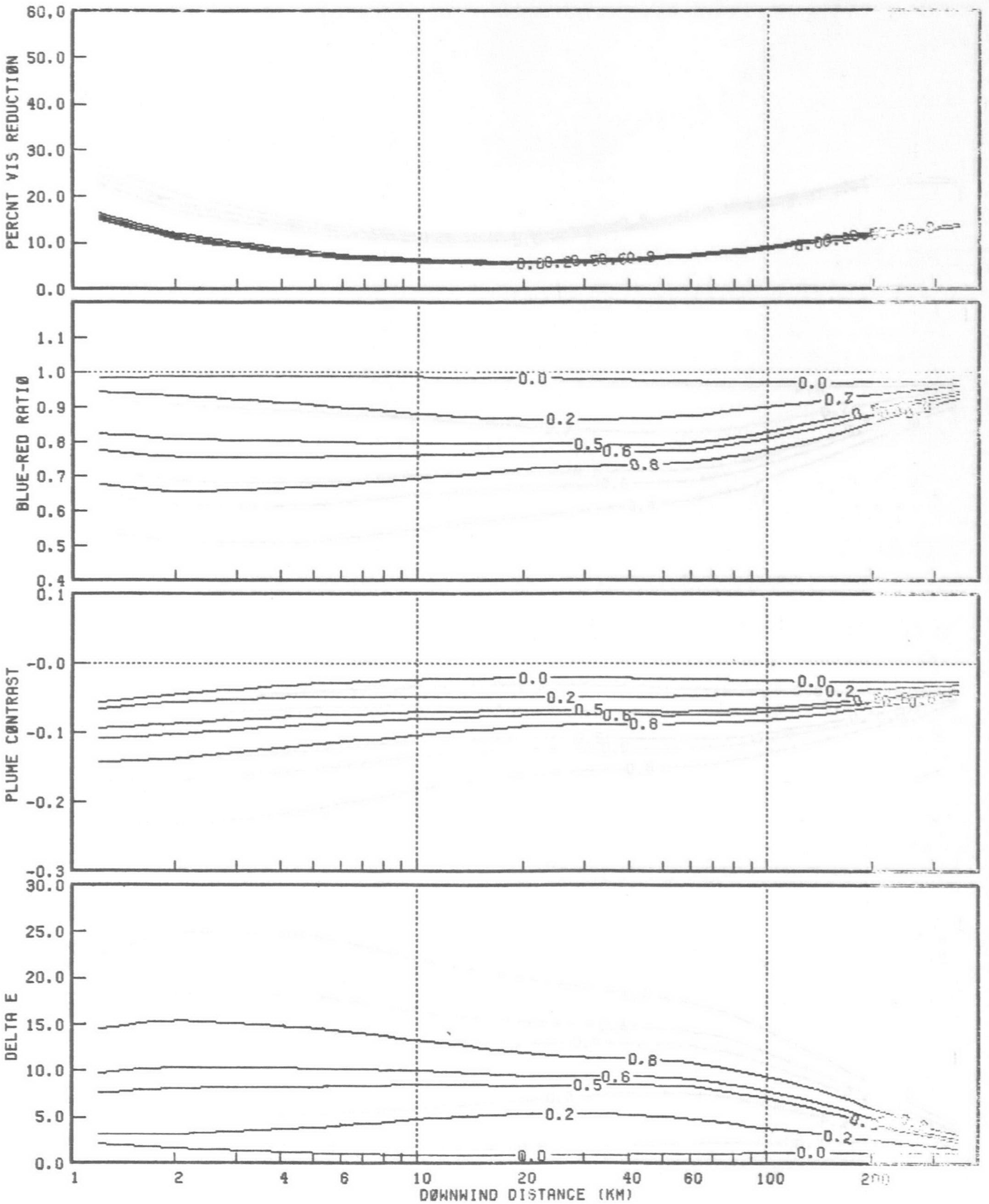
(d) Pasquill Stability F

FIGURE C-3 (Concluded)



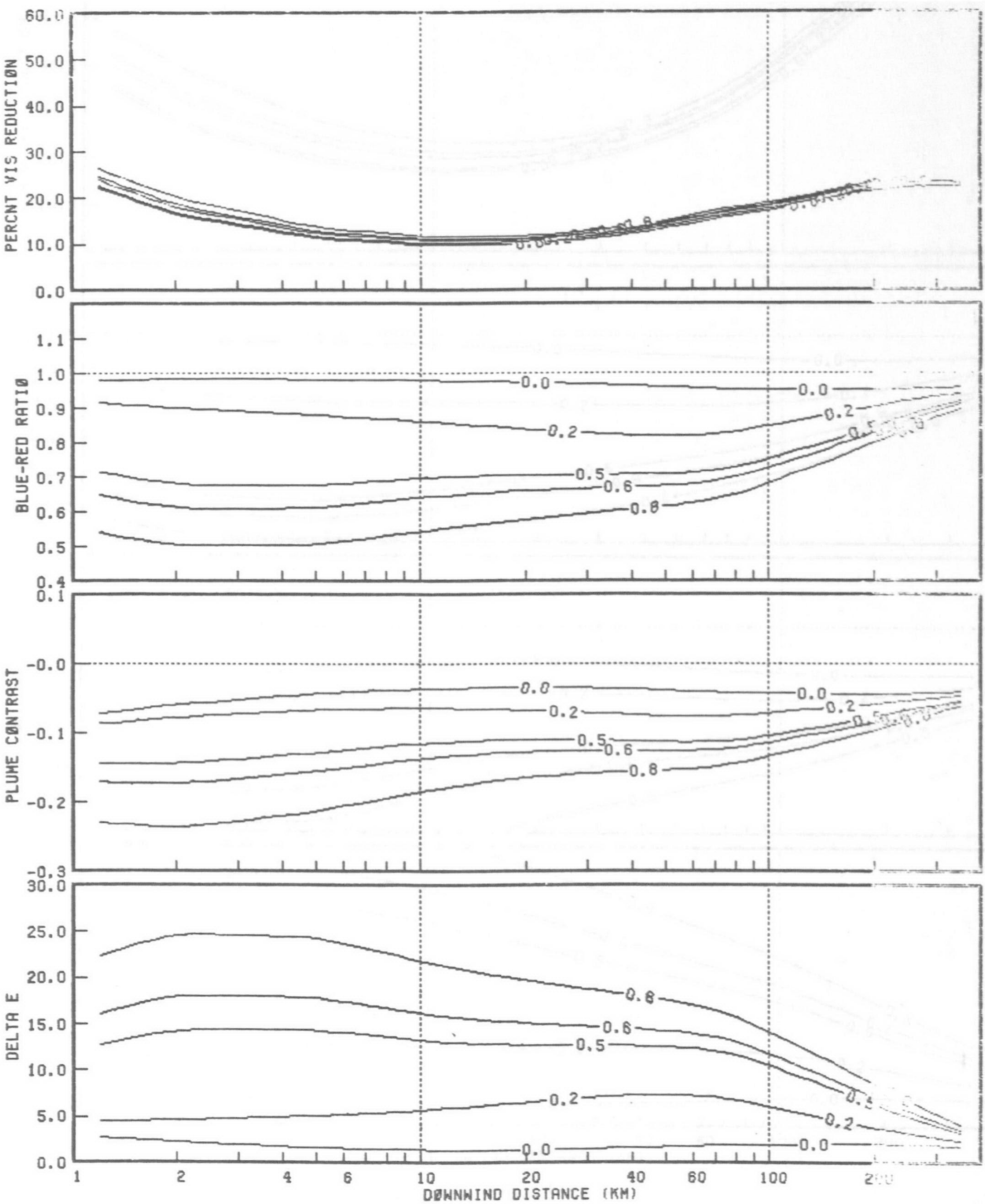
(a) Pasquill Stability C

FIGURE C-4. EFFECT OF NO_x EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 3000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. NO_x emission rates in pounds per million Btu are indicated.



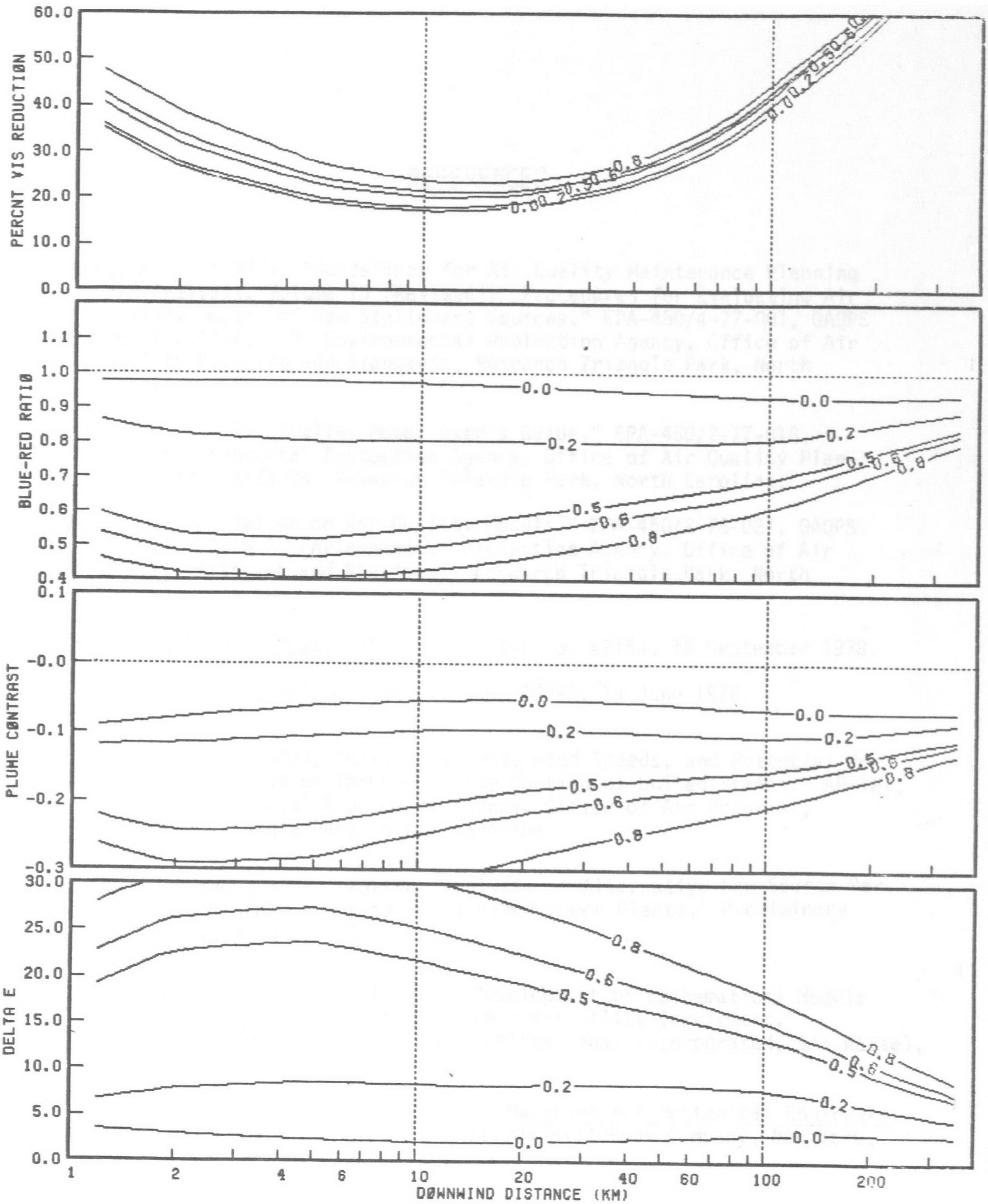
(b) Pasquill Stability D

FIGURE C-4 (Continued)



(c) Pasquill Stability E

FIGURE C-4 (Continued)



(d) Pasquill Stability F

FIGURE C-4 (Concluded)

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