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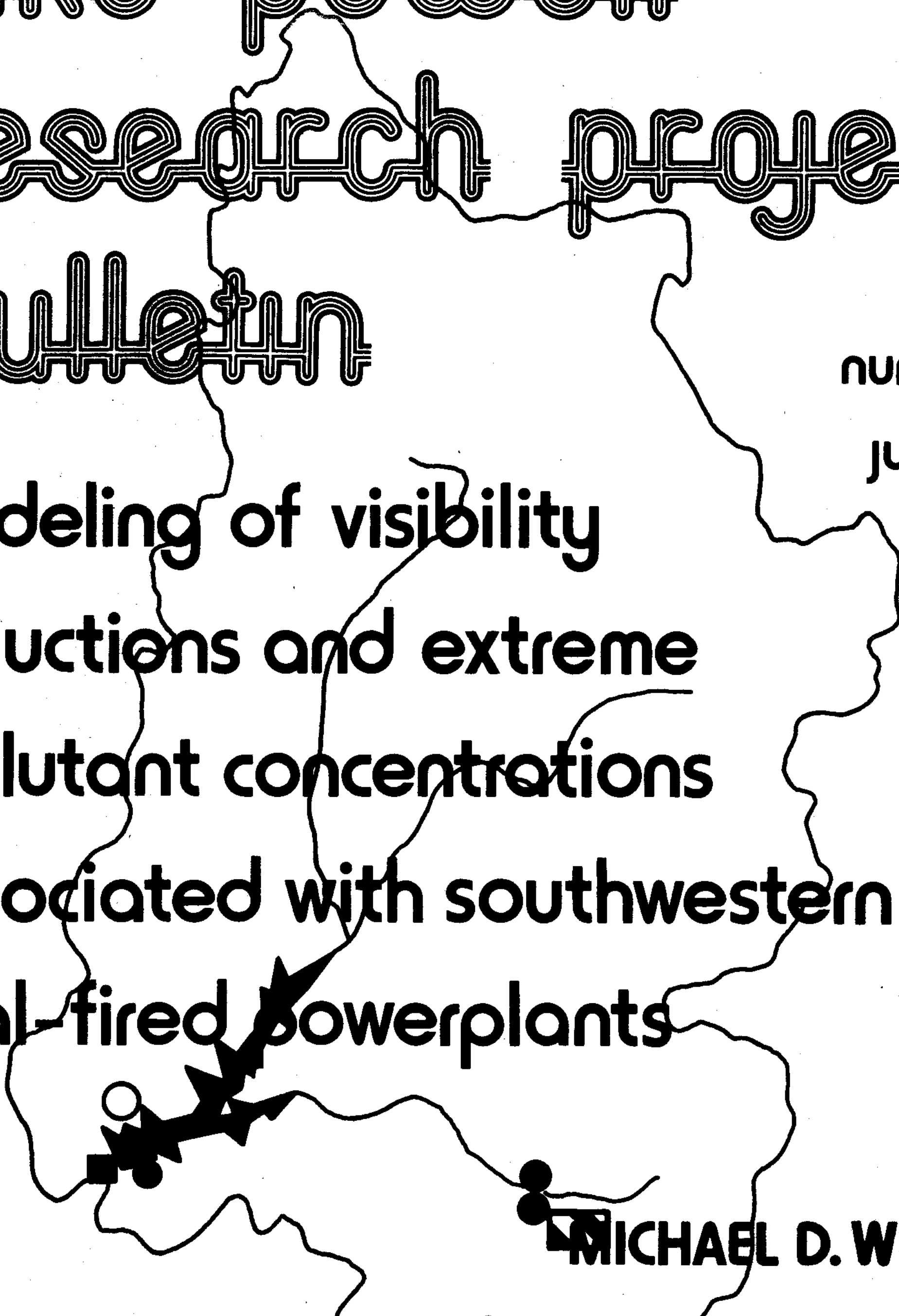

modeling of visibility reductions and extreme pollutant concentrations associated with southwestern coal-fired powerplants

MICHAEL D. WILLIAMS

National Science Foundation
pplied to National Needs

LAKE POWELL RESEARCH PROJECT BULLETIN

BULLETIN EDITORS

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MODELING OF VISIBILITY REDUCTIONS AND EXTREME POLLUTANT CONCENTRATIONS ASSOCIATED WITH SOUTHWESTERN COAL-FIRED POWERPLANTS

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LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Advanced Environmental Research and Technology in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreation Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Two major areas of uncertainty associated with the prediction of impacts of powerplant plumes in the Southwest are visibility effects and high terrain concentrations. This Bulletin reports on studies related to these two questions.

It was found that during low-wind-speed stable conditions a very marked visible plume is associated with a large southwestern powerplant. Measurements indicated that fly ash, nitrates, and nitrogen-dioxide were important in the measured opacities which were nearly 100 percent in some cases. In addition, high concentrations of pollutants were found on high terrain.

Predictive models are described which permit calculation of visibility effects and high terrain ground level concentrations.

INTRODUCTION

Powerplants may be expected to affect the environment in a number of ways. Two mechanisms which have received a great deal of attention in the Southwest include visibility reductions and possibly damaging concentrations of toxic gases. In the case of visibility reductions, the concern is that visitors to recreation areas may find distant vistas obscured by a gray or brown cloud of air pollutants. In the case of toxic gas concentrations, the concern is that plants or animals may be damaged by gases such as sulfur oxides or nitrogen dioxide.

The question of visibility reductions is a major element of the controversy which surrounds the operation of the Four Corners Powerplant in northwestern New Mexico[1] and which continued while the Mohave and Navajo plants were sited.[2] The most recent controversy was the furor over the proposed Kaiparowits plant in southern Utah, and was a principal area of concern for the National Park Service[3] (NPS) as it assessed the potential impact of the plant on areas such as Bryce Canyon National Park, Capitol Reef National Park, Glen Canyon National Recreation Area, Zion National Park, and Grand Canyon National Park. The NPS analysis suggested that park values might be impaired by operation of the Kaiparowits plant.

Visibility reductions are produced when pollutants emitted from sources either scatter and/or absorb light themselves or convert to materials which scatter and/or absorb light. With powerplants, the principal pollutant which may scatter or absorb light is fly ash. Fly ash is the mineral residue left in the gases after the coal is burned, and it normally consists primarily of clay or sand particles buried with the organic material which eventually formed the coal millions of years ago. When these clay or sand particles are released to the atmosphere, they scatter light. If enough of these particles are between an observer and a distant object which is being viewed, they may make it impossible to observe the object. This happens because the clay or sand particles scatter sunlight back toward the observer and also scatter the light reflected off the object away from the observer, and results in the outlines of the once-visible object being replaced by a gray haze. This effect is very much like a dirty windshield obscuring the view of the highway when one is driving toward the sun. If the air is less dirty, one can make out the object but it will be blurred and faint.

If the object is faint to begin with (for example, a light-gray rock seen against a white rock), the atmosphere will not have to be very dirty before the object seems to disappear. On the other hand, a black rock seen against a white rock will still be visible even though there are higher dust concentrations. In any case, the ability to see an object depends upon how much dust one has to look through. If the atmosphere is very dusty, one may be able to see objects which are only a short distance away. On the other hand, if the air is very clean, one may be able to see objects at a great distance. These considerations lead to the concept of visible range. Visible range is the distance at which a person with unimpaired eyesight is just able to see a distant high-contrast object (such as a large black bull's eye on a white target). The object will appear hazy and indistinct at a much shorter distance. Furthermore, persons with slightly impaired eyesight will be able to see only objects at shorter distances.

The upper limit of the visible range is defined by the light scattering which is produced by the cleanest of air. This light scattering gives the sky its blue color and at sea level would normally limit the visible ranges to 150 miles (241 kilometers).[4] At higher elevations, or when one is looking at a distant mountain top where the air is thinner, the range may be longer than the theoretical values at sea level.

In addition to fly ash, powerplants may produce other materials which affect visibility, such as nitrogen dioxide, particulate sulfate, and particulate nitrate. Usually, very little of these materials is found in the gases escaping the powerplant stack. However, in the atmosphere, nitric oxide, which escapes in large quantities, converts to nitrogen dioxide which may convert to particulate nitrate. Thus, although we initially have a colorless gas, nitric oxide, which has no effect on visibility, it converts to a red-brown gas, nitrogen dioxide, which may then convert to particulate nitrate. The reason for the brown appearance of nitrogen dioxide is that it strongly absorbs blue light, permitting red or yellow light to pass through with little effect. Thus, nitrogen dioxide may turn a blue sky into a brown one. In California a limit of 0.25 part per million (ppm) has been adopted as an adverse level because of the sky coloration effect.[5]

Particulate nitrate may have an even greater impact on visibility,[6] although the effect would not necessarily be to make the sky brown. At large distances the bulk of the nitrogen oxides might convert to nitrates. This would make possible nitrate concentrations much greater than the fly ash concentrations, and there would be a correspondingly greater impact on visibility.

In a similar fashion, sulfur dioxide, a colorless gas, may convert to particulate sulfate, which is an effective light scatterer.[7]

The appearance of the smoke plume from a powerplant stack will depend upon prevailing atmospheric conditions. In some conditions, the smoke will appear as a narrow band of dense haze. In other circumstances it may appear as a uniform haze from the ground level up to a height well above the ground; above this height the air will be clear again. On these occasions the smoke may not extend much beyond the immediate vicinity of the powerplant.

Another area of concern regarding the impact of powerplants on the Southwest is the possibility of high concentrations of toxic gases on high terrain. The gases most often mentioned in this context are sulfur dioxide and nitrogen dioxide. Other pollutants of concern are sulfates and nitrates.[8]

Until recently, the possibility of the presence of very high concentrations of pollutants on high terrain associated with powerplants was based on theoretical considerations plus some very limited experimental work[9] in the neighborhood of a smelter in the Canadian province of British Columbia. Models, which predicted very high concentrations on high terrain, were first used in the Southwest by investigators with the National Oceanic and Atmospheric Administration (NOAA).[10] The model they developed has been called the NOAA model and has been the subject of a great deal of discussion. A number of other models have since been proposed which differ considerably in their predictions, and, because models must be used to determine where a new powerplant may be built and with what controls, a great deal of money may ride on which model is correct.

In view of the uncertainties in visibility calculations and high terrain modeling, the Plume Analysis Subproject of the Lake Powell Research Project was designed to measure key parameters. The measurements were made, using aircraft, of such parameters as nitrate concentrations, nitrogen dioxide concentrations, and plume opacity. In addition to our measurements, a number of other groups have made measurements relevant to the high terrain situation.

FIELD PROGRAM

Procedures

The field program used a light plane as a mobile sampling platform. The plane would make repeated passes through the plume under observation, and samples were collected by project personnel. The sampling equipment permitted measurement of nitric oxide or total nitrogen oxides. The amount of nitrogen dioxide present was determined by subtracting the amount of nitric oxide obtained on one pass through the plume from the nitrogen oxides obtained on another pass. The device (a Mast meter) used was an instrument which used an electroconductivity principle to measure nitrogen dioxide; a prescrubber (di-chromate paper) was used to convert nitric oxide to nitrogen dioxide. Another scrubber (Ascarite) was used to remove nitrogen dioxide from the samples so the amount of nitric oxide present could be measured. The results were recorded on a strip-chart recorder. Thus, we examined the trace and determined the maximum amount of this pollutant and the period of time over which the pollutant was above background. The latter determination was used with the airspeed of the plane to determine the width of the plume.

In addition to the nitric oxide measuring equipment, filter holders were used to collect particulates on a glass fiber (for nitrates) or paper filter (for sulfates). In each case, since several minutes were required to collect an adequate sample, only one type of sample (sulfate or nitrate) could be collected at a time.

Nitrate samples were leached with water from the filter paper and analyzed via a wet chemistry technique.[12] A backup filter was also analyzed. Thus, gaseous nitrates could be separated from particulate nitrates for study.

Sulfate samples were analyzed via a ring oven technique.[13, 14] In this case backup samples were also taken.

In addition to collecting contaminants, photographic techniques were used to determine plume opacity. For the technique to work, it was necessary to have a high-contrast object behind the plume, such as a canyon with sunlit and shadowed walls. The light, Es , which reaches the camera from the sunlit walls is

$$Es = EsoTb + S \tag{1}$$

where

Eso = the light reflected toward the camera from the wall

Tb = the fraction of the light transmitted through the non-plume atmosphere

S = the sunlight scattered toward the observer in the non-plume atmosphere.

For the shaded portion of the canyon the light, Ed, is

$$Ed = EdoTb + S \quad (2)$$

where

Edo = the skylight reflected from the canyon.

If a portion of the canyon is partially obscured by the plume, the light reaching the camera from the sunlit wall is

$$Esp = EsoTbTp + S + Sp \quad (3)$$

where

Tp = the light transmitted through the plume toward the observer

Sp = the sunlight scattered in the plume

For the dark shaded canyon wall we have

$$Edp = EdsTbTp + S + Sp \quad (4)$$

From these relations we can obtain the light transmission of the plume:

$$Tp = \frac{Esp - Edp}{Es - Ed} \quad (5)$$

The opacity, O, is

$$O = 100 (1 - Tp) \qquad (6)$$

The values Esp, Edp, Es, and Ed are obtained by measuring the density of the negative at points corresponding to polluted and unpolluted shaded and sunlit canyon walls. The relative light values, Esp, Edp, Es, and Ed, are obtained from the densities by comparison with portions of the film which have been exposed to known light levels.

In addition to the photographs and contaminant samples, we also used the plane for recording temperatures at various altitudes. Temperature is a parameter which can be used to determine the stability of the atmosphere. The stability in turn influences the manner in which pollutants spread. For example, if the temperature increases or is constant with height, the atmosphere is stable and the pollutants spread very little vertically.

The plane was also used to gain information about the depth of the plume. In these cases, passes were made through the plume at different heights.

Finally, the aircraft measurements were supplemented by information on wind speeds (obtained from pilot balloons) and emission rates. This material was provided by the Salt River Project.

The flights reported here were conducted in the vicinity of the Navajo Generating Station which is operated by the Salt River Project at Page, Arizona. The plant has three units with a total generating capacity of 2310 megawatts. It has an efficient hot-side electrostatic precipitator which is designed to collect 99.5 percent of the fly ash, and it uses a low-sulfur coal and meets federal new-source performance standards for particulates, sulfur oxides, and nitrogen oxides. The resultant daily emissions are approximately 8 tons of particulates, 200 tons of sulfur dioxide, and 180 tons of oxides of nitrogen. The stacks are 775 feet tall.

RESULTS

On many of the flights, adequate photographic measurements were not made, usually because there was not a good high-contrast background present. On other occasions the powerplant was in startup with consequent excessive particulate emissions. In these cases there was no information on the actual particulate emission rate so that no calibration of models was possible. In addition, on a few of the flights there was rapid dilution of the plume caused by high winds or strong vertical mixing. In these cases the plume was usually visible only when viewed from a point directly downwind of the stack. In this case the plume-obscured portions of the photograph were not of sufficient size to enable accurate measurements to be made. Table 1 summarizes the results of the photographic measurements.

Figures 1 through 4 are examples of photographs used in Table 1. Figures 5 through 7 are examples of photographs which were not used because of a lack of appropriate background. In Figure 5 the plume appears dark against the sky. Plumes which have high light absorption (as opposed to light scattering) appear dark. Plumes which are made of light scatterers will appear dark if

Table 1: Photographic Measurements

Units Operating	Date	Time of Day	Meteorological Conditions	Filter	Distance Downwind	Angle with Plume Axis	Opacity (percent)
2	2/1/75	10:30 AM	N-5+mps-St	skylight	30 km	90°[a]	20[b]
2	5/14/75	9:00 AM	S-1 mps-V	blue	20 km	45°	50
2	12/9/75	10:00 AM	S-1 mps-V	blue	1 km	90°	100
2	12/9/75	10:00 AM	S-1 mps-V	red	1 km	90°	70
2	1/7/76	10:00 AM	S-5 mps-St	skylight	10 km	45°	90
2	1/7/76	10:00 AM	S-5 mps-St	red	10 km	45°	80
2	1/7/76	10:00 AM	S-5 mps-St	yellow	10 km	45°	80

a = an angle with the plume axis of 90° means the photograph was taken along a line directly transverse to the direction of plume travel

b = the various filters were used to provide information about which wavelengths of light were most affected by the contaminants; these data also provide information on the apparent color of the plume; for example, with a blue-filter opacity of 100 percent and a red-filter opacity of 70 percent the plume would appear brown

N = neutral stability

5+mps-St = winds were steady with a velocity of over 5 meters per second (16 feet per second)

S = atmosphere was stable

V = winds were variable

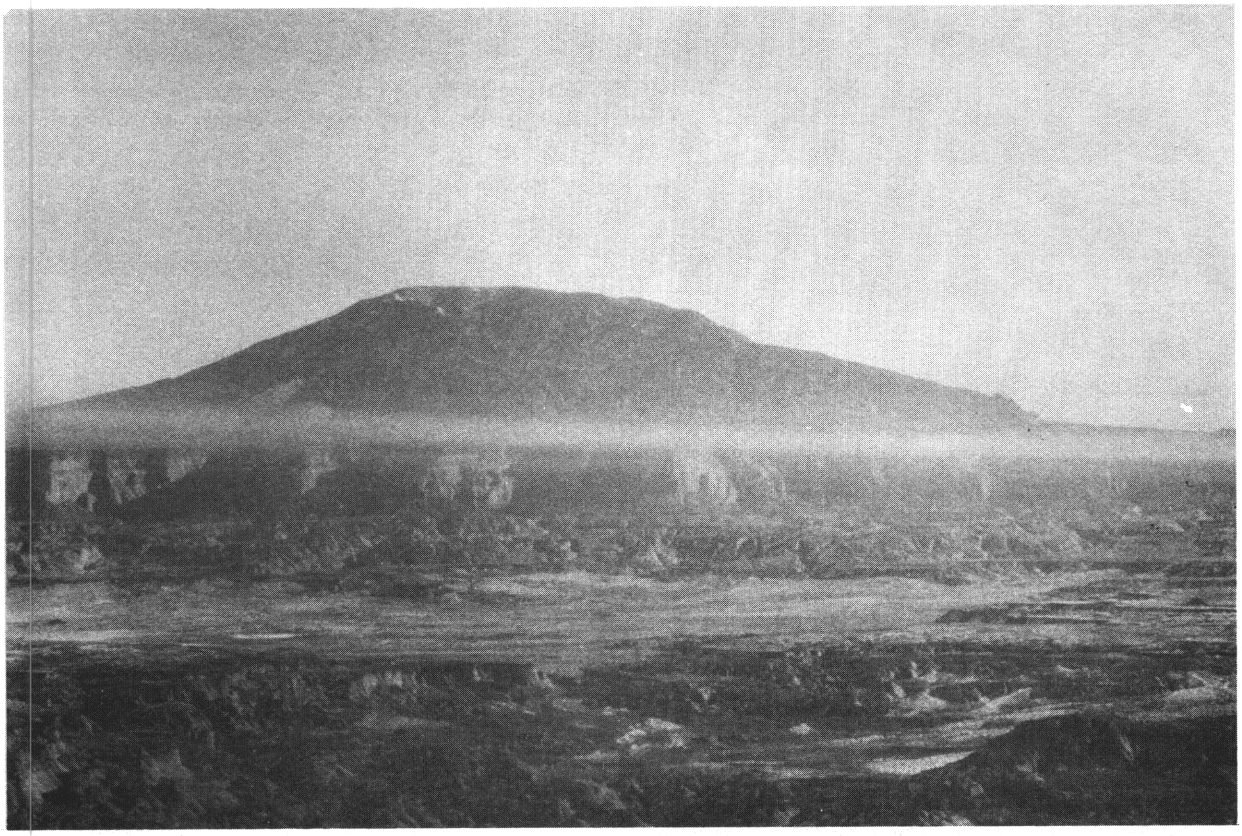

Figure 1: View of Navajo Mountain through the Navajo plume on January 7, 1976, with a skylight filter

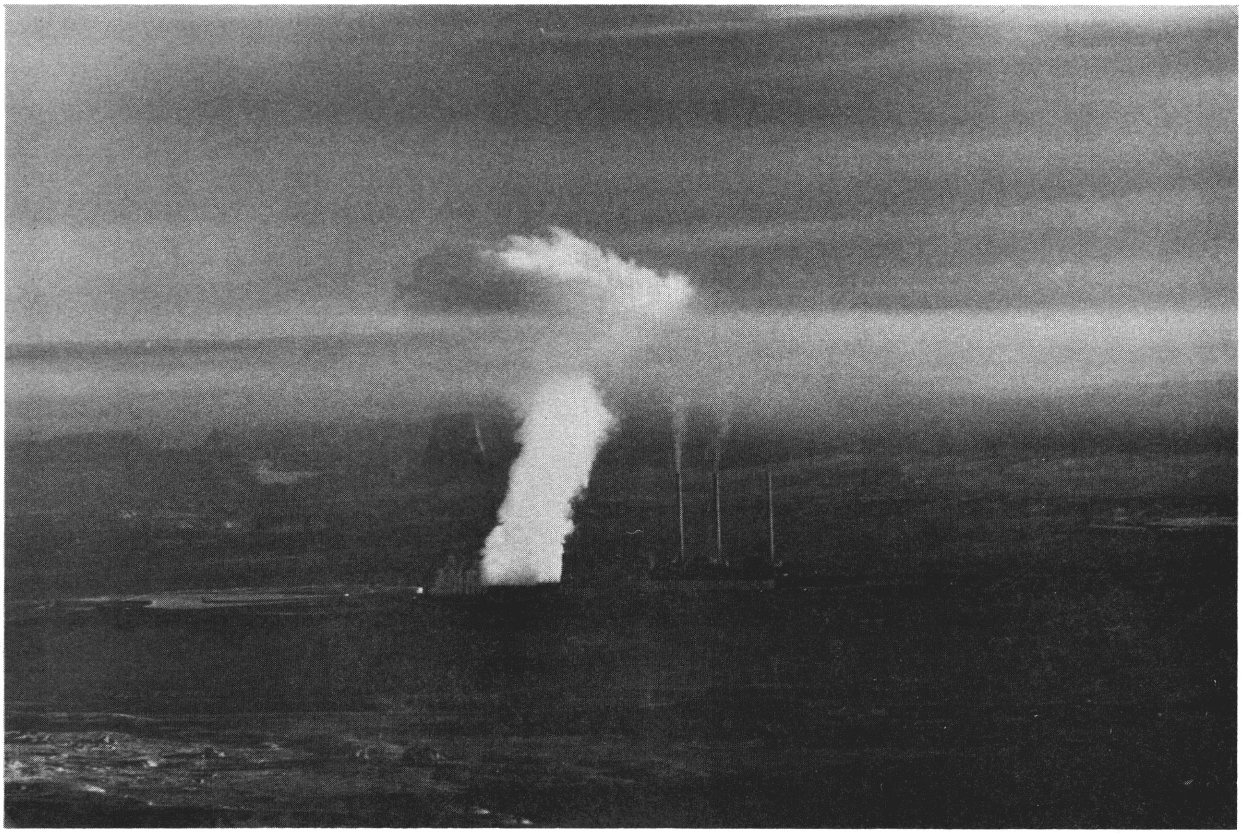

Figure 2: View of the cooling tower plume intersected by the smoke plume on December 9, 1975, through a red filter

Figure 3: View of Navajo Mountain through the Navajo plume on January 7, 1976, with a red filter

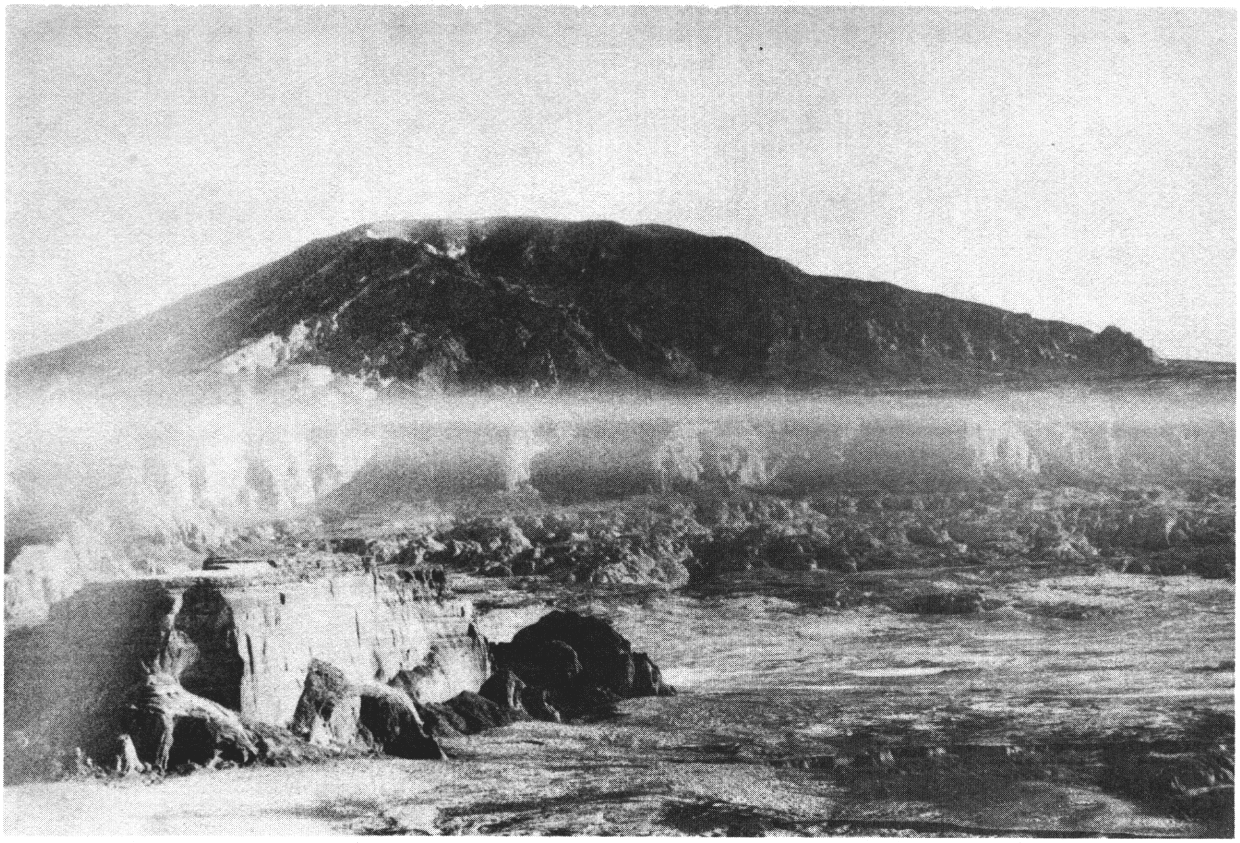

Figure 4: View of Navajo Mountain through the Navajo plume on January 7, 1976, with a yellow filter

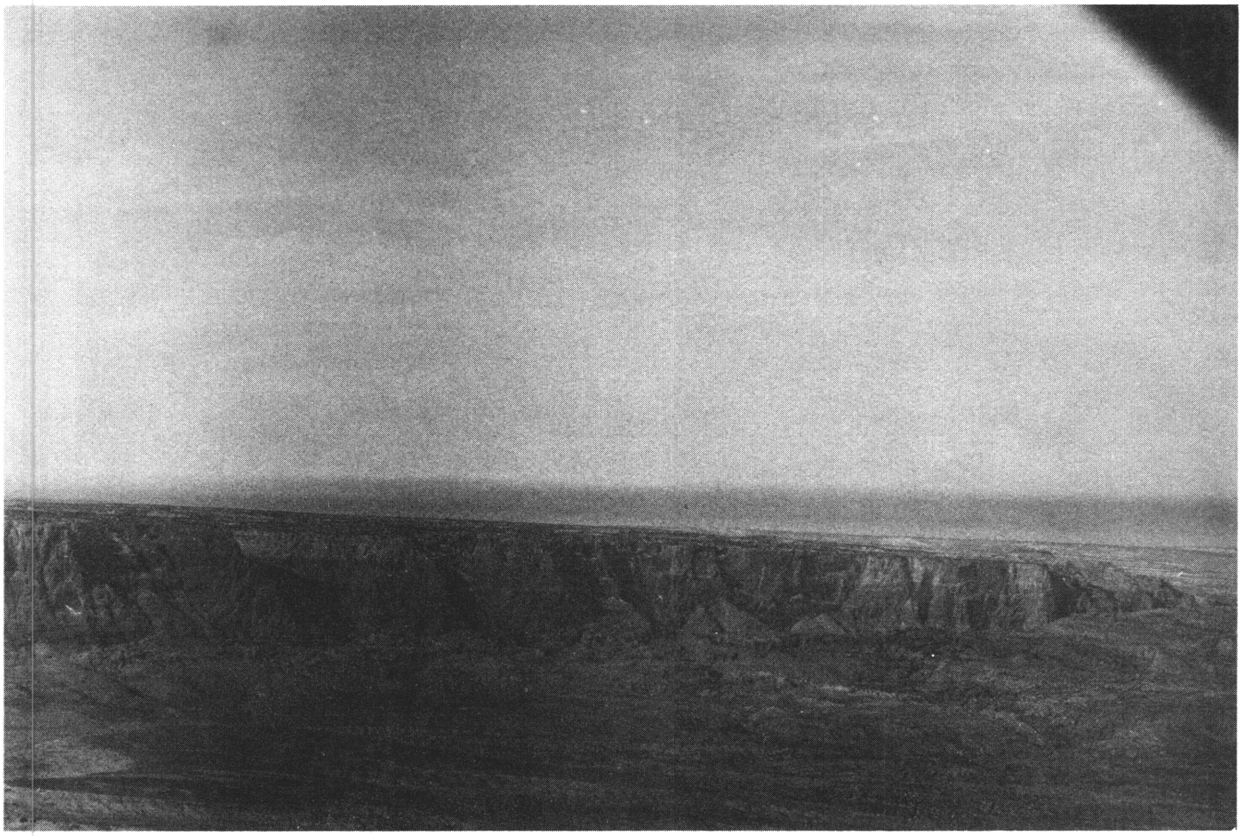

Figure 5: View of the Navajo plume above Glen Canyon National Recreation Area on January 29, 1975, with a blue filter

Figure 6: View of Tsai Tskizzi Rock through the Navajo plume on January 7, 1976, with a skylight filter

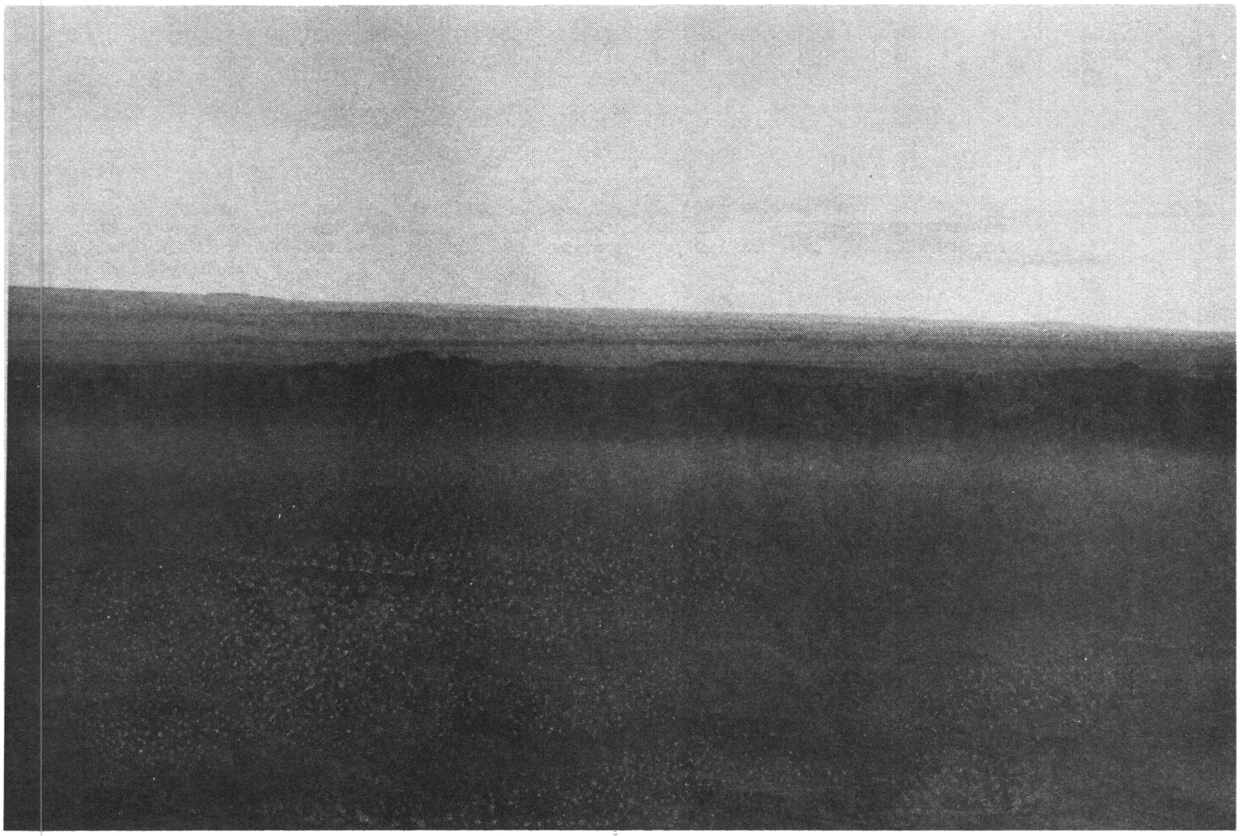

Figure 7: View of Vermillion Cliffs through the Navajo plume near Lees Ferry, on December 8, 1975, with a skylight filter

Table 2: Measured Nitrate Concentrations

Date	Meteorological Conditions	NO_3 ($\mu g/m^3$)[a]	NO_3 on Backup ($\mu g/m^3$)	Recovery	Fraction of Nitrogen Oxides	Distance
12/18/74	S - 1mps - V	12 ± 7	--	33%	--	0-25 km
1/29/75	S - 4mps - St	9 ± 6	--	25%	--	30 km
1/29/75	S - 4mps - St	1.2 ± 1.5	--	80%	--	2-15 km
2/1/75	N - 2mps - St	0 ± 2	--	67%	--	30 km
4/15/75	N - 11mps - St	10 ± 7	2 ± 7	40%	--	28 km
5/14/75	S - 1mps - V	0 ± 5	0 ± 5	60%	--	20 km
5/14/75	S - 1mps - V	5 ± 9	-5 ± 9	60%	--	n.p.[b]
5/15/75	N-S - 4mps - St	-3.7 ± 3.7	-3.7 ± 3.7	75%	--	28 km
5/15/75	N-S - 4mps - St	0 ± 3.7	-1.9 ± 3.7	75%	--	n.p.
5/16/75	N-S - 10mps - St	0 ± 3	0 ± 3	78%	--	32 km
5/16/75	N-S - 10mps - St	0 ± 3	0 ± 3	78%	--	n.p.
6/23/75	N-S - 3.5mps - St	5.2 ± 2.6	0 ± 2.6	n.d.[c]	--	5 km
12/9/75	S - 1mps - V	14 ± 5	15 ± 5	55%	9%	19 km
1/6/76	N - 9mps - St	4 ± 4	6 ± 4	73%	6%	26 km
1/7/76	S - 5mps - St	7.5 ± 15	-7.5 ± 15	78%	n.d.	30 km
1/8/76	S - 3mps - St	9 ± 6	0 ± 6	50%	6%	22 km
1/9/76	S - 1mps - V	-6 ± 4	-6 ± 4	73%	0	8 km
4/23/76	N	4 ± 4	3 ± 4	n.d.	n.d.	3 km

a = micrograms per cubic meter
b = sample taken from outside the coherent plume
c = no data
mps = meters per second

N = neutral stability
S = atmosphere was stable
St = winds were steady
V = winds were variable

the sun is behind them. In Figure 4 the white column is the condensed water vapor from the cooling towers. The abrupt disappearance at the edge of the cloud is typical of such clouds. Smoke plumes tend to fade away gradually, if at all.

The results of the nitrate measurements are summarized in Table 2.

In Table 2, the nitrate concentrations are given in micrograms per cubic meter ($\mu g/m^3$). The percent recovery is based on the fraction of nitrate placed on a filter which was recovered after leaching. The first two samples used a much larger diameter filter which made recoveries correspondingly worse. The notation 14 ± 5 means that analysis indicated a value of 14 with an estimated error of 5 in either direction. The analysis of the samples on January 9, 1976, involved an error in procedure although it is not clear that the error would explain the anomalous results. The percentages in the column headed "Fraction of Nitrogen Oxides" represent the fraction of nitrogen oxide which would have had to convert to NO_3 to explain the amount of nitrate found.

A typical background in the region for NO_3 would be about 0.5 $\mu g/m^3$.[15] For longer periods of time (24 hours) and for ground level concentrations, concern has been expressed about nitrate concentrations as low as 3 $\mu g/m^3$.[16]

The results of the flight on December 9, 1975, indicate that what is frequently recorded as particulate nitrate may not in fact have been particulate nitrate. In this case, since an equal amount was found on both the sample filter and the backup filter, the contaminant must have been gaseous. There are two possibilities: one is nitric acid, which could very well be as a gaseous form, and the other is nitrogen dioxide which might be absorbed onto the filter. In the latter case, when the filter was leached with water the nitrogen dioxide would convert to a nitrate. Since methods for sampling for nitrates normally use liquid extraction, most reported levels of particulate nitrates may in fact be of gaseous nitrate or nitrogen dioxide.

There were no cases in which unambiguous sulfates or acid aerosols were measured. In general, average sulfate levels of 7 to 15 $\mu g/m^3$ would have been required to produce a measureable result. This implies that sulfates comprised no more than 3 to 5 percent of the total sulfur oxides emitted.

Nitrogen dioxide was also measured during the program. Table 3 describes the values found and the ratio of nitrogen dioxide to total nitrogen oxides.

The asterisked values are total nitrogen oxides rather than nitrogen dioxide, and 1 ppm under the conditions of calibration was 1560 $\mu g/m^3$. The ratios of nitrogen dioxide to nitrogen oxides are based on the integrated values of each over the total plume width. The column marked "$\int NO_2 dy$" gives the integrated nitrogen dioxide concentrations across the plume. This parameter is important because the amount of light which is absorbed in passing through the plume along the same line as the aircraft is dependent upon this value. The column marked "Blue-Light Transmission" gives the fraction of the blue light which could penetrate through the plume. If one uses the edge of the plume as the point at which the concentrations

Table 3: Nitrogen Oxides and Plume Parameter Measurements

Date	Meterological Conditions	Distance	Nitrogen Dioxide (ppm)	Nitrogen Dioxide/ Nitrogen Oxide	$\int NO_2 dy$	Blue-Light Transmission (percent)	σy (km)	σz (m)
12/8/75	S - 1mps - V	8 km	.76	≃1.	2.04	17	.6	--
12/9/75	S - 1mps - V	5 km	2.2	≃1.	4.7	2	1.2	--
12/9/75	S - 1mps - V	5 km	1.8	.5	6.1	<1	1.5	--
12/9/75	S - 1mps - V	20 km	2.6[a]	--	--	--	1.2	--
12/9/75	S - 1mps - V	20 km	1.4	--	1.5	27	--	--
1/6/76	N - 9mps - St	10 km	.15	.9	--	--	.6	--
1/6/76	N - 9mps - St	26 km	.11	.8	--	--	.6	--
1/6/76	N - 9mps - St	26 km	.15[a]	--	--	--	.6	--
1/7/76	S - 5mps - St	8 km	1.3	≃1.	--	--	.5	--
1/7/76	S - 5mps - St	30 km	.9	.8	1.76	21	1.3	--
1/7/76	S - 5mps - St	30 km	.4	.4	.80	--	.9	--
1/7/76	S - 5mps - St	30 km	1.7[a]	--	--	--	.8	50
1/8/76	S - 3mps - St	22 km	1.2[a]	--	--	--	.5	50
1/8/76	S - 3mps - St	55 km	.56	.87	2.3	13	.6	50
1/9/76	S - 1mps - V	14 km	.3[a]	--	--	--	2.3	--
1/9/76	S - 1mps - V	6 km	.22	.85	.91	43	1.6	--
1/9/76	S - 1mps - V	7 km	.5	.86	.58	60	1.0	--

a = measured values of nitrogen oxides
mps = meters per second
N = neutral stability
S = atmosphere was stable
St = winds were steady
V = winds were variable

fall off to one-tenth of their maximum value, the width is 4.3 σy. In a similar fashion the depth is 4.3 σz. With the very low blue-light transmission reported, a brown plume would be expected if the plume were only nitrogen dioxide. The plume did have a marked brown color, but the photographs indicate that red light is attenuated also. Thus other species are important in addition to nitrogen dioxide.

In addition to the information about visibilities, two flights provided information about terrain interactions. On January 7, 1976, two units (a total of about 1500 MW) were operating. The plume height was approximately 6700 feet (2042 meters). A portion of the plume passed directly over a butte at 6312 feet (1924 meters). At 6500 feet (1981 meters), directly over the butte, concentrations of 0.444 ppm were measured. However, at 6300 feet behind the butte the concentrations were only 0.095 ppm. It appeared that neither the butte nor the gently rising terrain had produced any change in plume characteristics. The second flight was conducted while only one unit was operating. High concentrations of nitrogen oxide (0.46 ppm) were measured at 24 meters (80 feet) above ground at a distance of 55 kilometers (34 miles). The terrain was as sketched below:

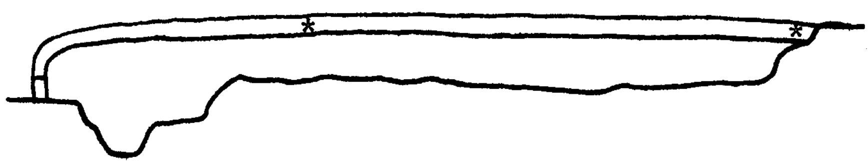

Figure 8: Terrain beneath the Navajo plume on January 8, 1976

The axis of the terrain at 55 kilometers was not directly transverse to the plume travel but instead represented barriers set at a 45° angle with the plume travel. The value found at 24 meters (80 feet) was not necessarily representative of the plume centerline at that height since the flight was not transverse to plume travel. At approximately 91 meters (300 feet) higher, flights were made transverse to the plume travel. Nitrogen oxides values of approximately 0.6 ppm or 1000 $\mu g/m^3$ were found consistently during over 15 minutes of sampling. At 7700 feet (268 meters) no evidence of the plume could be found. Visually it appeared to be lying on the ground. The nitrogen oxide emissions on the day in question were not recorded due to an instrument failure; however, data from other days at the same plant suggest that the emission rate would be about 620 grams per second (gm/sec) at full load which gives a concentration per unit emission rate (x/Q) of about 1.6×10^{-6} at 55 km. These values were measured by flights transverse to the plume centerline with an instrument with significant response time (probably about 20 seconds), and hence would probably represent averages appropriate to a few minutes.

The general meteorological conditions were obtained by examining maps obtained from the National Weather Service which give the height of a constant pressure surface above ground. These maps are similar to those used by weather forecasters to portray the location of storms, high-pressure systems, etc. The 850-millibar map for 1200 Greenwich time on January 8, 1976 (approximately 5:00 on the morning of the flight) indicated a high-pressure system over the sampling area. The 850-millibar level corresponds to about 5000 feet in elevation (1524 meters). With a high-pressure system over the area the winds would tend to be light and the atmosphere stable. The maps for 12 hours later (5:00 PM) indicated that the high had moved to the east of the area. This would generally give rise to winds out of the south, which is consistent with the actual plume travel. Maps for higher elevations, about 10,000 feet (3048 meters), showed a completely different pattern, with winds expected to be out of the northwest.

Small, hydrogen-filled balloons (known as pilot balloons or pibals) launched at 7:15 AM (versus 10:00 AM measurements) indicated winds out of the south at 6300 feet and out of the west at 7300 feet, shifting to out of the northwest at 8300 feet (1920, 2225, and 2530 meters respectively).

THEORETICAL DEVELOPMENT

The plume opacity along a particular line of sight may be estimated as follows:

$$O = 100[1 - \exp(-\sum_i \beta i \int_o^L \chi i ds)] \qquad (7)$$

where

- O = the opacity of the plume
- L = the distance to an object along the line of sight
- βi = the light extinction coefficient per unit mass concentration of contaminant i
- χi = mass concentration of contaminant i
- ds = an element of distance along the line of sight

Normally if one is considering a plume of finite width and the line of sight completely crosses the plume width, the distance L can be taken as infinity for mathematical purposes.

Alternatively, one may calculate the visual range as:

$$VR = VRB \left(1 - \frac{\sum_{i} \beta i \int_{o}^{x} \chi i ds}{3.9}\right) \tag{8}$$

where

VR = the visual range
VRB = the background visual range

If VR is less than the distance to the far edge of the plume, the observer cannot see across the plume. In this case the actual visual range can only be described as being less than the distance to the other side of the plume because the relation (8) is no longer valid.

The integral in (8) can be written as:

$$\int \chi i ds = \int_{-Sc Cos\,\theta}^{\infty} \frac{\chi(x,y,z)}{Sin\,\theta}\, dy \tag{9}$$

where

Sc = the distance to the plume centerline along the light path
θ = the angle between the light path and the plume travel direction

The downwind distance x is given by:

$$x = xc + y \text{ Tan } \theta \tag{10}$$

where

xc = the distance from the source to the intersection of the light path and the plume centerline

Alternatively, the integral can be expressed in terms of x when

$$\int \chi i ds = \int_0^\infty \chi(x,y,z) \frac{dx}{\text{Cos } \theta} \tag{11}$$

with

$$y = (x - xc) \text{ Tan } \theta \tag{12}$$

If one uses the Gaussian form:

$$\chi(x,y,z) = \frac{Q}{2\pi\sigma y\sigma t} \exp\left(-\frac{1}{2}\frac{y^2}{dy^2}\right)\left\{\exp\left[-\frac{1}{2}\left(\frac{H - z}{\sigma z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{H + z}{\sigma z}\right)^2\right]\right\} \tag{13}$$

and uses Turner[17] or TVA[18] dispersion relations in which σy and σz can be approximately described by

$$\sigma y = Cx^d \tag{14}$$

$$\sigma z = Ax^b \tag{15}$$

it becomes apparent that the principal contribution to the integral for cases in which $\sigma > 15°$ is in the region where $|y| < 3\sigma y$. The expression $\exp(+\frac{1}{2}\frac{y}{\sigma y^2})x$ can then be expanded about y equals σ in series expansion involving y/D where

$$D = \chi c \;\; \mathrm{Ctn}\;\theta \tag{16}$$

However, with Turner,[19] C, D, E, or F stabilities (for a more complete discussion of these stability classes, see LPRP Bulletin 8[20]) and distances xc of a few kilometers or more, the first-order and higher term of the series expansion contributes 10 percent or less to the integral. Thus, for most purposes it suffices to use the zeroth order term:

$$\int \chi i ds = \frac{Qi \left\{ \exp\left[-\frac{1}{2}\left(\frac{H - z}{\sigma z}\right)\right]^2 + \exp\left[-\frac{1}{2}\left(\frac{H + z}{\sigma z}\right)\right]^2 \right.}{\sqrt{2}\pi \; u \; \sigma z \; \mathrm{Sin}\;\theta} \tag{17}$$

This analysis presumes that the interest is primarily in heights z which are near to plume centerline where the largest effects occur. The analysis is also geared toward light paths which are nearly horizontal. For example, if the observer were 10 kilometers (6 miles) from a plume at 500 meters (1640 feet) above ground, the line of sight would be only 3 degrees above the horizontal.

For pollutants such as nitrogen dioxide which are converted from another pollutant, a slight modification must be used. If there is exponential decay, the effective source can be written as

$$Qa = Qo \; mcf \left[1 - \exp\left(-\frac{.693x}{u\;t\;\frac{1}{2}}\right)\right] \tag{18}$$

where

Q_a = the effective source strength for the secondary pollutant

mcf = the ratio of the mass of a molecule of the secondary pollutant to the mass of its precursor

$t_{1/2}$ = the conversion half-life.

For nitrogen dioxide we have assumed that the half-life is about 30 minutes, but that only 85 percent of the nitric oxide converts. The amount which converts probably depends upon the sun angle and cloudiness. Nearly full conversion would be expected at dawn; however, on clear days with the sun high overhead, a much lower figure, 40 or 50 percent, would probably be appropriate.

The role of nitrogen dioxide will be to dramatically reduce the visual range in blue light (4500 Å) versus green or red. Table 4 illustrates the effects which might be expressed for an observer stationed 52 kilometers (32 miles) west-northwest of a hypothetical 3000-MW powerplant with particulate emissions of about 13 tons per day. The winds are out of the east (the plume travel makes an angle of 17 degrees with the line to the observation location) with a speed of 1.8 meters per second (m/sec) and the stability is E .

A value βa of fly ash of 3.3 grams per square meter (gm/m^2) was used along with a background visual range of 160 kilometers (99 miles).

This technique gives the obscuration of distant objects by the plume; it does not necessarily give the plume visibility. The plume visibility in some instances

Table 4: Estimated Visual Ranges in Different Wavelengths of Light

Compass Bearing of Line of Sight (degrees)	Blue Light Visual Range (kilometers)	Green Light Visual Range (kilometers)	Red Light Visual Range (kilometers)
130	24	33	102
135	22	49	110
140	20	61	115
145	19	70	119
150	28	77	122
155	38	82	125
160	43	86	126
165	48	90	128
170	52	92	129
175	55	94	130
180	57	95	130
185	58	96	131
190	58	96	131
195	57	95	131
200	56	94	130
205	54	93	129
210	50	91	129
215	46	88	127

will be more directly related to Sp , the sunlight scattered in the plume toward the observer (see Equation 3). This parameter is very sensitive to sun angle. Thus when the observer is looking toward the sun, the plume may be very obvious even though the same plume seen with the sun higher overhead may be just barely distinguishable.

Recent studies[21,22] indicate that high concentrations of contaminants can occur on high terrain during stable or neutral flow. Furthermore, one of these studies suggests that high concentrations may be expected during unstable conditions. However, in both cases, Turner[23] equations, with the terrain height subtracted from the plume height, appear to overestimate the concentrations. However, if the ground reflection is not used so that ground level concentrations obey the relationship:

$$\chi = \frac{Q}{2\pi \; u\sigma y\sigma z} \exp \left[-\frac{1}{2} \frac{y^2}{\sigma y^2} - \frac{1}{2} \left(\frac{H - Ht}{\sigma z} \right) \right]^2 \qquad (19)$$

the agreement is greatly improved. In the case of the Rockwell work,[24] the measured results can be represented by the above equation. If the Turner[25] values are assumed to represent 10-minute averages, the 3-hour concentration is obtained by the relation:

$$X_{3h} = \left(\frac{3 \text{ hours}}{\frac{1}{6} \text{ hour}} \right)^{-.2} X_{10 \text{ minutes}} \qquad (20)$$

where

X_{3h} = the 3-hour average concentration

$\chi_{10\ minute}$ = the 10-minute average concentration.

In the case of the Start work[26] the concentrations may still be overestimated by 35 to 100 percent. There is physical justification for the modification suggested above. In the case of a slender obstacle, the plume separates around the object, while in other cases there is likely to be flow separation of some sort to permit plume centerline contact with the ground. In the case of the Start work, this was a fanning out of the flow. In the case of the Rockwell work,[22] there was probably a marked change in wind direction with height because the stack top data at 236 meters (774 feet) were not adequate to predict plume travel directions at an approximate height of 600 meters (1969 feet). In the case we studied there was also significant wind shear. Furthermore, the concentrations are well represented by (19) if σy and σz are determined by TVA relationships.[27] These parameters predict a much slower fall-off with distance than do the Turner relationships. Our measured values suggest the form:

$$\chi(x) \propto x^{-p} \qquad (21)$$

with $p = 0.65$. While the TVA values give $p = 0.76$, in comparison the Turner values give $p = 1.33$. Thus, for the worst case, distant transport in stable flow equations may be appropriate with the TVA dispersion parameters:

$$\sigma y = 58.96\ x^{.55} \qquad (22)$$

$$\sigma z = 28.67\ x^{.21} \qquad (23)$$

with x expressed in kilometers and σy and σz in meters. In the case we studied the wind speed was approximately 3 m/sec. With low wind speeds of 1 m/sec, the plume widths are greatly increased, as is evident in Table 3.

It is important that the input parameters used match those actually experienced. In our case we had slightly stable flow (E) with winds of 3 m/sec. In the case of the Rockwell work[28] the highest concentrations occurred with slightly stable flow and 2-m/sec winds. It is possible that somewhat higher concentrations might have been found in the Rockwell work had the stations been closer together. There was one case where very high uncertainties were associated with the expected maximum. The maximum was obtained by a computer interpolation scheme which required a minimum plume width. Unfortunately, the minimum plume width was greater than that found in aircraft studies. This might lead to underestimation of the maximum concentration.

SUMMARY AND CONCLUSIONS

Recent work indicates that relatively high concentrations of contaminants may be expected on relatively distant terrain (55 kilometers). A model has been developed to permit worst-case predictions for high terrain locations.

Visibility is expected to be significantly impacted by large powerplants in clean air areas. Obvious visible plumes are most likely to occur during low-wind-speed and stable or neutral atmospheric conditions. In the Southwest, these circumstances are more likely to occur in the morning hours and during the winter months. Under these conditions the plume may appear as a brown or gray smear across the sky.

The principal contributions to visibility reductions are expected to be fly ash, nitrogen dioxide, and nitrates. The role of sulfate is not yet clear, but it is expected to be more important at distant locations. A model has been developed for visibility calculations.

Another finding of interest is that powerplant plumes appear to include relatively elevated levels of nitrates, either particulate or gaseous. Nitrates have been identified as of potential significance for human health.

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GLOSSARY

Ascarite	a material composed of asbestos granules treated with potassium hydroxide
background	areas of the atmosphere outside the coherent plume
di-chromate paper	paper impregnated with dichromate solution
dispersion modeling	a technique used to predict the concentration of contaminants which are emitted from sources as a function of time, space, and meteorological conditions
electroconductivity principle	operation which is based on a solution's ability to conduct electricity
extinction coefficient	a measure of the ability of light to pass through gases, which permits the calculation of the light attenuation; the intensity of light, I, passing through a thickness τ of air is given by $I = I_o e^{-\alpha\tau}$ where α is the extinction coefficient and I_o is the incident light intensity
extinction coefficient per unit mass concentration	the extinction coefficient divided by the mass concentration of the light-attenuating constituent
fly ash	mineral solids emitted to the atmosphere during coal combustion
Gaussian form	a representation of dispersion in which the concentrations are normally distributed with respect to the vertical and horizontal distances from the plume centerline

hot side electrostatic precipitator — a device which uses electrical forces to collect particles at temperatures of 600 to 700°F

millibar — a measure of pressure; 1013 millibars equal a pressure of the atmosphere

neutral stability — a circumstance in which the atmosphere neither enhances nor supresses the vertical spread of pollutants

normal distribution — a statistical distribution in which the frequency is proportional to the negative exponential of a factor multiplied by the square of the variable

particulates — solid or liquid particles drifting in air

plume — a region in the atmosphere with elevated concentrations of contaminants associated with one or more sources

plume height — the height of the plume centerline; sometimes referred to as an effective stack height

plume interaction — a situation in which significant portions of an elevated plume reach ground level

plume opacity — the percentage of the light which is blocked by a plume

prescrubber — a device installed upstream of an instrument to remove certain contaminants

ring-over technique — a technique in which a soluble contaminant is washed from the center of a paper toward a heated ring; the evaporation of the fluid leaves the contaminant concentrated on a narrow ring; the darkness of the ring is a measure of the amount of material

stable atmosphere	a circumstance in which the atmosphere suppresses the vertical spread of pollutants; an inversion is an example of this circumstance
strip-chart recorder	a device which uses a pen and paper to record changes in electrical inputs
TVA	Tennessee Valley Authority
visual range	the distance at which an observer with good eyesight can just distinguish a high-contrast object
west chemistry technique	a technique which depends upon chemical reactions in the liquid state
wind shear	the variation of wind velocity with height

NOTATION

Es	sunlight reaching camera from sunlit walls
Eso	sunlight reflected from the sunlit walls toward the camera
Tb	fraction of the light transmitted through the non-plume atmosphere
S	sunlight scattered toward the observer in the non-plume atmosphere
Ed	light from the shaded portion of the canyon
Edo	skylight reflected from the canyon
Esp	sunlight from the sunlet wall reaching the camera after passing through the plume
Tp	light transmission through the plume
Sp	sunlight scattered in the plume
O	opacity
N	neutral stability
S	stable conditions
V	variable winds
St	steady winds
σy	horizontal dispersion coefficient
σz	vertical dispersion coefficient
L	distance to object along the line of sight
B_i	extinction coefficient per unit mass concentration of contaminant i
χ_i	mass concentration of contaminant i
ds	element of distance along the line of sight
$\propto$	proportional to
dy	element of crosswind distance

dx	increment of downwind distance
VR	visual range
VRB	background visual range
θ	angle between the light path and the plume travel direction
X	downward distance
xc	distance from the source to the intersection of the light path and the plume centerline
z	height
y	off-centerline distance
H	effective plume height
C	constant used in determining σy
d	exponent of distance used to calculate σy
A	constant used in determinig σz
b	exponent of distance used to calculate σz
D	equivalent off-centerline distance to the observer
Qi	source emission rate
u	wind speed
Qa	effective source strength of the secondary pollutant
$t_{1/2}$	conversion half-life
mcf	ratio of the mass of a molecule of the secondary pollutant to the mass of its precursor
x_{3h}	3-hour average concentration
$x_{10\ minutes}$	10-minute average concentration
p	exponent distance in centerline concentrations
Σ	summation
Qo	emission rate of primary contaminant

THE AUTHOR

Dr. Michael D. Williams is Research Coordinator for the John Muir Institute for Environmental Stidues, Inc., conducting analyses of the air pollution potential of various coal-fired generating station sites around the nation. In addition he reviews environmental impact statements and acts as one of the key technical representatives of national environmental groups such as the Sierra Club.

On the Lake Powell Research Project, Dr. Williams has been Senior Investigator on the Air Quality Subproject since 1972, analysing air quality data and calculating the theoretical dispersion of plumes. Beginning in June 1974 he became the Principal Investigator of the Plume Analysis Subproject in which he made field measurements of the Navajo Generating Station plume.

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