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predicted transport of  
air pollutants from the  
navajo and kaiparowits  
generating stations into  
lake powell

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ERIC G. WALTHER



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LAKE POWELL RESEARCH PROJECT BULLETIN

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PREDICTED TRANSPORT OF AIR POLLUTANTS  
FROM THE NAVAJO AND KAIPAROWITS GENERATING STATIONS  
INTO LAKE POWELL

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August 1976

## 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 Recreational 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.

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## ABSTRACT

This bulletin presents a theoretical and numerical analysis of the flow of 40 different substances in coal through combustion equipment in two large-scale thermal-electric generating stations, air pollution control devices, and tall stacks into the atmosphere. Meteorological data are then used to calculate the transport of these substances over nearby Lake Powell and their deposition into the lake and on the surrounding drainage basin. The complete systematic analysis predicts the concentrations of these substances expected in the water of the lake, assuming no partition onto sediments, and compares them with existing concentrations and the lowest concentrations detectable with current instrumentation. Calculations for this specific case indicate that only mercury may be added in concentrations sufficiently high to exceed some measured background concentrations, and possibly high enough to be worrisome. The conceptual framework of this analysis includes deposition, the important and often neglected process that connects airborne dispersion with effects at the earth's surface.



# PREDICTED TRANSPORT OF AIR POLLUTANTS FROM THE NAVAJO AND KAIPAROWITS GENERATING STATIONS INTO LAKE POWELL

## INTRODUCTION

Lake Powell was created from the Colorado River by the Glen Canyon Dam near the Arizona-Utah border. The lake, filled during the 1960s, has led to changes in recreation, downstream river water quality, and regional development. Besides making possible the production of hydroelectric power, the storage of river water in the lake has allowed the construction of the coal-fired thermal-electric Navajo Generating Station just east of Page, Arizona. Fifty-eight kilometers (36 miles) across the lake to the northwest of the Navajo Generating Station is Four Mile Bench, the formerly proposed site of the 3000-MW Kaiparowits Generating Station. Although the Kaiparowits Project was cancelled on April 14, 1976, it is nevertheless possible that another coal-fired plant of similar size might be constructed near this site in the future. Therefore, these calculations are presented for the two powerplants, both separately and together.

The Navajo Generating Station is already emitting air pollutants that are dispersed in the atmosphere and deposited on the earth's surface, including Lake Powell. The purpose of this bulletin is to present a theory and calculations for the expected addition of these pollutants to the lake from the combination of both powerplants. Complexities such as resuspension and redeposition are not considered, nor are the details of the natural sources for the substances added to Lake Powell.

## THEORY

As are all sources of air pollution, the initial emissions from coal-fired plants are dispersed into the atmosphere, carried downwind, and returned at least in part to the earth's surface by various deposition processes. In certain cases, some of the effluent may diffuse upwards into the stratosphere where it can reside for years. Otherwise, the initial emissions usually return to the earth's surface in times varying from minutes to weeks. The chemistry of the initial compounds may change through chemical reactions during transport, but the original atoms will still be deposited on the earth's surface, even if they are incorporated into new compounds. Unfortunately, the uncertainty in this atmospheric chemistry during transport is very large at present and cannot be resolved in this bulletin.

The initial emissions from coal-fired thermal-electric generating stations and many other types of sources comprise numerous elements and compounds, in gaseous, liquid, and solid phases. We will let  $Q_{oij}$  be the mass of substance  $j$  emitted per unit time from source  $i$ .

The transport of these substances to any target area depends on the frequency at which the wind blows from each source towards the target area. This frequency distribution  $f_i$  depends on the elevation of the emissions  $H_{e_i}$  after plume rise  $\Delta h_i$  has been added to the stack height  $H_{s_i}$ ;  $H_{e_i} = H_{s_i} + \Delta h_i$ . For a specified target area, the choice of the source  $i$  determines the direction between the target and the source.

The rise of a plume depends on wind speed, the distance downwind of the stack, the exit velocity and temperature of the stack effluent, the ambient air temperature around the plume, the stability of the atmosphere, and the inside radius of the

stack. Assumptions for the atmospheric stability and the distance from the stack are needed in order to choose a formula for calculating plume rise.

As a long-term average for the purpose of calculating deposition, the atmosphere is considered to have neutral stability (Bureau of Land Management, 1976), meaning that a parcel of air has no tendency to rise or fall even if it is initially displaced up or down by some external force. The distance from the stacks to almost all of the local drainage basin of the lake is greater than 10 times the stack heights. These conditions allow use of the plume rise formula of Briggs (1969):

$$\Delta h = 1.6 u^{-1} (10H_s)^{2/3} [gV_s r^2 (1 - T_a/T_s)]^{1/3} \quad (1)$$

where

- $\Delta h$  = plume rise (meters),
- $V_s$  = stack effluent exit velocity (meters per second),
- $r$  = inside radius of stack (meters),
- $T_a$  = ambient air temperature at stack height (°Kelvin),
- $T_s$  = stack effluent exit temperature (°Kelvin),
- $u$  = mean wind speed at stack height (meters per second),
- $H_s$  = stack height (meters), and
- $g$  = acceleration of gravity (meters per second per second).

As the plume travels up the stack, out into the atmosphere, and downwind towards the target, various chemical reactions are occurring. These reactions are often complex, leading to intermediate products, and the reaction rates depend on temperature and humidity. The result of these reactions is that certain initially emitted substances no longer exist with the same identity by the time deposition finally returns some of the substances to the earth's surface.

For example, part of the initially emitted sulfur dioxide ( $\text{SO}_2$ ) is oxidized to sulfate ( $\text{SO}_4^{=}$ ) before deposition returns these sulfur atoms to the earth's surface. If  $Q_{oij}$  is the mass of the substance  $j$  emitted per unit time from source  $i$ , then  $\gamma Q_{oij}$  replaces  $Q_{oij}$  to represent the resulting mass of the secondary substance transported per unit time from source  $i$ . This transformation is only applied to sulfur dioxide and gaseous nitrogen oxides ( $\text{NO}_x$ ). I assume complete conversion of  $\text{SO}_2$  and  $\text{NO}_x$  to  $\text{SO}_4^{=}$  and nitrate ( $\text{NO}_3^-$ ) by the time any deposit from the initial emissions reaches the water of Lake Powell.

The next part of the transfer process is deposition from the dispersing plume to the earth's surface. My treatment of deposition includes the effect of dispersion on the plume as a function of downwind distance  $x$  from the source.

The total deposition equals the sum of the deposition over each of the  $k$  circular annuli surrounding each generating station. This relation can be expressed as:

$$D_j = \sum_i \sum_k D_{ijk} A_{ik} \quad (2)$$

where

$$\begin{aligned} D_j &= \text{the total deposition of substance } j \text{ (kg/yr),} \\ D_{ijk} &= [D_{ij}(x)] = \text{the deposition flux of substance } j \\ &\quad \text{from source } i \text{ in circular annulus } k \\ &\quad \text{(kg/km}^2\text{/yr), and} \\ A_{ik} &= \text{the area of circular annulus } k \text{ (km}^2\text{) around the} \\ &\quad \text{source } i. \end{aligned}$$

If  $Q_{ij}(x)$  is the mass of substance  $j$  from source  $i$  passing distance  $x$  per unit time, then the mass of substance  $j$  depositing between  $x$  and  $x + dx$  per unit time is:

$$Q_{ij}(x) - Q_{ij}(x + dx) = - \frac{dQ_{ij}(x)}{dx} dx \quad (3)$$

and the area receiving 99 percent of this deposit is  $2Y_{99}(x)dx$  (Figure 1). The mass depositing per unit time and per unit area is:

$$D_{ij}(x) = - \frac{1}{2Y_{99}(x)} \frac{dQ_{ij}(x)}{dx} \quad (4)$$

In order to find  $Y_{99}(x)$ , let  $z = 0$  and  $\chi_{ij}(x, Y_{99}, 0) = 0.1 \chi_{ij}(x, 0, 0)$ . Then  $Y_{99}(x) = \alpha \sigma_y$  where  $\alpha = 3.03$ .

If one believes the plume reflects from the earth's surface (Figure 2), then point  $(x, y, z)$  receives a concentration

$$\frac{Q_{oij} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2}}{2\pi \sigma_y \sigma_z u} e^{-\frac{1}{2}\left(\frac{He_i + z}{\sigma_z}\right)^2}$$

from the real source and a concentration

$$\text{SRF} \frac{Q_{oij} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2}}{2\pi \sigma_y \sigma_z u} e^{-\frac{1}{2}\left(\frac{He_i + z}{\sigma_z}\right)^2}$$

from the reflected plume,

where

- $Q_{oij}$  = the initial emission rate of substance  $j$  from source  $i$  (kg/hr),
- $y$  = the crosswind distance (meters),
- $\sigma_y$  = the standard deviation in the crosswind direction of the plume concentration distribution (meters),
- $\sigma_z$  = the standard deviation in the vertical direction of the plume concentration distribution (meters),

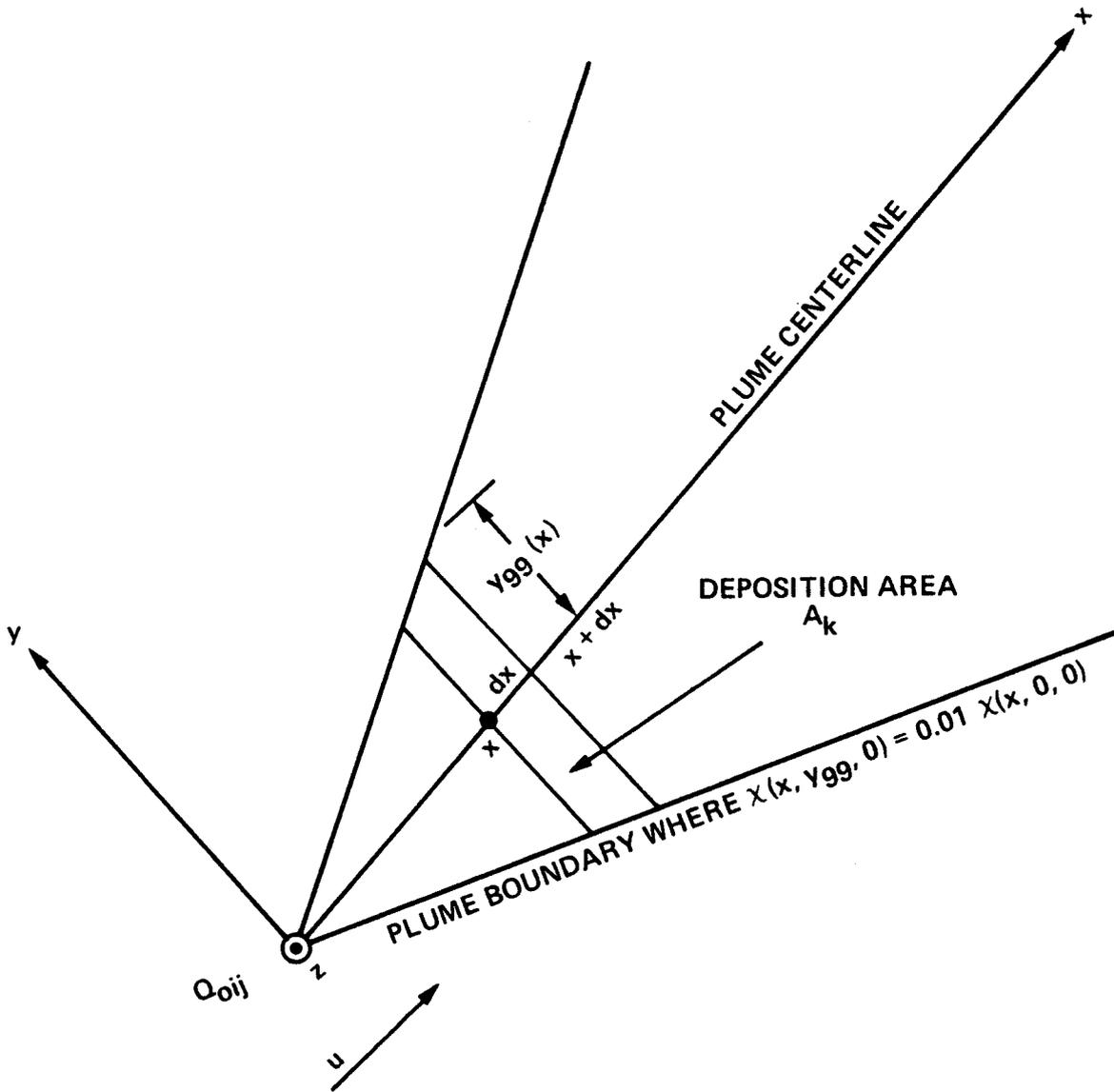


Figure 1: Geometry of the Deposition Area

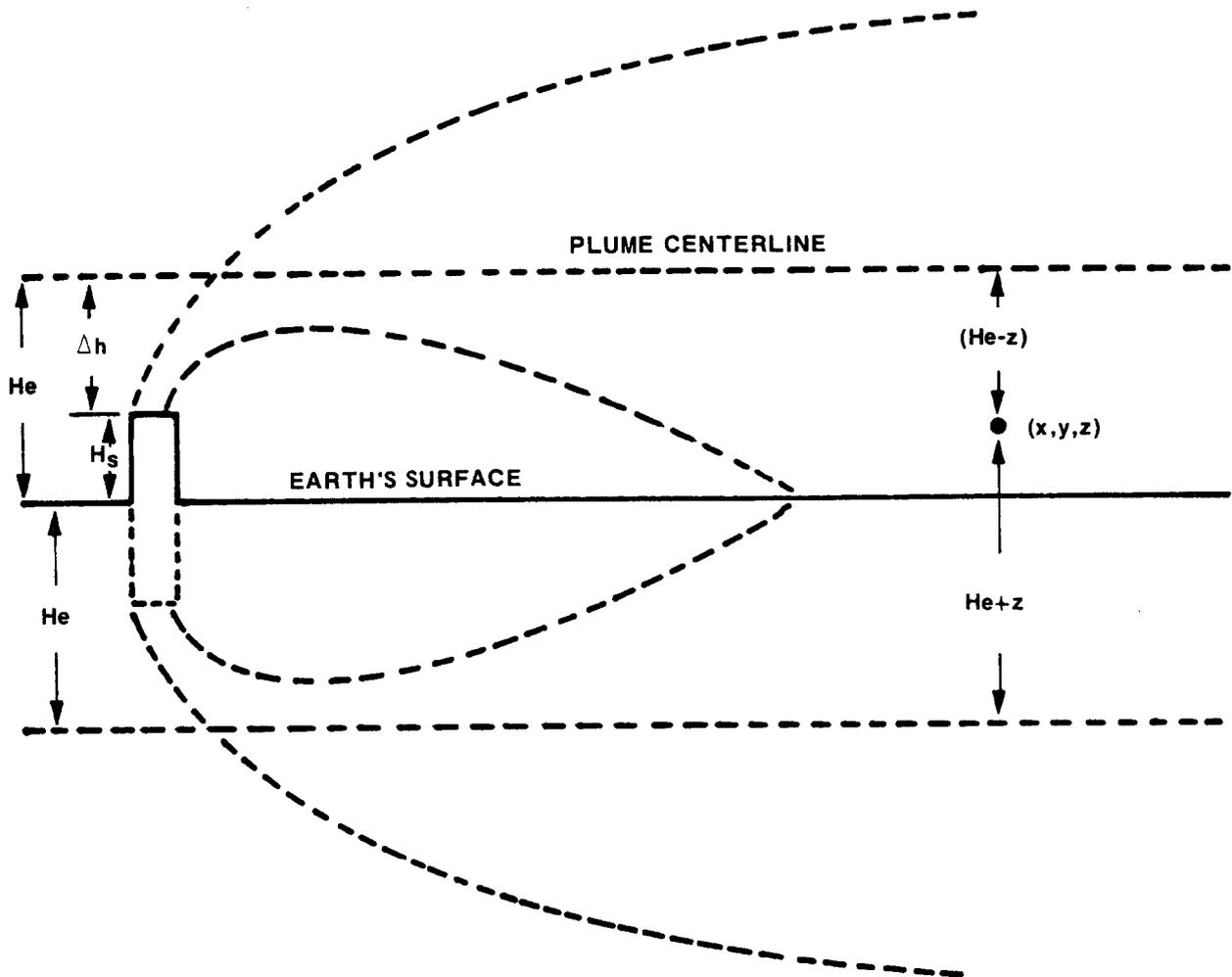


Figure 2: Geometry of the Reflection of the Plume  
from the Earth's Surface

$u$  = wind speed (meters per second),  
 $z$  = the height above ground (meters), and  
 SRF = surface reflection factor.

This second concentration is the same as a direct concentration from an imaginary source  $i$ , the mirror image of the real source. The point  $(x, y, z)$  has the same  $x$  and  $y$  for both real and imaginary sources but the vertical distance of the point from plume centerline is  $|z - H_e|$  for the real source and  $H_e + z$  for the imaginary source. In general, the airborne concentration of substance  $j$  from source  $i$  is:

$$\chi_{ij}(x, y, z) = \frac{Q_{oij}}{2\pi \sigma_y \sigma_z u} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \left[ e^{-\frac{1}{2}\left(\frac{H_e - z}{\sigma_z}\right)^2} + \text{SRF} e^{-\frac{1}{2}\left(\frac{H_e + z}{\sigma_z}\right)^2} \right] \quad (5)$$

For this theory of deposition, I assume that any amount of substance not reflecting from the earth's surface is deposited upon impact of the direct plume as it spreads out in its neutral stability cone. This assumption makes the deposition dependent on the value chosen for the surface reflection factor SRF, for which I know of no real measurements.

The mass of substance  $j$  from source  $i$  passing distance  $x$  per unit time must equal the product of the airborne concentration and the wind speed integrated over the entire  $y$ - $z$  plane at distance  $x$ . Hence,

$$Q_{ij}(x) = \int_0^{\infty} \int_{-\infty}^{\infty} u \chi_{ij}(x, y, z) dy dz \quad (6)$$

Combining equations (4), (5), and (6), we obtain

$$D_{ij}(x) = -\frac{1}{2y_{99}(x)} \frac{d}{dx} \int_0^{\infty} \int_{-\infty}^{\infty} \frac{Q_{oij}}{2\pi \sigma_y \sigma_z} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \left[ e^{-\frac{1}{2}\left(\frac{He_i - z}{\sigma_z}\right)^2} + \text{SRF} e^{-\frac{1}{2}\left(\frac{He_i + z}{\sigma_z}\right)^2} \right] dy dz$$

$$D_{ij}(x) = -\frac{Q_{oij}}{4\pi y_{99}} \left[ \frac{d}{dx} \int_0^{\infty} \frac{1}{\sigma_z} \left[ e^{-\frac{1}{2}\left(\frac{He_i - z}{\sigma_z}\right)^2} + \text{SRF} e^{-\frac{1}{2}\left(\frac{He_i + z}{\sigma_z}\right)^2} \right] dz \int_{-\infty}^{\infty} \frac{1}{\sigma_y} e^{-\frac{1}{2}\frac{y^2}{\sigma_y^2}} dy \right]$$

$$D_{ij}(x) = -\frac{Q_{oij} \sqrt{2\pi}}{4\pi y_{99}} \frac{d}{dx} \int_0^{\infty} \frac{1}{\sigma_z} \left[ e^{-\frac{1}{2}\left(\frac{He_i - z}{\sigma_z}\right)^2} + \text{SRF} e^{-\frac{1}{2}\left(\frac{He_i + z}{\sigma_z}\right)^2} \right] dz$$

$$D_{ij}(x) = -\frac{Q_{oij}(1-\text{SRF})}{4y_{99}} \frac{d}{dx} \operatorname{erf}\left(\frac{He_i}{\sqrt{2} \sigma_z}\right)$$

$$D_{ij}(x) = +\frac{Q_{oij}(1-\text{SRF})bHe_i}{2^{3/2} y_{99} \sqrt{\pi} \sigma_z x} e^{-\frac{1}{2}\left(\frac{He_i}{\sigma_z}\right)^2}$$

$$D_{ij}(x) = \frac{Q_{oij}(1-SRF)bHe_i}{\beta \sigma_y \sigma_z x} e^{-\frac{1}{2}\left(\frac{He_i}{\sigma_z}\right)^2} \quad (12)$$

where  $\beta = \text{constant} = 15.2$ .

Accounting for the frequency  $f_i$  at which the plume travels from source  $i$  towards the area of deposition, and inserting the subscript  $k$  for the  $x$  dependence,

$$D_{ijk} = \frac{f_i}{2} \frac{Q_{oij}(1-SRF)bHe_i}{\beta \sigma_{yk} \sigma_{zk} x_{ik}} e^{-\frac{1}{2}\left(\frac{He_i}{\sigma_{zk}}\right)^2} \quad (13)$$

The value 2 in the denominator is used because significant deposition only occurs under one of the two dominant atmospheric stability classes around Lake Powell which occurs half the time (Bureau of Land Management, 1976). This is neutral stability. The other dominant class is slightly stable, under which there is no significant deposition.

Therefore, the overall deposition of substance  $j$  is

$$D_j = \sum_i \sum_k (1-SRF) \frac{f_i bHe_i Q_{oij} A_{ik}}{2 \beta \sigma_{yk} \sigma_{zk} x_{ik}} e^{-\frac{1}{2}\left(\frac{He_i}{\sigma_{zk}}\right)^2} \quad (14)$$

Now let us examine the effect of this deposition on the concentration of substance  $j$  in Lake Powell.

Let  $C_{Tj}$  = total concentration of substance  $j$  in Lake Powell.  
 $C_{Tj} = C_{Bj} + C_{pj}$ , where  $C_{Bj}$  = background concentration and  $C_{pj}$  = concentration added by powerplants.

$C_{Pj} = C_{Kj} + C_{Nj}$  , where  $C_{Kj}$  = concentration added by Kaiparowits and  $C_{Nj}$  = concentration added by Navajo.

Any concentration  $C_{Tj} = M_{Tj}/M_W$  where  $M_{Tj}$  = mass of substance  $j$  in lake and  $M_W$  = mass of water in lake.  $M_W$  is assumed constant even though the actual water is continually being changed.

$M_{Tj} = M_{Bj} + M_{Pj}$  , where  $M_{Bj}$  = mass of substance  $j$  in the lake from natural sources and  $M_{Pj}$  = mass added by powerplants. Therefore,

$$C_{Tj} = \frac{M_{Bj}}{M_W} + \frac{M_{Pj}}{M_W} , \quad C_{Bj} = \frac{M_{Bj}}{M_W} , \quad \text{and} \quad C_{Pj} = \frac{M_{Pj}}{M_W} .$$

$M_{Pj} = D_j \Delta t$  where  $\Delta t$  is some time interval. During this time interval  $\Delta t$  ,  $M_{Pj} = D_j \Delta t$  is added to the lake by the powerplants;  $M_{Bj} = C_{Bj} F_W \Delta t$  is added by the input rivers; and  $M_{Tj} = C_{Tj} F_W \Delta t$  is removed from the lake at Glen Canyon Dam.  $F_W$  is the average river flow rate.

Continuity requires mass in equal mass out or

$$D_j \Delta t + C_{Bj} F_W \Delta t = C_{Tj} F_W \Delta t . \quad C_{Tj} = C_{Bj} + \frac{D_j}{F_W} .$$

Therefore,  $C_{Pj} = \frac{D_j}{F_W}$  and

$$C_{Pj} = \frac{(1-SRF)b}{2\beta F_W} \sum_i \sum_k \frac{f_i \text{He}_i Q_{oij} A_{ik}}{\sigma_{yk} \sigma_{zk} x_{ik}} e^{-\frac{1}{2} \left( \frac{\text{He}_i}{\sigma_{zk}} \right)^2} \quad (15)$$

## DATA

Emission Rates

The expected emission rates of the 40 substances are listed in Table 1 for the proposed 3000-MW Kaiparowits Generating Station and in Table 2 for the Navajo Generating Station.

The emission rates listed in Tables 1 and 2 are based on certain assumptions of load factor and the efficiency of air pollution control devices. The load factor is the average proportion of a powerplant's full capacity. Ideally, the plant would work at full load all the time until it is retired. In reality, the plant operates sometimes at full load, sometimes at partial load, and sometimes not at all. The predicted average load factor of 75 percent is based on experience (Bureau of Land Management, 1976). It will be used in these calculations because the goal here is to predict the deposition in Lake Powell over time periods of years.

I assume that electrostatic precipitators at the Navajo Generating Station release 1.0 percent (Bureau of Reclamation, 1971) of the possibly emitted fly ash over the long term and that the electrostatic precipitators at the Kaiparowits Generating Station will release only 0.5 percent (Bureau of Land Management, 1976). For the Navajo Generating Station there is no control equipment to remove  $\text{NO}_2$  or  $\text{SO}_2$  because it was not required to meet emission standards.

I assume 10 percent of the  $\text{SO}_2$  (Bureau of Land Management, 1976) and 67 percent of the  $\text{NO}_2$  (Arizona Public Service et al., 1973) will escape from the Kaiparowits Generating Station.

Several studies (Gladney, 1974; Klein et al., 1975; Radian Corporation, 1975ab; Kalb, 1975; Billings et al., 1973) provide

Table 1: Emissions from the Kaiparowits Generating Station<sup>a</sup>

Formula	Substance	Concentration in Coal (ppm)	Concentration in Ash (ppm)	Escape Fraction	Emission Rate (kg/hr)	Deposition Rate in Lake Powell Drainage Basin (kg/yr)
SO <sub>2</sub>	Sulfur dioxide	0.52% S	-	0.1	486	5.8x10 <sup>5</sup>
NO <sub>2</sub>	Nitrogen dioxide	-	-	0.67	940	1.2x10 <sup>6</sup>
SiO <sub>2</sub>	Silica	-	55.44%	0.005	180	2.2x10 <sup>5</sup>
Al <sub>2</sub> O <sub>3</sub>	Alumina	-	17.81%	(2-22)x10 <sup>-3</sup>	57.7	7.1x10 <sup>4</sup>
F	Fluorine	54	-	0.076	3.8	4700
CaO	Calcium Oxide	-	9.13%	(1.6-22)x10 <sup>-3</sup>	29.6	3.8x10 <sup>4</sup>
Fe	Iron	-	4.97%	(3.8-27)x10 <sup>-3</sup>	16.1	2.0x10 <sup>4</sup>
Mn	Manganese	6	-	(4.0-34)x10 <sup>-3</sup>	(2.2-19)x10 <sup>-2</sup>	28
MgO	Magnesia	-	2.04%	(8-26)x10 <sup>-3</sup>	6.6	8.2x10 <sup>3</sup>
Na	Sodium	-	1.50%	(3.9-23)x10 <sup>-3</sup>	4.9	6.0x10 <sup>3</sup>
U	Uranium	0.66	-	0.015	9.3x10 <sup>-3</sup>	11
Ti	Titanium	-	3000- 0.94%	(5.4-22)x10 <sup>-3</sup>	0.97-3.0	(1.2-3.7)x10 <sup>3</sup>
Cr	Chromium	3.6	-	(1.2-12)x10 <sup>-3</sup>	(4.0-40)x10 <sup>-3</sup>	5-49
Zn	Zinc	-	64	(2.6-7.2)x10 <sup>-2</sup>	2.1x10 <sup>-2</sup>	26
K <sub>2</sub> O <sub>3</sub>	Potassium Oxide	-	0.6%	(4-20)x10 <sup>-2</sup>	1.9	2.4x10 <sup>3</sup>

Table 1 (Continued)

Formula	Substance	Concentration in Coal (ppm)	Concentration in Ash (ppm)	Escape Fraction	Emission Rate (kg/hr)	Deposition Rate in Lake Powell Drainage Basin (kg/yr)
Pb	Lead	-	38	$(2.8-7.7) \times 10^{-2}$	$1.2 \times 10^{-2}$	14.5
As	Arsenic	0.83	-	$5 \times 10^{-4}$ -0.15	$3.9 \times 10^{-4}$ -0.12	0.48-147
Ni	Nickel	5	-	0.033-0.18	0.15-0.84	182-1040
P <sub>2</sub> O <sub>5</sub>	Phosphorus pentoxide	-	0.27%	0.5	0.87	1100
Se	Selenium	2-12.5	-	0.12-0.20	0.22-3.3	272-4050
Co	Cobalt	-	12	$(4.7-32) \times 10^{-3}$	$3.9 \times 10^{-3}$	4.8
Mo	Molybdenum	-	6	0.094	$1.9 \times 10^{-3}$	2.3
Cd	Cadmium	0.87-1.9	-	0.029	$(2.4-5.2) \times 10^{-2}$	29-65
Hg	Mercury	0.04-0.16	-	0.39-0.98	$2.5 \times 10^{-2}$ -0.15	19-188
Be	Beryllium	0.48-0.75	-	$5 \times 10^{-3}$	$(2.2-3.5) \times 10^{-3}$	2.7-4.4
V	Vanadium	8-10	-	$(9.5-24) \times 10^{-3}$	$7.1 \times 10^{-2}$ -0.22	87-275
Sb	Antimony	0.13	-	$(3.9-27) \times 10^{-2}$	$4.7 \times 10^{-3}$ - $3.3 \times 10^{-2}$	5.7-40
Ba	Barium	-	0.23%	$(9-260) \times 10^{-4}$	0.75	926
B	Boron	-	0.14%	0.005	0.45	559
Cu	Copper	-	80	$8 \times 10^{-3}$	$2.6 \times 10^{-2}$	32

Table 1 (Continued)

Formula	Substance	Concentration in Coal (ppm)	Concentration in Ash (ppm)	Escape Fraction	Emission Rate (kg/hr)	Deposition Rate in Lake Powell Drainage Basin (kg/yr)
Ga	Gallium	-	26	$2.5 \times 10^{-2}$	$8.4 \times 10^{-3}$	10
Li	Lithium	-	72	$5 \times 10^{-3}$	$2.3 \times 10^{-2}$	28
Sr	Strontium	-	560	$2.8 \times 10^{-2}$	0.18	216
Sc	Scandium	-	14	$(3.1-27) \times 10^{-3}$	$4.5 \times 10^{-3}$	5.6
Te	Tellurium	0.02	-	$5 \times 10^{-3}$	$10^{-4}$	0.12
Tl	Thallium	-	0.3	$(3.2-210) \times 10^{-3}$	$10^{-4}$	0.12
Y	Yttrium	-	44	$5 \times 10^{-3}$	$1.4 \times 10^{-2}$	17
Yb	Ytterbium	-	4	$1.6 \times 10^{-3}$	$1.3 \times 10^{-3}$	1.6
Zr	Zirconium	-	150	$2.2 \times 10^{-2}$	$4.9 \times 10^{-2}$	62

<sup>a</sup> Source: BLM (1976), APS et al (1973), USGS (1972), Bureau of Reclamation (1971) Klein et al (1975), Radian Corporation (1975a), Billings et al (1973), EPA (1972), Kalb (1975), Gladney (1974).

Table 2: Emissions from the Navajo Generating Station<sup>a</sup>

Formula	Substance	Concentration in Coal (ppm)	Escape Fraction	Emission Rate (kg/yr)	Deposition Rate in Lake Powell Drainage Basin (kg/yr)
SO <sub>2</sub>	Sulfur dioxide	0.5% S	0.88	6.807x10 <sup>3</sup>	2.2x10 <sup>6</sup>
NO <sub>2</sub>	Nitrogen dioxide	-	1	3.687x10 <sup>3</sup>	1.2x10 <sup>6</sup>
SiO <sub>2</sub>	Silica	2.8%	0.01	184-212	(6.1-7.0)x10 <sup>4</sup>
Al <sub>2</sub> O <sub>3</sub>	Alumina	-	(2.0-22)x10 <sup>-3</sup>	38-87	(1.3-2.9)x10 <sup>4</sup>
F	Fluorine	90	0.076	4.5	1.5x10 <sup>3</sup>
CaO	Calcium oxide	-	(1.6-22)x10 <sup>-3</sup>	30	9.8x10 <sup>3</sup>
Fe	Iron	3000-17000	(3.8-27)x10 <sup>-3</sup>	7.5-300	(2.5-98)x10 <sup>3</sup>
Mn	Manganese	13.5	(4.0-34)x10 <sup>-3</sup>	0.035-0.30	12-92
MgO	Magnesia	-	(8-26)x10 <sup>-3</sup>	6.6-7.7	(2.3-2.6)x10 <sup>3</sup>
Na	Sodium	1585-5000	(3.9-23)x10 <sup>-3</sup>	4.1-75	(1.3-25)x10 <sup>3</sup>
U	Uranium	0.1-7.6	0.015	9.8x10 <sup>-4</sup> -7.5x10 <sup>-2</sup>	3.2-25

Table 2 (Continued)

Formula	Substance	Concentration in Coal (ppm)	Escape Fraction	Emission Rate (kg/hr)	Deposition Rate in Lake Powell Drainage Basin (kg/yr)
Ti	Titanium	270	$(5.4-22) \times 10^{-3}$	1.0-3.9	320-1220
Cr	Chromium	5.4	$(1.2-12) \times 10^{-2}$	0.043-0.43	14-145
Zn	Zinc	4.9-15.1	$(2.6-7.2) \times 10^{-2}$	0.084-0.71	27-240
K <sub>2</sub> O <sub>3</sub>	Potassium Oxide	-	$(4.0-20) \times 10^{-2}$	2.2-2.6	720-850
Pb	Lead	3.6	$(2.8-7.7) \times 10^{-2}$	0.066-0.18	22-59
As	Arsenic	0.2-0.53	$5 \times 10^{-4} - 0.15$	$6.6 \times 10^{-5} - 0.052$	0.02-17
Ni	Nickel	0.2-10.5	0.033-0.18	$4.3 \times 10^{-3} - 1.2$	1.4-410
Cu	Copper	10.0-24.9	$8 \times 10^{-3}$	0.053-0.131	18-43
P <sub>2</sub> O <sub>5</sub>	Phosphorus pentoxide	-	0.5	50-55	$(1.6-1.7) \times 10^4$
Se	Selenium	1.6	0.12-0.28	0.13-0.29	39-90
Co	Cobalt	0.2-20.3	$(4.7-32) \times 10^{-3}$	$6.2 \times 10^{-4} - 0.43$	0.20-140

Table 2 (Continued)

Formula	Substance	Concentration in Coal (ppm)	Escape Fraction	Emission Rate (kg/hr)	Deposition Rate in Lake Powell Drainage Basin (kg/yr)
Mo	Molybdenum	0.63	0.094	0.039	12
Cd	Cadmium	0.014-0.090	0.029	$(2.7-17) \times 10^{-4}$	0.093-0.56
Hg	Mercury	0.025	0.39-0.98	$6.4 \times 10^{-3}$ - $1.6 \times 10^{-2}$	2.1-5.2
La	Lanthanum	5-13	$(3.6-19) \times 10^{-3}$	0.012-0.16	3.6-49
Cs	Cesium	6-147	$6.2 \times 10^{-3}$	0.024-0.60	7.3-180
Sm	Samarium	0.2-1.6	$(2.0-20) \times 10^{-3}$	$2.6 \times 10^{-4}$ -0.021	0.08-6.5
Th	Thorium	1-1.1	$(3.2-210) \times 10^{-3}$	$2.1 \times 10^{-3}$ -0.15	0.65-45
Sc	Scandium	1.8-5.2	$(3.1-27) \times 10^{-3}$	$3.7 \times 10^{-3}$ -0.092	1.1-28
Ba	Barium	450-500	$(9-260) \times 10^{-4}$	0.27-8.5	80-2500
Hf	Hafnium	2-31	$(3.4-17) \times 10^{-3}$	$4.5 \times 10^{-3}$ -0.35	1.3-100

a Sources: EPA (1972), Kresan and Long (1974), Klein et al (1975), Radian Corporation (1975), Billings et al (1973), Kalb (1975), Gladney (1974), Bureau of Reclamation (1971), Pfister (1976).

escape fractions for substances emitted from other coal-fired generating stations equipped with similarly efficient electrostatic precipitators. The resulting escape fractions are listed in Tables 1 and 2. It should be noted that these studies included extensive analytical measurements and they attempted to obtain complete mass balances. Therefore, the resulting ranges of escape fractions in Tables 1 and 2 are much more credible than mere guesses. Also, the ranges give a measure of the error and lack of data in this subject. Unfortunately, the other studies did not treat every substance listed here, including silicon, phosphorus, beryllium, boron, lithium, tellurium, and yttrium. These elements are assigned escape fractions equal to one minus the collection efficiency of the electrostatic precipitators. Phosphorus is assigned an escape fraction of 0.5 following Williams and Walther (1975).

The Navajo Generating Station consumes about  $6.6 \times 10^5$  kilograms of coal per hour at 75-percent load (Environmental Protection Agency, 1972). The proposed Kaiparowits Generating Station would have consumed  $9.35 \times 10^5$  kilograms of coal per hour at 75-percent load and would have produced  $6.48 \times 10^4$  kilograms of ash per hour (Bureau of Land Management, 1976). Of this amount,  $3.24 \times 10^2$  kilograms of ash per hour will escape from the stacks.

Although no data on concentrations in coal of some of the substances listed in Table 1 were available, concentrations of these components in the ash are reported in the literature.

#### Transport Direction

Meteorological data allow us to determine the directions the air pollutants travel away from the stacks of these powerplants. We wish to know how much of the time these pollutants travel over the local drainage basin of Lake Powell, because they may enter it either directly or indirectly. The direct entry is by

deposition from the plumes onto the water surface. Sufficiently heavy particles will settle on the surface under the influence of gravity, but the theory developed here ignores gravitational settling of large particles. Small particles and gases will diffuse to the surface either by molecular motions or larger scale turbulent eddies. The indirect entry consists first of deposition on the ground within the local drainage basin, followed by runoff into the lake through rainstorms or snowmelt. The surface area of the lake (Anderson and Perkins, 1973) is about 4 to 5 percent of the local drainage basin area assumed here (Figure 3). Direct deposition thus should be about the same percentage of total deposition assumed to reach the lake both directly and indirectly.

The proportion of the time the wind blows in the directions shown in Figure 3 depends on the elevation of the plume above ground.

#### Plume Rise

The numerical values for the plume-rise parameters and the resulting plume rises and effective stack heights are listed in Table 3 for both powerplants. These results indicate that for purposes of calculation, the 1515-meter-level (5000-foot) winds for the Navajo and Kaiparowits plumes should be used.

#### Frequency of Transport Towards the Lake Powell Drainage Basin

The calculated plume rises and the transport directions deduced from meteorological data indicate that the Navajo plume will cross over the Lake Powell drainage basin 60 percent of the time and the Kaiparowits plume will cross it 54 percent of the time. The wind data used in these calculations were measured by Dames & Moore (1974) near the Navajo Generating Station, but the distance (58 kilometers) between the two powerplant sites is small enough

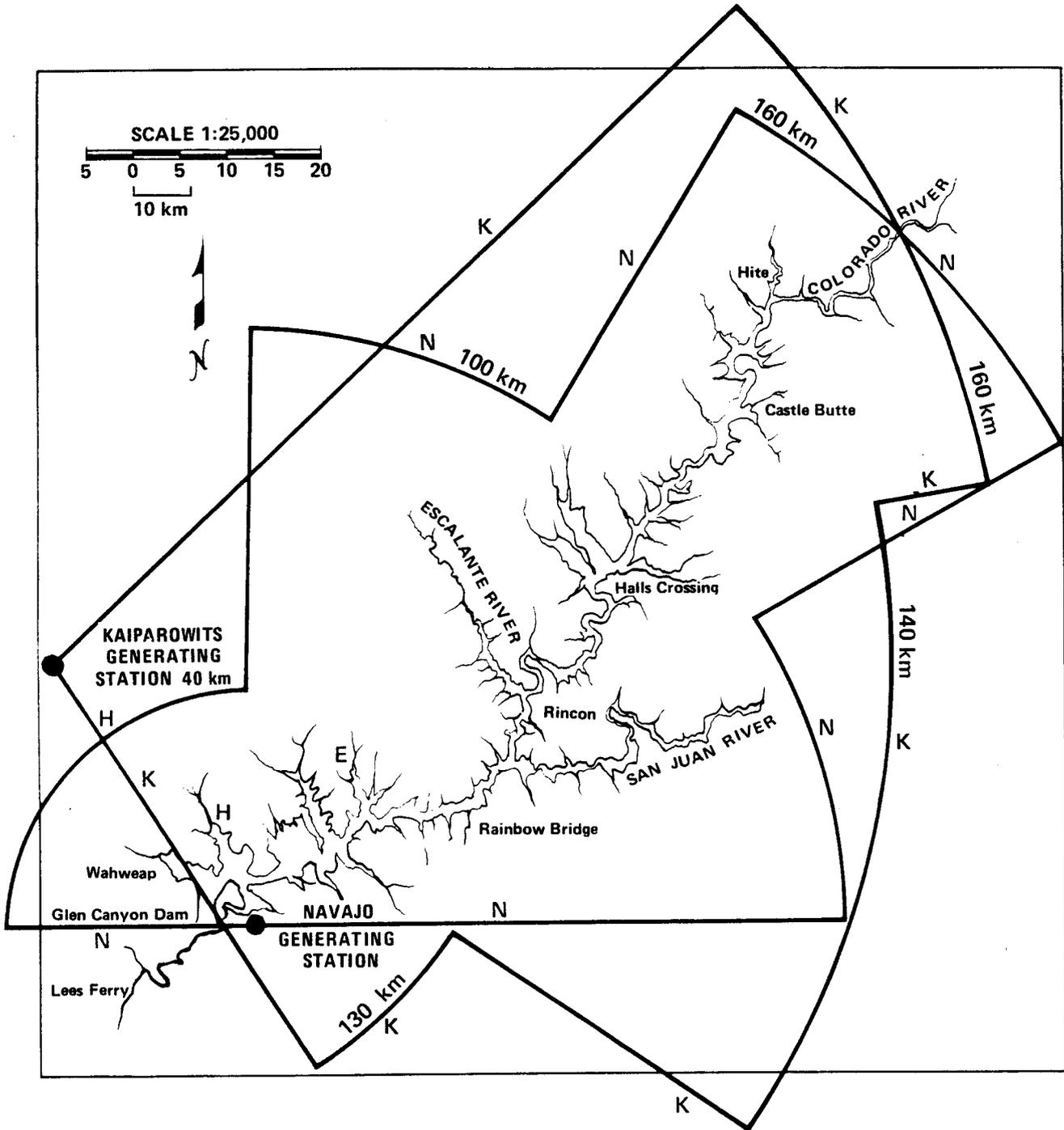


Figure 3: The Deposition Areas in the Lake Powell Drainage Basin Assumed for the Calculation of Deposition from the Kaiparowits and Navajo Generating Stations (N = Navajo Generating Station; K = Kaiparowits Generating Station)

Table 3: Plume Rise and Its Parameters

<u>Ambient</u>	<u>Navajo<sup>a</sup></u>	<u>Kaiparowits<sup>b</sup></u>
Mean wind speed at stack height, u(m/s)	2.63	3.42
Ambient air temperature at stack height, T <sub>a</sub> (°K)	289	284
<u>Stack</u>		
Height, H <sub>S</sub> (m)	236	183
Inside radius, r(m)	3.8	4.1
Effluent exit temperature, T <sub>S</sub> (°K)	412	355
Effluent exit velocity, V <sub>S</sub> (m/s)	30.2	21.3
<u>Other</u>		
Gravitational constant, g(m/s <sup>2</sup> )	9.8	9.8
Plume rise, Δh(m)	1170	622
Effective stack Height, H <sub>e</sub> = H <sub>S</sub> + Δh, (m)	1406 (~4613 ft.)	805 (~2640 ft.)
Plume height above Navajo Generating Station to nearest thousand feet	5000	5000

<sup>a</sup>Sources: Williams and Walther (1975), Dames & Moore (1974)

<sup>b</sup>Sources: Bureau of Land Management (1976), Dames & Moore (1974)

to use wind data at 1515-meter (5000-foot) levels for both locations with no significant error. Although it would be best to have continuous upper wind data, the only available data were based on two pilot balloon releases per day, one in the morning and the other in the afternoon. The amount of any substance moving towards the Lake Powell drainage basin from the Navajo Generating Station is 60 percent of the emission rates listed in the fifth column of Table 2. The analogous value for Kaiparowits is 54 percent of the sixth column in Table 1. Now we need to know the amounts of these substances that are deposited within the drainage basin defined in Figure 3.

#### Deposition from the Plumes onto the Lake Powell Drainage Basin

The deposition equation depends on the stability of the atmosphere, which is neutral half of the time and slightly stable the other half of the time (Bureau of Land Management, 1976). For lack of any field data on surface reflection, I assume SRF = 0.1, following Williams and Walther (1975).

The deposition equation must be integrated over the Lake Powell drainage basin in order to calculate the total deposition. The areas used for the two powerplants are shown in Figure 3. They are geometric simplifications of the approximate drainage area around Lake Powell, chosen to provide reasonable ease in calculating the areas of several circular annuli. Trial calculations of the annual deposition in successively smaller subdivisions of these areas have shown that dividing each area into four parts is sufficient to reduce the error to less than 8 percent. Also, the deposition under a slightly stable atmosphere is less than 0.05 percent of the total deposition and hence its contribution need not be calculated. The total deposition in kilograms per year for each substance into the Lake Powell drainage basin is presented in columns 7 and 6 of Tables 1 and 2, respectively.

## Resulting Concentrations in Lake Powell

I assume that the amounts of deposition listed in Tables 1 and 2 reach the lake either directly or indirectly over the time of one year. Because the area of the lake water surface is only 4 to 5 percent of the total area of the drainage basin assumed for this calculation, the indirect route dominates. Upon reaching the water of the lake, the specific chemical form of each element determines how much of it dissolves in the water, precipitates to the bottom sediment, or becomes attached to suspended sediment. This partition of the chemical substances is critical to the concentrations found in the different levels of the aquatic food chain, and thus determines whether the addition of a substance by powerplants causes a problem. Unfortunately, the partition functions for the various substances emitted by the powerplants are unknown. For the present, I assume all the depositing substances dissolve completely in the lake. If the  $1.67 \times 10^3$  kilograms per year of water flowing into the lake (Anderson, 1975) dilute the deposition of the various substances listed in columns 7 and 6 of Tables 1 and 2, respectively, then the resulting concentrations will be shown in columns 3 through 5 of Table 4. These concentrations are presented with only one significant figure if they are less than 1 ppb, because the lack of detailed knowledge of the model processes and input data allows no greater precision or accuracy.

For comparison, the present concentrations in Lake Powell of some of the substances are listed in column 6 and the lowest measurable concentrations are listed in column 7 of Table 4.

## CONCLUSIONS

Having compared the concentrations of substances that might be added by these powerplants to Lake Powell (column 5, Table 4) with the concentrations already existing in the lake (column 6),

Table 4: The Potential Additions of Various Substances to Lake Powell from the Kaiparowits and Navajo Generating Stations

Formula	Substance	C O N C E N T R A T I O N S (ppb)										Lowest*** Measurable	
		Added by Kaiparowits	Added by Navajo	Added by Both	Present in** Lake Powell								
SO <sub>2</sub>	Sulfur dioxide	54*	200*	254*	220,500*	1000*							
NO <sub>2</sub>	Nitrogen dioxide	94*	94*	190*	420*	44*							
SiO	Silica	14	3-4	17-18	--	1.2 (Si)							
Al <sub>2</sub> O <sub>3</sub>	Alumina	4	1.3-1.6	5-6	8,000	0.04 (Al)							
F	Fluorine	0.3	0.1	0.4	190	50							
CaO	Calcium Oxide	2.3	0.5-0.6	3	59,000-66,000 (Ca); 168,000	1.6 (Ca)							
Fe	Iron	1.2	0.4	1.6	25-73 (Fe); 70-194	0.09							
Mn	Manganese	1.6x10 <sup>-3</sup>	(5-50)x10 <sup>-4</sup>	2x10 <sup>-3</sup> -0.01	4-54	0.04							
MgO	Magnesia	0.5	0.1	0.6	21,000-23,000 (Mg); 60,000	0.03 (Mg)							
Na <sub>2</sub> O	Sodium Oxide	0.4	0.1	0.5	67,000-79,000 (Na); 186,000	0.016 (Na)							
U	Uranium	7x10 <sup>-4</sup>	(2-20)x10 <sup>-4</sup>	(1-3)x10 <sup>-3</sup>	--	0.1							
Ti	Titanium	0.07-0.22	8x10 <sup>-3</sup> -0.08	0.08-0.15	--	2.6 Ti							



Table 4 (Continued)

Formula	Substance	C	O	N	C	E	N	T	R	A	T	I	O	N	S	(ppb)	Lowest*** Measurable
		Added by Kaiparowits	Added by Navajo	Added by Both	Present in** Lake Powell												
Sb	Antimony	$(3-20) \times 10^{-4}$	-	$(3-20) \times 10^{-4}$	-	-	-	-	-	-	-	-	-	-	-	2	
Ba	Barium	0.06	$5 \times 10^{-3}$ -0.16	0.06-0.22	-	-	-	-	-	-	-	-	-	-	-	0.24	
B	Boron	0.03	-	0.03	-	-	-	-	-	-	-	-	-	-	-	50	
Cu	Copper	$2 \times 10^{-3}$	$(9-28) \times 10^{-4}$	$(3-5) \times 10^{-4}$	4-15	-	-	-	-	-	-	-	-	-	-	0.14	
Ga	Gallium	$6 \times 10^{-4}$	-	$6 \times 10^{-4}$	-	-	-	-	-	-	-	-	-	-	-	-	
Li	Lithium	$2 \times 10^{-3}$	-	$2 \times 10^{-3}$	-	-	-	-	-	-	-	-	-	-	-	-	
Sr	Strontium	$10^{-2}$	-	$10^{-2}$	50-60	-	-	-	-	-	-	-	-	-	-	-	
Sc	Scandium	$3 \times 10^{-4}$	$7 \times 10^{-5}$ - $2 \times 10^{-3}$	$(4-20) \times 10^{-4}$	-	-	-	-	-	-	-	-	-	-	-	-	
La	Lanthanum	-	$(2-30) \times 10^{-4}$	$(2-30) \times 10^{-4}$	-	-	-	-	-	-	-	-	-	-	-	-	
Te	Tellurium	$7 \times 10^{-6}$	-	$10^{-5}$	-	-	-	-	-	-	-	-	-	-	-	-	
Cs	Cesium	-	$4 \times 10^{-4}$ -0.01	$4 \times 10^{-4}$ -0.01	-	-	-	-	-	-	-	-	-	-	-	1.2	
Tl	Thallium	$7 \times 10^{-6}$	-	$7 \times 10^{-6}$	-	-	-	-	-	-	-	-	-	-	-	-	
Sm	Samarium	-	$4 \times 10^{-6}$ - $4 \times 10^{-4}$	$4 \times 10^{-6}$ - $4 \times 10^{-4}$	-	-	-	-	-	-	-	-	-	-	-	-	
Y	Yttrium	$10^{-3}$	-	$10^{-3}$	-	-	-	-	-	-	-	-	-	-	-	-	
Th	Thorium	-	$4 \times 10^{-5}$ - $3 \times 10^{-3}$	$4 \times 10^{-5}$ - $3 \times 10^{-3}$	-	-	-	-	-	-	-	-	-	-	-	-	
Yb	Ytterbium	$10^{-4}$	-	$10^{-4}$	-	-	-	-	-	-	-	-	-	-	-	-	

Table 4 (Continued)

Formula	Substance	C	O	N	C	E	N	T	R	A	T	I	O	N	S	(ppb)	Lowest*** Measurable
		Added by Kaiparowits			Added by Navajo				Added by Both					Present in** Lake Powell			
Hf	Hafnium	-			$8 \times 10^{-5} - 6 \times 10^{-3}$				$8 \times 10^{-5} - 6 \times 10^{-3}$					-			
Zr	Zirconium	$4 \times 10^{-3}$			-				$4 \times 10^{-3}$					-			

\* All these concentrations are for sulfate (SO<sub>4</sub>) and nitrate (NO<sub>3</sub>), not sulfur dioxide (SO<sub>2</sub>) and nitrogen dioxide (NO<sub>2</sub>).

\*\* Sources: Standiford et al. (1973), Gaud et al. (1975)

\*\*\*Sources: American Public Health Association (1965), Hwang (1972), Instrumentation Laboratory, Inc. (1975), Radian Corporation (1975ab)

I conclude that mercury is the only potentially significant powerplant addition. It will only be significant if the contributions from both powerplants are compared with the low present concentration. The values for mercury measured in Lake Powell before powerplant operation differ by a factor of three orders of magnitude.

The potential mercury addition is significant only if there is little or no partition of the depositing mercury onto suspended and bottom sediment. On the other hand, just this kind of partition could lead to more mercury being concentrated in the aquatic food chain by bottom feeders. The mercury addition to the food chain depends on its chemical form and its entry routes from the water through plankton or from the bottom sediment through bottom-feeding organisms. At least there is a possibility of resolving this mercury question because the lowest measurable concentration (column 7 in Table 4) is sufficiently low.

In many substances listed in Table 4, the lowest measurable concentration is too high to detect the concentrations potentially added by the powerplants.

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## GLOSSARY

oligotrophic	a state of bodies of water in which the concentrations of basic nutrients, specifically nitrogen and phosphorus, are very low
stability	the tendency of a system to return to its original state after being perturbed from this state; in the case of the atmosphere, stability describes the tendency of a parcel of air to return to its original position after it has been moved up or down
neutral stability	a stability class in which a parcel of air has a tendency to move further up or down after it has been moved from its original position
slight stability	a stability class in which a parcel of air has a slight tendency to return to its original position after it has been moved up or down
surface reflection	the process by which the downward moving part of a plume does not impact the earth's surface but instead mixes back up into the body of the plume

Notation

$A_{ik}$	the area of circular annulus $k$ around source $i$
$C_{Bj}$	the background concentration of substance $j$ in Lake Powell
$C_{Kj}$	the concentration of substance $j$ added to Lake Powell by the Kaiparowits Generating Station
$C_{Nj}$	the concentration of substance $j$ added to Lake Powell by the Navajo Generating Station
$C_{Pj}$	the concentration of substance $j$ added to Lake Powell by both powerplants
$C_{Tj}$	the total concentration of substance $j$ in Lake Powell
$D_{ijk}$	the deposition flux of substance $j$ from source $i$ in circular annulus $k$
$D_{ij}(x)$	the deposition flux of substance $j$ from source $i$ as a function of downwind distance $x$
$D_j$	the total deposition on the Lake Powell drainage basin of substance $j$
$f_i$	the frequency at which the wind blows from source $i$ toward the target area
$F_W$	the average flow of water into and out of Lake Powell (mass per unit time)
$g$	the acceleration of gravity
$He_i$	the effective stack height of source $i$ ; the height of the plume after it has leveled off

$H_s$	the height of the stack
$M_{Bj}$	the background mass of substance $j$ in Lake Powell
$M_{Pj}$	the mass of substance $j$ added to Lake Powell by both powerplants
$M_{Tj}$	the total mass of substance $j$ in Lake Powell
$M_w$	the mass of water in Lake Powell
$Q_{ij}$	the mass of substance $j$ emitted per unit time from source $i$
$r$	the inside radius of the stack
SRF	the surface reflection factor
$T_a$	the ambient air temperature at stack height
$T_s$	the exit temperature of the stack effluent
$u$	the mean wind speed at stack height
$V_s$	the stack effluent exit velocity
$x$	the downwind distance from a source
$y$	the crosswind distance
$y_{99}(x)$	the horizontal distance from the plume centerline within which the ground level concentration is greater than 1 percent of the ground level centerline concentration
$z$	the height above ground
$\alpha$	a coefficient
$\beta$	a constant
$\gamma$	the proportion of the mass emitted of a substance converted to a secondary substance by airborne and aquatic reaction

$\sigma_y$	the standard deviation in the crosswind direction of the plume concentration distribution
$\sigma_z$	the standard deviation in the vertical direction of the plume concentration distribution
$\chi_{ij}(x,y,z)$	the concentration of substance $j$ from source $i$ at position $(x,y,z)$
$\Delta h$	the rise of the plume above the stack
$\Delta t$	a time interval

## THE AUTHOR

Dr. Eric G. Walther is Manager of the Food Production/Climate Mission at the Charles F. Kettering Foundation in Dayton, Ohio. His main responsibility is to design and fund projects on the relationship between climatic variation and food production. On this subject of food and weather, he is preparing a review of over a hundred documents with special emphasis on crop/environment modeling. This review has been requested for publication in Agricultural Meteorology.

Dr. Walther is also a Research Associate of the John Muir Institute for Environmental Studies (located in Napa, California). In this position, he is being funded by the National Science Foundation to carry out the fifth year of the Air Quality Subproject of the Lake Powell Research Project. During the fifth year, the background air quality measurements made near Lake Powell are being prepared for publication as a future Bulletin. In addition, Dr. Walther is co-Chief Scientist with Professor Helen Ingram at the University of Arizona of an integrated report titled "The Role of Environmental Information in Natural Resource Decision-Making in the Lake Powell Region".

Dr. Walther's work in air quality also continues through his position as Visiting Research Scientist in the Atmospheric Sciences Research Center at The University at Albany (formerly the State University of New York at Albany). Currently, he is preparing a publication titled "How To Calculate the Importance of Air Pollutants and Their Sources" for presentation at the Fourth International Clean Air Congress scheduled for May 1977 in Tokyo. This work continues his involvement in air pollution research, which began with his Ph.D. research in atmospheric science and air pollution at The University of Albany and continued during his previous job as Coordinator of Environmental Studies at the Museum of Northern Arizona in Flagstaff.



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