

depth, that the conclusions derived therefrom can be defended under the questioning of knowledgeable intervenors and withstand the scrutiny of competent scientific review.

### **The Representative Electric Generating Plant (1000 MWe)**

Modern steam-electric generating plants utilize generating modules of approximately 500 to 1000 megawatt electric output (MWe) and are typically being proposed as multiple units with total capacities up to 2500 MWe. For purposes of quantification, the following analysis relates to a "typical" 1000 MWe installation. This is convenient because most of the input-output relationships scale linearly; however, in predicting environmental impact, such linear scaling is not always possible or

appropriate. The representative plant discussed here is a coal-fired unit similar to that proposed for the plant expansion at Dickerson, Maryland. Nuclear power generation is not treated in detail in this review.

Figure 2 sets forth the basic operating parameters used in the evaluation of aquatic and air impact of this representative plant. Various scrubber configurations influence the total solid waste residuals. The methods by which these various factors are considered in the detailed site evaluation are treated.

The discussion emphasizes those areas of evaluation accomplished by APL. The areas of marine biology and hydrology are principally responsibilities of the Department of Geography and Environmental Engineering and the Chesapeake Bay Institute.

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## **II. THE IMPACT OF COMBUSTION PRODUCTS\***

*The gaseous and solid products of fossil fuel combustion provide a major source of atmospheric pollution. Large fossil fueled electric generating plants are major sources of such emissions. Accurate prediction of the dispersion of pollutants and an evaluation of the efficacy of the best available technology for air pollution reduction are vital elements in impact prediction. Unfortunately, those pollutants removed from the flue gases usually appear as solid waste. Disposal to protect the land and groundwater resources is required.*

### **Air Quality**

**General Considerations**—Those products of fossil fuel combustion which are emitted from the stacks, including both gaseous and suspended particulate portions, provide a major source of environmental impact. For coal-fired plants, the emissions of greatest concern are gaseous sulfur dioxide (SO<sub>2</sub>), gaseous oxides of nitrogen (NO<sub>x</sub>), fly ash particulates, and gaseous hydrogen fluoride (HF). There has recently been increased concern with regard to the possible importance of sulfates and the submicron sized particles of the salts of various trace metals in the coal. The other principal gaseous components of flue gases, namely

carbon dioxide (CO<sub>2</sub>) and unreacted nitrogen are not ordinarily treated as pollutants.

In various concentrations, these combustion products could produce effects which vary from serious damage to the health of people, domestic animals, and plants, to less serious conditions of discomfort, odor, and soiling. The effects are highly variable from species to species, and individual to individual, and in addition, many types of plant life appear to be more sensitive to these pollutants than are animals. Work under way in other laboratories is directed toward further refinement of our knowledge in these areas; however, conclusive evidence is not easily obtained and often relies on tedious, time-consuming, and expensive epidemiological studies.

As a practical working tool for the pollution control engineer, both the Federal government

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\* In addition to the authors, Mr. J. A. Kagan and Mr. J. H. Meyer of the Power Plant Site Evaluation Staff made substantive contributions to Chapter II through the conduct of experiments, the analysis of data and the conduct of topical studies.

TABLE 1  
EMISSION STANDARDS  
NEW SOLID FUEL BURNING INSTALLATIONS

<i>Standard</i>	<i>Combustion Product</i>	<i>Physical Rate (grain/SFCD)*</i>	<i>Thermal Rate† (lb/million Btu)</i>
Federal	SO <sub>2</sub>	—	1.2
	NO <sub>2</sub>	—	0.7
State	Particulates	—	0.1
	SO <sub>2</sub>	—	‡
	NO <sub>2</sub>	—	0.5
	Particulates	0.3	—

\* Grains per standard cubic foot (0.075 lb) (dry) when burned with 50% excess air.

† Two hour average heat input.

‡ Sulfur content of fuel limited to 1% by weight.

and the various State governments have prepared "standards" against which the environmental impact of existing and proposed emitters can be assessed. These standards reflect current judgments as to the proper interpretation of the biological effect information currently available. In the studies for the State of Maryland conducted by APL, Federal Standards as set forth in the Federal Register of 23 December 1971, and Maryland Standards as set forth in Circular 10.03.38 of the Maryland State Department of Health have been used. Maryland Standards are, in many cases, significantly more stringent than the corresponding Federal Standards. Current regulatory philosophy for the control of air quality requires that both source emission standards and ambient air quality standards be met.

**Compliance with Emission Standards**—Table 1 presents current Federal and State Emission Standards for sulfur dioxide, nitrogen dioxide, and particulates. These standards consider the properties of coal combustion products and the state of the art in pollution control equipment. Direct comparison between Federal and State standards for NO<sub>2</sub> show the State standard to be slightly more stringent. There is reasonably good agreement between State and Federal emission standards with one being of greater stringency than the other in specific cases. As indicated in Fig. 2, present state of the art allows the emission standards to be met with 99% particulate removal and 1% sulfur coal (or scrubbing to an equivalent SO<sub>2</sub> level). This does not, however, ensure that the ambient air quality standards will also be met.

**Compliance with Ambient Air Quality Standards**—The prediction of the probable air quality impact in terms of the temporal and spatial distribution of gaseous pollutants in the area around the plant uses a plume dispersion model to de-

scribe plume behavior, time-variant climatological data, and a geographical distribution model to estimate annual ground level dosage rates which are then compared with applicable ambient air quality standards.

**Ambient Air Quality Standards.** The applicable Federal and Maryland State Air Quality Standards appear as Table 2. These standards state allowed levels, which may be exceeded only with a frequency which is also specified. The analysis that has been done in the Power Plant Site Evaluation Program attempts to compute these values for direct comparison to standards.

**Dispersion Modeling.** Dispersion occurs by material transport in the turbulent motion of the atmosphere. As the ground temperature rises throughout the day, the air near the ground is heated and becomes buoyant. The rising air cools at a rate approaching the dry adiabatic lapse rate and eventually achieves the same density as the surrounding air. Above this point, mixing due to surface heating is greatly diminished or totally absent, and this altitude is called the mixing height. The mixing height varies through the day; for example, the summer morning and afternoon average heights are 378 and 1844 meters respectively in the Washington-Baltimore area.<sup>4</sup> In addition, special meteorological situations may cause the ambient air near the ground to exhibit increased temperature with altitude (temperature inversion). The highly stable situation which then exists not only inhibits mixing, but traps pollution, moisture, and any other aerosols introduced, possibly producing fog, smog, and high concentrations of pollutants at ground level.

<sup>4</sup>G. C. Holzworth, *Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States*, U. S. Environmental Protection Agency, Office of Air Programs, Jan. 1972.

TABLE 2  
 AMBIENT AIR QUALITY STANDARDS

	Maryland Standards			Federal Minimum Standards		
	Standard		Times it May be Exceeded	Standard		Times it May be Exceeded
	$\mu\text{g}/\text{m}^3$	ppm		$\mu\text{g}/\text{m}^3$	ppm	
1. Sulfur Dioxide						
Annual arithmetic average	39	0.015	none	60	0.02	none
24-hour average	131	0.05	1/year	260	0.1	1/year
3-hour average				1300	0.5	1/year
1-hour average	262	0.10	1/month			
2. Nitrogen Dioxide						
Annual arithmetic average	100	0.05	none	100	0.05	none
3. Photochemical Oxidants						
1-hour average	160	0.08	1/year	160	0.08	1/year
4. Particulate Matter						
Annual average	65*		none	60†		none
24-hour average	140		1/year	150		1/year
5. Gaseous Fluoride						
72-hour average	0.4	0.0005	none			
24-hour average	2.0	0.002	none			

\* Arithmetic Average.

† Geometric Average.

A plume dispersion model (Fig. 3) has been prepared for use within regions in which such mixing occurs. Generally, it is desired to estimate the ground level concentration of pollutants downwind from the plant, directly under the plume.

The model consists of a plume rise phase and a Gaussian dispersion phase.<sup>5, 6</sup> The plume rise portion of the analytical model yields the rise of the plume centerline above the stack as a function of downwind distance, as determined by mass and heat flow rate from the stack, the plume's buoyancy (as determined from the environmental temperature lapse rate), and the wind velocity.

For those cases in which the plume height lies within the mixing layer, the ground level concentration (GLC), is given by a two-dimensional Gaussian model with  $x$  evaluated at  $z = 0$ :

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

in which  $\bar{u}$  is average wind speed (in  $x$  direction),  $Q$  is the source strength (mass flow rate of pollutant),

$\sigma_y$  and  $\sigma_z$  are the  $x$ -dependent standard deviations of the  $y$  and  $z$  dispersion, and  $H$  is plume height.

This equation, developed for conditions of turbulent homogeneity and for time-stationary situations, is also applicable in an average way for

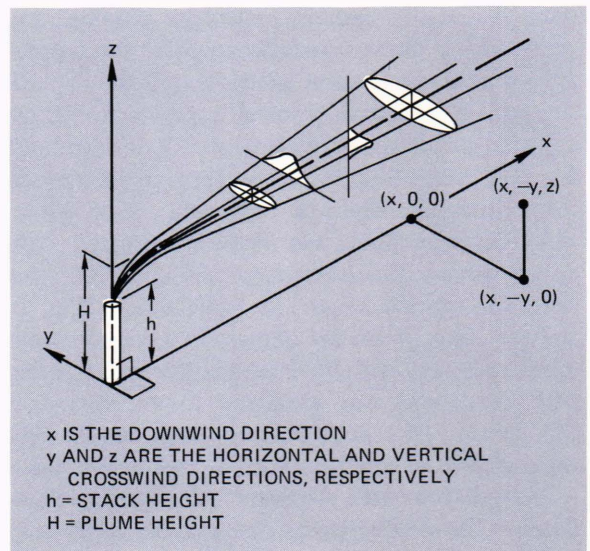


Fig. 3—Coordinate system showing Gaussian distributions in the horizontal and vertical.

<sup>5</sup> G. A. Briggs, *Plume Rise*, U. S. Atomic Energy Commission, Critical Review Series, TID 25075, Nov. 1969.

<sup>6</sup> D. B. Turner, *Workbook of Atmospheric Dispersion Estimates*, U. S. Environmental Protection Agency, Office of Air Programs, Rev. 1970.

many other conditions. The source strength,  $Q$ , can be computed from the stated characteristics of the power plant, and numerical values appropriate to a 1000 MWe plant are given in Fig. 1. The  $\sigma_y$  and  $\sigma_z$  are atmospheric parameters which depend on site specific meteorology. Published literature presents empirical  $\sigma$  values in a form directly useful for prediction. In each case, the data are categorized by atmospheric stability class, which has historically been estimated from average wind speed and radiation balance at the surface observer's site. While this stability classification system appears to be valid on the average, it is far from being accurate in specific instances.

During the conduct of the detailed site evaluation at Dickerson, Maryland, a site at which there is a currently operating power plant, data were taken to determine whether the use of a  $\sigma$  value obtained from the literature produced estimates of pollutant GLC in agreement with measured values. Agreement was poor, and as a result, the parameters of the dispersion were modified until optimum agreement was achieved. The use of experimental "on-site"  $\sigma$  values obtained in this manner is much preferable to the use of data taken from the literature. For sites without existing emitters such "on-site" data taking is generally not economically possible.

After the  $\sigma$  values have been adjusted to give best agreement with experimental GLC data, the Gaussian formula can be used to predict the expectation value of GLC for those cases in which emission is into the relatively steady air mass flow. This generally is true for emission from the stacks of coal or oil-fired generating plants. Problems still arise from local meteorological effects, e.g., terrain roughness, downwash from structures, and localized circulations, and these must be treated by other methods.

*Geographical Distribution Model.* The final step in determining the compliance with ambient air quality standards requires that a model be constructed to show the frequency of exception of allowed values at many points in the neighborhood of the plant. Such a model has been constructed using meteorological data taken at three-hour intervals by the Weather Bureau (at a nearby station) to allow a prediction of GLC (and the frequency of exceeding the standard values) at grid points located on one mile range rings and  $10^\circ$  incremental radials from the plant. These

results can be interpreted (after arithmetical and statistical correction) as the number of hours that the one-hour standard level is exceeded at each grid point per month. Twenty-four hours and annual average predictions can also be made as extensions of these calculations.

**Application to the 1000 MWe Station**—Using these models, along with the emission factors for  $\text{SO}_2$  (with 90% scrubbing), ground-level pollutant calculations have been prepared for the hypothetical 1000 MWe plant in order to illustrate the methodology used. In this case, emission factors for  $\text{SO}_2$  as presented in Fig. 2 were assumed. Meteorological and dispersion factors which apply to Dickerson were used in the dispersion model. This calculation has been done parametrically for a variety of stack height configurations and coal sulfur constants. The results give the number of times per month that various percentages of the State one-hour standard would be exceeded. Generally, the Bureau of Air Quality Control specifies that no single large emitter shall be allowed to exceed 50% of the State standard, and these results appear as Table 3. It can be seen that the use of a single 800-foot-tall stack allows this condition to be met for 2% sulfur coal, whereas the use of two 400-foot stacks requires 1% coal or better. Additional computer runs would be required to establish the sulfur level (between 2 and 3%) at which the one-hour standard would be exceeded once per month.

Our experimental data and analyses have indicated that the hourly requirement is the most stringent standard. However, an annual average isopleth set is shown as Fig. 4 to indicate that, in the neighborhood of the plant in which the larger integrated "doses" are received, the values, off-site, are considerably less than those allowed by standards.

In coal or oil-fired steam electric generating plants, the  $\text{SO}_2$  standard is the most difficult to meet of the standards given in Table 2. All others can readily be achieved by available technology even for plants significantly larger than 1000 MWe. For diesel/electric plants, the oxides of nitrogen are the more important emission.

## Solid Waste

**General Considerations**—The combustion of coal results in solid wastes which must be removed from the plant for disposal. Coal, while variable,

TABLE 3  
RESULTS OF SO<sub>2</sub> DISPERSION MODELING  
EVALUATION OF HYPOTHETICAL 1000 MWe  
FOSSIL-FUELED PLANT AT THE DICKERSON,  
MARYLAND SITE (DICKERSON METEOROLOGY)

Sulfur Content %	Hr/mo. that 50% of std. (50 ppb) is exceeded	
	Configuration 1	Configuration 2
1—800 ft stack 125°F exit temp.	2—400 ft stacks 125°F exit temp.	
1	0	0
2	0	45
3	4	132
4	12	195

Standards exceeded

1. Sulfur content allowed is about 2.5% with 800 ft stack/125°F exit temperature.
2. 90% SO<sub>2</sub> scrubbing assumed.

is typically 15% ash (all of which is recoverable as solid matter), and contains sulfur in quantities of about 0.5 to 7% by weight. If current emission and ambient air standards are to be met, most of the sulfur must be removed prior to combustion, or, alternatively, highly effective SO<sub>2</sub> removal must be performed on the combustion products. Sulfur

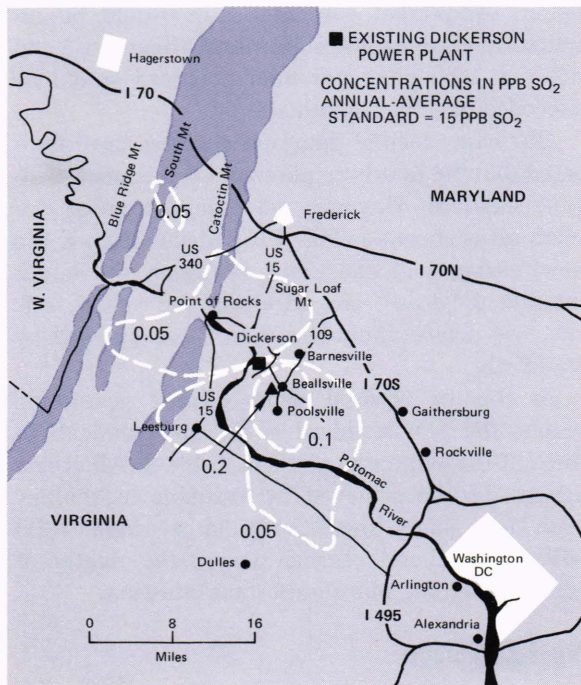


Fig. 4—Annual-average ground-level SO<sub>2</sub> concentration isopleths for hypothetical 1000 MWe fossil-fuel power plant located at Dickerson, Maryland.

removal from coal is under development and will, undoubtedly, play a significant role in future coal processing, but stack gas cleaning is currently considered to be the approach with the earliest likelihood of success.

**Particulate Removal**—Particulate removal is the most fully developed pollutant control process. It is also necessary in many industrial processes other than combustion. For combustors of the sizes used in large power plants, electrostatic precipitators are used almost exclusively. These precipitators pass the gas through a chamber in which gas-borne particles are given an electrical charge and then attracted to a surface of opposite charge. Removal efficiencies in excess of 99.7% are achieved with modern equipment.

**SO<sub>2</sub> Scrubber Waste**—Effective removal of gaseous pollutants from stack gases requires that the pollutant gas be soluble in the scrubbing liquids and enter into chemical reaction with them. A number of processes are under development which meet these criteria with respect to SO<sub>2</sub>. The systems under development are categorized as nonrecoverable processes and recoverable processes.

Nonrecoverable processes use limestone in which a nonreversible chemical process yields calcium sulfite or calcium sulfate as a nonmarketable solid waste. For such systems, the mass of scrubber by-product for disposal is comparable to that of the ash.

Recoverable processes under development permit the use of additional chemical reactions to recover elemental sulfur or sulfuric acid as useful products and the reuse of the scrubbing material. Several such systems are in pilot or prototype de-

TABLE 4  
NONRECOVERABLE LIMESTONE SCRUBBER  
INPUT/OUTPUT SOLIDS (TONS/HOUR)  
1000 MWe COAL FIRED: ELECTRIC GENERATING  
PLANT (FOR VARIOUS SULFUR CONTENTS)

Sulfur Content %	Input (Tons/Hour)		Output (Tons/Hour)	
	Coal	CaCO <sub>3</sub>	Ash	Scrubber Sludge
1	367	15.5	55	36
2	367	31	55	72
3	367	46.5	55	108
4	367	62	55	144

150% stoichiometry      12,500 Btu/lb coal  
9020 Btu/kWh heat rate      90% scrubber efficiency

velopment and are meeting with some success. Scrubbing efficiencies of 90% have been achieved. The marketing problems of the large quantities of sulfur and/or sulfuric acid are under study. Because of high and rising transportation costs, such systems are economical only if adequate local markets can be developed.

**The 1000 MWe Power Plant**—The magnitude of the solid waste problem produced by particulate and SO<sub>2</sub> (limestone scrubbing) as it relates to the reference 1000 MWe plant is shown in Table 4

which gives the input/output solids relationship as it would exist for typical sulfur contents. It is clear that even for 2% sulfur coal, provision must be made to transport and landfill a mass approaching one-third that of the coal used. This is a problem of major proportion.

Even if a recoverable scrubber system is used and useful by-products are obtained, fly ash is produced at about 55 tons/hr/1000 MWe from coal of 15% ash content. The disposal of this solid waste is in itself a major problem.

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### III. ENVIRONMENTAL IMPACT OF HEAT DISSIPATION\*

*More than two-thirds of the energy used in the generation of electricity is rejected at the site as waste heat. The use of natural water bodies in the dissipation of that heat can, in some instances, adversely affect aquatic biota. The use of other methods of heat dissipation, such as cooling towers, substantially reduces the influence on aquatic biota but can produce other undesirable effects. An objective of the site evaluation is to determine as quantitatively as possible the consequences of the use of feasible cooling systems.*

#### Background

The thermodynamic efficiency of a modern, fossil-fueled power plant is approximately 40%; that of a nuclear plant is 33%. Thus, for every kilowatt of electrical energy produced, 1.5 to 2 kilowatts of energy are rejected to the environment as heat in the generation process. Most of the waste heat is rejected from the power plant working fluid through the cooling systems. The cooling fluid receives its heat through conductive transfer at the condenser, where the low temperature vapor to liquid phase change of the working fluid assures a continuous pressure gradient across the turbines which drive the generator.

The waste heat is eventually transferred to the atmosphere through conduction, radiation, and primarily, evaporation. A variety of techniques can be used to accomplish this transfer. At present, the two most common types of heat rejection systems use water as a coolant. In the so-called "once-through" or open system, a large flow of water is withdrawn from a large body of water, it is passed once through the condenser where it undergoes a temperature rise, and then it is returned to the water body at a point physically removed from the intake. In other systems cooling is accomplished by the circulation of essentially the same mass of water which is alternately heated at the condenser and then cooled by some heat transfer device such as a cooling tower or pond. Such systems are frequently referred to as "closed" systems in spite of the fact that in most systems some water is continuously added to and removed from the circulating flow. In cooling ponds and wet cooling towers, evaporation is the primary cooling mechanism so most of the waste heat is absorbed in the latent heat of vaporization.

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Major responsibilities in the areas of hydrology resided with Dr. Donald Pritchard and Dr. Alan Elliott of the Chesapeake Bay Institute. The marine biology work was performed by a team from the Department of Geography and Environmental Engineering under the leadership of Dr. Loren Jensen.