Site Selection for Air Pollution Monitoring in the Vicinity of Point Sources

1978

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SITE SELECTION FOR AIR POLLUTION MONITORING IN THE VICINITY OF POINT SOURCES

BY

JOHN C. BROWN, JR
B.S., University of Washington, 1960
M.S., University of Michigan, 1966

RESEARCH REPORT

Submitted in partial fulfillment of the requirements for the degree of Master of Science in the Graduate Studies Program of Florida Technological University

Orlando, Florida
1978
ABSTRACT

Ever since air pollution became a national concern in the 1950's, more and more emphasis has been placed on collection of representative air samples for many purposes, to include (1) evaluation of the degree to which national ambient air quality standards are being met and (2) to monitor maximum emission levels from point sources. Until recently efforts were directed toward qualitative methods of siting monitors for representative sampling. Since the dispersion of effluents is most complex, the quality of the data collected on the basis of judgment and, more or less, incremental siting about the source, has become suspect. Furthermore, with the increasing demands for monitoring due to international growth in network monitoring systems, amendments to the Clean Air Act and the legislation on the Prevention of Significant Deterioration of Air Quality, it is not cost-effective to encircle point sources with large numbers of equally spaced monitors. This paper discusses the history of air pollution concerns that have resulted in the need for monitoring; the development of siting techniques through largely qualitative measures; and finally, summarizes three quantitative methodologies for monitoring point sources. Emphasis is placed on the methodology developed by Noll, et al., (1977), based on the author's belief that this methodology represents the state of the art.
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LIST OF SYMBOLS

\( C(X,Y,0;H) \): Concentration of pollutants at ground level at \( X \) distance downwind, \( Y \) distance crosswind and from a point source with effective height \( H \)

\( CR_s \): Coverage ratio for one station (Noll, et al., Methodology)

\( CR_T \): Total coverage ratio (Noll, et al., Methodology)

\( H \): Effective plume height

\( L \): Height of stable layer above earth's surface

\( N \): Number of occurrences of events annually in binomial distribution

\( n \): Number of observed events used with binomial distribution

\( N_s \): Number of stations required by Noll, et al., Methodology for desired coverage

\( Q \): Stack emission concentration

\( R_1 \): Radius from emission source of front side of potential monitoring area (Noll, et al., Methodology)

\( R_2 \): Radius from emission source of back side of potential monitoring area (Noll, et al., Methodology)

\( \sigma_x \): Standard deviation of plume concentration distribution in the horizontal

\( \sigma_y \): Standard deviation of plume concentration distribution in the vertical

\( u \): Mean wind affecting the plume

\( x \): Distance downwind from a point source

\( x_{10} \): Downwind distance through monitoring station where concentrations are 90% of station concentrations (Noll, et al., Methodology)

\( Y \): Distance crosswind from plume centerline
$Y_{10}$: Distance crosswind through monitoring site where concentrations are 90% of station concentrations (Noll, et al., Methodology)

$Z$: The number of standard deviations from the mean associated with a given probability in the normal distribution
INTRODUCTION

The existence of air pollution is well documented as far back as the thirteenth century. John Evelyn, an English diarist, penned in 1661 the following account of the effect of the burning of sea-coal in London: "It was one day, as I was walking in Your Majestie's Palace at White-Hall, that a presumptious smoake did so invade the court that men could hardly discern one another for the clowd, and none could support, without manifest inconveniency." (Te Brake 1975).

In the United States, the first steps to attempt to control air pollution were initiated in California in the 1940's (Brown and Cooper 1978). The first federal air pollution legislation enacted was the Air Pollution Control Act of 1955. That legislation was followed by Air Pollution Control Act Amendments of 1960, 1962, and the Clean Air Act of 1963. Other acts and amendments representing many changes and culminating with The Clean Air Act as amended in August 1977, have placed stringent controls on potential air pollution sources. The controls have been imposed by the establishment of Federal Ambient Air Quality Standards, Standards of Performance for Stationary Sources, National Emissions Standards for certain hazardous air pollutants, and Federal Automobile Exhaust Emissions Standards for passenger cars. The Clean Air Act Amendments of 1977 stipulated the requirement for increasingly stringent controls on heavy duty vehicles.
Although monitoring of all sources of air pollution is considered important, this report is primarily concerned with the siting of equipment for monitoring of point sources. Thus, the standards of concern are Federal Ambient Air Quality Standards and Standards of Performance for Stationary Sources, presented in tables 1 and 2 (CFR 40 1977).

To assess the effectiveness of standards, it is essential to have a monitoring system with the capability of measuring ambient air concentrations of pollutants and maximum ground levels from point sources. Monitoring systems may vary considerably with the purpose for which monitoring is being done. Elaborate systems such as the one deployed for the St. Louis Regional Air Pollution Study (RAPS) provides a detailed network for determining regional air pollution trends (Chapter 4). One of the primary concerns, today, is the detection of maximum concentrations about point sources with a high level of confidence that the maximum concentrations have been observed. Further, it is essential that this be done cost effectively. Thus, optimum siting and the capability for mobility of monitoring equipment are very important.

In the past monitoring sites have been selected on the basis of qualitative decisions. Recently, there has been emphasis on the siting of monitoring receptors by more quantitative methods. This paper attempts to outline the methods used in the past and to follow up with a summary of the rationale and methodology of the most recent analytical techniques of monitor siting.
<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>PRIMARY</th>
<th>SECONDARY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particulate matter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual geometric mean</td>
<td>75</td>
<td>60</td>
</tr>
<tr>
<td>Max. 24-hr concentration</td>
<td>260</td>
<td>150</td>
</tr>
<tr>
<td><strong>Sulfur Oxides</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual arith. mean</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Max. 24-hr concentration</td>
<td>365</td>
<td>260</td>
</tr>
<tr>
<td>Max. 3-hr concentration</td>
<td></td>
<td>1300</td>
</tr>
<tr>
<td><strong>Carbon monoxide</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. 8-hr concentration</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Max. 1-hr concentration</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Photochemical oxidents</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. 1-hr concentration</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td><strong>Hydrocarbons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. 3-hr (6-9am) conc</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td><strong>Nitrogen oxides</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual arith mean</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

1All measurements are expressed in micrograms/m$^3$ except for carbon monoxide, which is expressed in mg/m$^3$.

2Not to be exceeded more than once per year.
## TABLE 2
**NEW SOURCE PERFORMANCE STANDARDS, PARTIAL LISTING**

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>EMISSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel-fired steam generators (250 million BTU/hr hear input or greater)</td>
<td></td>
</tr>
<tr>
<td>Particulates</td>
<td>0.1 lb/10^6 BTU (Max. 2-hr avg)</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>0.8 lb/10^6 BTU</td>
</tr>
<tr>
<td>Oil fired.</td>
<td>1.2 lb/10^6 BTU (Max. 2-hr avg)</td>
</tr>
<tr>
<td>Coal fired.</td>
<td></td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td></td>
</tr>
<tr>
<td>Gas fired.</td>
<td>0.2 lb/10^6 BTU</td>
</tr>
<tr>
<td>Oil fired.</td>
<td>0.3 lb/10^6 BTU</td>
</tr>
<tr>
<td>Coal fired.</td>
<td>0.7 lb/10^6 BTU (Max. 2-hr avg)</td>
</tr>
<tr>
<td>Visible emissions</td>
<td>Not to exceed 20% opacity, except that for 2 min. in any 1 hr, 40% opacity applies</td>
</tr>
<tr>
<td>Incinerators</td>
<td></td>
</tr>
<tr>
<td>Particulates</td>
<td>0.08 grains/scf</td>
</tr>
<tr>
<td>Sulfuric acid plants</td>
<td></td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>4 lb/ton acid</td>
</tr>
<tr>
<td>Acid mist.</td>
<td>0.15 lb/ton acid</td>
</tr>
<tr>
<td>Visible emissions</td>
<td>Less than 10% opacity</td>
</tr>
<tr>
<td>Nitric acid plants</td>
<td></td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>3 lb/ton acid</td>
</tr>
<tr>
<td>Visible emissions</td>
<td>Less than 10% opacity</td>
</tr>
<tr>
<td>Portland cement plants</td>
<td></td>
</tr>
<tr>
<td>Particulates</td>
<td></td>
</tr>
<tr>
<td>Kilns.</td>
<td>0.3 lb/ton fired</td>
</tr>
<tr>
<td>Clinker coolers</td>
<td>0.1 lb/ton fired</td>
</tr>
<tr>
<td>Visible emissions</td>
<td></td>
</tr>
<tr>
<td>Kilns.</td>
<td>10% opacity</td>
</tr>
<tr>
<td>Others</td>
<td>Less than 10% opacity</td>
</tr>
</tbody>
</table>
I RATIONALE FOR MONITORING

A recent EPA report (Ball and Anderson 1977) lists twelve major reasons for monitoring SO$_2$. These reasons, listed below, apply to any of the air pollutants from point sources.

1. Judging attainment of SO$_2$ National Ambient Air Quality Standards (NAAQS)

2. Evaluating progress in achieving/maintaining the NAAQS or state/local standards

3. Developing or revising state implementation plans (SIPs) to attain/maintain NAAQS; evaluating control strategies

4. Reviewing new sources

5. Establishing baseline air quality levels for preventing significant deterioration (PSD) and for air quality maintenance planning (AQMP)

6. Providing data for model development and validation

7. Providing data to implement the provisions of the Energy Supply and Environmental Coordination Act (ESECA) of 1974

8. Supporting enforcement actions

9. Documenting episodes and initiating episode controls

10. Documenting population exposure and health research

11. Providing information to the public

12. Provide information for city and regional planners and air quality policy decision makers for activities related to programs such as air quality maintenance planning (AQMP), prevention of significant deterioration (PSD) and the preparation of environmental impact statements

The Clean Air Act Amendments of 1977, contained an additional provision which directed the EPA, within one year of enactment of the
Clean Air Act of 1977, to promulgate regulations establishing an air quality monitoring system throughout the United States which:

1. Utilizes uniform air quality monitoring criteria and methodology and measures such air quality according to a uniform air quality index

2. Provides for air quality monitoring stations in major urban areas and other appropriate areas throughout the United States to provide monitoring such as will supplement (but not duplicate) air quality monitoring carried out by the States required under any applicable implementation plan

3. Provides for daily analysis and reporting of air quality based upon such uniform air quality index

4. Provides for recordkeeping with respect to such monitoring data and for periodic analysis and reporting to the general public by the Administrator with respect to air quality based upon such data.

The concept of objectively siting receptors for proper monitoring is an important step toward "uniform air quality monitoring criteria and methodology" as discussed above.

Further, the 1977 Amendments to the Act generally make more stringent the Prevention of Significant Deterioration (PSD) provisions promulgated by EPA in 1974. The provisions designate three classes of areas and limit the maximum allowable increases in sulfur oxides and total suspended solids for each class as shown in table 3 (Goldsmith and Mahoney 1978 Table 1). Class I areas include all international parks, national wilderness areas and national memorial parks greater than 6000 acres in area. All other areas are designated Class II by EPA. States may redesignate areas classes I or II except the following areas greater than 10,000 acres in size: present national monuments, primitive areas, wild and scenic rivers, wildlife refuges, lakeshores and seashores, and future national parks and
wilderness areas. Obviously, the best possible accuracy in monitoring both ambient conditions and peak concentrations is essential if this provision of the law is to be judiciously enforced.

TABLE 3

PSD PERMITTED INCREMENTS\(^1\) (Micrograms/M\(^3\))

<table>
<thead>
<tr>
<th></th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>NAAQS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Primary</td>
</tr>
<tr>
<td>(\text{SO}_2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>2</td>
<td>20</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>24-hour</td>
<td>8</td>
<td>91</td>
<td>182</td>
<td>365</td>
</tr>
<tr>
<td>3-hour</td>
<td>25</td>
<td>512</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>TSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>5</td>
<td>19</td>
<td>37</td>
<td>75</td>
</tr>
<tr>
<td>24-hour</td>
<td>10</td>
<td>37</td>
<td>75</td>
<td>260</td>
</tr>
</tbody>
</table>

\(^1\)All 24-hour and 3-hour values may be exceeded once per year

\(^2\)Indicates secondary standard

In addition to the federal requirements, some states have initiated legislation which further imposes monitoring requirements. Montana, the state that contains one-third of the nation's coal, has become particularly conscious of air pollution hazards as a result of a report (Monitoring Update) which indicates a mortality rate for asthma, emphysema and bronchitis 50% higher than the national average. Montana has adopted a state equivalent of the National Environmental Policy Act (NEPA) which requires preparation of environmental impact statements before starting projects.

Beginning in August 1978, air quality monitoring will be required as part of the permit process for new sites unless the
states determine that adequate data already exist. For new facilities and modification of existing facilities one year of baseline monitoring data will be required as part of the permit application. Thus, some proposed facilities can expect a substantial lengthening of the total time required to achieve issuance of a permit. With maximum efficiency, Goldsmith and Mahoney (1978), suggest the time period for specifying the monitoring required, achieving one-year baseline monitoring, data analysis, etc., will result in two years' delays in acquiring permits.
II SIGNIFICANCE OF ATMOSPHERIC MONITORING

A report from the 4th Joint Conference on Sensing of Environmental Pollutants (Goldsmith and Mahoney 1978) indicates that the Federal Government spent $691 million in 1976 on the collection of data and statistics. Approximately 43 percent of that expenditure was made by environmental agencies. The same report expresses concern and doubt about the adequacy and interpretation of the data and states that most data today are inadequate for their intended use.

A second report (Morgan 1977) indicates that many monitoring efforts have resulted in less than adequate data, have not been cost effective, and have, in some cases, resulted in costly programs that provided questionable benefits. Science and Technology (ESAT 1977), in quoting the director of Monitoring and Data Analysis Division of the Environmental Protection Agency, reports that $49 million were spent on monitoring activities in fiscal year 1976.

According to the same report, more than 100 networks plus an additional 200-300 monitoring stations, worldwide, will be operational by 1980. During the period 1970-1975, monitoring was conducted by EPA for various pollutants at the number of locations indicated: Total Suspended Particulates, 4060; Sulfur Dioxide, 2579; Nitrogen Dioxide, 1726; Oxidants, 509; and Carbon Monoxide 443.

The Global Environmental Monitoring System (GEMS) was formed in 1974 as part of the United Nations Earthwatch Program. By 1981,
it is estimated that GEMS will have as many as 150 Monitoring Stations. Other examples such as the Western Energy Environmental Monitoring Study and the Montana Air Pollution Study have resulted in major efforts to monitor air data (Monitoring Update). Environmental Research and Technology, Philips, Rockwell, and Radian are among the companies that have built or are building complete air monitoring networks. Other companies, such as Bendix (U.S.), Hartman and Brown (Germany), and Seres (France), provide only instrumentation. At the 1978 Air Pollution Conference in Houston, Texas, more than 150 vendors displayed air pollution monitoring equipment.
III DIFFUSION EQUATIONS

The current quantifiable techniques for siting monitoring equipment make use of one or more mathematical models for determining maximum concentrations. Typical of these models is the equation below (Turner 1970) for concentrations calculated at ground level from a point source at effective emission height \( H \) (Figure 1).

\[
C(x,y,;H) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp \left[-\frac{k_y (\frac{y}{\sigma_y})^2}{2}\right] \exp \left[-\frac{k_z (\frac{H}{\sigma_z})^2}{2}\right]
\]  

Equation 3-1 assumes that the plume spread has a Gaussian distribution in both the horizontal and vertical planes with standard deviations of plume concentrations in the horizontal and vertical of \( \sigma_y \) and \( \sigma_z \), respectively. The mean wind affecting the plume is \( u \) and total reflection of the plume takes place at the earth's surface.

Although the model above is widely used, it is appropriate to indicate the limitations or potential inaccuracies of the model as a prelude to its application in monitor site selection. According to Turner (Perkins 1974), \( \sigma_y \) and \( \sigma_z \) are based on empirical data and may be in error by a factor of 2. Likewise, the stability categories on which \( \sigma_y \) and \( \sigma_z \) are based, are determined by subjective criteria such as moderate or slight incoming solar radiation, and may easily result in use of the improper stability category. The clockwise turning of the wind with height due to the decreased frictional effect is neglected since the model normally uses the wind at the effective
FIG. 1. DISPERSION OF A PLUME FROM A POINT SOURCE
height of the emission source. Absorption and deposition at the
ground are not considered. Chemical reactions along the path such
as a gradual change of $SO_2$ to $SO_3$ and then to $H_2SO_4$ are ignored.
Wind shifts and gustiness are not considered. Finally, the model
discussed above assumes a sampling time of about ten minutes. The
EPA (Turner 1970) has developed charts which provide a method of
determining relative ground level concentrations times wind speed
($CU/Q$) for various effective heights of emissions for each stability
class (A through F). Turner has superimposed on these graphs the
effect of mixing levels that are low enough to limit vertical mixing
at any distance downwind from the source (Figure 4).

To illustrate the methods used by Turner, table 4 and figure 2
show the results for the class B stability assuming an effective
height of emission of 150 meters and a mixing height of 1500 meters.

Two equations are utilized for the computations as shown
below:

$$C(x,0,0;H) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp \left( \frac{H^2}{\sigma_z^2} \right)$$  \hspace{1cm} (3-2)

$$C(x,y,z;H) = \frac{Q}{(2\pi)^{\frac{1}{2}} \sigma_y \sigma_z \sigma_y \sigma_u} \exp \left[ \frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right]$$  \hspace{1cm} (3-3)

Equation 3-2 is utilized to a distance $X_L$ where $\sigma_z$ equals .47$L$ and
assumes a Gaussian distribution in the vertical as well as the hori-
zontal. At the distance $X_L$ from the source, the dispersion is
assumed to be influenced by the stable layer at a distance $L$ above
the surface. At a distance 2$X_L$ equation 3-3 applies.
Figure 4 portrays an example of EPA's complete graph for the B stability (Turner 1970).

### TABLE 4
**CALCULATION OF CU/Q FOR VARIOUS DISTANCES**

<table>
<thead>
<tr>
<th>X(KM)</th>
<th>$\sigma_Y$ (m)</th>
<th>$\sigma_Z$ (m)</th>
<th>CU/Q ($m^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.3</td>
<td>50</td>
<td>30</td>
<td>7.6x10^-10</td>
</tr>
<tr>
<td>.5</td>
<td>83</td>
<td>51</td>
<td>1.0x10^-6</td>
</tr>
<tr>
<td>.8</td>
<td>129</td>
<td>85</td>
<td>6.1x10^-6</td>
</tr>
<tr>
<td>1.0</td>
<td>157</td>
<td>110</td>
<td>7.4x10^-6</td>
</tr>
<tr>
<td>3.0</td>
<td>425</td>
<td>365</td>
<td>1.9x10^-6</td>
</tr>
<tr>
<td>5.5</td>
<td>720</td>
<td>705</td>
<td>5.5x10^-7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>X(KM)</th>
<th>$\sigma_Y$</th>
<th>L</th>
<th>CU/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.0</td>
<td>1300</td>
<td>1500</td>
<td>1.8x10^-7</td>
</tr>
<tr>
<td>30.0</td>
<td>3000</td>
<td>1500</td>
<td>7.9x10^-8</td>
</tr>
<tr>
<td>100.0</td>
<td>8200</td>
<td>1500</td>
<td>2.9x10^-8</td>
</tr>
</tbody>
</table>
FIG. 2. $\frac{C}{Q}$ VERSUS DISTANCE FOR EMISSION HEIGHT OF 150 METERS AND MIXING HEIGHT OF 1500 METERS, B STABILITY
The increasing requirements for monitoring, the ever growing cost of monitoring, and serious questioning of the quality of monitoring discussed in the previous sections of this report have been responsible for a trend toward greater objectivity in site selection. As a prelude to discussion of some quantitative methodologies some of the methods and guidelines that have precluded the objective methods are discussed below.

As early as 1974, the Environmental Protection Agency provided guidelines for locating monitors in a region (Hougland, and Stephens 1976). Although no models then existed for prescribing or recommending specific site locations, EPA specified consideration of:

1. Priority to highest concentration areas
2. Attention to densely populated areas
3. Quality of air entering the region, and
4. Projected growth in the region

Other criteria cited in the literature for siting include precautions against undue influence by high walls, buildings, or trees or highly localized meteorological conditions (Morgan 1977). Recognizing the need for a comprehensive study of an urban area to investigate the interrelated processes affecting pollutant emission, dispersion and composition, EPA began a major study in 1973 called
the St. Louis Regional Air Pollution Study (RAPS). The Study incorporated the use of 25 remotely operated, automated stations. The locations of the 25 stations were arranged in approximate rings of radii from the central urban station of 5, 11, 22, and 44 kilometers (Schiermeier 1978). This symmetric siting of monitors conformed to the EPA guidance for "minimum spacing where concentrations were greatest". The outer ring, consisting of four rural stations located approximately 90° apart, provided a capability of collecting samples from the North, South, East, and West. Obviously, there is nothing which makes these directions representative directions for collection of samples.

The Alabama Power Company in 1976, sited SO₂ sensors as part of its real time environmental data acquisition system in a somewhat more objective manner. Location of the sensors was determined by modeling the SO₂ concentration through the use of variables to include plant stack height, emission rates, Pasquill stability conditions and prevailing wind direction and speed. Isopleths of SO₂ concentrations were established for each plant and sites were selected on the basis of likely areas for maximum SO₂ concentrations. Further, the shelters containing the monitoring equipment can readily be moved to other sites if deemed appropriate (PAT Report 1976).

An EPA Report (Ball and Anderson 1977) provides guidance on optimum SO₂ monitoring which reflects the latest federal guidance available in regard to siting of air monitoring receptors. Although
specifically related to $SO_2$, many aspects of this report apply to other sensors as well. The report provides guidance for selecting sites to measure regional mean concentrations, interregional $SO_2$ transport, representative concentrations for areas of various sizes, peak concentrations in urban areas, and emergency episode levels. In addition, procedures for selecting sites to monitor impacts from isolated point sources are provided. The guidance in this report is somewhat of a general nature with more emphasis of what to do rather than how to do it.

A review of the ideas presented is deemed appropriate to establish the trend toward the objective methodologies to follow. Not unlike the objective techniques described in the next section of this report, EPA (Bell and Anderson 1977) recommends the use of diffusion modeling results and graphical solutions to the Gaussian diffusion equations to provide the basic initial guidance for locating the representative monitor siting areas. Next, specific prospective sites within the areas are gradually eliminated until a small subset of acceptable sites remain. Final selection is made from this subset.

Basic to the siting process is the acquisition and development of background material regarding the physical characteristics of the siting area. Data include the terrain and land-use setting of the prospective monitor siting area, the proximity of large water bodies, the distribution of $SO_2$ sources in the area, and the location of appropriate National Weather Service airport stations.
from which weather data may be obtained.

Isopleth maps which are generated from diffusion models are recommended for use in locating monitor sites. Various point source models are recommended for point source monitoring. Among these models are PTMPT, PTDIS and PTMAX.

PTMPT calculates hourly concentrations for as many as thirty receptors whose locations are specified from up to 25 point sources. Required program inputs consist of the number of sources to be considered, the emission rates, physical heights, stack gas temperatures, volume flow or stack gas velocity and diameter, the source locations, and their heights above the ground. The hourly meteorological information required consists of wind direction and speed, stability class, mixing height, and ambient air temperature.

PTDIS and PTMAX are similar computer models which can be used. For the purpose of this report, the significant point is that computer models exist for predicting ground level concentrations from which isopleths can be constructed.

To acquire the data necessary for the models described, above, emission inventory information for point sources is available from the EPA for any area of the country for annual and seasonal averaging times. More specific information such as diurnal variations or load curves can be obtained from the emission source. Meteorological data from the National Weather Service Stations or the National Climatic Center "Star" program (Table 5) will usually
TABLE 5
EXAMPLE OF STAR PROGRAM OUTPUT F STABILITY

<table>
<thead>
<tr>
<th>SPEED (KTS)</th>
<th>0-3</th>
<th>4-6</th>
<th>7-10</th>
<th>11-16</th>
<th>17-21</th>
<th>Greater than 21</th>
<th>Total</th>
</tr>
</thead>
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<td>Direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
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<td>0.019444</td>
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<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
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<td>0.000000</td>
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<td>0.000000</td>
<td>0.004784</td>
</tr>
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</tr>
<tr>
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<td>0.000000</td>
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<td>0.000000</td>
<td>0.000000</td>
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</tr>
<tr>
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<td>0.000000</td>
<td>0.000000</td>
<td>0.021596</td>
</tr>
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<td>0.000000</td>
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</tr>
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<td>W</td>
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<td>0.000000</td>
<td>0.000000</td>
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<td>0.000000</td>
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<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.021596</td>
</tr>
</tbody>
</table>

**Total** | 0.104167 | 0.150000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 1.000000 |

**NOTE:** Relative frequency of occurrence of F Stability = 0.254167. Relative frequency of calms with F Stability = 0.041667.
suffice. In extreme cases, it may be necessary to accumulate data by special observations for the period of one year. For those models requiring mixing heights the STAR program is not adequate. Thus, mixing height data must be obtained from other sources.
Prior to 1976, the design of a monitoring network and particularly the siting of receptors for monitoring was based largely upon experience, judgment, and the general guidance provided by EPA as discussed earlier in this report. According to an Air Pollution Control Association (APCA) report (Hougland and Stephens 1976), there were no models for prescribing or recommending specific locations or areas. In January of 1976, the first largely analytical methodology for multiple point sources monitoring was presented by Hougland and Stephens. Late the same year, a second report (Noll, et al., 1977a) discussed a methodology which remains, in the opinion of this author, the most completely objective methodology to date for siting of monitors for large point sources. Another objective methodology was presented at the Annual Meeting of the APCA in June 1978 (Smith 1978). Each of these methodologies is summarized below to illustrate the current state of the art. The Noll, et al., method is discussed in detail since this methodology is presented in a manner which is particularly amenable to a basic understanding of the underlying principles. Secondly, discussion with the principle author indicates that the methodology is being computerized and that a computer program and user's guide will ultimately be available for relative ease in application of the model. Most significant, it represents the state of the art in monitor siting.
Hougland and Stephens Methodology

Citing "air pollution sampling site selection as one of the most important and vexing problems faced by those responsible for attainment and maintenance of the National Ambient Air Quality Standards", Hougland and Stephens developed a methodology for siting of multiple point source monitoring equipment (Hougland and Stephens 1976). The methodology is described below.

Potential monitoring sites are identified by superimposing a grid over a map of the area. The intersections of the grid lines, 2.5 to 3 km apart, are designated as potential monitoring sites.

The effectiveness of coverage (Aijk) from each source and each wind direction is calculated by the following equation (Hougland and Stephens 1976, equation 2).

\[ A_{ijk} = \text{Freq.}(k) \times \text{Str.}(i) \times \left[ \frac{1}{1 + D_{ij}} \right] \]  

(5-1)

where:  
\( i \) = source  
\( j \) = monitor  
\( k \) = wind direction, based on sixteen segments  
Freq = strength of the source  
D = distance from the source

After calculating the coverage factors (Aijk) a "source oriented" scheme is recommended for optimization of site locations. This scheme considers for each source and wind direction the monitor with the largest coverage factor. The assignment of monitors to sites is determined by maximizing the sum of these coverage factors subject to the limit of monitors on the basis of cost effectiveness.
or other limiting considerations. This is expressed by the following equation (Hougland and Stephens 1976, equation 5).

\[ \text{MAX } M = \sum_{i} \text{MAX}_{j} (A_{ijk} \cdot x_j) \]

subject to \( \sum_{j} x_j \leq K \), where \( k \) = number of monitors available.

where:  
\( x_j = 1 \) if a monitor is assigned to \( j \)  
\( = 0 \) if no monitor is assigned to \( j \)

\( M \) = sum of coverage

One apparent weakness of this methodology seems to be the assumption that ground level concentrations are strictly proportional to distance from the pollution source. The methodology is reportedly being revised to incorporate a factor which considers distance from the point of theoretical maximum ground level concentrations rather than source to monitor distances. This should greatly improve the model.

**Noll, Miller, Norco and Raufer Methodology**

A second methodology (Noll, et al., 1977a) which utilizes far more objectivity than any previous method for siting monitoring equipment for point sources has been tested. The authors claim that their techniques provide increased cost-effectiveness in the design of air monitoring surveys, time savings in obtaining required data results, and the capability to make trade off decisions between fixed and mobile monitoring options. The objective procedure utilizes statistical methods to determine the location and number of monitoring sites from the ratios of the areas defined by (a) the
range of available historical meteorological conditions producing maximum concentrations and (b) a predetermined concentration measurement tolerance range around the maximum concentration. Statistical considerations permit siting for the desired confidence level of measuring a specified maximum air pollution value. The procedures developed by Noll, et al., are described below.

The first step in the procedure is to identify potential zones where maximum concentrations may occur. Potential zones at this point represent distances downwind where maximum concentrations may occur under differing meteorological conditions. The objective of this procedure is to identify zones of maximum ground level concentrations to determine the maximum impact on air quality in the immediate area of the point source. Thus, meteorological conditions that are associated with highest ground level concentrations should be considered. EPA (Turner 1970) summarizes the meteorological conditions associated with maximum ground level concentrations from elevated sources as follows:

1. Maximum "instantaneous" concentrations occur with unstable conditions when portions of the plume that have undergone little dispersion are brought to the ground

2. Maximum concentrations for time periods of about half an hour can occur with fumigation conditions

3. Under stable conditions, the maximum concentrations at ground level are less than those occurring under unstable conditions and occur at greater distances from the source

Noll and Miller in their textbook illustration considered the following as examples of conditions associated with maximum concentrations, except for 6, as discussed (Noll and Miller 1977, Figure 48):
1. Coning, critical wind conditions
2. Plume trapping conditions
3. Inversion breakup fumigation conditions
4. Unstable-Wind speed 1-2 m/sec
5. Stable-Wind speed 1-3 m/sec
6. Neutral-Wind speed 8-12 m/sec

The neutral condition, wind speed 8-12 m/sec, is suggested to document that ambient levels are less outside the major impact area described by the other conditions.

Utilizing the stability classes (Turner 1970), shown in table 6, ranges for maximum ground level concentrations for the stable classes E and F, the unstable classes, A, B, and C, and the neutral class D can be determined for the range of wind speeds given by Application of the Gaussian plume equation below.

\[
C = \frac{Q}{\pi \sigma_y \sigma_z u} \exp \left[ -\frac{1}{2} \left( \frac{H}{\sigma_z} \right)^2 \right]
\]

Concentrations for the coning plume, trapped plume and inversion breakup fumigation can be determined from the TVA nomograms (Montgomery, et al., 1973). To determine maximum ground level concentrations, it is necessary to determine the effective stack height. This can be calculated by the methods of Fay, et al., Briggs, Turner or conveniently determined by nomograms provided by TVA (Noll and Miller 1977b). The station location (Figure 3) is determined from the dispersion modeling to be at the point of maximum concentration. A tolerance range is then established about the station location.
<table>
<thead>
<tr>
<th>Surface Wind Speed (at 10m) meters/sec</th>
<th>Day</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Incoming Solar Radiation</td>
</tr>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>Less Than 2</td>
<td>A</td>
<td>A-B</td>
</tr>
<tr>
<td>2-3</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>3-5</td>
<td>B</td>
<td>B-C</td>
</tr>
<tr>
<td>5-6</td>
<td>C</td>
<td>C-D</td>
</tr>
<tr>
<td>Greater Than 6</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>
FIG. 3. POTENTIAL MONITORING ZONE AND SINGLE STATION COVERAGE
To establish this tolerance range which is an elliptical area, two new parameters, $X_{10}$ and $Y_{10}$, are determined. $X_{10}$ is the distance in the wind direction through the station in which the concentrations are within 10 percent of the peak concentration. This distance represents a region with 90 percent of the expected absolute maximum concentration. $Y_{10}$ is the crosswind distance at the station location in which concentrations are within 10 percent of the peak concentrations. Peak concentrations occurring within the elliptical area will result in a minimum of 90 percent of the peak concentrations at the station location.

$X_{10}$ is determined from the Turner charts discussed in chapter III and further illustrated by figure 4. $X_{10}$ is the horizontal distance represented on these graphs between the two points where $CU/Q$ is equal to 90 percent of the maximum $CU/Q$ as shown in figure 4.

$Y_{10}$ is derived from the equation below (Noll and Miller 1977b equation1).

$$0.9 = \exp -\frac{Y_{10}^2}{4 \sigma_y}$$

(5-4)

The right side of the equation represents the ratio between ground level concentrations at a perpendicular distance, $Y$, from points downwind from the emission source and the centerline, downwind, concentration as shown below:

$$\frac{C(x,y,0;H)}{C(x,0,0;H)} = \frac{Q}{\pi \sigma_y \sigma_z} \exp -\frac{Y^2}{2 \sigma_y} \exp -\frac{H^2}{2 \sigma_z}$$

(5-5)

For the area where the concentrations are within 90 percent of the
FIG. 4. CU/Q VERSUS DISTANCE FOR PASQUILL STABILITY, CLASS B
centerline values, the ratio above equals .9, and $Y = Y_{10}/2$. Noll and Miller have prepared charts for determining $X_{10}$ and $Y_{10}$, figures 5 (Noll, et. al., 1977a, Figure 3) and 6 (Noll, et. al., 1977a, Figure 4), based on the procedures described above.

Three things are utilized to determine the number and location of monitoring sites; the size of the potential monitoring zone requiring monitoring, the frequency of occurrence of meteorological conditions causing maximum concentrations, and the size of the monitoring station area under maximum concentration conditions.

The coverage area, $CR_s$, of one station is defined as the ratio between the size of the monitoring station area under maximum concentration conditions and the size of the potential zone requiring monitoring. Without considering wind direction, this ratio can be determined as follows: (Noll and Miller 1977b, equation 3)

$$CR_s = \frac{\text{Area of Ellipse}}{\text{Area of Potential Zone}} = \frac{\pi \left( \frac{X_{10}}{2} \right) \left( \frac{Y_{10}}{2} \right)}{\pi (R_1^2 - R_2^2)} = \frac{X_{10} Y_{10}}{4(R_1 - R_2)} \quad (5-6)$$

Figure 3 illustrates the areas above and the meaning of the variables in the equation. The denominator in equation 5-6 is often only a fractional part of the area shown and can be determined on the basis of the frequency distribution of wind directions for the meteorological conditions which are responsible for the potential monitoring zone being considered. The total coverage ratio is the sum of the coverage ratios for all stations.

The binomial distribution function, below, can be used to calculate the probability that one station will measure the maximum concentration $n$ times given a frequency of occurrence of $N$ times
FIG. 5. GRAPHICAL METHOD FOR DETERMINING $X_{10}$ VERSUS DISTANCE DOWNWIND TO $X_{\text{max}}$
FIG. 6. GRAPHICAL METHOD FOR DETERMINING $Y_{10}$ VERSUS DISTANCE DOWNWIND FOR SIX STABILITIES
(Noll and Miller 1977b, equation 4).

\[ P = \frac{N!}{n!(N-n)!} \cdot CR_T^R(1 - CR_T)^{N-n} \]  

(5-7)

To develop the graph, figure 7, Noll, et al. (1977a Figure 5) solved the normal approximation (Eq. 5-8) to the binomial distribution. Z in equation 5-8 is the number of standard deviations from the mean associated with the probability (confidence level) desired. \( CR_T \) in equation 5-8 is the total coverage ratio.

\[ Z = \frac{n-N(CR_T)}{(N(CR_T)(1-CR_T))^{1/2}} \]  

(5-8)

Figure 7 can be used to determine the total coverage ratio required to permit, with 99% confidence, successful measurements of maximum concentration given the frequency of occurrence, \( N \), each year of the meteorological events producing maximum concentration. The number of stations needed in the crosswind direction can be calculated from the following equation (Noll and Miller, 1977b, Equation 7).

\[ N_S = \frac{CR_T}{CR_S} \]  

(5-9)

where:  
\( N_S \) = number of stations needed  
\( CR_S \) = coverage ratio of one station  
\( CR_T \) = total coverage ratio required to achieve desired result

In summary, the Noll, et al., system of siting employs a totally objective methodology. The steps involved are:

1. **Determination of potential monitoring zones by dispersion modeling and consideration of the frequency of meteorological conditions causing maximum concentrations**

2. **Establishment of a tolerance range about the maximum concentration in the X and Y directions which determines the coverage**
FIG. 7. COVERAGE RATIO REQUIRED TO OBSERVE $C_{max}$, $n$ TIMES, WITH 99% CONFIDENCE, VERSUS THE NUMBER OF OCCURRENCES, $N$, OF METEOROLOGICAL PHENOMENA CAUSING $C_{max}$
area of the station

3. Computation of coverage ratios for each station

4. Determining the total coverage ratio required for observing the maximum concentration n times with the desired confidence level, given the number of occurrences, N, of meteorological phenomenon causing maximum concentrations

5. Determining the number of stations needed in the crosswind direction by dividing the total coverage ratio by the station coverage ratio

Correspondence with the primary author indicates that a computer program is being developed to provide air monitoring network designs based on the methodology described above. The work is being funded by the Electrical Power Research Institute and will allow the design procedure to be applied to meteorological conditions present at potential plant sites throughout the United States. They also plan to generate solutions for the design procedure with the completed computer program to evaluate the design procedure based on one year's data collected from a fifteen-station air monitoring network.

Further, the authors plan to develop a new set of objective criteria which will allow site selection based on dosage. This will allow the flexibility of monitoring site selection for concentrations which are related to receptor response and air quality standards.

SMITH METHODOLOGY

The methodology described by Smith (1978) is a computer assisted modeling method of siting for monitoring of single, multiple, area, or line sources. Inadequate information is available for the level of description provided in this report for the Noll, et al., methodology. Thus, the discussion is limited to a description of the
program output, an example of which is given in table 7 (Smith 1978, table 11).

In order for the program to provide the ranking of sites as shown in table 7, the following constraints are supplied:

1. Resolution of peak concentrations
2. Number of monitors to be ranked
3. Specific weather classes to be included
4. Ranking criterion: frequency of exposure and
5. Frequency of measurements required to justify station cost

Table 7, output from the monitor program utilized in the methodology is described as follows:

Threshold values are those values representing pollutant concentrations, below which, there is no interest in the site-selection process. Column 1 ranks the sites by the order of importance. Column 2 gives the wind directions that should be monitored and columns 3 and 4 the zone (in meters) of maximum concentration radially for the station in the appropriate downwind direction. Columns 5 and 6 show the coverage values, or the fraction of the concentrations above the threshold in a wind sector, which will be successfully detected by a monitor within the specified zone. Both the incremental and cumulative values are given.

Columns 7 and 8 present the exposure, incremental and cumulative. The exposure is defined as the product of each peak concentration and its frequency. Columns 9 and 10 give the frequency, incremental and cumulative, of meteorological events causing the plume to
impact in the zone. Column 11 gives the fractional part of the time that those conditions will exceed the threshold value.
<table>
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<tr>
<th>RANK</th>
<th>WIND DIR.</th>
<th>INTERNAL</th>
<th>COVERAGE</th>
<th>EXPOSURE</th>
<th>FREQUENCY</th>
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<td></td>
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<td>$x_2$</td>
<td>VALUE</td>
<td>CUM.</td>
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<td>4.27 E-02</td>
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SUMMARY

Over a period of two to three decades, the demands for monitoring have greatly increased. These demands for monitoring resulted in the establishment of monitors about point sources with little or no apparent regard for the probable location for most representative sampling. Critics have claimed that the results were far from optimum in determining maximum ground level concentrations, representative ambient air quality measurements, or in general, satisfactory for the purpose for which the measurements were made. Since 1976, three methodologies have emerged which are based on quantitative consideration. This author considers the Noll, et al., (1977) methodology to be most rigorous and representative of the state of the art. The Noll methodology involves steps as follows:

1. Determination of potential monitoring zones by dispersion modeling and consideration of the frequency of meteorological conditions causing maximum concentrations

2. Establishment of a tolerance range about the maximum concentration in the X and Y directions which determines the coverage area of the station

3. Computation of coverage ratios for each station

4. Determining the total coverage ratio required for observing the maximum concentration n times with the desired confidence level, given the number of occurrences, N, of meteorological phenomena causing maximum concentrations

4. Determining the number of stations needed in the cross-wind direction by dividing the total coverage ratio by the station coverage ratio

Like all foreseeable quantitative methods, final siting may be af-
fected by physical characteristics such as the terrain, non-availability of power sources, or failure to have access to the land which represents an optimal monitoring site. Further, they are limited by the inherent inaccuracies and assumptions contained in the dispersion models and other equations utilized in the decision-making process. Based on information from the primary author regarding a computer model for the Noll, et al., methodology, further study, perhaps another research report or thesis, is recommended. Examination of the computer model, when available, with local (Florida) climatology as an input could be an interesting and rewarding endeavor.
LIST OF REFERENCES


