Nashville Air Pollution and Health Study

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AN EXTENSIVE air pollution and health study was conducted in Nashville, Tenn., in 1958 and 1959 by the Division of Air Pollution, Public Health Service, and Vanderbilt University School of Medicine, together with cooperating State, county, and local agencies. The purpose was to investigate possible relations between air pollution and health and to gather information on a number of medical, engineering, and meteorological phases of air pollution. Such a study was prompted by a need to assess the chronic or long-term health effects that may occur as the result of daily, and often lifetime, exposure to air pollution. Nashville was selected because it was believed to have a chronic but relatively modest, air pollution problem. In large measure, the pollution was caused by the combustion of coal.

Numerous scientific articles have been written on various aspects and phases of this study. In this paper we have presented a bibliography of all the published articles, together with a brief outline of the study and a summary of the important findings.

The multiple objectives of the Nashville study stemmed from two primary problems: (*a*) how to assess the atmospheric pollution of a community most accurately, with reference to both temporal variations and long-term averages, and in relation to quantity, composition, and the factors affecting it; and (b) how to assess the health effects that might result from this contamination as they vary in geographic and temporal distribution and with the recognition that many other factors also might affect them. The large-scale investigation was undertaken primarily to ascertain whether proper measurements and experimental procedures could be designed to meet these objectives.

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Objectives and Conduct of Study

The study (*1*) was divided into two concurrent phases: medical and engineering.

Medical phase. Four separate but related medical studies were conducted: a morbidity survey, a mortality survey, a cardiorespiratory disease study, and an anthracosis study.

To determine the possible relations between air pollution and health, the following objectives were outlined.

1. Collect general and specific morbidity data on residents of Nashville and determine if there is an association between morbid conditions and exposure to air pollutants.

2. Determine mortality rates for specific causes by census tracts and study relation between these death rates and demographic, social, and economic data.

3. Determine whether deaths from specific causes vary significantly with residence in areas of relatively high or low atmospheric pollution that have similar demographic, social, and economic characteristics.

4. Determine whether persons known to have specific cardiorespiratory disease show variation in frequency or severity of attacks, depending

on diurnal or seasonal variation in exposure to environmental air pollutants.

5. Determine whether the course of disease in persons known to have a specific cardiorespiratory disease differs according to their residence in areas of relatively high or low air pollution.

6. Determine whether autopsies on residents of Nashville showed a greater degree of anthracosis than autopsies on nonresidents.

7. Determine whether the degree of anthracosis in Nashville residents varies according to where they reside in the city.

8. Determine whether anthracosis is commonly associated with any other pulmonary or cardiac pathology and whether anthracosis is identified with any specific symptomatology.

A questionnaire designed to produce general and specific morbidity information was distributed to residents in approximately 5 percent of the occupied dwellings. A portion of the test group was examined medically to provide a check on validity of information.

Mortality data were obtained from Davidson County death certificates from 1949 to 1956. Patients suffering from cardiorespiratory diseases were given complete physical examinations after a detailed history was obtained. The patients mailed report cards with appropriate information at specified intervals after receiving their examinations.

The results of autopsies performed at Vanderbilt University Hospital between 1953 and 1956 provided data for the anthracosis study.

Engineering phase. A number of related objectives were interwoven into the investigations with the mission of providing air-quality data for use in medical studies. The following objectives were outlined.

1. Determine the representativeness of air-quality data with respect to number and location of sampling stations, sampling frequency, and sampling time.

2. Evaluate analytical methods, equipment, and procedures.

3. Study and evaluate dispersion characteristics of pollutants.

4. Determine public opinion on air pollution as related to pollution levels and population characteristics.

5. Attempt to classify atmospheric stability by use of radiosonde data.

6. Determine the relations between air pollution concentrations at a selected station and meteorological parameters measured at the same station and at different stations.

Sampling stations were established at 123 sites in the Nashville area. Of these, 119 were within an area about 9 miles in diameter, centered at a downtown site. The sites, located on an equilateral triangle grid pattern, were about 0.87 mile apart. The remaining four control stations were located in the four cardinal compass directions about 8 miles from the central station.

The sampling network consisted of three general types of stations (determined by the amount and kind of aerometric and meteorological equipment) and several stations for specific measurements. The urban area was covered by the three general types of stations in a reasonably uniform manner. A summarization of the major aerometric measurements taken at the various stations follows:

Number of stations	*Aerometric measurements*
123	Monthly dustfall. Monthly sulfur dioxide (lead peroxide candle method).
36	24-hour daily soiling spot samples. 24-hour daily volumetric sulfur dioxide (West-Gaeke method). 24-hour daily total wind movement.
11	12 2-hour (high-pollution seasons) or 6 4-hour (low-pollution seasons) daily soiling spot samples, American Iron and Steel Institute (A.I.S.I.) method. 24-hour daily suspended particulate (high-volume samples).
9	Continuous ambient temperature, relative humidity, and wind speed and direction.
7	12 2-hour daily volumetric sulfur dioxide (West-Gaeke method).
1	Continuous sulfur dioxide (Thomas autometer). Continuous nitrogen dioxide and oxidant (Kruger model 73 atmosphere analyzer). Continuous carbon monoxide (Luft-type infrared analyzer).

Special studies consisted of a sulfur dioxide (SO_2) emission inventory, a study of dustfall measurement techniques, a public opinion survey, pollen measurements, pollution level forecasts, and automobile traffic counts.

The numerous technical and scientific papers relating to air pollution in Nashville produced many important medical, aerometric, meteorological, and miscellaneous findings.

Medical Findings

Several relationships between air pollution and health have been determined from the studies of Zeidberg and associates. Their findings are presented in the following series of six papers on "The Nashville Air Pollution Study."

I. "Sulfur Dioxide and Bronchial Asthma; A Preliminary Report" (*2*). A group of 84 patients (49 adults and 35 children) with bronchial asthma reported 3,647 asthmatic attacks during 27,440 person-days of observation, or a total attack rate of 0.133 per person-day. In adults, the asthmatic attack rate varied directly with the level of sulfation in their residential environment. Attack rates on days with the highest and lowest SO_2 values were significantly different. A 1-day lag showed even more significant differences.

The influence of temperature, humidity, and barometric pressure on the asthmatic attack rate could not be demonstrated, but wind velocity showed an inverse relation. Pulmonary function tests indicated that persons with a 1-second-timed vital capacity of less than 50 percent had a significantly higher attack rate than patients with more than 75 percent function.

II. "Pulmonary Anthracosis as an Index of Air Pollution" (*3*). In 641 consecutive autopsies, excluding those on subjects under 5 years of age, performed at Vanderbilt University Hospital from 1953 to 1956, microscopic evidence of pulmonary anthracosis was sought.

The deposition of anthracotic pigment increased with age; it was more severe in men than in women and in Nashville residents than out-of-city dwellers. Among Nashville residents, it increased with length of residence in the city and was more severe, at least in women, in those who had lived in the more polluted areas of the city. The influence of occupation could not be demonstrated because of insufficient occupational history.

No association was found between anthracosis and specific pulmonary or cardiac symptoms or pathology. Pulmonary anthracosis appeared to reflect a person's exposure to environmental air polluted with coal smoke.

III. "Morbidity in Relation to Air Pollution" (*4*). A method for studying the association of air pollution and morbidity in an urban population and its limitations were discussed. Direct correlations of total morbidity and levels of pollution as measured by the soiling index and 24-hour SO_2 were observed among persons 55 years old and older of the middle socioeconomic class. Direct correlations for the same aerometric parameters were also noted for cardiovascular diseases but not for any other specific group of diseases.

Refinement of analyses to differentiate home and occupational environment influences on morbidity revealed that white women keeping house manifested direct correlations of pollution and total morbidity for all aerometric parameters, while white women who worked showed none. Nonwhite women tended to show direct correlations in both housekeeping and working groups. The effect of pollution on specific diseases of the respiratory, cardiovascular, or gastrointestinal systems could not be demonstrated because such breakdowns produced numbers too small for valid analysis.

IV. "Sulfur Dioxide and Bronchial Asthma; A Multivariate Analysis" (*5*). This progress report demonstrates the association of a variable (day from beginning of study) with asthmatic attacks. The next most important variable in the multiple correlation and regression analysis was sulfur dioxide. Much additional work was thought necessary to investigate the possibility that susceptible people have attacks on or about the same day. Further study also was recommended on the environmental factors characterizing the days on which large numbers of patients report attacks. It was also suggested that the linear analysis made thus far should be supplemented by nonlinear methods.

V. "Mortality From Diseases of the Respiratory System in Relation to Air Pollution" (*6*). This study of respiratory-disease mortality in relation to air pollution was designed to control socioeconomic factors as well as degree of exposure to air pollutants.

Except for lung and bronchial cancer, mortality from respiratory diseases varied inversely with the socioeconomic class when the degree of exposure to air pollutants was kept constant.

With the socioeconomic factor controlled, respiratory disease mortality was directly related to the degree of exposure to sulfation and soiling, except for lung and bronchial cancer, bronchitis, and emphysema. Age-specific respiratory disease mortality rates up to 65 years of age were directly related to the degree of exposure measured by sulfation. After 65 years, the highest rates were observed in the low pollution group.

At all levels of exposure to sulfation, respiratory disease mortality rates were higher for men than for women. The difference was especially marked for mortality from lung and bronchial cancer. Except for lung and bronchial cancer, respiratory-disease mortality rates for nonwhites were higher than for whites at high and moderate levels of exposure to sulfation. The deviation of mortality by lung and bronchial cancer, bronchitis, and emphysema from the pattern shown by other respiratory diseases was discussed.

VI. "Cardiovascular Disease Mortality in Relation to Air Pollution" (*7*). Socioeconomic factors as well as degree of exposure to air pollution were controlled in this study of the relation of cardiovascular disease to air pollution.

When the level of exposure to air pollutants was kept constant, a generally regular pattern of an inverse relation between socioeconomic class and mortality rates for cardiovascular disease was observed for the Nashville metropolitan area for the 12-year period 1949 through 1960. An exception was arteriosclerotic heart disease, which showed a direct relation. Of the four pollutants studied for their association with cardiovascular mortality, the most consistent pattern was noted for suspended particulate matter as measured by the soiling index. The authors had no explanation for this observation.

With the socioeconomic factor controlled by limiting the analyses to the middle-class population, men generally were subject to higher mortality rates from cardiovascular diseases than women. This was particularly true for arteriosclerotic heart disease. When comparisons of mortality were made by air pollution exposure for each sex, a regular pattern of association appeared for women but not for men. Except for arteriosclerotic heart disease, cardiovascular mortality rates were higher among nonwhites than whites of the same socioeconomic class. This was generally true at all pollution levels.

Mortality rates for cardiovascular disease increased regularly with age, except for rheumatic heart disease, which peaked at 65 to 74 years. When analysis was made on the basis of air pollution exposure, the greatest proportional difference was found in those under age 45, and the smallest difference in those age 75 and over. This analysis pointed to the need for additional studies designed to control such factors as stress, smoking, diet, and occupation.

Aerometric Findings

Stalker and co-workers outlined their work on "Sampling Station and Time Requirements for Urban Air Pollution Surveys" in a group of four papers. Their findings follow.

I. "Lead Peroxide Candles and Dustfall Collectors" (*8*). Seven uniformly spaced lead peroxide air sampler stations were selected to estimate the mean seasonal and annual sulfation rates over the community. The estimates agreed with the results obtained at the 119 stations actually used, but with a considerably less statistical degree of confidence.

By use of two samplers per square mile or 119 sampling stations, the true annual mean sulfation rates and dustfall levels were estimated within 10 percent with a 95 percent degree of confidence. This density of stations was required to describe adequately the geographic distribution for the purpose of supporting the health-effects phase of this study. In the selection of sampling stations for the determination of sulfation rates or frequency distributions, uniformity of spacing appeared to be the most important criterion; this became more apparent as the number of sampling stations was reduced.

In selecting sampling stations for the determination of dustfall levels or frequency distributions, the random selection of stations on a uniform network grid appeared to be the most important criterion. Again this became more apparent as the number of sampling stations was reduced.

When circumstances required a sampling program of limited duration it was possible, at least in communities resembling the area investigated in this study, to obtain reliable estimates of annual means and frequency distributions for both sulfation and dustfall by sampling only during the fall or spring season.

The authors devised a statistical tool that will assist any investigator in designing and evaluating his sampling program.

II. "Suspended Particulate Matter and Soiling Index" (*9*). At least 60 sampling stations (about 1 station per square mile) for this community would be required to estimate the daily mean level of suspended particulate matter with 95 percent assurance of being within 20 percent of the daily mean value. At the seven urban stations used in the study, the true daily mean (±20 percent) was estimated with good assurance on only 8 percent of the 26 days of study. However, monthly, seasonal, and annual means were probably estimated within 35 percent of the respective true mean values. About one station per 4 square miles would be required to estimate monthly, seasonal, and annual means with ±20 percent accuracy.

By means of a network consisting of only two sampling stations (one high-pollution urban and one suburban), the annual mean particulate matter over the community was estimated within 2 percent of the sample mean measured by a network of the seven urban stations. No significant difference occurred between the annual, seasonal, and most monthly means measured by the two networks, and their 95 percent confidence intervals were in close agreement. Even the daily mean estimates of the two networks were reasonably close.

Annual, seasonal, and most monthly mean levels of particulate matter were estimated almost as well by the use of several highly reduced, sampling-frequency schedules. The most extreme reduction in number of stations and sampling frequencies that continued to give good estimates of annual and seasonal means was the combination of an elevated central urban station and one suburban station operating only 22 days a year. The annual mean measurement obtained with this reduced sampling program differed by only 8 percent and the seasonal mean by a maximum of 14 percent from the respective sample means obtained at the seven-station urban network, by means of which 2,098 samples were collected during the study. Confidence limits for the smaller network mean were very good (±19 percent), considering the small number of samples collected.

Cumulative frequency distributions of measurements in the reduced sampling programs agreed well with that of the seven-station urban network, and geographic distribution of suspended particulate matter could be fairly well described by several of the smaller sampling programs. None of the suspended particulate networks used in this study, however, would supply the geographic detail desirable for the best support of a communitywide health-effects study.

For 95 percent assurance of estimating the daily mean community-soiling index (24-hour samples) within 20 percent of the true mean, about six uniformly placed stations per square mile would be required. The stations would be spaced slightly less than one-half mile apart. By means of the 32-station network (one station per 2 square miles) used in the study, the true daily mean (±20 percent) was estimated with good assurance only on 6.3 percent of the 23 days of the study. However, true monthly and seasonal means most likely were estimated within 30 percent, and the true annual mean within 20 percent. Networks with less than one station per 2 square miles were not thought to be consistently reliable for estimating monthly, seasonal, or annual mean 24-hour soiling indexes, particularly to support epidemiologic studies.

The seasonal cumulative frequency distributions of soiling-index measurements closely resembled those of monthly sulfation measurements in that both fall and spring distributions corresponded with the annual distribution. If it were necessary to describe the annual mean soiling index and annual frequency distributions by limited sampling, fall or preferably spring would be the time to conduct such a program.

Reducing either the number of stations or the frequency of sampling resulted in only fair estimates of monthly, seasonal, and annual 24-hour soiling-index means.

III. "Two- and Four-Hour Soiling Index" (*10*). At least two automatic spot sampling stations per square mile (about 0.87 mile between stations) would be required to estimate the 24-hour mean soiling index in this community with good assurance of ±20 percent accuracy. For the seven urban stations used in the study, the true daily mean (±30 percent) was estimated with good assurance on about 18 percent of the days.

From four to six stations per square mile would be required to estimate mean urban soiling for any single 2- or 4-hour period with good assurance of ±20 percent accuracy. At least one station per square mile (1.22 miles between stations) would be needed to determine the monthly mean of any single 2- or 4-hour period with ±20 percent accuracy. One station per 3 square miles (2.1 miles between stations) would be required for diurnal seasonal means, and one station per 6 square miles (3.0 miles between stations) for diurnal annual means.

The true 2-hour mean (±20 percent accuracy) was estimated for the seven-station urban network used in this study only 6.2 percent of the time. Estimated diurnal (2-hour) monthly means usually had accuracy limits ranging from 20 to 50 percent; diurnal seasonal means, from 20 to 40 percent; and the diurnal annual mean, ±22 percent.

Close estimates of mean monthly and seasonal soiling indexes and cumulative frequency distributions were obtained by combining the sampling data obtained from one central urban and one suburban (south control) station. Most 2-hour seasonal mean soiling values obtained by this small network were not significantly different from those of the full seven-station urban network.

At least 20 percent of the geographic detail in 2-hour seasonal mean soiling patterns over the community was probably lost as a result of using a 7-station network instead of a 22-station network (1 station per 3 square miles). Such detail may be significant in various types of epidemiologic studies.

Sampling on a reduced-frequency schedule, such as every other day, every fourth day, or weekdays only, gave acceptably close estimates of diurnal monthly, seasonal, and annual means, cumulative frequency distributions, and geographic distributions for use in most general monitoring programs.

From October through April significant differences in most monthly mean 4-hour soiling-index values were noted; however, from May through September, insignificant differences were found between the diurnal means. Diurnal sampling during this 5-month period was therefore usually unjustified insofar as soiling-index measurements were concerned in the community studied.

IV. "2- and 24-Hour Sulfur Dioxide and Summary of Other Pollutants" (*11*). At least 245 stations or 4 stations per square mile (spaced about 0.62 mile apart) would be required in this community to estimate most daily mean levels of sulfur dioxide with 95 percent assurance of ±20 percent accuracy. With the 32-station network (1 station per 2 square miles) used in this study, daily means were estimated with ±20 percent accuracy on 51 percent of the days of the 1-year study, but only on 2 percent of the days during the winter season. There was, however, assurance of ±50 percent accuracy for the 32-station network on 85 percent of the days throughout the year. About 60 stations (1 per square mile) were required for estimating the winter seasonal and monthly means during the heating season (October through March), but only 1 or 2 stations were required for the entire community during the nonheating period (May through September). About 24 stations (1 per 3 square miles) were required for estimating spring and fall seasonal means.

With a network of 7 uniformly spaced stations (1 per 9 square miles), estimates of monthly and seasonal sulfur dioxide means in most cases were not significantly different from the means obtained by the larger 32-station network. With the 7-station network, daily mean sulfur dioxide estimates usually agreed closely with the 32-station network, but with a wider confidence range than the larger network. For less precise general monitoring purposes, estimates of monthly and seasonal means that were usually within 40 percent of the larger network means were provided by two stations (one urban station in the high-pollution area and one suburban station).

Annual, seasonal, and most monthly mean sulfur dioxide levels were estimated almost as well by several reduced-frequency sampling schedules (for example, every second day and weekdays only) as by everyday sampling.

The seasonal cumulative frequency distributions of daily sulfur dioxide measurements were similar to the distributions of monthly sulfation and daily soiling measurements. The annual frequency distribution was similar to fall and spring distributions and could be approximated by sampling in fall or spring only. The frequency distributions of 24-hour concentrations could be closely approximated by samplings from smaller networks, such as seven uniformly spaced stations or even by a two-station network. The seasonal distribution slopes of everyday sampling could also be closely approximated by sampling on reduced frequency schedules such as every other day or weekdays only.

Geographic distributions of seasonal mean sulfur dioxide concentrations, based upon daily samples from 32 stations, could be closely approximated by everyday measurements from 16 stations (1 station per 4 square miles). For providing data to support health-effect studies, everyday sampling for sulfur dioxide at the least number of stations possible was the most economical approach; for example, four stations per square mile for daily measurements and at least one station per 2 square miles for determination of monthly and seasonal mean values (preferably one station per square mile during heating season).

The number of stations required for measuring mean 2-hour sulfur dioxide concentrations with ± 20 percent accuracy would be the same as for 24-hour sulfur dioxide or for 2-hour-soiling quality determinations; that is, four stations per square mile for daily 2-hour means and at least one station per 2 or 3 square miles for monthly and seasonal 2-hour means. Cumulative frequency and geographic distributions of 2-hour seasonal sulfur dioxide means could be approximated by samples taken from a small number of stations, on a reduced frequency schedule, or in the same manner as with 24-hour sulfur dioxide sampling.

The seasonal mean, 24-hour sulfur dioxide concentrations measured at the urban center and at several distances from the center were found to fit the normal distribution curve fairly well. Thus from sulfur dioxide measurements at the urban center and in the suburban area only, seasonal mean concentrations at several distances from the center could be approximated by use of the modified Gaussian equation.

Larsen and associates found that both sulfur dioxide emission data and sulfation data appeared to fit a Gaussian or normal curve with distance from center of city. The relations are given in "The Radial Distribution of Sulfur Dioxide Source Strength and Concentration in Nashville" (*12*). The variation in emission may be expressed as follows:

$$E=E_c e^{-\frac{1}{2}\left(\frac{r}{s_r}\right)^2}$$

where E is emission strength (in pounds of SO_2 per square mile per day), E_c is emission strength at the center of Nashville, e is the transcendental number 2.718, r is the radial distance in miles from the center of Nashville, and s_r is a new parameter, termed "standard radial deviation," which is analogous to standard deviation in the "normal" equation. In Nashville s_r was 1.2 miles, or about one-fourth the radius of Nashville, for each season and the total year.

A similar equation may be used to express sulfation in Nashville:

$$S=S_b+S_c e^{-\frac{1}{2}\left(\frac{r}{s_r}\right)^2}$$

where S is sulfation, S_b is the background sulfation 7.5 miles from the center of town, and S_c is the sulfation level in the center of town $(-S_b)$. (S_c is the measured sulfation from which is substracted the background value S_b.) For sulfation, s_r varied from 0.2 of the radius of Nashville in the summer to 0.4 of the radius of Nashville in the winter. The fall, spring, and annual values were 0.3 of the radius of Nashville.

The fall, spring, and annual sulfation values were of comparable magnitude. Winter sulfation at the center of Nashville was three times as great as the annual value; summer sulfation was one-fourth the annual value. For each season and the total year, sulfation measurements at the center of Nashville were approximately seven times the nonurban values. A computer-solved mathematical model relating source strength to sulfation indicated a "fairly good fit" to the study findings when sulfation was considered as being inversely proportional to the square of distance between source and receptor.

McCormick and Xintaras observed diurnal variations of carbon monoxide concentrations and traffic density at "curbside" studies in Nashville. The following findings were presented in "Variation of Carbon Monoxide Concentrations As Related to Sampling Interval, Traffic, and Meteorological Factors" (*13*).

This investigation showed that in urban areas some order could be found in carbon monoxide (CO) fluctuation with time, but that a complete interpretation of such "curbside" data in terms of source and meteorological factors was very complex. The hourly variation of CO concentration with traffic density confirmed a moderate degree of correlation between these two factors; however, this limited correlation emphasized also the importance of local conditions of transport and dispersion on this variation. Marked positive anomalies of the normal CO trends could be associated with wind speed decay, and therefore a technique was suggested for evaluating the effects of traffic changes on CO levels, with wind speed incorporated as a contributory element.

The results of single-source field experiments validated to some extent the interpretation of data collected in Nashville. Reasonable first-approximation estimates of the higher short-period concentations during 1-hour sampling periods are now possible. Further information on the diurnal variation of the ratios is required, however, before the general effect of time of day on the estimates can be determined.

Park and associates evaluated the method for measuring soiling index and suggested calibration procedures in "Developments in the Use of the A.I.S.I. Automatic Smoke Sampler" (*14*). They found that 11 automatic A.I.S.I. smoke samplers were in continuous and simultaneous operation as part of a year-long Public Health Service field study in Nashville, Tenn., and that the heavy load of reading so many tapes prompted the development of an automatic spot evaluator that could read approximately 12 samples per minute.

Tests revealed that the flow rate varied significantly between samplers and between filter tape rolls, and that the flow rate decreased at a predictable rate during the sampling cycle. The tape used in this study did not show a significant variation in the flow rate of areas within the roll.

An A.I.S.I. sampler calibration procedure was developed that was both simpler and more accurate than previous procedures.

In "Atmospheric Sulfur Dioxide and Particulate Matter: A Comparison of Methods of Measurements" (*15*), Stalker and co-workers described the variations of pollution concentrations with different methods of measurement. Interrelations between sulfur dioxide and particulate matter were investigated. Their findings follow:

The 2-hour, automatic smoke sampler was a more reliable and much less variable method of measuring soiling quality than the 24-hour, slow flow-rate method. For determining ambient SO_2, the 24-hour standard bubbler method was more efficient than the 2-hour sequential sampling method used in the Nashville study.

From measurements of certain types of particulate matter in a community, other types of airborne particulate matter could be reasonably well estimated. For example, total dustfall could be estimated from measurements of water-insoluble dustfall, suspended particulate matter from either water-insoluble dustfall or total dustfall, organic or sulfate particulates from total suspended particulate matter, and soiling quality from suspended particulate matter. In the Nashville study, these estimates were always more reliable during the winter than during other seasons, but were often acceptable in all seasons for general air pollution monitoring purposes.

The relations between results obtained with different methods of measuring SO_2 were best during the fall and winter when atmospheric concentrations were highest. During the winter season of high SO_2 levels, 1 mg. of SO_3 per 100 square centimeters per day (sulfation rate), measured by the peroxide candle method, was equivalent to 0.042 part per million SO_2 measured by the sodium tetrachloromercurate method (TCM). During the fall season of moderate SO_2 levels, the 1-mg. equivalent was 0.035 part per million SO_2, and during the spring season, the 1-mg. equivalent decreased to only 0.015 part per million SO_2. On the average, the

Thomas autometer measurements of SO_2 were about twice as high as simultaneous 24-hour TCM measurements of SO_2.

Atmospheric concentrations of suspended organic particulate matter over urban and suburban areas apparently could be estimated with reasonable confidence from the measurements of volumetric SO_2 during the fall, winter, and spring seasons in coal-burning communities. The seasonal regression slopes or equivalents differed, particularly the slope for the fall season when the measured SO_2 was equivalent to about twice as much organic particulate matter as during winter or spring. Suspended sulfate particulate matter was reasonably well associated with volumetric SO_2 during the winter season only ($r=0.70$).

Volumetric SO_2 and atmospheric soiling quality were significantly related during the winter season only ($r=0.70$); the relation, however, varied geographically (from station to station) and temporally (from month to month).

Many SO_2 and particulate matter relations might be reliable enough to use for general air pollution monitoring. Before the measurement of one pollutant could be reliably used for predicting the concentration of another type of pollutant, however, these relations would have to be investigated in several different communities.

A detailed method for inventorying sulfur dioxide emissions by square-mile areas was described by Stalker and co-workers in "Nashville Sulfur Dioxide Emission Inventory and the Relationship of Emission to Measured Sulfur Dioxide" (*16*). The emission inventory supplied considerable useful information for (*a*) control purposes, (*b*) development of a mathematical diffusion-ambient sulfur dioxide prediction equation, and (*c*) demonstration of a simple regression relation between average emission and average ambient concentrations of sulfur dioxide.

In Nashville, a square-mile area with an average winter-season emission of 1 ton of sulfur dioxide per day showed an atmospheric sulfur dioxide concentration of 0.022 ppm, an area in which 5 tons per day were emitted showed a concentration of 0.042 ppm, and one in which 10 tons of sulfur dioxide per day were emitted showed a concentration of 0.067 ppm.

Reference 17 is not outlined in this paper.

Sampling, analytical, and standardization procedures used to measure sulfur dioxide were presented in "Developments in the Measurement of Atmospheric Sulfur Dioxide" (*18*), by Welch and Terry.

The TCM method for collection and analysis of low concentrations of sulfur dioxide was found to be accurate, highly sensitive, flexible, and practical in this study. The adaptation of this method for use with an automatic analytical instrument, and methods of rapid midget bubbler handling, washing, and filling were described.

The relation between this modified TCM method and two other methods was investigated by using synthetic mixtures of sulfur dioxide in air. A dynamic calibration procedure showed that the Thomas autometer and TCM results were identical. The relation between the hydrogen peroxide and TCM methods was found to be (H_2O_2 results in ppm) $=0.72\times$ (TCM results ppm) $+0.04$.

The lead peroxide candle method used in Nashville for the estimation of sulfur dioxide also was described.

Meteorologic Findings

The data in Baulch's, "Relation of Gustiness to Sulfur Dioxide Concentration" (*19*) showed significant relations between the two most common gustiness classes (Brookhaven types B and D) and SO_2 concentration. Although the simplicity of this method may be criticized from a theoretical point of view, the Brookhaven classification of gustiness provides a useful index of turbulence for this type of analysis. Further application and refinement of the method will be necessary, however, before it will be satisfactory for use in determining atmospheric diffusion on a routine basis.

Effective application of this method of analysis could provide a useful tool for the development of a diffusion climatology for communities of all sizes. The economic advantages of utilizing gustiness data in addition to standard meteorological observations would make such a method especially valuable to smaller communities for which the cost of more extensive diffusion research has been prohibitive.

A method of forecasting air pollution levels was discussed by Boettger and Smith in "The Nashville Daily Air Pollution Forecast" (*20*). Their findings and recommendations follow.

The tested meteorological criteria were shown to be good indicators of three air pollution levels during the winter season, but could discriminate between only two levels during the spring and summer. Of three methods of measuring air quality, only the total particulate levels were high enough to be considered as a year-round air pollution indicator. Sulfur dioxide and soiling-index measurements were very low during the summer season and, when considered alone, implied the absence of community air pollution problems during that season.

While the forecasting results were not outstanding, the skill could be improved with further experience. More elaborate meteorological criteria could be used that might give better discrimination among the levels, but such a method would lack the forthrightness of the one used. Other straightforward criteria could be devised and tested with the same air quality data and associated meteorological conditions. Various weather parameters that could be investigated were average wind speed and direction and the presence or absence of an upper inversion. An additional influential parameter could be the duration of low wind speeds or interruption of these low speeds by periods of significant wind speed or both.

This program demonstrated that objective forecast methods could be used by local Weather Bureau offices to forecast daily air pollution levels during the seasons of the year when air pollution concentrations are high and troublesome. The forecast method was general enough that it could be adapted to other cities after consideration of climatology, topography, industrial locations, and the individual needs of the organizations that would use the forecasts.

Frederick found that, in an area of numerous but well-spaced, mature deciduous trees or clumps of trees, after defoliation the wind increased by a factor nearly 25 percent over "average exposure" and as much as 40 percent over exposures in areas nearly devoid of trees, and slowly decreased by the same amount as the leaves emerged and matured. Values varied somewhat according to number of trees, tree height, and distances between trees. These findings were presented in "A Study of the Effect of Tree Leaves on Wind Movement" (*21*).

In his paper "On the Representativeness of Surface Wind Observations Using Data from Nashville, Tennessee" (*22*), Frederick discussed the mean wind speed as applied to air pollution sampling. He found that carefully designed minimum-sized wind networks yielded reasonably reliable data for studies of urban airflow and ventilation. On the scale of the "Nashville Community Air Pollution Study," the correlation of wind measurements was independent of any parameter readily available or obtainable for other cities. It appeared to be dependent upon micro-environmental exposure.

The Weather Bureau Airport Station's hourly wind observations at Nashville were highly correlated with the average airflow over the city. Measurements of the urban area wind at Nashville averaged 60 to 70 percent of the suburban wind as measured at the airport.

Some generalized statements were possible about the reliability of wind direction observations at the Weather Bureau Airport Station.

Pooler used an empirical diffusion equation, with published summaries of wind direction and speed frequencies obtained at the Nashville Weather Bureau Station, to compute patterns of mean monthly relative concentrations. He discussed the following findings in "A Prediction Model of Mean Urban Pollution For Use With Standard Wind Roses" (*23*):

Hillside locations facing the sources showed generally higher than predicted values, and valley locations sheltered from the sources by intervening terrain showed lower values. Higher wind speeds appeared to increase the sulfation rate.

Relative monthly emission rates, determined from a comparison of predicted and observed values for the area, showed a close linear relation to monthly degree-day totals for the 5 months considered. A dropoff from the linear trend could be noted for nonheating and transitional months.

In "A Diffusion Model For An Urban Area" (*24*), Turner presented a working model for the diffusion of gases from multiple sources in an urban area. He found that the model, while giving encouraging results, generally tended to overcalculate, especially downwind of major sources. Calculated gaseous concentrations exceeded observed concentrations more frequently (28 percent) than observed concentrations exceeded calculated concentrations (14 percent) for 32 stations for 35 periods.

Undercalculation upwind of the major sources also was noted. It probably resulted from the fact that pollutant concentrations at the center of a square-mile area received no contributions from sources within that area but only from sources in other areas.

Despite the overcalculation, 58 percent of all calculated concentrations were within ± 1 part per hundred million (pphm) of the observed concentrations for the thirty-five 24-hour periods randomly chosen from the winter half of the year. When zero values of both calculated and observed concentrations were excluded, 70 percent of the calculated values were within a factor of two of the observed values. The model results were better than constant-concentration estimates in four of the five statistics used for comparison. The model had a skill score of 0.38 (significant at the 0.1 percent level) in estimating three classes of concentration: threshold, 0 to 1 pphm; low, 2 to 10 pphm; and high, more than 10 pphm. These results were especially encouraging in view of the following limitations of the model.

1. Area sources were represented as Gaussian-distributed crosswind line sources.
2. A constant effective height of 20 meters was assumed.
3. Topographic variations were ignored.
4. Meteorological elements were given no spatial variation.
5. The temporal variation of meteorological elements was by 2-hour periods only.
6. Emissions occurring during a 2-hour period reached receptors during the same 2-hour period regardless of travel time.

Although the model indicated the levels of concentrations and the general area extent of the pollution, certain sources of error were pointed out. From this experience, improvement was expected in future attempts at devising models.

The author planned to test a modified version of this diffusion model in another urban area and if possible with other pollutants, since knowledge of conversion rates of sulfur dioxide to sulfur trioxide, sulfuric acid droplets, and sulfates was limited. He thought improvement could possibly be achieved by more direct measurements of stability than were possible in Nashville. Increasing the complexity of either the diffusion model or the source inventory did not appear to be warranted for this time-and-space scale (24 hours with several kilometers between sampling stations) until air pollutant field measurements with lower thresholds and greater accuracy could be routinely obtained.

Another study by Turner on the "Relationships Between 24-Hour Mean Air Quality Measurements and Meteorological Factors in Nashville, Tennessee" (*25*) showed that meteorological variables of temperature, wind speed, and stability were well related to 24-hour citywide sulfur dioxide concentrations and soiling indexes. Sulfur dioxide concentrations and soiling indexes varied directly with degree-day value and 24-hour mean stability, and inversely with 24-hour mean wind speed. This study illustrated the magnitude of the variability of daily citywide air-quality levels, which might be explained by meteorological parameters that were routinely measured or obtained objectively from routine measurements.

Miscellaneous Findings

Morbidity and mortality data were collected by personal interview from a sample of 3,000 households in Nashville and certain surrounding areas. Finkner and co-workers described the design, conduct, and results of the Nashville morbidity survey in their paper, "Nashville Morbidity Survey: Design of a Household Survey For Air Pollution Research" (*26*).

Keilin used data from the morbidity survey for his "A Use of the Information Statistic as a Measure of Conformity in Comparing Two Sets of Responses" (*27*). He found that the use of the basic information theory provided an easy and interpretational method for analyzing two sets of responses to the same questions. In addition it had the advantage of being directly applicable to useful tests of significance.

Smith and associates presented the following conclusions in "Public Reaction to Air Pollution in Nashville, Tennessee" (*28*).

Responses to questions put to people in Nashville indicated an increasing awareness of and concern about air pollution as pollution levels in the respondents' neighborhoods increased. Air pollution levels were not the only factor influencing people's awareness of and concern about air pollution. Women were more concerned than men, and socioeconomic factors influenced awareness and concern.

Up to 3.8 percent of the respondents in the sample population were sufficiently aware of and concerned about air pollution as a health problem that they so expressed themselves of their own volition. An extension of the sample population to the total population of the Nashville area in 1958 indicated that somewhat less than 10,000 people were concerned about air pollution as a health problem.

Twenty-three percent of the respondents when asked the direct question said they were bothered by smog in one way or another. An extension of the sample to the total population indicated that about 50,000 people in the Nashville area were bothered by smog. In reply to direct questions, 18 to 51 percent of the respondents said they were bothered by some specific nonhealth effect of smog. Again, an extension of the data indicated that 40,000 to more than 100,000 people in the survey area were bothered by the soiling of surfaces and objects, decreased visibility, odors, and damage to property because of air pollution.

The data indicated that the people's awareness of and concern about air pollution were more influenced by the frequency of days of unusually high pollution than by the high monthly, seasonal, or annual average levels of pollution.

Summary

An extensive air pollution study was conducted in Nashville, Tenn., to investigate possible relations between air pollution and health and to gather information on a number of medical, engineering, meteorological and other phases of air pollution.

Bronchial asthma, anthracosis, morbidity, respiratory disease mortality, and cardiovascular disease mortality were studied in relation to air pollution.

More than 200,000 aerometric observations provided air quality data for use in the medical studies as well as in determining the representativeness of air quality data with respect to number and location of sampling stations, sampling frequency, and sampling time, and evaluating analytical methods, equipment, and procedures. These findings, plus an emission inventory and a discussion of the diurnal variation of carbon monoxide concentrations, have been outlined.

Meteorological factors were studied in relation to air quality. A method of forecasting air pollution levels and a discussion of a mathematical diffusion model have been presented along with the meteorological findings.

The findings from miscellaneous studies on design of morbidity surveys and opinions of people indicating their awareness and concern about air pollution have been presented.

A bibliography of papers on the Nashville study was included.

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