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CHICAGO AIR POLLUTION SYSTEMS ANALYSIS PROGRAM

FINAL REPORT

ARGONNE NATIONAL LABORATORY

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CHICAGO DEPARTMENT OF ENVIRONMENTAL CONTROL

• • •
U.S. ENVIRONMENTAL PROTECTION AGENCY

• • •
U.S. ATOMIC ENERGY COMMISSION

DIVISION OF BIOLOGY AND MEDICINE

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FINAL REPORT

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February 1971

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NOTE

This report summarizes work conducted from 1967 through 1970. During that period, several of the organizations involved were reorganized or had their official titles changed. In general, these organizations are referred to in this report according to the names by which they were known when the work was done. However, these names should be considered interchangeable with those indicated below.

On December 1, 1969, the Center for Environmental Studies (CES) was formally established at Argonne National Laboratory (ANL).

On February 1, 1970, the Chicago Department of Air Pollution Control (DAPC) was merged into the City of Chicago's Department of Environmental Control (DEC).

On December 2, 1970, with the formation of the U.S. Environmental Protection Agency, the National Air Pollution Control Administration (NAPCA) was designated the Air Pollution Control Office (APCO-EPA). Subsequent to the preparation of this report, APCO was renamed Office of Air Programs (OAP).

FOREWORD

The City of Chicago Air Pollution Systems Analysis Program discussed in this report represents a joint effort conducted and funded by the Atomic Energy Commission, the Department of Health, Education, and Welfare,* and the Chicago Department of Air Pollution Control.

Program direction, system analysis, and computer programming are provided by Argonne National Laboratory. Meteorology studies and computer model development are performed by Argonne and the National Center for Air Pollution Control, Cincinnati, Ohio. The Chicago Department of Air Pollution Control supplies emission and air quality data for the atmospheric dispersion studies.

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The objectives of this program were based on the fact that comprehensive urban air resource management involves relationships among technical, economic, and administrative factors. These relationships must be taken into account in the development of effective air pollution control strategies. If an air quality control region, whether of urban or interstate dimensions, is not treated as a unified system of interrelated components, then any localized or partial air management strategies developed are likely to be suboptimal. That is, either the desired air quality goals will not be attained, or unacceptable economic and operational penalties will be paid in the achievement of the established air quality standards. The Chicago project was therefore oriented around the use of the methodologies of system analysis to develop effective air pollution episode control strategies and long-range air quality control plans for urban areas.

The system-analysis program was designed to attain three primary objectives:

1. The development of a computerized methodology for 12- to 24-hr advance prediction of ambient sulfur dioxide concentrations produced by the combustion of coal and oil in residential, commercial, and industrial sources and power plants. Such a forecasting scheme would make it possible to formulate effective episode control strategies by providing the lead-time necessary to implement air-pollution-alert and emission-control plans. This effort is centered primarily on analytical and experimental studies necessary for the development of a source-oriented atmospheric-diffusion model.
2. The development of optimal air pollution episode control strategies. A matrix of practical, air pollution episode control plans must be based on detailed analyses of the operational and economic constraints imposed on emission control of various types of pollution-producing processes, on maximum exploitation of air pollution control resources, such as natural gas, and on cost-effectiveness studies of alternative control strategies. This approach should result in air pollution episode control plans that involve the minimum possible disruption of normal operations consistent with the attainment of acceptable air quality standards during an episode.
3. The integration of air pollution control into the long-range planning for an urban area. This involves a determination of the most effective use of emission-control legislation, zoning ordinances, land-utilization planning, highway routing, etc., to ensure that the urban area will evolve, during the next 10-15 yr, in such a way that no new air pollution source clusters will be created and that the layout of residential, commercial, and industrial areas and transportation networks will be consistent with the maintenance of acceptable air quality standards. This long-range planning effort involves taking account of population, economic and industrial growth patterns, and interaction with other urban planning agencies.

A critically important aspect of the planning effort involves evaluation of the long-range economic impact of air pollution control, since it is clearly unfeasible to formulate control plans that would seriously compromise key elements in the economic base of the urban area.

A combination of a computerized, source-oriented, atmospheric, pollution-dispersion model and use of the techniques of operations research are key elements in the long-range planning phase discussed in this report.

The system-analysis studies are conducted on the premise that the results must be generally applicable on a national scale. That is, the City of Chicago serves as a test case or demonstration city for the development of methodologies, techniques, models, and procedures which can be readily applied in other urban areas. Emphasis is therefore placed on the study and solution of air pollution problems that the Chicago metropolitan area shares with other medium-to-large urban concentrations, rather than on elements that are local and peculiar to Chicago alone.

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CHICAGO AIR POLLUTION SYSTEMS ANALYSIS PROGRAM FINAL REPORT

ABSTRACT

This is the final report of the Chicago Air Pollution Systems Analysis Program. This study shows how an integrated planning effort can bring together the data base for an urban area, establish a system for data management, and produce useful air pollution control strategies as a result. An atmospheric dispersion model was developed and successfully applied to the Chicago urban area. Statistical and experimental tests of the model are reported. Short-term strategies for control of air pollution episodes are presented. Long-range planning for air pollution abatement is shown to be feasible for a large dynamic metropolitan area.

1. A PROGRAM OVERVIEW

(E. J. Croke, Program Director)

1.1 Introduction

In September 1967, the Chicago Air Pollution Systems Analysis Program (CHAPSAP) began at Argonne National Laboratory under the joint sponsorship of the National Air Pollution Control Administration (NAPCA), the Atomic Energy Commission (AEC), and the Chicago Department of Environmental Control* (DEC). Program policy direction was provided by the NAPCA Division of Meteorology. The Argonne Center for Environmental Studies was responsible for research and development activities within the context of an interdisciplinary program organization that included the Argonne Divisions of Radiological Physics and Applied Mathematics. Consulting services were provided by Northwestern University. The Chicago Department of Environmental Control supplied data, facilities, personnel for field studies, and general technical assistance.

At the time the program was organized, the Clean Air Act of 1967 was a relatively new legislative instrument, and the thrust of the National Air Pollution Control program was directed toward the control of sulfur oxides and particulate matter discharged by industrial, residential, commercial, and institutional sources within and adjacent to developed metropolitan areas. The Clean Air Act promoted the concept of interstate regional control, and provided the funding necessary to develop the techniques and methodologies required to design and administer such programs at the state and local levels.

It was recognized that the design of effective urban and regional air resource management programs would involve an amalgam of technical, economic, political-legal, and managerial disciplines. Although substantial work had been done in most of these areas before 1967, a unified, interdisciplinary planning methodology did not exist. In part, this was attributable to the fact that the state of the art of many of the techniques involved had not reached a level at which they were suitable for operational use. For example, atmospheric dispersion simulation models remained in a highly experimental state of development. Beyond technique development, as such, larger questions relating to the interactive effects of imposing emission controls on the various sectors of an urbanized region had scarcely been explored. Thus, the effects of an episode control operation on an electric power distribution system, the physical and economic impact of large-scale conversions to alternative energy sources or the susceptibility of an urban transportation system to air pollution control activities had not been assessed.

*Formerly called the Department of Air Pollution Control (DAPC).

In response to the need for a comprehensive planning methodology, the Chicago program was organized as an interdisciplinary systems analysis. The planning problem was formulated in terms of the two distinct time scales for which operational air pollution control programs are designed: Short-term or episode control planning for events occurring on a time scale of roughly 12-72 hr; and long-range control, focused on the reduction of seasonal or annual average air pollution dosages. This resulted in the definition of four specific program objectives:

1. The development of a computerized, air pollution data-management system capable of processing, storing, retrieving, analyzing, and displaying the diversity of data required to formulate and assess the effectiveness of air resource management policies, and to support related scientific studies.
2. The development and validation testing of atmospheric dispersion models that could be applied to the design and evaluation of long-range and episodal emission-control programs and for short-range forecasting of ambient air pollution concentrations and dosages.
3. The development of techniques and procedures for the design and implementation of air pollution episode control strategies, and for the evaluation of the demands imposed by these strategies on the economic and physical resources of an urban area.
4. The development of methodologies for integrating long-range air resource management with urban and regional planning, including evaluation of the effects of economic growth and land development.

The greatest single resource available to the Argonne research team was almost certainly the very substantial inventory of emission and air-quality data provided by the Chicago Department of Environmental Control, and the opportunity to deploy the resources of that Agency in full-scale experiments which, in effect, exploited the City of Chicago as a real-world test bed for the evaluation of control techniques and strategies. The excellent cooperation provided by Chicago public utilities and industrial and commercial firms was also a material asset.

The results of this three-year study have been extensively documented in a series of nine progress reports (ANL/ES-CC-001 through 009). This final report summarizes the accomplishments of the program in all topical areas, and presents a detailed account of those aspects of the research which were not treated in previous reports. This section provides an overview of the entire study, which will serve as a guide to a prospective user of the program reports.

1.2 An Air Pollution Data Management System

The air pollution systems studies involved the analysis of a three-year inventory of sulfur dioxide data acquired by the Chicago network of eight telemetered air-monitoring stations. The data consisted of 5-min average, ambient concentrations recorded every 15 min on a 24-hr-per-day basis. The data were provided in the form of a partially edited magnetic-tape storage record. Evaluation of the data required the acquisition and processing of hourly average airport surface meteorology data, rural radiosonde balloon vertical temperature data, temperature and sulfur oxide data acquired by an instrumented helicopter, and vertical temperature data acquired by the Argonne meteorology facility. Most of this information was available in magnetic-tape storage format. In addition, an extensive annual average sulfur oxide emission inventory, supplemented with diurnal, weekly, and seasonal operating-cycle data for major sources, was provided in the form of tabular records. To cope with this substantial and diverse array of information, the APICS (Air Pollution Information and Computation System) data management system was developed. APICS is structured around the IBM PL-1 storage code, which is nested within a series of specialized input and output processing routines. These include a stepwise multivariate-discriminant analysis code, a source-emission simulation program, single- and multiple-source atmospheric dispersion models and tabular and graphical data-display routines. The system is user-oriented and includes provisions for access to data through user-developed FORTRAN programs, as well as through the standard processing routines. Any subset or group of subsets of the available data can be retrieved, processed, analyzed, and displayed. The APICS system has been documented in detail in ANL/ES-CC-006, which includes computer listings.

1.3 Development of Atmospheric Dispersion Model

Four atmospheric dispersion models were developed during the program. Of these, two are receptor-oriented statistical models adapted to meteorological analyses and short-range forecasting. The first of these stochastic systems is a linear regression model based on historical, meteorology, and air quality data; the second is a multivariate discriminant model. The regression model is discussed extensively in ANL/ES-CC-001 and -002; the discriminant model is presented in reports -002 and -003 of the series. Although neither of the statistical models was subjected to sufficient validation testing to render it a reliable operational forecasting system, both proved to be effective analytical tools in the study of urban air-pollution micrometeorology and dispersion phenomena. Both contributed significantly to the formulation of the source-oriented dispersion models described below.

The second set of dispersion models developed during the program consisted of source-oriented, quasi-deterministic simulations. The first of these was the "integrated-puff" transient model. The puff model is based

on a three-dimensional Gaussian kernel and is designed to simulate dispersion phenomena on a 1- to 24-hr time scale. The complete puff system includes a subroutine which estimates the urban mixing-layer altitude on the basis of rural radiosonde data and an urban surface-temperature measurement. The system also includes a subroutine (PLANTSIM) for simulating the diurnal operating cycles of a wide variety of source types. The puff model was validated against over 10,000 hr of air quality data, which included 1-, 6-, and 24-hr average sulfur dioxide concentrations. Compared to chance, the model is a significant predictor at better than the 99.9% confidence level, and has demonstrated skill scores of 0.77 to 0.84 in gaming tests. The puff model is extensively documented in reports -005 and -007 of the series.

A second source-oriented dispersion model was formulated to meet the requirements of long-range planning studies in which the simulation of short-time-scale phenomena is of secondary importance. This steady-state model was based on a two-dimensional Gaussian kernel and is essentially an improved version of the Turner-Nashville or Martin-Tikvart genre. It includes a "climatology" submodel, which generates historical frequency distributions for any specified combinations, range intervals, and persistence periods, of surface meteorology data recorded in the format of the standard national weather record center. It also contains an emission simulation routine which reproduces long-term electric power and fuel use distribution patterns and operating cycles for a power plant system and an aggregate of major industrial and space heating sources. Details of the steady-state model development and testing are recorded in report -008 of the series.

1.4 Air Pollution Episode Control Studies

The episode control studies are divided into three fairly distinct investigations. These are described below:

1.4.1 Optimal Control Study

A mathematical programming package was developed for on-line design of optimal power-load shifting and natural-gas allocation strategies during episodes. This package couples a transient atmospheric dispersion model with a linear programming model of a system of power plants and/or dual fuel sources. Economic and physical constraints on the distribution of power among generator units and conversion of dual fuel units to low-sulfur fuel are incorporated in the model. The hourly-average ambient sulfur dioxide concentration levels due to all plants in a system are maintained at or below a specified threshold limit during a predicted episode, and estimated system power demands are satisfied. Since the computer program requires less than 2 min of run time, revised strategies can be created as often as changes in meteorological or demand forecasts indicate the need. This study is discussed in report -003 of the series and in the present report.

1.4.2 Emission-control Field Tests

A series of emission-control field tests was designed and implemented in Chicago. These tests included participation by industrial, commercial, residential, and utility sources, which account for better than 80% of Chicago fuel-burning emissions. Three tests were conducted during a 27-month period. The first of these was a 21-day fuel switch test in which major sources were cycled according to a preset schedule. Meteorology and air-quality data acquired during this period were analyzed to establish the effectiveness of selective control strategies, and fuel-consumption records provided by participating sources were evaluated to identify diurnal operating patterns. The results of this test are discussed in detail in report -001 of the series. The second test was designed to simulate an episode-control operation, in that two 48-hr emission-control exercises, conducted during a 2-week interval, were triggered on the basis of meteorological forecasts. Operating cycle, meteorology, and air-quality data for the test periods were analyzed, and the effectiveness of the control response was assessed. This test is discussed in report -003 of the series and in Sec. 9 of this report.

The third and last test was organized as a full-scale, multistage, episode control operation, and was administered by Department of Environmental Control personnel assisted by Argonne technical advisers. The organizational system, computational and decision-making techniques, communications system, data formats, and procedures required to implement an episode control operation were tested during two 48-hr "war-game" exercises in which control activities were triggered by meteorological forecasts. The episode control war-game tests are discussed in report -004 of the series, and in more detail in the present report.

1.4.3 Economic and Resource Allocation Studies

A cost-effectiveness study of alternative episode control fuel-use policies was performed, using Chicago as a demonstration case. The economic impact of various fuel-switch alternatives on key sectors of the urban economy was compared with the resultant marginal reduction of total sulfur oxide emissions, within the constraints imposed by the availability of natural gas and the dual fuel capacity of major sources. These studies also included evaluation of the feasibility of a seasonal, emergency-"demand" gas contract through which a municipality could acquire a priority block of contingency natural gas, which could be allocated to major pollution sources during episode conditions. The cost-effectiveness studies are documented in reports -003 and -004 of the series, and the demand contract study is included in the present report.

1.5 Long-range Planning Studies

The long-range planning aspect of the program was designed to complement concurrent NAPCA-sponsored studies, in the sense that it focused

on the integration of air resource management with urban and regional planning, rather than on methods for superimposing air pollution control programs on an existing economic activity structure. Particular emphasis was placed on the dynamical aspects of the long-range planning problem in an effort to develop emission-control strategies that would not obsolesce as a result of the urban-development process. Two related, but fairly distinct studies resulted.

1.5.1 Land Use as an Organizational Basis for Air Resource Management Planning

A technique for using an atmospheric dispersion model to design emission-density-limited land-use plans and zoning ordinances was devised. This approach results in the creation of a regulatory mechanism which is compatible with more traditional "per-source" types of control, but which is comparatively immune to obsolescence. The technique allows maximum freedom of choice to operators of pollution-producing sources and is flexible enough to allow for changes in projected land-use patterns. It provides a quantitative means of relating land-use distribution and development intensity to a set of episodal and long-term regional air-quality standards, and provides for the design of regulatory programs having an inherent economic optimality. In support of this planning methodology, a practical technique for developing a regional zoning inventory was devised and tested in the Chicago Metropolitan Air Quality Control Region. This technique and the total planning methodology are discussed in detail in report -008 of the series. (The development of computer algorithms required to implement this methodology is now in progress at Argonne under a separate research program.)

1.5.2 An Air Quality Projection Model

A second element of the long-range planning study involved the development of a time-series projection model for the extrapolation of the growth and/or decline of existing industrial, residential, commercial, institutional, and utility sources in an urbanized region. This growth model, coupled with the climatology model, the long-term, source-operating-cycle simulation, and the steady-state dispersion model described above, was applied to Chicago as a demonstration case. The result was a set of computer-printed sulfur oxide isopleth maps which reflect emissions in all sectors, projected through 1975 and 1980.

The methodology and formats for acquiring and organizing the necessary data base, the computer code itself, and instructions for its use have been documented in detail in report -008 of the series. Maximum emphasis was placed on generalization of the growth projection model, so that its use is in no sense restricted to Chicago, which was regarded simply as a convenient test area for the methodology.

1.6 Urban Micrometeorology Studies

In support of the development of the atmospheric dispersion model, the substantial data base and computational system represented by the APICS package was used to conduct a number of micrometeorological studies of urban air-pollution dispersion phenomena. These studies focused primarily on the identification and study of meteorological "regimes," that is, persistent and recurrent combinations of observed meteorological parameters that appeared to correlate significantly with ambient air-pollution levels. These studies included investigation of such phenomena as the "fumigation" effect, the "lake breeze" effect, and the "heat island" effect, as well as a number of case studies of historical high air-pollution episodes in Chicago.

The results of the urban micrometeorology studies are presented in all reports of the series.

1.7 Conclusion

Aside from the substantive results of the CHAPSAP,* the project represents an encouraging example of how a national policy-making agency, an interdisciplinary scientific-research team, and a well-endowed local administrative agency can jointly mount an effective and broad-based attack on a significant problem of contemporary urban-industrial society. The merging of these three diverse perspectives within the framework of a research and development program designed to approach the air-pollution problem as a totality provided an extremely beneficial environment for creative methodological research.

A second aspect of the program that deserves mention is the effectiveness of the systems-analysis approach when applied in the (somewhat) unusual context of a research project in which study objectives must be framed in a comparatively general way. The formal systems approach provided a suprisingly serviceable means of focusing the innovative spontaneity that is characteristic of a research-oriented operation on the development of mission-oriented problem solutions.

*Chicago Air Pollution Systems Analysis Program.

2. EMISSION INVENTORY

(J. J. Roberts, L. A. Conley, J. Lin, and E. J. Croke)

2.1 Introduction and Summary of Results

A major task element of CHAPSAP was the development, in cooperation with the Chicago Department of Air Pollution Control (DAPC) of an inventory of hourly-average emissions from power plants and industrial, residential, commercial, and institutional SO_2 sources, which are the primary contributors to Chicago's sulfur dioxide air-pollution problem.

The structure, extent, and detail of the emission inventory were based on two fundamental considerations: the uses to which the data were to be put, and the available information. Several studies were contemplated. Argonne was interested in evaluating the possibility of identifying statistically the contribution from individual power plants in the Chicago area to the pollution levels measured at the eight telemetered air quality monitoring stations operated by the City of Chicago. Thus we anticipated performing statistical correlations between known emissions and observed values with the data stratified according to wind direction, wind speed, and other meteorological parameters. A hoped-for result of these statistical studies was the evaluation of improved dispersion coefficients for the urban area to be used in an urban atmospheric dispersion model. Data describing emissions on a short-term basis or information that would permit proration of longer-term emission data were recognized as essential inputs to the study.

Since a dispersion model was to be designed to yield air-quality estimates on a time scale of 6-48 hr in order to serve as a useful tool for the evaluation of episode-control strategies, it was evident that the maximum period over which time-variant emissions could be averaged for input to the model would, in general, be 6 hr. The minimum meaningful time for which SO_2 emissions could be averaged was dictated by the fact that the DAPC air quality monitoring system yields 5 min averaged wind and air quality data at 15-min intervals.

The decision to seek emission data averaged over 1-hr periods was, in the end, predicated on the manifest impossibility of obtaining meaningful emission data on any shorter time scale, and by the fact that the Weather Bureau meteorological records, which represent an essential component of the model, are, in general, based on hourly data or hourly-averaged data. An additional consideration of practical importance was associated with the fact that the magnitude of the task of processing emission data from those sources for which accurate continuous fuel-consumption records are kept would be altogether excessive if emission data averaged on a shorter time scale than 1 hr were sought.

The identification of the fuels that would be associated with SO_2 production presented no significant problem, since essentially all the SO_2 sources in Chicago burn southern Illinois or Kentucky coal or one of several grades of fuel oil. No other energy source used in the area (e.g., natural gas, automotive or aviation gasoline, etc.) contains enough sulfur to constitute a major source of SO_2 ; hence the emission inventory could legitimately be confined to coal- and oil-burning plants.

The ultimate emission inventory data base was developed from a melange of informational sources. It was keyed to the period December 1966 through December 1967 and is most accurate for calendar year 1967. Hourly SO_2 output from power plants was derived from actual megawatt logs for the period; other major sources were analyzed by prorating annual fuel-use data according to seasonal and diurnal patterns established by plant interviews in 1968; industrial area source data were derived from a 1963 Chicago DAPC survey of annual fuel use; commercial SO_2 emissions were based on a 1961 survey by the markets and rates department of Peoples Gas, Light, and Coke Company; and residential source data were taken from a 1967 survey by the same company.

Figure 2.1 shows the location and distribution of the largest individual coal- and oil-burning sources of sulfur oxides. Figure 2.2 shows the source density of residential, commercial, and industrial emitters which were too numerous to inventory individually. Figure 2.3 depicts the distribution and magnitude, by source category, of Chicago's SO_2 emitters.

For routine statistical analyses and for input to dispersion-model studies the emission inventory data were handled in three ways. Hourly emissions from power plants were stored in a master file in parallel-time series with meteorological and air quality data (see Sec. 3). Hourly emissions from industrial sources and from major institutional sources were calculated from longer-term emissions by the PLANTSIM code in Sec. 2.3 of the present report and Sec. 7 of ANL/ES-CC-007. These hourly values, although they could have been merged with the master file, were stored on a separate magnetic tape. Area-source data for residential, commercial, and industrial components were stored in card form as annual average emissions and prorated by algorithms within the dispersion model.

2.2 Power Plants

Since a major task element of CHAPSAP was to explore the possibility of statistically identifying the contributions from major sources such as power plants to individual monitoring stations, significant effort was placed on acquiring as accurate as possible an inventory of these sources on an hourly basis. For an operational control agency, the acquisition of hourly megawatt output is clearly impractical, except perhaps for special real-time computer runs made during episodal situations. Dispersion

Fig. 2.1. Chicago Map of Major Sources. ANL Neg. No. 112-8979 Rev. 3.

Fig. 2.2. Chicago Map of SO₂ Area Sources.
ANL Neg. No. 113-1169.

Fig. 2.3. Sulfur Dioxide Source Distribution Prepared by Chicago DAPC, 1967: ANL Neg. No. 112-7209.

models have usually assumed a uniform proration of annual fuel use, thus disregarding marked seasonal and diurnal variations in both total system load and in the division of this load among the units within the system. Therefore, in addition to the acquisition of hourly power-plant data for statistical studies, Argonne developed algorithms which, using statistics normally compiled by utilities, realistically simulate variations in power-plant output. The results of these simulations were not used as input to the dispersion model, nor were these algorithms tested by statistical comparison with the actual emissions recorded in the master file. A study of this sort does seem simple to perform and quite worthwhile in view of the interest of simulating power-plant emissions on a short-term basis for use in analyzing control strategies during air-pollution episodes. The power-plant simulation technique is described in detail in Sec. 7 of ANL/ES-CC-007. Algorithms to simulate short-term variations have been incorporated into the code, so that the capability now exists for performing detailed time-dependent analyses.

Electric power for the Northern Illinois region is provided by a network of 15 power-generating stations. Of these, six are located in the Chicago metropolitan area. These six coal-fired plants, whose locations are shown in Fig. 2.1, account for approximately 65% of the sulfur oxides released into the Chicago atmosphere. Table 2.1 indicates the relative contribution of each plant in terms of its annual fuel consumption.

Because of the extremely large emission rates associated with the urban power plants and because of their complex, but relatively consistent, diurnal emission cycle, the acquisition of the most accurate body of emission data that could be obtained was a priority task element of the emission

inventory. Fortunately, the Chicago utility maintains excellent records of plant operation. These were provided for January 1966 through December 1967. The data array required was:

1. Hourly power generation, in megawatts, for each generator unit of each power plant, including an indication of whether the power was generated with coal or gas.
2. Monthly coal and natural-gas consumption rates for each boiler-generator combination.
3. Monthly average coal-sulfur content analyses for each plant.
4. A set of boiler-turbine-generator efficiency curves for each generator unit. These presented efficiency versus power output for each unit.
5. A set of curves of stack temperature versus output for each plant.
6. A physical description of each plant layout, including the relationship between boilers, turbines, generators, and stacks, stack heights, etc.

TABLE 2.1. Sulfur Dioxide Emissions from Electric Utilities
(1967 data, Chicago DAPC)

Plant Designation ^a	SO ₂ , tons per year	SO ₂ , percent of city total
Crawford	107,954	18.97
Ridgeland	100,540	17.67
Fisk	73,438	12.90
State Line	70,606	12.42
Northwest	10,566	1.86
Calumet	10,016	1.76
Total	373,120	65.58

^aOf these installations, four--the Fisk, Crawford, Ridgeland, and State Line plants--are capable of partial or total conversion from coal to natural gas during periods when the latter fuel is available at "dump or interruptible" rates.

The above information was combined in a computer algorithm which yielded a calculation of the hourly fuel consumption and SO₂ emission rates

for each stack of each plant of the system. Details of the computational procedure are provided in the program progress reports (Croke et al., 1968 a,b,c).

The resultant body of power-plant emission data was stored in the master data file of the APICS from which it could be retrieved and automatically input to the dispersion model.

2.3 Industrial Sources

There are over 2500 relatively large coal- and oil-burning industrial plants in Chicago. On an annual average basis, these are responsible for approximately 10% of the sulfur oxides emitted within the city limits. The largest 100 of these plants account for over 83% of the total industrial emissions, and the largest 50 plants account for over 77% of this total.

The inventory of industrial emissions was derived from five sources.

a. Department of Air Pollution Control Survey. A comprehensive annual average inventory compiled in 1963 by the Chicago Department of Air Pollution Control was computer-processed to establish industrial SO₂ emissions on a square-mile basis. Within any given square-mile sector, industrial emissions were assumed to be uniformly distributed. Emissions from major point sources were subtracted from the appropriate square-mile values. The results are displayed in Fig. 2.2.

b. Argonne National Laboratory Field Survey. Detailed data on fuel consumption and physical and operating cycles for the 50 largest SO₂ sources were obtained through a field-survey system designed by Argonne and implemented by Laboratory and city engineers. This involved a program of site visitations and personal or telephone interviews with plant personnel.

c. Natural-gas Utility Records. The natural-gas consumption records for 1966-1967 and fuel costs for all dual fuel plants among the 50 largest SO₂ sources were obtained from the local, natural-gas supply utility.

d. Fuel-supply Records. The Midwest Coal Producers' Institute, an organization of wholesale coal suppliers, provided records of the annual average coal consumption by major industrial sources during 1966-1967.

Industrial sources that were not sufficiently large to be included among the largest 50 emitters were aggregated into uniformly distributed square-mile area sources. All plants in this category were assumed to have a stack height of 150 ft.

e. Hourly Records. For a limited number of major industrial plants, especially those located adjacent to power plants, special effort was devoted to acquiring accurate hourly emissions. In some cases, steam-flow records were available from which hourly fuel consumption could be calculated. Other plants kept monthly fuel purchase records or maintained daily boiler log sheets from which, given typical plant operating schedules, hourly emissions could be accurately estimated. These emissions, calculated from daily or monthly records, were entered in the master file, along with the hourly emissions from power plants for January 1966 through December 1967. Industries in this category include Campbell Soup, Cuneo Press, and the Metropolitan Sanitary District. Because of the time-consuming nature of this effort (see ANL/ES-CC-002, pp. 86-94), it was abandoned in favor of the PLANTSIM approach.

The 50 largest sources of SO_2 were treated as individual point sources in the dispersion model. A detailed analysis of the diurnal, weekly, and seasonal operating pattern of each of these plants, in combination with fuel-consumption records, gas-use patterns, and such characteristics as process versus space-heating fuel-use practices was used in an industrial-plant emission-simulation computer program (PLANTSIM) to generate an operating shift-oriented emission estimate for each plant.

The data file for large industrial sources is designed to include enough information about each plant to characterize its "expected" emission pattern by operating shifts for each day throughout the year. For this purpose, "shifts" are defined as follows:

Shift 1: 12 midnight to 8 a.m. (0000) to (0800).

Shift 2: 8 a.m. to 4 p.m. (0800) to (1600).

Shift 3: 4 p.m. to 12 midnight (1600) to (2400).

Up to three daily emission patterns may be assigned to each plant. These are as follows:

(1) W: Weekday or normal operation.

(2) S: Saturday.

(3) H: Sunday or special holidays.

Finally, a monthly weighting is provided to allow for variation due to seasonal patterns, etc. Each plant requires three computer cards: a source-identification card, and two source-emission cards. Formats and an example of each are shown in Figs. 2.4* and 2.5, respectively. Items

*To allow more room for recording the name and address of each company, the card depicted in Fig. 2.4 was broken into two cards, as is evident by comparison with the actual PLANTSIM input shown in Table 2.4.

Fig. 2.4. Source Identification Card. ANL Neg. No. 113-2863.

on the cards are described in Tables 2.2 and 2.3. Data for 52 major sources in Chicago (excluding utilities) is presented in Table 2.4 according to the PLANTSIM formats. The origin of the coordinate system (+X west, +Y south) is designated by the crossed arrows ( ) in Figs. 2.1 and 2.2.

TABLE 2.2. Items on Source Identification Card

No.	Item	Description
1	SOURCE NO.	Plant sequence number
2	NAME	Plant name (not to exceed 25 characters including blanks); address may be included if sufficient space is available
3	TYPE	Standard industrial code
4	GRID	City of Chicago square-mile number
5	COORDINATES	The x and y coordinates relative to standard City of Chicago coordinate system
6	STACK DATA	Four stacks maximum (1, 2, 3, 4) HGT: Stack height in feet %: The percent of total emission emitted from each stack
7	WORK SCHEDULE	Each day of the week is assigned to one of the following patterns; i. W: Weekday ii. S: Saturday iii. H: Sunday or Holiday

TABLE 2.3. Items on Source Emission Card

No.	Item	Description
1	SOURCE NO.	Plant sequence number
2	MAX SPACE HTG LOAD	Maximum hourly thermal requirements for space heating
3	MAX PROCESS LOAD	Maximum hourly thermal requirements for process
4	MONTHLY FUEL USE WEIGHTING	Achieves monthly variation in process fuel use. Each month is assigned a weight (0, 1, ..., 9) which corresponds to the average percent (0, 10, ..., 90%) of maximum process fuel used during that month
5	SHIFT FUEL USE WEIGHTING	Within each daily pattern (W, S, H), a weight (0, ..., 99%) is assigned to each shift, which corresponds to the average percent of current monthly process fuel used during that shift
6	% SULFUR COAL	Average percent of sulfur in coal
7	AVG % COAL	Average percent of thermal load due to coal (Zero implies coal is not used.)
8	% SULFUR OIL	Average percent of sulfur in oil
9	AVG % OIL	Average percent of thermal load due to oil (Zero implies oil is not used.)
10	% GAS SP HTG	The percent of space-heating thermal requirements that can be supplied by gas
11	% GAS PROCESS	The percent of process thermal requirements that can be supplied by gas
12	AVG GAS TEMP	The average ambient temperature (°F) at which the dual fuel plant receives gas on an "interruptible" supply contract (varies among plants, but 45°F is representative).
13	GAS PRICE	The gas rate (\$/therm) for dual fuel plants (Much of this data was unobtainable; PLANTSIM disregarded this variable.)

TABLE 2.4. Computer Card Input to PLANTSIM
for Major SO₂ Sources in Chicago, 1966-1967

SOURCES=52 ;

```

1 MARBHEAD MARELEHEAD LIME CO. 3245 E. 103 ST.
1 2819 26C1 C.5 -12.C 70101C0301C0301003C hhhhhhhh
1 10 2816 sssssssssssss sssssssssssssssssss 1.0 100 0. 0 100 30 45 .0325
2 CAMPBELL CAMPBELL'S SCUP CO. 2550 W. 35 ST
2 2032 CEC5 8.2 -3.5 17525175252505C0000 hhhhhsh
2 0 C 666554246766 7059957C2C203C303C 2.9 100 0. 0 100 100 45 .0420
3 PRCC_GAM PRCTCR AND GAMBLE 1232 W. NORTH AVE.
3 2841 03C7 6.5 2.0 225502255C0C0C0C00G0 hhhhhss
3 200 25C0 676655344567 60707C5C505C5C5C5C 2.7 100 0. 0 0 0 45 .0
4 SHER_WM SHERWIN-WILLIAMS 11541 SC. CHAMPLAIN
4 2851 28C5 4.1 -13.6 16099C00C0C0C0C000C0 hhhhhhhh
4 0 3150 665521C0C046 sssssssssssssssssss 2.8 100 0. 0 100 100 45 100.
5 INTRLAK1 INTERLAKE STEEL CORP 13500 SO. PERRY
5 3441 32C6 5.2 -16.C 225502255C0C0C0C000C hhhhhhhh
5 0 1365 sssssssssssss sssssssssssssssssss 2.6 100 0. 0 100 100 45 .0000
6 INT_HAR1 INTERNATIONAL HARVESTER 2600 W. 31 BLVD
6 3522 C6C5 8.2 -2.3 100201C02010C202044C hhhhhss
6 0 C 65553133445 6599853C55403C554C 3.0 100 0. 0 100 90 45 .0267
7 CON_1 CONTAINER CORP OF AMERICA 404 E. NORTH WATER ST.
7 2655 01C5 4.5 0.5 1965C1965C0C0C0C0000 hhhhhhhh
7 40 1400 666666666666 6059996C9999609999 2.2 100 0. 0 100 100 45 .0262
8 US_STEEL U.S. STEEL CORP 3426 E. 69 ST
8 3441 28C1 C.7 -10.2 15C99C00C0C0C0C0C0C hhhhhhhh
8 0 6970 sssssssssssss sssssssssssssssssss 0. 0 0.6 100 100 100 45 .0000
9 INT_HAR2 INTERNATIONAL HARVESTER 2800 E. 106 ST
9 3522 2602 1.5 -12.4 100501C05C0C0C0C00C0 hhhhhss
9 0 C 76553133445 6599853C55403C554C .97 95 1.7 5 100 0 45 .0
10 GEN_SOYA CENTRAL SCYA 1825 NO. LARAMIE
10 2042 0512 11.4 2.3 1674C1253C1253C0C00C hhhhhss
10 120 30C0 666666555666 5050702C504C20504C 3.0 100 0. 0 0 0 45 .0
11 DARLING1 DARLING AND CO. 1251 W. 46 ST.
11 2013 1CC7 6.7 -4.9 6120 90301575C00C0C0 hhhhhss
11 100C 6CC 595688888759 505999377575377575 3.0 99 .94 1 100 100 45 .0262
12 INTRLAK2 INTERLAKE STEEL CO. 11236 SC. TCRFENCE
12 3441 28C2 1.5 -13.1 6099C0C0C0C0C0C0C0C hhhhhhhh
12 0 64E sssssssssssss sssssssssssssssssss 3.0 78 1.5 27 0 0 45 .0
13 REP_SIL REPUBLIC STEEL CO. 11236 SC. TCRFENCE
13 3441 28C2 1.0 -13.1 10C501C05C0C0C0C00C hhhhhhhh
13 0 38C1 sssssssssssss sssssssssssssssssss 0. 0 0.8 100 100 80 45 .0000
14 CRANE CRANE CO. 4100 SC. KECZIE
14 3433 101C 9.C -4.3 2255C2255C0C0C0C0C0C hhhhhss
14 0 C 596531111159 2059332C20202C2020 3.2 93 1.5 7 100 100 45 .0300
15 ARMOUR ARMOUR AND CO. 1355 W. 31 ST
15 2011 08C7 6.4 -3.C 12050 7025 7025C0C0C hhhhhsh
15 10 0 ssscc0C00099 sssssssssssssssssss 0. 0 0. 0 100 0 45 100.
16 CHI_MSC CHICAGO MET. SANITARY DIST. 5901 W. PERSHING RD.
16 4952 1C13 12.4 -4.C 17525175251752517525 hhhhhhhh
16 0 8820 sssssssssssss sssssssssssssssssss 3.0 91 0.4 9 0 0 45 .0
17 INT_HAR3 INTERNATIONAL HARVESTER 1015 W. 120 ST.
17 3522 3CC7 6.3 -14.2 12099C00C0C0C0C0C0C0 hhhhhss
17 1000 13C0 76553133445 6599853C55403C554C 2.4 100 0. 0 100 100 45 .0640
18 GLIDDEN GLIDDEN CO. 2333 W. LCGAN
18 2033 07C6 7.9 3.3 1506C 5020 5020C000C hhhhhss
18 75 7C7 sssssssssssss 40707C4C505C4C505C 2.3 93 1.5 7 0 0 45 .0
19 WRIGLEY WILLIAM WRIGLEY CO. 410 NO. MICHIGAN
19 2073 01C5 4.7 C.5 12C99C00C0C0C0C0C0C hhhhhss
19 800 4CC sss543333569 508C8C5C8C8C508C8C 0. 0 2.0 100 100 100 45 .0310
20 DARLING2 DARLING CO. 4210 SC. ASPLAND
20 2013 1CC6 7.C -4.4 28C99C0C0C0C0C0C0C0C hhhhhss
20 0 C sssssssssssss sss98C102015102015 2.9 99 0.9 1 100 100 45 .0262
21 CONT_2 CONTAINER CORP OF AMERICA 900 W. LGDEN

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When the temperature is greater than 40°F, it is assumed that both space-heating and processing demands will be met 100% by natural gas; i.e., the plant has agreed to buy gas at or below the rate ($\$/\text{therm}$) most likely to be associated with this temperature.

The PLANTSIM code is completely general, in that large, individual space-heating sources or major institutional sources such as coal-fired water-pumping stations can be treated in exactly the same manner as industrial plants. For heating plants, the process-load portion of the operating-cycle input is zeroed and emissions are calculated solely on the basis of temperature. A special-purpose plant such as a pumping station may be treated as an industrial plant which consumes fuel according to a characteristic processing cycle.

2.4 Residential Space-heating Sources

Residential space-heating sources account for approximately 15% of the annual total emissions for the city. The inventory of coal- and oil-fired residential space-heating sources was derived primarily from data supplied by the market-research organization of the local natural-gas-supply utility. This information was in the form of a citywide, field-sampling survey of space-heating sources categorized by fuel use and by the number of dwelling units per building surveyed. For the emission inventory, the survey data were aggregated into two groups--moderate-sized residential structures of 19 dwelling units or less, and large apartment complexes of 20 or more dwelling units (see Fig. 2.2).

Since residential sources are generally too small and too numerous to treat individually, the two building-size categories described above were treated as uniformly distributed square-mile area sources. The source density per square mile for each category was assigned on the basis of the natural-gas-utility market-research data.

Studies by Peoples Gas, Light and Coke Company (PGLC) of the daily gas consumption of single-family residences in Chicago and by Turner (1967) on hourly gas consumption in St. Louis substantiate the strong coupling between fuel use and outside temperature. In the PGLC experiments, other parameters such as wind and sun played recognizable but relatively minor roles in the resulting scheme for predicting fuel requirements.

The operating cycle of the moderate-sized heating plants was based on a 65°F degree-day proration of a seasonal average fuel consumption, modified by an empirical function which represents the daily cycle of automatic stoking during waking periods, followed by a hold-fire and cooldown during sleeping periods. This cycle was simulated by a "Janitor Function," which maintains heating sources on an automatic stoking cycle between 6 a.m. and 10 p.m. on days having a minimum night ambient temperature in

Fig. 2.6. Janitor Function for Low-rise Space Heaters. ANL Neg. No. 113-1178.

excess of 5°F. For nights with a minimum temperature below 5°F, the automatic stoking period was assumed to begin at 3 a.m. The first heating hour of each day represents a building warmup period with approximately twice normal stoking requirements. In Fig. 2.6, this event is averaged over a 2-hr period to account for variability among buildings. This pattern was derived through an interview survey of building superintendents and heating-plant operators. A hot-water-heating base-load equal to 20% of the annual fuel use was assumed for all residential buildings in this category. All moderate-sized residences were assigned a uniform physical stack height of 50 ft.

Large residential buildings were considered to operate on an automatic stoking cycle at all times. Fuel use and SO₂ emissions were based on a 65°F degree-day proration, and a hot-water-heating baseload equal to 20% of the annual fuel use was assumed. All buildings in this size category were assumed to have a 200-ft physical stack height.

To substantiate the proposed "Janitor Function" for moderate-sized residences, a limited experimental study was initiated in which two Hyde Park buildings were instrumented to determine hourly coal consumption. Originally, Esterline Angus, clock-wound, pen-recording voltmeters were connected in parallel with the stoker relay. Instrument failures such as a defective escape mechanism and clogged capillary pens rendered this experiment unsuccessful. A proposed follow-up effort using event recorders with pressure-sensitive paper was abandoned due to the task of reducing the data within the limited funds available in the program.

2.5 Commercial and Institutional Sources

Very large steam-heated structures which account for slightly less than 20% of the total annual SO₂ emissions fall into two general categories: residential structures such as apartment complexes operated by the Chicago Housing Authority, and "commercial" institutions such as hospitals and universities. Commercial and institutional sources account for about 8% of total emissions in Chicago. Although the functions of these two classes of buildings are different, they may be expected to have similar fuel-use patterns, since all the heating plants operate on a 24-hr basis and the users generally are not prone to economize by significantly reducing the nighttime heating demands. It is anticipated, therefore, that fuel use in these buildings will closely follow a linear relationship with hourly temperature, the only complication being a time lag consistent with the thermal inertia of the large buildings.

Daily fuel-consumption figures were obtained for The University of Chicago (UC), Illinois Institute of Technology (IIT), and the Stateway (STWY) apartment buildings of the Chicago Housing Authority. Figures 2.7 and 2.8 show the daily data for December 1966 and January 1967 for IIT and Stateway. Table 2.5 lists results of a statistical study based on the regression equation

$$F_n = C_0 + C_1 DD_n + C_2 S_n + C_3 DDY_n + C_4 W_n, \quad n = 1, \dots, N,$$

where

$$F_n = \left(\begin{array}{c} \text{fuel fraction} \\ \text{for day } n \end{array} \right) \equiv (\text{Fuel used})_n / \sum_{j=1}^N (\text{Fuel used})_j,$$

$DD = 65^\circ\text{F} - (\text{Daily avg. temperature}),$

$S = \text{Hours of sunshine},$

$W = \text{Daily average wind (miles per hour)},$

and

$DDY = \text{Yesterday's degree day}.$

According to Table 2.5, the correlation between daily fuel use and heating degree days for several high-pressure steam systems is quite uniform. Considering the similarity of regression coefficients for daily fuel requirements, we may reasonably assume that these high-pressure steam plants can be represented on an hourly basis by the fuel-consumption rates for The University of Chicago for which hourly steam-flow records were obtained. Results in Table 2.6 are representative of many regressions based on a linear relationship between hourly fuel consumption at

Fig. 2.7. Fuel-use Data for Illinois Institute of Technology, December 1966 and January 1967. ANL Neg. No. 112-9723.

Fig. 2.8. Fuel-use Data for Stateway Apartments, December 1966 and January 1967. ANL Neg. No. 112-9724.

TABLE 2.5. Fuel-use Study for High-pressure Steam Plants, December 1966

Sources	Regression Coefficients (Eq.2)					Multiple Regression Coefficient
	C_0	C_1	C_2	C_3	C_4	
UC	1.8×10^{-2}	4.0×10^{-4}	a	a	a	0.907
	1.8×10^{-2}	4.1×10^{-3}	-3×10^{-5}	a	a	0.907
	1.8×10^{-2}	3.9×10^{-4}	a	1.9×10^{-5}	a	0.907
	1.6×10^{-2}	4.2×10^{-4}	a	a	1.5×10^{-4}	0.914
	1.4×10^{-2}	4.1×10^{-3}	-8×10^{-5}	4.4×10^{-5}	1.8×10^{-3}	0.917
IIT	2.0×10^{-2}	3.3×10^{-4}	a	a	a	0.732
	2.0×10^{-2}	3.5×10^{-4}	-6×10^{-5}	a	a	0.733
	2.1×10^{-2}	3.8×10^{-4}	a	-7×10^{-5}	a	0.739
	2.1×10^{-2}	3.3×10^{-4}	a	a	-3×10^{-5}	0.733
	2.2×10^{-2}	3.9×10^{-4}	-2×10^{-5}	-7×10^{-5}	-6×10^{-5}	0.740
STWY	1.8×10^{-2}	3.9×10^{-4}	a	a	a	0.930
	1.9×10^{-2}	3.5×10^{-3}	1.6×10^{-4}	a	a	0.937
	1.7×10^{-2}	2.9×10^{-3}	a	1.4×10^{-3}	a	0.956
	1.8×10^{-2}	3.9×10^{-4}	a	a	1×10^{-5}	0.930
	1.7×10^{-2}	2.7×10^{-4}	9×10^{-5}	1.3×10^{-4}	6×10^{-5}	0.959
ALL						
THREE	1.9×10^{-2}	3.7×10^{-4}	a	a	a	0.853
	1.9×10^{-2}	3.7×10^{-4}	2×10^{-5}	a	a	0.853
	1.9×10^{-2}	3.5×10^{-4}	a	3×10^{-5}	a	0.854
	1.8×10^{-2}	3.8×10^{-4}	a	a	5×10^{-5}	0.854
	1.8×10^{-2}	3.7×10^{-4}	-1×10^{-6}	4×10^{-5}	6×10^{-5}	0.855

^aCorresponding variable not included in the regression analysis.

TABLE 2.6. The University of Chicago Hourly Fuel-use Correlations

$$Q = C_0 + C_1 [\text{Midway hourly temperature}]$$

Data Set	No. of Points	C_0	C_1	R
January 1966, December 1966, January 1967 Hours 10-15 Cloud cover ≤ 0.8	241	20	-0.18	0.90
January 1966, December 1966, January 1967 Hours 1-24 Cloud cover ≤ 0.9	1088	19	-0.18	0.85

The University of Chicago and Midway Airport temperature. These show that the University heating plant is well characterized by the same temperature dependence for all hours of day and night. Furthermore, no significant improvement in the regression results were obtained by relating the fuel use at hour η to the temperature at hour $\eta - \Delta$ for delays Δ of up to four hours.

3. DATA MANAGEMENT

(C. Chamot and A. S. Kennedy)

One of the most difficult problems confronting the environmental scientist, the urban and regional planner, and the environmental-control agency official is associated with the organization, storage, retrieval, processing, analysis, and display of the very large and diverse inventory of data often required to characterize an environmental system. In the field of air resource management and planning, three distinct types of information must be manipulated in order to devise effective air-pollution control implementation plans. These are emission-inventory data, meteorological observations, and calculated or measured air quality data. APICS (a computerized data-management system) was developed as an aid to research associated with the Chicago Air Pollution Systems Analysis Project. APICS consists of a series of codes and subroutines which make it possible to manipulate the three types of data in any desired way. Since early in 1967, the system has proved to be an invaluable analytical tool for the meteorology, systems-analysis, mathematical-modeling, and planning studies conducted at Argonne. Some of the applications of the system in the City of Chicago Air Pollution study are listed in Table 3.1. The system is well adapted to the creation of an urban or regional environmental data bank.

TABLE 3.1. A Summary of Uses of APICS^a

Category	Description
Data Retrieval	<ol style="list-style-type: none"> 1. Selective searches for meteorological phenomena which affect air pollution concentrations, such as inversions, fumigations, lake breezes, and stagnations. 2. Time-series charts of air pollution and meteorological variables for 1966 and 1967. 3. Pollution episode identification studies.
Data Analysis	<ol style="list-style-type: none"> 1. Pollution episode frequency studies. 2. Air pollution percentile tabulations as a function of meteorological variables. 3. Wind-direction frequency studies. 4. Emission-source fuel-use regression-analysis study. 5. Analysis of adverse medical effects of SO₂.
Prediction Models	<ol style="list-style-type: none"> 1. Development of receptor-oriented air quality forecasting and analysis models based on linear regression analysis. 2. Multiple-discriminant-analysis air quality prediction system. 3. Validation of multiple-source atmospheric dispersion model.
Air Pollution Control Resource Allocation Models	<ol style="list-style-type: none"> 1. Power-plant system optimal fuel-switching and load-shifting control model. 2. Gas-allocation model for industrial plants with dual-fuel capability. 3. Computation of natural-gas demand for dual-fuel switching during pollution "season."

^aThe APICS applications listed are among those devised for CHAPSAP. The potential uses of the system are not restricted to these and are constrained primarily by the ingenuity of the user.

The flow of information through the APICS system is shown in Fig. 3.1. The system includes programs to create and maintain master files of combined data types, to search master files for desired information,

and to pass the data to the various display and computation programs. These programs may be used to generate printed or graphical displays such as those shown in Figs. 3.2 and 3.3, to perform various types of statistical analysis (e.g., Sec. 4.4), to generate tables for predicting local pollution levels based on meteorological phenomena (see Sec. 6), and for dispersion-model studies (see Sec. 7).

Fig. 3.1. Information Flow through APICS. ANL Neg. No. 113-1139.

Fig. 3.2. Mesometeorological Map for Chicago. ANL Neg. No. 113-1147.

Fig. 3.3. Time-series Plots for TAM Data. ANL Neg. No. 113-1145.

The system is fully documented in ANL/ES-CC-006, which emphasizes those aspects of the system that may be generally applicable to similar situations in other cities and indicates how other data types and analysis programs could be incorporated into the system. The programs in APICS are coded in PL/I and FORTRAN for the IBM System 360/75 computer. The system has been used to retrieve and analyze specified data items from master files containing more than 4,000,000 observations. (This represents $2\frac{1}{2}$ years' worth of hourly values for 200 parameters.) The format of the data values in the master files is shown in Fig. 3.4. The names associated with each data item are available for accessing the data and for identifying output generated by the display and computation programs. The use of the descriptive key names to identify stations and parameters (as opposed to a numbering scheme) facilitates the use of the system and reduces input errors.

DATE: 66/01/01

TIME	MIDWAY				TAM-3			CAMPBELL		...
HOURL	TEMP	WIND_DIR	WIND_VEL		SO ₂	WIND_DIR	WIND_VEL	SO ₂ -TOT		
1										
2										
3										
•										
•										
23										
24										

Fig. 3.4. Sample Master File Record Format. ANL Neg. No. 113-1140.

The principal design philosophy for the development of APICS was flexibility in the following two respects:

- 1) The ability to incorporate data in the master files from sources that could not be anticipated.
- 2) Facility to add computational programs which operate on the data base as the need arises.

The studies that have been performed using APICS at Argonne indicate that the desired flexibility has been achieved. The open-ended feature of the system has made it possible for new programs to be continually added to the system by participating scientists, thus increasing its capability. The emphasis on a well-planned modular system from the outset of the project has contributed significantly to the rapid development and successful operation of APICS.

4. AIR POLLUTION METEOROLOGY

(H. Moses, D. F. Gatz, J. E. Carson, F. C. Kulhanek, G. A. Zerbe,
J. E. Norco, J. E. Ash, J. P. Bradley, and E. W. Klappenbach)

4.1. Introduction (H. Moses)

In urban areas, if the emission rate and the advection of contaminants remain constant, the meteorological conditions and the nature of the terrain determine the severity of air pollution. Concentrations of atmospheric contaminants may be 1000 times greater during the least favorable as compared to the most favorable diffusion conditions. The role of meteorology in influencing levels of air pollution is examined in this chapter.

Meteorologists divide weather phenomena into three broad categories: (1) the large scale or synoptic, (2) the mesoscale, and (3) the microscale. The individual meteorological elements characteristic of each of these scales contribute to the air quality over a given region.

This chapter consists of five sections devoted to various aspects of each of these three scales of meteorological phenomena. Section 4.2 covers the influence of cyclones (lows) and anticyclones (highs) upon air pollution. Section 4.3 deals with mesoscale phenomena such as the sea breeze. Studies on the breakup of the nocturnal inversion with the accompanying fumigation phenomena are reported, but these are rather brief. Other important mesoscale features are mountain-valley circulations, thunderstorms, frontal passages, and precipitation processes. These are not covered.

Local weather phenomena on a scale of a mile or less may influence concentrations of air contaminants. Some of these micrometeorological processes may result in a deviation in the general wind direction or on the development of local ground fog. Section 4.4 compares the wind directions at a number of TAM stations and those at the Chicago Midway Airport. Micrometeorological processes may account for the observed differences.

Section 4.5 reports on a study of the height of the aerosol mixing layer. The mixing height is the height of the layer in contact with the ground in which concentrations of contaminants are relatively high but fall off rather sharply above this height. The layer appears as a smoke screen to one approaching a city by plane or automobile.

Section 4.6 provides a detailed study of the air pollution episode over Chicago during November 5-12, 1969. This episode received considerable attention in the newspapers. As will be seen, meteorological influences played an essential role in bringing about the high pollution levels.

4.2 Meteorological Aspects of Air Pollution Episodes (Harry Moses, John P. Bradley,* Donald F. Gatz, and Edward W. Klappenbach**)

4.2.1 Introduction

The U.S. National Weather Service issues air pollution potential forecasts for regions of the United States when atmospheric diffusion is expected to be poor for 36 hr or more. These forecasts provide a general picture of what may occur over a given area. Appreciable judgment is often necessary to apply these forecasts in practice.

Periods shorter than 36 hr during which pollution is high are often of concern to persons breathing this air. Further, over a large urban complex with its multitude of area sources and stacks of different heights, the concentration levels at any one time may differ appreciably from one part of the city to another. A municipality or air quality region must have information not only on the locations, strengths, operating characteristics, and schedules of the sources, but also on how local weather and terrain influences the time and space variation of pollutants. A department of air pollution control must therefore have the capability to identify and act on air pollution episodes that are more restricted in duration and area than those covered by the federal air pollution potential forecasts.

An understanding of the conditions leading to air pollution episodes is essential to anticipate their occurrence and to take corrective action. For example, reliable meteorological forecasts can be used to advise public utilities and other coal users with the capability of switching to gas to activate an air pollution abatement strategy. Such action would prevent concentration levels from exceeding adopted standards.

Information is presented on how to identify those weather conditions which lead to high ground concentrations of pollutants. As will become evident, conditions providing high pollution in the Midwest may be quite different from those on the West coast or in Appalachia. Nevertheless, the methods used here may be applied to any area of the country. Chicago was used as an example because SO₂ concentration data and good meteorological data were readily available and because we are familiar with the special features of the area.

4.2.2 Techniques for Identifying an Air Pollution Episode

The first step in providing a picture of the conditions leading to high-pollution situations consisted of identifying the 20 periods with the most serious air pollution conditions which occurred over the two-year period 1966-1967. (See Table 4.1.) These episodes were then related to the large-scale and micrometeorological conditions, including terrain effects.

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**Present affiliation: Department of Environmental Control, Chicago, Illinois.

TABLE 4.1. The Twenty Most Serious Air Pollution Episodes over Chicago, Illinois; January 1, 1966 to December 31, 1967

Episode No.	Date of Beginning	First Hour of Episode, CST	Duration, hr	Last Hour of Episode, CST	Date of Ending
1	Jan 5, 1966	0200	41	1800	Jan 6, 1966
2	Jan 17, 1966	0400	62	1700	Jan 19, 1966
3	Jan 19, 1966	1900	23	1700	Jan 20, 1966
4	Jan 23, 1966	2300	38	1200	Jan 25, 1966
5	Jan 26, 1966	0400	32	1100	Jan 27, 1966
6	Jan 28, 1966	0000	106	0900	Feb 1, 1966
7	Feb 1, 1966	2200	52	0100	Feb 4, 1966
8	Feb 20, 1966	1700	50	1800	Feb 22, 1966
9	Dec 26, 1966	0200	39	1600	Dec 27, 1966
10	Dec 29, 1966	0600	49	0600	Dec 31, 1966
11	Jan 2, 1967	2000	51	2200	Jan 4, 1967
12	Feb 9, 1967	0300	13	1500	Feb 9, 1967
13	Feb 12, 1967	0200	12	1300	Feb 12, 1967
14	Feb 16, 1967	1500	19	0900	Feb 17, 1967
15	Feb 24, 1967	0100	58	1000	Feb 26, 1967
16	Mar 1, 1967	0500	7	1100	Mar 1, 1967
17	May 9, 1967	2000	7	0200	May 10, 1967
18	Nov 28, 1967	1400	25	1400	Nov 29, 1967
19	Dec 20, 1967	0500	7	1100	Dec 20, 1967
20	Dec 28, 1967	0500	36	1600	Dec 29, 1967

Appropriate air quality standards may be assumed as a means for identifying an episode. For this study, a concentration of 0.3 ppm for a duration of four or more consecutive hours was arbitrarily used as the minimum standard for considering the existence of an air pollution episode.

4.2.2.1 The IDA Index. The severity, S , of an air pollution episode depends upon (1) the intensity, I , of the pollutant concentration; (2) its duration, D ; and (3) the number of people affected, A . (For convenience, A can be represented by the product of the population density and the area involved.) The product of the intensity and the duration represents the dose received by an individual. The dose times the number of people or the man-dose figure may serve as an index for assessing the severity of the given episode. In symbolic terms,

$$S = I \times D \times A.$$

If air quality monitoring stations are representative of the same number of persons, then the number of stations may be a measure of the number of people involved. Where the population density varies with location, as it does, a weighting factor should be used. In this study, the weighting factor was neglected.

Figure 4.1 shows the chart used to select the 20 cases. This gives a possible index of the impact of an episode. For convenience, the duration is plotted on a logarithmic scale, and the number of persons affected is represented by the average area covered during the episode. The derived variable, the area coverage ratio (ACR) is given by

$$\text{ACR} = \frac{\text{No. of station hours with SO}_2 \text{ concentrations} \geq 0.3 \text{ ppm}}{\text{No. of consecutive hours in episode}}$$

In general, the 20 points farthest from the origin were selected. These do not necessarily represent the points* having the maximum man-doses--probably a sounder criterion.

Fig. 4.1

Episode Impact Chart. (Episode numbers are beside the points.)
ANL Neg. No. 149-4620.

The SO_2 concentrations were based on the eight telemetered automatic monitoring (TAM) stations distributed over the city of Chicago, as shown in Fig. 4.2. Each hourly value represents the average of five of the 15-min readings centered about the hour. Table 4.2 shows the distribution of groups of stations showing 0.3 ppm or greater for each month. The seasonal effect is marked. In January and February, as many as six stations recorded 0.3 ppm or more simultaneously. In July, no more than one station recorded this value. Table 4.3 summarizes a similar analysis showing frequency of occurrence of episodes having the indicated durations for 1966 and 1967 and the combination of the two years.

4.2.2.2 The Air Pollution Episode. Another technique for identifying the severity of an air pollution condition has been called the Air Pollution Index (API). This may be defined as

*The episodes may be denoted by points in a three-dimensional space represented by a rectangular coordinate system where the axes represent intensity, duration, and area covered.

Fig. 4.2

Map of Chicago Area Showing Telemetered Automatic Monitoring (TAM) Stations. Midway Airport (MDW), O'Hare Field (ORD), Glenview Naval Air Station (NBU), Meigs Field (CGX), and Argonne (ARG). ANL Neg. No. 149-4448.

TABLE 4.2. Number of Hours in Which Indicated Number of TAM Stations Recorded SO_2 Concentrations ≥ 0.3 ppm

	Total Number of TAM Stations								Total Station Hours	Heating Degree Days		Total Number of TAM Stations								Total Station Hours	Heating Degree Days
	1	2	3	4	5	6	7	8				1	2	3	4	5	6	7	8		
1966											1967										
Jan	224	121	92	37	10	2	0	0	952	1437	Jan	272	33	6	0	0	0	0	356	1113	
Feb	148	79	25	4	2	2	0	0	419	1031	Feb	232	133	30	16	2	0	0	562	1198	
Mar	160	36	12	4	0	0	0	0	284	761	Mar	135	65	7	3	1	0	0	303	814	
Apr	92	17	1	0	0	0	0	0	129	511	Apr	44	18	1	1	0	0	0	87	437	
May	38	3	0	0	0	0	0	0	44	314	May	39	9	4	1	0	1	0	79	330	
June	21	0	0	0	0	0	0	0	21	33	June	8	0	0	0	0	0	0	8	10	
July	7	0	0	0	0	0	0	0	17	0	July	4	0	0	0	0	0	0	4	26	
Aug	15	1	0	0	0	0	0	0	17	4	Aug	14	1	0	0	0	0	0	16	16	
Sept	18	3	0	0	0	0	0	0	24	83	Sept	21	0	0	0	0	0	0	21	104	
Oct	57	9	2	0	0	0	0	0	81	363	Oct	77	16	0	2	0	0	0	117	381	
Nov	174	38	10	2	0	0	0	0	288	653	Nov	194	82	22	5	0	0	0	444	803	
Dec	354	63	9	3	1	0	0	0	524	1116	Dec	172	88	14	3	1	0	0	407	1027	
Total	1308	370	151	50	13	4	0	0	2790	6306	Total	1212	445	84	31	4	1	0	2304	6259	

TABLE 4.3. Frequency of Occurrence of Consecutive Hourly Intervals in 1966-1967 with at Least One TAM Station Recording ≥ 0.3 ppm SO_2

	Number of Consecutive Hours										Total
	<4	4-8	9-13	14-18	19-23	24-28	29-33	34-38	39-43	≥44	
1966	280	84	12	9	8	3	2	1	2	5	406
1967	282	76	20	16	6	4	2	2	0	2	410
1966/1967	562	160	32	25	14	7	4	3	2	7	816

$$API = \frac{\sum_{j=1}^8 \sum_{i=1}^{24} C_{ij}}{N},$$

where

C = SO_2 concentration,

i = hour of the day,

j = station number,

n_i = number of hours used in computing the average,

n_j = number of stations used in computing the average,

and

$$N = n_i n_j.$$

Stated more simply, the API is calculated by first obtaining the 24-hr average SO_2 concentration for each station. These are averaged again to obtain the eight-station daily average.

Figure 4.3 shows the histograms and Fig. 4.4 shows the cumulative-frequency charts of the API for 1966, 1967, and for both years. Figures 4.5 and 4.6 show the histograms and cumulative-frequency bar diagrams of the average daily concentration for each TAM station for 1966 and 1967. A marked difference of the air pollution conditions over different sections of the Chicago area is clearly shown: A picture of the day-to-day variation of the Chicago API is shown in the bar diagrams of Fig. 4.7. These figures provide a picture of the distribution of SO_2 average concentration and their daily variation, for January and July 1966.

Fig. 4.3. Air Pollution Index (API) Histograms.
ANL Neg. No. 149-4621.

Fig. 4.4. Cumulative Bar Diagrams of API.
ANL Neg. No. 149-4622.

Fig. 4.5. Average Daily SO₂ Concentrations for Chicago TAM System for 1966 and 1967.
ANL Neg. No. 149-4623.

Fig. 4.6. Cumulative-frequency Chart of Average Daily SO₂ Concentrations for Chicago TAM System for 1966 and 1967.
ANL Neg. No. 149-4624.

Fig. 4.7

Bar Diagram Showing API
for January and July 1966.
ANL Neg. No. 149-4625.

4.2.2.3 The API during the Twenty Selected Episodes. The API is based upon a 24-hr period; the IDA episodes are based on the number of consecutive hours in which concentrations of SO_2 equaled or exceeded 0.3 ppm. The duration of IDA episodes ranged from 7 to 106 hr. Further, the API considers all the measurements, but the IDA cases include only values at or above the 0.3-ppm threshold. Nevertheless, a comparison is possible under certain conditions. The comparison was based on those days in which 12 or more hours were part of an episode. Table 4.4 shows this comparison. In the 20 episodes, there were 32 days in which 12 or more hours were part of the IDA episode. It is evident that the 16 days having the highest API were also days chosen by the IDA technique. These days

TABLE 4.4. API on Days Selected by the Intensity-duration-area
Method as the Twenty Most Serious Episodes

API			API		
SO_2 Concentration, ppm	No. of Cases	No. of Days with Given API Also Showing 12 hr or More in IDA Groups	SO_2 Concentration, ppm	No. of Cases	No. of Days with Given API Also Showing 12 hr or More in IDA Groups
0.31	1	1	0.20	4	4
0.30	0	0	0.19	9	5
0.29	0	0	0.18	5	1
0.28	0	0	0.17	8	2
0.27	1	1	0.16	10	2
0.26	0	0	0.15	14	2
0.25	3	3	0.14	17	1
0.24	3	3	0.13	21	1
0.23	0	0	0.12	21	1
0.22	3	3	0.11	27	0
0.21	1	1	0.10	34	1

had values of SO_2 concentration of 0.20 ppm or greater. Eighty percent of the days with an API value of 0.18 ppm or greater were also included in the IDA classification. For smaller values, the correspondence degraded rapidly.

4.2.3 Relation between Synoptic Weather Patterns and Air Pollution

An examination was made of the synoptic and micrometeorological conditions associated with the IDA episodes to identify the factors that contribute substantially to the occurrence of an air pollution episode. An objective in identifying these meteorological factors was to determine what must be forecast to anticipate an air pollution episode.

4.2.3.1 The Booz-Allen Classification. A classification system devised by Booz-Allen (Hallanger, 1968) for producing diffusion forecasts was examined. The classification system consists of 35 surface-weather types and 20 patterns of the 500-millibar surface; these are listed in Tables 4.5 and 4.6. Although the identification procedure was designed to be objective, considerable subjective judgment is necessary both in classifying the weather maps and in interpreting the classifications.

Application of the method to the weather maps associated with the pollution episodes resulted in the identification of certain preferred weather types. Figure 4.8 shows the frequency of simultaneous occurrence of surface and 500-millibar types associated with the episodes. The 0000 CST Daily Weather Map was used in the identification procedure.

The most frequent 500-millibar flow associated with air-pollution episodes in Chicago was meridional (primarily posttrough), since such flow is often associated with below-normal temperatures and high SO_2 production for space-heating needs. Zonal flow at 500 millibars was also frequently associated with air-pollution episodes. This flow is usually accompanied by relatively weak, rapidly moving surface systems.

The majority of the surface types fell under the "High, Center North" and "Ridge or High, Center South" grouping. The Deep Closed Low category involved a deep closed low, distant from Chicago, most often on the east coast. Actually, Chicago was more properly under the influence of an elongated ridge of high pressure to the west that had a "cyclonic dent" in the isobars over the Great Lakes.

In fairness to the Booz-Allen classification, it must be pointed out that it was not designed for the type of episode discussed here. Its shortcomings must therefore be judged accordingly.

TABLE 4.5. The Booz-Allen Surface Types

Type No.	Description
	<u>1. Deep Closed Low (deepening or mature cyclone)</u>
	a. Center North
1	(1) Advance Zone
2	(2) Prefrontal and frontal (occlusion or warm front) (or trough)
3	(3) Postfrontal (or trough) (cold front or occlusion)
4	(4) Warm sector
5	(5) Prefrontal and frontal (cold)
	b. Center South
6	(1) Advance Zone
7	(2) Pretrough
8	(3) Posttrough
	<u>2. Open Wave Cyclone Moving SE or E</u>
	a. Center North
9	(1) Advance Zone
10	(2) Prefrontal (warm)
11	(3) Warm sector
12	(4) Prefrontal and frontal (cold)
13	(5) Postfrontal (cold)
	b. Center South
14	(1) Pretrough
15	(2) Posttrough
	<u>3. Open Wave Cyclone Moving NE</u>
	a. Center North
16	(1) Frontal (warm)
17	(2) Warm sector
18	(3) Prefrontal and frontal (cold)
19	(4) Postfrontal (cold)
	b. Center South
20	(1) Advance Zone
21	(2) Pretrough, warm front zone
22	(3) Posttrough
23	(4) Warm sector
	<u>4. Meridional Trough (N-S or tilted)</u>
24	a. Pretrough
25	b. Posttrough
26	c. Trough or frontal zone
	<u>5. Inverted Trough</u>
27	a. Pretrough
28	b. Posttrough
	<u>6. Ridge, or High, Center South</u>
29	a. Preridge
30	b. Postridge
	<u>7. High, Center North (or same latitude)</u>
31	a. Preinverted ridge
32	b. Center
33	c. Postinverted ridge
34	d. E-W gradient
	<u>8. Flat Pressure Area</u>
35	Cols or other areas (except high centers) where wind is determinate

4.2.3.2 Similarities in Weather Patterns Associated with Episodes.

An examination of the synoptic surface charts associated with the episode showed a number of similarities: (a) weak pressure gradient, resulting in light winds, (b) low surface temperatures, and (c) clear skies, especially at night.

4.2.3.2.1 Weak Pressure Gradient. One of the outstanding features about the synoptic surface charts was that a weak pressure gradient was the rule with very few exceptions during the air pollution episodes. The two years of daily weather charts showed that levels of SO₂ concentrations invariably increased when weak pressure gradients, such as occur in a col or in an anticyclone center, passed over the city. The weak pressure gradients ordinarily mean light surface winds, but local terrain influences may act to increase air movement.

4.2.3.2.2 Low Temperatures. Another striking feature was the occurrence of high pollution with cold waves. This is understandable, because the need for increased space heating results in more coal burning and consequently more SO₂ emitted into the atmosphere.

A combination of high winds and low temperature produces a high wind-chill factor. Higher winds therefore are associated with two opposing factors concerning the production of high concentrations of SO₂. On the one hand, high winds are associated with pronounced turbulent mixing, tending to keep SO₂ concentrations low; on the other hand, high winds produce increased cooling, lending to the greater production of SO₂ and higher ground concentrations. The complex balance of opposing influences results in the observed SO₂ levels.

4.2.3.2.3 Stability. The presence of an inversion, either ground-based or located within the first 5000 ft, is significant in providing high levels of SO₂ concentration. An inversion aloft may produce a "lid" to keep the pollutant confined to a restricted layer. Although data on the variation of temperature with height were lacking, it is well known that during clear nights with light winds, ground-based inversions are certainties in rural areas; over urban areas, an inversion may not form, but the stability increases. The increase in stability is conducive to the development of high SO₂ concentrations. Light winds and clear skies are conditions associated with anticyclones, especially near their centers or in the ridge areas between centers in multi peaked systems.

4.2.3.3 Anticyclone Types. The conditions conducive to high levels of pollution, light winds, low temperatures and stability occur most frequently though not always with anticyclones. Attempts have been made to classify (Korshover, 1960) anticyclones according to their origin, shape, and thermodynamic structure. Of course, the high pressure per se has nothing to do with the occurrence of high pollution levels. Actually, the center of any type of high is conducive to high pollution conditions.

4.2.3.3.1 Cold Arctic Outbreaks. The most outstanding anticyclone type that produces high pollution levels is the Arctic High. Often the cold air flows over the Midwest as a series of cold "pushes." The colder the air usually the more intense the episode. An example of this type is the 1056-millibar anticyclone of January 28-31, 1966. (See Figs. 4.9 and 4.10.) The temperature at the Chicago Midway Airport dropped to -20°F during this episode. Its duration, 106 hr, was the longest of the 20 episodes. The onset of such outbreaks often follows the Atlantic "Northeaster," i.e., the northward movement of a deep low up the Atlantic coast and close to or over New England. A substantial fraction of the 20 episodes were associated with this pattern.

4.2.3.3.2 The Stagnating Bermuda High. Frequently, during the summer and fall, the Bermuda High retrogrades and becomes relatively stationary over eastern U.S. These situations are associated with heat waves in summer and the "Indian Summer" in fall. Although light winds and subsidence inversions may be associated with this pattern during the day and light winds and ground-based inversions at night, high SO_2 levels are not as common, probably because of the lack of residential space heating with its associated atmospheric injection of SO_2 . High particulate loading is more likely under this weather pattern.

4.2.4 Urban Air Pollution Case Studies

Although synoptic surface and upper-air weather charts provide a picture of the large-scale motion, they are frequently ineffective in determining what the local weather elements are likely to be. This is especially so for those weather elements such as wind speed, wind direction, or stability, which markedly affect air pollution over a given area. To obtain a realistic picture of what is actually happening, each municipality must make a local investigation. Section 4.2.4.3 presents three detailed case studies showing the onset, development, and ending of an air pollution episode and its relation to the wind-field patterns. Of special note is the nonuniformity of pollution concentrations over the urban area. Some parts of the city may exhibit high pollution levels, while others remain clean. Also of importance is the way in which "pockets" of pollution move across the city.

4.2.4.1 Terrain Influence. The character of the terrain (e.g., the orographic features such as the presence of a lake, a hill-valley complex, or the degree of urbanization which gives rise to rural-urban differences) is most important in determining the distribution and in influencing the levels of air pollution concentration. Another important terrain factor is the geometric shape of the city. When the wind blows along the long axis of a rectangular city, pollutants accumulate on the downwind edge. Further, the surface of the city causes a reduction in the surface winds with a consequent uplifting or convergence which may affect cloudiness, resulting in changes of the vertical motions and diffusion conditions. Three case studies

Fig. 4.10. 500-millibar Weather Maps for January 27-30, 1966. ANL Neg. No. 149-4628.

presented in Sec. 4.2.4.3 show a detailed view of the growth and the decay of high-concentration pockets of SO_2 . These pockets are primarily results of both the large-scale and the local conditions as well as the relation of wind direction to the location of SO_2 sources.

4.2.4.2 Local Meteorological Influences. The pollution one observes over a given urban area depends on the amount of material injected into the atmosphere from the large number of sources; the meteorological elements--wind speed and stability--are also extremely important. When the winds are light, the ventilation rate is low. Material may be injected into the city faster than it is carried away. Levels of SO_2 concentration therefore arise. There are other factors operating to affect pollution levels. For example, when the winds reach a critical value, there is an increase in downwash from buildings. Thus, an increase in speed may result in higher levels of SO_2 , in spite of the increased ventilation rate. The geometry and the aerodynamic effects of particular buildings, as well as the atmospheric stability, influence the concentration levels.

At night, when light winds and a strong inversion are present, the effluent from elevated sources, circa 100 ft, will remain high above the ground. Under these conditions, the motions are suppressed, so that concentrations from these sources reaching the ground are low. When the sun comes up and convection starts, these sources can contribute markedly to the ground-level pollution. In the extreme case, there may be a fumigation effect; i.e., the effluent is brought rapidly to the ground giving particularly high concentrations.

The pollution episode appears to terminate when fairly brisk winds set in to ventilate the city. This often occurs in the afternoon. The episode is initiated most frequently in the dark hours during stable conditions. (See Table 4.7.)

TABLE 4.7. Times of Beginning and Ending of the Twenty IDA Episodes

Time Interval, CST	Frequency of Onset	Frequency of Ending
0100-0600	11	3
0700-1200	0	7
1300-1800	3	9
1900-2400	6	1

4.2.4.3 Three Case Studies. Three case studies are presented, each bringing out the factors mentioned above.

4.2.4.3.1 The Episode of February 12, 1967

4.2.4.3.1.1 Background. The pollution episode of February 12, 1967, was relatively short-lived. Sulfur dioxide concentrations in excess of 0.29 ppm were first recorded at 0200 CST in the Loop (TAM-3) and in Hyde Park (TAM-4) and subsequently at one or more of the eight TAM stations through 1300 CST. During these 12 consecutive hours, there were at least 30 station hours of SO₂ concentrations of at least 0.3 ppm. At 0800 CST, four TAM stations recorded high SO₂ levels simultaneously.

The area coverage ratio (the number of consecutive station hours of SO₂ greater than 0.29 ppm, divided by the number of consecutive hours in the pollution episode) provides a measure of the geographical area over which the pollution pall existed. For this example, the area coverage ratio was 2.50 including that on the average between two or three TAM stations which simultaneously recorded high SO₂ levels.

During the predawn hours of February 12, Midway Airport reported temperatures of zero or below, e.g., 0°F at 0300, and -3°F at 0600, 0700, and 0800 CST. Northwest of the city, the air was much colder; O'Hare Airport recorded a minimum of -16°F between 0400 and 0600 CST.

Light winds, about 4 knots, prevailed over the city, backing slowly from near north at midnight to west-northwest just before sunrise. By midmorning, under brilliant sunshine and continuing light winds, temperatures rose markedly. At 1000 CST, O'Hare recorded a value above zero; the afternoon high was 17°F. The Midway temperature picture was similar.

By midafternoon, snow began to fall and continued for several hours. An inch of new snow had fallen at O'Hare by 1800 CST, bringing the total on the ground to 18 in. During the same period, 2 in. of snow were deposited at Midway, bringing the total there to 19 in. By late evening, both the snow and the air pollution episode had ended.

4.2.4.3.1.2 Synoptic Conditions. The 500-millibar and surface charts are shown in Fig. 4.11. The upper-air charts show pronounced northwesterly flow over Chicago, characteristic of cold outbreaks. The fast-moving air steered the surface patterns so that the weather systems at the ground moved by quite rapidly.

The surface chart shows a 1032-millibar arctic high centered over western Wisconsin. It was part of a larger system extending far north into Canada. As it moved over the Great Lakes region, the horizontal pressure gradients were extremely weak. Clear skies prevailed. The only cloud cover associated with this high was a narrow band along its western side produced by moderate overrunning of Pacific air to the west. These pre-warm-frontal conditions moved over Chicago during the late afternoon. Radiosonde soundings taken at 0600 CST at Green Bay, Wisconsin, and

Peoria, Illinois, are shown in Fig. 4.12. Both show warmer air aloft and colder air near the ground. A strong radiation inversion was present at Green Bay at 0600 CST. Also of importance is the strong shear layer in the lowest 3000 ft above ground.

Fig. 4.12. Radiosonde and Winds-aloft Data for Green Bay, Wisconsin, and Peoria, Illinois, on February 12, 1967. ANL Neg. No. 149-4630.

4.2.4.3.1.3 Sulfur Dioxide Concentrations. Detailed analyses of the hourly SO_2 concentrations are shown in Fig. 4.13. The isopleths during the early morning hours exhibited a general north-south orientation with the higher SO_2 concentrations near the lakeshore and southward from the Loop; lower levels occurred to the west and north. This pattern persisted through 0800 CST. Sulfur dioxide levels increased dramatically, especially in the Hyde Park area, where it reached 0.89 ppm at 0700 CST. The TAM station in the Loop (TAM-3) recorded 0.69 ppm at 0500 CST. These are hourly average values.

After 0800 CST, two significant changes occurred. The first was substantial reduction in SO_2 concentrations over parts of the city and primarily at Hyde Park; and the second, an apparent shift toward the Loop and northwest of the high SO_2 levels. A tongue of "cleaner" air characterized by very low SO_2 values moved from south-southwest to north-northwest through the city at about 4 mph, cutting off the highest levels and isolating them west and northwest of the Loop. This clean tongue persisted more or less intact through the remainder of the day.

4.2.4.3.1.4 Surface-wind Patterns. Isogon (lines parallel to the wind direction) and isotach (lines of equal wind speed) analyses were performed for selected hours of the episode using the TAM wind data as well as the O'Hare and Midway winds. These turned out to be particularly enlightening when superimposed upon the corresponding SO_2 isopleth figures.

Fig. 4.13. Isopleths of SO_2 Concentrations, Wind Speed (Isotachs), and Wind Direction (Isogons) over Chicago on March 12, 1967. ANL Neg. No. 149-4631.

Note that Fig. 4.13 clearly shows the flow steadily backing with time at all stations instead of veering in the usual manner when a high pressure to the north moves eastward.

Of particular interest is the orthogonal relationship between streamlines and isopleths of SO_2 . This feature persists and is evident in all parts of Fig. 4.13. The orthogonality is most evident near and to the south of the Loop. When the isopleths of SO_2 concentration and wind streamlines are normal to each other, advective transport is most effective. Parallel streamlines and SO_2 concentration isopleths imply no SO_2 advection.

Also of interest is the correspondence between the wind maximum and the tongue of cleaner air. This shows the effectiveness of high winds in reducing air pollution.

4.2.4.3.1.5 Comments. A detailed study of this episode leads to the following observations:

1) Extremely cold temperatures contributed markedly to the occurrence of abnormally high SO_2 concentrations from the three sources: residential, commercial, and industrial.

2) The general synoptic features indicate the confinement of the effluent to a shallow layer close to the ground, and the establishment of a strong horizontal temperature gradient.

3) The weak horizontal pressure gradient and strong temperature gradient across the city, as well as the changing synoptic pattern, were primarily responsible for the "abnormal" backing of the wind.

4) The surface winds appeared to transport regions of high SO_2 concentrations. As this volume containing relatively large amounts of SO_2 moved across the city, it was detected at many TAM stations.

Features of this air pollution episode may be expected to occur in other cities. This episode occurred in a winter situation in which increased combustion of sulfur-bearing fuels contributed to high ground SO_2 concentrations. Since the bulk of the land east of the Rocky Mountains excluding the deep south is subject to cold temperatures and the effects of moving anticyclones, a similar episode is possible.

The presence of snow cover greatly enhances temperature contrasts between the inner-city and surrounding rural areas, and can, under weak pressure-gradient conditions, alter the "normal" behavior of airflow close to the ground.

This is likely to have occurred in this case. The airflow was also affected by the size of the city with its roughness elements. Further, the temperature contrasts between Lake Michigan and the city no doubt modified the wind direction, with the resulting change in the distribution of SO_2 concentrations.

4.2.4.3.2 The Episode of March 1, 1967

4.2.4.3.2.1 Background. The pollution episode of March 1, 1967, lasted only 7 hr, one of the briefest of the 20 cases studied. Sulfur dioxide concentrations in excess of 0.29 ppm were first recorded at 0500 CST at Austin High School (TAM-7) and subsequently at one or more of the eight stations through 1100 CST. During this period, there were 20 station hours of SO_2 levels of at least 0.30 ppm. No less than five stations recorded high SO_2 levels simultaneously at 0800, 0900, and 1000 CST. The area-coverage ratio for this episode was 2.86, a fairly high value.

The episode was brought to an end by an increase in the horizontal pressure gradient with increasing wind speeds over the city during the late morning. This case study illustrates a synoptic pattern (Fig. 4.14 a and b) in which an anticyclone moved fairly rapidly across the area, in contrast to that of the stagnating anticyclone. In spite of the rapid movement, there was a 7-hr period in which appreciably high values of SO_2 concentrations were recorded over a fairly large part of the city.

4.2.4.3.2.2 Synoptic Conditions. The upper airflow, e.g., 500 millibars (Fig. 4.14 c and d), shows strong northwesterly flow--80-knot winds--at 0000 CST. The elongated north-south 1029-millibar anticyclone centered over Green Bay, Wisconsin, extended southward through central Illinois to Louisiana. A warm front was located in the Great Plains. During the early morning hours, the anticyclone moved southeastward to northern Indiana, and by 1200 CST was located over northern Ohio. The air pollution episode ended when the flat pressure gradient associated with the high was replaced by the stronger gradient behind the departing anticyclone. The upper-air radiosonde soundings showed strong warming aloft, which intensified the inversion.

4.2.4.3.2.3 Sulfur Dioxide Concentrations. A detailed analysis of the hourly SO_2 concentrations for the period of the episode is shown in Fig. 4.15. The SO_2 levels rose sharply near sunrise, reaching their highest value in the central and southern parts of the city around 0900 CST. High readings thereafter shifted to the northern parts of the city and dropped to very low values upon the termination of the episode. Lines showing the wind direction and isopleths of wind speeds were drawn for the hours corresponding to this episode and are shown in Fig. 4.15. Before the onset of the episode, winds in the western part of the city were blowing gently from the northwest and gradually backed southerly by sunrise.

(a)

(b)

(c)

(d)

Fig. 4.14. Surface and 500-millibar Charts for North America on February 28 and March 1, 1967. ANL Neg. No. 149-4632.

Fig. 4.15. Isopleths of SO₂ Concentrations, Wind Speed (Isotachs), and Wind Direction (Isogons) over Chicago on March 1, 1967, 0500 to 1100 CST. ANL Neg. No. 149-4633.

This wind pattern suggests convergence into the city before the episode, and to the north of the city during the episode. The lower speeds seen over the city, as compared to those of Midway, are probably a result of increased surface roughness over the urban complex. A comparison of the wind and SO₂ charts reveals the generally downwind increase in SO₂ concentrations and a significant reduction when TAM wind speeds exceed 8 knots.

4.2.4.3.2.4 Summary and Comments. On the morning of March 1, 1967, under clear skies, light winds, and low temperatures (Midway minimum was 17°F, O'Hare minimum was 3°F), the Chicago area was subjected to unusually high levels of SO₂ for 7 hr. This air pollution episode began at 0500 CST and terminated at 1100 CST. When the weak pressure gradient was replaced with a strong pressure gradient, wind speeds increased from nearly 5 knots to nearly 15 knots. This had occurred by noon. Sulfur dioxide levels were sharply reduced when TAM wind speeds exceeded 8 knots.

Three factors contributed to the high SO₂ measurements:

- 1) Low temperatures.
- 2) Light winds.
- 3) The presence of an inversion aloft over the city (see Fig. 4.16).

A snow cover over the ground (5 in. at Midway and 8 in. at O'Hare) contributed to the low surface temperatures, which contrasted with temperatures near 32°F over Lake Michigan. This strong temperature gradient, together with the urban-rural gradient, no doubt contributed to the observed behavior of the airflow, which for most locations backed for a time, although from the synoptic aspects alone, they would have been expected to veer as the anticyclone centered north of Chicago moved southeastward.

Fig. 4.16. Radiosonde and Winds-aloft Data for Green Bay, Wisconsin, and Peoria, Illinois, on March 1, 1967. ANL Neg. No. 149-4634.

With a rapidly moving anticyclone system such as was present on March 1, 1967, the duration of the air pollution episode is expected to be short. The high levels of SO_2 occurred because the air was cold enough to result in high space-heating loads and the rapid production of SO_2 . This type of synoptic situation may occur in many areas of the country.

4.2.4.3.3 The Episode of January 19-20, 1966. It is important that individual cases of anomalously high or low pollution be investigated in detail in order to facilitate the identification of distinct air pollution meteorological regimes. One such case is the high air pollution episode of January 19-20, 1966. During this period, SO_2 concentrations greater than 1.00 ppm occurred at TAM-4, and relatively high levels were observed at most other TAM stations as well.

Figure 4.17 shows the progression of SO_2 concentrations at TAM-4 for January 16-21, 1966. Figure 4.18 shows the same data for TAM-5 (an inland station). Highest level of SO_2 concentration occurred at TAM-4 on January 19 and 20, but the incident actually lasted for about $4\frac{1}{2}$ days. Note the gradual day-to-day increase of SO_2 concentration at both stations.

Fig. 4.17. Time Series of TAM-4 SO_2 and Winds, plus Midway Temperature on January 16-21, 1966. ANL Neg. No. 112-9777.

Fig. 4.18. Time Series of TAM-5 SO_2 and Winds, plus Midway Temperature on January 16-21, 1966. ANL Neg. No. 112-9778.

After this brief examination of the pollution situation that occurred in this case, it is appropriate to evaluate the prevailing synoptic weather pattern.

Figure 4.19 shows a series of daily surface weather maps (at 1200 CST) for January 15-21, 1966. On January 15, easterly anticyclonic flow prevailed over the Chicago area, north of a stationary front across southern Illinois. The high center in central Canada drifted southward during the next day and extended a ridge line across the central U.S. plains. This caused a major reorientation of the pressure gradient in the Chicago area and a corresponding wind shift to westerly by noon on January 16. The next two days brought a gradual southward drift and a drop in the central pressure of the high-pressure area. At the same time, the pressure gradient in the Chicago area weakened, so that winds became lighter. With the approach of the next cold front during the next two days, the high center again increased in pressure and moved northeastward. The pressure gradient remained weak over Chicago, so that light winds continued.

The local weather accompanying these large-scale meteorological events is seen in Figs. 4.17 and 4.18. The wind direction shifted abruptly to westerly at midday on January 16. (Note the resulting large increases in SO_2 at TAM-4 and TAM-5.) The direction remained remarkably constant from the west, especially at TAM-4, except for a temporary shift to easterly on the afternoon of January 19. Wind speed dropped rapidly at the time of the wind shift on January 16 and after that continued to decrease slowly until January 20. It was less than 10 knots all during the high-pollution period. Temperatures dropped all day on January 16 as cold Canadian air reached Chicago. A low temperature of zero occurred just before dawn on January 18, and gradual warming followed.

Figures 4.17 and 4.18 show some interesting details in the SO_2 concentrations recorded for this period. The generally high levels, the gradual increase, and the extremely high concentrations at TAM-4 on January 19 and 20 are all significant. Note the temporary drop in SO_2 levels with northeast winds, since TAM-4 is a lakefront station. These winds bring in clean air from over Lake Michigan. What is surprising is that a temporary shift to northeast winds occurred over part of the city. Such occurrences are common in warm seasons because of lake breeze effects, this situation developed during the middle of January with temperatures in the 20's and lower.

Figure 4.20 shows that the recorded wind shift occurred at other TAM stations as well as TAM-4. Winds shifted from west or northwest to northeast at TAM-2, -3, -4, -5, and -6 and then back again. These stations recorded northeast winds for varying periods of time between 1300 and 2000 CST on January 19.

(a) 15 JANUARY	(d) 18 JANUARY
(b) 16 JANUARY	(e) 19 JANUARY
(c) 17 JANUARY	(f) 20 JANUARY
	(g) 21 JANUARY

Fig. 4.19

Surface Weather Maps for January 15-21, 1966
(1200 CST). ANL Neg. No. 112-9780.

Fig. 4.20. Time Series of SO_2 and Winds for TAM-2 through -6 on January 19, 1966. ANL Neg. No. 112-9781.

SO_2 and winds. There is only slight evidence for a convergence-zone pollution buildup. However, TAM-4 is near the lake and would see clean air immediately upon a wind shift, and the TAM-3 data have too many missing hours to distinguish a clear pattern.

The city wind pattern is clear; however, it shows that winds were converging over the center of the city. This pattern suggests that we have found a city-rural circulation much like that described by Lowry (1967) and pictured schematically in Fig. 4.22.

Two conditions are usually required for city-rural circulations to begin. The first is a temperature excess in the city; the second is sufficiently light ambient winds. Figure 4.23 shows a definite temperature excess at Midway Airport (in the city) relative to O'Hare Airport and Argonne (essentially rural sites). Figure 4.21 shows that surface winds were light in the Chicago area on January 19, and Fig. 4.24 shows the same for winds aloft at Peoria, Illinois, and Green Bay, Wisconsin--the two rawinsonde stations nearest to Chicago. Therefore, favorable temperature and wind conditions for a city-rural circulation did exist.

A better way to evaluate these events on an hour-to-hour basis is to examine hourly maps of wind direction. Figure 4.21 shows wind directions for the TAM network, Argonne, and the airports for eight selected hours on January 19. The 0600 map shows a straight westerly flow of light winds over the Chicago area. At 1300, most stations still had west winds, but winds had begun to shift to more northerly directions near the lake. A convergence line is suggested. At 1400, convergence over the city was clear, with northeast winds at the three TAM stations along the lakeshore and westerly or northwesterly winds inland. The circulation was still strong at 1600, and the convergence line had moved west of TAM-5 and -6 once more. The weakening continued during the next 2 hr; the 2000 map shows only a hint of weak convergence in the southeastern part of the city.

These wind fields are remarkably similar to those observed in lake-breeze cases (Lyons 1969), and it is worth searching for a "pollution band" associated with the convergence zone, as found by Lyons. Figure 4.20 shows a time-series plot of both

Fig. 4.21. Wind Field over Chicago on January 19, 1966. ANL Neg. No. 112-9782.

Fig. 4.21 (Contd.). ANL Neg. No. 112-9783.

Fig. 4.22. Schematic Diagram of a City-Rural Circulation
(after Lowry, 1967). ANL Neg. No. 112-9784.

Fig. 4.23

Temperature Variations at Midway,
O'Hare, and Argonne on January 19,
1966. ANL Neg. No. 112-9785.

Fig. 4.24
Winds Aloft at Green Bay and
Peoria on January 19-20, 1966.
ANL Neg. No. 112-9786.

Figure 4.24 also reveals another pertinent fact: Wind direction at Green Bay and Peoria averaged near north--roughly parallel to the convergence line--in the first few kilometers above the surface on January 19.

The available data suggest a city-rural circulation somewhat different from the classical form. The classical case is for a somewhat circular city. The corresponding circulation is a ring vortex, with air rising in the center of the doughnut and returning to the surface at the outer perimeter.

Chicago's topography and demography are not classical, because the city lies along a lake shore. The heat island is not circular, but is instead a north-south band. Thus, Chicago's city circulation may have an axis of symmetry, rather than a center of symmetry.

For analysis of this episode, we must also consider possible interactions with the synoptic-scale airflow. This point is not clear; perhaps the outside air simply flows around or over the city air "dome" with little interaction between the two. There is some evidence that interaction did occur in this case, however. The wind fields at 1400 and 1600 (see Fig. 4.21) show definite southerly components in both converging currents. This indicates that momentum is being transferred downward from the northerly winds aloft.* The Chicago circulation observed on January 19-20, 1966, appears to have the following basic characteristics:

- 1) Relatively warm city air rose over the axis of the heat island.
- 2) To preserve continuity, air from the edge of the city was drawn inward.
- 3) At the upper limit of convection, the rising air began to spread outwards, to the east and west, at the same time gaining a southward momentum from synoptic winds in this region.
- 4) The parcel of air was thus carried to the outer limits of the circulation, perhaps 10-20 km away, and reached ground level at a point south of where it ascended.
- 5) From this point, the air was drawn back into the city, where it was repolluted. If this circulation pattern prevailed, air could have been recycled through the city several times before finally exiting at the south end of the metropolitan area.

One additional item of evidence to support the existence of this kind of circulation is found in the recorded SO_2 concentration of air arriving

*It is necessary to verify that the circulation reaches high enough altitudes to interact with the northerly winds. The depth of penetration of the rising city air was estimated from the 0600 temperature sounding at Peoria and the Midway high temperature of 24. The limit of penetration was about 1 km. This is high enough for the rising air to encounter north winds.

at TAM-4 from the northeast. Figure 4.20 shows concentrations near 0.20 ppm. This is an unusually high concentration for northeast winds and is independent evidence of a recirculation of once-polluted air back into the city.

One curious aspect of this episode is that the circulation died (about 1900) as the city-rural temperature difference increased. This is the opposite of what theory predicts--the strength of the circulation should increase in proportion to the temperature difference. The explanation probably lies with some change in the external conditions (especially winds) that allow city circulations to continue.

There is considerable latitude for speculation here, but one thing is clear: An unusual circulation prevailed in Chicago on January 19, 1966. This event is of significance to Chicago's air pollution potential, and as far as we know, has not been described for this city before.

On the basis of an analysis of only one case, it is difficult to draw definitive conclusions about critical pollution parameters or their threshold values for permitting a city circulation in Chicago; however, two points are worth noting:

- 1) Surface winds outside the city were mostly less than 5 knots between January 18 and 20. Winds aloft at Peoria and Green Bay were mostly less than 10 knots up to 700 millibars on the day of the circulation--January 19.

- 2) The city-rural temperature difference ranged from 3 to 10°F on January 19. The larger values occurred at night.

4.3 Studies of Chicago Weather and Air Pollution Relationships (Donald F. Gatz)

4.3.1 Introduction

The purpose of the meteorological investigations was to identify weather phenomena associated with high pollution concentrations and provide the necessary weather information to sensitize the computer model to these situations.

Specifically, several things about the meteorology of such periods were sought:

- 1) What specific meteorological phenomena are involved?
- 2) What weather parameters identify them? What are their critical values?
- 3) What broad-scale pressure and frontal patterns are associated with them?

The first step was to identify the important phenomena. Several were selected for further study because (1) their influence on air quality had been pointed out previously in the literature, and (2) their characteristics seemed to fit conditions observed during periods of high SO₂ concentrations in Chicago.

The specific phenomena selected for study were:

- 1) Morning inversion breakup fumigations.
- 2) Nighttime inversions.
- 3) Lake breezes and other winds off Lake Michigan.

For each of these phenomena, the first task was to verify that it occurs in Chicago and that it causes increased pollution concentrations. Until these facts were established, it would have been premature to document the meteorological conditions important to the model.

4.3.2 Methods

These studies were made using Chicago air-quality (SO₂) data and weather data from four Chicago area airports and Argonne. Limited field measurements (especially vertical distributions) of SO₂ and a few meteorological parameters were also part of the total program, but these were too limited in scope to provide information useful to the study of the relationships of air pollution to weather.

Thus, these studies were an attempt to use readily available air-quality and airport-surface-weather data to study rather complex meso- and micro-meteorological processes. This was an approach that could be used immediately without long and costly field measurements. It was begun knowing that certain extremely important information--namely vertical distributions of pollutant concentrations and weather parameters--were not available.

The extent to which this approach was successful indicates what can be learned about urban pollution meteorology with only surface data on air quality and weather.

4.3.3 Inversion-breakup Fumigations

Hourly TAM SO₂ averages at all eight stations plotted on the same graph (versus time) often show sharp peaks simultaneously (± 1 hr) at several stations. During the two years (1966-1967) studied, these peaks often occurred on sunny mornings following clear, nearly calm nights. The peaks also tended to occur more often downwind of known high-stack pollutant source regions on such days, and less often elsewhere. This evidence

suggests that the peaks are caused by inversion breakup of fumigations of the type described by Hewson (1955), and described in the following paragraphs:

In rural areas, surface inversions develop on clear nights with little wind. In cities, the inversion base may extend to the ground only infrequently; more commonly, it is found aloft at several times the mean rooftop level. Pollutant plumes released into the stable layer remain essentially undiluted, and in light winds tend to accumulate over the city. After sunrise, turbulence and mixing increase in the air layer next to the ground in response to the warming of the surface by the sun. The depth of the mixed layer increases as the sun rises and heats the surface more strongly. When the mixing reaches the layer of the concentrated pollutants, contaminants are rapidly mixed downward to the surface, causing a sudden increase in surface concentrations. The top of the mixed layer continues to rise as time goes on, thus increasing the mixing volume; surface concentrations decrease as this volume increases.

Davis and Newstein (1968) have presented evidence that fumigations occur in Philadelphia essentially as described above. They examined time changes of vertical SO_2 profiles on a 1000-ft TV tower.

The evidence cited earlier suggests that fumigations cause the morning peaks of SO_2 concentrations observed in Chicago. However, it is also possible that at least some of these peaks reflect an increase in emissions at that time, caused by morning residential-furnace fire-up.

To gauge the effects of fumigations on air quality, we need to know how to distinguish fumigation SO_2 peaks from furnace fire-up peaks. We tried to distinguish these two kinds of peaks in two ways:

- 1) By examining at TAM stations the time distribution of SO_2 from residential directions, to see if that peak comes at a different time than ones from industrial directions.

- 2) By examining the variation of maximum morning SO_2 with direction at individual TAM stations. This was done both for days when fumigations were likely and for days when they were not likely, to see if peaks occurred in industrial directions but not in residential directions when fumigations were likely.

Both approaches were unsuccessful, primarily because two winter seasons of data (40 cases of likely fumigation) are not enough to show significant differences between wind directions at a single station. For example, at TAM-7, five of the eight 45° wind-direction bands had five or fewer cases. In addition, the first effort was unsuccessful, because only a flat, weak,

morning SO_2 peak occurs from residential directions (see Fig. 4.25) and it occurs between 0600 and 1000, the same time that the suspected fumigation peaks occur. Thus, fire-up peaks were not distinguishable from fumigation

peaks, either by time of occurrence or by directional differences.

Fig. 4.25. Ninetieth Percentile SO_2 Concentrations vs. Hour of Day. Averages based on all TAM stations. Winds from residential areas--November 1, 1966 through March 31, 1967. No precipitation present.

Therefore, we can say at this point only that inversion breakup fumigations are suspected as the cause of some of the observed morning SO_2 peaks in Chicago. During these times, SO_2 concentrations may reach 0.50 ppm and above for 1-2 hr or less and then drop off sharply. Thus, on a total-dose basis, they are not as serious as would be indicated by the maximum concentration.

The suspected fumigations occur with winds mostly less than about 8 knots during the night, with

clear skies or high ceilings, and surface-temperature inversions in rural areas. They can occur under any of a variety of synoptic conditions that produce clear skies and weak pressure gradients. Large high-pressure regions accompany suspected fumigations frequently, but not exclusively.

4.3.4 Nighttime Inversions

In this case, the defining parameter for the phenomenon is known--it is the vertical temperature gradient. Unfortunately, the nearest measurements available for the period of this study were made at Argonne, outside the city. An additional difficulty was that there was no characteristic pollution "signature" (as, for example, the morning peaks in the case of fumigations) help to identify cases.

To gauge the effect of nighttime inversions on Chicago SO_2 concentrations, we attempted to "calibrate" the city for the Argonne vertical temperature measurements. That is, we tried to determine if there was some critical value of the Argonne lapse rate above which pollution trapping in or below an inversion in the city becomes significant. This approach was not successful, again principally because there were not enough data to establish significant differences between categories of lapse rates.

The same weather conditions that occur with inversion breakup fumigations can be expected to occur with nighttime inversions, which are, of course, a prerequisite for the fumigations.

For inversions and fumigations, which are defined by, or dependent on, the vertical variation of temperature, the lack of data in the vertical dimension essentially prevented us from identifying individual cases and thus from assessing their influence on SO_2 concentrations. Lake breezes, the final weather phenomenon investigated in this program, are fortunately identifiable from the horizontal wind field over the city. This permitted a much better assessment of weather effects on pollution concentrations. This study is presented in Sec. 4.3.5.

4.3.5 Sulfur Dioxide Pollution Characteristics of Chicago Lake Breeze Circulations

The main objective of this study was to investigate the incidence of high SO_2 concentrations in lake-breeze situations. Specifically, the following questions were posed:

1) How do frequencies of $\text{SO}_2 > 0.15$ ppm in lake air (i.e., in east winds off Lake Michigan during lake breezes) compare with average conditions?

2) How do these frequencies vary with season?

3) How do they vary with station location?

A second objective was to compare, for all lake-breeze events, regardless of pollution level, the SO_2 concentrations in the lake air with those in the air displaced at each station the lake air passed. The questions asked were:

4) Do SO_2 concentrations increase or decrease as the lake breeze passes a sensor?

5) Does the location of the sensor determine whether the SO_2 concentration increases or decreases as the lake-breeze front passes?

The remaining objective was developed during the study when it was discovered that certain lake-breeze events not of the conventional kind occur in Chicago. Because transport of pollutants is such an important part of the pollution picture, and because the circulations of these "other" lake breezes, at least at the surface, appear to be identical to those of conventional lake breezes, all occurrences of both types of events were identified for 1966 and 1967. The final objective of this work was thus to compare "classical" and "other" lake breezes (from now on called Types I and II, respectively) with respect to the questions listed earlier.

4.3.5.1 Definitions, Data, and Procedures. Choosing the criteria for identifying lake-breeze cases and their beginnings and endings was difficult. The criteria finally chosen are based mostly on characteristics of lake breezes described in the literature. The choice was also influenced by experience gained in this study through the examination of almost 100 lake breezes of both types. The criteria involve certain limits on three parameters: circulation, cloudiness, and wind speed.

4.3.5.1.1 Circulation. The circulation requirement was as follows: A wind shift from a "westerly" sector to an "easterly" sector must occur. This wind shift must occur first along the lakeshore, creating a convergence zone some distance inland, with easterly winds to the east and westerly winds to the west. Usually the convergence zone moves inland with time, sometimes as a series of advances and retreats. However, only the existence of an inland convergence zone is required--not its movement.

The "westerly" sector chosen was 1 to 135°. The "westerly" sector was defined only for use in the first step of data screening to select cases. This step was done by computer and consisted of listing all hours during the two years of data during which westerly winds were observed inland (at Midway Airport) at the same time that easterly winds were observed on the lakefront (at Meigs Field). The actual limits chosen were not crucial to the eventual identification of cases, as long as they were sufficiently broad that at least two consecutive hours of every valid case were found by the computer. Final selection of cases was made, using hourly plots of winds and other weather data from the eight Chicago Telemetered Air Monitoring (TAM) stations (Booras and Zimmer, 1968), four Chicago-area airport weather stations, and Argonne. Station locations are shown in Fig. 4.2.

Two different definitions of the "easterly" wind sector were used during different stages of the identification procedure. For the initial computer-screening, a 1-170° sector was used. A more appropriate choice of easterly sector was that used to determine the duration of the lake breeze. At each TAM station, duration was taken as the number of consecutive hours that the wind direction was between 1 and 135°. The northerly limit is most justified physically for the lakefront TAM stations, where it separates land trajectories from lake trajectories. It could be argued that a more easterly direction should be required for stations farther inland. However, that seemed to be an unnecessary complication of the procedure. As a practical matter, when lake air arrives at a station, a large wind shift occurs, and the final direction is well east of 1°. The choice of 1° seldom affected the duration by more than a few station-hours.

The choice of the limiting wind direction toward southeast was more difficult. In contrast to the sudden, large wind shift through north at the onset, most Chicago lake breezes end in a gradual wind shift from northeast

or east to southeast, then to south-southeast, and eventually to south or southwest. Moreover, the choice affects the incidence of high SO_2 concentrations in lake air because of the concentration of large sources in the southeastern and southern sections of the city. There were two basic reasons for choosing 135° :

1) It is approximately the southern limit of an over-lake trajectory for most TAM stations.

2) A wind shift through 135° at the end of the lake breeze is usually irreversible. That is, once past 135° , the wind usually continues to shift toward south, and does not return. The wind shift through 135° is thus a clear indication that the lake breeze is over.

There is one qualification to the rules for fixing the duration of the lake breeze: The latest hour allowed for the end of an event was midnight of the day it began. This measure was necessary to provide a reasonable end point for certain Type II lake breezes in which easterly winds continue on for many hours or even days.

4.3.5.1.2 Cloudiness. If the convergence line (also called the wind-shift line, or lake-breeze front) passed Midway, the average cloudiness (not including the contribution of cirriform clouds) between the first and last hours of winds between 1 and 135° at any TAM station was required to be less than 0.6 (see Hall, 1954) for the event to be classed as a Type I lake breeze. There was no maximum-cloudiness limit if the lake breeze front did not reach Midway.

4.3.5.1.3 Wind Speed. We also know from the work of Hall (1954) that lake breezes are unlikely when the 2000-ft wind speeds measured at 1000 CST at Joliet are over 13 knots from the north or 10 knots from the south or southwest. However, soundings are no longer taken at Joliet, and it is difficult to translate these limits to surface wind speeds at one of our ground-level stations. Examination of many lake breezes in this study showed that surface wind speeds at Midway were consistently less than 10 knots before lake breeze onset. Therefore 10 knots was selected as the maximum preonset wind speed allowable (at Midway Airport) for a Type I lake breeze. In practice, it was found that whenever wind speeds over 10 knots occurred before an intrusion of lake air, the event was clearly Type II, due to the presence of heavy cloudiness.

One feature of most textbook descriptions of lake breezes is absent from the definition used here: namely, a horizontal temperature gradient across the shore line. This temperature difference is usually considered to be the driving force of the lake-breeze circulation. However, a number of the lake breezes examined in this study occurred even though air over

the land was cooler than air over the lake (e.g., Meigs Airport temperature during the first hour of onshore winds). These events were similar in all other ways to the lake breezes that occurred with warmer air over the land. It seems reasonable that they were indeed lake breezes. Therefore, in this study, warmer air over the land was not required for an event to be listed as a lake breeze.

Type I lake breezes are defined as events that meet the circulation, cloudiness, and wind-speed criteria; Type II lake breezes meet the circulation criteria, but fail one or both of the others.

4.3.5.2 Results and Discussions. Table 4.8 summarizes both types of lake breezes identified in Chicago in 1966 and 1967. Sixty Type I and 35 Type II lake-breeze days were found. The numbers of events in both categories were slightly higher in 1966 than in 1967.

TABLE 4.8. Summary of Type I and II Lake Breezes in Chicago, 1966-1967

Month	1966		1967		Total	
	I	II	I	II	I	II
Jan	1	3		1	1	4
Feb	1	2	1		2	2
Mar	2	3		2	2	5
Apr	1	4		1	1	5
May	3	2	4		7	2
June	6		3	3	9	3
July	4	2	6	3	10	5
Aug	7	1	5	3	12	4
Sept	4	1	2	1	6	2
Oct	5		3		8	
Nov			2		2	
Dec		2		1		3
Total	34	20	26	15	60	35

Both types were found throughout the year, except for an absence of Type I in December and Type II in October and November. The frequency of Type I lake breezes varies strongly with season; the largest numbers occur from May through October. Type II lake breezes are rather uniformly distributed throughout the year.

Many of the Type II lake breezes were associated with precipitation; some of these appear to be similar to the "lake snow" case documented by Williams (1963). The cases with precipitation, and some other cases as well, were accompanied by heavy cloud cover.

One other subtype of Type II occurred frequently and was sometimes accompanied by 0.8 to 0.9 cloud cover. This subtype occurs in response to changing wind directions associated with shifting pressure patterns or frontal passages. When the gradient wind shifts from offshore to onshore, a convergence zone sometimes forms near the shore and moves inland with time, just as the lake-breeze front does. In contrast to the lake breeze, however, this circulation does not die out in the late evening. On the contrary, easterly winds may continue for many hours or even days.

The main concern in this study was to determine the incidence of high SO_2 concentrations in lake air. Sulfur dioxide concentrations above 0.15 ppm occurred often enough to provide reasonable statistics for comparison with average conditions. Hence, this value was chosen as the reference.

Table 4.9 shows, for each year of the study, and for both lake-breeze types, the number of station-hours of lake air observed and the number and percentage of hours with $\text{SO}_2 > 0.15$ ppm. For each year, the city-wide average percentage of hours of $\text{SO}_2 > 0.15$ ppm is also given for comparison.

TABLE 4.9. Severity of SO_2 Pollution in Lake Air

Type	Year	Total Station-hours of Lake Air	$\text{SO}_2 > 0.15$ ppm in Lake Air	
			Station-hours	Percent of Total
I	1966	1440	87	6.0
	1967	991	57	5.8
II	1966	997	145	14.5
	1967	953	56	5.9

City-wide annual percentage of hours with $\text{SO}_2 > 0.15$ ppm:
1966--14.9 and 1967--14.4.

For both years, the annual percentage of hours with $\text{SO}_2 > 0.15$ ppm during Type I lake breezes was about half the city-wide average for that entire year. This is perhaps inconclusive, because most of the Type I lake breezes occur during the summer, when average pollution conditions are also lower than the yearly average.

The percentage of station-hours with $\text{SO}_2 > 0.15$ ppm in Type II lake breezes was almost equal to the annual city-wide average in 1966, but about half that average for 1967. Type II lake breezes are quite uniformly distributed over the year, so the comparison is a valid one in this case.

The annual variation of lake-breeze station-hours per month and the percentage of those hours with SO_2 over 0.15 ppm is shown in Fig. 4.26. For Type I lake breezes, the station-hours per month peak during the summer, but SO_2 in lake air is seldom above 0.15 ppm then. Winter has relatively few hours of Type I lake breezes, but when they occur they are likely to be high in SO_2 .

Fig. 4.26. Annual Variations of Type I and II Lake Breeze Station Hours per Month and the Percents of Those Hours with $\text{SO}_2 > 0.15$ ppm. ANL Neg. No. 149-4447.

Figure 4.26 shows that significant numbers of Type II lake-breeze hours occur in winter and that 20-50% of these hours have SO_2 over 0.15 ppm.

The stations receiving the most hours of high SO_2 concentrations in lake air are revealed in Table 4.10. Type I lake breezes give high SO_2 values to TAM-6 most often, while Type II lake breezes pollute TAM-3 most, and to an even greater extent. These results probably reflect the greater role of Type II lake breezes during winter in an area with strong sources nearby.

TABLE 4.10. Hours of $\text{SO}_2 > 0.15$ ppm on Lake Air at TAM Stations, 1966-1967

TAM Station	1	2	3	4	5	6	7	8	Total
Type I	3	5	28	14	20	35	23	16	144
Type II	1	2	73	21	42	32	19	11	201
Total	4	7	101	35	62	67	42	27	345

The second major concern of this study was the change in SO_2 concentration that occurs as the lake air front passes a station. Visual observations indicate that lake air is frequently very smoky, especially the first few hundred feet behind the front (Hall, 1954). Hourly averages of SO_2 concentrations at the TAM stations were examined to see whether SO_2 behaves like the smoke in lake breezes. The investigation involved listing the SO_2 average for the last hour when the vector average wind direction was westerly and the first hour when it was easterly for every passage of a lake air front over a TAM station. The difference between these two figures was taken as the change in SO_2 at the wind shift line. Figures 4.27, 4.28, and 4.29 show the distribution of these changes in SO_2 during both types of lake breezes at each TAM station.

Figure 4.27 shows results for TAM-3 and -4. There is a clear trend, especially at TAM-4, for SO_2 to decrease when the lake air passes. Thus at these lakefront stations the lake air is cleaner than the air present there before the lake air moved in. This is true for both types. There is an apparent paradox here. Sulfur dioxide concentrations usually decrease at TAM-3 as the lake air comes in. Yet TAM-3 had the highest number of hours with $\text{SO}_2 > 0.15$ ppm in Type II lake-breeze air (see Table 4.10). The explanation is that SO_2 concentrations in the original air are frequently high enough so that the decreases that occur with a shift to lake air can still leave SO_2 concentrations above 0.15 ppm.

Figure 4.28 shows results for TAM-2, -6, and -8. At these stations, there is usually no change at all in SO_2 concentrations as the lake air moved in. For the small number of cases where some change was noticed, increases and decreases, sometimes quite large, were about equally likely. The one exception to this pattern was TAM-6 Type I lake breezes, which

Fig. 4.27. Frequency Distribution of SO_2 Concentration Change at Type I and II Lake Breeze Fronts for TAM-3 and -4. ANL Neg. No. 149-4446.

Fig. 4.28. Frequency Distribution of SO_2 Concentration Change at Type I and II Lake Breeze Fronts for TAM-2, -6, and -8. ANL Neg. No. 149-4445.

Fig. 4.29. Frequency Distribution of SO_2 Concentration Change at Type I and II Lake Breeze Fronts for TAM-1, -5, and -7, ANL Neg. No. 149-4444.

were more likely to produce increases than decreases. Figure 4.29 shows the results for TAM-1, -5 and -7. Here again there was a strong tendency for no change, but when changes occurred, they were likely to be increases, sometimes large ones.

The general picture appearing from these figures is one in which pollution at stations near the lakeshore, like TAM-3 and -4, decreases in air fresh off the lake. At intermediate distances (TAM-5 and -8), SO₂ might increase or decrease as the front passes. What happens in an individual case probably depends on the particular combination of the general pollution level that day and the exact direction of the wind with respect to upwind sources. The farthest inland stations (TAM-1 and -7) occasionally show SO₂ increases. The frequency distributions of changes in SO₂ at individual stations tell only part of the story, however. It is also helpful to consider the values of SO₂ concentration during the last hour of westerly winds and the first hour of easterly winds averaged over all events of each type. These averages are presented in Table 4.11 for both lake-breeze types and for both years of data at each station.

TABLE 4.11. Comparison of Average SO₂ Concentrations for Hours before and after Arrival of Lake Air at TAM Stations

		I		II		I		II	
		1966	1967	1966	1967	1966	1967	1966	1967
Station:		TAM-1				TAM-2			
Before		0.01	0.02	0.03	0.02	0.04	0.04	0.05	0.06
After		0.03	0.04	0.04	0.03	0.04	0.04	0.05	0.05
		TAM-3				TAM-4			
Before		0.10	0.10	0.24	0.16	0.14	0.13	0.30	0.10
After		0.09	0.07	0.21	0.11	0.07	0.07	0.17	0.06
		TAM-5				TAM-6			
Before		0.07	0.07	0.12	0.09	0.04	0.04	0.10	0.04
After		0.07	0.04	0.13	0.07	0.07	0.05	0.10	0.05
		TAM-7				TAM-8			
Before		0.02	0.02	0.08	0.05	0.03	0.04	0.09	0.07
After		0.03	0.06	0.11	0.08	0.03	0.07	0.12	0.07

Table 4.11 reveals several important points. First, at all stations the direction of change found for 1966 is remarkably consistent with that found for 1967, and these directions agree with the trends indicated for the

various stations in Figs. 4.27-4.29. Second, Table 4.11 shows that stations 3 and 4 had the highest SO_2 concentrations in the air that the lake air replaced. This is true for both types of lake breezes. Hence, the beneficial effects of the clean lake air occur where they are needed most. Moreover, the stations that experience increases in SO_2 as the lake air comes in usually have rather low SO_2 to start with, so the increases are not a serious matter.

We have seen that the picture painted by city-wide data on pollution in lake air is rather bright. It is also useful to consider conditions in local areas.

High SO_2 concentrations (approaching 1 ppm) have been observed at Chicago TAM stations during lake breezes. These occurrences are few in number, but they show that lake breezes can lead to high pollution levels in local areas near large sources. Most of these cases probably are not detected by the existing TAM network.

Visual observations of industrial plumes along the lakeshore by us and by Lyons (1969), indicate that dense concentrations of smoke can reach the surface within a few stack-heights of their source. This occurs through the fumigation mechanism. The unstable boundary layer that forms in the lake air as it moves inland quickly grows upward and reaches plume height, and pollutants are rapidly mixed downward to the surface. Observations indicate that the problem is most severe along Chicago's south lakeshore, where a number of large industries are located.

4.3.5.3 Chicago Lake-breeze Structure. We have seen that lake breezes can affect the concentrations of SO_2 in Chicago. In order to use an urban air pollution model to compute SO_2 concentrations for lake-breeze regimes, we need to know the structure of the lake breeze. Our current knowledge draws heavily on the recent work and literature reviews of Olsson (1969) and Olsson and Lyons (1969).

The lake-breeze circulation at Chicago consists of the lake breeze itself, an onshore-flowing layer 300-700 m thick, and above this a return flow layer that may be more than 1000 m thick. The lower portion of the lake breeze is very stable over the lake.

The stable layer may be up to 300 m thick. As it moves ashore, a superadiabatic layer grows upward into it from the effects of the warm land and the rough city surface. The stable layer is completely destroyed by the superadiabatic layer within a few (<5) km of the shoreline.

The lake-breeze front moves inland at about 1 m/sec. Winds within the lake-breeze layer are ordinarily less than about 5 m/sec, with the maximum speed within 100-300 m of the surface. Ordinarily, winds behind the front exceed the speed of the front itself. Continuity principles indicate,

and observations confirm, the existence of a convergence zone at the lake-breeze front. This zone may be less than 500 m across and contain updrafts averaging 0.5 to 1.0 m/sec. In extreme cases, updrafts may reach 5 m/sec.

In the return flow, wind speeds are usually less than 5 m/sec, but may exceed that occasionally.

The circulation is completed by subsidence over the lake, where downdraft speeds may reach 0.6 m/sec.

4.3.5.4 Conclusions

1) In Type I lake-breeze air, percentages of hours with $\text{SO}_2 > 0.15$ ppm are about half the annual city-wide percentages. This comparison is not conclusive, because most lake breezes occur in summer, when average pollution levels are also lower than the annual average. A more valid comparison will be made using monthly city-wide percentages.

In 1966, the percentages of hours with $\text{SO}_2 > 0.15$ ppm in Type II lake breezes were very close to the city-wide annual percentage. In 1967, the percentage in Type II lake breezes was only about half the city-wide value. These comparisons are probably valid because this type occurs quite uniformly throughout the year.

2) Frequencies of $\text{SO}_2 > 0.15$ ppm vary markedly with season for both lake-breeze types, being highest in winter.

3) These frequencies also vary markedly with station location. In Type I lake breezes, the highest frequency occurred at TAM-6; in Type II, the highest frequency was at TAM-3.

Although high SO_2 concentrations sometimes occur locally during lake breezes, city-wide average pollution levels are generally low. In particular, at lakeshore stations TAM-3 and -4, a lake-air intrusion means cleaner air. Farther inland, most often there is no change in SO_2 concentration. At the farthest inland stations, the changes that do occur are likely to be increases in concentration. However, these stations usually start with low SO_2 values, so the increases that occur are not serious. This applies to both types of lake breezes.

4.4 Wind-direction Differences in Chicago (Donald F. Gatz)

We have found from examining TAM and airport data that sensors in different parts of the city often indicate different wind directions. Such differences are known to occur occasionally for valid reasons. For example, a lake breeze may affect some stations but not all of them. The rather high frequency of occurrence of direction differences between TAM-4 and

Midway Airport nevertheless raised questions about the validity of TAM winds. These findings also raised the broader question of whether to use winds from the TAM stations for analytical purposes or to assume that one wind (probably from Midway) is representative of the entire city.

To answer these questions, we compared wind directions measured concurrently at several locations in and around the city.

Midway Airport, O'Hare Airport, Glenview Airport, and Argonne record winds regularly and are known to have well-sited instruments. If winds at these stations are compared, normal and valid spatial variations in the wind field should be evident.

For a given wind direction at Midway, the corresponding directions for O'Hare and Glenview were found by computer. A printout of these data for a selected period was obtained. The frequency distributions shown in Figs. 4.30 (O'Hare) and 4.31 (Glenview) were then constructed. (The Midway directions 210 and 315° were chosen so the distributions could be compared with those for TAM-4, which had been plotted previously.)

Fig. 4.30. Distribution of Wind Direction at O'Hare for Specified Midway Winds. ANL Neg. No. 112-9769.

Fig. 4.31. Distribution of Wind Direction at Glenview for Specified Midway Winds. ANL Neg. No. 112-9770.

Argonne wind-direction distributions for selected Midway wind directions are shown in Fig. 4.32. These distributions were computed previously by Moses and Bogner (1967) for 1950-1964. Therefore, they represent a time period different from that used for the other comparisons--January 1966 through May 1967. The results are still valid, however.

Figures 4.30-4.32 show occasional wind-direction differences of several tens of degrees, but at these stations with well-sited wind instruments the peaks of the distributions always fall within about 10° of the concurrent Midway direction.

Fig. 4.32. Distribution of Wind Direction at Argonne for Specified Midway Winds. ANL Neg. No. 112-9771.

directions in the same way. Furthermore, no evidence of seasonal or diurnal influences on the direction anomaly was found.

A computer program was also used to investigate wind-direction differences between Midway Airport and the eight Chicago TAM stations. We found that for some directions at some stations, the agreement was much poorer than was found at O'Hare, Glenview, and Argonne. For example, Fig. 4.33 compares Midway with TAM-6 for eight compass points.

There is reasonable agreement from 40° (NE), 90° (E), and 140° (SE), but agreement is poor from the other five directions.

In contrast, TAM-7 (see Fig. 4.34) shows good agreement with Midway from all eight directions studied.

Not all directions at TAM-6 are affected, so the problem there does not appear to be aerovane mis-calibration, which would affect all

Fig. 4.33. Distribution of Wind Direction at TAM-6 for Specified Midway Winds. ANL Neg. Nos. 112-9772 and 112-9773.

Fig. 4.34. Distribution of Wind Direction at TAM-7 for Specified Midway Winds. ANL Neg. Nos. 112-9774 and 112-9775.

If miscalibration and seasonal and diurnal effects are not the cause of the problem, then it appears that the observed discrepancies in wind direction must be associated with the less than ideal instrument locations that we must accept for city wind measurements. The buildings the instruments are on, or nearby buildings, apparently deflect winds from certain directions, thereby causing apparent direction differences between Midway and TAM station winds when no difference actually exists in the flow aloft.

Figures 4.33 and 4.34 show distributions at TAM stations for certain Midway winds. This is a legitimate way to compare two stations, but it only hints at a way to evaluate the validity of a specific TAM wind measurement. An examination of Midway wind-direction distributions for certain TAM winds is more revealing. These distributions are given in Fig. 4.35 for the TAM-4 station.

For most wind directions, TAM-4 appears to represent valid data, because the peak of the Midway distribution falls within 10° of the TAM direction. However, from certain directions, southwest and west in particular, the agreement is poor. Winds from the southwest and west at TAM-4 should therefore be used with caution.

In spite of the poor quality of some of the TAM wind measurements, investigation of individual pollution events at TAM-4 shows that important local wind anomalies do occur (mostly lake breezes) and that their magnitude is such that TAM measurements are accurate enough to detect them.

Fig. 4.35. Distribution of Wind Direction at TAM-4 for Specified Midway Winds. ANL Neg. Nos. 112-9776A & B.

Often these cases involve east winds at TAM-4 when Midway winds are westerly. The superiority of local measurements may be less significant at stations distant from the lake, where the frequency of lake breezes is lower. Nevertheless, the TAM-X wind should be used for the study of TAM-X, rather than assuming that the Midway wind is valid for all eight stations. The TAM winds, despite their deficiencies, are accurate enough to distinguish between those directions that are important for air pollution dispersion analyses.

4.5 Objective Depth Estimates of Mixing Layers (J. Norco and J. Ash)

Existing theoretical and empirical diffusion studies demonstrate the importance of the mixing depth as a factor influencing the dispersion of pollutants in the atmosphere. The inclusion of this parameter is statistical (e.g., tabulation prediction technique, Sec. 6.), and deterministic (e.g., dispersion model, Sec. 7.) methods for estimating air quality are clearly desirable. Since, at the time of the Chicago study, vertical soundings were not routinely performed in the region, a method of estimating the hourly mixing depth over Chicago was developed. A program for comparing such estimates with EMSU soundings currently being taken in Chicago is presently under way.

4.5.1 Mixing Depth Estimate Methodology

The objective mixing layer depth estimates are based on a computerized interpolation scheme between two rawinsonde stations: Green Bay, Wisconsin and Peoria, Illinois. Green Bay is approximately 180 miles north of Chicago and Peoria about 140 miles southwest. The sounding data in the form of magnetic tape was supplied by the Weather Records Center, Asheville, N.C. Both mandatory and significant levels are available up to 700 millibars. The soundings are usually taken at 0600 and 1800 CST. The schematic flow diagram (Fig. 4.36) illustrates the basic computational procedure used in the computer program; a detailed description follows.

Fig. 4.36. Calculation of Hourly Mixing Depth over Chicago. ANL Neg. No. 113-1119.

The mandatory and significant levels for each station are merged to form a single pressure-temperature array for each sounding. The Chicago rural (Argonne) temperature profile is formed either by "shifting" one or two to the Argonne surface temperature or by interpolation between the Peoria and Green Bay soundings. If only one station was in the same air mass as Chicago, the sounding from that station is transposed, without changing its shape, to the Argonne surface temperature at sounding time.

If both Peoria and Green Bay were in the same air mass as Chicago (as determined by inspection of the daily weather map), then the interpolation was performed. Interpolation is done by temperature weighting; that is, the computed Argonne profile tends to resemble that of the sounding site whose surface temperature is nearest to Argonne's. As an example, see Fig. 4.37. Using the surface temperatures, we calculate the ratio

$$R_1 = \frac{T_{ANL} - T_{GRB}}{T_{PIA} - T_{GRB}}$$

For every 20-millibar level above the surface, the Argonne temperature is computed using the relation

$$T_{ANL} = T_{GRB} + (T_{PIA} - T_{GRB}) R_1.$$

This procedure forms a pressure-temperature array for the 0600 and 1800 rural profiles.

Fig. 4.37. Construction of Chicago Rural Temperature Profile. ANL Neg. No. 113-1120.

The next step is to compute the hourly rural profiles using temporal weighting. The profile for any hour is an interpolation in time between the bracketing 0600 and 1800 rural soundings, as computed above. At 0900, for example, the ratio

$$R_2 = \frac{T_{0900} - T_{0600}}{T_{1800} - T_{0600}}$$

is computed using Argonne surface temperatures. Then the profile is formed using the relation

$$T_{0900} = T_{0600} + (T_{1800} - T_{0600}) R_2$$

at every 20-millibar level above the surface.

The hourly urban mixing depth and mixing-depth indices are now

computed. The mixing depth is defined as the height of the intersection of a dry adiabat from the urban surface temperature with the constructed Argonne rural temperature profile. The mixing depth index is one-tenth of the pressure difference (in millibars) between this intersection point and the surface. For each hourly Midway (urban) temperature and pressure, the potential temperature is computed. An iterative searching procedure is used to locate the intersection of the constant-potential temperature line (dry adiabat) and the rural profile for the same hour. The mixing depth is then calculated by applying the hydrostatic equation to the straight-line segments of the sounding up to the intersection point and summing the individual heights. Figure 4.38 illustrates graphically the construction of the mixing depth.

The hourly mixing depth and mixing-depth indices are calculated for the two years of data, 1966-1967, and stored in the master data file for general use.

4.5.2 Comparison with Other Estimated and Measured Mixing Depths

Since June 1968, a Chicago-area consulting meteorology firm has estimated hourly mixing depths for the Argonne air pollution program.

Fig. 4.38. Construction of the Mixing Depth.
ANL Neg. No. 113-1121.

Although these estimates are based on the Peoria and Green Bay soundings, they are more subjective than the computerized technique. The rural lapse rate and mixing-depth indices proved by the professional meteorological service are developed each day on the basis of meteorological forecasting experience and subjective analyses of all current weather data. These factors are not present in the objective, computerized method. For instance, the mixing-layer estimates are modified pursuant to frontal passages, strong warm or cold advection aloft, wind and temperature patterns on the 850-, 700-, and 500-millibar charts, etc.

A comparison of the mixing-depth indices was made for September 1968. Results from the computer program are plotted with the subjective estimates in Fig. 4.39 for the first 10 days of the month, which give a representative comparison of the diurnal variations of mixing depth.

There seems to be good agreement in terms of trend tendencies. Both reach maximum and minimum values at approximately the same time each day.

Soundings have also been taken over Chicago using an aircraft or helicopter. Two of these are discussed below:

1. On December 16, 1968, a helicopter sounding was made over Chicago at 10:00 a.m. Figure 4.40 shows the measured vertical temperature profile. It can be seen that the lower portion characterized by a dry adiabat extends to about 2000 ft. The objective mixing-depth estimate technique produced a mixing depth of 2300 ft, an error of 15%.

2. A sounding was taken over Midway Airport on March 5, 1969, at about 11:00 a.m. with a light plane. The data indicated a dry-adiabatic lapse rate to the maximum elevation attained, 2700 ft. The objective estimate placed the mixing depth at about 3000 ft.

Fig. 4.39. Comparison of the Computerized Objective Mixing-depth Index with Corresponding Subjective Estimates. ANL Neg. No. 113-1122.

Fig. 4.40. Argonne-Chicago Department of Air Pollution Control Helicopter Sounding of December 16, 1968. ANL Neg. No. 113-1123.

4.6 The Anatomy of an Air Pollution Episode* (Harry Moses, Donald F. Gatz, James E. Carson, Frank C. Kulhanek, and Gunther A. Zerbe)

4.6.1 Introduction

During the first and second weeks of November 1969, dispersive properties of the atmosphere over Chicago were poor. As a result, high concentrations of pollutants accumulated in the lower layers. More so than on other occasions, the news media became particularly responsive to the situation. Many newspaper columns were devoted to the prevailing conditions. Attention was called to the responsibility of industry and public officials in alleviating the episode. This writeup examines the air quality conditions and weather associated with this episode.

4.6.2 Patterns of SO₂ Concentrations

A picture of the distribution of SO₂ concentrations over Chicago during November 4-12, 1969, including the most severe part of the episode is given by Figs. 4.41-4.46. Chicago has in operation a Telemetered Automatic Monitoring (TAM) network which allows a citywide assessment of air pollution conditions. These data were plotted automatically on machine-drawn maps as shown in these figures. (Figure 4.2 shows the location of the TAM stations.) Figures 4.41 and 4.42 show the distribution of the SO₂ concentrations at 0800 and 1400 for November 4 and 5. On November 4, the winds were fairly brisk, up to 12 mph in the afternoon, and the concentrations were fairly low. A buildup occurred on November 5; this was associated with lighter winds blowing from the southwest. There we see a pocket of high concentration, 0.29 ppm, at TAM-3. The greater mixing in the afternoon at 1400 shows a reduction in levels of SO₂.

Figure 4.43 shows the buildup of SO₂ concentrations on November 6. The stippled area shows the portions of the city recording SO₂ levels of 0.20 ppm or greater. The peak values of SO₂ concentrations occurred at 1200 on November 6 when TAM-7 showed a value of 0.75 ppm. During this time, the winds were light and a lake breeze was beginning to come in, as seen by the flow at Station 1. By 1400, an easterly wind had set in and

*We wish to acknowledge the cooperation of several groups who have furnished data to make this study possible. These are:

- 1) The Chicago Department of Environmental Control for furnishing the TAM station data; in particular, Mr. Edward W. Klappenbach and Mr. Samuel Booras (present affiliation: Environmental Pollution Control Systems, Chicago, Illinois).
- 2) The National Oceanic and Atmospheric Administration for providing the upper-air soundings, in particular, Mr. Arthur W. Strong.

Invaluable computer-programming assistance was provided by the following personnel of the Argonne Applied Mathematics Division: Cynthia Chamot, Janet B. Anderson, and Martin Kraimer.

Fig. 4.41. SO_2 Concentration Isopleths and Wind Data for November 4, 1969 at TAM Stations, Chicago. ANL Neg. Nos. 149-4308 and 149-4309.

Fig. 4.42. SO_2 Concentration Isopleths and Wind Data for November 5, 1969 at TAM Stations, Chicago. ANL Neg. Nos. 149-4310 and 149-4311.

AT 0000 CST

AT 0200 CST

AT 0600 CST

AT 0800 CST

Fig. 4.43. SO_2 Concentration Isopleths and Wind Data for November 6, 1969 at TAM Stations, Chicago. ANL Neg. Nos. 149-4314, 149-4312, 149-4315, and 149-4316.

Fig. 4.43 (Contd.). ANL Neg. Nos. 149-4321, 149-4317, 149-4319, and 149-4323.

Fig. 4.44. SO₂ Concentration Isopleths and Wind Data for November 10, 1969 at TAM Stations, Chicago. ANL Neg. Nos. 149-4330 and 149-4331.

Fig. 4.45. SO₂ Concentration Isopleths and Wind Data for November 11, 1969 at TAM Stations, Chicago. ANL Neg. Nos. 149-4332 and 149-4333.

Fig. 4.46. SO₂ Concentration Isopleths and Wind Data for November 12, 1969 at TAM Stations, Chicago. ANLNeg.Nos. 149-4335 and 149-4334.

the concentrations were substantially reduced. Nevertheless, the western part of the city showed concentrations greater than 0.20 ppm as indicated by the stippling. Levels of pollution continued to decrease through 2200 on November 6. We see that although there is a pocket of high values in the west, all stations were recording values below 0.20 ppm. Figure 4.44 show the values of SO₂ at 0800 and 1400 on November 10. A pocket of high pollution occurred at 0800 with southwesterly winds, but by 1400 the winds increased and the levels of SO₂ concentration had decreased. The episode was considered over on 1400, November 12. Figures 4.45 and 4.46 shows the isopleth patterns for SO₂ concentrations at 0800 and 1400 on November 11 and 12, respectively.

These charts show the patchiness of the SO₂ distribution over the city. Even though Chicago was recognized as having an air pollution episode, some parts of the city were relatively clean; the high concentrations were confined to limited areas. It is important to realize that in a city like Chicago, with diverse terrain and a heterogeneous distribution of sources, uniform conditions do not prevail. A change in the wind direction can result in a marked change of the air quality in a given part of the city.

4.6.3 Air Quality Standards

As a result of the Clean Air Act of 1967, states are required to set up air quality standards in their respective air quality regions. A single

air quality region may cover more than one state, and a single state may have more than one quality region within it. The air quality region of which Chicago is a part includes the Illinois counties Cook, Du Page, Lake, Will, and McHenry, and the Indiana counties Lake and Porter. Table 4.12 shows the air quality standards for the Chicago Metropolitan Air Quality Region in 1969. These standards may be compared with the readings obtained on the charts showing the distribution of SO_2 concentrations over Chicago. With the value of 0.42 ppm as the maximum 1-hr reading to be allowed during 1 hr of the year, we see that these standards were violated on several of the maps. These standards were violated frequently during 1966-1969.

TABLE 4.12. State of Illinois Air Pollution Standards for SO_2 , 1969.
Standard to be reached by January 1, 1972.^a

Maximum annual geometric mean: 0.015 ppm (24-hr samples) ($40 \mu\text{g}/\text{m}^3$)
24-hr concentration of 0.10 ppm not to be exceeded more than 1% of the days per year ($265 \mu\text{g}/\text{m}^3$)
24-hr concentration of 0.17 ppm not to be exceeded more than 1 day/yr ($450 \mu\text{g}/\text{m}^3$)
1-hr concentration of 0.42 ppm not to be exceeded more than 1 hr/yr ($1110 \mu\text{g}/\text{m}^3$)

^aStandards are applicable at each sampling station.

4.6.4 Sources of Air Pollution

Figure 4.47 shows the distribution of sources of SO_2 over Chicago. The Commonwealth Edison stacks contributed up to 50-60% of the SO_2 emitted over Chicago during 1966-1969. This utility company switched to gas during this episode at a cost exceeding \$150,000. Note the nonuniform distribution of sources due to commercial and residential space heating. The heterogeneity of the sources contributes to the structure of the isopleth patterns of Figs. 4.41-4.46.

4.6.5 Weather Conditions Associated with the November Episode

4.6.5.1 Synoptic Charts. Figure 4.48 shows the surface synoptic charts for 0700 EST (0600 CST) for November 4-6, 1969. Also presented are the 500-millibar charts for the same times. The synoptic chart of November 6 shows Chicago as being under the influence of a very flat pressure system. The pronounced high pressure ridge extended over the city of Chicago with a blocking high aloft to the northeast. This situation contributes to very slow-moving or stagnating conditions.

Fig. 4.47. Map Showing Distribution of Sources of SO₂ in Chicago, Based on 1967 Data. ANL Neg. No. 112-9133 Rev. 1.

Fig. 4.48. Surface and 500-millibar Weather Charts for November 4-6, 1969. (Published by U.S. Dept. of Commerce, ESSA.) ANL Neg. No. 149-4495.

Fig. 4.48 (Contd.). ANL Neg. No. 149-4496.

Fig. 4.48 (Contd.). ANL Neg. No. 149-4497.

4.6.5.2 Time Cross Sections. One of the most interesting weather charts describing the November episode is shown in Fig. 4.49. This represents a time cross section of temperature and wind for November 3-14, 1969. The ordinate is the height above ground in hundreds of meters, and the abscissa is time. The vertical lines represent atmospheric soundings. On

Fig. 4.49. Time Cross Section of Temperature ($^{\circ}\text{C}$), Wind Direction, and Speed (knots). ANL Neg. No. 149-4305.

this line were plotted the wind direction and speed. Also plotted but not shown were temperatures at each level. Isotherms were drawn to show the lines of equal temperature. Stippling was included in the region of temperature greater than 8°C . Double stippling was used for temperatures exceeding 10°C . Cold air shown on the upper left- and upper right-hand part of the chart was delineated with stippling of still another pattern. The striking part of the chart shows the layer of warm air over the city on November 6-7, and also on November 10 and 11. This warm lid, together with the light winds during this period, contributed markedly to the stagnation conditions and high concentrations of pollutants.

4.6.5.3 Time-series Charts. To present a detailed picture of weather conditions prevailing during the episode, time-series plots of the meteorological variables and the air quality at the most polluted station (Station 7) and the least polluted station (Station 5) are shown in Figs. 4.50 and 4.51, respectively. Figure 4.50 gives the Argonne lapse rate, the wind speed and direction at TAM-7, the SO_2 concentration at TAM-7, the solar and sky radiation on a horizontal surface at Argonne, the net radiation at Argonne, and the ceiling height at Midway. Figure 4.51 shows the same data for TAM-5. Hourly averages of the measured data were used in these plots.

Figure 4.50 shows high concentrations observed over TAM-7, together with simultaneous measurement of the meteorological variables. Note that the winds were less than 5 mph during a good part of the series and that the atmospheric stability was particularly high. Of interest is that the sun was fairly bright and that the conditions were relatively clear, as indicated by both the solar radiation and net radiation curves and the ceiling values at Midway.

A similar presentation for TAM-5 is given in Fig. 4.51. Here again the wind speeds are quite low. Figures 4.52 and 4.53 show other meteorological variables, but TAM-7 and -5 are plotted on the same chart. Here we see the temperature and relative-humidity curves typical of a clear day, the two curves being 180° out of phase. The Midway visibility was low during the periods of maximum SO_2 concentrations. These charts also show a period of precipitation of lesser extent occurred on November 13.

4.6.6 Comparison of 24-hourly SO_2 Concentrations with Other Years

To present this episode in proper perspective, the data for the previous Novembers are compared with those of November 1969. Figure 4.54 shows the Chicago Air Pollution Index (API) for November during 1966-1969. The Chicago API may be expressed as the eight-TAM-station average of the 24-hourly means. The 24-hourly mean is based on the 24 one-hourly average values taken from midnight to midnight. Algebraically it may be expressed as

(a) November 1-7, 1969

Fig. 4.50. Time-series Plots of SO₂ Concentrations and Meteorological Variables at TAM-7. ANL Neg. No. 149-4292 Rev. 1.

(b) November 8-15, 1969

Fig. 4.50 (Contd.). ANL Neg. No. 149-4293 Rev. 1.

(a) November 1-7, 1969

Fig. 4.51. Time-series Plots of SO₂ Concentrations and Meteorological Variables at TAM-5. ANL Neg. No. 149-4298 Rev. 1.

Fig. 4.52. Time-series Plots of SO₂ Concentrations and Meteorological Variables at TAM-7 and -5 for November 1-7, 1969. ANL Neg. No. 149-4301 Rcv. 1.

Fig. 4.53. Time-series Plots of SO₂ Concentrations and Meteorological Variables at TAM-7 and -5 for November 8-15, 1969. ANL Neg. No. 149-4300 Rev. 1.

Fig. 4.54. Air Pollution Indices, November 1966-1969, Chicago, Based on TAM Station Network Data. In each group of four bars, reading from left to right, the bars represent the data for the years 1966, 1967, 1968, and 1969. ANL Neg. No. 149-4306.

$$API = \frac{1}{8 \times 24} \sum_{i=1}^8 \sum_{h=1}^{24} C(h,i),$$

where $C(h,i)$ represents the SO_2 average concentration during the h th hour at the i th station. On this chart the ordinate represents the API in ppm and the abscissa represents the date. Note that the bars occur in groups of four. The one on the extreme left represents data for 1966; the second, 1967; the third, 1968; and the one on the extreme right, 1969. Also shown as heavy horizontal lines are the Illinois State Air Pollution Standards for SO_2 . The 0.10 line (line B) indicates the standard, which states that the SO_2 concentrations must not exceed 0.10 ppm on more than 1% of the days during any year. Line A corresponds to the 0.17-ppm value of the standard, indicating that not more than one day should show the value of 0.17 ppm. Since these data represent the average for eight stations, the averaging process reduces the averages when compared to that of a single station. Note that November is not necessarily the worst month. Higher levels of SO_2 concentration occur during December, January, and February. Even though many violations of the standards are evident for November, more occur in December, January, and February.

Figure 4.55 compares the stations for 1966-1969 using the annual arithmetic means and the hybrid geometric mean, also referred to as the Hybrid Geometric Air Pollution Index (HGAPI). It may be defined as

$$HGAPI = \left[\prod_{d=1}^{365} \left(\frac{1}{24} \right) \sum_{h=1}^{24} C(h,d) \right]^{1/365},$$

Fig. 4.55. Annual Averages for the Eight TAM Stations. In each group of four bars, reading from left to right, the bars represent the data for the years 1966, 1967, 1968, and 1969. ANL Neg. No. 149-4002 Rev. 1.

where $C(h,d)$ is the SO_2 concentration at a given station on the h th hour, and the d th day. Figure 4.55 shows that the dirtiest stations are TAM-3, -4, and -7, in that order. During the November 1969 episode, nevertheless, TAM-7 had the highest concentrations. The horizontal line represents the 0.015-ppm annual standard; this standard was violated each year by all stations but TAM-1. These charts portray the heterogeneity of the SO_2 concentrations over the city and point out the extent of the differences between the dirtiest parts and the cleanest.

4.6.7 Probability of Exceeding Hourly Values of Indicated SO_2 Concentrations

Table 4.13 provides a picture of the frequency of occurrence of hourly values of SO_2 concentrations which exceed the Illinois standards. This table shows the percent of the total number of observations of hourly SO_2 concentration values above the values indicated in the first column. These tables are based on 3 years of data beginning with January 1, 1966, through December 31, 1968. In a substantial part of the time, values occur greater than 0.45 ppm. (The standard is 0.42 ppm.) The number of cases is given in the next to the last line, and the maximum values for each station on the last line.

4.6.8 Comments and Conclusions

The weather conditions associated with this episode were typical of high-pollution conditions. Winds were light to heights of about 2000 ft, and a warm layer of air over the city at about this level produced an inversion lid. As a result, vertical mixing was markedly suppressed and the urban ventilation was small enough to allow an accumulation of contaminants. These conditions are usually associated with flat high-pressure areas such as prevailed over the Chicago area during this time.

Although the episode may be considered as extending from November 4 to 12, 1969, there were two periods of particularly high pollutant concentrations. The first occurred on November 6 and the second on November 11. On these days, the time cross section shows an enhancement of the upper warm air layers and light winds characteristic of episode conditions.

This study further points out the patchiness of the SO_2 concentration distribution over the city. Even when extremely high SO_2 levels were found (e.g., 0.75 ppm at TAM-2 at 1200 on November 6), TAM-4 showed only 0.06 ppm. The substantial difference in cleanliness is further brought out in Fig. 4.55, which shows the annual arithmetic and hybrid geometric average for each TAM station during 1966-1969.

TABLE 4.13. Percent of Hourly SO₂ Concentrations above Indicated Values for Chicago, January 1, 1966 to December 31, 1968

INDICATED VALUES CF SO ₂ CONC. (PPM)	TAM-1	TAM-2	TAM-3	TAM-4	TAM-5	TAM-6	TAM-7	TAM-8
1.00	0.02	0.0	0.04	0.03	0.02	0.01	0.0	0.00
0.95	0.02	0.0	0.06	0.05	0.03	0.01	0.0	0.00
0.90	0.02	0.00	0.08	0.09	0.05	0.02	0.0	0.00
0.85	0.02	0.01	0.13	0.11	0.06	0.04	0.01	0.00
0.80	0.03	0.01	0.20	0.17	0.07	0.04	0.01	0.00
0.75	0.04	0.01	0.34	0.23	0.08	0.05	0.02	0.01
0.70	0.05	0.01	0.55	0.36	0.09	0.08	0.06	0.01
0.65	0.07	0.04	0.82	0.48	0.10	0.11	0.09	0.01
0.60	0.11	0.07	1.37	0.66	0.11	0.14	0.18	0.01
0.55	0.14	0.11	2.12	1.01	0.14	0.22	0.31	0.03
0.50	0.22	0.25	3.53	1.52	0.21	0.30	0.56	0.04
0.45	0.30	0.39	5.34	2.29	0.27	0.41	0.92	0.08
0.40	0.48	0.63	7.69	3.41	0.44	0.50	1.41	0.11
0.35	0.71	0.93	10.33	4.76	0.67	0.63	2.02	0.19
0.30	1.01	1.73	14.25	7.05	1.05	0.98	3.14	0.39
0.25	1.59	3.24	20.56	11.24	1.88	1.56	5.53	0.92
0.20	2.53	5.63	27.39	17.20	3.08	2.80	9.00	1.94
0.15	4.76	10.57	35.96	26.05	5.94	5.42	14.74	4.12
0.10	8.04	19.01	45.17	35.52	11.22	10.24	23.73	8.46
0.05	17.47	40.43	59.94	53.00	27.32	24.39	44.41	23.95
NO.OF CASES	22290	23762	22663	24140	22723	23320	24424	23371
MAX HRLY VALUES=	1.28	0.90	1.97	1.04	1.24	1.19	0.90	1.14

The first week or two in November is the time during which people burn their leaves. During light winds and stable conditions, the smoke from leaf-burning is dispersed slowly, substantially reducing visibility. This happened on a number of days during this episode. Leaf-burning was responsible, in part, for the general haziness and poor local visibility that prevailed during periods of this episode.

An important point brought out in this study--not recognized by the general public--is that there were many times in 1966-1969 during which

conditions were as bad or worse. For the November conditions given in Fig. 4.54, we see that the highest city-wide 24-hr average, which occurred on November 6, was exceeded seven times in the previous years 1966, 1967, and 1968. Since we know that pollution levels are appreciably higher in the winter months of December, January, and February than in November, many more 24-hr city-wide SO_2 concentration values, exceeding the worst day of this episode, occurred during the period of record.

An examination of hourly values and 24-hourly values at individual stations during the episode points out that the levels indicated for the Illinois Air Pollution standards have been frequently exceeded. This is shown in Table 4.13 and in many of the figures in this section. It must be remembered that the standards apply to an individual station. Figure 4.54 presents the data averaged over the entire city including high- as well as low-concentration areas. Thus individual stations would show much higher concentrations and greater occurrence frequencies.

Hopefully, with the enactment and implementation of new regulations to reduce the amount of SO_2 emitted into the atmosphere, the concentration levels will be reduced to values below the indicated standards. The data show that a substantial reduction is necessary.

To assess properly the effect of high concentrations of harmful pollutants, one must make measurements where the people are. In the Chicago Loop area and the near north side, there are many high-rise apartment buildings. An appreciable number of people live 100 ft or more above ground. Further, the ventilation-air intakes of such buildings are 100 ft or more above ground level.

Since many of the major SO_2 sources are elevated sources (i.e., the emitting stacks are several hundred feet high), it is certain that the concentration of pollutants increases with height. Therefore, measurements of ground-level concentrations must not be applied to evaluating the air quality above 100 ft. From this reasoning it appears that a valid evaluation of the impact of an episode would require measurements of pollutant concentrations at elevated levels where a significant number of the population is found.

5. CHICAGO URBAN METEOROLOGICAL EXPERIMENTS

(J. E. Carson, D. F. Gatz, D. M. Nelson, T. L. Duffy,
R. Kasper, and E. W. Klappenbach)

5.1 Introduction (J. E. Carson)

To accurately predict SO_2 concentrations in an urban area, we must know how the atmosphere transports and dilutes effluents injected into it. That is, we must know the diffusive capacity of the atmosphere over Chicago and its variations in time and space and from one meteorological regime to another. Some diffusion parameters (sigmas) can be indirectly estimated from standard surface-meteorological data, such as wind speed, time of day, and cloud cover. When this project began in 1967, three types of meteorological measurements needed to accurately estimate diffusion rates over Chicago were not being made. These are the vertical temperature gradient, wind direction and speed in the zone of mixing and transport, and the depth of the mixing layer. The vertical temperature gradient (lapse rate) determines atmospheric stability and dilution rates. When combined with wind speed and surface roughness, the lapse rate determines the intensity and spectrum of turbulence. The depth of the mixing layer (that is, the volume of air in which the pollutants can be mixed) is determined by the height above ground and intensity of stable layers (inversions) aloft; it is very difficult if not impossible to estimate this critical pollution parameter without direct measurements.

The low-level lapse rate varies with time and height as well as horizontally in an urban area such as Chicago with its mixture of tall and low buildings, roads, parks, Lake Michigan, etc. In dispersion calculations, the lapse rate in the first several hundred feet above ground is usually estimated from standard weather observations (wind speed, cloud cover, time of day, etc.) using objective techniques, such as those proposed by Gifford (1961), Pasquill (1961), and Turner (1967). Unfortunately, these procedures cannot provide accurate space and time estimates of the mixing depth.

Several experimental programs were initiated to obtain additional meteorological measurements in Chicago and to measure dispersion rates over the uneven terrain of the city. The four programs in which Argonne is involved are: (1) aircraft sounding program, (2) instrumentation of tall buildings in the city, (3) tracer studies, and (4) fuel-switch tests. The fuel-switch program is discussed in Chapter 9 of this report.

The National Weather Service (formerly, U.S. Weather Bureau), using funds from NAPCA, began a radiosonde observing program in Chicago in April 1969, to provide wind and temperature data from the surface to a height where air pressure is 700 millibars (about 10,000 ft). This program

is providing useful data and can be expected to increase the accuracy of pollution forecasts. Most of the balloon releases to date have been at Midway Airport; some have been made at other locations, including Argonne.

Slow-rising radiosondes are used to obtain temperature and humidity data; the balloons are followed optically to give wind speed and direction. An overinflated 100-g pilot balloon is used to lift the package. Normally, two flights are made each normal work day, one at 0500 or 0600 CST and the other at 1000 or 1100 CST. None are made on weekends or holidays, unless an air-pollution episode or stagnation period is forecast or observed. More than two soundings per day can be made during high pollution potential periods.

Figure 5.1 shows the results of a recent low-level balloon sounding made in Chicago, and shows very dramatically why information in the zone of mixing and transport is needed in air-pollution studies. Temperature and dewpoint profiles as well as wind direction and wind speed (knots) are shown. During the morning hours of September 25, 1969, five of the eight TAM stations (TAM-2, -3, -4, -5, and -7) reported moderate (about 0.20-ppm) levels of SO_2 . Much lower concentrations were observed in the afternoon, due to increasing southwesterly winds and destruction of the surface inversion (confirmed by the 1100 CST radiosonde flight).

The 0600 CST surface weather map on September 24, 1969, showed that this area was under the influence of a large high-pressure center over Hudson Bay with a strong ridge extending to the SSW across Iowa into Texas. During the next 24 hr, the pressure ridge and center moved eastward; at 0600 CST on September 25, the ridge was just east of Chicago and a weak cold front ran through western Minnesota and Iowa.

Figure 5.1 shows a ground-based nocturnal radiation inversion up to 500 ft, and an adiabatic layer to the base of a strong subsidence inversion at 3500 ft above the surface. Note the extremely dry air in this inversion layer. Twenty-four hours earlier, the base of this inversion was at 6000 ft. The 1100 CST sounding on September 25 showed an adiabatic lapse rate from the surface to the base of the inversion aloft, which had dropped to 3000 ft. By the next morning, the cold front had passed Chicago Midway Airport, and the upper inversion was no longer present.

Figure 5.1 shows many interesting features related to diffusion rates that could not be determined or estimated from routine surface-weather measurements. Pollutants released into the shallow surface inversion would tend to remain at the level of release and move to the southeast until this inversion was destroyed by solar heating. Sources with effective stack heights equal to or greater than 500 ft would diffuse through a layer 3000 ft thick and move toward the west. Estimates of ground-level concentrations

Fig. 5.1. Vertical Wind, Temperature, and Humidity Profiles, Chicago Midway Airport, September 25, 1969. Wind speeds in knots. ANL Neg. No. 149-4199.

of SO_2 for "fumigation" conditions expected at the time of breakup of the surface inversion, using the observed surface wind direction, would be incorrect. This figure shows the importance of detailed, low-level soundings in urban areas for air-pollution studies and forecasts. How else can details of the winds in the zone of mixing and transport above the city be measured or estimated, and the thickness of the mixing layer be accurately determined?

5.2 Aircraft Sounding Program (J. E. Carson and D. M. Nelson)

Since vertical lapse-rate data are so important in air-pollution work, and since no data were being collected locally, the City of Chicago Department of Environmental Control (DEC) purchased an airborne instrument package designed to measure SO_2 , pressure altitude, wet-bulb depression, and air temperature. The instrument was developed and manufactured by Sign-X Laboratories, Inc., Essex, Connecticut. This package, mounted on a Chicago Fire Department helicopter, began measuring SO_2 and temperature profiles over the city in March 1969. Several examples of the types of information that can be obtained from such a system are given below. DEC personnel have operated the equipment on most flights. Additional soundings in the area have been made by Mr. Donald Nelson of Argonne, using a thermistor-Wheatstone Bridge temperature sensor loaned to Argonne National Laboratory by the National Air Pollution Control Administration (NAPCA).

Fifteen flights have been made by DEC and Argonne personnel to measure vertical sulfur dioxide and temperature profiles in and near Chicago. Both helicopters and light airplanes have been used. The primary objective of this sounding program was to evaluate atmospheric and diffusion conditions (such as the horizontal and temporal variations of the urban lapse rate; the height, thickness, and intensity of inversion layers; SO_2 concentrations aloft; and the altitude of maximum SO_2 concentration) for a number of typical weather situations. Argonne's primary role in this program is to assist in the design of the flight program and to analyze the resulting data inventory.

As originally planned, the City of Chicago instrument package was to be flown on a City Fire Department helicopter each Wednesday. Due to a malfunction of the flight package and limited availability of the helicopter, only 12 flights have been made with the system.

The helicopter system was to be used to obtain vertical temperature and SO_2 soundings on a regularly scheduled basis and to study in detail these profiles in the city and how they vary horizontally and with time during "typical" weather and pollution situations. The original schedule called for vertical profiles to be routinely measured at Meigs, Midway, and Argonne. The National Weather Service radiosonde program frees the

helicopter from making these routine observations. The balloons also give wind information in the zone of transport over the city, data not observable from a helicopter.

By far the most interesting of the helicopter flights was made on March 19, 1969. The 0600 CST weather map showed an east-west stationary front across Wisconsin, Lake Michigan, and Michigan just north of Chicago. Winds were mostly light and variable south of the front, weak north to northeast behind the front. This frontal zone pushed to the south during the morning hours, passing Meigs and Midway Airports before the helicopter started its flight program. Figure 5.2 shows the temperature profiles at Meigs Airport, Midway Airport, and Argonne. Unfortunately, no SO_2 data were collected during this flight. The cool air behind the front and off the lake was considerably moderated by the time it reached Midway Airport; a dry adiabatic layer about 400 m thick had been generated, with a stable layer above. The cold air did not pass Argonne until 1320 CST. The maximum temperature was 19°C (66°F), reached just before frontal passage. After frontal passage, the winds at Argonne became ENE at 9-11 mph and the skies remained clear. The Argonne sounding, made at 1100 CST, showed an adiabatic layer to the top of the sounding at 1100 m.

Fig. 5.2. Vertical Temperature Profiles, Meigs and Midway Airports and Argonne National Laboratory, March 19, 1969. ANL Neg. No. 113-1125.

The pall of pollution brought to Argonne in the new air mass was visible as it approached; there were enough smoke and solid pollutants in the air to reduce solar-radiation intensity about 15-20%. Figure 5.3 shows the solar-radiation data at Argonne on this date; data for May 18, a clear but clean day, are included to show the reduction of insolation due to polluted city air. These data show that the pollutants were within the new air mass, not ahead of it.

Fig. 5.3. Solar-radiation Data at Argonne National Laboratory, March 18 and 19, 1969. ANL Neg. No. 201-8981.

Wind data at Argonne show that the intensity of turbulence in the new air mass was quite low; for example, the standard deviation of the vertical wind direction (as measured by a bivan and sigma meter) 11.4 m (37.5 ft) above the ground changed from 13° before the lake air arrived to 6° after. The standard deviation of the azimuth angle changed from 40 to 10° . The lapse rate as measured on the 150-ft Argonne Meteorology Tower showed no change of stability; the observed large drop in diffusion rates would not be expected from the objective techniques proposed by Gifford (1961), Pasquill (1961), and Turner (1967).

By far the best SO_2 and temperature profile data collected by the helicopter were obtained between 0940 and 1100 CST on April 11, 1969. The flight path and sounding locations were selected using existing weather conditions and modified during the flight to obtain maximum useful information. Mr. Nelson of the Argonne National Laboratory flew in the helicopter, operated the instruments, and directed the flight pattern.

On April 11, a large, cold high-pressure area was centered over the upper peninsula of Michigan, moving ESE. The sky was mostly clear, with a few scattered middle clouds. Surface winds in the area were ENE at 7-9 mph. This flow concentrated the pollutants emitted by the complex of industries and power plants along the Stevenson Expressway into a single visual plume. The flight pattern was altered en route to take advantage of this concentration of pollutants. The original plan was to make vertical soundings at Meigs, Midway, and Argonne, the standard flight schedule. A decision was made while in the air to detour to Hinsdale Airport in order to make an additional sounding near the center of the visible smoke plume moving along the Expressway. Most of the plume appeared to the observer on the aircraft to originate in the Ridgeland Power Station

and the Chicago Sanitary District Plant in Stickney. (Hinsdale Airport is about 10 miles from these sources.) The SO_2 and temperature profiles at this airport are shown in Fig. 5.4. A dry adiabatic lapse rate 620 m thick was observed just below a weak inversion. The air-quality data show that SO_2 levels were high and rather uniformly mixed in this layer, with a very rapid decrease to background levels above the base of the inversion. This figure demonstrates the importance of the mixing-layer concept and how even a weak inversion aloft can act as a lid to dispersion and further vertical mixing.

Fig. 5.4. Vertical SO_2 and Temperature Profiles, Hinsdale Airport, April 11, 1969 (1020 CST). ANL Neg. No. 201-8983.

The temperature profiles at Midway and Argonne were similar to those shown in Fig. 5.4; the SO_2 concentrations below the inversion were considerably lower than that observed at Hinsdale Airport. The soundings at Meigs showed near-zero SO_2 levels at all heights, with a cool surface layer caused by on-shore winds.

One leg of the return flight was flown at constant height (about 250 m above ground) along County Line Road from 95th Street (Des Plaines River) to Cermak Road (2200 south). (County Line Road runs N-S along the boundary between Cook and Du Page Counties.) The SO_2 recorder trace for this leg is shown in Fig. 5.5. Sulfur dioxide levels were quite high (0.25-0.34 ppm) in the visible plume, much lower on either side. The figure shows that valuable information can be gained on horizontal as well as vertical flights. The ragged nature of the SO_2 cross section is interesting and may be due to incomplete horizontal mixing from several large point sources. A simple diffusion calculation, using typical SO_2 outputs from the two plants mentioned above, the Gifford (1961) diffusion parameters, and

the observed weather information, shows that most of the observed SO_2 concentration at Hinsdale Airport could have originated at these two sources. Not too much should be inferred from this calculation, as the real SO_2 emission rates were not known and the SO_2 contributions from all the other possible sources were ignored.

Fig. 5.5. SO_2 Concentrations Observed during Horizontal Traverse along County Line Road, 250 m above Ground Level, April 11, 1969. ANL Neg. No. 201-8980.

Figure 5.6 shows the SO_2 and temperature profiles at Argonne on April 16, 1969, at 1100 CST. South winds at 8 mph with clear skies were present when the sounding was made. The temperature data show the expected adiabatic layer with a weak ($\sim 1^\circ\text{C}$) inversion at 2000 ft. Even this inversion was enough to limit vertical mixing. Profiles at the other airports were similar. (The SO_2 sensor on the flight package uses the Davis conductivity method and is unable to distinguish between SO_2 and CO_2 ; a scrubber is used periodically to remove SO_2 from the airflow so that the contribution of CO_2 to the signal can be measured. The CO_2 value is then subtracted from the CO_2 plus SO_2 reading.)

Additional soundings have also been made by Mr. Nelson using a simple thermistor-bridge combination furnished by the National Air Pollution Control Administration. This package has been flown both on a helicopter and on a light airplane. The thermistor, inside an aluminum radiation shield, was mounted at the forward end of the landing skid of the helicopter or on a strut of the airplane. The thermistor resistance was measured by manually nulling a Wheatstone Bridge having the thermistor as one resistance element and a 10-turn potentiometer as another. Temperatures were then determined from a resistance-versus-temperature calibration chart. Heights were taken directly from the aircraft altimeter.

Fig. 5.6. Vertical SO_2 and Temperature Profiles, Argonne National Laboratory, April 16, 1969 (1100 CST). ANL Neg. No. 201-8982.

The airplane flights conducted between 1200 CST on April 24 and 0600 CST on April 25 show how an aircraft can be used to measure both the space and time variability of lapse rate in the area. The thermistor-bridge system was used every 4-5 hr to make profile measurements at Lewis Airport in Lockport, Illinois (a rural area), Midway Airport (a city location), and Meigs Airport (a lakefront site). Additional soundings were made at other locations.

A large, strong high-pressure area was moving from NW to SE across Chicago during the flight program. As the center of the high passed, the winds veered from north at 8 mph at the start of the flight program through ESE at 5 mph at 2100 CST on the 24th, through S at 4 mph at midnight, and to SW at 4 mph by the end of the period. The sky remained clear.

The time variability of lapse rate at Midway is shown in Fig. 5.7. Considerable warm advection occurred above 2400 m between 1220 and 2100 CST. The mixing depth decreased from 900 to 500 m between 1200 and 1630 on April 24. The surface nocturnal inversion extended to 300 m by 2100 CST; the intensity but not the depth of the inversion increased during the nighttime hours. The data show that the mixing depth on April 25 was much deeper than on the previous day.

Fig. 5.7
Vertical Temperature Profiles, Midway
Airport, April 24-25, 1969. ANL Neg.
No. 201-8984.

5.3 Instrumentation of Tall Buildings (J. Carson and E. Klappenbach)

The helicopter is an ideal sensor platform for obtaining data over large areas rapidly and at moderate cost. Unfortunately, neither helicopters nor radiosonde balloons permit continuous observations.

The Chicago Department of Environmental Control has obtained permission to locate one aspirated temperature sensor on each of the two television towers on the roof of the John Hancock Building in Chicago. These sensors will be about 365 m (1200 ft) above ground level and about 30 m above the roof of the structure. Another sensor will be located about 45 m (150 ft) above street level on the nearby Chicago Water Tower. DEC will shortly begin discussions with the operator of one or two intermediate-sized buildings in the area to obtain sites for additional sensors so that temperature profiles to 365 m can be measured on a continuous basis. It may not be possible to obtain exact temperature profiles in this manner, because of heat from buildings and obstructions to wind flow, and because the sensors are not placed vertically; but for the purpose of diffusion analysis, information on the lapse-rate class (inversion, isothermal, near neutral, or unstable) is probably adequate.

The accuracy and representativeness of building sensor data can be tested by having an instrumented helicopter fly at the height of the sensor

but away from the building heat. If these building-mounted sensors prove useful and accurate, a significant advance in city meteorological observation techniques will have been achieved. Similar low-cost observations could be made at other locations in Chicago as well as in other cities.

The temperature sensors and recorder have been calibrated by Argonne personnel. The equipment will be mounted soon and data collection begun.

5.4 Sulfur Hexafluoride Tracer Studies (J. E. Carson, D. F. Gatz, T. L. Duffy,* and R. Kasper*)

5.4.1 Introduction

The SO_2 concentration observed at any location in urban areas is the sum of the contributions of a very large number of individual sources. However, the specific contribution of any one source or combination of sources cannot now be calculated with the degree of accuracy and certainty needed for effective, optimal abatement strategies. For pollution studies in general, but especially during serious pollution episodes, control authorities must know the relative contribution of each major upwind source.

The use of appropriate tracers enables one to isolate and measure the relative contribution of a particular source (or group of sources) in a fixed monitoring system if its reactions in air are sufficiently similar to the pollutant being studied. Experiments under various weather conditions, using different types of sources, should provide considerable information about the relative importance of the sources and test the ability of the diffusion equations to accurately predict their dispersion.

The diffusion parameters (sigmas) used in most dispersion calculations were determined primarily by tracer studies in relatively flat, rural areas. The techniques used to estimate these parameters from wind speed, cloud cover, and solar radiation reflect rural turbulence characteristics. Due to tall buildings, local heat sources, and the change in surface types, cities are more complex and variable.

It was decided that a series of tracer studies performed in Chicago to measure dispersion rates in the city could yield extremely useful information. A system for the release, collection, and analysis of the tracer was developed and tested. Approximately 200 air samples were analyzed for background levels of the tracer. Unfortunately, funds and personnel to conduct a series of full-scale releases in the City of Chicago were not made available; thus no actual releases were made in the city.

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5.4.2 Sulfur Hexafluoride Analysis System

The tracer material selected for use was sulfur hexafluoride (SF_6). The collection and analysis systems were similar to those developed by the Department of Health, Education, and Welfare's National Air Pollution Control Administration in Cincinnati for this tracer gas (Saltzman *et al.*, 1966; Niemeyer and McCormick, 1968). The ultrasensitive detectability of this material results from the high response characteristics of electron capture detectors to certain halogenated materials.

The analysis system initially chosen was similar to that designated "System B" by Saltzman, Coleman, and Clemons (1966), which uses a tritium detector. Much of the experimental work to date has been to optimize procedures so that very high sensitivities could be realized. A sensitivity of 0.050 ppb (50 pl/liter) was achieved with this system.

A more detailed description of the SF_6 release, collection and analysis equipment, and procedures appears in ANL/ES-CC-003 and -004. These reports also spell out in some detail the planned experimental releases in Chicago.

On the basis of work performed by R. K. Stevens and others in the Cincinnati NAPCA, a more sensitive measurement system was built and tested. A ^{63}Ni detector replaced the tritium foil detector and a pulsed voltage source replaced the dc voltage source. The detector was operated at 220°C , using ultrapure nitrogen (99.999%) as the carrier gas. A 2-ml sampling loop has been found to be optimum in this work. The sensitivity of this system is about 0.5 parts SF_6 in 10^{12} parts of air (0.5 pl/liter).

5.4.3 Background SF_6 Measurements

Sulfur hexafluoride is an extremely stable and inert gas. Since it has a higher dielectric constant than dry air, it is used by industry as an insulator in high-voltage devices. Releases, both intended and accidental, from this equipment add SF_6 to the atmosphere, where natural removal processes have been reported to be minimal (Saltzman *et al.*, 1966). There have been recommendations (American Chemical Society, 1969) that atmospheric SF_6 concentrations should be regularly monitored to detect any buildup.

As a prelude to the use of SF_6 in a tracer experiment, it was necessary to establish the atmospheric background for the location and to determine whether there are any local sources that could interfere with the interpretation of experiments.

The objective of this study was to monitor atmospheric background concentrations of SF_6 . Two sites were chosen: Argonne National Laboratory,

which is the site of several known sources, and the Chicago area in which SF_6 tracer studies were planned. A limited number of background values have been previously reported for urban areas in New York City (Turk *et al.*, 1968) and in Cincinnati (Clemons *et al.*, 1968).

5.4.4 Sampling and Analysis Procedures

Air was collected in two different types of samplers. Evacuated steel cylinders were used to collect nearly "instantaneous" samples of approximately 5-sec duration. Samples of 1 hr and longer were pumped into 12-liter Saran bags using small Teflon pumps. Samples were analyzed using a gas chromatograph to separate SF_6 from other components of the air mixture. The SF_6 was detected with an electron capture detector.

The detector system was calibrated against SF_6 standards prepared by successive dilutions of commercial SF_6 . Independent standard preparations checked to within 25%. Nevertheless, because of the inherent difficulties and uncertainties in preparing standards in the picoliter/liter range, the results summarized in this section are considered accurate to only $\pm 50\%$ on an absolute scale. Relative accuracy is better. Efforts to obtain improved absolute calibration samples are continuing.

Sample analysis was performed on 2-ml aliquots of the original unconcentrated air sample. At least two aliquots of each sample were analyzed. Reproducibility was ordinarily within 25%, except for values < 5 pl/liter, where it might reach 100%. For some of the earlier results, the detection limit was between 20 and 30 pl/liter. Those samples containing undetectable SF_6 at a higher limit of detection are reported as < 30 pl/liter.

5.4.5 Sample Results

Approximately 200 air samples in Chicago urban and suburban areas (including Argonne) have been collected and analyzed. Most of these samples showed SF_6 levels below the level of detectability at the time of analysis.

The locations and sampling times of all background air samples are given in Table 5.1. The results obtained with bag samples are shown in Table 5.2. Out of 89 air samples, 47 had less than detectable amounts of the tracer gas and most of these were less than 2 pl/liter. Twenty-four had SF_6 concentrations between 10 and 99 pl/liter.

A summary of all cylinder-sample results is given in Table 5.3. Most of these samples were collected when the level of detection was 20-30 pl/liter. A number of these samples contained SF_6 well above the detection limits. Six samples had concentrations of at least 100 pl/liter, and another nine were in the 10-99 pl/liter range. Tables 5.4 and 5.5 are summaries of samples containing detectable SF_6 collected at the Argonne Site, and off-site, respectively.

TABLE 5.1. Summary of Background Samples Collected

Location	Sampler Type	Approximate Sampling Time	No. of Samples
Argonne	Bag	1-4 hr	22
	Bag	24 hr	38
	Bag	1 hr	9
	Cylinder	5 sec	40
Chicago	Bag	1 hr	20
	Cylinder	5 sec	34
Chicago Western Suburbs	Cylinder	5 sec	33
Total			196

TABLE 5.2. Results Obtained with SF₆ in Bag Samples

Location	Approximate Sampling Time, hr	No. of Samples	No. of Samples with Less than Detectable SF ₆		No. of Samples with Detectable SF ₆	
			<2 pl/liter ^a	<30 pl/liter ^a	2.0-9.9 pl/liter ^a	10-99 pl/liter ^a
Argonne	1-4	22	1		14	7
Argonne	24	38	31		4	3
Argonne	1	9		2		7
Chicago	1	20	8	5		7
Total		89	40	7	18	24

^a±50%.TABLE 5.3. Results Obtained with SF₆ in Cylinder Samples

Location	No. of Samples	No. of Samples with Less than Detectable SF ₆		No. of Samples with Detectable SF ₆		
		<2 pl/liter ^a	<30 pl/liter ^a	2.0-9.9 pl/liter ^a	10-99 pl/liter ^a	>100 pl/liter ^a
Argonne	40	11	15	2	7	5
Chicago	34		33		1	
Chicago Western Suburbs	33		31		1	1
Total	107	11	79	2	9	6

^a±50%.

TABLE 5.4 Summary of Cylinder and 1-hr Bag Samples with Detectable SF₆ at Argonne

Date	No. of Bags or Cylinders	SF ₆ , pl/liter	Detection Limit, pl/liter	Wind Direction ^a , deg	Remarks
October 21, 1969	2 (cyl)	168	30	210	Downwind of Zero Gradient Synchrotron (ZGS) source.
	39 (cyl)	568	30	210	
	44 (cyl)	104	30	240	
	8 (cyl)	64	30	240	
	41 (cyl)	128	30	240	
November 20, 1969	24 (cyl)	60	20	270	Downwind of Tandem Van de Graaff source.
	47 (cyl)	48	20	270	
January 8, 1970	25 (cyl)	3	2	260	Upwind (west) of ANL sources.
	21 (cyl)	2	2	260	
	2 (cyl)	40	2	270	Downwind of ZGS.
	41 (cyl)	160	2	270	Downwind of Tandem Van de Graaff.
January 28, 1970	31 (cyl)	20	2	210	Downwind of ZGS.
	47 (cyl)	48	2	210	
	36 (cyl)	98	2	210	
October 30, 1969	1 (bag)	20	20	120-140	Upwind of ANL sources.
	3 (bag)	25	20	90	
	4 (bag)	25	20	120	
	5A (bag)	20	20	110	
	5B (bag)	28	20	120	
	7 (bag)	28	20	110	Probably upwind of ANL sources.
	9 (bag)	35	20	90	

^aMeasured at Argonne, 19 ft above ground level.TABLE 5.5. Summary of Chicago and Suburban Samples with Detectable SF₆

Date	No. of Bags or Cylinders	SF ₆ , pl/liter	Detection Limit, pl/liter	Wind Direction, deg	Remarks
<u>Chicago Samples</u>					
October 30, 1969	19 (cyl)	24	24	90-110	Argonne not upwind.
May 28, 1969	1 (bag)	22	20	320-70	Argonne not upwind.
	2 (bag)	64	20		
	3 (bag)	80	20		
	5 (bag)	26	20		
	6 (bag)	48	20		
	7 (bag)	33	20		
	11 (bag)	48	20		
<u>Suburban Samples</u>					
October 30, 1969	8 (cyl)	30	24	80-140	At Naperville; Argonne is possible source.
November 7, 1969	51 (cyl)	141	24	60	At I-55 and U.S. 45; source east of Argonne.

5.4.6 Discussion

The best background information has been obtained from the set of 24-hr bag samples obtained at Argonne between February 11 and May 4, 1970. These samples were collected in the same place on a regular schedule over three months, and the sensitivity of the analysis at the time was the best obtained.

The samples were collected at two sites, both near the perimeter of the Argonne Site. Location A1 was the Meteorology Building, southwest to the west of the four known on-site sources of SF_6 . Location A2 was northeast of the known sources. The 24-hr samples collected at these locations should give a rough approximation of the SF_6 concentrations leaving the Argonne Site on a regular basis. Sampler A2 should detect any SF_6 arriving at Argonne from Chicago industrial areas to the east and northeast, and both samplers should detect "ambient" background concentrations in air arriving from the west or north.

Table 5.6 is a summary of the Argonne 24-hr samples. Only seven of 38 had detectable concentrations, and in each of these cases the wind was blowing from Argonne sources to the sampler for at least part of the sampling period, based on wind measurements at the meteorology site. There are four pairs of simultaneous samples at the two sites when only one site was downwind of Argonne sources. In all four cases, the downwind sampler had detectable SF_6 , and the upwind sample did not.

TABLE 5.6. Frequency Distribution of SF_6 Concentrations Measured at Argonne in 24-hr Samples, February-April 1970

Concentration Range, pl/liter ^a	Number of Samples	Wind at Least Partially from ANL Sources?	
		Yes	No
< 2.0	31	10	21
2.0-9.9	4	4	
>10.0	3	3	
	Total 38		

^a $\pm 50\%$.

Thus, in the Argonne 24-hr samples, only the SF_6 sources at Argonne were detectable; all samples of air from off-site contained less than 2 pl/liter.

It is also useful to consider the results of shorter-duration samples. For example, in considering the feasibility of a tracer experiment in Chicago, with 1- to 2-hr sampling times, backgrounds over similar time periods would establish what baseline level the released gas must be planned to exceed. The following discussion is based on Tables 5.4 and 5.5, which list the detectable samples collected at Argonne (Table 5.4) and in Chicago and suburban areas (Table 5.5).

As might be expected, shorter sampling periods yield higher SF_6 concentrations than those found in 24-hr samples. Of the 21 Argonne samples with detectable SF_6 , collected on five different days, nine samples were associated with wind directions such that the sources could not have been at Argonne. Concentrations of 2 and 3 pl/liter, barely above detection limits, were detected in 5-sec samples in westerly winds at the western boundary of the Argonne Site on January 8, 1970. On October 30, 1969, seven 1-hr bag samples detected SF_6 with ESE winds. Again, Argonne could not have been the source. The SF_6 concentrations in these samples were only slightly above the detection limit of 20 pl/liter prevailing when the samples were analyzed. Nevertheless, it appears likely that non-Argonne sources of SF_6 may be present to the east or southeast.

The Chicago and suburban samples with detectable SF_6 are summarized in Table 5.5. Cylinder 19 may be disregarded as being too close to its detection limit to be absolutely certain that SF_6 was detected. However, the set of bag samples collected on May 28, 1969, provided stronger evidence. Samples 1 and 5 were collected sequentially at South Lake Shore Drive and 31st Street; samples 2 and 6 were collected sequentially at Lake Shore Drive and Ohio Street. A fourth pair of samples, collected sequentially in Lincoln Park, both showed less than detectable SF_6 . The consistency of SF_6 concentrations in consecutive 1-hr samples at these four locations is evidence that SF_6 was actually present. The associated wind directions (near north) indicate that Argonne (southwest of the sampling points) could not have been the source of the SF_6 on this occasion.

Table 5.5 indicates that two suburban cylinder samples also contained detectable SF_6 . The October 30, 1969, sample could have detected the sources at Argonne, but recall that also on this day SF_6 was detected in southeast winds at Argonne from non-Argonne sources. The November 7, 1969, sample was collected between Argonne and Chicago in easterly winds and indicates a source somewhere in the Chicago industrial region.

Table 5.7 compares our results for Chicago urban and suburban areas with previous results in other cities. Our measured concentrations agree with the measurements of Turk et al. (1968) in the vicinity of Manhattan power plants, and are considerably greater than found in Cincinnati.

TABLE 5.7. Background Concentration of SF₆ in Urban Areas

City	Investigator	SF ₆ Concentration, pl/liter ^a	
New York	Turk <u>et al.</u> (1968)	Near power plants	10-400 ^b
		Not near power plants	0-10 ^b
Cincinnati	Clemons <u>et al.</u> (1968)	0.04-0.20	
Chicago	This study	22-140	

^a±50%.

^bIt is not clear whether these numbers also include container backgrounds of up to 10 pl/liter.

5.5 Conclusions

Several preliminary conclusions may be made. First, only Argonne SF₆ sources have been detected in 24-hr samples at Argonne. Second, there is a strong likelihood that additional sources of SF₆ exist within the Chicago industrial region. Third, ambient concentrations upwind of these sources are less than 2 pl/liter. Finally, although additional background measurements would be valuable, the total system developed is capable of providing information useful in predicting diffusion parameters from tracer releases.

6. STATISTICAL STUDIES OF AIR POLLUTION

(H. Moses and J. J. Roberts)

6.1 Introduction

Mathematical models yielding estimates of air quality will have their greatest impact on the design of control strategies if they stem from first principles or approximations thereto, in particular, if they are intrinsically devoid of region-dependent, statistically derived parameters or correlations. Nevertheless, just as the National Weather Bureau relies on local weather forecasters who by intelligent questions based on long-term experience in a region compete quite favorably with the predictions of numerical models, so regional air-pollution agencies, while willing to look over mathematically derived estimates, will temper these with a forecaster's intimate, quasi-statistical feelings for how things are likely to be.

This tension between the development of general, source-oriented dispersion models and region-dependent, statistical forecasting techniques was evident in the Argonne study. On the one hand, a clear need was recognized for a mathematical model which could estimate the effects of control strategies and regional evolution that would significantly alter the geographic and temporal distribution and magnitude of sources. That such a model should be independent of statistical correlations which reflect historical air quality and emission data is evident. On the other hand, extensive files of such data can serve as a statistical basis for near-term predictions and, if cleverly mated with elementary models of dispersion, can yield effective schemes for designing control strategies.

The design of long-term emission-control regulations, The Air Quality Display Model (AQDM) is an excellent example of this latter category of semiempirical models. In AQDM, a source-oriented plume model yields annual averages which are statistically correlated with observations. The resultant linear regression equation force-fits the plume model to the region. If estimates of the geometric standard deviation are available, Larsen's semiempirical theories can then be used to forecast statistical distributions of pollutant levels.

For the problem of forecasting and then controlling air-pollution episodes, a semiempirical, statistical approach may also prove worthwhile (or in fact, necessary for pollutants such as CO and photochemical oxidants for which successful source-oriented models have yet to be derived). This section of the present report describes two such studies: The first represents an attempt to correlate observed air quality with known emission patterns in order to derive estimates of air-pollution levels and the relative contributions from different sources or classes of sources. The second study was more general in nature and to a tabular presentation of air-quality data in a form compatible with the needs of an air-pollution forecaster. Of

the two studies, the first led to an understanding of regional SO₂ profiles and eventually to a source-oriented dispersion model (Chapter 7). The second (tabulation prediction method) has been employed quite effectively in regional episode-control activities and should be considered for inclusion in the library of computer routines used to process air-quality data in the SAROAD system.

6.2 Statistical Correlations (J. J. Roberts)

The Argonne Air Pollution Information and Computations System (ACPICS; see Chapter 3 and ANL/ES-CC-006) was structured so that extensive histories of air-quality, meteorological, and emission data could be manipulated with ease and subfiles formed for analysis and display.

In formulating the program of research, we found it advantageous to incorporate these many observations into a statistical model correlating known emission or emission patterns with observed SO₂ values at the eight TAM stations. We recognized that a principal difficulty in this approach would be filtering the SO₂ and emission data to identify the SO₂ signals from each significant source relative to the background from all other sources and the inherent noise, so that the contribution of each source to any receptor could be evaluated. This involved the estimation of coupling coefficients between each significant source and each receptor for all plausible meteorological conditions (conceptually similar to the Gaussian kernels of earlier models evaluated at a particular point [t,y,z,u]). Eventually, these coupling coefficients could be fit to some algebraic generalization such as the Gaussian kernel, which might then be incorporated in a model similar to that for St. Louis. However, in contrast to earlier models, this is the end product of a statistical correlation, which should automatically incorporate the inhomogeneities of the Chicago landscape. A statistically based scheme for estimating air quality without the above potential for generalization was not considered an acceptable goal for this phase of the study.

6.2.1 Pollution Regimes

In almost all plume theories, a set of criteria including such observables as time of day, gustiness, and insolation is used to determine the existence of a particular stability classification. This then determines parameters in equations such as the one used by Turner in the Nashville study,

$$\sigma_y(t) = at^b.$$

In other words, it is assumed that each proposed set of meteorological parameters determines a regime within which certain atmospheric dispersion properties or relationships remain constant, or approximately so.

In a like manner, stability classifications, or pollution regimes as we have chosen to call them, can be established to emphasize meteorological conditions peculiar to Chicago, such as the lake breeze, as well as more traditional parameters, such as cloud cover.

6.2.2 "Met Set" and Significant Point Sources

A relationship was to be determined by means of a linear-regression analysis which correlated SO_2 observations at the eight TAM receptors with known emission patterns, such as one due to residential heating and known emissions from large point sources. Numerical coefficients in the overall pollution model were to be evaluated in a stepwise fashion by considering one TAM station at a time. Pollution regimes, wind sectors, and wind-speed bands were specified, each combination of these three items to be considered separately as a particular "met set." For example, the concurrence of the three wind criteria: (1) gustiness class B_1 , (2) direction from the Sector 270-300°, and (3) speeds between 6 and 8 mph might specify the existence of a single met set. Thus the SO_2 data for each TAM station were partitioned and analyzed according to the proposed met sets.

The point sources included in each regression analysis depended upon the chosen met set, in particular upon the wind sector, since one would certainly expect close-in, upwind sources to dominate the SO_2 observations. The preliminary determination of whether a given source is a significant source for a particular TAM station and met set was based on a direct application of the plume equation and coefficients given by Turner (1964) for the Nashville model.

6.2.3 Mathematical Statement

The mathematical statement relating SO_2 concentrations, X_n , and the significant emissions for a chosen TAM station and met set has the form

$$X_n = B + H_1 P_{1n} + H_2 P_{2n} + \sum_{i=1}^I K_i Q_{in}, \quad n = 1, \dots, N, \quad N \gg I + 3. \quad (6.1)$$

The subscript n refers to a particular hourly average of that known quantity. Although this subscript runs from 1 to N , the corresponding hours need not be consecutive.

The constants B , H_1 , H_2 , and K_i , $i = 1, \dots, I$, are coefficients to be determined by linear regression. B represents a constant background; for example, a "hold fire" is maintained at all times throughout the year in almost all automatic stoker-fired coal boilers.

The function P_{1n} describes the hourly emission pattern of residences with automatic stoker-fired boilers. This function takes into account the

outside hourly average temperature (by its deviation from 65° and the time of the day or "janitor function"). For example, regardless of the temperature, only the hold fire is maintained between 12 midnight and 4 a.m. (see Fig. 6.1).

Fig. 6.1. Plot of Janitor Function. ANL Neg. No. 112-7214.

Emission pattern P_{2n} , similar in concept to P_{1n} , describes the fuel consumption of large buildings and complexes such as the Chicago Housing Authority projects which operate high-pressure steam-heating systems. Since these heating units run day and night, they must be represented by a different fuel-use pattern than the typical six-flat pattern, P_{1n} . Separate regression analyses using Chicago Housing Authority and The University of Chicago data demonstrated that the function P_{2n} should describe a degree-hour dependence superimposed upon a uniform base load for hot water (see Sec. 2).

The terms K_i and Q_{in} , $i = 1, \dots, I$, represent the contributions from significant point sources, where Q_{in} is the hourly average SO_2 emission from source i during a particular hour preceding the actual observation X_n . Symbolically, one could write $K_i Q_{i,n-\tau_i}$ where τ_i represents the transport delay between source i and the detector (for the chosen wind speed). Although the data are handled in this manner, the simpler subscript n is used in the mathematical notation to signify the value of source Q_i associated with the measurement X_n at time n . K_i is the coupling coefficient or conversion factor between the emission Q_i and the receptor for a given met set and corresponds to the evaluation of a plume dispersion kernel. For example, it might represent a particular numerical value of X/Q in Turner's model of Nashville, which is based on the equation

$$\frac{X}{Q} = \frac{\exp[-\frac{1}{2}(y^2/\sigma_y^2 + H^2/\sigma_z^2)]}{\pi u \sigma_y \sigma_z}$$

6.2.4 Correlation of TAM Station SO_2 Measurements with Temperature-dependent Sources

6.2.4.1 Quadrant Survey. In a 1965 report to the Northeast Illinois Planning Commission, Longbrake demonstrated strong correlations between heating degree days and 24-hr SO_2 samples taken at Hyde Park High School

(now TAM-4) and Taft High School (now TAM-1). Furthermore, he was able to show that annual SO_2 averages at 18 monitoring stations could be linearly related to heating season emissions with a multiple-correlation coefficient of 0.9. A study of 15 months of 6-hr SO_2 averages for Reading, England, emphasized the poor correlation of SO_2 concentrations with industrial stacks and the close relationship to residential density. This argument was pursued in Chicago by testing, on an hourly basis, for temperature dependence associated with different wind directions at the eight TAM stations and comparing the results to known residential and commercial emissions.

Residential and commercial fuel use has been inventoried by both the City of Chicago (DAPC) and Peoples Gas, Light and Coke Company (PGLC) on a square-mile basis (see Chapter 2). This quantification, coupled with the assumption that low-lying sources within a mile of the TAM receptors dominated the air quality measurements means that reasonable wind direction bands could be resolved to no better than about 90° .

Table 6.1 lists the results of the quadrant survey for January, February, and March 1967. Each line in the table represents a single linear regression using data with TAM wind speeds in the range 5.5-9.5 mph, TAM wind directions in the appropriate quadrant, stability Class 4, and no measurable precipitation. All hours of the day were considered by using two heating patterns: heating degrees ($55^\circ\text{F} - T$, where T is temperature in $^\circ\text{F}$), and heating degrees multiplied by the janitor function (see Fig. 6.1). This survey was designed to permit assessment not only of temperature dependence but also of the relative importance of high- and low-pressure steam-heating systems.

An examination of Table 6.1--in particular the right-hand column, which lists multiple correlation coefficients (R)--indicates that direct temperature correlations are relatively weak in the majority of cases. In only about one in four examples does the regression line explain as much as 25% of the variance in the original data. Nevertheless, the standard deviations (σ) tabulated in the adjacent column are low when one considers that SO_2 values within some of these data sets range from 0.01 to greater than 0.4 ppm, depending upon location and temperature. Outlying sources, such as Cicero and Gary, and distributed industry in general appear to be responsible for a background or SO_2 "noise level" throughout the city at the level of 0.02-0.05 ppm SO_2 , and that only areas of strong residential or commercial source strength significantly penetrate this level with significant temperature-dependent emission signals.

Wind speed and direction for the 32 runs described here were based on TAM station values as opposed to Midway Airport data. (See Sec. 3 for a discussion of this decision.) Because of discrepancies between aerovane readings--some due to actual variations in the wind field, and others due to

building interference--and because of missing SO₂ or aerovane data, the numbers of data points for winds in each quadrant are not consistent from station to station.

TABLE 6.1. Quadrant Survey of Temperature Dependence.
Wind speed range: 5.5-9.5 mph; neutral stability (Class 4)

TAM	Wind Direction	Temp Range, °F	No. of Data Points	Regression Coefficients ^a				
				C ₀ , ppm	C ₁ × 10 ³ , ppm/°F	C ₂ × 10 ³ , ppm/°F	σ, ppm	R, ppm
1	NE	28 ± 8	55	-0.01	1.0	1.2	0.05	0.33
	SE	28 ± 6	49	-0.09	8.6	-0.3	0.09	0.50
	SW	28 ± 10	138	0.02	1.1	0.3	0.06	0.24
	NW	18 ± 11	92	0.02	0.3	0.2	0.01	0.28
2	NE	30 ± 8	40	0.06	0	2.0	0.03	0.65
	SE	30 ± 7	28	0.19	-2.5	1.6	0.09	0.17
	SW	31 ± 12	53	0.17	0.2	3.3	0.11	0.37
	NW	22 ± 13		0.06	0.3	0.9	0.04	0.49
3	NE	30 ± 8	47	0.10	2.9	2.1	0.05	0.66
	SE	28 ± 4	37	0.31	1.6	-1.9	0.12	0.19
	SW	29 ± 10	132	0.27	1.3	1.8	0.13	0.26
	NW	21 ± 12	125	0.23	3.8	1.7	0.11	0.49
4	NE	31 ± 7	55	0.01	1.4	1.0	0.04	0.34
	SE	26 ± 7	29	-0.14	7.7	3.6	0.12	0.60
	SW	28 ± 9	182	0.13	-0.7	4.1	0.07	0.60
	NW	15 ± 10	73	0.18	0.6	2.7	0.11	0.45
5	NE	30 ± 6	72	0.01	1.1	1.9	0.05	0.42
	SE	25 ± 8	49	0.01	1.2	0.8	0.04	0.44
	SW	29 ± 11	76	0.04	0.4	0.7	0.03	0.38
	NW	22 ± 12	79	0.14	-1.4	0.7	0.06	0.31
6	NE							
	SE	26 ± 7	49	0.01	0.2	0.6	0.03	0.30
	SW	29 ± 10	157	0.03	0	0.5	0.03	0.23
	NW		151	0.03	0.4	0.5	0.04	0.26
7	NE	27 ± 12	42	0.27	-6.1	5.4	0.14	0.38
	SE	29 ± 10	183	0.10	-0.7	2.3	0.10	0.27
	SW	21 ± 12	129	0.05	-0.5	1.1	0.05	0.37
	NW	31 ± 8	46	0.14	-3.0	0.8	0.05	0.41
8	NE	31 ± 7	48	0.00	-1.2	1.4	0.05	0.31
	SE	24 ± 11	40	0.05	0	0.6	0.03	0.27
	SW	29 ± 11	87	0.06	-0.3	0.4	0.03	0.12
	NW	22 ± 12	86	0.07	-0.6	1.0	0.07	0.23

^aRegression coefficients based on: $X_n = C_0 + C_1(55^\circ\text{F} - T_n) + C_2(55^\circ\text{F} - T_n)(\text{Janitor function})$.

Janitor function = 1 hours 6-23;
0 hours 24 and 1-5.

6.2.4.2 SO₂ Levels Correlated with Residential and Commercial Emissions. Figure 6.2 compares the sulfur dioxide level characteristic of each quadrant at each TAM station to the sum of emissions from residential (1-19 DU/building) and commercial sources for the appropriate upwind square mile. Where the temperature relationship is significant, the SO₂ value has been corrected to 25°F using the regression coefficients of Table 6.1. Standard deviations of up to ±0.1 ppm are associated with the data points. Residential units in both the 1-7 and 8-19 DU/building

Fig. 6.2. Quadrant Survey of SO_2 Levels vs. Residential--1-19 DU/Building--and Commercial Emissions (January-March 1967); wind speed 5.5-9.5 mph; heating hours; stability class 4). ANL Neg. No. 112-9755.

0.05 ppm and a multiple correlation coefficient of 0.9 when based on all 32 data points. However, this seems unfairly weighted by the 15 points to the left of the line I-I near the origin. The standard deviation and multiple correlation coefficient as recomputed on the basis of the origin and data points to the right of the line I-I, excluding point 2a, are 0.06 and 0.7 ppm, respectively.

As a test of the hypothesis that low-rise sources dominate the SO_2 data, Fig. 6.2 was replotted in Fig. 6.3, using all residential and commercial emissions. It is evident that points representing those quadrants most affected by this modification are moved far to the right and appreciably below the regression line from Fig. 6.2. Clearly, emissions from high-rise apartment buildings in quadrants 4b, 4c, 4d, 2b, 2d, and especially 2a do not contribute proportionally to SO_2 concentrations near the ground.

From the results shown in Fig. 6.2, one may hope to assess the significance of utilities and industry as major consumers of coal, and therefore, their potential responsibility for high SO_2 levels. The data points of interest involve winds from isolated

categories were chosen for the abscissa of this plot on the assumption that low-rise (one- to four-story) sources were mainly responsible for ground-level SO_2 . Older Chicago buildings up to the 19 DU/building class are typically court-type, three- or four-story structures. The accuracy of emissions plotted along the abscissa of this figure is certainly no better than $\pm 10\%$ of the estimated annual SO_2 emission.

The correlation in Fig. 6.2 seems remarkably good. With the exception of TAM-2(NE, 2a), all data points fall about the indicated straight line. This linear relationship, a visual approximation to the regression line, yields a standard deviation of

Fig. 6.3. Quadrant Survey of SO_2 Levels vs. Residential--All Buildings--and Commercial Emissions (January-March 1967; wind speed 5.5-9.5 mph; heating hours; stability class 4). ANL Neg. No. 112-9756.

power plants such as the Northwest station or from the industrial corridor along the Stevenson Expressway (see Fig. 6.4).

Fig. 6.4. Map of Pollution Episode Control Plan. ANL Neg. No. 112-8979 Rev. 1.

The significance of these large sources is supported by several observations:

- 1) TAM-3 records the same SO_2 levels with winds from the SW as from the NE, even though the SW quadrant has only one-third of the SO_2 emission rate.
- 2) TAM-2 records comparatively high readings for winds from the SW quadrant, which includes the NW CECO plant (2 miles away) and most of Chicago's industry (about 8 miles away).
- 3) TAM-5 NW receives SO_2 from two CECO plants, the sanitary district plant and local industries, including the nearby American Can Company plant. By comparison with point 5c, these sources might account for 0.1 ppm on a typical Chicago day.
- 4) Winds from the north at Stevenson Elementary School (8a, d) seem to be associated with slightly higher SO_2 levels than those from the south.

The following observations are in contrast to the above, and show that not all TAM stations are significantly affected by SO_2 contributions from large point sources:

- 1) Hyde Park's NW quadrant (4d), which views the industrial corridor, is nearly identical to quadrant 4c in SO_2 concentrations, and residential emission density is higher.
- 2) The SE and SW quadrants at Austin (TAM-7) are not significantly out of line with the general linear relationship shown in Fig. 2.3, even though this station is only 5 miles from the industrial corridor.
- 3) TAM-6 NE should be, but is apparently not, affected by the Calumet and Stateline CECO plants as well as by the more distant Gary-Hammond industrial complex.

From the above, it appears that contributions from industry and utilities to ground level SO_2 concentrations are likely to fall in the range of 0.05 to 0.1 ppm. This is substantiated by the observed deviations from the regression line in Fig. 6.2, by the standard deviations associated with the individual temperature correlations listed in Table 6.1, and by the point source calculations presented in Chapter 7.

In conclusion, it should be emphasized that this survey was restricted to neutral or slightly unstable days typified by Brookhaven Class B1 and Turner's Classes 3 and 4. Large point sources may be quite important in any estimation of SO_2 levels during the breakup of nocturnal inversions,

lake-breeze regimes, or other unusual meteorological situations which can be associated with high-pollution episodes.

6.2.4.3 Octant Survey at TAM-4. An octant survey (135-180°, 180-225°, 225-270°, and 270-315°, other wind directions being from Lake Michigan) similar to the quadrant survey described previously has been assembled. In both efforts, data for all hours were analyzed and linear regressions performed with heating degrees (55°F - T) as the independent variable. However, in the octant correlations, the independent variable was redefined to give more weight to data points at low temperatures. Since less than 10% of the hours analyzed have temperatures below 15°F, these data points were dominated in the linear regression by the mass of winter temperatures in the 25-32°F range. Yet these few low-temperature days are associated with higher fuel use and often with greater atmospheric stability, both of which imply higher SO₂ levels. Thus, in order to give equal weight over the whole temperature scale, as opposed to equal weight for each data hour, the temperature scale was divided into 3°F bands and all data hours within each band were averaged to yield a representative SO₂ level for that average temperature. Regressions were then performed on these SO₂ averages rather than on the multitude of original data points. This approach clearly emphasizes temperature dependence and tends to suppress perturbations in SO₂ level due to variations in emissions from industrial and utility sources.

The 20 regression lines (some of them superimposed) are displayed in Figs. 6.5-6.8. In the high-wind category (see Fig. 6.6), the regression lines corresponding to WNW, WSW, and SSW winds were each based on about 80 original data hours; however, only the WNW sector had data over a large temperature range, as indicated by the length of the regression lines in the

Fig. 6.5. Regression Lines for TAM-4; Winds 6-9 mph (January-March 1967; stability class 4; no precipitation). ANL Neg. No. 112-9757.

Fig. 6.6. Regression Lines for TAM-4; Winds 10-13 mph (January-March 1967; stability class 4; no precipitation). ANL Neg. No. 112-9758.

Fig. 6.7

TAM-4 Average SO₂ Values for 3°F Temperature Bands; Wind Direction: 225-270° (stability class 4). Numbers indicate number of hourly data points averaged together. ANL Neg. No. 112-9759.

Fig. 6.8

TAM-4 Average SO₂ Values for 3°F Temperature Bands; Wind Direction: 270-315° (stability class 4). Numbers indicate number of hourly data points averaged together. ANL Neg. No. 112-9760.

figures. No physical explanation for the negative slopes of lines representing WSW and SSW sectors in Fig. 6.6 is apparent.

Considering the regression line in Figs. 6.7 and 6.8 as representing an algorithm for predicting SO₂ levels at Hyde Park (TAM-4) for hours within the prescribed met set, one can then validate the model by predicting corresponding SO₂ concentrations for winter of 1968. The success of this approach is demonstrated in Fig. 6.9. The central shaded area represents uniform spreading of 55 data points. The rectangle at the origin represents data for winds off the lake which are predicted as zero, but which occasionally yield concentrations as high as 0.08 ppm. The narrow rectangle at 0.05 ppm represents 2 days in a block of 5 consecutive days for which the SO₂ levels at TAM-4 were recorded as a steady 0.05 ppm, regardless of temperature, wind direction, time of day, or degree of atmospheric stability. DAPC personnel feel that these data points are probably invalid. In our evaluation of the predictive capability of the set of regression equations, we have disregarded both the data near the origin (because one should not take credit for predicting extremely low SO₂ levels) and the data of questionable validity in the unshaded rectangle.

Fig. 6.9. Prediction of January-February 1968 SO₂ Levels by Algorithms Derived from 1967 Data. ANL Neg. No. 112-9761.

The standard deviation about the line of perfect prediction is 0.06. In terms of an improvement over assuming that an average value of 0.23 ppm would prevail for all hours (except for easterly winds)--and one could not predict this average in advance--the variance is reduced by 40%. Unfortunately, no hours of very low temperature were included in the data set to permit testing of the algorithm in the 0.35- to 0.45-ppm range. If used as a predictor of whether a given hourly SO₂ average would exceed a threshold of 0.25 ppm, the algorithm would have been correct for 92 out of 110 hr, with 12 successful warnings, 13 unnecessary ones (borderline cases, however), and 6 missed episodes.

6.2.5 A Limitation on the Discrimination of Major Point Sources

As the regression equation (Eq. 6.1) is presently formulated, each coupling coefficient is based on source emissions equally weighted for all winds within the allowable band. For example, assume the Crawford power plant is the only SO₂ source in Chicago, and that because of the uncertainty of our wind-direction predictions, two data points are included, both with Crawford at full power, $Q_{\max}$. One data point might correspond to a centerline concentration of 0.16 ppm, the other for a wind only 5° off center (these are hourly averages of wind direction) might be 0.06 ppm. The regression matrix would appear as follows:

$$0.16 = C_0 + K_1 Q_{\max};$$

$$0.06 = C_0 + K_1 Q_{\max}.$$

The best fit to the coupling coefficient K_1 would therefore be representative of the average of the Crawford plume over the two wind directions.

The effect of the size of the wind band on the determination of coupling coefficients from point sources can be assessed by assuming that the data are distributed uniformly in wind direction over the allowable band and then averaging the plume equation over this arc. The equation is of the form

$$\chi = F(z, x/u) \exp(-y^2/\sigma_y^2) \quad (6.2)$$

which, for $y \ll x$, can be approximated by the angular deviation (θ) from the centerline:

$$\chi \cong F(z, x/u) \exp(-x^2\theta^2/\sigma_y^2). \quad (6.3)$$

Thus, for a wind band $\pm\theta_m$ about the plume centerline,

$$\begin{aligned} \bar{\chi} &= \frac{F(z, x/u)}{\theta_m} \int_0^{\theta_m} d\theta \exp(-x^2\theta^2/\sigma_y^2) \\ &= \frac{0.886\sigma_y F(z, x/u)}{x\theta_m} \left[\operatorname{erf} \left(\frac{x\theta_m}{\sigma_y} \right) \right] \\ &= \frac{0.886\sigma_y}{x\theta_m} F(z, x/u) \quad \text{for } \frac{x\theta_m}{\sigma_y} \geq 2.* \end{aligned} \quad (6.4)$$

For a 30° wind-direction band, this averaging process implies mean concentrations of from 10 to 30% of the maximum centerline values (see Table 6.2). Thus, hourly contributions from Crawford can easily vary by a factor of five within a given data set, even though the plant is operating at a steady power level.

Techniques to deal with this problem in a regression analysis are not yet clear. One can obviously narrow the wind band, but it is clear that mean hourly wind directions and wind profiles of Chicago will never be specified better than $\pm 10^\circ$, nor would they have much physical meaning at lower tolerances. Thus, whether one is predicting SO_2 contributions directly by using a plume equation and verifying by comparison with SO_2 data, or if one is using our regression approach and correlating SO_2 data with point-source emissions, the uncertainty caused by an inability to specify plume trajectories implies a fundamental uncertainty in the ability to verify the model.

6.2.6 Identification of Point Sources

An important element in the original formulation of the Chicago Air Pollution Study was the proposition that large point sources might be identified by suitable filtering of the extensive TAM data file. The suggested approach was to stratify the data by defining met sets and by means of linear regression seek coupling coefficients K_i in an equation of the form

$$\chi_n = B + H_1 P_{1n} + H_2 P_{2n} + \sum_{i=1}^I K_i Q_{in}, \quad n = 1, \dots, N, \quad N \gg I. \quad (6.6)$$

*The error function is defined by

$$\operatorname{erf}(t) = \frac{\sqrt{2}}{\pi} \int_0^t dt e^{-t^2}. \quad (6.5)$$

TABLE 6.2. Point-source Contributions to TAM Stations
Directly Downwind (Wind speed = 10 mph)

	Fisk on TAM-4	Crawford on TAM-4	UC on TAM-4	Northwest on TAM-2	Crawford on TAM-7
Max Q_{plant} , ^a M Btu/hr	3300	3000	90	830	3000
No. of stacks	1 ^b	4	2	2	4
Stack height, ft	450	300 ^c	200	300	300
Downwind distance, mi	6.0	7.7	0.7 ^d	1.7	4.2
<u>Unstable (Class 3)</u>					
Plume rise, ^e ft	2200	2100	400	1100	2100
σ_z , ^f ft	1700	2100	200	500	1200
σ_y , ^f ft	2600	3300	400	900	1900
Max ppm ^g per stack	0.04	0.04	0.02	0.03	0.03
Max ppm, ^g all stacks	0.04	0.16	0.04	0.06	0.12
Avg ppm, ^g all stacks; 30° wind sector	0.01	0.04	0.01	0.02	0.04
<u>Stable (Class 5)</u>					
Plume rise, ^e ft	600	600	100	300	600
σ_z , ^f ft	400	400	100	150	300
σ_y , ^f ft	1300	1600	200	400	1000
Max ppm ^g per stack	0.02	0.1	0.03	~0	0.02
Max ppm, ^g all stacks	0.02	0.4	0.06	~0	0.08
Avg ppm, ^g all stacks; 30° wind sector	0.002	0.06	0.01	~0	0.01

^aBased on $Q_{\text{stack}} = 0.2 \times Q_{\text{plant}}$. Calculations assume 3% sulfur coal at 10^4 Btu/lbm.

^bCalculation does not consider the 292-ft stacks, which are used less frequently.

^cConservative value, since two stacks are 375 ft high.

^dUC distance is actually about 3 miles. These concentrations therefore represent an upper bound on UC at TAM-4.

^eCarson and Moses (1967).

^fTurner (1967).

^g μ moles/mole.

The constants B , H_1 , H_2 , and K_i , $i = 1, \dots, I$, are coefficients to be determined statistically. The coefficient B represents a constant background (e.g., hold-fires); P_{1n} , the hourly emission pattern of residences with low-pressure boilers; P_{2n} , the emission pattern describing the fuel consumption of high-pressure steam systems in large apartment houses; and terms of the form $K_i Q_{in}$, $i = 1, \dots, I$, representing the contributions from significant point sources, where Q_{in} is the hourly average SO_2 emission from source i during a particular hour preceding the actual TAM observation, χ_n .

Section 6.2.4 has presented results based on the reduced equation,

$$\chi_n = B + H_1 P_{1n} + H_2 P_{2n}, \quad (6.7)$$

with the following two conclusions:

1) Where upwind residential emissions are excessive, such as at TAM-4 and -5 with wind from the southeast, the correlation is fairly strong ($R = 0.4-0.7$).

2) Regardless of the correlations between residential heating patterns and SO_2 at the TAM stations, a quadrant study detailed in ANL/ES-CC-003 yields significant linear relationships ($R = 0.7-0.9$) between SO_2 emissions ($lb\ SO_2/mi^2$) from space-heating sources and downwind SO_2 levels.

Within the variations about the temperature regression lines should lie the point-source contributions and thus the coupling coefficients K_i . In attempting to evaluate these coefficients, we concentrated, with only limited success, on met sets with medium (6-9 mph) and high (10-13 mph) winds, neutral stability, and no precipitation. Within these restricted data sets, correlations were sought between hourly average SO_2 values and emissions from large point sources within upwind arcs of 20 and 30° at distances of up to 7 miles.

Coupling coefficients could not, in general, be determined with any useful measure of confidence between appropriate downwind TAM stations and one or more of the following sources: four CECO plants (Northwest, Fisk, Crawford, and Ridgeland), the Campbell Soup Co. (located near the Crawford plant, the second largest industrial SO_2 emitter), and the Chicago Metropolitan Sanitary District Plant (adjacent to Ridgeland).

The emissions were based on historical data obtained from steam-flow and electrical output charts. Care was taken to choose wind direction bands that had a minimum number of upwind major sources.

Typical results are shown in Table 6.3. In each case, the wind direction band is a 30° sector centered about a direct line from source to receptor.

TABLE 6.3. Point-source Correlations

Wind speed = 6-9 mph; Stability Class 4; No precipitation

$$X \text{ (ppm)} = B + H_1[DD_{55} \times J] + H_2[DD_{55}] + K_{Ridge}[Q_{Ridge}(lb\ SO_2/hr)] + K_{CMSD}[Q_{CMSD}]$$

TAM	WD	B	H_1/CL^a	H_2/CL^a	K_{Ridge}/CL^a	K_{CMSD}/CL^a	σ/R	No. of Data Points
7	180-210	0.14	0.004/0.999	-0	-	-	0.09/0.5	83
		0.15	0.004/0.999	-0	$1 \times 10^{-7}/0$	$-2 \times 10^{-6}/0$	0.09/0.5	
5	270-300	0.09	$5 \times 10^{-4}/0.6$	$-5 \times 10^{-4}/0.6$	-	-	0.07/0.2	58
		0.01	$3 \times 10^{-4}/0.5$	$-3 \times 10^{-4}/0.5$	$3 \times 10^{-6}/0.95$	-	0.06/0.3	
		0.19	$4 \times 10^{-4}/0.5$	$-9 \times 10^{-4}/0.5$	-	$-2 \times 10^{-5}/0.99$	0.06/0.4	
		0.11	$3 \times 10^{-4}/0.5$	$-7 \times 10^{-4}/0.5$	$3 \times 10^{-6}/0.95$	$-2 \times 10^{-5}/0.99$	0.06/0.4	
8	320-350	0.04	0.003/0.999	-0	-	-	0.06/0.5	64
		-0.08	0.001/0.8	-0	$6 \times 10^{-6}/0.999$	-	0.05/0.7	
		0.1	0.003/0.999	-0	-	$-1 \times 10^{-5}/0.8$	0.06/0.5	
		-0.01	0.001/0.8	-0	$6 \times 10^{-6}/0.999$	$-2 \times 10^{-5}/0.95$	0.05/0.7	

^aCL: Confidence Level.

The t statistic has been used to estimate a confidence level (CL) for which it is false that the regression coefficient is zero.

At first glance, the results for the Ridgeland power plant appear encouraging. Its contribution at TAM-8 is 6×10^{-6} Q lb SO₂/hr, which implies an average level of 0.16 ppm due to this source alone. In comparison, a standard plume calculation yields an average SO₂ concentration of 0.15 ppm for stability Class 4 using the Moses-Carson plume rise relationship. Based on arguments presented in Sec. 6.2.5, this latter value was calculated by modifying the centerline concentration by the factor $0.886\sigma_y/x\theta_m = 0.3$ to account for a data set that included mean winds in a 30° band about the centerline. With this modification, there appears to be excellent agreement between the statistically and objectively determined coupling coefficients in this example. More significant, however, in deciding whether one can believe the Ridgeland coupling coefficient is the negative coupling between the Chicago Metropolitan Sanitary District (adjacent to Ridgeland) and TAM-8, which, on the average, represents -0.09 ppm contribution to the regression equation. The nature of multiple linear regression is to give a best mathematical fit between given patterns (sources) and systematic (correlated) variations in the dependent variable. Regardless of causality, therefore, it is probable that some other important variable, possibly a diurnal meteorological effect not recognized by the met set, correlates significantly with the pattern of the Sanitary District plant. Unfortunately, inconsistencies such as the negative coupling coefficient between the Sanitary District plant and TAM-8 compromised our attempts to evaluate the culpability of individual sources.

In general, we can attribute these difficulties to one or more of the following interrelated causes:

- 1) Inadequate number of data points in the met set.
- 2) Noise from close-in sources, primarily low buildings, which masks the signals from distant point sources.
- 3) Insufficient variation in emissions from the source (e.g., Chicago Metropolitan Sanitary District).
- 4) Inability to specify wind direction to better than $\pm 15^\circ$, thus reducing the effective coupling between point sources and TAM stations (see Sec. 6.2.5).
- 5) Variability of dispersion conditions within a given met set.
- 6) Inadequate number of point sources in the data file.

Item 4 represented an unavoidable problem; further stratification in the definition of met sets (item 5) would reduce the numbers of data hours to unacceptably low levels (item 1). Adding to our detailed record of point sources (item 6) would have involved an effort unwarranted by the results

already achieved; synthesis of an hourly emission inventory by day of week and shift patterns would not be accurate enough for this statistical approach.

6.3 The Tabulation Technique for Forecasting Concentrations of Air Pollutants (H. Moses)

When material is injected into the atmosphere, whether it be from a distributed area source or a point source, the meteorological conditions determine the rates of dispersion and consequently the concentrations observed downwind. This section describes a method of using APICS in order to correlate historical meteorology and air quality data in such a way that a short-range (24-hr) receptor-oriented air quality forecasting system can be produced. APICS is required to create a set of prediction tables, but once they are available, real-time access to a computer is not required in order to make an air quality prediction. The system may be updated as often as changes in source emissions or distribution indicate the need.

6.3.1 Description of the Tabulation Prediction Technique

The relation between meteorological variables and pollutant concentrations may be displayed by arranging combinations of significant meteorological variables in an ordered sequence and presenting the associated probability distribution for each entry, as shown in Table 6.4. This procedure is referred to as the "Tabulation Prediction Technique" or the "Look-up Technique" and is based on hourly readings. For each combination of meteorological variables the minimum value, 10, 25, 50, 75, 90, 95, 98, and 99 percentiles, and maximum value of SO₂ concentrations are shown. Also presented are the interquartile range, i.e., the difference in SO₂ concentration between the 75th and 25th percentiles, and that of the 95th and 75th percentiles. The number of cases observed for each combination of meteorological variables is shown in the last column. To arrange combinations of meteorological variables into an ordered sequence, each selected variable must first be divided into appropriate bands. For example, wind direction might be grouped into three classes, time of day also into three, wind-speed categories into five, and so forth. Since the combinations of meteorological variables are ordered, it is possible to look up any combination just as one would look up a name in a telephone book or a word in a dictionary to obtain the probability distribution of SO₂ concentrations for this combination of meteorological variables.

To develop the Tabulation Prediction Technique for a system of air quality monitoring stations, values of air pollution concentrations, wind speed, and wind direction are obtained for the appropriate monitoring station; computer-tape or punch-card records for other meteorological variables are obtained for the local area from the National Weather Records Center at Asheville, N.C. A computer code is then used to generate a set of prediction tables for each monitoring station.

SEASON: MARCH, APRIL, MAY				PRECIPITATION: NO		STATION: TAM 4		PERIOD OF DATA: JAN 1, 1966 - DEC 31, 1967										
WIND DIR	CEILING	WIND SP	TEMP	HOUR	PERCENTILE VALUES OF SO2 (PPM) CONCENTRATIONS											MEAN	ST DEV	FREQ
DEGREES	FEET	KT	DEG F	CST	MIN	25	50	75	90	95	98	99	MAX	75-25	95-75			
0-140	7000-****	0-3	70-79	0-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	0-3	70-79	4-15	0.01	0.01	0.03	0.04	0.06	0.06	0.06	0.06	0.06	0.03	0.02	0.03	0.0183	6
0-140	7000-****	0-3	70-79	16-23	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0	0.0	0.01	0.0	1
0-140	7000-****	0-3	80-89	0-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	0-3	80-89	4-15	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.01	0.0	0.02	0.0050	2
0-140	7000-****	0-3	80-89	16-23	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.0	0.0	0.02	0.0	1
0-140	7000-****	4-7	10-19	0-3	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.0	0.02	0.0047	3
0-140	7000-****	4-7	10-19	4-15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	4-7	10-19	16-23	0.08	0.08	0.10	0.12	0.12	0.12	0.12	0.12	0.12	0.04	0.0	0.10	0.0200	2
0-140	7000-****	4-7	20-29	0-3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.0	0.0	0.02	0.0	1
0-140	7000-****	4-7	20-29	4-15	0.09	0.10	0.15	0.20	0.21	0.21	0.21	0.21	0.21	0.10	0.01	0.15	0.0460	4
0-140	7000-****	4-7	20-29	16-23	0.05	0.05	0.07	0.10	0.27	0.27	0.27	0.27	0.27	0.05	0.17	0.12	0.0864	4
0-140	7000-****	4-7	30-39	0-3	0.01	0.01	0.03	0.04	0.05	0.06	0.08	0.08	0.08	0.03	0.02	0.02	0.0175	17
0-140	7000-****	4-7	30-39	4-15	0.01	0.02	0.04	0.09	0.13	0.15	0.28	0.29	0.30	0.07	0.06	0.06	0.0650	24
0-140	7000-****	4-7	30-39	16-23	0.01	0.02	0.04	0.09	0.13	0.15	0.27	0.27	0.27	0.06	0.06	0.06	0.0652	41
0-140	7000-****	4-7	40-49	0-3	0.01	0.01	0.03	0.04	0.05	0.07	0.09	0.09	0.10	0.03	0.03	0.02	0.0249	25
0-140	7000-****	4-7	40-49	4-15	0.01	0.01	0.03	0.04	0.05	0.08	0.09	0.10	0.14	0.03	0.03	0.02	0.0233	96
0-140	7000-****	4-7	40-49	16-23	0.01	0.01	0.03	0.04	0.05	0.09	0.12	0.13	0.13	0.03	0.05	0.03	0.0253	59
0-140	7000-****	4-7	50-59	0-3	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.0	0.01	0.0043	8
0-140	7000-****	4-7	50-59	4-15	0.01	0.01	0.03	0.04	0.05	0.05	0.09	0.17	0.20	0.03	0.01	0.02	0.0246	127
0-140	7000-****	4-7	50-59	16-23	0.01	0.02	0.03	0.05	0.09	0.13	0.25	0.25	0.25	0.03	0.08	0.04	0.0467	36
0-140	7000-****	4-7	60-69	0-3	0.04	0.04	0.05	0.07	0.09	0.09	0.09	0.09	0.09	0.03	0.02	0.06	0.0250	2
0-140	7000-****	4-7	60-69	4-15	0.01	0.01	0.03	0.04	0.05	0.06	0.06	0.06	0.06	0.03	0.02	0.02	0.0172	59
0-140	7000-****	4-7	60-69	16-23	0.01	0.01	0.03	0.04	0.05	0.11	0.12	0.12	0.12	0.03	0.08	0.03	0.0355	8
0-140	7000-****	4-7	70-79	0-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	4-7	70-79	4-15	0.01	0.01	0.03	0.04	0.07	0.08	0.09	0.09	0.09	0.03	0.04	0.03	0.0227	26
0-140	7000-****	4-7	70-79	16-23	0.01	0.02	0.04	0.12	0.14	0.14	0.15	0.15	0.15	0.10	0.02	0.06	0.0592	7
0-140	7000-****	4-7	80-89	0-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	4-7	80-89	4-15	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.0	0.0	0.02	0.0	4
0-140	7000-****	4-7	80-89	16-23	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.0	0.0	0.10	0.0	1
0-140	7000-****	8-12	30-39	0-3	0.01	0.01	0.03	0.04	0.06	0.08	0.08	0.08	0.08	0.03	0.04	0.03	0.0257	8
0-140	7000-****	8-12	30-39	4-15	0.01	0.02	0.03	0.05	0.26	0.28	0.28	0.28	0.28	0.03	0.23	0.06	0.0849	25
0-140	7000-****	8-12	30-39	16-23	0.01	0.02	0.04	0.06	0.08	0.09	0.10	0.10	0.10	0.04	0.03	0.04	0.0254	14
0-140	7000-****	8-12	40-49	0-3	0.01	0.02	0.03	0.05	0.06	0.06	0.06	0.06	0.06	0.03	0.01	0.03	0.0228	8
0-140	7000-****	8-12	40-49	4-15	0.01	0.01	0.03	0.04	0.08	0.10	0.13	0.14	0.15	0.03	0.05	0.03	0.0313	44
0-140	7000-****	8-12	40-49	16-23	0.01	0.02	0.03	0.05	0.07	0.09	0.12	0.13	0.14	0.03	0.05	0.03	0.0278	35
0-140	7000-****	8-12	50-59	0-3	0.01	0.01	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.0	0.02	0.0100	2
0-140	7000-****	8-12	50-59	4-15	0.01	0.01	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.02	0.00	0.02	0.0099	44
0-140	7000-****	8-12	50-59	16-23	0.01	0.02	0.03	0.05	0.09	0.11	0.13	0.13	0.13	0.04	0.06	0.03	0.0371	15
0-140	7000-****	8-12	60-69	0-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	8-12	60-69	4-15	0.01	0.02	0.03	0.05	0.10	0.13	0.13	0.13	0.13	0.03	0.08	0.03	0.0342	19
0-140	7000-****	8-12	60-69	16-23	0.01	0.02	0.04	0.11	0.13	0.14	0.14	0.14	0.14	0.09	0.03	0.05	0.0613	3
0-140	7000-****	8-12	70-79	0-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	8-12	70-79	4-15	0.01	0.01	0.03	0.04	0.06	0.06	0.06	0.06	0.06	0.03	0.02	0.02	0.0186	6
0-140	7000-****	8-12	70-79	16-23	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.0	0.0	0.02	0.0	1
0-140	7000-****	8-12	80-89	0-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	8-12	80-89	4-15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
0-140	7000-****	8-12	80-89	16-23	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.0	0.0	0.10	0.0	1
0-140	7000-****	13-18	30-39	0-3	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.0	0.0	0.05	0.0000	2
0-140	7000-****	13-18	30-39	4-15	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.0	0.0	0.03	0.0	1
0-140	7000-****	13-18	30-39	16-23	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.0	0.0	0.05	0.0000	5

TABLE 6.4. Sample Tabulation Prediction Technique Data Display

6.3.2 The Influence of Meteorological Variables on Air-pollutant Concentrations

Since the Tabulation Prediction Technique depends on the relations between observed air pollution concentration at a receptor and certain critical meteorological variables, it is necessary to understand the principles underlying the meteorological processes. Each meteorological variable (wind speed, wind direction, temperature, relative humidity, stability, net solar-terrestrial radiation flux, mixing depth, ceiling, or visibility) may play an important role, depending on the local air pollution climatology and type of pollutant involved.

The role played by meteorological variables in processes that affect air pollution concentration levels is discussed by Moses, Anderson, and Gatz (1969).

6.3.3 Selection of Variables

The relationships between air pollution concentrations and meteorological variables are generally not linear, and some are monotonic while others are not. For example, wind direction and time of day are cyclic rather than monotonic predictor variables. To treat these two variables, plots were made of SO₂ concentration versus wind direction and time of day for each of the telemetered air quality monitoring (TAM) stations in the system. Examples of these charts are shown in Figs. 6.10-6.13. These were developed from Chicago air quality data. In these figures, the 50th, 90th, and 95th percentile values as well as the maxima are shown. These charts and a tabulation of the data on which the charts were based were used to select time bands and wind-direction bands within which the variation of the pollutant concentration was relatively small. For example, the bands for time of day and wind direction selected for each Chicago telemetered air monitoring (TAM) station are presented in Table 6.5.

Figures 6.10-6.13 illustrate a number of significant factors in the development of a short-range (24-hr) air quality prediction system. For example, the relative positions of clean areas or pollution sources with respect to the monitoring stations are indicated. The charts also indicate how air-pollutant percentile plots can be used to analyze the air pollution meteorology of a city or region and to determine the most effective time and wind direction bandwidths for each monitoring station.

The interquartile range is a measure of the spread of the data for each combination of meteorological measurements. The amount of noise or uncertainty in the prediction is shown by the magnitude of the interquartile range. Similarly, the difference between the 95th and 75th percentile values represents the amount of skewness present. Since the percentile distributions approximate the log normal function, one would expect appreciable skewness.

Fig. 6.10. Selected Percentile Curves Relating SO₂ Concentrations to Wind Direction at TAM-1 through TAM-4. ANL Neg. No. 113-2343.

Fig. 6.11. Selected Percentile Curves Relating SO₂ Concentrations to Wind Direction at TAM-5 through TAM-8. ANL Neg. No. 113-2344.

Fig. 6.12. Selected Percentile Curves Relating SO₂ Concentrations to Time at TAM-1 through TAM-4. ANL Neg. No. 113-2342.

Fig. 6.13. Selected Percentile Curves Relating SO₂ Concentrations to Time at TAM-5 through TAM-8. ANL Neg. No. 113-2345.

TABLE 6.5. Tabulation Prediction Technique Bands for
Wind Direction and Hour of Day

(Chicago Air Quality Monitoring System)

TAM Station	Wind Direction, deg			Hour, CST		
	Band I	Band II	Band III	Band I	Band II	Band III
1	55-105 205-355 5-15	111-195	25-45	1-2 18-24	6-17	3-5
2	15-135 275-355	145-265 5		9-14	1-8 15-24	
3	355 5-195	205-345		2-20	1 21-24	
4	5-135	145-265 335-355	275-325	1-4	5-16	17-24
5	165-205 245-255	45-95 135-155 215-235 265-355	5-45 105-125	1-3 5-6 9-10 12-24	4 7-8 11	
6	15-55 145-285 335-345	5 295-325 355	65-135	1-7 23-24	14-22	8-13
7	5-65 275-325 355	225-265 335-345	75-215	2-4	1 5-9 17-18 23-24	10-16 19-22
8	45-65 135-305	5-35 75-125 315-355		1-6 11-15 17-24	7-10 16	

Before a final choice is made of the meteorological variables used in the Tabulation Prediction Technique, each must be examined. This may be done in several ways, one of which is to plot the percentile values of pollutant concentration versus each meteorological variable and examine the relationships. The 50, 90, and 95 percentile and maximum curves can be plotted for this purpose in the same format as shown in Figs. 6.10-6.13.

Where a network of stations is available, such as exists in New York City, Los Angeles, Washington, or Chicago, the receptor-oriented Tabulation Prediction Technique may be applied to each station to obtain isopleths of pollutant concentrations.

6.3.4 Construction of the Tabulations

The meteorological variables recommended for the construction of a Tabulation Prediction Technique are:

- 1) Wind direction
- 2) Ceiling height
- 3) Wind speed

- 4) Temperature
- 5) Hour of the day.

The significance of atmospheric stability has been noted, but such data are usually unavailable. A substitute is provided by the choice of the variables ceiling height, hour of the day, and wind speed. Combinations of these are closely related to stability. For example, during high winds, e.g., near 15 knots, the stability is usually neutral. This is true during the day or night. During periods with unlimited ceilings accompanied by light winds, an inversion is quite likely at night, but unstable conditions are to be expected during the day.

Recommended bandwidths for the variables ceiling height, wind speed and temperature are shown in Table 6.6. As a first step, the data are stratified by season and by the presence or absence of precipitation. An intermediate tabulation is then prepared in which wind direction and hour of day are listed as Band I, Band II, and so on. For example, for TAM-1, in Chicago, the wind directions 5-15, 55-105, 205-355 are all contained in wind-band category I. The final form of the tabulation should substitute actual values of wind direction and hour in numerical order, as shown in Table 6.4. The percentile distribution of SO₂ or any other pollutant

TABLE 6.6. Units and Group Intervals for Variables Used in the Tabulation Prediction Technique

1. Wind Speed	
Unit: Miles per hour	
Group Interval: 0-3, 4-7, 8-12, 13-18, 19-24, ≥ 24	
2. Wind Direction:	
Unit: Degrees	
Group Interval: Standard 45° grouping (0-45, 45-89, 90-135, etc.) or according to bandwidths selected as indicated in Sec. 6.3.4.	
3. Temperature	
Unit: °F	
Group Interval: -20 to -11, -10 to -1, 0-9, 10-19, 20-29, 30-39, 40-49, 50-59, 60-69, 70-79, 80-89, 90-99	
4. Ceiling Height	
Unit: Feet	
Group Interval: 0-999, 1000-2499, 2500-6999, ≥ 7000	
5. Hour of Day	
Unit: One hour	
Group Interval: Selected uniform intervals or intervals selected according to bandwidths as indicated in Sec. 6.3.4.	
6. Season	
Group Interval: December-January-February	
March-April-May	
June-July-August	
September-October-November	
7. Precipitation (optional)	
a. All hours for which no more than trace amounts of precipitation are recorded.	
b. All hours for which more than trace amounts of precipitation are recorded.	

corresponding to the wind-band category, in combination with the appropriate meteorological variables, is then presented for wind direction in each of these ranges.

The order of the variables in the columns is arranged so that the last column represents the variable that influences the SO_2 concentrations the least and the first column the most. Further, wind speed and temperature are presented in descending order, since lowest values of each correspond to highest SO_2 concentrations. Thus, the tabular arrangement shows a general increase in values of SO_2 concentration as one reads down from the top of the table.

In summary, the construction of a tabulation prediction table for a system of telemetered air-monitoring stations consists of the following steps:

- 1) Partition the meteorology and air quality data for each station by season.
- 2) Prepare plots of pollution concentration versus wind direction and versus time of day for each group of data obtained in 1 above.
- 3) From the plots prepared in 2 above, select from two to four time intervals and up to eight wind-direction intervals within which the variation of pollution concentration is relatively small. Several different wind-direction intervals may be collected together in one wind band, if the pollution concentrations observed for these intervals do not vary significantly. For example, if 95% of the SO_2 concentrations observed at a given station were between 0.1 and 0.2 ppm for winds in the intervals $10-20^\circ$ and $95-120^\circ$, data from both of these wind-direction intervals could be assigned to the same wind band.
- 4) Partition and print out the data in each wind direction and time band determined from 3 above, by time band, ceiling height, wind direction, wind speed, and temperature. This operation is performed by the computer code included in this manual once the wind direction and time bands have been selected. The computer code contains an option to accept or reject data associated with periods during which precipitation occurred.
- 5) Repeat the above procedure for each monitoring station in the system. The wind direction and time bands selected will normally differ from one station to the next due to differences in the operating characteristics and distribution of sources in the vicinity of the monitoring stations.

6.3.5 Construction of a Simplified Version of the Tabulation Prediction Technique

The procedure described above was designed to make the most efficient use of the available data by minimizing the number of wind-direction

and time bands and therefore maximizing the amount of data displayed in each band. As indicated above, an analysis of the available meteorological and air quality data is required in order to select the most efficient set of wind and time bands. This analysis may be avoided, and a somewhat simplified version of the tabulation prediction system may be produced if standard wind-direction and time bands are used for all stations. For example, a set of "standard" wind-direction bands might be as listed in Table 6.7.

TABLE 6.7. "Standard" Intervals for Wind-direction and Time Bands

Wind Direction	Time
Band 1: 0-45°	Band 1: 0700-1100
Band 2: 45-90°	Band 2: 1100-1700
Band 3: 90-135°	Band 3: 1700-2300
Band 4: 135-180°	Band 4: 2300-0700
Band 5: 180-225°	
Band 6: 225-270°	
Band 7: 270-315°	
Band 8: 315-360°	

Inspection of a source-distribution map for the control region may indicate that certain wind-direction bands could be expected to be significant for a given monitoring station. Use of these bands would be more effective than an arbitrary grouping of data by wind quadrants or octants, etc.

6.3.6 Application of the Tabulation Prediction Technique to Daily Operations

Since the variables used in the Tabulation Prediction Technique are wind direction, wind speed, temperature, ceiling height, and hour of day, these are the variables (except, of course, the hour of day) for which meteorological forecasts are required. The forecasts should be made for each hour. The forecast may be for a particular group interval, e.g., a wind-speed forecast of 4-7 mph. These should correspond to the intervals recommended in Table 6.6.

The meteorological forecast for the day is preferably made between 0700 and 0800 so that the early-morning pollution peak will be covered. The development of forecasts for 12-24 hr is a reasonably routine procedure. These forecasts may be issued every 6, 12, or 24 hr, depending on the local requirements. Of course, during potential or actual severe-pollution conditions, constant surveillance is necessary and automatic 6-hr updating of the 24-hr forecast is appropriate.

A format for recording the forecasts and the computed and observed pollution concentrations is provided in Figs. 6.14 and 6.15. More variables are indicated on the form than may actually be used in preparing an air quality prediction; but a control agency may use this form as a guide in preparing one that is tailored to its specific needs. (The symbol Prb on this form stands for the probability estimate of the forecast verification.)

After the meteorological forecast values are received, the 50th percentile entry of the Tabulation Prediction Technique (e.g., Table 6.4) may be used to produce an air pollution concentration prediction for each hour of the forecast period. A better method of using the tables, however, is to determine, from the actual, measured air pollution concentrations for the first hour of the forecast period, what percentile entry should be used to make the prediction for the next 6 hr. For example, if the actual SO_2 value for the first hour of the forecast period is 0.3 ppm and this value corresponds to the 80th percentile entry in the appropriate part of the table, then the air quality predictions for the next 6 hr should be taken from the 80th-percentile entries. The 50th percentile may be used for the remaining 18 hr of the forecast period. When the forecast is updated 6 hr later, a new percentile entry is determined from the most recent measured air quality data, and the procedure is repeated to produce an updated air quality prediction.

With the availability of on-line computer facilities, some functions may be automated. For example, the hourly meteorological forecast may be entered into the computer and a printout of the 50th-percentile air pollution level may be produced, based on Tabulation Prediction Technique tables stored on a disc or tape memory. It is possible to produce computer-plotted maps of the control region with pollutant concentration levels and meteorological variables. Such maps are currently generated at Argonne National Laboratory using the APICS display program described in ANL/ES-CC-003.

6.3.7 Advantages and Disadvantages of the Tabulation Prediction Technique

Among the advantages of the Tabulation Prediction Technique are:

- 1) It is easy to use and does not require on-line, real-time access to a computer.
- 2) It provides rapid on-line prediction of pollution concentrations.
- 3) It provides the entire percentile distribution of pollutant concentrations to allow a forecaster to "fine-tune" his predictions based on synoptic situations.

DATE: _____
 TIME: _____
 GIVEN BY: _____
 RECEIVED BY: _____

CONTROL POINT :
 MIDWAY AIRPORT:

HOUR	1. SURFACE WIND DIRECTION		2. SURFACE WIND SPEED		3. MIXING HEIGHT INDEX		4. DRY BULB TEMPERATURE (SURFACE)		5. CEILING BELOW 7,000		6. RELATIVE HUMIDITY		7. CLOUD COVER		8. CEILING HEIGHT		9. PRECIPITATION (OVER A TRACE)		10. VISIBILITY		11. STABILITY CLASS		12. MIXING HEIGHT	
	Prb.	(MPH)	Prb.	Prb.	(°F)	Prb.	(YES NO)	Prb.	(%)	Prb.	Prb.	(ft.)	Prb.	(YES NO)	Prb.	(mi.)	Prb.	Prb.	(ft.)	Prb.				
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Fig. 6.14. Air Quality Prediction System Data Form: Air Quality Prediction System. ANL Neg. No. 113-1155.

HOUR	1		2		3		4		5		6		7		8	
	PRED.	ACT.	PRED.	ACT.	PRED.	ACT.	PRED.	ACT.	PRED.	ACT.	PRED.	ACT.	PRED.	ACT.	PRED.	ACT.
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Fig. 6.15. Air Quality Prediction System Data Form: SO₂ Predictions and Actual Readings. ANL Neg. No. 113-1156.

4) It takes into account nonlinearities in the relationship between meteorological variables and pollution concentrations.

5) It is an effective method of analyzing and displaying air quality and air pollution meteorology data.

Disadvantages of this method are that:

- 1) A digital computer is required in order to construct the tables.
- 2) The tables must be updated at 1- to 2-year intervals as the source strength and distribution patterns of the area change.
- 3) Being a receptor-oriented method, it cannot predict air pollution concentrations at points between monitoring stations, except indirectly through interpolation or logical inference.

6.3.8 Computer Program for Tabulation Prediction Technique

To construct the prediction table described above, hourly values of selected meteorological variables over the time range of interest must be available. The bases for selecting these variables have been discussed above.

The information flow to the computer program is depicted schematically in Fig. 6.16. Details of the preprocessing codes as well as the Tabulation Prediction Technique are given in ANL/ES-CC-006.

Fig. 6.16

Information Requirements of Tabulation Prediction Technique. ANL Neg. No. 113-1157.

7. MODELS OF ATMOSPHERIC DISPERSION

(J.J. Roberts, A. S. Kennedy, and J. E. Norco)

7.1 Introduction

A review of the scope of the Chicago Air Pollution Systems Analysis Program or of the implementation planning process in general will identify three major objectives:

- 1) Development of techniques for the manipulation and analysis of information concerning emissions, meteorology, air quality, and other indices of urban activity, such as land use and economic data.
- 2) Development of optimal air pollution episode control strategies for cities and regions. This includes the creation of data-management techniques and operational strategies for use by air pollution control agencies during air pollution episodes.
- 3) Integration of air pollution control with long-range urban and regional planning. This effort includes prediction of the effects of industrial growth, technological developments, population migration, and economic influences on the air quality of the city of the future. The objective is to develop guidelines for the creation of legislation, zoning ordinances, tax incentives, etc., which cause a city or region to evolve in a direction such that acceptable air quality exists under all combinations of meteorological conditions.

Models of the transport of air pollutants in the urban environment play central roles in each of these three categories. In matters of siting major power sources or in evaluating specialized ordinances such as stack-height restrictions or simply in understanding the workings of complex multisource models, there are needs for simple, single-source analyses. The design of strategies for control of air pollution episodes is facilitated by a simulation of time-dependent variations of contaminant levels, whereas statistical (air pollution climatological) models are more suitable for long-range planning. For both time horizons, there is a hierarchy of applications: estimating air quality, testing strategies in terms of reductions of concentrations of pollutants, and embedding these calculations in cost/benefit or cost/effectiveness models seeking optimal solutions to the control problem.

During the CHAPSAP, a number of models were developed to satisfy the multiplicity of demands outlined above. This section of this final report describes these models first in terms of algorithms used to evaluate individual sources and then in terms of two multisource computer programs: the "integrated-puff" simulation of air pollution transients and a dispersion-climatology model.

4

7.2 PLUME, A Single-source, Steady-state Gaussian-plume Model

Wherever applicable, formulas describing the steady-state distribution of pollutant given a source distribution are clearly more tractable than algorithms depicting transient situations. One criterion for applicability is that ratio of time-of-flight (downwind distance/mean wind speed) to the averaging time for meteorological variables be less than 1. Others, such as the identification and avoidance of specialized meteorological regimes (e.g., lake breeze), are more difficult to quantify, and, in essence, the use of steady-state models to describe pollution profiles involves some intuition, art, and a very pragmatic attitude.

For convenience in evaluating the relative culpability of individual sources and as a dispersion module for climatology studies, a computer subroutine (PLUME) was developed based on the prescription by Turner (1967).

7.2.1 Basic Equation

In a Cartesian-coordinate system with the z-axis vertical and the horizontal axes rotated so that the x-axis coincides with the downwind direction, the basic kernel describing the concentration χ at a receptor point x_r, y_r, z_r , due to a steady emission from the point $x = 0, y = 0, z = H$, in an infinite medium is

$$\chi(x, y, z; H) = \frac{Q_s}{2\pi U \sigma_y \sigma_z} \exp \left\{ -0.5 \left[\left(\frac{y_r}{\sigma_y} \right)^2 + \left(\frac{z_r - H}{\sigma_z} \right)^2 \right] \right\}, \quad (7.1)$$

where

Q_s = pollutant emission rate (micrograms/sec),

U = mean wind speed (meters/sec),

σ_y = crosswind dispersion coefficient (meters), a function of downwind distance, x ,

σ_z = vertical dispersion coefficient (meters), a function of downwind distance, x ,

y_r = crosswind distance (meters),

z_r = height of receptor (meters),

H = effective height of emission (meters),

and

χ = pollutant concentration ($\mu\text{g}/\text{m}^3$).

Figure 7.1 shows an isopleth and employs the nomenclature used in the isopleth-area tables described in Sec. 7.2.5. The following additional abbreviations are used:

QSO ₂	Source strength, in pounds of SO ₂ per hour;
DLE	Distance from the source to the leading edge of the isopleth in the downwind direction, in miles;
LGTH	Length of the isopleth, in miles;
WDTH	Maximum width of the isopleth, in miles;
CHIMAX	Maximum concentration of SO ₂ , in ppm;
DOM	Distance downwind from the source to the point of maximum concentration (CHIMAX), in miles.

Fig. 7.1

A Single-source Ground-level Isopleth

7.2.2 Dispersion Coefficients

The dispersion coefficients, σ_y and σ_z , are functions of the downwind distance, x , and are parameterized according to six classes of atmospheric stability. The dispersion coefficients shown in Figs. 7.2 and 7.3, are based on a sampling or averaging time of about 10 min. The smallest time increment of interest in determining expected isopleths is 1 hr. Thus, for use in Eq. 7.1 the values of σ_y and σ_z in Figs. 7.2 and 7.3 have been multiplied by the factor $(60 \text{ min}/10 \text{ min})^{0.2} = 1.43$ (Cramer et al., 1964). The stability class is determined according to Turner's (1967) objective (tabular) relationship between insolation and wind speed.

The units of χ are $\mu\text{g}/\text{m}^3$. To convert $\mu\text{g}/\text{m}^3$ of SO₂ to parts per million (ppm) at standard temperature (32°F) and pressure (1 atm), divide χ in Eq. 7.1 by 2854. A further correction for the actual temperature is not warranted, considering the uncertainties inherent in the assumed form of the dispersion equation and in the experimentally determined values of σ_y and σ_z .

Fig. 7.2. Horizontal Dispersion Coefficient as a Function of Downwind Distance from the Source. ANL Neg. No. 149-3546.

Fig. 7.3. Vertical Dispersion Coefficient as a Function of Downwind Distance from the Source. ANL Neg. No. 149-3545.

7.2.3 Ground-level Reflection

The assumption that the pollutant is not absorbed when it makes contact with the ground or with buildings can be approximated by a model based on perfect reflection at the ground. In Fig. 7.4a, two infinite-medium sources are superimposed: the actual source at effective height H , and an image source H meters below the reflecting ground plane.

7.2.4 Mixing-height Assumption

A stable layer existing at height H_m above an unstable or neutral zone inhibits vertical diffusion and acts as a lid. This phenomenon can be approximated by assuming the existence of a reflecting plane at height H_m , so that in a manner analogous to reflection at ground level, an image source is introduced above the lid plane at height $2H_m - H$ (see Fig. 7.4b).

Fig. 7.4. Reflection of Plumes by Use of Virtual Images

The problem is now complicated by the existence of two reflecting planes: ground and lid. As anyone who has stood between two mirrors knows, the result is describable by introducing multiple (infinite) pairs of reflections at increasing distances from the true source. Figure 7.5 shows two pairs of image sources. Close to the source, the images G_2 and L_2 are insignificant. At greater distances downwind, σ_z increases (see Fig. 7.3) and the second set of images becomes important. For example, when $2.15 \sigma_z = 2H_m + H$ in Fig. 7.5, the contribution at ground from the image source L_2 is 10% of the concentration on the centerline of the plume.

Fig. 7.5. Multiple Reflections between a Stable Layer and Ground Represented Mathematically by Two Sets of Image Sources. The image G_1 is reflected above the lid at L_2 . The image L_1 is reflected below ground at G_2 . ANL Neg. No. 113-2859 Rev. 2.

The mathematical representation of the concentration of pollutants trapped between two reflecting planes is therefore represented by pairs of images which become important with increasing downwind distance. Eventually, the vertical distribution of pollutants is approximately uniform and the following modified version of Eq. 7.1 can be employed:

$$\chi(x, y) = \frac{Q_s}{\sqrt{2\pi}\sigma_y U H_m} \exp[-0.5(y/\sigma_y)^2], \quad (7.2)$$

where H_m = height of mixing layer (meters), and other parameters are as defined in Eq. 7.1.

The transition from multiple images (Eq. 7.1 and Fig. 7.5) to the uniform distribution can be made smoothly after three pairs of image sources have been introduced and at a downwind distance x_u defined by

$$2.15\sigma_z(x_u) = 4H_m - H. \quad (7.3)$$

The right-hand side of Eq. 7.3 is the height above ground of the image L_3 , which is the reflection of G_2 (see Fig. 7.5) above the lid.

Figure 7.6 shows the approach to the asymptotic distribution of Eq. 7.2. Equations 7.1 and 7.2 have been normalized to remove all dependence on σ_y , U , or Q . The transition from three pairs of images to the uniform distribution (Eq. 7.2) occurs at $x = 9$ km in Fig. 7.6. The jump in concentrations due to the change of algorithms has been emphasized by choosing an example in which plume rise is inhibited by a lid at altitude $H_s = H_m$.

Fig. 7.6

Approach to a Uniform Distribution in the Vertical. $H_m = H = 150$ meters. Stability Class D.

7.2.5 Applications of Subroutine PLUME

Inputs to subroutine PLUME are the parameters Q_s , U , y_r , z_r , H , and x as defined in the nomenclature associated with Eq. 7.1. Atmospheric stability is also input in order to determine the appropriate dispersion functions.

Subroutine PLUME is designed to be coupled to simple input-output routines for evaluating any single-source situation. For example, the contributions of a number of major point sources to the air pollution levels observed at several telemetered air-quality monitoring stations in Chicago were evaluated (see Table 7.1), in order to assess the possibility of detecting the plumes from these plants as peaks above the normal air pollution levels at the monitoring sites.

TABLE 7.1. Point-source Contributions to TAM Stations
Directly Downwind (Wind speed = 10 mph)

	Fisk on TAM-4	Crawford on TAM-4	UC on TAM-4	Northwest on TAM-2	Crawford on TAM-7
Max Q_{plant} , ^a MBtu/hr	3300	3000	90	830	3000
No. of stacks	1 ^b	4	2	2	4
Stack height, ft	450	300 ^c	200	300	300
Downwind distance, mi	6.0	7.7	0.7 ^d	1.7	4.2
<u>Unstable (Class 3)</u>					
Plume rise, ^e ft	2200	2100	400	1100	2100
σ_z , ^f ft	1700	2100	200	500	1200
σ_y , ft	2600	3300	400	900	1900
Max ppm ^g per stack	0.04	0.04	0.02	0.03	0.03
Max ppm, ^g all stacks	0.04	0.16	0.04	0.06	0.12
Avg ppm, ^g all stacks; 30° wind sector	0.01	0.04	0.01	0.02	0.04
<u>Stable (Class 5)</u>					
Plume rise, ft	600	600	100	300	600
σ_z , ft	400	400	100	150	300
σ_y , ft	1300	1600	200	400	1000
Max ppm ^g per stack	0.02	0.1	0.03	~0	0.02
Max ppm, ^g all stacks	0.02	0.4	0.06	~0	0.08
Avg ppm, ^g all stacks; 30° wind sector	0.002	0.06	0.01	~0	0.01

^aBased on $Q_{\text{stack}} = 0.2 \times Q_{\text{plant}}$. Calculations assume 3% sulfur coal at 10^4 Btu/lbm.

^bCalculation does not consider the 292-ft stacks, which are used less frequently.

^cConservative value, since two stacks are 375 ft high.

^dUC (The University of Chicago heating plant) distance is actually about 3 miles. These concentrations therefore represent an upper bound on the effect of UC on TAM-4.

^eCarson and Moses (1967).

^fTurner (private communication).

^g $\mu\text{moles per mole of air}$.

Figure 7.7 shows the nonlinear coupling of plant output and ground-level concentrations. The elementary plume equation shows that the pollutant concentration, χ , is directly proportional to the pollutant source, Q . Thus, from Eq. 7.1, one might conclude that a 10% increase in Q results in a 10% increase in χ . However, an increase in stack emissions will usually increase the plume rise and consequently the mean transport velocity; both of these effects tend to diminish the ground-level concentration. This nonlinearity is anticipated only at short range. Figure 7.7 indicates that a plant located 1 mile upwind is likely to be linearly coupled with the receptor, whereas, at a distance of 1/4 mile downwind of the source, the relationship of centerline sulfur dioxide concentrations to plant output is nonlinear.

Fig. 7.7

Nonlinear Effect of Plume Rise.
Based on a UC stack (200 ft
high with maximum output of
6 Mcal/sec). Stability Class 4.
ANL Neg. No. 112-9762.

Subroutine PLUME was also used to evaluate isopleths downwind of single sources. These results were presented in the form of isopleth-area tables which list for specified pollutants levels the length and width of the isopleth and the location of the upwind edge. A typical single-source, ground-level isopleth is illustrated in Fig. 7.1; the nomenclature is that used in the tables. This information enables a control official to plot quickly the pattern associated with major sources. Table 7.2 is extracted from these isopleth-area tables which, along with descriptive material, will appear in an episode control manual to be published by Argonne National Laboratory.

Section 7.3 describes a dispersion-climatology model used to evaluate control strategies in terms of present and anticipated emissions. Subroutine PLUME is used in this computer code.

7.3 Dispersion-climatology Model

To interpret in terms of air quality the changes in emission patterns due to regional evolution and the effects of alternate, long-range control strategies, the inventory of sources (present or potential) must be folded in with a climatological history of the region via a dispersion model to estimate pollution levels. The Air Quality Display Model (AQDM; TRW, 1969) is designed to perform this function. This semiofficial A.P.C.O. computer program was not available at the time of the Argonne study on long-range planning; therefore a similar, computerized, dispersion-climatology model had to be designed to be coupled with the model for projection of regional emissions. (See Sec. 10 of this report and ANL/ES-CC-008.)

TABLE 7.2. Isopleth-area Table

45
 MIXING HEIGHT..... 1000.0 FT
 WIND SPEED..... 5.0 MPH
 EFFECTIVE STACK HEIGHT..... 1000.0 FT
 STABILITY CLASS..... UNSTABLE-B

QS02 LB/HR	-----ISOPLETH LEVEL=.01 PPM-----						-----ISOPLETH LEVEL=.10 PPM-----						-----ISOPLETH LEVEL=.20 PPM-----					
	AREA SQ MI	DLE MI	LGTH MI	WDTH PI	CHIMAX PPM	DCM MI	AREA SQ MI	DLE MI	LGTH MI	WDTH MI	CHIMAX PPM	DCM MI	AREA SQ MI	DLE MI	LGTH MI	WDTH PI	CHIMAX PPM	DCM MI
250	0.5	0.8	1.0	0.5	0.02	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
500	2.0	0.3	4.0	0.5	0.04	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
750	7.2	0.2	6.5	1.2	0.05	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1000	12.0	0.3	9.0	1.5	0.07	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2500	90.5	0.3	25.0	4.5	0.18	1.0	0.5	0.8	1.0	0.5	0.18	1.0	0.0	0.0	0.0	0.0	0.0	0.0
5000	472.6	0.3	>50.0	5.5	0.36	1.0	2.0	0.2	4.0	0.5	0.36	1.0	0.5	0.8	1.0	0.5	0.36	1.0
15000	1119.4	0.2	>50.0	22.5	1.07	1.0	29.5	0.2	14.0	2.5	1.07	1.0	7.3	0.3	6.5	1.5	1.07	1.0
25000	1366.1	0.2	>50.0	27.5	1.79	1.0	90.5	0.3	25.0	4.5	1.79	1.0	21.8	0.3	11.5	2.5	1.79	1.0
35000	1517.4	0.2	>50.0	30.5	2.51	1.0	185.3	0.3	36.5	6.5	2.51	1.0	44.0	0.3	17.0	3.5	2.51	1.0
50000	1616.9	0.3	>50.0	32.5	3.58	1.0	472.6	0.3	>50.0	9.5	3.58	1.0	50.5	0.3	25.0	4.5	3.58	1.0
75000	1766.1	0.2	>50.0	35.5	5.37	1.0	721.4	0.3	>50.0	14.5	5.37	1.0	217.5	0.3	39.0	7.5	5.37	1.0
100000	1865.6	0.2	>50.0	37.5	7.16	1.0	920.4	0.3	>50.0	18.5	7.16	1.0	472.6	0.3	>50.0	9.5	7.16	1.0

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 MIXING HEIGHT..... 1000.0 FT
 WIND SPEED..... 5.0 MPH
 EFFECTIVE STACK HEIGHT..... 1000.0 FT
 STABILITY CLASS..... NEUTRAL-C

QS02 LB/HR	-----ISOPLETH LEVEL=.01 PPM-----						-----ISOPLETH LEVEL=.10 PPM-----						-----ISOPLETH LEVEL=.20 PPM-----					
	AREA SQ MI	DLE MI	LGTH MI	WDTH PI	CHIMAX PPM	DCM MI	AREA SQ MI	DLE MI	LGTH MI	WDTH MI	CHIMAX PPM	DCM MI	AREA SQ MI	DLE MI	LGTH MI	WDTH PI	CHIMAX PPM	DCM MI
500	1.3	0.2	2.5	0.5	0.01	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
750	12.8	0.8	11.5	1.5	0.02	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1000	22.0	0.2	17.0	1.5	0.02	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2500	214.9	2.3	>50.0	4.5	0.06	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5000	456.4	1.8	>50.0	5.5	0.11	6.5	1.3	6.3	2.5	0.5	0.11	6.5	0.0	0.0	0.0	0.0	0.0	0.0
15000	659.6	1.8	>50.0	14.5	0.34	6.5	54.8	2.8	26.5	2.5	0.34	6.5	12.8	3.8	11.5	1.5	0.34	6.5
25000	755.6	1.3	>50.0	15.5	0.56	6.5	214.9	2.3	>50.0	4.5	0.56	6.5	40.5	2.8	22.0	2.5	0.56	6.5
35000	804.4	1.2	>50.0	16.5	0.79	6.5	310.4	2.3	>50.0	6.5	0.79	6.5	77.8	2.8	30.5	3.5	0.79	6.5
50000	851.1	1.2	>50.0	17.5	1.13	6.5	458.4	1.8	>50.0	9.5	1.13	6.5	214.9	2.3	>50.0	4.5	1.13	6.5
75000	950.6	1.3	>50.0	19.5	1.69	6.5	554.9	1.8	>50.0	11.5	1.69	6.5	258.1	2.3	>50.0	7.5	1.69	6.5
100000	950.6	1.3	>50.0	19.5	2.26	6.5	603.1	1.8	>50.0	12.5	2.26	6.5	456.4	1.8	>50.0	9.5	2.26	6.5

47
 MIXING HEIGHT..... 1000.0 FT
 WIND SPEED..... 10.0 MPH
 EFFECTIVE STACK HEIGHT..... 100.0 FT
 STABILITY CLASS..... UNSTABLE-B

QS02 LB/HR	-----ISOPLETH LEVEL=.01 PPM-----						-----ISOPLETH LEVEL=.10 PPM-----						-----ISOPLETH LEVEL=.20 PPM-----					
	AREA SQ MI	DLE MI	LGTH MI	WDTH PI	CHIMAX PPM	DCM MI	AREA SQ MI	DLE MI	LGTH MI	WDTH MI	CHIMAX PPM	DCM MI	AREA SQ MI	DLE MI	LGTH MI	WDTH PI	CHIMAX PPM	DCM MI
100	0.3	0.2	0.5	0.5	0.01	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
250	0.3	0.2	0.5	0.5	0.03	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
500	0.5	0.3	1.0	0.5	0.07	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
750	1.3	0.2	2.5	0.5	0.10	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1000	2.0	0.2	4.0	0.5	0.13	0.5	0.3	0.3	0.5	0.5	0.13	0.5	0.0	0.0	0.0	0.0	0.0	0.0

48
 MIXING HEIGHT..... 1000.0 FT
 WIND SPEED..... 10.0 MPH
 EFFECTIVE STACK HEIGHT..... 100.0 FT
 STABILITY CLASS..... NEUTRAL-D

QS02 LB/HR	-----ISOPLETH LEVEL=.01 PPM-----						-----ISOPLETH LEVEL=.10 PPM-----						-----ISOPLETH LEVEL=.20 PPM-----					
	AREA SQ MI	DLE MI	LGTH MI	WDTH PI	CHIMAX PPM	DCM MI	AREA SQ MI	DLE MI	LGTH MI	WDTH MI	CHIMAX PPM	DCM MI	AREA SQ MI	DLE MI	LGTH MI	WDTH PI	CHIMAX PPM	DCM MI
20	0.3	0.3	0.5	0.5	0.01	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50	0.5	0.3	1.0	0.5	0.04	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	1.0	0.3	2.0	0.5	0.07	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
250	1.8	0.3	3.5	0.5	0.19	0.5	0.3	0.3	0.5	0.5	0.19	0.5	0.0	0.0	0.0	0.0	0.0	0.0
500	2.0	0.3	6.0	0.5	0.37	0.5	0.5	0.3	1.0	0.5	0.37	0.5	0.3	0.3	0.5	0.5	0.37	0.5
750	5.0	0.3	8.0	1.5	0.56	0.5	0.8	0.3	1.5	0.5	0.56	0.5	0.5	0.3	1.0	0.5	0.56	0.5
1000	10.0	0.3	10.0	1.5	0.74	0.5	1.0	0.3	2.0	0.5	0.74	0.5	0.5	0.3	1.0	0.5	0.74	0.5

Subroutine PLUME is the basis for all dispersion calculation in the computer program. It is applied to all point and square areal sources* in the region.

A climatology code (see Sec. 8 and ANL/ES-CC-008) was used to generate frequencies of met sets for each season according to the breakdown of Midway Airport weather variables listed in Table 7.3.

TABLE 7.3. Meteorological Variables and Associated Bands^a

		Winter (D J F)	Spring (M A M)	Summer (J J A)	Fall (S O N)
Temperature band, °F	1	≤20(13)	≤40(35)	≤65(62)	≤45(40)
	2	21-30(25)	41-50(46)	66-73(70)	46-55(51)
	3	>30(37)	>50(60)	>73(80)	>55(61)
Stability-class band (Turner class)	1	1-3(2)	1-3(2)	1-3(2)	1-3(2)
	2	4	4	4	4
	3	5	5	5	5
Wind-speed band, mph	1	≤6(4)	≤6(4)	0-4(3)	0-5(4)
	2	7-12(9)	7-12(9)	5-8(6)	6-9(7)
	3	>12(15)	>12(15)	>8(10)	>9(11)
Wind-direction band (16-point compass)	1	N-NE(NNE)	NNW-NNE(N)	N-NE(NNE)	N-NE(NNE)
	2	ENE-SE(ESE)	NE-ESE(ENE)	ENE-ESE(E)	ENE-ESE(E)
	3	SSE-SSW(S)	SE-S(SSE)	SE-S(SSE)	SE-S(SSE)
	4	SW-W(WSW)	SSW-WSW(SW)	SSW-WSW(SW)	SSW-WSW(SW)
	5	WNW-NNW(NW)	W-NW(WNW)	W-NNW(NW)	W-NNW(NW)

^aThe value in parentheses indicates the numerical value used in the diffusion-model computations to represent a band.

Generally speaking, the rationale for choosing the bands listed in Table 7.3 was to:

1) Keep this total number of combinations to a reasonable level (for conservation of computer time). This breakdown develops 135 met sets, all of which have nonzero frequencies.

2) Tailor the bands to each season.

3) Provide roughly an equal number of observations in each band for each individual variable. This was accomplished with the aid of a climatological summary (Moses and Bogner, 1967).

In a manner similar to AQDM, the value of mixing height was chosen depending on the stability class according to the schedule in Table 7.4.

*A square areal source is simulated by a virtual point source located at a distance X_0 upwind of the center of the square such that $\sigma_y(X_0) = (\text{square side})/2.4$. This is discussed further in Sec. 7.5.

TABLE 7.4. Rules for Selecting Values
for the Mixing Height

Stability Class	Mixing Height
1-3	Climatological value
4	50% less than the climatological value or 100 meters, whichever is greater
5	100 meters

The climatological value is the average afternoon mixing height which can be found tabulated by Holzworth (1964). The values used in this study were developed from data acquired from the ESSA-EMSU balloon soundings taken at Chicago's Midway Airport. Seasonal rather than annual averages are employed. Based on the above criteria, the mixing heights used in the dispersion model are those listed in Table 7.5.

TABLE 7.5. Seasonal Values of Mixing Height Based on
ESSA-EMSU Soundings at Midway Airport

Stability Class	Mixing Height, ft			
	Winter	Spring	Summer	Fall
1-3	2300	4100	4775	3600
4	1150	2050	2400	1800
5	330	330	330	330

The input wind direction is shifted to the nearest of the 16 compass points for all calculations. At each specified dose point, the contributions of all sources within approximately a 45° angle centered on the wind direction are evaluated. An adjustment, similar to the method of Clarke (1964), to account for the distribution of wind direction within each sector was not, but should have been, included. This oversight was partially corrected by averaging concentrations at all other grid points adjacent to (surrounding) each grid point. Variable-sized area sources are generated by homogenizing the individual square-mile source to increase the area-source size as the distance from the dose point increases (see Fig. 7.8). Concentrations at each dose point are summed for each of three source classes: residential/commercial area sources, industrial area sources, and major point sources.

In order to apply the total system for long-range planning, the emission inventory was developed and the dispersion model run for Chicago only. As discussed in ANL/ES-CC-008, the base-year (1970) inventory was compiled

Fig. 7.8. Nonuniform Grid for Area-source Emissions. ANL Neg. No. 113-2972.

by updating emissions from major sources and using the projection model to extrapolate a 1967 residential survey to 1970. Estimated annual averages of SO_2 at some 20 points in the city based on this 1970 inventory, coupled with a 15-year climatological history (Moses, 1967), were compared to 1968 and 1969 annual averages measured by the Chicago DEC. The numbers in the scattergrams (Figs. 7.9 and 7.10) correspond to monitoring sites shown on the map in Fig. 7.11.

Although this limited comparison is not adequate for evaluation of the dispersion model, some appraisal is possible.

From Fig. 7.9, it is evident that the estimates* agree quite well with observations made in 1968. (A separate study at Argonne indicated that AQDM results using the meteorological history for 1968 were similar to those using the 15-year climatological summary.) The model overpredicts. (This is even more apparent in Fig. 7.10.)

Fig. 7.9. Comparison of Estimated Annual SO_2 Averages Using 15-year Climatological Data and 1970 Emission Inventory with Observed Annual Averages for 1968. Data courtesy of Chicago DEC.

Fig. 7.10. Comparison of Estimated Annual SO_2 Averages Using 15-year Climatological Data and 1970 Emission Inventory with Observed Annual Averages for 1969. Data courtesy of Chicago DEC.

*The same set of estimates is used in both scattergrams.

Fig. 7.11. Sulfur Dioxide Monitoring Sites in the CMAQCR. ANL Neg. No. 190-33.

Most of the data points above the line of perfect prediction represent monitors located at the periphery of the City, beyond which no inventory was acquired.

From 1968 (Fig. 7.9) to 1969 (Fig. 7.10) the observed annual averages drop significantly--in one case, from 0.04 to 0.005 ppm. We have not investigated the significance of this situation, although it is known that the winter of 1968-1969 was warmer than that of 1967-1968.

These comparisons indicate that the model performs about as well as or perhaps slightly better than AQDM. If the model is in fact superior to AQDM, it may be due to the introduction of seasonal and temperature dependence of emission and meteorological data. This aspect of the important problem of designing more reliable dispersion-climatology models should be examined, perhaps by modification of AQDM rather than by continued study of the Argonne computer code.

7.4 ONEPUFF, A Single-source Model Based on the Gaussian Puff Kernel

As implied in Sec. 7.2, it is possible to use a steady-state Gaussian plume model to approximate certain near steady-state conditions. Where transient conditions are important, such as in the time-dependent buildup of pollutant levels during fumigation periods, a model designed specifically to simulate these transients is desirable. The integrated-puff model of atmospheric transport simulates the response to a time series of piecewise constant emission and meteorological variables. Program ONEPUFF is a single-source version analogous to subroutine PLUME. The fundamental assumption in the transport model is that the dispersion associated with an instantaneous release can be described by a puff moving with the mean wind and diffusing about its centroid according to a Gaussian distribution. This section describes the basic transport algorithms used in program ONEPUFF. Section 7.5 describes an adaptation of program ONEPUFF to the development of optimal abatement strategies for major sources during air pollution episodes. (See Sec. 8 of this report.) Section 7.6 focuses on the adaption of the integrated-puff transport kernel to a computer program which describes time-dependent emissions and concentrations in an urban area. This work is documented in ANL/ES-CC-007.

7.4.1 Dispersion Kernel

For a steady mean wind U in the downwind (x) direction, with y and z representing unbounded* crosswind and vertical dimensions, a normal distribution yields the following Green's Function:

$$\frac{\chi(t, t')}{Q(t')} = \frac{\exp\left(-\left\{\frac{[x - U(t - t')]^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right\}\right)}{(2\pi)^{3/2}\sigma_x(t - t')\sigma_y(t - t')\sigma_z(t - t')} \exp[-0.693(t - t')/T_{1/2}], \quad (7.4)$$

where $\chi(t, t')$ is the concentration at time t due to an instantaneous release Q at time t' and position $(0, 0, 0)$ (Pasquill, 1962; Slade, 1966). The origin of the Cartesian system is arbitrary. The dispersion coefficients σ_x , σ_y , and σ_z are assumed to be functions only of the delay time $T = t - t'$ and the atmospheric stability class as defined by Turner (Turner, 1964). $T_{1/2}$ is the half-life of radioactive decay or of any other removal mechanism that can be characterized by an exponential decay.

*Modifications to account for the finite geometry associated with the ground and with inversions aloft are similar to those described for subroutine PLUME in Sec. 7.2.

Assume $Q(t)$ piecewise constant over a fundamental time interval Δ (the computer program is written for $\Delta = 1$ hr); then, for the special case of a steady wind in the x -direction, the concentration $\chi(x, y, z, M)$ at time $t = M\Delta$ can be found by a convolution of the piecewise constant emissions with a series of integrals (the discrete transfer function) evaluated over periods of duration Δ :

$$\begin{aligned}\chi(x, y, z, M) &= \sum_{N=1}^M Q_{M-N+1} \int_{(N-1)\Delta}^{N\Delta} dT \frac{\exp\left\{-\left[\frac{(x-UT)^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right]\right\} \exp(-0.639T/T_{1/2})}{(2\pi)^{3/2}\sigma_x(T)\sigma_y(T)\sigma_z(T)} \\ &= \sum_{N=1}^M Q_{M-N+1} G_N.\end{aligned}\quad (7.5)$$

This is represented schematically in Fig. 7.12 by the buildup of SO_2 due to three ($M = 3$) consecutive 2-hr ($\Delta = 2$) piecewise constant emissions.

Fig. 7.12

Buildup of SO_2 as the Superposition of Consecutive 2-hr Releases. ANL Neg. No. 112-9734.

Equation 7.5, the contribution from an individual source to the concentration at time $M\Delta$, must then be summed over all sources.

The following development is a generalization of Eq. 7.5 to account for variations (piecewise constant) in wind direction, wind speed, and atmospheric stability. The coordinate system used will take z in the vertical direction perpendicular to the plume axis (assumed horizontal), and the x and y directions (also velocity components, u, v) in the horizontal plane, as shown in Fig. 7.13. If θ is the conventional wind direction, then $u = U \sin \theta$ and $v = U \cos \theta$.

7.4.2 Generalized Wind Direction

Let the dose point x, y in the coordinate system of Fig. 7.13 be associated with the angle $\psi = \tan^{-1}(x/y)$. Consider a coordinate system rotated

from the standard system of Fig. 7.13 through an angle θ , so that the dose point (x, y) is now represented by its crosswind and downwind distances $\bar{x}$ and $\bar{y}$ (see Fig. 7.14).

Fig. 7.13. Coordinate System for This Discussion.
ANL Neg. No. 113-1106.

Fig. 7.14. Rotation of the Coordinate System.
ANL Neg. No. 113-1107.

The equations for $\bar{x}$ and $\bar{y}$ (in Fig. 7.14) can be substituted directly into Eq. 7.5, and, since $\sin \psi = x/\sqrt{x^2 + y^2}$, $\cos \theta = v/U$, $\cos \psi = y/\sqrt{x^2 + y^2}$, and $\sin \theta = u/U$, the integrals in Eq. 7.5, expressed in terms of the standard coordinate system of Fig. 7.13, become

$$\int_{(N-1)\Delta}^{N\Delta} dT \frac{\exp \left\{ - \left[\frac{(x - uT)^2 + (y - vT)^2}{2\sigma_h^2} + \frac{z^2}{2\sigma_z^2} \right] \right\}}{(2\pi)^{3/2} \sigma_h^2(T) \sigma_z(T)} \exp(-0.693T/T_{1/2}). \quad (7.6)$$

Note that this simplification is contingent upon the assumption of $\sigma_x = \sigma_y = \sigma_h$, a horizontal dispersion coefficient. There are valid arguments (reviewed in ANL/ES-CC-007) why this assumption is questionable, especially for stable atmospheric conditions. From a computational standpoint, the puff appears circular if $\sigma_x = \sigma_y$, and, consequently, since its x-y shape is independent of wind direction, the generalization of the kernel to accommodate variations in wind direction is greatly simplified.

7.4.3 Variable Wind Speed and Direction

Consider at time $M\Delta$ the circular puff ($\sigma_x = \sigma_y = \sigma_h$) corresponding to an emission during the time period $(M - N)\Delta$ to $(M - N + 1)\Delta$. (Note that the index N "looks backwards" in time.) The leading edge of the puff (emitted $T = N\Delta$ hours ago) undergoes x-advection according to

$$(u_{M-N+1} + u_{M-N+2} + \dots + u_M) \Delta, \quad (7.7)$$

and the trailing edge of the puff (emitted 1 hr later at $T = (N - 1)\Delta$) undergoes x-advection according to

$$(u_{M-N+2} + \dots + u_M) \Delta. \quad (7.8)$$

Thus, the integrals over T represented by Eq. 7.6, which describe a continuous constant emission (from leading to trailing edge) during a period Δ , become

$$G_{M,N} = \int_{(N-1)\Delta}^{N\Delta} dT \frac{\exp \left[- \left(\left\{ x - \Delta \sum_{j=M-N+2}^M u_j - u_{M-N+1} [T - \Delta(N-1)] \right\}^2 / 2\sigma_h^2(T) + \left\{ y - \Delta \sum_{j=M-N+2}^M v_j - v_{M-N+1} [T - \Delta(N-1)] \right\}^2 / 2\sigma_h^2(T) + z^2 / 2\sigma_z^2(T) \right) \right]}{(2\pi)^{3/2} \sigma_h^2(T) \sigma_z(T)} \exp(-0.693T/T_{1/2}) \quad (7.9)$$

where variations in wind velocity are represented by the piecewise constant series $[u_j]_1^M$ and $[v_j]_1^M$. The propagation of a circular puff for varying wind speed and direction is easily visualized by the schematic diagram of

Fig. 7.15. Propagation for Three Hours of an Instantaneous Release under Assumption $\sigma_x = \sigma_y$. ANL Neg. No. 113-1108.

Fig. 7.15. In Fig. 7.15, the center of the instantaneous release at time 0 ($t' = 0$ in Eq. 7.4) is advected according to the three consecutive, hourly-average, space-independent velocity vectors.

The simulation of lake breezes and unusual urban circulations requires continuity in the wind field and conservation of the mass of pollutant and thus the introduction of a vertical velocity component. This component, as well as the horizontal quantities u and v , will be highly dependent upon space and time. Equation 7.9 considers only time dependence of the wind, although one can use different sequences $[u_j]_1^M$ and $[v_j]_1^M$, depending upon the location of the dose point. Using the lake breeze, and in particular a dose point near the confluence, as an example, we must allow for two converging streams and a vertical motion that is highly space-dependent. The algorithms presented

in this report are not yet expressed in a sufficiently general manner to handle this space dependence. However, it is relatively straightforward to

approximate a three-dimensional velocity field by the three components $u(x, y, t)$, $v(x, y, t)$, and $w(x, y, t)$ and restate the basic algorithm.

7.4.4 Dispersion Coefficients for Program ONEPUFF

The basic integral (Eq. 7.5) is of the form

$$\chi \propto \int_A^B \frac{\exp \left\{ - \left[\frac{(x - UT)^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} + 0.693T/T_{1/2} \right] \right\}}{\sigma_x \sigma_y \sigma_z} dT, \quad (7.10)$$

where σ_x , σ_y , and σ_z are functions of travel time t . Program ONEPUFF and the original version of the integrated-puff model (ANL/ES-CC-005) used the set of dispersion coefficients (designated in this report by σ_{TSL}) of time-dependent dispersion curves derived by Turner (1967) for use in his St. Louis model. These are shown in Figs. 7.16 and 7.17.

Fig. 7.16. Transverse Dispersion Parameter (Turner, 1967). ANL Neg. No. 113-2876.

Fig. 7.17. Vertical Dispersion Parameter (Turner, 1967). ANL Neg. No. 113-2869.

7.4.5 The Effective Lid Height (H_L)

The existence (or assumption) of physical limits to vertical dispersion requires special treatment when plume or integrated-puff formulas are

the basic transport models, since the fundamental equations are written for an infinite medium. A reasonable approach for steady-state solutions (Turner, 1967) uses the point-source plume equation over the travel distance X_c defined by $\sigma_z(X_c) = 0.74H_m$; for travel distance greater than $2X_c$, uniform vertical mixing is assumed; for intermediate distances, a linear interpolation is used. Since, mathematically, the solution for uniform mixing is equivalent to the superposition of an infinite number of multiple reflections (four pairs usually suffice), this method has been employed. It has an advantage over the first method in that the proximity of the actual plume (centerline + $2\sigma_z$) to the lid is considered rather than σ_z alone, an advantage that is particularly important when time-dependent variations of lid height are considered.

To calculate the concentration at time M due to an emission between hours $(M - N)$ and $(M - N + 1)$, a single lid height H_L must be selected which is most representative of the N hours since the emission began. The following rules are used to determine the value of $\bar{H}_L$:

- 1) If $N = 1$, then $\bar{H}_L = H_M$; i.e., for releases at most 1 hr old, the model uses the mixing-layer height that occurred during the period of the emission. (All meteorological data and emission data are stored as constant values for each hour.)
- 2) If the puff has existed for more than 1 hr, i.e., $N > 1$, beneath a mixing layer that is steadily rising, such as often occurs after sunrise, then the final (maximum) mixing height is used. This assumption for a steadily rising lid is based on the consideration that, if the proximity of the lid to a given plume results in a notable limitation of the vertical dispersion, then a rising lid implies a steadily increasing dilution volume, and, thus the lid height during the most recent hour is most representative.
- 3) The problem of approximating plume behavior during a period of steadily falling lid height is more complicated. When the lid is higher than (effective stack height + $2\sigma_z$), the interaction between plume and lid is insignificant. As the steadily falling lid moves downward through the plume, it is assumed that the pollutant now above the lid is not reflected by the lid. (Clearly, the lid does not act in the manner of a piston compressing the plume into a smaller volume.) Thus, the situation of a steadily falling lid during the lifetime of a puff is approximated by setting $\bar{H}_L$ equal to the first value of the lid height which is less than (effective stack height + $2\sigma_z$). This phenomenon is important in regions such as Los Angeles where the diurnal rising and falling of the lid with reasonably brisk winds aloft will remove a significant amount of otherwise trapped pollutant.
- 4) The effect of a lid height that risers and falls during the lifetime of a puff has not been studied sufficiently, and based on the arguments for the previous two cases, $\bar{H}_L$ is set at the maximum value that occurs during the lifetime of the puff.

5) If at the time of the emission, the effective stack height is greater than the mixing layer height and if the lid does not rise above the plume centerline, the stability class used to calculate plume dispersion is set equal to 5 (stable), and no lid effects are considered. This assumption is more satisfactory than a complete neglect of emissions above the lid, but certainly does not attempt to approximate the details of diffusion from the stable layer downward into the more unstable layer beneath the lid.

6) The fumigation phenomenon, which depicts a plume emitted into stable air above a rising lid and then subjected to strong vertical diffusion as the mixing layer rises above the plume centerline, is modeled by setting the effective lid height, $\overline{H}_L$, equal to the maximum mixing-layer height during the plume lifetime and then adjusting the hourly stability index J_{stab} so that $J_{stab} = 5$ (stable) when $H_L < \text{effective stack height}$ and $J_{stab} = 4$ or 3 (depending on insolation) when $H_L \geq \text{effective stack height}$.

7.4.6 Effective Stack Height (H)

The effective stack height H is the height above ground that best defines the centerline of the plume. The plume is assumed to originate as a point source at an altitude H feet above ground at the location of the stack. If aerodynamic downwash causes the plume to break up and mix rapidly downward in the vicinity of the stack, H may be set equal to the actual physical height H_s . Observations of a local utility indicate this phenomenon occurs frequently for wind speeds greater than 15 mph. Otherwise a plume rise ΔH is added to the physical stack height H_s , so that

$$H = H_s + \Delta H, \quad (7.11)$$

where ΔH is estimated as described below.

Smoke-rise calculations in this model are based on a formula derived from observations at TVA stations and other power plants (Carson and Moses, 1967). (The momentum term in their original formulation is omitted in the following equation since its contribution is generally negligible compared to thermal buoyancy.)

$$\Delta H \text{ (feet)} = KQ_s^{1/2}/U, \quad (7.12)$$

where

ΔH = plume rise (feet),

Q_s = heat-emission rate from stack (Btu/hr),

U = wind speed (mph) at the height of the stack,

and

$K = 0.870$ (unstable: Class 3), 0.354 (neutral: Class 4),
 0.222 (stable: Class 5).

Three restrictions are placed on the use of Eq. 7.12:

1) Low Wind Speeds (U)

If U is estimated to be less than 4 mph, the value 4 mph is used in Eq. 7.12.

2) Stability Class and the Coefficient K

If the physical stack height (H_s) is equal to or greater than 200 ft, $K = 0.354$ (neutral) is used, even though the stability index indicates unstable conditions.

3) Mixing-layer Height (H_m)

a) If the physical stack height H_s is greater than H_m , an infinite value for H_m is assumed with plume rise and dispersion according to stable atmospheric conditions.

b) A minimum plume rise $\Delta H_{\min}$ is calculated based on the coefficients for stably stratified air. If this minimum effective stack height, $H = H_s + \Delta H_{\min}$, is greater than the lid height H_m , this value of H is used and the plume analyzed as described in restriction 3a.

c) If $H_s + \Delta H_{\min} < H_m$ and if the plume rise ΔH based on the actual stability class yields an effective stack height greater than H_m , i.e., if $H_s + \Delta H_{\min} < H_m$ and $H_s + \Delta H \geq H_m$, the effective stack height is restricted to the lid height H_m .

Restriction 1 limits the minimum wind speed to be used in Eq. 7.12. This reflects the fact that the equation is an empirical one in which the parameters n and m in an equation of the form $\Delta H = KQ_s^n U^m$ were found by multiple linear regression. A comparison of Eq. 7.12 with TVA data (Carpenter *et al.*, 1967) indicates good agreement down to wind speeds of about 6 mph. Below this, the $1/u$ factor in the equation causes an over-estimation of the plume rise. An arbitrary restriction on a minimum value of U in Eq. 7.12 has therefore been made.

Restriction 2 occurs because for plume-rise calculations the vertical variation of temperature at heights greater than 200 ft is best characterized by a neutral lapse rate, even though unstable conditions may exist in the first few hundred feet above ground.

Restriction 3 is a variation on the standard assumption of an impenetrable lid. Rather than obey a law of perfect reflection, effluent emitted beneath an inversion is assumed to penetrate the stable layer at least as far as would be anticipated if the effluent were emitted in stably stratified air.

This characterization is particularly important in estimating ground-level concentrations due to power plants. For example, a 300-MWe plant (single stack) will have a plume rise of approximately 400 ft in stable air and 600 ft under neutral conditions (note restriction 2) when the wind speed at the physical stack height, H_s , is 10 mph.

For a representative physical stack height of 400 ft, restriction 3 implies the following:

a) If $H_m = 3000$ ft, the effective stack height is 1000 ft and the peak ground level concentration of 0.1 ppm occurs approximately 7 miles downwind.

b) If $H_m = 900$ ft, the effective stack height is limited to 900 ft and the 0.2-ppm isopleth can be approximated by a narrow footprint with an area of 4 square miles with a peak concentration of 0.3 ppm occurring 6 miles downwind.

c) If $H_m = 500$ ft, the effective stack height is assumed to be 800 ft and the maximum ground-level concentration, 0.05 ppm 10 miles from the source, is calculated assuming dispersion in stable air with an infinite lid height. This estimate would presently be used for this particular stack for all lids < 900 ft and certainly is suspect for H_m between 800 and 899 ft. A transition in stability class from stable to neutral (or unstable) when $H - \sigma_z = H_m$ might be more realistic. If the ground-level concentration for $H_m = 500$ ft were calculated based on the assumption of an impenetrable lid at 500 ft, the concentration 2 miles downwind would be greater than 1 ppm and the 0.5-ppm ground-level isopleth would extend 8 miles downwind. Short-term peaks of this magnitude are not observed at the Chicago TAM stations, whereas peaks in the range of 0.1-0.3 ppm are often found when major point sources are upwind.

7.4.7 Puff Significance--Comparison with a Plume Model ("Test Plume")

To identify sources that have negligible contributions to the pollutant level at a given receptor for a given hour, a test is made using a simple dispersion calculation. This "test plume" is of interest here because it enables the computer program to skip many unnecessary integrations and thus leads to considerable savings in run time. Furthermore, the "test-plume" algorithm may be useful as a pseudotransient model to replace the less efficient integrated-puff formulation. This latter aspect is being investigated at Argonne National Laboratory.

The test-plume routine, a version of the continuous Gaussian-plume formulation, is used to test whether a given 1-hr release between hours $M - N$ and $M - N + 1$ is significant at time M for a given receptor. The routine as presently employed is best described by the following example.

Fig. 7.18 describes the history of the leading puff of a 1-hr release beginning at time $M - 3$. The trailing puff or end of the hour-long release describes the path in Fig. 7.19. Figure 7.20 shows the superposition of these two trajectories and the locus (dotted line) of the entire hour-long release. The actual concentration field is represented by horizontal and vertical diffusion about the line segment TL. Figure 7.20 also shows three representative dose points (R1, R2, and R3) for which the concentration is to be estimated via the standard Gaussian-plume formula

$$\chi_{\text{Test}} = \frac{Q}{2\pi U \sigma_y \sigma_z} \left\{ \exp \left[\frac{-Y^2}{2\sigma_y^2} \right] \right\} \left\{ \exp \left[\frac{-Z^2}{2\sigma_z^2} \right] + \exp \left[\frac{-Z_2^2}{2\sigma_z^2} \right] + \exp \left[\frac{-Z_3^2}{2\sigma_z^2} \right] \right\} \quad (7.13)$$

and

$$\sigma_y = \sigma_y(T + T_y), \quad \sigma_z = \sigma_z(T + T_z),$$

where

Y = minimum distance from the receptor point to the centerline segment TL; in Fig. 7.20, $Y = R1 - T$, $R2 - I$, and $R3 - L$ for the three receptor points, R1, R2, and R3;

Fig. 7.18

Trajectory of Leading Puff of 1-hr Release. ANL Neg. No. 113-1166.

Fig. 7.19

Trajectory of Trailing Puff of 1-hr Release. ANL Neg. No. 113-1167.

Fig. 7.20

Locus (· · ·) of Puff Centers at Time M due to Release between Hours $M - 3$ and $M - 2$. ANL Neg. No. 113-1168.

T = time of flight to the point on the centerline segment used to determine the distance Y ; T is used to calculate the dispersion coefficients σ_y and σ_z ; for sources with initial dimensions, e.g., area sources, represented by σ_{y_0} and σ_{z_0} , the quantities T_y and T_z satisfy $\sigma_{y_0} = \sigma_y(T_y)$, $\sigma_{z_0} = \sigma_z(T_z)$;

U = mean wind speed during time T ;

Z_1 = vertical distance from plume centerline to receptor;

Z_2 = vertical distance from the first below-ground image to the receptor;

Z_3 = vertical distance from the first above-lid image to the receptor;

and

Q = source-emission rate during hour $M - N$ to $M - N + 1$.

A receptor R upwind of the source S may be influenced by upwind diffusion during the first hour of the release, i.e., when $N = 1$. In this case, according to the notation of Fig. 7.20, $Y = R - T = R - S$, $T = 0$, and Eq. 7.13 may be invalid, since $\exp[-Y^2/2\sigma(0)] = 0$ if $T_y = 0$. In this situation, we check whether the advection rate U is sufficiently greater than the horizontal diffusion rate $\sigma_y(T)$ by evaluating the concentration χ_{test} at R based on the distance $Y = R - T = U$ and dispersion coefficient $\sigma_y(1 \text{ hr})$.

The concentration at a given receptor due to each 1-hr release from each source is thus approximated by a modified version of the standard plume equation. If $\chi_{\text{test}} < \text{EPS}$, the release is considered to have a negligible effect. The tolerance EPS is most conveniently set at from 1 to 10% of the lowest detectable pollutant concentration. The accuracy of validation runs for TAM-1 through TAM-5 in January 1967 was not affected by raising the tolerance from 0.0001 to 0.001 ppm SO_2 .

7.4.8 Present Applications of ONEPUFF

Program ONEPUFF, with some modifications, eventually became the transport subroutine in the integrated-puff urban atmospheric dispersion model. (See ANL/ES-CC-007 and Sec. 7.6 of this report.) In its present form, the program is designed to calculate pollutant concentrations from a single source for each hour of a 24-hr period at up to 1000 points. Twenty-four 1-hr average values of plant thermal output, plant pollutant output, wind speed, wind direction, lid height, and atmospheric stability are input to the code. Receptors can be designated individually or on a uniform rectangular grid in the horizontal x - y plane or vertical x - z plane, where x is the downwind distance and y the crosswind distance.

7.4.9 Future Applications of ONEPUFF

Program ONEPUFF offers an excellent means of evaluating concentrations from existing or proposed major point sources. Time-dependent transients or climatological distributions of effluent can be estimated with minor modifications of the program. Analyses of this sort are also of critical importance in the siting of major airports. In this regard, the program should be modified to account for the fallout of particulate matter emitted by aircraft during takeoff and landing. A validated study of such a problem deserves a high priority in federal air pollution planning.

7.5 DAVKERN (A Version of ONEPUFF for the Design of Optimal Control Strategies)

7.5.1 Theory

In support of an operations-research study of optimal strategies for pollution abatement, a computer code DAVKERN was written which couples major point sources with selected receptors. Assuming that each source is controlled in piecewise constant, 2-hr steps, the concentration of SO_2 at each receptor at time T can be evaluated as a convolution sum of the products of the piecewise constant, 2-hr emissions during the intervals $(T - \tau - 2, T - \tau)$, $\tau \geq 0$, and a discrete transfer function associated with the delay time τ .

The transfer function is based on a diffusion kernel derived from that used in program ONEPUFF. The function has been evaluated for several wind speeds (0, 1, 2, 3, 4 mph) and wind directions (225, 270, 315°).

7.5.2 Diffusion Kernel

With the assumptions that a lid of height H exists over the city and that the concentration of SO_2 is uniform from ground $z = 0$ to height $z = H$, Eq. 7.4 becomes*

$$\chi(t, t') = \frac{Q(t')}{2\pi H \sigma_x \sigma_y} \exp \left\{ -\frac{[x - u(t - t')]^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} \right\}, \quad (7.14)$$

where the revised normalization follows from

$$\int_{-\infty}^{\infty} dx e^{-a^2 x^2} = \sqrt{\pi/a}. \quad (7.15)$$

*Decay of SO_2 has been neglected here.

The assumption of complete mixing up to a height H is reasonable for pollution episodes and, perhaps more important, simplifies the computer analysis and greatly reduces the amount of tabulated data.

7.5.3 Dispersion Parameters

Dispersion coefficients or variances are generally derived from experimental data--smoke or luminous tracer releases over rather uniform terrain, quite unlike urban regions. The data are then fit to a standard plume equation such as

$$\chi = \frac{Q \exp\{-\frac{1}{2}(y^2/\sigma_y^2 + H^2/\sigma_z^2)\}}{\pi u \sigma_y \sigma_z} \quad (7.16)$$

to determine σ_y and σ_z . Note that this equation has no x diffusion and consequently cannot be applied to the zero-wind ($u = 0$) case. Although in practice the $u = 0$ case will not persist throughout a pollution episode (nor would any single wind velocity), this case represents a realistic bound on the buildup of SO_2 during stagnation regimes. Turner (1964) with some subjective modifications presents a set of σ_y curves

$$\sigma_{y,i}(t) = a_{y,i} t^{b_{y,i}}, \quad i = 1, 5, \quad (7.17)$$

where i corresponds to one of five classes of atmospheric stability.

Since by symmetry $\sigma_x = \sigma_y$ when $u = 0$, it was assumed for the limited purposes of this study that $\sigma_{x,i}(t) = \sigma_{y,i}(t)$ for all u and that the parameters $a_{y,i}$ and $b_{y,i}$ will be those of Turner (1964).

Thus,

$$\sigma_{x,i}(t) = \sigma_{y,i}(t) = \sigma_i(t) = a_i t^{b_i} \quad (7.18)$$

where for mks units,

$a = 2$ and $b = 0.85$ where $i = 1$ (extremely unstable)

and

$a = 0.4$ and $b = 0.9$ where $i = 5$ (extremely stable).

In units of miles and hours,

$a = 1.3$, $b = 0.85$ for $i = 1$

and

$a = 0.4$, $b = 0.9$ for $i = 5$.

7.5.4 Derivation of the Discrete Transfer Function

Substituting Eq. 7.18 into the puff kernel, Eq. 7.14, one has

$$\chi(t, t') = \frac{Q(t')}{2\pi H a_i^2 (t - t')^{2b_i}} \exp \left\{ -\frac{[x - u(t - t')]^2 + y^2}{2a_i^2 (t - t')^{2b_i}} \right\} \quad (7.19)$$

If emissions Q are in piecewise constant, 2-hr steps, then the concentration (normalized) at time t , $t \geq 2$, due to a steady emission during the time interval $(0, 2)$ is

$$G(x, y, u, t) = \frac{\chi(t)H}{Q} = \frac{1}{2\pi a_i^2} \int_0^2 dt' (t - t')^{-2b_i} \exp \left\{ -\frac{[x - u(t - t')]^2 + y^2}{2a_i^2 (t - t')^{2b_i}} \right\}, \quad (7.20)$$

and with the substitution $T = t - t'$,

$$G(x, y, u, T) = \frac{\chi(t)H}{Q} = \frac{1}{2\pi a_i^2} \int_{T-2}^T dT T^{-2b_i} \exp \left[-\frac{(x - uT)^2 + y^2}{2a_i^2 T^{2b_i}} \right], \quad T \geq 2, \quad (7.21)$$

where $G(x, y, u, T)$ is the discrete transfer function describing a 2-hr emission beginning T hours ago. Substituting $L = T/2$, one can then introduce the index L into the transfer function as $G_L(x, y, u)$, $L \geq 1$. Let Q_n be the emission during the 2-hr interval ending at time $= 2n$. The convolution sum that yields the SO_2 concentration for any given piecewise constant past history is therefore

$$\chi(t = 2N) = \chi_N = H \sum_{j=1}^6 \sum_{n=1}^N Q_{n,j} G_{N-n+1,j}, \quad (7.22)$$

where the summation over j includes all six power plants. This is analogous to Eq. 7.5. N will be less than 50, since the maximum duration of hypothesized pollution episodes will be 4 days. Furthermore, one can assume $G_L = 0$ for $L > 20$.

Schematically, this sum for $t = 12$ hr ($N = 6$) from the start of the problem is

$$\chi(t = 12) = \chi_6 = \{Q_1 G_6 + Q_2 G_5 + \dots + Q_6 G_1\} H. \quad (7.23)$$

(See Fig. 7.21.)

Fig. 7.21

Graphical Representation of the Application of the Discrete Transfer Function. ANL Neg. No. 112-9731.

7.5.5 Computer Results

7.5.5.1 Printed and Punched Output. The discrete transfer function G_L , which is required in Eq. 7.22, has been evaluated for $L = 1$ through 20 corresponding to emissions during the preceding 40 hr. Beyond this, G_L can be assumed to be zero; that is, the contribution to the present SO_2 concentration of emissions more than 40 hr ago will be neglected in this study. Equation 7.18 has been evaluated, printed, and punched on IBM cards for six Commonwealth Edison sources, three wind directions ($225, 270, 315^\circ$), five wind speeds (0, 1, 2, 3, 4 mph), two TAM stations (Hyde Park and Lindblom), and two stability classes (1 = extremely unstable, and 5 = extremely stable).

Users of this information are provided with a complete listing of the associated arrays as well as punched cards. Each card has the source identified, the wind direction, the wind speed, the TAM station and stability class, and sequential numbering from 1 to 360 in columns 77-80. The associated G_L arrays, $L = 1, \dots, 20$, appear sequentially.

In addition to the printout of the G_L arrays, these values have been appropriately summed to indicate the buildup of SO_2 following startup at time $t = 0$. This is printed at 2-hr intervals and should aid in evaluating the relative contributions of the six different sources under various conditions of wind direction, wind velocity, and stability regimes.

This function is defined by

$$C_N = \sum_{L=1}^N G_L \quad (7.24)$$

with $C_0 = 0$.

7.5.5.2 Comments on Numerical Results. The integration subroutine was verified to four place accuracy by evaluation of

$$\int_0^{\pi} \sin x \, dx.$$

The program DAVKERN was compared to the standard plume modified by the assumption of constant mixing up to height $z = H$:

$$\left. \frac{\chi(H)}{Q} \right|_{\text{Std. Plume}} = \frac{1}{(2\pi)^{1/2} \bar{u} \sigma_y(t)} \exp \left[-\frac{y^2}{2\sigma_y(t)^2} \right], \quad (7.25)$$

which can be evaluated directly for given u , y , and $t = x/u$. This is compared to steady-state concentrations

$$C_{20} = \sum_{L=1}^{20} G_L$$

calculated by the code.

Table 7.6 shows the satisfactory agreement between the plume equation and the steady-state concentrations predicted by the code. This is discussed further in ANL/ES-CC-005, Sec. 4.4. That DAVKERN generally

TABLE 7.6. Program DAVKERN vs. Standard Plume Equation

Plant No.	WD/WS	TAM/Stab.	x	y	σ	$\left. \frac{\chi(H)}{Q} \right _{\text{Plume}}$	$\left. \frac{\chi(H)}{Q} \right _{\text{Code}}$
1							
Northwest	315/1	HP/5	11.75	4.0	3.6	0.060	0.059
Northwest	315/1	HP/1	11.75	4.0	10.5	0.035	0.028
2							
Fisk	315/1	HP/5	6.0	1.125	2.0	0.171	0.167
Fisk	315/1	HP/1	6.0	1.125	5.9	0.066	0.054
4							
Ridgeland	315/1	HP/5	8.88	5.38	2.8	0.022	0.030
Ridgeland	315/1	HP/1	8.88	5.38	7.3	0.041	0.028
5							
Calumet	315/1	HP/5	-4.75	2.0	-	0	2×10^{-5}
1							
Northwest	315/4	HP/5	11.75	4.0	1.05	3×10^{-4}	1×10^{-4}
Northwest	315/4	HP/1	11.75	4.0	3.22	0.057	0.014
1							
Northwest	270/1	HP/5	5.5	11.12	1.8	0	7.6×10^{-4}
2							
Fisk	270/1	HP/5	3.25	5.12	1.12	4×10^{-5}	0.005
3							
Crawford	270/1	HP/5	6.75	3.5	0.220	0.051	0.058
4							
Ridgeland	270/1	HP/5	10	2.5	3.20	0.092	0.090
5							
Calumet	270/1	HP/5	-2.0	4.75	-	0	9×10^{-5}
1							
Northwest	270/4	HP/5	5.5	11.12	0.54	~0	~0
Northwest	270/4	HP/1	5.5	11.12	1.72	~0	~0

predicts lower values than the standard plume equation is due primarily to the consideration of x dispersion and thus greater dilution. Discrepancies, where they occur, are often for relatively insignificant sources and can be explained by the extra dispersion dimension. This observation does not suggest that either model is the correct one, and it certainly does not imply that one could use the simple plume equation in the abatement study, since this equation does not describe SO_2 transients and is not appropriate for the $u = 0$ case.

7.6 The Multiple-source, Integrated-puff, Dispersion Model

The multiple-source urban atmospheric dispersion model summarized in this section is essentially a scheme for repetitively applying the integrated-puff transport algorithms (see Sec. 7.4) to each areal and point source in the region. Report ANL/ES-CC-007 gives a detailed description of the complete model and its validation. To estimate the spatial and temporal variations in pollution levels, the model must be supplied with a time series of emission inventory and meteorological data as well as measured pollutant concentrations for comparison with predictions. These data management requirements have been met by the development of a master Air Pollution Information and Computation System (APICS; Chamot *et al.*, 1970; and Sec. 3 of this report) designed to automate the entire process of data storage, retrieval, manipulation, analysis, and display associated with the dispersion-model studies.

A major task element of the Chicago Air Pollution Systems Analysis Program was the development of an inventory of hourly average emissions for the power plants and industrial, residential, commercial, and institutional SO_2 sources which are the primary contributors to Chicago's SO_2 air pollution problem. Thus, in contrast with Program ONEPUFF, the integrated-puff dispersion model requires an array of thermal and pollutant emissions from each point and area source for each hour. The details of the acquisition of data by Argonne and the Chicago Department of Environmental Control and subsequent estimation of hourly emissions have been discussed in detail (Roberts *et al.*, 1969, and Sec. 2 of this report).

Many of the algorithms employed in the integrated puff model have been described elsewhere in this report--in particular Sec. 2 (emission inventory) and Sec. 7.4 (program ONEPUFF)--so that only unique features of the integrated puff model are covered here.

7.6.1 Basic Transport Kernel

The integrated-puff dispersion model uses the same transport sub-model as does program ONEPUFF, described in Sec. 7.4 of this report.

7.6.2 Dispersion Coefficients

The basic integral is of the form

$$\chi \propto \int_A^B \frac{\exp \left\{ - \left[\frac{(x - UT)^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} + \frac{0.693T}{T_{1/2}} \right] \right\}}{\sigma_x \sigma_y \sigma_z} dT, \quad (7.26)$$

where σ_x , σ_y , and σ_z are functions of travel time T . Both the original version of the integrated-puff model (Roberts *et al.*, 1969) and program ONEPUFF used the set (designated in this section by σ_{TSL}) of time-dependent dispersion curves used by Turner (1968) in his St. Louis model. These are shown in Figs. 7.16 and 7.17.

In the limit $U \rightarrow 0$, Eq. 7.26 with $\sigma(T) = \sigma_{TSL}(T)$ leads to a $1/x^2$ distribution for a ground level ($z = 0$) source. In a plume model with $\sigma_{TSL}(T)$, the plume concentrations away from the source ($\chi \propto 1/U\sigma_y\sigma_z$) tend to 0 as $U \rightarrow 0$, since T , the time of flight to the dose point, goes to infinity, as do $\sigma_y(T)$ and $\sigma_z(T)$.

At high wind speeds (>10 mph), both plume and integrated-puff models which employ $\sigma(T)$ describe the effluent from a point source as a very narrow, highly concentrated beam. In the simulation of ground-level concentrations due to large power plants, the severe directional dependence associated with the above situation causes fluctuations of up to 1 ppm for changes in the mean hourly wind direction of less than 3° . Short-term, direction-sensitive peaks of this magnitude are not observed in the Chicago data (2 years of hourly SO_2 readings at eight monitoring stations). A first attempt to remedy this anomaly, which seriously affects estimates of peak hourly but not daily average dose rates, is to introduce an alternate set of dispersion coefficients.

In most Gaussian plume models of atmospheric diffusion (for example, Pasquill, 1962, and 1969), dispersion coefficients are usually expressed in terms of the downwind distance, x , rather than the time of flight, T . Thus, the rate of spread is not expressed as an explicit function of wind speed. Typically, first approximations to σ_y and σ_z are obtained by fitting power laws

$$\sigma_y = A_y \chi^{B_y}, \quad \sigma_z = A_z \chi^{B_z} \quad (7.27)$$

to field data. Figures 7.2 and 7.3 show the horizontal and vertical dispersion coefficients suggested by Turner (1967) in the Workbook of Atmospheric Estimates. These must be modified for hour-long rather than 10-min averages. (In this discussion, this modified set will be designated σ_{TWB} .)

The apparently unrealistic directional sensitivity at high wind speeds of the model with $\sigma_{TSL}(T)$ was partially corrected by the following assumption:

$$\sigma(i, t) = \max \{ \sigma_{TSL}(t), \sigma_{TWB}(Ut) \}, \quad (7.28)$$

where the downwind distance, x , of the puff center is expressed by $x = Ut$. For horizontal dispersion, the result is a transition from $\sigma_{TSL}(t)$ to $\sigma_{TWB}(x - Ut)$ for wind speeds greater than 7 mph. For vertical dispersion, the critical wind speed is usually greater than 20 mph. The exact value of the wind speed for which σ_{TSL} equals σ_{TWB} in Eq. 7.24 depends upon the time t , the atmospheric stability class, and whether the vertical or horizontal dispersion coefficient is being evaluated. For example, with a wind speed of 20 mph and a receptor 10 miles downwind of a power plant, $\sigma_{y,TSL}(0.5 \text{ hr}) = 0.33 \text{ mile}$ ($\pm 1 - \sigma$ cone of 4°) and $\sigma_{y,TWB}(10 \text{ mi}) = 0.75 \text{ mile}$ ($\pm 1 - \sigma$ cone of 9°). The use of Eq. 7.28 is thus responsible for about a 60% reduction in the plume peak and a corresponding increase in width. Nevertheless, even with the assumption of Eq. 7.28, both plume and puff models will, in general, reflect this directional sensitivity for major point sources. Looking at the problem from another angle, one can conclude that, since the trajectory of the centerline of a plume can rarely be specified to better than $\pm 10^\circ$, the short term estimated and observed concentrations can easily differ by a factor of 2, regardless of the model used. Thus, whether one is estimating pollutant contributions and verifying by comparison with observations, or one is using a regression approach to correlate observed data with point-source emissions, the uncertainty caused by an inability to specify plume trajectories implies a fundamental uncertainty in the ability to verify the model. These observations are in contrast to Hilst (1969) who, considering a statewide model of relatively homogeneous area sources, concluded that his results were insensitive to σ_y .

7.6.3 Finite-source Geometry

The realistic modeling of residential, commercial, and industrial zones characterized by multiple sources too numerous to represent by individual plumes is critical to the success of a source-oriented atmospheric dispersion model. A similar need for synthesizing emissions from these area sources arises in the design of regional implementation plans based on land use, a method whereby one seeks to assign emission-density limits (lb/hr-mi^2) to land in each of several zoning classes (Roberts and Croke, 1970). Often major point sources can be modeled more realistically by assigning initial dimensions to the plume in order to approximate, for example, multiple stacks or aerodynamic downwash.

The integrated-puff model is ideally suited to the task of synthesizing these source configurations. In contrast to the plume equation, limited to

crosswind and vertical coordinates and thereby representing a two-dimensional front, the puff incorporates the downwind coordinate and thus represents a three-dimensional cloud of pollutant.

Be it an area source or a point source with initial dimensions, the source of finite initial volume is approximated by a pseudo upwind point source. This is similar to algorithms employed in plume models, but as mentioned above, the more sophisticated puff kernel results in a volumetric source rather than a two-dimensional wave front. Therefore, in addition to a more realistic description of downwind dispersion, the puff model can directly evaluate the effect of the area source upon the area itself.

The volumetric source is synthesized by specifying three initial dispersion coefficients: σ_{x0} , σ_{y0} , and σ_{z0} . These are then associated with times t_x , t_y , and t_z , which are the solution to

$$\sigma_{x0} = \sigma_x(i, t_x), \quad \sigma_{y0} = \sigma_y(i, t_y), \quad \sigma_{z0} = \sigma_z(i, t_z),$$

where $\sigma(i, t)$ is the family of functions describing the dispersion coefficients at time t for stability Class i . A virtual source is thus defined at upwind distances $\delta_x = ut_x$, $\delta_y = vt_y$, from the center of the volumetric source. Since the model is presently constrained by the assumption of circular

($\delta_x = \delta_y$) puffs, it follows that $t_x = t_y$ (see Fig. 7.22). The transport equation (Eq. 7.4) is then modified with $x - \delta_x$ replacing x , $y - \delta_y$ replacing y , and $T + t_x$, $T + t_y$, and $T + t_z$ replacing T in the appropriate locations.

Fig. 7.22. Synthesis of an Area Source of Buildings of Height Z . ANL Neg. No. 113-1111.

For a square area source of side length n , the initial value of the horizontal dispersion coefficients σ_{y0} and σ_{x0} ($\sigma_{y0} = \sigma_{x0}$) is defined by

$$\sigma_{y0} = n/2.4. \quad (7.29)$$

Figure 7.23 depicts a row of square area sources of uniform strength. Pollutant concentrations along the line A-A are determined by summation of concentrations due to each individual area source. The concentration profile

for each square is governed by σ_{y0} . Uniformity of emissions above A-A implies that, when the concentration fields for all squares are superimposed, the dose at point a in Fig. 7.23 should equal that at point b. Equation 7.29 ensures that this will occur for two adjacent squares and is within 10% of uniformity for five adjacent squares.

Fig. 7.23. Choice of $\sigma_{y0} = n/2.4$ to Ensure That Concentrations Will Be Uniform along the Line A-A. ANL Neg. No. 113-2867 Rev. 1.

The choices of σ_{z0} and the effective source height z (see Fig. 7.22) for area sources depend upon the representative building height for each square mile and the mode of initial transport; i.e., emissions are characterized either by plume rise or by downwash. The quantity σ_{z0} also approximates the actual variation in stack heights within a given class, as well as the vertical spread due to transport within the area source.

Table 7.7 shows values of building height, critical wind speeds, plume rise, and σ_{z0} for the three classifications of area sources in Chicago. For example, if the wind speed is 10 mph, low-rise residential buildings are represented by a source at $z = 50$ ft with $\sigma_{z0} = 50$ ft, and industrial-area sources by $z = 300$ ft and $\sigma_{z0} = 150$ ft.

TABLE 7.7. Parameters Used to Describe Area Sources in Chicago

Source Class	Physical Stack Height, ft	Critical Wind Speed, WS_c , mph	$WS \leq WS_c$		$WS > WS_c$	
			Plume Rise, ft	σ_{z0} , ft	Plume Rise, ft	σ_{z0} , ft
Low-rise Residential/Commercial	50	6	50	50	0	50
High-rise Residential/Commercial	200	6	100	200	0	200
Industrial	150	15	150	150	0	150

Major point sources are also characterized by initial dimensions σ_{x0} ($= \sigma_{y0}$) and σ_{z0} , which, for properly designed stacks, depend upon whether a critical wind speed (here, 15 mph at 75 ft) is exceeded. Downwash conditions are assumed to always occur for sources with poor aerodynamic characteristics such as vents or stubby stacks. Under normal plume-rise conditions, the parameters σ_{x0} , σ_{y0} , and σ_{z0} are each set at 100 ft to describe the initial source volume. Under downwash conditions, σ_{x0} and σ_{y0} are set at 750 ft and σ_{z0} at 150 ft. As with area sources, these choices are somewhat intuitive and, since the downwash effect is a primarily local one, really should be tailored to each source or source type. For example, one may

assume that large commercial and residential establishments are dominated by buildings with improperly designed stacks and that a good assumption for initial source dimensions to simulate downwash would then be the size of a representative building (Shieh, 1969). In Chicago, major point sources in this category are typified by Union Station, approximately one city block wide and 100-150 ft high. This observation influenced our selection of initial source dimensions under downwash conditions. All sources homogenized and treated as area sources are effectively given a $\sigma_{x0} = \sigma_{y0} = 0.4$ mile.

7.6.4 Area-source Grid

All points in a region are represented by a right-hand Cartesian coordinate system with +X to the west and +Y to the south (see Fig. 7.24). Data recorded in any other system can easily be read into the program and converted by one or more additional statements. The region is overlaid by a uniform grid on which square area sources are defined. This area-source grid is specified by five parameters: its origin in the Cartesian coordinate system (XSORIG, YSORIG); the number of grid squares in the X and Y directions (NSXMAX, NSYMAX); and the length of the side (miles) of each source grid square (DGRID). The origin of the area-source grid system is the North-east corner (see Fig. 7.24). Each grid square is assigned a pollutant emission rate (QTOT, LB/YEAR) for each of the three source types: low-rise space heaters, high-rise space heaters, and industry. Corresponding to these are three representative stack heights assumed to apply to the entire region (e.g., Table 7.7).

Fig. 7.24. Superposition of Area-source and Receptor Grids for a Region: (XSORIG, YSORIG) = (-4, -10), (NSXMAX, NSYMAX) = (10, 12), DGRID = 2; (XRORIG, YRORIG) = (2, -6), (NWEST, NSTH) = (2, 3), DRGRID = 6. ANL Neg. No. 113-1162.

7.6.5 The Receptor Grid

An array of points at which concentrations are to be estimated must lie within and must coincide with vertices of the area-source grid.* For example, the area-source grid might be 10 squares by 12 squares, 2 miles on a side; receptors could then be defined by a 2 x 3 array of squares 6 miles on a side with its origin coinciding with the corner of an area-source square. Figure 7.24 presents this example. The receptor grid is defined by five parameters: an origin in the Cartesian system (XRORIG, YRORIG); the grid spacing (DRGRID, which must be a multiple of DGRID); and the number of squares in the X and Y directions (NWEST, NSTH). The total number of receptor points is thus $(NWEST+1) \times (NSTH+1)$.

7.6.6 Calculation of Concentrations due to Area Sources

The representation of an area source by a virtual upwind point source has been discussed. Table 7.7 lists representative stack heights and initial plume dimensions for Chicago.

Instead of calculations to estimate separately the contribution at each point on the receptor grid due to emissions from each area in the regional source array, a preliminary evaluation of coupling coefficients between area sources on a reference grid and a central reference receptor is made. This coupling-coefficient array is then used to evaluate actual concentrations by translating the central reference receptor about the desired receptor grid and using actual emissions from the regional source grid. This approach offers a tremendous saving in computer run time whenever concentrations are to be evaluated for a dense regional grid. However, it is based on the assumption of a space-independent wind field for the region (or at least for the part of the region that influences the receptor grid). Clearly, the next level of sophistication for this dispersion model, and a realistic one, is to eliminate this uniform wind assumption and ensure reasonable computer run times by precalculating the integrals of Eq. 7.9.

7.6.7 Output

Calculated concentrations are printed out in two formats. Values at each receptor grid point for receptor arrays of up to 12 points in the East-West dimension are displayed with reasonably accurate geographical scaling. The receptor data array contains a breakdown of the total pollutant concentration into contributions from utilities, industry, and residential/commercial sources as well as the sum of these. These four numbers are printed (in the above order) for each receptor point. A sample printout for 1 hr is shown in Fig. 7.25 with a hand-drawn overlay map of the City of Chicago.

*In validation studies using data from eight receptors in Chicago, minor modifications were required to compensate for stations at intervening points.

Fig. 7.25. Sample Printout of Subroutine PROUT with Chicago Map Overlay.
12 Noon 1/15/67; Wind WNW at 10 mph. ANL Neg. No. 113-1189.

If one of the receptor points corresponds to a particular monitoring site, the hourly values computed for this point can be merged with an output array of meteorological data and air-quality observations at the same site and printed in tabular form.

Punched-card output is also available when one of the receptors corresponds to a particular monitoring site. In addition to the tabular print-out comparing observed and estimated pollution concentrations, the two arrays can be transferred to punched cards for subsequent statistical analysis and graphical display.

7.6.8 Validation of the Integrated-puff Dispersion Model

Over 10,000 hourly averages of SO₂ levels at each of five monitoring stations (TAM-1 through TAM-5) were estimated for the periods December 1966-February 1967 and August 1967-September 1967. The five receptor locations represent a wide range of geographical and emission features, and all are far enough from the city limits so that the sources within the inventory dominate the measured pollutant concentrations. The 1967 season was chosen since it is closest to the 1968 residential and updated industrial inventories (see Sec. 2).

There are numerous statistical tests and formats for comparison of observed and estimated pollutant concentrations. The importance attached to any test depends upon the magnitude and range of the variables and, above all, upon the use to which the model is to be put (Moses, 1969). Seven criteria or display methods are used to compare observed and computed SO₂ data:

- 1) Mean values (monthly and seasonal): μ_{obs} versus μ_{est} .

$$2) \quad \frac{\text{Standard deviation}}{\text{Mean}} \equiv \left[\frac{1}{N_{\text{obs}} - 1} \sum_{i=1}^{N_{\text{obs}}} (X_{\text{obs}i} - X_{\text{esti}})^2 \right]^{1/2} / \mu_{\text{obs}}$$

$$= \sigma_{\text{oe}} / \mu_{\text{obs}}.$$

- 3) Percent of estimates within ± 0.05 ppm of corresponding observations (PCT05).
- 4) Percent of estimates within a factor of 2 of corresponding observations (PCTF2).
- 5) Contingency tables for 6-hr averages.
- 6) Percent reduction in variance ($R^2 \times 100$).
- 7) Episode estimation: 2 x 2 contingency tables for prediction of levels above and below threshold.

Table 7.8 presents the data according to the first four criteria listed above. A glance down the columns of means (μ_{obs} and μ_{est}) or at Fig. 7.26 indicates that, with the exception of TAM-4, February 1967, monthly and seasonal means for all and for individual TAM stations are accurately estimated over a wide range of values.

Although the ratio of the standard deviation (observed-estimated) to the observed mean ($\sigma_{\text{oe}}/\mu_{\text{obs}}$ in Table 7.8) is not a true statistic, in that it cannot be related by, for example, a confidence level to a random distribution of uncorrelated pairs of values, it is a ratio commonly used to evaluate the success of models. Marsh and Withers (1969) indicate that, for their Reading, England, model, as well as for others in the literature, the ratios $\sigma_{\text{oe}}/\mu_{\text{obs}}$ are all higher than 1.1 for 6- and 24-hr averages during the heating season. From Table 7.8, the corresponding values are 0.5 for 24-hr averages and 0.8 for 6-hr averages. For low SO_2 values (<0.05 ppm) such as those at TAM-1 in winter and all TAM's in summer, the accuracy of the instrumentation (± 0.01 ppm under laboratory conditions) and the heterogeneity of local sources lead to short-term errors and thus larger values of $\sigma_{\text{oe}}/\mu_{\text{obs}}$.

Figures 7.27-7.34 show contingency tables for 6- and 24-hr averages. The 6-hr time period was chosen since it is the minimum practical time step for implementation of episodal control strategies (Croke and Booras, 1969). The heavy "staircase" lines bracket a zone of successful estimations defined in terms of the accuracy required of a model used for planning episodal control strategies as well as for evaluating regional air-quality statistics. On a citywide basis, the 6-hr averages are estimated with a skill score* (based on chance) of 0.55. Also listed are the R^2 values for the original data set. This statistic, defined by $(\sigma_{\text{obs}}^2 - \sigma_{\text{oe}}^2)/\sigma_{\text{obs}}^2$, is the fractional reduction in the variance of the original observed data set about the observed mean (σ_{obs}^2) when the model is employed. This figure is 0.43 for 6-hr averages and 0.71 for 24-hr averages when all TAM stations are considered in the same data set. Results (6-hr values) for individual TAM stations vary widely from $R^2 = 0.53$ at TAM-2 to $R^2 \approx 0$ at TAM-5. The significant discrepancy between the skill score (0.35) and R^2 (~ 0) values for TAM-5 occurs because the former considers a band of acceptable error, whereas the latter is based on actual calculated and observed values. (For example, if $X_{\text{obs}} = 0.03$ ppm and $X_{\text{est}} = 0.01$ ppm, the skill score considers this pair a "success," whereas, for the purpose of calculating R^2 , this pair represents an error of 0.02 ppm.

*Skill scores are defined by the ratio $(V - V^1)/(T - V^1)$, where V is the number of correct estimates (within the heavy lines), T the total number of cases, and V^1 the value of V expected by some means other than the model under evaluation. For example, instead of chance, a simpler plume model might be used.

TABLE 7.8: Compilation of Validation Statistics

TAM's	Average Period	Data Period	N _{obs}	μ_{obs} ppm	μ_{est} ppm	σ_{oe}/μ_{obs}	PCT05	PCTF2
1-5	1	Winter-Summer 1967	10,800	0.11	0.11	1.1	62	47
	1s ^a		10,800			1.0	63	51
	6		1,800			0.9	65	55
	24		450			0.6	74	66
1-5	1	Winter 1967	8,300	0.14	0.13	1.0	56	52
	1s		8,300			0.9	58	56
	6		1,383			0.8	60	61
	24		345			0.5	69	75
1-5	1	Summer 1967	2,496	0.03	0.03	1.8	83	31
	1s		2,496			1.6	83	31
	6		416			1.4	83	33
	24		104			1.1	89	41
1-5	1	Dec 1966	2,876	0.13	0.15	1.2	60	52
	1s		2,876			1.1	61	57
	6		479			1.0	62	62
	24		119			0.6	71	77
1-5	1	Jan 1967	2,784	0.12	0.11	0.8	62	56
	1s		2,784			0.7	63	61
	6		464			0.6	66	67
	24		116			0.4	77	76
1-5	1	Feb 1967	2,712	0.16	0.12	0.9	48	49
	1s		2,712			0.8	49	51
	6		452			0.7	51	56
	24		113			0.5	58	68
1	1	Winter-Summer 1967	2,232	0.03	0.03	1.7	84	25
	1s		2,232			1.5	85	28
	6		372			1.3	86	32
	24		93			0.9	92	34
2	1		2,112	0.10	0.09	0.9	66	55
	1s		2,112			0.8	68	59
	6		352			0.7	71	62
	24		88			0.5	77	71
3	1		2,040	0.24	0.24	0.9	34	53
	1s		2,040			0.8	34	56
	6		340			0.7	35	62
	24		85			0.4	48	74
4	1		2,136	0.14	0.12	0.9	55	54
	1s		2,136			0.8	55	58
	6		356			0.7	57	62
	24		89			0.6	64	74
5	1		2,280	0.07	0.07	1.1	70	50
	1s		2,280			1.0	72	53
	6		380			0.8	75	58
	24		95			0.5	85	80

^aSmoothed 1-hr averages (X_{1s}): $X_{1s}(N) = \frac{X_1(N-1) + 2X_1(N) + X_1(N+1)}{4}$

TABLE 7.8 (Contd.)

TAM's	Average Period	Data Period	N _{obs}	μ_{obs} , ppm	μ_{est} , ppm	σ_{oe}/μ_{obs}	PCT05	PCTF2
1	1	Winter 1967	1,776	0.03	0.03	1.7	81	23
	1s		1,776			1.5	83	27
	6		296			1.3	83	32
	24		74			0.9	91	37
2	1		1,656	0.12	0.10	0.8	62	63
	1s		1,656			0.7	64	68
	6		276			0.6	68	71
	24		69			0.4	74	80
3	1		1,392	0.34	0.31	0.8	18	62
	1s		1,392			0.7	19	68
	6		232			0.6	19	75
	24		58			0.4	33	90
4	1		1,584	0.17	0.16	0.8	45	64
	1s		1,584			0.7	45	68
	6		264			0.7	47	71
	24		66			0.5	55	85
5	1		1,896	0.07	0.07	1.1	66	52
	1s		1,896			0.9	68	56
	6		316			0.8	70	63
	24		79			0.5	82	84
1	1	Dec 1966	576	0.02	0.02	2.1	90	19
	1s		576			2.0	91	26
	6		96			1.8	92	33
	24		24			1.4	92	38
	1	Jan 1967	648	0.03	0.05	2.0	77	25
	1s		648			1.7	79	31
	6		108			1.4	79	37
	24		27			1.1	85	33
	1	Feb 1967	552	0.04	0.03	1.3	77	24
	1s		552			1.2	78	22
	6		92			1.0	79	24
	24		23			0.6	96	39
	1	Summer 1967	456	0.03	0.02	1.5	95	35
	1s		456			1.3	94	33
	6		76			1.2	95	30
	24		19			0.9	100	26
	1	Dec 1966	432	0.08	0.10	1.2	63	53
	1s		432			1.1	65	57
	6		72			0.9	72	61
	24		18			0.8	72	72
	1	Jan 1967	576	0.12	0.10	0.7	64	64
	1s		576			0.6	67	69
	6		96			0.6	71	71
	24		24			0.4	75	83
	1	Feb 1967	648	0.15	0.11	0.6	58	70
	1s		648			0.6	60	74
	6		108			0.5	62	77
	24		27			0.4	74	82
2	1	Dec 1966	432	0.08	0.10	1.2	63	53
	1s		432			1.1	65	57
	6		72			0.9	72	61
	24		18			0.8	72	72
	1	Jan 1967	576	0.12	0.10	0.7	64	64
	1s		576			0.6	67	69
	6		96			0.6	71	71
	24		24			0.4	75	83
	1	Feb 1967	648	0.15	0.11	0.6	58	70
	1s		648			0.6	60	74
	6		108			0.5	62	77
	24		27			0.4	74	82

TABLE 7.8 (Contd.)

TAM's	Average Period	Data Period	N _{obs}	μ_{obs} ppm	μ_{est} ppm	σ_{oe}/μ_{obs}	PCT05	PCTF2
2 (Contd.)	1	Summer 1967	456	0.04	0.02	1.9	81	29
	1s		456			1.9	81	26
	6		76			1.7	80	32
	24		19			1.3	79	37
3	1	Dec 1966	600	0.34	0.36	0.8	17	62
	1s		600			0.7	19	68
	6		100			0.7	17	73
	24		25			0.5	32	96
	1	Jan 1967	432	0.33	0.25	0.6	23	68
	1s		432			0.5	26	73
	6		72			0.4	26	83
	24		18			0.3	50	03
	1	Feb 1967	360	0.35	0.30	0.6	15	56
	1s		360			0.6	13	62
	6		60			0.5	13	68
	24		15			0.3	13	87
	1	Summer 1967	648	0.03	0.06	2.1	67	32
	1s		648			1.8	67	31
	6		108			1.6	69	32
	24		27			1.3	82	41
4	1	Dec 1966	648	0.13	0.17	1.2	55	65
	1s		648			1.1	55	69
	6		108			1.0	55	69
	24		27			0.7	70	85
	1	Jan 1967	432	0.15	0.14	0.5	59	81
	1s		432			0.5	60	85
	6		72			0.4	65	90
	24		18			0.3	78	100
	1	Feb 1967	504	0.25	0.15	0.6	19	49
	1s		504			0.5	18	51
	6		84			0.5	23	57
	24		21			0.5	14	71
	1	Summer 1967	552	0.03	0.01	1.3	86	23
	1s		552			1.2	86	29
	6		92			1.1	84	35
	24		23			0.9	91	44
5	1	Dec 1966	552	0.06	0.06	1.1	74	56
	1s		552			0.9	77	62
	6		92			0.7	79	69
	24		23			0.4	96	96
	1	Jan 1967	696	0.06	0.07	1.1	71	55
	1s		696			1.0	71	60
	6		116			0.8	74	66
	24		29			0.6	86	90
	1	Feb 1967	648	0.09	0.09	1.0	52	44
	1s		648			0.9	55	47
	6		108			0.8	58	54
	24		27			0.6	67	67

Fig. 7.29

Six-hour Averages for TAM-1, All Seasons;
 $R_{6\text{-hr}}^2 = 0.19$; $R_{24\text{-hr}}^2 = 0.28$. ANL Neg.
 No. 113-1183.

Fig. 7.30

Six-hour Averages for TAM-2, All Seasons;
 $R_{6\text{-hr}}^2 = 0.46$; $R_{24\text{-hr}}^2 = 0.53$. ANL Neg.
 No. 113-1184.

Fig. 7.31

Six-hour Averages for TAM-3, All Seasons;
 $R_{6\text{-hr}}^2 = 0.22$. ANL Neg. No. 113-1185.

Fig. 7.32

Twenty-four-hour Averages for TAM-3, All Seasons;
 $R_{24\text{-hr}}^2 = 0.60$. ANL Neg. No. 113-1186.

Fig. 7.33

Six-hour Averages for TAM-4, All Seasons;
 $R_{6\text{-hr}}^2 = 0.22$; $R_{24\text{-hr}}^2 = 0.44$. ANL Neg.
 No. 113-1187.

Fig. 7.34

Six-hour Averages for TAM-5, All Seasons;
 $R_{6\text{-hr}}^2 \approx 0$; $R_{24\text{-hr}}^2 \approx 0$; Skill Score_{6-hr} =
 0.35. ANL Neg. No. 113-1188.

Tables 7.9 and 7.10 illustrate the use of the model in evaluating the frequency of short-term air pollution episodes. The contingency tables are based on the following air pollution action criteria:

- 1) A threshold SO_2 level is defined for a given averaging period.
- 2) If the model predicts that this level will be exceeded, then action is taken.
- 3) If the observed average is greater than the threshold less a tolerance, then an episode is said to have occurred.
- 4) If the observed average is less than the threshold plus a slight tolerance, then an episode is said not to have occurred.

TABLE 7.9. Episode Frequency Analysis of TAM-1
 through TAM-5 for 6-hr Episodes, Winter 1967

Symbol	Threshold, ppm	Tolerance, ppm	Skill Score (based on chance)
x	0.2	0.05	0.81
y	0.3	0.05	0.77

O c c u r	Yes	x 56	x 247
		y 42	y 109
	No	x 1052	x 29
		y 1222	y 21
		No	Yes
		Predict	

TABLE 7.10. Episode Frequency Analysis of TAM-1
through TAM-5 for 24-hr Episodes, Winter 1967

Symbol	Threshold, ppm	Tolerance, ppm	Skill Score (based on chance)
x	0.2	0.025	0.84
y	0.3	0.025	0.77

O c c u r	Yes	x 13	x 58
		y 11	y 30
	No	x 271	x 4
		y 301	y 4
		No	Yes

Predict

When compared to chance, the model is significant at better than 99.9% confidence level and the skill scores for this air pollution episode range from 0.77 to 0.84. In terms of episode-control policies, taking serious actions such as temporarily curtailing industrial production is costly. Air pollution cost-benefit studies at Argonne show that as much as \$10 million per day can be involved in lost wages and production for a city such as Chicago. Thus, in practice, the tolerance used above would be enlarged sufficiently to ensure that the model scores significantly better than shown in Tables 7.9 and 7.10.

8. THE DESIGN OF EPISODE CONTROL PROGRAMS*

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8.1 Introduction

From 1966 to 1970, Argonne National Laboratory conducted several related studies regarding the economics of control of air pollution episodes as part of its overall effort in the Chicago Air Pollution Systems Analysis Program. The purpose of these studies was to discover the significant difficulties in effecting comprehensive air quality management during periods of high concentration of pollutants as well as developing research, computational, and administrative techniques in order to aid urban air pollution control officials.

It was recognized that the only permanent solution to the problem presented by the air pollution episode is in the integration of air-resource management with long-range urban and regional planning. That is, emission-control legislation, zoning ordinances, transportation systems design, etc., must be so developed that medically and esthetically acceptable air quality standards will be met. Until air quality history is accumulated that proves episodes will not occur, however, the air pollution episode must be treated as a recurrent, short-term crisis created by a combination of natural, man-made, causative agents. As for other crisis situations, it is necessary to develop a matrix of responsive emergency control strategies that can be implemented on relatively short notice and to the extent required by the existing circumstances. Such strategies must be adaptive; that is, they must be sufficiently flexible that they may be tailored to a dynamically changing situation. They must also be pragmatic. That is, they must exploit existing resources and recognize existing constraints imposed on the implementation of emergency control.

Four aspects of the air pollution control problem were considered significant enough to be the subject of major studies within the Chicago Air Pollution Systems Analysis Program. These are the following:

- 1) A cost-effectiveness analysis of episode-control techniques.
- 2) Analysis of the natural-gas resources available for episode control.
- 3) The development of an allocation model for natural gas during air pollution episodes.

* We wish to acknowledge the cooperation of the staff of the Chicago Department of Environmental Control for their help and cooperation during these studies. We also gratefully acknowledge the cooperation of the Commonwealth Edison Company and The Peoples Gas Light and Coke Company for graciously granting the interviews and furnishing the information that made these studies possible.

4) The development of administrative procedures to be used during episode-control operations.

The cost-effectiveness study (Sec. 8.2) was initiated in order to define and describe the most important alternative strategies available to an air pollution official for episode control. The analysis sought to rank the effectiveness of strategies such as fuel switching, industrial curtailment, and electrical power load shifting, and to estimate the relative cost of these alternative strategies for the metropolitan Chicago area.

Once these strategies had been compared in the cost-effectiveness study, an attempt was then made to determine what supply of clean fuel would be necessary under present and projected conditions in order to employ these strategies. Since switching fuel from high-sulfur coal or oil to natural gas was the most economical of the control strategies studied, the second analysis in the Chicago program focused on an investigation of the natural-gas resources available for episode control. This study, described in Sec. 8.3, defines the real-time constraints on the supply of the natural gas that could be used to combat an air pollution episode. It also analyzes the allocation procedures of a Chicago-based natural-gas supply company to determine whether any changes in their allocation process could provide more discretionary gas for air pollution control. A general discussion is made regarding the expansion of the supply of clean fuels on a regional basis in order to improve the effectiveness of a fuel-switching strategy.

Regardless of the amount of clean fuel available to combat air pollution episodes, effective maintenance of air quality demands that some efficient technique be used in allocating this supply of clean fuel in such a way that the resultant change in the emission pattern of the city will produce the most significant effect on air quality. A methodology for the development of optimal air pollution abatement strategy during air pollution episodes is proposed in Sec. 8.4. The approach is based on the results of a pilot study of the Commonwealth Edison Company conducted by Argonne National Laboratory. This pilot study resulted in the formulation of a computerized mathematical programming method for optimal generator-load shifting and natural-gas management for a power-plant network. Strategies were developed within the constraints imposed by the requirement that ambient SO_2 concentrations produced by large power plants must be maintained at a limiting threshold value during an air pollution episode. The Edison control model, designed to be closely integrated with the normal power-plant systems operation, took full account of the physical operational and economic constraints associated with the electrical power generation. The model produces a minimum-cost, maximum-effectiveness episode-control strategy for SO_2 from power plants. The study also proposed a series of extensions of the optimal control methodology which was developed in the Edison pilot study.

The fourth aspect of the development of effective air pollution episode-control planning considers the administrative difficulties in effecting such control. An effective command and control organization, with channels of communication, logistical support, and trained personnel, is required to implement an emission-control strategy in a complex urban setting. Effective control strategies, the availability of sufficient natural resources, and the development of efficient allocation techniques will be of little use without such an organization. Consequently, in the spring of 1969 an operational test of emission-control strategies was developed and executed as part of the Chicago Air Pollution Systems Analysis Program. This test sought to determine whether a proposed administrative structure for a city department would allow for the efficient and effective use of research techniques developed during the Argonne study on episode control. Specific functions were assigned to personnel in the Chicago Air Pollution Control Department, and an Argonne monitoring team was assigned to report on the effectiveness of the proposed procedures. A detailed description of the procedures as well as a report on the significant events occurring during the air pollution exercise is given in Sec. 8.5. Air quality changes observed from actual fuel-switch tests are discussed in Sec. 9.

Certain general conclusions can be drawn on the basis of the findings of these reports, i.e., concerning what Argonne feels to be those areas in which episode-planning techniques are most deficient. With respect to the cost-effectiveness analysis and resource study, it soon became evident that fuel switching seems to be the most feasible method of controlling short-term episodes. It is evident, however, from the resource studies made in the Chicago program that a sufficient supply of clean fuels is not available under the present natural-gas rate structure. Neither the natural-gas allocation process, the process by which low-sulfur oil or coal can be delivered to industries or residential units, nor the electrical-power distribution system, have been designed in such a way that significant changes in the emission pattern of the city can be made in response to high concentrations of pollution. There are only a few sets of meteorological conditions in which available fuel resources can effectively alter the emission patterns of a city to the degree necessary to control episodes. Based on these studies, our recommendations are as follows:

- 1) Alterations of the natural-gas rate structure and interregional supply and distribution systems should be considered to determine whether it is possible to provide a greater amount of natural gas for discretionary pollution control.

- 2) The ability of cities to substitute other types of clean fuels for the purpose of episode control should be studied.

- 3) The transportation and storage capabilities of the coal and oil suppliers should be analyzed in order to measure their effects on the fuel pattern of the city in terms of a short-term response to high pollution concentrations.

4) The attractive, though limited, option of electrical power shifting should be further investigated for possible increased flexibility through interregional exchange of emergency power.

With regard to the allocation of clean fuels and/or reallocation of electrical power load during an episode, our studies indicate that computational techniques necessary for an optimal allocation are available and seem to be adequate at this state of control. The allocation techniques used in the Commonwealth Edison study and those used in the air pollution control exercise seemed to be efficient and effective. Methods are needed that display the results of allocation models in such a way that the recommendations generated by such models can be implemented in a short period of time. The ability of an air pollution-control official to obtain timely information from allocation models will determine the eventual usefulness of such schemes in producing a strategy of maximum effectiveness and minimum cost for episode control.

The investigations of alternative strategies for episode control have, for the most part, stopped short of a detailed analysis of production curtailment possibilities. This is because the cursory investigation of such measures (Sec. 8.2) indicates that extremely high comparative costs are associated with the curtailment of manufacturing activity. However, the short-run curtailment of public incineration activity, a major source of air pollution, has not been studied. Such a study should include operating procedures, short-run inventory capacity, etc., in a manner analogous to the electric-power and natural-gas utilities studies presented here. In fact, a comprehensive systems analysis of the general response capability of all public pollution activity to episodes is recommended.

The design of the air pollution control exercise underscored our belief that long-range administrative planning for episode control is of absolute necessity if any effective control is to be realized within the time constraints placed upon the air pollution control official. In the description of the air pollution control exercise in this report, it is evident that all strategies for air pollution abatement must be preplanned and that those personnel taking part in the exercise or in the actual control operations must be clearly briefed as to what their respective roles are, what communication links will be necessary during the episode, and what decisions must be made in order to alter the emission pattern of the city sufficiently to maintain a specified degree of air quality. Our recommendations in this area would include a greater degree of documentation of the techniques used to design administrative strategies to be employed during episodes. The work at Argonne was designed to indicate the necessary planning to be done to generate an efficient administration process. However, many questions remain if these techniques are to be applied for the development of episode-control capability by other urban departments.

Of vital importance, in our experience, has been the necessity for developing individual plans for each source, submitted by the companies. This requires determining understandable and equitable guidelines, publishing them, and obtaining action plans that meet them. Evaluation of the guidelines remains, requiring modeling or even a controlled test. In fact, evaluation of the effectiveness of the actual plans would be even more educational.

8.2 An Analysis of the Cost Effectiveness of Episode Control Strategies

8.2.1 Introduction

The objective of this study was to determine the feasibility and examine the costs involved in the implementation of city-wide abatement strategies during a general air pollution episode.

The conventional separation of sulfur dioxide emitters into power plants, industrial, commercial, and residential sources was adopted, since it allowed the isolation of sources which are administratively unmanageable in the short time periods involved in an episode alert, namely, the commercial and residential sources. Except for a few special cases, such sources are too small and numerous to be subject to control during an alert.

The first step in conducting the study was to convert the annual SO₂ emission figures for the four source types into daily figures for October through March when the probability of a major episode is greatest and when most interruptible gas users are using coal and oil. The results are summarized below (data as of 1968):

Source	Annual Emissions, tons	Interval When High Sulfur Fuel Is Used, months	Oct-Mar Daily Emissions, tons	Percentage of Daily Total
Power plants	373,120	8	1,530	62.0
Commercial	47,216	6	260	10.6
Residential	83,027	6	457	18.6
Industrial	59,138	6	107	8.8
		12	109	
	<u>562,501</u>		<u>2,463</u>	<u>100.0</u>

Those industrial plants with known dual fuel capacity are assumed to burn high sulfur fuel during six months of the year (October through March); all others are assumed to burn it uniformly throughout the year.

Because of the administrative problems described above, the emphasis in the development of an emission-oriented alert system must be placed on control of the utilities with 62% of the daily SO₂ emissions and industry with 8.8%. This implies that almost 30% of all SO₂ emissions are uncontrollable--a percentage that increases during abnormally cold periods, since residential and commercial emissions are highly temperature-dependent.

8.2.2 Power Plant SO₂ Abatement

Because their operation was evaluated in some depth as a part of the study outlined in Sec. 8.4 of this report, the six urban Commonwealth Edison plants are not treated here in as much detail as would otherwise be indicated. Nevertheless, an outline of the economics of CECO abatement strategy is important in integrating various alternative sulfur dioxide episode-control strategies. Three major abatement strategy possibilities are feasible. These are high/low sulfur fuel switching, power load shifting to generating plants outside the Chicago area, and the purchase of power from plants outside the CECO system.

8.2.3 Load Shifting and Power Purchasing

Since only 38% of the power generated by the total CECO, Northern Illinois, and Indiana power systems is generated at the six metropolitan Chicago plants, the possibility of significant load shifting is an attractive alternative. Unfortunately, transmission-line capacity constraints within the CECO system appreciably limit the effectiveness of this technique. Although Commonwealth Edison estimates that for 99 days out of 100 it could generate 22% of the electricity produced at the six urban plants outside the metropolitan area (principally by filling in off-peak loads at other plants), the power grid is set up so that only 11% could be transmitted into the city. About 50% of the time, 22% could be shifted, and on exceptional, low-demand days, up to 50% could be shifted.

For an air pollution abatement strategy, it is prudent to rely only on the relatively certain 11% shift which would yield a 6.8% reduction in total sulfur dioxide emissions in the city (11% of 62.0%) at a cost estimated by CECO of \$2725/day or \$380/day per grand-percent reduction in SO₂ emissions.

The same transmission line constraint makes purchasing power from other systems an impractical option, excepting in cases of extreme emergency, since the CECO system itself has more than sufficient capacity to generate enough power to supply the city and the purchased power is generally more expensive to CECO than is power produced within the system.

8.2.4 High/Low-sulfur Fuel Switching: Electric Generating Utilities

Two possible options for fuel switching exist: switching from coal to gas or from high-sulfur coal to low-sulfur coal. However, the latter

alternative is not technically feasible without significant modification of the CECO boiler system.

All the CECO plants in the Chicago area (except the Northwest plant, which burns less than 3% of the coal) have the capacity to switch to gas (at least partially) when gas is available. In terms of capacity, this ability to shift is broken down as follows (data as of 1968):

Plant	Total Capacity, MW	Capacity That Can Be Shifted to Gas, MW
Ridgeland	667	645
Crawford	669	599
Fisk	554	344
Calumet	210	153
State Line	923	385
Total	3023	2126

Thus, slightly over 70% of the total capacity of these five plants can be shifted to gas. Since the average utilization of total plant capacity over a normal working day is below 70%, this limitation on the ability to use gas would seem to be significant only during a few peak hours. A more exact estimate of the limitation is in process, but is not yet available; since the effect is apparently slight, it is ignored in the remainder of this study. Thus, a 100% shift from coal to gas is assumed to be possible for the purposes of the present analysis.

Since the sulfur content of gas is virtually zero (roughly 0.02 lb for the gas-heating equivalent of a ton of coal), switching to gas would remove a final 53.5 grand-percent SO_2 emission attributable to CECO after a minimum power load shift of 11% had already eliminated 6.8 grand-percent of emissions. Thus:

62.0%	CECO Contribution to City SO_2 Emissions during Winter Period
-1.7	Northwest Unswitchable Capacity
60.3%	
-6.8	Grand Percent Removed by Load Shifting
53.5%	

To estimate the cost of the gas/coal shift, daily coal-consumption figures are required. The six CECO plants burned 6,570,000 tons of coal in 1967 during an eight-month period, or an average of 26,600 tons/day. The

coal cost is approximately 3¢ per therm with a Btu rating of 10,200 Btu/lb. The CECO air pollution gas contract with The Peoples Gas Light and Coke Company provides for a small block of winter gas at 7¢ per therm, for a 4¢-per-therm cost differential. The total daily cost of winter-gas shift would thus be approximately:

$$\frac{26,600 \text{ tons}}{\text{day}} \times \frac{204 \text{ therms}}{\text{ton}} \times \frac{4¢}{\text{therm}} = \$217,500/\text{day}.$$

This is equivalent to \$4070/day/1% total SO₂ reduction. Only a limited amount of winter gas is available to CECO, and if the temperature is extremely low, even this gas may be unobtainable. The question of whether any surplus gas available during an air pollution crisis would be most effectively used by CECO or by other SO₂ emitters is considered below.

Shifting CECO from high-sulfur to low-sulfur coal would avoid the question of gas availability if it were technically feasible, but this is not the case without substantial equipment modifications. The high-ash fusion point of low-sulfur coal means that the boiler waste must be extracted as a solid rather than as the liquid that the present CECO boilers are designed to handle. A study of Ohio electric utilities with 4025 MW of capacity revealed that conversion costs of \$271 million would be required. Applying a cost of \$0.067 million/MW to CECO's 3400 MW of capacity yields a capital cost estimate of \$228 million to render the CECO boilers capable of using low-sulfur coal.

An interesting sidelight of boiler conversion is that reducing the SO₂ in the effluent degrades the efficiency of the electrostatic precipitators, thus lowering the amount of fly ash removed from the emissions. Improvement of the SO₂ situation therefore tends to aggravate a related air pollution problem. This effect results from the fact that SO₂ is a relatively good electrical conductor. The Ohio study estimated that \$33 million of additional equipment would be required to allow switching to low-sulfur coal while maintaining precipitator efficiency.

In any case, high/low-sulfur coal switching does not appear to be a workable alternative for CECO, at least in the short run, leaving gas availability as the critical resource in the implementation of a CECO emission-control exercise.

8.2.5 Industry SO₂ Emission Abatement

As for the power-plant complex, there are two basic methods of reducing industrial sulfur dioxide emissions: reduced activity and substitution of lower sulfur fuels. Unlike the CECO situation, however, the former alternative--rife with economic disruption and adverse competitive effects--does not appear to be a practical recourse at present.

8.2.6 Reduced Industrial Activity

Two major costs are involved in the curtailment of industrial processing activity: the direct and indirect value of foregone production and damage to capital. In this situation, order-of-magnitude figures for wage losses alone indicate that temporarily halting industrial operations is not a desirable alternative. Using 1967 Chicago manufacturing data, the wage losses if all major industrial operations were curtailed for one day would be over \$12 million, as follows:

$$\frac{\$3.14}{\text{man-hr}} \times 8 \text{ hr} \times 480,000 \text{ workers} = \$12,050,000.$$

Whether workers are laid off or are paid for not working is unimportant and only determines whether the employer or employee bears the loss. The cost per grand percent of SO₂ emission is over a million dollars, on the basis of one-shift working day,

$$\frac{\$12,050,000}{8.8\%} = \$1,370,000/\text{grand-percent reduction in SO}_2 \text{ emission.}$$

Some of this wage loss would no doubt later be recovered through overtime, but other losses such as reduced profits, capital damage (blast-furnace linings, limestone kiln walls, spoiled-food-processing inventories, etc.), and any indirect effects have been ignored. Indirect effects include any "multiplier effects" of losses--the reduced income to those who would normally sell to those who have suffered losses. In view of this situation, the only practical recourse for economically feasible industrial emission control lies with low-sulfur fuel substitution.

8.2.7 High/Low-sulfur Fuel Switching: Industrial Sources

The 99 largest industrial sulfur dioxide emitters represent a wide assortment of coal, oil, and gas users; some are switchable to lower-sulfur fuel, some are not. Total emissions from the various boiler types are summarized as follows:

Type of Boiler	Annual Tons of SO ₂	Tons of SO ₂ per Day, Oct-Mar
Coal-gas convertible	14,779	81.2 (37.8%)
Can use low-sulfur coal	7,487	
Cannot use low-sulfur coal	7,292	
Coal only	21,349	58.5 (27.2%)
Can use low-sulfur coal	6,758	
Cannot use low-sulfur coal	14,591	
Oil-gas convertible	4,680	25.6 (11.8%)
Oil only	6,847	18.7 (8.6%)
Total for 99	47,655	
Plants other than 99	11,483	31.5 (14.6%)
Total Industrial	59,138	215.5 (100%)

From the table it is clear that 49.6% of the 8.8% winter-month industrial grand percent could be eliminated by switching to gas if available; 37.8% by coal/gas switching, and 11.8% by oil/gas switching. It is important to separate these two methods, since the cost effectiveness of each is different.

The analysis of the shift from coal to gas follows the pattern of the power plants. The price of coal to the lower-volume industrial users is slightly higher -- roughly 3.1¢ per therm (for Southern Illinois coal costing \$6.78 a ton and of 11,000 Btu/lb). The price of gas is uncertain, since none of the 99 industrial users have bargained with the gas supply utility for wintertime air pollution gas as has CECO. Peoples Gas Light and Coke Company has an emergency rate of 12¢ a therm, which would seem to be applicable, but for the sake of cost-efficiency comparisons with CECO, the 7¢ -per-therm price that CECO received was applied to the industrial analysis.

The incremental cost of substituting gas for coal is \$16,300/day as shown below

$$\frac{7¢ - 3.1¢}{\text{therm}} \times \frac{1896 \text{ tons coal}}{\text{day}} \times \frac{220 \text{ therms}}{\text{ton}} = \$16,300/\text{day}.$$

The cost per grand percentage of industrial SO₂ emission reduction is therefore

$$\frac{\$16,300}{37.8\% \text{ of } 8.8\%} = \frac{\$16,300}{3.3\%} = \$4940/\text{grand percent}.$$

This estimate applies up to a maximum of 3.3 grand percent.

The incremental cost of substituting gas for oil can be found by a similar method. The price per therm of No. 6 oil is 4.9¢ a therm (calculated from a price of \$0.075 per gallon and a Btu rating of 151,000 Btu per gallon). The daily cost of oil-gas switching then is \$5420, as shown below:

$$\frac{7¢ - 4.9¢}{\text{therm}} \times \frac{172,000 \text{ gallons oil}}{\text{day}} \times \frac{1.5 \text{ therms}}{\text{gallon}} = \$5420/\text{day}.$$

The cost per grand-percent reduction is thus

$$\frac{\$5420}{11.8\% \text{ of } 8.8\%} = \frac{\$5420}{1.04\%} = \$5200/\text{grand percent}.$$

This applies up to a maximum of 1.04 grand percent.

Of the nonswitchable (coal-only) boilers, those responsible for approximately 6758 tons per year of SO₂ emission (32% of the coal-only boiler emissions) or 18.5 tons per day have burners that can efficiently

accommodate low-sulfur coal. Traveling grate stokers, the major part of the remaining 68%, require coal with a large ash content but low coking properties--a combination of characteristics found only in the higher-sulfur coals. The other 32% can be shifted to low-sulfur coal, though not without some loss of efficiency.

To analyze the economics of a high/low-sulfur coal shift, we have the following characteristics:

<u>Coal Source</u>	<u>Avg Sulfur Content</u>	<u>Mine Price per Ton</u>	<u>Transport Cost in 2500-ton Lots</u>	<u>Total Delivered Price</u>
Southern Illinois	3.3	\$3.85	\$2.93	\$6.78
Western Kentucky	3.45	3.45	3.40	6.85
Eastern Kentucky	1.00	4.27	5.12	9.39

The Southern Illinois and Western Kentucky coals average 11,000 Btu/lb while Eastern Kentucky coal averages 13,000 Btu/lb. This energy difference narrows the differential cost of using premium, Eastern Kentucky coal to \$2.20/ton.

On the average day, the coal-only boilers that allow switching to low-sulfur coal burn 368 tons of high-sulfur coal. The cost of switching to low-sulfur coal then is

$$\frac{368 \text{ tons}}{\text{days}} \times \frac{\$2.20}{\text{ton}} = \$810/\text{day.}$$

Since this could be expected to reduce the daily SO₂ emissions from 18.5 tons/day to 5 tons/day or by 13.5 tons, the cost per grand-percent reduction is

$$\frac{\$810}{0.55 \text{ grand percent}} = \$1470/\text{grand percent per day,}$$

up to a maximum of 0.55 grand percent.

The following information is useful in determining the cost and effect of high/low-sulfur oil switching:

<u>Type of Oil</u>	<u>Avg Sulfur Content</u>	<u>Price per Gallon, 6000-gal Lots</u>	<u>Btu per Gallon</u>
No. 2	0.4	\$0.110	142,000
No. 6	2.5	0.075	151,000

In general, then, for an incremental cost of \$0.037 per gallon for using No. 2 oil in place of No. 6, we could expect a 79% reduction in sulfur dioxide

emissions. However, a weight average of the sulfur content of No. 6 oil in oil-only boilers as indicated in the emission inventory, turns out to be 0.9%--not near the 2.5% general average--so the SO₂ reduction achieved is only 51% for shifting to No. 2 oil, or 9.35 tons.

The total cost would be

$$\frac{254,000 \text{ gallons}}{\text{day}} \times \frac{\$0.037}{\text{gallon}} = \$9400 \text{ per day,}$$

which, per grand percent, is

$$\frac{\$9400}{0.38\%} = \$24,800 \text{ per grand percent per day.}$$

This cost is much higher than for coal, partially because of the low initial sulfur content and partially because of the large proportional increase of No. 2 oil price over No. 6.

Assuming that gas is available, the total strategy alternatives are presented below in tabular form from least to most costly per grand-percent SO₂ emission reduction.

Method	Percent Reduction in Industrial Emissions	Grand-percent Reduction	Cost per Grand Percent	Total Cost
High/low-sulfur coal	6.3	0.55	\$ 1,470	\$ 810
Coal/gas	37.8	3.30	4,940	16,300
Oil/gas	11.8	1.04	5,200	5,420
High/low-sulfur oil	4.3	0.38	24,800	9,400
Total	60.0	5.27		\$31,930

If gas were not available, the situation would change considerably. Examination of emission-inventory data reveals that only 41.2 tons of the 81.2 tons of SO₂ emitted by coal/gas boilers were produced by boilers with stokers that allow the use of low-sulfur coal. The others must remain uncontrolled. The substitution of Eastern Kentucky coal would eliminate only about 20 tons of SO₂, since the weighted average sulfur content of coal in this category is less than 2%. Since we have already calculated the cost of the high/low-sulfur coal switch, we need only apply it to the 20-ton reduction. The total cost of eliminating this SO₂ tonnage is

$$\frac{20}{215.5} \times 8.8 \text{ grand percent} \times \frac{\$1470}{\text{grand percent}} = \$1204.$$

The oil/gas boilers could also be switched to low-sulfur oil, if gas were unobtainable. Because the weighted average sulfur content of the No. 6 fuel oil used in these burners (as indicated in the emission inventory) was 1.9%, switching to low-sulfur oil would be a more effective measure in this case than in the situation involving oil-only boilers. Seventy-four percent of the daily 25.6 tons of SO₂ would be eliminated by switching to No. 2 oil, or 0.784 grand percent. The cost of the switch would be

$$\frac{171,000 \text{ gallons oil}}{\text{day}} \times \frac{\$0.037}{\text{gallon}} = \$6350/\text{day}.$$

This works out to \$8100 for one grand-percent reduction in SO₂, as follows:

$$\frac{\$6350/\text{day}}{0.784 \text{ grand percent}} = \$8100/\text{grand percent}/\text{day}.$$

The effectiveness of the total abatement strategy, if gas is not available, is thus less impressive than when gas can be used. The relevant figures are as follows:

Method	% Reduction in Industrial Emissions	Grand-percent Reduction	Cost per Grand Percent	Total Cost
High/low-sulfur coal	6.3	0.55	\$ 1,470	\$ 810
	9.3	0.82	1,470	1,204
High/low-sulfur oil	4.3	0.38	24,800	9,400
	8.8	0.78	8,100	6,350
Total	28.7	2.53		\$17,764

These results indicate that the possible reduction in SO₂ emissions from industry is more than halved when gas is not available.

8.2.8 Power Plant/Industry Abatement Strategy Summary

The total abatement options available to the City of Chicago are summarized below with gas available:

Method	Grand-percent SO ₂ Emission Reduction	Cost/grand percent/day	Cost/day
CECO power shift	6.8	\$ 380	\$ 2,750
Industry high/low-sulfur coal	0.55	1,470	810
CECO coal/gas	53.5	4,070	217,500
Industry coal/gas	3.30	5,200	16,300
Industry oil/gas	1.04	24,800	5,400
Industry high/low-sulfur oil	0.38		9,400
Total	65.57		\$252,160

When gas is available, then, a sulfur dioxide alert system appears to be an effective, if expensive, method of dealing with an episode, at least relative to gross average emissions. For \$250,000/day, almost 66% of all city SO₂ emissions could be eliminated; however, with no gas available, the total reduction capability is provided by the following table:

Method	Grand-percent SO ₂ Emission Reduction	Cost/grand percent/day	Cost/day
CECO power shift	6.8	\$ 380	\$ 2,750
Industry high/low-sulfur coal	1.4	1,470	2,014
Industry high/low-sulfur oil	0.8	8,100	6,359
	0.4	24,800	9,400
Total	9.4		\$20,514

If an episode should occur when large quantities of natural gas were not available, all alternative control strategies would be largely ineffective, and less than 10% of city-wide sulfur dioxide emissions could be eliminated. To the degree that gas is available, this analysis indicates that it should be allocated to CECO and to industrial plants with boilers that do not allow switching to low-sulfur coal, namely, those equipped with traveling-grate stokers.

8.3 Analysis of Natural-gas Resources Available for Episode Control

8.3.1 Natural-resource Aspects of Air Pollution Episode Control Planning

The objective of this study was to determine the feasibility of allocating natural gas to deal with a sulfur dioxide episode in a major metropolitan area*--the City of Chicago. A combination of interviews with concerned parties and organizations, a study of the fuel price structure, and physical and operational data gathered by Argonne and the Chicago Department of Air Pollution Control were used to develop an estimate of the resource implications of a coordinated air pollution episode control strategy. Specifically a study was made to relate the demand for natural gas for episode control to the conditions under which the supply of natural gas under the existing rate structure would be sufficient for this purpose. Recommendations regarding the long-range expansion of "clean fuel" supplies to combat episodes were then presented.

8.3.2 Effectiveness of Short-term Episode Control with Existing Fuel Resources

The necessity of long-range planning in the development of an effective episode-control system is apparent when one considers the crippling

* Or, the feasibility of an episode-control strategy for SO₂ in a metropolitan area.

nature of a natural-gas constraint in such a program. With sufficient natural gas, 66% of all Chicago sulfur dioxide emissions could be eliminated within a reasonably brief time period. Without any natural gas, the maximum short-term response is reduced dramatically to 9.4%. The crucial dimension of the gas-availability question is its extreme temperature dependence. During low-temperature periods, only small amounts of discretionary gas reserves are available. Space-heating demands are heavy, and it is a peak load period for the gas-distribution system. Unfortunately, it is during these periods that high air pollution concentrations are most likely to occur. In this analysis, the probability of having discretionary gas available during an air pollution crisis period is estimated.

The strong temperature dependence of gas reserves is reflected in existing contracts for Chicago power plants and industrial gas. The percentages of total daily energy requirements that can be met by gas under the special air pollution gas agreement between the Chicago gas utility and the local power utility and under the various industrial interruptible gas contracts are as follows:

Clearly, the natural-gas restriction is severe below 40°F. Moreover, several of the urban power plants have no low-temperature gas agreements whatsoever; hence the total control picture is even less optimistic.

For planning purposes, we may assume a situation in which dual-fuel urban power plants and dual-fuel industrial SO₂ emitters had arranged the same type of air pollution gas-supply agreements as those in force between the gas-supply utility and the Chicago power plants. If this is translated into a possible reduction in total Chicago SO₂ emissions during

a short-term episode, the temperature dependence of the complete response, including high/low-sulfur coal and oil switching, power dual shifting and conversion of dual fuel installation to natural gas, is as follows:

Below 40°F, the response would be very slight; below 2°F (when essentially no discretionary gas is available), the 9.4% reduction shown is due to high/low-sulfur coal and oil switching and electrical power-load shifting.

Obviously, the effectiveness of any short-term crisis alert is highly dependent on the prevailing temperature. Unfortunately, there is a strong negative relationship between SO₂ concentration and temperature. Let us define two levels of air pollution crises--Class I: a 0.3-0.5 ppm SO₂ daily average; Class II: a 0.5 ppm or greater daily average. The 1966 records indicate that none of the 17 recorded Chicago episodes in Class I occurred above 37°F and none of the seven in Class II occurred above 20°F. The respective mean temperatures were 17 and 10°F. If this information is tabulated in the context of possible emission reduction, the problem is apparent:

Temperature records for 1966 indicate that this was a particularly severe year, but a study of the first six months of the milder 1967 indicates the same extreme temperature dependence of episodes, though far fewer of them. The implication, however, is clear--with the present gas-availability situation, it would be difficult to ensure that the city could make an effective response in the short run to a major air pollution crisis in terms of exploiting available discretionary natural gas as a pollution-control resource.

8.3.3 Allocation of Natural Gas during Heating Season

Since the restrictions on the amount of natural gas available for air-quality control places severe limitations on the reduction of SO_2 emissions attainable by fuel switching, a study of the operational and allocation activities of a Chicago gas-supply utility was also initiated.

Since the probability of occurrence of high pollution concentrations is greatest during the winter months, the investigation was limited to an analysis of the methods employed to allocate natural gas during this season. During the heating season, the bulk of the annual urban demand for natural gas occurs in the form of fuel consumed for space heating. This demand is, of course, dependent on the severity of the winter.

Since a local gas distributor contracts for a fixed withdrawal from the regional primary pipeline supplier, the local utility normally uses several types of contractual arrangements in order to ensure that it can market the full amount of natural gas that it receives by pipeline at an essentially constant rate throughout the year. During the summer months, of course, the space-heating market is almost nonexistent, and therefore other sources of demand must be found. Due to the fluctuation of temperature during the heating season, temporary winter surpluses also exist. These must be disposed of in such a way that the primary supply contract is satisfied and distribution profits are maximized. Contractual agreements which provide for the marketing of natural gas generally fall into three classes, and a fourth is proposed.

1) Firm-rate Contracts. This is the highest rate at which natural gas is normally purchased. It is usually reserved for space-heating consumers, although a limited number of industrial and commercial firm-rate contracts do exist. This type of agreement guarantees the delivery of gas upon the customer's demand; such demands cannot be backlogged or foregone. Firm-rate contracts provide the base demand for the gas-utilities supply system, because of the strict compliance conditions associated with these agreements.

2) Interruptible-rate Contracts. Several types of contracts actually fall under this heading, but for the purposes of the present analysis, they can all be regarded as essentially identical. An interruptible gas contract applies to

dual fuel customers who use gas during the heating season only when the gas company deems it to be available in surplus amounts and at relatively low rates. During the warmer parts of the heating season, low space-heating demands may free a certain amount of gas. Firms with interruptible-rate contracts are then given an option to purchase the gas at a certain unit cost. The "interruptible-gas" contract itself can be regarded as an instrument through which the option is purchased and the unit cost is specified. Differences between the various interruptible contracts are essentially differences in the relative priority of the option to purchase surplus gas.

Two sets of rates should be distinguished at this point. First, there is the "process-rate" contract under which available gas is purchased for industrial processing uses. Second, a "boiler-rate" gas option may be contracted at a lower priority level than is associated with the process rate. It should be emphasized that the consumer has no control over the timing of the availability of this gas. A customer may reject gas when it is offered, but may not arbitrarily demand gas at any given time. The only exception to this situation is that interruptible customers may purchase a limited amount of "emergency" gas at a premium rate that is approximately four times the normal interruptible rate.

3) Off-peak Contracts. This type of contract generally covers the off-peak demand seasons. It represents an attempt to "smooth" demands by marketing the excess supply of gas at considerably lower rates when space heating demands are down. Off-peak or dump-rate users usually have gas available on a continuous basis from about May to October. Dump-rate consumers, such as certain large dual fuel processing plants, enjoy the lowest seasonal rates during this period.

4) Air Pollution Gas Contract. This type of contract is somewhat unusual due to its special purpose nature. A contract of this kind, negotiated in Chicago by the local power-plant system, was developed for the purpose of air pollution control and power-demand peak shaving. This contract is described in detail in ANL/ES-CC-003.

8.3.4 Gas Storage Facilities

Contractual arrangements are only one of the means used by the gas-supply utility to smooth the uneven seasonal demand pattern. The utility has access to a reserve of gas stored in two underground reservoirs in central and southern Illinois: the Hirscher and Mahomet reservoirs. These reservoirs are filled in the summer months during low space-heating demand periods and are depleted during the heating season. In addition to providing a seasonal inventory, the reservoirs are used as an auxiliary supply to the pipeline gas when extremely high space-heating demands occur. A limited inventory of liquified (LP) gas is also available for use during extremely high demand periods. The local gas-supply utility

maintains LP gas storage capacities sufficient to yield about 100,000 million cubic feet (Mcf) of fuel gas use per season. This type of production is relatively expensive, however, and is only exploited for peak shaving during periods of maximum demand. The replenishment of LP gas is a rather expensive and cumbersome operation, by the standards of the gas-supply utility, since this fuel must be imported by rail and off-loaded, as a liquid, into the utility storage facilities. Up to 10 trainloads may be required to refill depleted LP reserves.

8.3.5 Demand-forecast and Gas-allocation Techniques

To assess its ability to meet current and long-range demands for natural gas with the resources at its disposal, the gas utility uses past heating demands as a standard against which to evaluate the current supply

Fig. 8.1. Typical Natural-gas Seasonal Supply Schedule. ANL Neg. No. 113-1132.

and demand situation. Figure 8.1 illustrates the two criteria against which the current seasonal withdrawal rate is measured. The ordinate of this plot is in units of "equivalent days," which correspond to a "standard" daily withdrawal rate of 468,000 Mcf. The abscissa of Fig. 8.1 indicates the time during the heating season.

The "equivalent day" is used as a general measure of the daily demand for gas for space-heating purposes. The total available operational underground reservoir capacity is 45 equivalent days. This corresponds to the amount of storage capacity available at the beginning of the heating season. For technical reasons, the storage reservoir cannot be depleted below about 15 equivalent days at any time. The figure thus depicts the gas-supply inventory situation as a function of time throughout the season.

The 1935-1936 demand year was the most severe heating season encountered in the operating history of the local gas utility. In accordance with the fixed policy that space-heating demands must always be satisfied, the utility will not distribute gas to interruptible users if the present heating season appears that it will be more severe or generate more demands than the reference 1935-1936 demand period. Demand schedule 1 on Fig. 8.1 illustrates such a condition. If a temporary warm period should occur during such a season, the resultant surplus gas is used to replenish the reservoir inventory which was drawn down during the earlier, more severe, part of the season. Demand schedule 2 on the figure depicts a milder winter,

which does not generate a significant space-heating demand. In such cases, gas is made available to dual-fuel interruptible users. The gas utility also maintains a running average of the "normal" winter consumption rate against which to compare its current demands. Interruptible gas is made available to consumers on the basis of the priority level of the contractual arrangements described previously.

In addition to the seasonal allocation of gas, there exists a day-to-day distribution problem which must be resolved. Seasonal inventory considerations do, in part, determine when and which industrial users will receive surplus gas, but even if the seasonal inventory level is high, the distribution problem imposes another constraint on short-term gas allocation. Advance predictions of the daily gas demand must be provided in order to allow the gas dispatcher to answer the following questions.

- 1) Are pipeline supplies adequate to handle the predicted daily demand?
- 2) If not, how much gas must be drawn from the large underground reservoirs or the small oil-seal reservoirs?
- 3) If interruptible users do receive gas, which ones should receive it and for what period of time?

Since the demand for gas is highly sensitive to meteorological conditions, the "gas dispatcher" must be provided with meteorological forecasts, a method of translating those forecasts into projected gas demands, and a procedure for deciding which dual-fuel customers should receive gas for that period. From the standpoint of supply, the dispatcher must decide what source of gas--pipeline, reservoir, or liquified gas--will be used to satisfy the demand. A 6- to 12-hr planning horizon is normally used, although changes in meteorological conditions occasionally necessitate rapid revisions in the demand estimates.

Figure 8.2 illustrates the series of procedures involved in the gas-dispatching process. The gas dispatcher first receives a meteorological forecast of parameters that have been found to correlate with the space-heating gas demand. The most critical of these, of course, is the hourly variation of temperature. Wind speed and insolation are also significant, although they are of secondary importance in comparison to temperature. Statistical regression equations based on past demand records are used to convert the meteorological forecast into a total firm gas-withdrawal rate. Depending on the predicted rate of withdrawal, the supply of flow gas from the primary pipeline may or may not be augmented by stored gas withdrawals. A chart such as Fig. 8.3 is used, together with other supply considerations, such as the allowable reservoir withdrawal rate, to determine which supply sources will be exploited, and to what extent.

Fig. 8.2. Natural-gas Allocation and Dispatching Process. ANL Neg. No. 113-1133.

Fig. 8.3. Typical Natural-gas Withdrawal Rate vs. Temperature. ANL Neg. No. 113-1134.

The seasonal demand situation, as well as the daily projected space-heating withdrawal, indicates whether any interruptible dual-fuel users will receive gas during a given planning period. If the projected demand for space heating gas is low enough, and if the seasonal inventory is high enough, the dispatcher will allocate gas to the interruptible customers on the basis of the appropriate contract priority. The customer is contacted and offered the option of using the available gas. The process of switching a plant to gas from coal may require anywhere from 0.5 to 3 hr. An oil-to-gas switch is generally more rapid. Metering devices in the dispatching office indicate the approximate consumption rate of each interruptible user.

8.3.6 The Temperature Dependence of Air Pollution Episodes

The previous discussion indicates that the temperature dependence of space-heating demands puts the supply of gas for air pollution control in roughly the same category as that for interruptible use. Indeed, gas available on an interruptible contractual basis does in fact constitute the only existing possible source of discretionary air pollution control resource at present.

To determine how effective this interruptible gas supply would be for episode-control purposes, the frequency of occurrence of 24-hr-average SO_2 concentrations measured at the eight Chicago air-quality monitoring stations was plotted against temperature (see Fig. 8.4). Dosage rate, geographical extent, and season were treated as the critical parameters. Since there are eight air-quality monitoring stations in Chicago, an episode in which four or more stations indicated high concentrations of SO_2

Fig. 8.4. Frequency of Occurrence of 24-hr-average SO_2 Concentrations, Measured at Eight Monitoring Stations, Plotted against Temperature

would affect roughly half the city. This analysis uses data taken in Chicago throughout a two-year period. Three sections of the figure are frequency plots for individual months, while the other two are episode frequency plots for the entire heating season from October through April.

Several observations can be made on the basis of these figures. The months of April and October have roughly equivalent temperature histograms, in which the mean temperature of episodes occurs at nearly 50°F. Furthermore, by subtracting the number of episodes occurring at four or more stations from those occurring at two or more stations, one may conclude that episodes occurring at the beginning or toward the end of the heating season are usually localized in extent and occur in the upper temperature ranges in which pollution from space heating sources is not extensive. This would seem to indicate that if the interruptible gas-rate structure can be altered during these types of episodes to provide discretionary natural gas for episode control, this reallocation of clean fuel would be effective in controlling such localized episodes.

Episode frequency in January naturally exhibits a much lower mean temperature of episode occurrence than that of April or October. It also shows a marked skewness in the distribution toward lower temperature, especially for the more severe episodes. Since industrial emissions are not generally highly temperature-dependent, it is likely that the skewness evident below 25°F is due to increased emissions from residential space-heating sources. Other studies conducted during the Chicago Air Pollution Systems Analysis Program (Croke *et al.*, 1968) confirm a high correlation between temperature and air quality in certain areas of Chicago in which there is a predominance of coal-fired residential space heaters. One may tentatively conclude that industrial natural-gas fuel-switching control techniques would not be effective below 25°F, due to the large residential space-heating effect. Note that this skewness also occurs for the distributions over the entire heating season. In fact, localized episodes above 0.3 ppm during the entire October to April period exhibit a marked bimodal distribution with respect to temperature.

8.3.7 Fuel-switching Control Techniques in Different Temperature Ranges

Three distinct temperature regions appear to require consideration in order to formulate appropriate episodal fuel-switching strategies. Above 40°F, the reorganization of the interruptible gas-rate structure would be effective in reallocating natural gas for emergency air pollution control purposes. Below 25°F, industrial dual fuel switching does not seem to be as appropriate, because of the dominant effects of space-heating emissions. This casts doubt on the applicability of industrial fuel switching for a considerable number of episodes occurring in the 25-40°F range. It may be assumed that in this range both space heating and industrial emissions play a significant role.

It is in this area that effective fuel-switching techniques for episode control would necessitate the negotiation of an emergency low-temperature firm-gas rate contract. This type of contract allows the gas customer to use natural gas on demand. As noted previously, such a contract has been negotiated by the Chicago electric utility.

The difficulty with such a pollution-control contract is that the local gas distributor, in order to fulfill the contract, may have to make a large expenditure in capital equipment to deliver the additional firm gas and/or negotiate for an additional amount of gas from its primary supplier. The natural gas is then delivered, whether air pollution episodes occur or not, and either the local or regional pollution-control agency or the individual consumers could be paying for natural gas which would ordinarily not be used. The control agency, of course, only needs the option of using natural gas on a contingency basis.

There are two possible solutions to this difficulty. The air pollution control agency could negotiate a contract with some other large user of natural gas to share in the cost of the contract, so that during periods of low air pollution concentration, the alternate user of gas would have the option to burn the natural gas. The cost of this gas option would then be divided between the control agency (the public) and the other user.

A second possible method of securing a block of gas for pollution-control purposes in the 25-40°F range depends on the inventory capability of the gas supplier in the region. If excess seasonal inventory capacity exists, an air pollution firm-gas contract could be arranged on a contingency basis.

8.3.8 Long-term Steps to Increase Effectiveness of Episode Control

The critical gas constraint makes it apparent that even a short-term episode control strategy must be supported by long-term planning in order to be effective. One long-term measure to increase the effectiveness of episode control policy has already been taken in Chicago. As a byproduct of the recent emission-control limitations imposed on fuel burning in the city, some high-sulfur coal users will be forced to shift to coal-combustion equipment that can accommodate low-sulfur coal or to oil-fired equipment. This will relieve one of the existing constraints on high-sulfur to low-sulfur coal switching* (the presently predominant chain-grate stokers, which are essentially incapable of burning high-sulfur coal) and so should increase the "no-gas" response to an episode. Several other alternatives to relieve the natural-gas availability problem are worth considering. The most obvious of these is, of course, to expand the natural-gas supply system capacity. Another is the creation of a low-sulfur-oil standby system for coal-fired equipment. Since oil could be stored at individual plant sites, or in central

* In fact, those switches that have been made have generally been from coal to firm gas (obviously deepening the overall gas shortage).

storage facilities convenient to the city's industrial complex, the peak load problem associated with gas distribution could be avoided. A third sulfur dioxide emission-control technique, which may be promising but is not yet at the operational state, is the dolomite-injection process, which appears to involve significantly small incremental capital and operating costs than other sulfur dioxide extraction techniques such as the molten-carbonate process. Since the dolomite-injection technique is still in the developmental state, as are other SO_2 emission-reduction concepts, we consider only the state-of-the-art, oil and gas fuel switch alternatives in the present evaluation.

8.3.9 Low-sulfur-oil Backup System

From an operational standpoint, the installation of equipment that would render coal-fired systems capable of conversion to low sulfur oil--a few days supply of which could be inventoried at fairly moderate cost--appears to be an attractive way of circumventing the complexities of the natural-gas-resource management problem. The cost per therm of low-sulfur oil is not significantly different from the cost of firm heating season gas. For example, the cost of No. 2 oil is on the order of 7.7¢ per therm. Moreover, the reduction in sulfur dioxide emissions for a coal/oil shift is comparable to that of a coal/gas shift, so that the cost per unit of SO_2 reduction is only slightly greater for oil. Natural gas is virtually sulfur free and low-sulfur oil combustion involves an SO_2 emission of about 0.04 lb per therm, compared to 0.54 lb of SO_2 per therm for 3% sulfur coal.

The increase in operating cost per unit reduction of SO_2 emissions of coal/oil shifting over coal/gas shifting is therefore on the order of 25%. The capital costs associated with the adaptation of existing equipment to accommodate oil would be an additional cost, as would the inventory costs of the oil. The availability of low-sulfur-content oil, if wholesale conversion were to result, presents another problem. Oil that is naturally low in sulfur content is a relatively scarce commodity, although large-scale imports of Mediterranean crudes having a maximum sulfur content of about 1% have proven feasible. East Coast power plants have been supplied with 1% sulfur residual oils from these imported crudes at an incremental cost of only about 30¢ per barrel above the \$2.25-per-barrel rate associated with high-sulfur Caribbean crude residuals.

Economical desulfurization of oil is commercially feasible. It has been estimated (Stern, 1967) that an incremental cost of about 30¢ per barrel would be entailed in achieving a reduction of fuel-oil sulfur content from 3 to 2%, while a reduction from 3 to 1% would involve an increment of 72¢ per barrel and from 3 to 0.5% would involve about \$1.00 per barrel. Aside from these fairly significant incremental fuel costs for desulfurized oil, a comparatively large capital investment on the part of the petroleum processing industry would be required if large-scale use of desulfurized fuel oil were

promoted as an air pollution control resource. To justify a multimillion-dollar investment in desulfurizing equipment, the processing industry would have to be assured of a steady market for desulfurized fuel oil. This investment would be minimized if the oil were used only for air pollution episode control. However, this would involve the development of storage facilities to contain the emergency supply of low-sulfur oil, and an incremental inventory cost would be entailed.

The long-range prospects for the use of natural or desulfurized low-sulfur oil nevertheless appear rather attractive from the standpoint of air pollution control. Even a shift to 1.5% sulfur oil would result in a 75% reduction in Chicago SO₂ emissions relative to 3.0% sulfur coal, per Btu generated. The development of an emergency backup system therefore appears to deserve serious consideration.

8.3.10 Natural-gas Resource Management

The relaxation of the natural-gas constraint is another approach that could lead to greater short-term episode-control effectiveness. The major difficulty here is that the "air pollution control gas," normally needed at a time of peak gas demand, requires an expansion of the existing gas-storage and -distribution system. This expedient leads to two nonmarket-oriented problems involving the Federal Power Commission, which regulates both the electric power and gas supply utilities. The first obstacle to the expansion of gas supply facilities is the apparent reluctance of the FPC to recognize gas distribution for air pollution abatement purposes as a legitimate use for this fuel. Moreover, the maximum allowable profit rate set by the FPC appears to be less than the rate of interest that the gas supply utilities would have to pay in order to finance the construction of an expanded supply system.

Assuming that the constraints imposed by the FPC will eventually be removed in the public interest, the question still remains as to how the capital costs of the expanded supply system should be distributed among its users. Requiring urban industrial firms to pay for this premium-price gas will clearly have competitive effects, since no equivalent cost increase would be imposed on firms outside the city. In the long run this might be desirable, if it forces some large pollution producers out of the heavily urbanized areas. In this way, the misallocation of resources which resulted from the fact that, in the past, many corporate entities could and did ignore the social cost of pollution, would be reduced. Nevertheless, an equity question remains, since the rules of the economic game have, in effect, been changed in midcourse.

The electric utilities, as a system of regulated monopolies, are free of direct competitive effects if higher costs are imposed on them, and thus are a more "natural" target--particularly because of their large relative

and absolute pollution emissions. In this case, the higher fuel costs associated with air pollution control could, and perhaps should, be passed on to the consumer. In a well-regulated monopoly, as in the competitive market, the firm should be in such a position that its net returns just offset its private costs--in the broadest definition of that term. The result is that it is the user of electricity who ultimately benefits from the lower private cost of electricity which is made possible by the neglect of pollution as a cost of production. It therefore seems equitable that the consumer should bear the cost of eliminating power-plant pollution. To accomplish this, a variable electricity tariff might be devised which would allow higher rates during periods when the power-plant system is constrained to burn premium-priced fuel. The power-plant system could also expand its existing transmission network to accommodate larger power shifts and power imports during high-pollution periods.

8.3.11 Conclusions

Using the Chicago situation, we have attempted to estimate some of the possibilities and economic implications of an effective air pollution episode control program. The results of this preliminary analysis indicate that, under a limited set of circumstances, a significant response to an air pollution episode is both feasible and moderately priced; that is, a maximum 66% of all Chicago SO₂ emissions could be abated for a daily cost of about \$250,000. The disquieting result of this study is associated with the rather general conditions under which an adequate response is not feasible at any price. To relieve this problem, it seems evident that long-range planning for the management of primary energy resources will have to be integrated into the development of effective air pollution episode control strategies.

8.4 An Analysis of Allocation Methods for Natural Gas during Episode Control

8.4.1 Introduction

As noted in Sec. 8.3, the scarcity of clean fuels during certain seasons generates a serious problem for any abatement plan. Under any given set of conditions, the most efficient use of clean fuels may demand concentration of their use in only certain industries. An abatement program must also account for the rationing of clean fuel throughout the whole of the high-episode season. Excessive employment of clean fuels early in a high-episode season may prohibit their use for episodes later in the year. All these difficulties place a computational and analytical burden on the episode program to effectively reflect the total urban system. This section focuses on the optimal allocation of natural-gas resources during an episode in order to achieve the maximum effectiveness with available supplies of clean fuel.

8.4.2 Commonwealth Edison Company Pilot Study

A pilot study of the Commonwealth Edison Company (CECO) explores alternative solutions to the difficulties of operational control and constitutes the first operational test of an air pollution episode control model. The objective of this study was to test an episode control model which would yield control programs that are physically and economically compatible with CECO operations and simultaneously keep the pollution levels at an acceptable level. The predictive inputs used by the control model were based on a source-oriented physical dispersion model (described in ANL/ES-CC-002), but the control model was so constructed that it could also incorporate statistical prediction techniques.

The Commonwealth Edison Company was a logical choice for this study for the following reasons:

- 1) CECO operations are subject to most of the types of economic constraints that a control program would encounter on a city-wide basis.
- 2) A large inventory of accurate emission and air-quality data is available to provide an excellent validity check for the model.
- 3) A power-generating network is amenable to both of the types of control described above.
- 4) Power-generating stations tend to be among the largest single sources of SO_2 in the city environment.

8.4.3 The Pilot Study Control Subsystem

A subsystem of the total CECO network was selected as the object of this study. This subsystem is shown in Fig. 8.5. It includes the Fisk, Crawford, and Ridgeland plants and the Lindblom and Hyde Park TAM stations. This configuration was chosen because:

Fig. 8.5. Power-plant Pilot Study System.
ANL Neg. No. 112-9792.

- 1) The Fisk, Crawford, and Ridgeland plants are three of the largest plants in the urban power system.
- 2) The physical layout of this subset of plants is such that, for certain meteorological conditions, their SO_2 emissions might be expected to affect the air quality detected at the TAM stations.

8.4.4 Physical Characteristics of the Power Generation System

CECO is part of a major network of power companies distributed throughout the north central United States. These companies are linked together to permit electrical power to be transferred from one utility system to another in case of emergencies or when it is economically advantageous to do so. CECO's position in this network is shown schematically in Fig. 8.6

Fig. 8.6. Power Company Network. ANL Neg. No. 112-9793.

CECO generates its own power in a 15-plant network distributed over northern Illinois. Each plant contains a number of generator units of varying size and efficiency. Each unit has an effective operating range over which its output may be varied to meet continuously changing demands for power.

Many of these boiler-generator units are capable of burning either coal or natural gas. Decisions to commit units to the network are made on a more or less continuous basis to meet the power demands required of the system. These decisions are made by a "load dispatcher," whose duties are described in detail in Sec. 8.4.5.

To maintain air quality above a certain threshold limit, it may prove necessary during pollution episodes to restrict SO_2 emissions from CECO plants. This, of course, implies restrictions on unit operating levels and fuel usage, which, in turn complicates the load dispatcher's decision-making process. It is, therefore, important to understand the process by which units are committed to the system and power demand is distributed among committed units so that controls can be imposed that are economically feasible and least likely to disrupt normal CECO operations.

8.4.5 The Power-dispatching Decision Process

The focal point of the CECO power generation system is the load dispatcher. It is his responsibility to predict the power demands on the system and to ensure that generating capacity will be available to supply these demands continuously throughout the day. The load dispatcher's problem is thus one of meeting demands on the system and minimizing the cost of producing electricity. This involves commitment of the most efficient units available during his planning period, taking account of equipment outages, planned maintenance, etc. He must have equipment "on line" to meet demand, but he does not wish to have less efficient equipment on line if it is not needed. How well the dispatcher achieves this goal depends largely on how well he can predict the hourly variation of loads during his planning period.

Figure 8.7 shows the hourly load curve for February 1, 1966--a typical daily winter pattern. The exact shape of these bimodal patterns is a function of the meteorological situation. The experienced dispatcher is extremely accurate in his load predictions. Errors in the neighborhood of 1 or 2% are the rule, a 5% error being rare. Once he has predicted the load curve, the dispatcher schedules his "peaking units" onto the system so that they are available as the demand increases.

Fig. 8.7. Typical Winter Daily Load Pattern. ANL Neg. No. 112-9794.

The informational input used by the load dispatcher in his prediction and decision-making functions is shown schematically in Fig. 8.8.

Fig. 8.8. Utility-power Generation Control System. ANL Neg. No. 112-9795.

8.4.6 Weather Information

Since weather conditions cause much of the variability in system load demands, one of the most important inputs to the dispatcher is the short-range weather forecast. The meteorological parameters considered to affect the system most are:

- 1) Sky condition (i.e., percent cloud cover, cloud type, light intensity, etc.).
- 2) Temperature.
- 3) Wind speed and direction.

Weather information comes into the central dispatching office from three sources.

8.4.6.1 Contracted Meteorological Forecasts. CECO has contracted with a Chicago meteorological consulting firm to receive forecasts specifically designed for use by the load dispatcher. The four forecasts provided each day are the most important parameters required to estimate the power-demand schedule.

8.4.6.2 Weather Bureau Reports. Weather Bureau reports and forecasts are teletyped directly into the CECO dispatching office. These reports are continuously compared with the contract meteorological predictions.

8.4.6.3 Reports from Neighboring Electrical Companies. Telephone communication with other electrical companies often provides useful additional information on weather conditions, etc.

8.4.7 Load Prediction and "Model Weather Day"

Having obtained a weather prediction, the dispatcher searches recent weather records for a day with meteorological conditions similar to those predicted for his planning period. He can then use the loads that actually occurred on this "model day" as a guideline for current load predictions. Naturally, he keeps a close watch on weather conditions, since a sudden change could warrant a shift to a new model day. It is not unusual for model days to change three or four times during a 24-hr period, due to unforeseen meteorological conditions.

For prediction purposes, each 24-hr day is divided into approximately two planning horizons, one covering each of the morning and evening peak loads. It is the responsibility of the night dispatcher to schedule equipment onto the system for the morning peak, and of the day dispatcher to set the system up for the anticipated evening load.

8.4.8 Load Prediction and Equipment Selection

Once the load prediction is made, the dispatcher must allocate this demand to the various generating units in the system. The availability and capacity of different units will change from day to day due to planned maintenance on certain units, unexpected equipment outages, steam-regeneration problems, etc. The load dispatcher receives a daily report from each plant regarding the expected condition of the generating units for the time period of the dispatching decision.

After the status of equipment is reported, the dispatcher seeks to satisfy the load prediction of the day by using the most economically efficient units available. A list is prepared relating the available units to their economic efficiency. The units are listed in order of most to least efficient, using an incremental cost per kilowatt hour as the index of efficiency for each unit. The incremental cost is calculated for each unit at the most efficient operating load level. This is ordinarily at or near unit capacity.

The number of units to be put on line that day is determined by noting the peak load expected and then selecting units from the unit efficiency list, according to minimum incremental cost, until that peak capacity is met. A spinning reserve of some 300 MW is kept on line for contingencies. Since peak loads do not occur until later in the day, the full capacity is not put on line immediately. The dispatcher generates a schedule for the units so that programmed increases in unit capacity will correspond to his load curve for the day.

Included in his operating plan is the possibility of buying or selling electricity from neighboring companies. That is, when the price of purchased electricity is less than the cost of adding a unit, the dispatcher "shops around" among his neighbors to buy the required amount of power at the least possible price. Similarly, he may be called upon to "sell" electricity if it is available in the system. Thus, the ability to purchase electricity is analogous to having an additional unit in the system whose capacity and cost are continuously varying.

8.4.9 System Operation

After preparing the system operating plan for his planning horizon, the dispatcher informs the plants of their load schedules (i.e., when they are to have certain units ready to bring onto the system and to what capacity); he then begins the task of monitoring the system's operation.

Although the major equipment decision for the 12-hr period is made, the network is constantly subject to smaller-scale demand perturbations which require continuous monitoring of the output of each unit. The committed units were selected on the basis of their peak efficiency. Because of these

small demand perturbations, however, the units cannot be run at peak efficiency at all times, but must vary their output according to the instantaneous demands of the system. The monitoring function then seeks an instantaneous response to demand perturbation by continuous control of the actual power generation from the units.

Assisting the dispatcher in this task is the automatic dispatch system (ADS). This is an electronic analog device which has the operating characteristics of each unit built into its controlling mechanism. The ADS seeks to control the committed, on-line units so that electricity is being produced as economically as possible at any instant in time. It accomplishes this by automatically opening and closing "valves" on the units. Opening a valve causes an increase in the energy input to the unit, resulting in a higher electrical output. Each unit has several valves, and associated with each valve is an incremental cost of producing electricity which depends on the operating level of the unit. The incremental cost of each valve may be regarded as a point on a cost-versus-load curve for each unit. The ADS has this information built into its controls and when demand on the system increases, ADS automatically opens the next most efficient valve.

The dispatcher follows the operation of the ADS by preparing a "system operating guide." This is a list of all valves ordered by increasing incremental cost, regardless of the unit to which the valve corresponds. By knowing what the current incremental cost of generating power is, the dispatcher knows which valves are open.

The dispatcher continually monitors the operation of the system via a control panel containing several strip-chart recorders. The control panel provides such information as the total system load in megawatts, the current incremental cost of producing electricity in mills per kilowatt, the individual plant loads, and the amount of electricity flowing into (or out of) the system from neighboring companies.

8.4.10 Feasibility of Control

In order to develop a method for perturbing the CECO system for episode control, three basic questions must be considered:

1. What types of control are feasible, and how readily can they be applied?
2. What are the economic and physical consequences of applying feasible controls?
3. What are the economic and physical constraints associated with the application of feasible controls?

8.4.11 Control by Load Reduction

CECO is constrained to meet the total load demand on its system. There is, however, a wide choice in the way this demand is met, if the system is not being operated at capacity. Thus, load reduction at one plant or even a number of plants is usually feasible by shifting the power demand to other plants in the system.

As discussed above, CECO's equipment-selection rules are largely economic in nature, although occasional equipment outages may necessitate temporary deviations from such rules. Such deviations are somewhat analogous to the imposition of air pollution constraints on the operating system--they may cause CECO to deviate from an otherwise economically optimal operating procedure for a short period of time. CECO's general solution to temporary equipment outages is to have enough "slack" in the system to shift load to another plant. Although such a shift increases the cost of producing electricity, the increase incurred for a small load shift from a temporarily polluted area may not be excessively disruptive. Thus, load shifting within the physical limits of the CECO system for the abatement of "localized" episodes may be a highly desirable control mechanism.

The amount of power that can be shifted at any time depends on the plant involved, the status of the system, and the nature of the load curve as shown in Fig. 8.7. Load shifting is difficult to accomplish when the system is near peak or minimum load (Periods 2, 4, and 6).

For widespread (i.e., city-wide) pollution episodes, power shifting out of the city (and indeed out of the system) may be necessary. Although a large shift is certainly more costly and more difficult to accomplish, the prospects of purchasing power from neighboring companies may become attractive under aggravated air pollution conditions. In the future, it may be possible to form reciprocal agreements to obtain "pollution-abatement" power from neighbor companies during a pollution episode and return this borrowed power at some later date.

8.4.12 Control by Fuel Switching

On the average, about two-thirds of CECO's urban capacity could be produced by natural gas if this fuel were available. This is, in fact, the case during the summer when CECO burns mostly gas that is available at "dump rates." During the winter, however, gas is usually available only at premium rates.

Many units of the urban network are capable of burning gas in combination with coal, and some can generate entirely on gas. For those units equipped to burn gas, nearly any combination of coal and gas is possible.

The gas company provides CECO with a 30-min advance notice when gas can be made available and at what plants. The dispatcher then informs the affected plants which units are to engage in a fuel switch.

CECO has purchased a block of gas which may be used during the heating season in the event of a pollution episode. This winter gas is relatively expensive, and the supply is limited. A severe cost penalty is assessed if the contract limit is exceeded. The availability of this "pollution gas" is also limited with regard to hourly delivery rate. The latter is dependent on temperature (i.e., the lower the temperature, the less the delivery rate in therms per hour). These limitations obviously imply the judicious use of this gas. However, since CECO has purchased and agreed to burn this gas during the winter season, if the end of the season is approaching and the gas has not been used, it becomes increasingly desirable to expend it.

8.4.13 Combining Fuel Switching and Load Reduction

The above discussion indicates that a combination of fuel switching and load shifting is a possible air pollution abatement technique. Since pollution gas is relatively expensive to use, a feasible strategy that satisfies the pollution constraints would first shift power within the physical limitations of the system. If load shifting does not produce an acceptable air-quality condition, then pollution gas must be used for minimal operational and economic disruption. Power shifting and gas usage should be minimized. The attainment of this objective is the purpose of the control model developed during this pilot study. The model is described in Sec. 8.4.14 below.

8.4.14 Formulation of the Mathematical Control Model

The discussion above identified the essential components of an optimal emission-control model. These components are:

- 1) The planning horizon--the predicted length of the pollution episode in hours.
- 2) The variables that can be manipulated for control purposes--the hourly amount of gas burned (in therms) and the hourly amount of load shifted (in megawatts) for each unit.
- 3) The objective--to minimize the hourly gas usage and load shift for each unit.
- 4) The constraining relationships which limit the values the control variables may assume, e.g., the maximum allowable hourly pollution concentration (in ppm) measured at each TAM station, and the maximum feasible hourly gas usage and load shift for each unit.

This problem must now be translated into symbols so that a mathematical solution technique can be applied. To simplify the formulation of the problem, the mathematical statement of the control model described here will be limited to a planning horizon of 2 hr and a two-plant (i.e., two-unit), two-receptor system. The extension to the general case was made and implemented for a three-plant, two-receptor system with an extended time horizon. The simplified model described below is provided solely for explanatory purposes.

The indices needed to formulate the control model are:

- 1) An hour index $t(t = 1, 2)$.
- 2) A unit index $j(j = 1, 2)$.
- 3) A receptor index $i(i = 1, 2)$.

For this formulation: $j = 1$ is the Fisk plant; $j = 2$ is the Crawford plant; $i = 1$ is the Lindblom receptor; and $i = 2$ is the Hyde Park receptor.

8.4.14.1 The Control Variables. Let the amount of gas burned in unit j during hour t be $G_j(t)$ and the amount of electricity produced be $D_j(t)$. Also, let $U_j(t)$ be the load on unit j in hour t predicted by the load dispatcher. Then the total load shift is given by

$$Y_j(t) = U_j(t) - D_j(t). \quad (8.1)$$

Thus, the control variables are $G_1(1)$, $Y_1(1)$, $G_2(1)$, $Y_2(1)$, $G_1(2)$, $Y_1(2)$, $G_2(2)$, and $Y_2(2)$.

8.4.14.2 The Objective Function. The most economically attractive type of control is a load shift from the units contributing to high pollution levels. In the application of this control, however, the objective is to shift only what is necessary to reduce the pollution to an acceptable level. Let $d_j(t)$ be the cost (or "penalty") per megawatt of deviation from the predicted load, $U_j(t)$, for unit j during hour t . Then $d_j(t)Y_j(t)$ is the total cost incurred by the company during hour t for a shift of $Y_j(t)$ megawatts from unit j . The objective is to minimize this quantity for all hours of the episode and each unit j . Thus, it is necessary to minimize

$$Z_1 = d_1(1)Y_1(1) + d_2(1)Y_2(1) + d_1(2)Y_1(2) + d_2(2)Y_2(1). \quad (8.2)$$

Each unit has a minimum operating level, which depends on time. If this is denoted by $L_j(t)$, the maximum load shift, $\bar{Y}_j(t)$, is given by

$$\bar{Y}_j(t) = U_j(t) - L_j(t), \quad j = 1, 2; t = 1, 2. \quad (8.3)$$

Thus, if all units in the system are operating at their minimum levels and the pollution reading at some receptor is still above an acceptable level,

some gas must be used to reduce it. The objective here is to use only as much gas as is needed to accomplish the required reduction. If g_j denotes the cost per therm of burning gas in unit j , and c_j is the cost of burning coal, the total cost incurred by the company for burning $G_j(t)$ therms of gas during hour t in unit j is $(g_j - c_j) G_j(t)$. Again, the objective is to minimize this quantity for all hours of the episode and each unit j . Thus, it is necessary to minimize

$$\begin{aligned} Z_2 = & (g_1 - c_1) G_1(1) + (g_2 - c_2) G_2(1) \\ & + (g_1 - c_1) G_1(2) + (g_2 - c_2) G_2(2). \end{aligned} \quad (8.4)$$

Finally the objective is to minimize

$$Z = Z_1 + Z_2 \quad (8.5)$$

by minimizing both types of control.

A difficulty associated with the direct use of this objective function is the assignment of values to $d_j(t)$ --a result of the complexity of CECO's cost-allocation system. However, a simplified objective function which circumvents this problem can be formulated. Since the differential cost of burning gas is relatively constant between units and since the amount of load shifted from one or two units will produce only microscopic changes in the total system operating cost, the fuel differential cost weights of Eq. 8.4 can be dropped and the objective function can be simplified to minimize

$$\begin{aligned} Z = & G_1(1) + G_2(1) + G_1(2) + G_2(2) \\ & + Y_1(1) + Y_2(1) + Y_1(2) + Y_2(2). \end{aligned} \quad (8.6)$$

The only difference between Eqs. 8.5 and 8.6 is that Eq. 8.6 does not discriminate between units on a differential fuel-cost basis. This is acceptable to CECO, however, for this is exactly what they are equipped to do by using the ADS mentioned earlier. This objective function will seek to impose controls on unit j solely on the basis of its contribution to the pollution level at each receptor during the episode.

8.4.14.3 The Constraints. A basic assumption of dispersion models and most air-quality prediction schemes is that of source superposition. That is, the contribution from individual sources to the air quality sensed by a particular receptor can be arithmetically summed to yield the total pollution concentration at that receptor. If $Q_j(\tau)$ denotes the emission from source j during hour τ and $\alpha_{ij}(t - \tau + 1)$ is the fraction of the pollutant emitted τ hours ago that is "received" at receptor i during hour t , then the total contribution to the receptor reading is $\alpha_{ij}(t - \tau + 1) Q_j(\tau)$. For this control model, the

coefficients $\alpha_{ij}(t - \tau + 1)$ are calculated by the DAVKERN "integrated-puff" physical-prediction model.* These coefficients are normalized so that the calculated receptor contributions are measured in ppm. By superposition, the total receptor value during hour t is obtained by summing the contributions from all units j and all previous hours τ . For each hour during the episode and each receptor, these values are constrained to be less than a prescribed value, say p ppm. Thus, for the simplified system under consideration, the following four "pollution" constraining relationships must hold:

$$\left. \begin{aligned} (i = 1, t = 1) \quad & \alpha_{11}(1)Q_1(1) + \alpha_{12}(1)Q_2(1) \leq P; \\ (i = 2, t = 1) \quad & \alpha_{21}(1)Q_1(1) + \alpha_{22}(1)Q_2(1) \leq P; \\ (i = 1, t = 2) \quad & \alpha_{11}(2)Q_1(1) + \alpha_{12}(2)Q_2(1) \\ & + \alpha_{11}(1)Q_1(2) + \alpha_{12}(1)Q_2(2) \leq P; \\ (i = 2, t = 2) \quad & \alpha_{21}(2)Q_1(1) + \alpha_{22}(2)Q_2(1) \\ & + \alpha_{21}(1)Q_1(2) + \alpha_{22}(1)Q_2(2) \leq P. \end{aligned} \right\} \quad (8.7)$$

These constraints have been written in terms of SO_2 emitted, and not in terms of the original control variables, $G_j(t)$ and $Y_j(t)$. To accomplish this substitution, it may be noted that the thermal input of coal to unit j during hour t [denoted by $C_j(t)$] is proportional to the emission $Q_j(t)$. Thus, assuming that this proportionality constant is incorporated into the normalization of the coupling coefficients, the constraints can be rewritten with the $C_j(t)$ replacing the $Q_j(t)$. Now letting $T_j(t)$ denote the total thermal input to unit J in hour t , and assuming that only gas or coal or a combination of both is burned, the total thermal input becomes the sum of the coal input and gas input. Thus,

$$T_j(t) = C_j(t) + G_j(t),$$

or

$$C_j(t) = T_j(t) - G_j(t). \quad (8.8)$$

Now the total thermal input is a function of the load on the unit. That is,

$$T_j(t) = F_j[D_j(t)] = F_j[U_j(t) - Y_j(t)] = F_j[Y_j(t)]. \quad (8.9)$$

Finally, the required substitution becomes

$$C_j(t) = F_j[Y_j(t)] - G_j(t). \quad (8.10)$$

*The constraining relationships developed in this section will apply to any predictive model for which the assumption of superposition of sources is retained.

The pollution constraints now become

$$\left. \begin{aligned}
 &(i = 1, t = 1) \alpha_{11}(1)\{F_1[Y_1(1)] - G_1(1)\} \\
 &\quad + \alpha_{12}(1)\{F_2[Y_2(1)] - G_2(1)\} \leq P; \\
 &(i = 2, t = 1) \alpha_{21}(1)\{F_1[Y_1(1)] - G_1(1)\} \\
 &\quad + \alpha_{22}(1)\{F_2[Y_2(1)] - G_2(1)\} \leq P; \\
 &(i = 1, t = 2) \alpha_{11}(2)\{F_1[Y_1(1)] - G_1(1)\} \\
 &\quad + \alpha_{12}(2)\{F_2[Y_2(1)] - G_2(1)\} \\
 &\quad + \alpha_{11}(1)\{F_1[Y_1(2)] - G_1(2)\} \\
 &\quad + \alpha_{12}(1)\{F_2[Y_2(2)] - G_2(2)\} \leq P; \\
 &(i = 2, t = 2) \alpha_{21}(2)\{F_1[Y_1(1)] - G_1(1)\} \\
 &\quad + \alpha_{22}(2)\{F_2[Y_2(1)] - G_2(1)\} \\
 &\quad + \alpha_{21}(1)\{F_1[Y_1(2)] - G_1(2)\} \\
 &\quad + \alpha_{22}(1)\{F_2[Y_2(2)] - G_2(2)\} \leq P.
 \end{aligned} \right\} \quad (8.11)$$

As mentioned above, the amount of load shift is limited by $U_j(t) - L_j(t)$. That is

$$0 \leq Y_j(t) \leq \bar{Y}_j(t) = U_j(t) - L_j(t), \quad j = 1, 2; t = 1, 2. \quad (8.12)$$

The maximum hourly thermal delivery of gas to each plant has been negotiated between CECO and the gas company. If this amount is denoted by $\bar{G}_j(t)$, the gas-usage constraints become

$$0 \leq G_j(t) \leq \bar{G}_j(t), \quad j = 1, 2; t = 1, 2. \quad (8.13)$$

The complete mathematical form of the problem can now be stated. The objective is to minimize

$$Z = G_1(1) + G_2(1) + G_1(2) + G_2(2) + Y_1(1) + Y_2(1) + Y_1(2) + Y_2(2)$$

subject to the following constraints:

1) Pollution

$$(i = 1, t = 1) \alpha_{11}(1) \{F_1[Y_1(1)] - G_1(1)\}$$

$$+ \alpha_{12}(1) \{F_2[Y_2(1)] - G_2(1)\} \leq P;$$

$$(i = 2, t = 1) \alpha_{21}(1) \{F_1[Y_1(1)] - G_1(1)\}$$

$$+ \alpha_{22}(1) \{F_2[Y_2(1)] - G_2(1)\} \leq P;$$

$$(i = 1, t = 2) \alpha_{11}(2) \{F_1[Y_1(1)] - G_1(1)\}$$

$$+ \alpha_{12}(2) \{F_2[Y_2(1)] - G_2(1)\}$$

$$+ \alpha_{11}(1) \{F_1[Y_1(2)] - G_1(2)\}$$

$$+ \alpha_{12}(1) \{F_2[Y_2(2)] - G_2(2)\} \leq P;$$

$$(i = 2, t = 2) \alpha_{21}(2) \{F_1[Y_1(1)] - G_1(1)\}$$

$$+ \alpha_{22}(2) \{F_2[Y_2(1)] - G_2(1)\}$$

$$+ \alpha_{21}(1) \{F_1[Y_1(2)] - G_1(2)\}$$

$$+ \alpha_{22}(1) \{F_3[Y_3(2)] - G_2(2)\} \leq P.$$

2) Gas usage

$$0 \leq G_j(t) \leq \bar{G}_j(t), \quad j = 1, 2; t = 1, 2.$$

3) Load shift

$$0 \leq Y_j(t) \leq \bar{Y}_j(t) = U_j(t) - L_j(t), \quad j = 1, 2; t = 1, 2.$$

The extension of the above to a general model is now quite straightforward. If T denotes the length of the episode, J the number of units, and I the number of receptors, the general formulation is

$$\text{minimize } Z = \sum_{j=1}^J \sum_{t=1}^T G_j(t) + Y_j(t), \quad j = 1, 2, \dots, J; t = 1, 2, \dots, T,$$

subject to the following constraints:

1) Pollution

$$\sum_{j=1}^J \sum_{\tau=1}^t \alpha_{ij}(t-\tau+1)\{F_j[Y_j(\tau)] - G_j(\tau)\} \leq P, \quad i = 1, 2, \dots, I; t = 1, 2, \dots, T.$$

2) Gas usage

$$0 \leq G_j(t) \leq \bar{G}_j(t), \quad j = 1, 2, \dots, J; t = 1, 2, \dots, T.$$

3) Load shift

$$0 \leq Y_j(t) \leq \bar{Y}(t), \quad j = 1, 2, \dots, J; t = 1, 2, \dots, T.$$

An interesting feature of this formulation is that by appropriate use of the upper-bound constraints on gas usage and load shifts, the model may be forced to consider only load shifts or gas usage, but not both. To accomplish load shifting only on unit j , the gas-usage limits $\bar{G}_j(t)$ are merely set to zero. To prohibit load shifting, the minimum loads, $L_j(t)$, are set equal to the predicted loads, $U_j(t)$. Thus, solution of this model can provide hourly schedules of gas usage, load shifting, or combinations thereof as guides to pollution abatement.

8.4.14.4 Solution of the Mathematical Control Model via Linear Programming. The model as formulated above consists entirely of linear relationships between the control variables, except for the functions $F_j[Y_j(t)]$. Fortunately, these functions are "almost" linear, and a least-squares linear

fit yields errors of less than 5% over most of the unit operating ranges.

Figure 8.9 shows a typical curve of gross thermal input versus load and the approximating straight line.

Thus, we have

$$F_j[Y_j(t)] = A_j Y_j(t) + B_j, \quad (8.17)$$

where A_j and B_j are the coefficients of the least squares linear fit for unit j . Substitution into Eq. 8.6 gives

$$\sum_{j=1}^J \sum_{\tau=1}^t \alpha_{ij}(t-\tau+1)\{A_j Y_j(\tau) - G_j(\tau) + B_j\} \leq P. \quad (8.18)$$

Fig. 8.9. Typical Gross Thermal Input vs. Load Curve and Least-squares Approximating Line. ANL Neg. No. 112-9798.

Fig. 8.10. Graphical Solution of a Linear-programming Problem. ANL
Neg. No. 112-0707.

The model is now in classical linear form (called a linear program) for solution by a well-known technique called the simplex method of "linear programming." A sample linear-programming problem and its graphical solution are shown in Fig. 8.10. The linear constraint relationships form the boundaries of the feasible region (shaded in the figure) in which the solution is constrained to lie. The objective function Z can be slid parallel to itself until the maximum is found within the feasible region. For a linear-programming problem, the solution will coincide with one of the lettered vertices (in this case, B). Obviously, graphical solutions of these relationships are difficult for problems with three variables, and impossible for those containing more than three. The simple method for the general problem of n variables is a computational algorithm for searching the vertices of the feasible region in such a way that the value of the objective function is always improved.

The control model (including the DAVKERN prediction model to calculate the transfer coefficients) and its solution via the simplex method have been coded for the IBM 360 Model 75 computer. For the present demonstration, the code considers only a 6-hr control period, but it can be extended easily. The limitations on the use of this system for advance control are, of course, imposed entirely by the meteorological ability to produce accurate advance forecasts.

Sample runs are exhibited in Tables 8.1 and 8.2. The inputs to the program are the predicted weather parameters, the dispatcher's predicted hourly load schedule, $U_j(t)$, and the hourly minimum loads, $L_j(t)$. The program will then compute the gas usage, $G_j(t)$, and unit load shifts, $Y_j(\tau)$, which satisfy the pollution constraints and minimize the objectives.

Desirable features of the program are:

- 1) It is flexible; it takes account of CECO's daily operational and economic situation.

TABLE 8.1. Optimal Emission Control Strategy; Predicted and Minimum Loads and Resulting Pollution Levels without Abatement Programs (Typical Computer Output)

RUN 1 WS = 2 MPH GAS USAGE ONLY													
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION		LEVELS (ppm)
	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	LINDBLOW	HYDE PARK	
4	0.0	0.0	210.0	210.0	0.0	0.0	153.0	153.0	268.0	268.0	0.000	0.000	0.0000
5	0.0	0.0	240.0	240.0	0.0	0.0	177.0	177.0	298.0	298.0	0.199	0.0068	0.0068
6	0.0	0.0	282.0	282.0	0.0	0.0	178.0	178.0	304.0	304.0	0.603	0.0820	0.0820
7	26.0	26.0	310.0	310.0	0.0	0.0	210.0	210.0	331.0	331.0	0.692	0.2290	0.2290
8	87.0	87.0	323.0	323.0	0.0	0.0	219.0	219.0	353.0	353.0	0.734	0.3170	0.3170
9	145.0	145.0	330.0	330.0	55.0	55.0	212.0	212.0	360.0	360.0	0.804	0.3710	0.3710

RUN 2 WS = 2 MPH GAS USAGE AND LOAD SHIFT													
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION		LEVELS (ppm)
	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	LINDBLOW	HYDE PARK	
4	0.0	0.0	210.0	175.0	0.0	0.0	153.0	125.0	268.0	130.0	SAME AS ABOVE		
5	0.0	0.0	240.0	175.0	0.0	0.0	177.0	125.0	298.0	130.0			
6	0.0	0.0	282.0	175.0	0.0	0.0	178.0	125.0	304.0	130.0			
7	26.0	26.0	310.0	175.0	0.0	0.0	210.0	125.0	331.0	130.0			
8	87.0	40.0	323.0	175.0	0.0	0.0	219.0	125.0	353.0	130.0			
9	145.0	40.0	330.0	175.0	55.0	30.0	212.0	155.0	360.0	150.0			

RUN 3 WS = 4 MPH GAS USAGE ONLY													
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION		LEVELS (ppm)
	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	LINDBLOW	HYDE PARK	
4	0.0	0.0	210.0	210.0	0.0	0.0	153.0	153.0	268.0	268.0	0.036	0.0000	0.0000
5	0.0	0.0	240.0	240.0	0.0	0.0	177.0	177.0	298.0	298.0	0.216	0.0170	0.0170
6	0.0	0.0	282.0	282.0	0.0	0.0	178.0	178.0	304.0	304.0	0.240	0.0210	0.0210
7	26.0	26.0	310.0	310.0	0.0	0.0	210.0	210.0	331.0	331.0	0.248	0.0240	0.0240
8	87.0	87.0	323.0	323.0	0.0	0.0	219.0	219.0	353.0	353.0	0.276	0.0280	0.0280
9	145.0	145.0	330.0	330.0	55.0	55.0	212.0	212.0	360.0	360.0	0.297	0.0340	0.0340

HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION		LEVELS (ppm)
	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	LINDBLOW	HYDE PARK	
4	0.0	0.0	210.0	210.0	0.0	0.0	153.0	125.0	268.0	130.0	SAME AS ABOVE		
5	0.0	0.0	240.0	240.0	0.0	0.0	177.0	125.0	298.0	130.0			
6	0.0	0.0	282.0	282.0	0.0	0.0	178.0	125.0	304.0	130.0			
7	26.0	26.0	310.0	310.0	0.0	0.0	210.0	125.0	331.0	130.0			
8	87.0	87.0	323.0	323.0	0.0	0.0	219.0	125.0	353.0	130.0			
9	145.0	145.0	330.0	330.0	55.0	30.0	212.0	155.0	360.0	150.0			

TABLE 8.2. Optimal Emission Control Strategy; Gas Usage, Loads, and Resulting Pollution Levels Using Abatement Programs (Typical Computer Output)

RUN 1 WS = 2 MPH GAS USAGE ONLY												
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION	LEVELS (ppm)
	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	LINDBLOM	HYDE PARK
4	C.C	0.0	C.C	210.0	0.0	0.0	13102.2	153.0	12442.0	268.0	0.000	0.0000
5	C.C	0.0	C.C	240.0	0.0	0.0	15171.3	177.0	6422.1	298.0	0.052	0.0068
6	C.C	0.0	583C.3	282.0	0.0	0.0	15257.5	178.0	24701.5	304.0	0.260	0.0750
7	2499.5	26.0	787.3	310.0	0.0	0.0	18016.3	210.0	26905.1	331.0	0.200	0.1650
8	0.0	87.0	C.C	323.0	0.0	0.0	12140.3	219.0	0.0	353.0	0.015	0.2000
9	C.C	145.0	C.C	330.0	0.0	55.0	0.0	212.0	0.0	360.0	0.200	0.2000

RUN 2 WS = 2 MPH GAS USAGE AND LOAD SHIFT												
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION	LEVELS (ppm)
	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	LINDBLOM	HYDE PARK
4	C.C	0.0	C.C	175.0	0.0	0.0	7673.1	125.0	0.0	130.0	0.000	0.0000
5	C.C	0.0	C.C	175.0	0.0	0.0	10688.3	125.0	697.5	130.0	0.076	0.0056
6	C.C	0.0	C.C	175.0	0.0	0.0	6736.3	125.0	0.0	130.0	0.200	0.0630
7	C.C	26.0	C.C	196.5	0.0	0.0	10688.3	125.0	4196.1	130.0	0.200	0.1400
8	C.C	87.0	C.C	323.0	0.0	0.0	0.0	125.0	0.0	130.0	0.200	0.1590
9	C.C	145.0	C.C	330.0	0.0	55.0	0.0	212.0	0.0	360.0	0.200	0.1850

RUN 3 WS = 4 MPH GAS USAGE ONLY												
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION	LEVELS (ppm)
	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	LINDBLOM	HYDE PARK
4	C.C	0.0	C.C	210.0	0.0	0.0	1900.0	153.0	0.0	268.0	0.034	0.0000
5	C.C	0.0	C.C	240.0	0.0	0.0	6369.0	177.0	0.0	298.0	0.200	0.0170
6	C.C	0.0	C.C	282.0	0.0	0.0	7180.8	178.0	0.0	304.0	0.200	0.0200
7	C.C	26.0	C.C	310.0	0.0	0.0	11001.6	210.0	0.0	331.0	0.200	0.0230
8	C.C	87.0	C.C	323.0	0.0	0.0	18792.2	219.0	307.9	353.0	0.200	0.0270
9	C.C	145.0	C.C	330.0	0.0	55.0	0.0	212.0	0.0	360.0	0.200	0.0320

HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION	LEVELS (ppm)
	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	LINDBLOM	HYDE PARK
4	C.C	0.0	C.C	210.0	0.0	0.0	0.0	131.0	0.0	268.0	0.034	0.0000
5	C.C	0.0	C.C	240.0	0.0	0.0	0.0	125.0	0.0	274.9	0.200	0.0160
6	C.C	0.0	C.C	282.0	0.0	0.0	0.0	125.0	0.0	272.0	0.200	0.0200
7	C.C	26.0	C.C	310.0	0.0	0.0	0.0	125.0	0.0	286.0	0.200	0.0230
8	C.C	87.0	C.C	323.0	0.0	0.0	0.0	125.0	0.0	218.3	0.200	0.0270
9	C.C	145.0	C.C	330.0	0.0	55.0	0.0	212.0	0.0	360.0	0.200	0.0320

- 2) It is specific to the control of each different predicted episode.
- 3) It is adaptive; the program can easily be rerun if weather conditions change.

Experiments in implementing this program on teleprocessing equipment are currently being conducted. If the use of such equipment is feasible, a terminal could be installed in the CECO dispatching center or in the air pollution control department and linked to a computing facility, where the prediction and control code would be stored. Weather forecasts and predicted power demands could be typed into the teleprocessing console when a dispersion-prediction model indicated excessively high concentrations that were expected. An optimal emission-control program would

immediately be computed and returned. Required access to the computer would be sporadic and of short duration, but near real-time response would be desired. Thus, a high priority would have to be given pollution-control requests if such a system is to be operationally successful. Figure 8.11 is a schematic diagram of the operation of such a real-time pollution-control system.

Fig. 8.11. Schematic Diagram of Teleprocessing Control System.
 ANL Neg. No. 112-9798.

8.4.14.5 Discussion of Results and Model Validity. Once the control model had been developed, a search was made for a realistic test of its validity. Since the diffusion analysis studies indicate that the Hyde Park area is highly "self-polluting," the search centered about the Lindblom

receptor. The master data program was instructed to search the 1966-1967 Lindblom air-quality records for pollution concentrations in excess of 0.2 ppm and low wind speeds between 270 and 360°. Three "episodes" (of 12-hr duration or more) were found, and one which looked as though the Crawford plant might be a major contributor was chosen as the sample test case. The test episode began on January 31, 1966, at 8 a.m. the day after a wind change caused the ambient pollution level to drop. The SO₂ levels recorded at the Lindblom station are shown in Fig. 8.12.

A statistical analysis using Crawford SO₂ emission data and temperature as independent variables indicated that Crawford's contribution to the air quality monitored at the Lindblom receptor during this time was significantly different from zero at the 0.97 confidence level. This finding was used only as an indication that Crawford did contribute to this episode in order to obtain realistic data for testing the control model. It cannot be used as proof of Crawford's culpability due to the small data sample size and the absence of data which would resolve the contributions of other possible sources. "Episode analysis," as such, was not within the scope of this study.

Fig. 8.12. Predicted and Measured Air Quality at Lindblom Receptor during Test Episode. ANL Neg. No. 112-9799.

The Argonne meteorology group has provided the following analysis of weather conditions during this period.

8.4.14.6 Meteorological Profile for January 31-February 1, 1966.

January 31 and February 1 were the last two days of a weather period that began on January 21 with a cold front passage. For three days extremely cold arctic air drained southward into the U.S. as a high-pressure ridge remained west of Chicago (see Fig. 8.13). The temperature at Midway Airport was zero or below for 72 consecutive hours--between 1500 on January 27 and 1400 on January 30. The lowest temperature reached during the period was -16 at 0700 on January 29. On January 30, the wind shifted to westerly and some warm-

ing began. High temperatures of 3, 17, and 29 were reached on January 30 and 31 and February 1, respectively.

In contrast to the January 19-20, 1966 episode, described earlier in this report, winds were stronger--mostly 10 knots or above--until late on January 31. From 2100 on January 31 to 0900 on February 1, however, winds were mostly 5 knots or less.

Skies were partly cloudy to overcast during much of the period. The only long period of clear skies occurred between 0000 on January 30 and 1100 on January 31.

These clear skies account for the radiation inversion observed on the 0600 temperature soundings at Peoria and Green Bay. Figure 8.14 shows a Chicago rural temperature sounding constructed from the Chicago rural (Argonne) 0600 temperature and the average slopes of individual segments of the Peoria and Green Bay temperature profiles. The mixing depth was estimated as the height above the surface where the dry adiabat from the 0600 Midway (city) temperature intersects the Chicago rural sounding. The estimated mixing depth is 180 m (590 ft).^{*} The constructed Chicago sounding is colder at about 960 mbar than both Green Bay and Peoria. This temperature estimate is probably too low--the actual temperature is probably intermediate between the Green Bay and Peoria temperatures. This means that the estimated mixing depths probably errs on the side of being too high by 40-50 m.

^{*}The mixing depth was read as a pressure from Fig. 8.14 and converted to a height above the surface using the measured Peoria pressure-height relationship.

Fig. 8.13. Surface Weather Map, 1200 CST, January 31, 1966. ANL Neg. No. 113-1100.

Fig. 8.14. Atmospheric Temperature Soundings, Showing Construction of Chicago Rural Sounding and Estimation of Chicago Mixing Depth. ANL Neg. No. 113-1101.

The mixing depth was also estimated from Fig. 8.14 for other hours using current Midway temperatures. The estimated mixing depths for 0000 to 0800 on February 1 are given in Table 8.3.

8.4.14.7 Episode-control Tests. The following "average" meteorological parameters were selected as inputs to the DAVKERN dispersion simulation which is incorporated in the control model:

Temperature:	+15 degrees;
Wind speed:	1 and 4 mph;
Turner stability:	5;
Mixing height:	0.2 mile;
Wind direction:	315 degrees.

The "steady-state" buildup of pollution as simulated by DAVKERN is shown in Fig. 8.12 for both wind speeds. These results indicate that the use of the DAVKERN coupling coefficients in the control model provides a "realistic" episode for which control programs can be generated, although the validity of the absolute value of the DAVKERN air-quality estimates has not been verified.

TABLE 8.3. Estimated Chicago Mixing Depths, February 1, 1966

Time, CST	Estimated Mixing Depth, m
00	60
01	60
02	60
03	95
04	60
05	95
06	180
07	255
08	430

To illustrate the capability of the control model, four programs were run for this episode as shown in Tables 8.1 and 8.2. The period from 4 to 10 a.m. was chosen for control, because it coincides with the highest pollution levels of the episode. The actual loads and minimum loads (i.e., maximum load shifts) for this period were furnished by CECO. These data are shown in Tables 8.1 and 8.2 along with the DAVKERN predicted pollution levels if coal were used to produce these loads. The total thermal input required to satisfy these power demands at the two plants over the episode period is 2.7×10^6 therms. Thus, if a general switchover to gas at each plant was imposed due to this episode, this is the number of therms of gas that would have had to be supplied assuming that gas was available and that all boilers could burn 100% gas. (In fact, not all Fisk and Crawford boilers are equipped for dual fuel use, but this constraint can easily be added to the model.) The success of the control program can be measured against this maximum required gas usage.

Each program illustrates a different capability of the control model and the saving that can be achieved by its use. These programs are discussed individually below. Figures 8.15-8.17 show the hourly SO_2 levels resulting from the use of each program versus those associated with no control program.

a. Program No. 1: Wind Speed = 2 mph, Gas Usage Only. A wind speed of 2 mph was used in runs 1 and 2 because it yields a significant contribution to the Hyde Park station for the 315° wind direction. Thus, the

entire subsystem linkage is tested. Run 1 assumes that load shifting cannot be imposed and the entire pollution reduction must be achieved by switching to gas. The gas-usage program computed by the model and the resulting pollution levels are shown in Table 8.1. The gas usage was 1.5×10^5 therms, a reduction more than one order of magnitude.

Fig. 8.15. Hourly SO₂ Levels at Lindblom Receptor for 2-mph Wind Speed. ANL Neg. No. 113-1102.

Fig. 8.16. Hourly SO₂ Levels at Hyde Park for 2-mph Wind Speed. ANL Neg. No. 113-1103.

Fig. 8.17. Hourly SO₂ Levels at Lindblom for 4-mph Wind Speed. ANI. Neg. No. 113-1104.

b. Program No. 2: Wind Speed = 2 mph, Gas Usage and Load Shifts from Crawford and Fisk.

Run 2 is the same as run 1, except now feasible load shifts are allowed. With this program, gas usage at Fisk is no longer needed and the gas input to Crawford is 4.1×10^4 therms, another order-of-magnitude reduction. The total load shifted from the two plants was 1537 MW during the 6-hr period.

c. Program No. 3: Wind Speed = 4 mph, Gas Usage Only.

With a 4-mph wind speed, the contribution to the Hyde Park receptor is no longer significant. This is reflected in the model by no gas usage at the Fisk plant which is the major contributor to Hyde Park for 315° winds. This program allocates a total of 4.6×10^4 therms of gas to the Crawford plant.

d. Program No. 4: Wind Speed = 4 mph, Gas Usage and Load Shifts from Crawford. Program No. 4 illustrates the value of load shifting. Here the episode is controlled entirely by load shifting from the Crawford plant. Gas has not been used at all. A significant reduction from the 2.7×10^6 therms is required for the general alarm. The load-shift program is shown in Table 8.2. The total load shifted from Crawford was 541 MW during the 6-hr period.

8.4.14.8 Conclusions Based on Sample Results. The sample programs above indicate the significant economic advantages of using a control model such as described here. Each run took about 6 sec of 360 Model 75 computer time. Thus, control on a near-real-time basis, through the use of teleprocessing equipment, is feasible.

This control model must rely on the effectiveness of the SO_2 dispersion model. Since the imposition of any control is disruptive, and the amount of control depends on the relative predicted contributions to pollution levels, one must have assurance that controls are being applied properly and fairly. In other words, if it is indicated that CECO should burn 7200 therms of gas at the Crawford plant between 6 and 7 a.m. to reduce the level of pollution at Lindblom and Hyde Park to 0.2 ppm at 9 a.m., control should only be imposed if there is reason for confidence in the prediction that the 9 a.m. air-quality reading will be approximately 0.2 ppm as a result.

An obvious concluding question for this pilot study is to consider the possibility of extending a control model of this type to other SO_2 sources or to the city as a whole. This topic is explored in Sec. 8.5 below.

8.5 The Design of an Air Pollution Episode Control Plan

Following from these studies of air pollution episode control effectiveness, resource availability and allocation, an array of practical, contingency plans for use in field operations was developed. Argonne National Laboratory, the Chicago Department of Air Pollution Control, and the National Air Pollution Control Administration initiated a series of air pollution episode control tests as a part of the Chicago Air Pollution System Analyses program. The objectives of these tests were:

- 1) To develop and field-test the command, control, and organizational structure necessary to implement an air pollution episode control operation.
- 2) To determine and acquire the data base, logistical support, and informational inputs required for a successful control operation.
- 3) To identify the resources available for air pollution episode control and the legal, physical, operational, and economic constraints imposed on such an exercise.

- 4) To train air pollution control department personnel in the tactical operations and procedures associated with air pollution episode control.
- 5) To evaluate the effects of emission control and urban micro-meteorological conditions on ambient air quality.
- 6) To identify, establish, and test the channels of communication required to implement an episode control exercise.

The initial effort to develop and field-test a prototype operational air pollution episode control strategy was focused on the control of sulfur dioxide emissions from coal- and oil-burning industrial sources, large commercial and residential structures, and urban power plants. The emphasis placed on sulfur dioxide emission control was dictated partly by the fact that the Chicago telemetered air-monitoring (TAM) system was available to provide a near-real-time assessment of the effectiveness of an emission-control test, and partly by virtue of the fact that fuel-combustion processes are more susceptible to short-time horizon operational control than, for example, are vehicular traffic or waste incineration. If further rationalization of this approach were required, the fact that consistently high ambient sulfur dioxide concentrations represent one of Chicago's most serious air pollution problems constitutes ample justification for this course of action.

The field-test program designed to culminate in the development of an episode control strategy was divided into three phases:

- 1) Fixed-response emission-control tests.
- 2) Meteorologically initiated emission-control tests.
- 3) Air pollution episode-control war games.

8.5.1 Fixed-response Emission-control Tests

The first phase of this program, the fixed-response emission-control test series, had two primary objectives:

- 1) To evaluate the ability of major sulfur dioxide sources to respond to a fixed emission-control schedule established well in advance of the test period.
- 2) To assess the relative effectiveness, in terms of resultant ambient air quality, of imposing control on various elements (power plants, industrial sources, etc.) of the urban sulfur dioxide-producing complex.

Another objective of this and subsequent tests was to acquire fuel-consumption data that could be used to develop diurnal and weekly emission

patterns or schedules for major source aggregates. This information would be used to refine the Chicago emission inventory and would serve as input data for air-resource management studies based on the use of a computerized atmospheric diffusion model which at that time was being developed by Argonne National Laboratory.

The fixed-response emission-control test took place during a three-week period in October and November 1967. During the first week of the test, the major dual fuel power plants in Chicago were switched from coal to natural gas and back according to a preset schedule while participating industrial and commercial fuel users burned high-sulfur coal and oil. During the second week of the test, the power plant system burned high-sulfur coal, while dual fuel industrial and large residential and commercial heating plants operated on a fuel switch schedule. In the third week, both power plants and dual fuel industrial and heating plants were asked to operate on a preset fuel switch schedule which called for all sources to alternate between high-sulfur fuels and natural gas. All participating fuel users, including single-fuel plants which could not engage in a fuel-switching operation, were requested to maintain hourly fuel-consumption records during the three-week test period.

The results of this first emission-control test may be summarized as follows:

- 1) Given that an adequate supply of natural gas is available, operational control of dual-fuel power plants proved to be quite feasible. The Chicago power-plant system demonstrated a capability for rapid and flexible response to emission-control operations, which, when combined with power-load shifting to downwind or extra-urban generating stations provided a significant degree of control. This capability can be exploited during situations in which atmospheric diffusion conditions are such that sulfur dioxide from high power-plant stacks reaches the ground in significant amounts. The major restrictions on power-plant operational control are associated with the fact that discretionary natural gas may not be available during the heating season when the highest sulfur dioxide concentrations are normally observed in Chicago; moreover, the feasibility of power load shifting is strongly dependent on the real-time demand imposed on the system. During periods of minimum consumption, as much as 50% of Chicago's power demand can be imported; during peak load periods, only about 11% can be provided by extra-urban generating facilities. The mechanics of partial or total switching of dual-fuel power-plant boilers from gas to coal normally presents no significant operational problems.

- 2) A significant temporary reduction in utility, industrial, and space-heating SO₂ emissions was accomplished through the conversion of the city power plants and approximately 20 large dual-fuel plants to natural gas. These plants account for over 70% of Chicago SO₂ emissions. Switching

from coal or oil to natural gas on fairly short notice (1-2 hr maximum) does not impose a serious operational penalty on most dual-fuel facilities; however, a request to switch from gas to coal may involve a longer lead time, since additional personnel are often required to fire up and operate furnaces. Reconversion from gas to oil normally presents no significant operational problems.

3) An estimate of the economic penalties associated with dual fuel switching was obtained. A differential fuel cost is imposed on any dual-fuel plant which is requested to convert to natural gas during periods when this fuel is not available at the "off-peak," "dump," or "interruptible" rates at which the firm normally purchases gas. Firms that contract for "interruptible" gas at 2.5-3.5¢ per therm could, under extreme circumstances, be obliged to purchase gas at an emergency rate of 12¢ per therm.

4) Due to the prevalence of unseasonable meteorological conditions, including prolonged periods of high wind speed, precipitation, and low temperature, it was not possible to develop meaningful correlations between controlled emissions and ambient air quality during the test period. Relatively low (0.05-ppm) ambient sulfur dioxide concentrations were recorded throughout the test.

5) Fuel-consumption records maintained by approximately 50 participating industrial and space-heating fuel users, a complex of large municipal pumping stations, and the six local electric utility plants provided a data base for refining Chicago's emission inventory and planning future tests. A portion of the records returned by participating plants was incomplete, and the need for increased liaison between departmental personnel and plant operators was indicated in some instances.

8.5.2 Meteorologically Initiated Emission-control Tests

The second phase of the test program was conducted during a three-week period from June 16 through July 6, 1968. The objectives of the second test series were essentially identical to those of the first, with the significant exception that the emission-control operations were initiated on the basis of meteorological forecasts of weather conditions conducive to the acquisition of useful air-quality data. The second test series was thus a major step closer to the implementation of an air pollution episode control operation, since such an exercise would also be initiated by a meteorological forecast.

The control schedule devised for the second test series was markedly different from that of the first and represented an attempt to maximize (1) the probability of conducting the tests during favorable meteorological conditions, and (2) the number of control operations that could be conducted

during the test period. Moreover, the modified control schedule reflected the necessity--made evident during the first test series--of increased coordination between DEC personnel and participating industrial and heating-plant operators.

During the first week of the test series, the control schedule required all participating industrial and power plants to maintain hourly fuel-consumption records. No fuel switching or other controls were imposed during this period; however, department personnel visited each participating plant to ensure that appropriate records were being maintained and that plant operators were fully aware of their role in the operations projected for the following weeks.

During the second week of the tests, all participants were required to begin the work week on Monday morning using high-sulfur-content fuels. The power-plant system and operators of dual-fuel industrial and heating plants had been advised, in advance, that they would be requested to switch to natural gas at some time during the week. This request would be transmitted with a lead time of approximately 24 hr. The switching operation was not to be initiated before 0800 CDST on the selected day and was to be completed by 1200 CDST of that day. Once the fuel conversion was accomplished, the plant was asked to burn natural gas for at least three days or until notified that the test was terminated, whichever event occurred first. All participants, including single-fuel plants, continued to maintain hourly fuel-consumption records during this period.

Emission control during the second week was initiated on the basis of meteorological forecasts provided by the Chicago office of the U.S. Weather Bureau. To separate the effects of industrial and power-plant emissions on ambient air quality, the utilities were asked to implement their conversion to natural gas 24 hr later than were the industrial and heating plants. The advance warning lead time provided to both source aggregates was essentially the same. That is, the utilities received notification of a pending fuel switch approximately 24 hr later than did their industrial counterparts.

The third week of the tests was designed to be a duplicate of the second week, except that the meteorological forecast might be expected to require the fuel switch to take place on a different day of the week than was the case for the previous week. Thus, during both the second and third weeks of the test period, participating plant operators did not know in advance exactly when a fuel switch would be requested--a fair approximation of the conditions that might prevail during a genuine episode control operation.

The results of this test are as follows:

- 1) The first week of the test, during which the recordkeeping procedures of the participating plants were monitored by departmental personnel,

resulted in the acquisition of considerably better and more complete fuel-consumption records than had been developed during the first test series. Communications between the department and plant operating personnel were improved.

2) Operations during the second week of the test period were conducted as planned; however, unfavorable meteorological conditions, including high winds and precipitation, resulted in the early termination of the test. This was dictated in part by the fact that many major fuel users in Chicago maintain only limited stockpiles of coal or oil during the spring and summer, and the depletion of these stockpiles without acquiring significant air-quality data during this test week would have compromised the prospects for a more successful third test week under more favorable meteorological conditions. The successful initiation and termination of second-week operations on the basis of prevailing meteorological conditions constituted a fairly significant test of the communications requirements and response capability of the participating fuel users. Fuel-consumption records were also acquired for this period.

3) During the third week of the test period, meteorological conditions were quite favorable for the emission-control test and the operation resulted in the acquisition of a significant body of air quality data. Correlations between emissions and air quality were observed and virtually all objectives of the test were attained.

8.5.3 Air Pollution Episode Control Exercise

The third phase of the program to develop an episode control strategy involved the addition of a new dimension to the emission-control operations of the earlier phases. The third emission-control test was designed as an episode control exercise which includes a considerably more realistic simulation of the command and control structure, organization, communications, logistical support functions, technological aids, and decision processes involved in the implementation of an episode control operation than was attempted in either previous exercise. This exercise includes:

1) Liaison with local and regional air pollution meteorological forecasting services.

2) Real-time monitoring and advance forecasts of air quality and meteorological conditions.

3) Use of a source-oriented atmospheric dispersion model to assess, on a real-time basis, the relative effectiveness and feasibility of alternative control strategies.

4) Optimal management and allocation of natural gas as a resource for emission control.

- 5) Responsive control of the urban power-plant system.
- 6) Identification, definition, and testing of key technical and administrative roles in an episode control operation;
- 7) Utilization of surveillance and enforcement resources, including radio-dispatched patrol units, an instrumented helicopter, and a television monitoring system.

The prototype command and control schematic diagram for this exercise is shown in Fig. 8.18, which also illustrates the information flow involved in the implementation of the strategy. The organizational structure implied in Fig. 8.18 was deliberately designed to correspond as closely as possible to electric-power and natural-gas dispatching operations. Although an episode control operation must be closely coordinated with energy resource management, the information flow and command structure of utility dispatching operations, which are highly sensitive to meteorological conditions and which involve a continuous process of preliminary planning, responsive decision-making, real-time communications, and situation evaluation, can be shown to be remarkably similar to the procedures required to implement an episode control operation. To illustrate this point, a brief description of the utility dispatching operation is appropriate.

Perhaps the major difference between the power and gas dispatching functions and an air pollution control operation is that the former are conducted on a continuous basis, while the latter is an emergency mode of operation that would prevail only during an air pollution crisis situation. Nevertheless, the analogy that can be drawn between the day-to-day management of energy resources and an air pollution episode control operation that a municipal or regional control agency would wish to conduct is sufficiently strong that it is appropriate to organize the latter along the lines developed and tested by the utilities.

8.5.4 Utility Dispatching Operations

The demands for power and natural gas in a large urban complex vary from hour to hour and are strongly dependent on prevalent meteorological conditions. It is the function of the electric-power dispatching office to develop predictions of the total system power demand for periods up to 12 hr in advance, on the basis of meteorological forecasts and recent power-consumption data. A schedule for bringing the most effective combination of generator units up to power and on-line is then created. This schedule, which is sensitive to current fuel costs, equipment efficiency, outages, and plant operational constraints, seeks to generate each increment of power required during the planning period with the most efficient and economical combination of equipment available. Changes in meteorological conditions or

Fig. 8.18, Command and Control Schematic Diagram of Air Pollution Episode Control Strategy. ANL Neg. No. 190-125.

unforeseen equipment failures require immediate revision of the operating schedule and communication of the resultant decisions to a statewide interconnected network of power plants.

The natural-gas dispatching functions are even more sensitive to meteorological conditions than the power dispatching operation. The predicted space-heating requirements of a service region must be satisfied by allocating gas from primary supply pipelines, underground storage reservoirs, and liquified-gas storage facilities. Any residual or discretionary gas that remains after the heating budget of the area has been balanced may either be distributed to a network of "interruptible," industrial, commercial, or residential dual-fuel plants, or stored.

A continuing process of assessing the meteorological situation, predicting energy demands, evaluating the status of the system, preparing system operating schedules, and implementing energy management decisions through established channels of communication thus characterizes both utility dispatching functions.

8.5.5 Organization of an Episode Control Operation

Given the premise that air-resource management during a crisis situation is analogous, in many respects, to energy-resource management under normal conditions, an organizational structure of the kind indicated in Fig. 8.18 is appropriate. Three key functional roles are evident in this command and control schematic diagram:

- 1) The air pollution meteorologist.
- 2) The operational strategist.
- 3) The tactical dispatcher.

These roles are described below.

8.5.5.1 The Air Pollution Meteorologist. The task of the air pollution meteorologist in an episode control operation is to produce a real-time assessment and short-range (12-24 hr) advance forecast of the state of the urban atmosphere, and to translate these evaluations into an air pollution potential estimate which can be used directly in the development of optimal control strategies and their tactical implementation. The meteorologist must therefore reduce the results of a technically complicated analysis of an array of synoptic, meso- and microscale meteorological parameters which influence air pollution dispersion into a highly condensed and functional status report and forecast which can be used immediately in the field operations associated with emergency control.

In Chicago, the air pollution meteorologist can draw upon five primary sources of information in the development of his summary report:

- 1) ESSA regional air pollution potential alert reports.
- 2) Local weather data and forecasts provided by the U.S. Weather Bureau stations sited at Midway, O'Hare, and other Chicago area airports, including EMSU soundings.
- 3) Specialized air pollution meteorology forecasts, including mixing-layer altitude and atmospheric-stability estimates provided by a local professional meteorology firm.
- 4) Real-time measurements of sulfur dioxide concentrations, wind speed, and direction from eight telemetered air-monitoring stations.
- 5) Real-time measurements of the local vertical temperature profile, relative humidity, and sulfur dioxide concentrations distribution aloft. These are obtained by means of a helicopter-borne instrument package.

The utility of this array of information is more or less self-evident. We have arranged the regional and local meteorological forecasts as parallel inputs to the air pollution meteorologist, rather than as a series in which a regional forecast triggers the development of a local forecast. This is the case because micrometeorological conditions in Chicago and other urban concentrations are often conducive to the accumulation of locally high air pollution concentrations when no regional air pollution potential warning is warranted.

To reduce the available information to an appropriate air quality estimate, the Chicago meteorologist has at his disposal two, essentially equivalent, receptor-oriented statistical-forecasting techniques for estimating the probable air quality at each station of the TAM network. These are:

- 1) A statistical technique, based on multivariate discriminant analysis of historical data from each TAM station. This method provides an estimate of the probability that the sulfur dioxide at each station will exceed a critical threshold value. Probabilities are calculated as functions of critical meteorological parameters. This methodology, which has been undergoing operational testing in Chicago since January 1969, includes the interesting feature that the computerized data-analysis technique automatically eliminates parameters that are not statistically significant in the determination of air quality.

Figure 8.19 shows the standard format currently employed in the presentation of a discriminant-analysis air quality forecast.

- 2) A tabular, "look-up" type of air quality forecasting scheme, based on statistical analyses and display of recent, historical sulfur dioxide

DATE: _____
 TIME: _____
 GIVEN BY: _____
 RECEIVED BY: _____

CONTROL POINT:

MIDWAY AIRPORT:

HOUR	1. SURFACE WIND DIRECTION		2. SURFACE WIND SPEED*		3. MIXING HEIGHT INDEX		4. DRY BULB TEMPERATURE (SURFACE)		5. CEILING BELOW 7,000		6. RELATIVE HUMIDITY		7. CLOUD COVER	8. CEILING HEIGHT		9. PRECIPITATION (OVER A TRACE)		10. VISIBILITY		11.
	Prb.	(MPH)	Prb.	(MST)	Prb.	(°F)	Prb.	(YES/NO)	Prb.	(%)	Prb.	Prb.	(ft.)	Prb.	(YES/NO)	Prb.	(mi.)	Prb.		
NOON																				
1 pm																				
2 pm																				
3 pm																				
4 pm																				
5 pm																				
6 pm																				
7 pm																				
8 pm																				
9 pm																				
10 pm																				
11 pm																				

HOUR	TAM SO ₂ PREDICTIONS AND ACTUAL READINGS - PROBABILITIES ARE FOR SO ₂ > 0.3															
	1		2		3		4		5		6		7		8	
	PROB.	ACT.	PROB.	ACT.	PROB.	ACT.	PROB.	ACT.	PROB.	ACT.	PROB.	ACT.	PROB.	ACT.	PROB.	ACT.
NOON																
1 pm																
2 pm																
3 pm																
4 pm																
5 pm																
6 pm																
7 pm																
8 pm																
9 pm																
10 pm																
11 pm																

REMARKS: _____ _____ _____ _____ _____ _____	* BEAUFORT WIND SCALE GRADUATIONS:	LOG:	
	1 - 3 mph	19 - 24 mph	☐ FORECAST EFFECTIVE.
	4 - 7 mph	25 - 31 mph	☐ FORECAST NOT EFFECTIVE.*
	8 - 12 mph	32 - 38 mph	* REASONS: _____
	13 - 18 mph	39 - 40 mph	_____

Fig. 8.19. Format for Discriminant-analysis Air Quality Forecast

concentration data stratified in terms of significant meteorological parameters. The tabular method of presentation is perhaps more physically meaningful than the statement of threat probabilities provided by the discriminant-analysis technique. To use the system, the analyst need only refer to a set of tables, indexed in terms of meteorological parameters, in order to determine, for a given meteorological situation, season, and time of day, the historical percentile distribution and maximum and minimum sulfur dioxide concentrations recorded at a given monitoring station. A sample of the display format is shown in Table 6.4.

Chicago is fortunate in that the available data and resources yield a meteorologist's status report, which presents information in the most compact and physically meaningful terms--a statement of present and anticipated air pollution concentrations and distribution patterns. Operational personnel who must make control decisions on the basis of such input are not, therefore, burdened with a complex interpretive task. A comparison of past and projected sulfur dioxide concentrations with what are currently regarded as biologically acceptable dosages indicates whether, and to what extent, control operations are required. The development of an equivalent meteorological status summary for regions or municipalities that have not yet accumulated a fairly significant body of air quality data would, we believe, be somewhat more difficult in the sense that the meteorologist's analysis could not as readily be reduced to a single air pollution potential index having the same direct significance for planning purposes as a biological air pollution dose rate.

During an episode, it is the responsibility of the air pollution meteorologist to revise his estimates as often as the meteorological situation warrants. Following the pattern established by the public utilities, automatic updating of the air-quality status report at approximately 6-hr intervals is considered appropriate, whether or not the local meteorological situation has undergone significant change since the preceding estimate was developed.

8.5.5.2 The Operational Strategist. The operational strategist integrates the air-quality status report and forecast provided by the meteorologist with an assessment of the resources available for emission control (such as the current inventory of discretionary natural gas), the operational status and controllability of significant pollution producers, and the relative effectiveness of controlling various sources. This compilation of information is used to develop a responsive control strategy which is tailored to the prevailing and predicted meteorological situation and to the current capability of the city or region to comply with an emission-control plan. The strategist seeks to impose the minimum degree of control that is practical and consistent with the attainment of acceptable air-quality standards.

As the master planner of an air pollution episode control operation, the strategist has duties that fall into five primary categories:

1) To initiate an air pollution episode control operation on the basis of a report from the air pollution meteorologist and an analysis of data returned by a system of air-quality monitoring (TAM) stations.

2) To allocate discretionary natural gas among the city's dual-fuel industrial and heating plants and develop a process control plan for single-fuel plants. The strategist accomplishes this by compiling a list of controllable sources and a natural-gas availability report, which are used to formulate an operational control schedule for air pollution abatement. An atmospheric diffusion model is a key element in the development of this control strategy.

3) To determine when the transition from one state of control to the next should occur.

4) To keep the public informed of all major changes in the air quality of the city which may affect their health or welfare.

5) To determine when episode control measures may be terminated, on the basis of meteorological forecasts, air-quality predictions, and recorded dosages.

8.5.5.3 The Tactical Dispatcher. The preceding discussion described the functions of the operational strategist, who is, in effect, the master planner and policy maker of the episode control operation. To implement the strategy, however, a tactician or field commander must provide liaison with the public utilities and the municipal, industrial, and commercial sulfur dioxide sources involved in the episode control exercise. As indicated in Fig. 8.18, the "tactical dispatcher" must also monitor, direct, and deploy the various surveillance and enforcement resources available to the department.

The primary responsibility of the dispatcher is to ensure that the fuel users involved in the control strategy comply with the emission-control measures devised by the strategist. During the watch period, therefore, the dispatcher acquires current operational status information for all sources involved in the emission-control plan. These data are displayed on a master source-status board (see Fig. 8.20) which is continually updated during the episode.

Source-status information is derived primarily by telephone contact with the utility dispatching officers and the plant operators, building superintendents, etc., who are involved in the control operation. In large cities such as Chicago, however, additional surveillance is possible through deployment of a fleet of radio-dispatched patrol cars, an instrumented helicopter or aircraft, and a TV monitoring system (eye-in-the-sky).

DATE _____

TOTAL GAS AVAILABLE _____ THERMS

[illegible]

Fig. 8.20. Episode Control Status Log. ANL Neg. No. 190-124.

Field-patrol units are normally employed for routine inspection and enforcement operations; however, during an episode, they are placed on alert status and deployed in areas involved in emission-control operations. These units report violators, enforce compliance with emission-control directives, and provide area-wide surveillance of a controlled corridor.

If available, an instrumented helicopter or aircraft can provide both meteorological data for the air-quality forecasts and aerial surveillance of the city for the tactical dispatcher. The helicopter maintains constant radio contact with the air pollution control center and is normally deployed on observational patrol sorties by the tactical dispatcher; however, the dispatcher releases control to the meteorologist when a data-acquisition sortie is required.

Additional informational inputs for the tactical dispatcher may be provided by TV monitors atop one or more tall buildings in an urban concentration, and by a file of panoramic photographs of the area surrounding each air-quality monitoring station. The TV monitor yields real-time views of the central city area; the photographic file supplies a visual record of the distribution of sources and neighborhood layout in the vicinity of each receptor.

The tactical dispatcher, at the center of a city-wide or regional communications network, is both a relayer of information (to and from the operational strategist, the utilities, and the controlled sources) and a field commander, deploying surveillance resources and implementing and enforcing compliance with the control strategy. His functions and responsibilities are clearly separate from those of the air pollution meteorologist and the operational strategist, but his role is equally important, since it is he who must translate the results of the forecasting and planning activities into an effective emission-control operation.

9. EMISSION CONTROL TESTS*

(J. E. Carson, E. W. Klappenbach, R. J. Votruba,** and J. W. Lin)

9.1 Introduction

A primary reason for developing an urban diffusion model is that it can be used on a basic component of an effective and economical abatement strategy to prevent or at least reduce the severity of air pollution episodes.

Complete details of the pollution abatement plan developed under this contract can be found elsewhere in this report (see Sec. 8) and in the literature (Croke and Booras, 1970). Briefly, the proposed air pollution control plan is to use selective fuel switching to prevent air pollution levels from reaching unacceptable levels during periods of weak winds and weak dispersion. That is, major sources of the pollutant located upwind of an area of existing or forecast poor air quality and able to use low-polluting fuels are asked to convert to those fuels when meteorological conditions are unfavorable.

There is only one way to reduce the concentration of a given air pollutant during a period of poor ventilation in an urban area: reduce or stop the emission of that material. Ideally, the reduction in the rate of release of the effluent should begin before the atmospheric concentrations have a chance to build up to undesirable levels.

Sulfur dioxide is a major (but certainly not the only) pollutant in the Chicago area. Unfortunately, the supply of near-zero-sulfur fossil fuels is not sufficient for all fuel users to permanently convert to nonpolluting energy sources. Also, technology that would permit the burning of our major sources of fossil energy--coal and oil--without emitting most of the sulfur oxides to atmosphere has not yet been developed.

*We wish to express our thanks to the industrial plants, power-generating stations, and commercial establishments that cooperated with the City of Chicago's Department of Environmental Control in conducting this unique and valuable experiment in air pollution abatement and absorbed the costs of participation. The contributions of the operating engineers of the various plants who actually made the fuel switches and kept fuel use records are acknowledged. The assistance provided by Mr. Robert Lundberg of the Commonwealth Edison Company and Mr. Charles Vanek of the Peoples Gas Light & Coke Company was invaluable.

Special thanks are due two members of the Chicago Office of the National Weather Service: Mr. Joe Fulks, for the special weather forecasts used to initiate the 1968 test; and Mr. Arthur Strong (EMSU or Environmental Meteorological Support Unit), for the mixing-depth radiosonde data.

The stability index information was supplied by Murray and Trettel, Inc., a private consulting meteorological service organization. Messrs. Loquercio and Murphy (DEC) were very active in the operational stages of the control tests.

**Deceased, October 16, 1969.

Several techniques are available to reduce the amount of SO_2 emitted into the atmosphere during periods of unfavorable meteorological conditions. One technique would be to require all the SO_2 producers, large and small, in the Chicago area to stop emitting this gas during poor ventilation periods. Such a drastic procedure could not be implemented; for example, the cost in lost industrial production would be prohibitive. Also, many homes and apartments are not able to use low-sulfur fuels for space heating, and these could not be turned off during the winter.

A second technique would be to require all large fossil-fuel users in Chicago with dual-fuel capability (coal/gas or oil/gas) to burn only low-sulfur fuels when an air pollution episode exists or is forecast. The resulting reduction in the production of this material would act to "shave the peak" of SO_2 levels in the entire area. Unfortunately, the supply of natural gas and other near-zero-sulfur fuels available for pollution abatement is limited, especially during the heating season when most Chicago air pollution episodes are observed.

Croke and Booras (1970) have found that most SO_2 air pollution episodes in Chicago affect only 20-50% of the area of the city. (For example, see the air pollution maps for Chicago during the November 1969 air pollution episode, Sec. 4.) During these periods, a better (in that it would be less costly and less disruptive to the normal activities of the city) method to reduce SO_2 concentrations in the polluted areas is to use the available supply of low-sulfur fuels in those dual-fuel plants located upwind of the affected areas.

It is obviously a waste of valuable and scarce pollution-control resources to use low-sulfur fuels in plants not contributing significantly to the polluted areas. Also, since its cost varies with season, gas becomes an expensive fuel during the heating season when most needed for pollution control. Industry would object to increasing its costs in the name of pollution control when in fact the action did not have the desired effect.

The production of SO_2 in the city can also be reduced by having the local utility shift the generation of electric power either to plants outside the city or to plants downwind of the affected area. Load shifting is a basic component of the episode-control plan.

As a corollary, it could be argued that major fuel users should conserve the supply of low-sulfur fuels by burning high-sulfur fuels during periods of low pollution, such as in summer when space heating is not needed and during the winter whenever strong winds and rapid dispersion act to prevent the buildup of unacceptable SO_2 concentrations. Thus, more low-sulfur fuels would be available for pollution control when needed.

The Argonne urban diffusion model, plus current and forecast meteorological conditions, current air quality data, and known fuel-consumption patterns, are used to forecast future pollution levels in the city. If an area of unacceptably high SO_2 concentrations is either observed or forecast to develop, the computer model can be used to estimate the relative contribution of specific large SO_2 sources on air quality in the polluted areas, and also the relative cost of converting each plant to low-sulfur fuels. The air quality control officials would then select for fuel switching those plants which, when converted, would have the maximum improvement of air quality with the lowest cost and least disruption of normal operations. This episode-control plan has an advantage in that it can be implemented during the heating season when limited supplies of low-sulfur fuels are available for pollution abatement.

The dispersion calculations may show that SO_2 emitted from tall chimneys with significant plume rise (such as utility stacks) may not reach the ground in the affected area. If so, these plants should remain on their regular fuel and the available supply of natural gas be used by those dual-fuel plants having shorter stacks.

The Argonne episode-control plan is based on the assumption that the best way to reduce SO_2 emissions during periods of poor air quality is to impose minimum control on sources consistent with the preservation of acceptable air quality levels.

The effectiveness of this control strategy will depend on many factors, including (1) the ability of the diffusion equations to accurately predict ground-level SO_2 concentrations from single and multiple sources in an urban area, (2) the ability of the meteorologist to forecast the weather (especially wind speed and direction), (3) the availability and cost of alternate fuels, and (4) the location of dual-fuel plants with respect to the polluted areas.

In contrast with other episode-control plans proposed in the past, the one developed under this contract has been tested in a full-scale laboratory, the City of Chicago. The Argonne episode-control plan is a complex operation involving many organizations and people with conflicting interests and involving not insignificant economic considerations. This plan, like all other contingency plans, should be tested in the real world to determine its effectiveness, to locate weaknesses in the plan itself (such as the availability of alternate fuels, the ability of fuel users to convert on short notice, and the ability of the electrical utility to shift its load to alternate generating sites), and to suggest ways in which the control scheme can be improved.

The Chicago Department of Environmental Control (DEC), in co-operation with engineers and scientists from the Argonne National Laboratory (ANL), have conducted three full-scale tests of the episode-control plan.

In these trial runs, the City of Chicago was used as an "outdoor laboratory" to test in actual operations the mechanics of the Argonne pollution-abatement plan. Those industries who took part in this series of tests, often at no small cost or effort, are to be commended.

Section 8 of this report and the paper by Croke and Booras (1970) describe in greater detail the philosophy and modus operandi of the Argonne episode-control plan based on selective fuel switching. Croke and Booras discuss the facilities available to DEC to implement, monitor, and verify the control actions, the role of the various DEC personnel in the actual operation of the plan (such as the tactical dispatcher, the control strategist, and the air pollution meteorologists), and the mechanics of the control techniques. Also discussed are the objectives, schedule, and results of the three fuel-switch tests performed in Chicago.

9.2 Implementation of the Fuel-switch Tests

This section deals primarily with the changes of air quality observed during the fuel-switch test periods and to relate these changes to weather conditions and changes in SO_2 emission.

Chicago was the first major city in the U.S.A. (and perhaps the entire world) to deliberately vary the rate of production of an atmospheric pollutant on a city-wide basis on a schedule designed to test an air pollution abatement strategy and to learn more about diffusion and transport over a large urban area. The episode control tests discussed in this report represent a joint effort conducted by the Chicago Department of Environmental Control, the Atomic Energy Commission, and the National Air Pollution Control Administration of the Department of Health, Education, and Welfare. The Chicago DEC was responsible for program direction and for handling the mechanics of the fuel-switch tests. DEC personnel contacted each plant, secured their cooperation, and provided the appropriate plant officials with details of the test schedule and objectives and verified their cooperation, etc. DEC also provided the necessary forms for logging fuel-consumption data.

Engineers and scientists from the Center for Environmental Studies and the Radiological Physics Division of Argonne National Laboratory cooperated with the DEC in the planning and operational phases of these simulated "pollution episode control tests." The plan for the third test was about as close to a controlled laboratory experiment as one could hope to conduct in an area as large and diversified as Chicago. Ideally, changes from low- to high-sulfur fuel and back should be made during periods of fairly constant weather conditions for periods of 24-72 hr so that the effect of the time variations of SO_2 production on air quality can be isolated and studied.

The techniques practiced during this test were used to good advantage during a period of stagnation and high SO_2 pollution, November 5-11, 1969.

These city-wide pollution experiments had three primary objectives: (1) to act as a trial run for establishing procedures for implementing effective SO_2 abatement procedures during periods of air pollution buildup, (2) to observe changes in air quality due to fuel changes and to relate these changes with those computed from the diffusion equations, and (3) to provide Argonne scientists with detailed air quality, meteorological, and SO_2 emission data during short periods to aid in the development of better methods for predicting air pollution levels and fuel-consumption patterns.

These outdoor experiments did bring into sharper focus the practical actions that industry can and cannot realistically take to reduce or curtail SO_2 output during pollution episodes. Any air pollution abatement strategy must, of course, be based on accurate assessments of the availability of low-sulfur fuels and industrial-commercial operating procedures, so that no impossible burden will be asked of industries, commercial establishments, and large space-heating facilities by air pollution control operations.

During all three fuel-switch tests, no reduction in the rate of SO_2 production from the major single-fueled plants or from the tens of thousands of other small smoke stacks in the city (such as coal- and/or oil-fired heating plants in small factories, commercial establishments, apartments, and residential space-heating units) was attempted. In a real pollution emergency, it may be necessary to either turn off these small but numerous SO_2 sources or force them to use low-sulfur coal and/or oil. The tests showed that significant amounts of SO_2 are advected into the city from sources outside the city.

Air pollution meteorologists at present do not know enough about air motions and the rate of dispersion and dilution of pollutants from either a single or a small number of sources over large urban areas under all weather conditions to make accurate ground-level concentration predictions. The fuel-switch tests described in Sec. 9.3 below were designed in part so that a better understanding of air currents and dispersion mechanisms over Chicago would result.

Those companies whose concern for improving air quality in Chicago was great enough to undertake the additional cost and effort required to participate in these tests are to be commended for their efforts and community spirit.

9.3. Fuel-switch Test, Fall 1967

The first of the three fuel-switch tests was conducted during a three-week period in October 1967. The six power plants and the next 60 largest SO_2 sources (based on annual emission data) in the city were asked

to participate. All plants were asked to keep hourly fuel use data so that the hourly emission rates of SO_2 could be determined. The utility and the 20 dual-fuel plants in the group were also requested to make several fuel changes (to natural gas from their usual high-sulfur fuel and back) during the period. The plants asked to convert to maximum use of low-sulfur fuels (or to switch power loads) account for about 70% of the annual SO_2 production in the city (Croke and Booras, 1970). Since most plants are not able to convert completely to gas, a 70% reduction in SO_2 is not possible to achieve.

The fuel-conversion schedule was prepared several weeks in advance. For an outdoor experiment to yield useful data on the relation between air quality and SO_2 emission rates, the only variable should be the known SO_2 output rate. This means that weather conditions (wind speed and direction, height of the mixing layer, and air temperature--which controls space-heating fuel use) must remain reasonably constant. Before this fuel-switch test began, it was hoped that weather conditions at the time of the fuel switches would be sufficiently steady that observed air quality changes could be related to fuel use. Unfortunately, the weather did not cooperate. Strong and shifting winds, precipitation (including some snow flurries), and unseasonable cold prevailed during the times of fuel switching. As a result, air quality remained good (SO_2 concentrations less than 0.05 ppm); no correlation between air-quality changes and fuel changes was observed despite a marked reduction in SO_2 production.

The primary objectives of this first test were reached (Croke and Booras, 1970). This test proved that most large dual-fuel plants could shift to natural gas on short notice (1-2 hr), and that with an adequate supply of natural gas, SO_2 production could be significantly reduced. Much information on plant operating procedures and their ability to reduce SO_2 emissions was obtained, as were data on the economics of fuel switching. The test showed that future fuel-switch tests should be scheduled on the basis of a short-term weather forecast and that better lines of communications between the DEC and plant operating personnel were needed. The fuel consumption data collected during this period proved to be most useful in the Laboratory's emission-inventory investigation (see Chapter 2).

9.4 Fuel-switch Test, Summer 1968

9.4.1 Test Schedule

The second fuel-switch test was conducted between June 16 and July 6, 1968. A total of 76 plants, which produce on an annual basis 85% of the city's SO_2 , were asked to participate.

The objectives of this test were the same as those for the fall 1967 experiment. The schedule for the second test was a marked improvement over

the first, in that the switches from high- to low-sulfur fuels were to be made on the basis of a weather forecast rather than a calendar. The lessons learned during the fall 1967 test were incorporated into the 1968 fuel-switch experiment. The second experiment was much closer to an implementation of an air pollution episode control plan. Croke and Booras (1970) have called this field experiment a "meteorologically-initiated emission control test."

It was decided that the fuel-conversion test should cover a three-week period. No actual changes in fuel use by industry were requested during the first week. This period was planned in part to allow the operating engineers of the various plants to become familiar with furnishing hourly fuel-use data, to establish lines of communications between DEC and the operating engineers of the plants, and to ensure the cooperation of the various SO₂ sources.

Figure 6.4 shows the locations of the city's eight Telemetered Air Quality Monitoring (TAM) reporting stations, three airports, the six Commonwealth Edison power plants, several large commercial establishments and multiple residences, and the 50 largest industrial plants in numerical order of their annual SO₂ production. Those industrial sources with dual-fuel capacity (coal/gas or oil/gas) are shown as double circles. The eight TAM stations have been reporting SO₂ and wind data every 15 min since January 1, 1966.

Industries and other large SO₂ producers with single-fuel capacity (coal or oil) were asked to collect and submit detailed hourly fuel-consumption data for the entire test period. Plants with dual-fuel capacity were also asked to maintain hourly fuel-use records for the entire period; they were further requested to burn their usual fuel for that season during the first week of the test, and convert to maximum use of high-sulfur fuels between 0700 and 1100 CST on both June 24 and July 1, 1968.

During the week of June 23, Commonwealth Edison was to convert their plants to minimum use of high-sulfur fuels after 24, 48, or 72 hr on coal, with industry converting one day later. All firms were notified 24 hr before the time of the change from one type of fuel to another; in a real pollution episode, such a long lead time would most likely not be available. The exact date of the return to low-sulfur fuels by the power plants was based on special weather forecasts prepared by the National Weather Service (formerly the U.S. Weather Bureau). It was hoped that fairly steady or uniform weather conditions (same wind speed and direction, no rain, etc.) would prevail for 48 hr or more after the first fuel switch was made so that the SO₂ concentration changes observed at each of the eight TAM stations could be compared with fuel changes. Unfortunately, these ideal conditions did not occur during the first week.

Again on the morning of July 1, all plants with dual-fuel capacity were asked to convert to maximum-sulfur coal or oil. During this week, industry was asked to reconvert to minimum-sulfur fuel on a date selected on the basis of the weather forecast, with the Edison Company following one day later. Fortunately, this time the weather did cooperate.

During the test period (midsummer), space heating, with its unmeasured and highly variable SO_2 emission rates, would be at a minimum. DEC's previous experience indicated that most plants with dual-fuel capability would be using gas, and that the cost of switching to and from high-sulfur fuel would be minimized. It was also believed that most dual-fuel plants would still have supplies of oil/coal available for use and would not have completed their conversions to pure-gas fuel.

DEC officials prepared and sent letters to the major SO_2 emitters in the city, outlining the test program and asking for their cooperation. Two letters, one for single-fuel plants and the other for dual-fuel ones, were distributed. Copies of these letters were sent to several major fuel suppliers in the area to explain the program. Twenty copies of a prepared form for recording hourly fuel use were sent to each plant.

Seventy-six firms were contacted; DEC records show that these plants produce (on an annual basis) 85% of the city's SO_2 . Two major SO_2 producers outside of Chicago's city limits were contacted and did participate: Western Electric in Cicero and the Sanitary District plant in Stickney. Five Chicago City Water Pumping plants, large coal users, were contacted and did submit fuel-consumption data. The response of industry to this air pollution control exercise was only moderately favorable: Only 20 out of 44 dual-fuel and 18 of 22 single-fuel plants agreed to cooperate. The electrical utility and its six urban generating stations cooperated with this and the other two tests by both load shifting and fuel changes. For various reasons, some of the dual-fuel plants were unable or unwilling to follow the schedule. This lack of cooperation naturally reduces the value of the experiment and makes it more difficult to isolate air-quality improvements. Some of the fuel-consumption records were incomplete, others useless.

DEC combustion engineers then placed telephone calls to each plant to enlist their cooperation in the test program, and to obtain the name and phone number of the person(s) to be notified as to the exact time for the fuel switch. These calls were also used to further explain the objectives and scheduling of the test and to answer any questions.

9.4.2 Implementation of the Test

The test began on June 16 with all plants asked to burn their usual fuel for the season and to record hourly fuel-consumption data, if possible. DEC inspectors visited more of these plants to ensure that adequate records

were being collected and that the various plant engineers were aware of their duties during the test period. As a result of these efforts, the fuel-use data were of much higher quality than those previously collected.

For an outdoor experiment of this type to yield useful data, the only variable should be the controlled and known SO_2 output. This means that weather conditions must remain reasonably steady. Weather conditions during the week of June 23 were unfavorable for the experiment, with numerous periods of rain, strong winds, and continually varying wind direction. Industry and the utility plants did convert to high-sulfur fuels on June 24. Rain fell for most of June 25, and the forecast made on that date correctly called for strong easterly winds on June 26 and 27. Since some plants (especially Commonwealth Edison) were running short of coal, and since rain and/or easterly winds would result in data of limited usefulness anyway, it was decided to end this phase of the test. Little useful data relating air-quality changes to SO_2 emission-rate changes were obtained.

Weather conditions for the final week of the test were much more favorable (see Figs. 9.1-9.4). Based on an accurate weather forecast, industry was asked to convert to gas after 24 hr on coal and the power plants one day later (July 3). During and following the switches from natural gas to coal and/or oil and return to natural gas, Chicago was in a westerly to northwesterly flow of cool air behind a strong (for the season) cold front. The low-pressure center associated with this front was over Iowa on Sunday morning, June 30, the day before the test started. This low-pressure center moved to the north and then northeast, with the cold front crossing the city between 2200 and 2400 CST on June 30. Light thunderstorms accompanied the frontal passage, with 0.09 in. of rain falling at Argonne and 0.04 in. at Midway Airport.

At Argonne, strong (15-25 knots) SW surface winds were observed before the arrival of the cold front. The wind switched to moderate (10-15 knots) NW for about 6 hr while the frontal zone passed, and back to W for the remainder of the night and the daylight hours on Monday. The winds veered to moderate NW to N flow until 1400 CST on July 3. Wind speeds decreased as the center of the cold polar high-pressure area moved from WNW to ESE on a path south of Chicago. The Argonne wind direction backed to W and SW on July 1 and remained there through July 4. Except on July 3, when a lake-breeze circulation covered all of Chicago but did not reach Argonne, the wind reports at the airports and the eight TAM stations were basically similar.

The strength of the front and of the cold air mass is shown by the departures from normal temperatures at Midway Airport: June 30, before the cold front arrived, was 9°F above normal; July 1, 1°F above; July 2 and 3, 11°F below; and July 4, 7°F below. These cool maximum temperatures (71°F on July 2, 75°F on July 3) would indicate that electrical power requirements for air conditioning were at a minimum.

Fig. 9.1. Synoptic Weather Map for 0600 CST, June 30, 1968

MONDAY, JULY 1, 1968

Fig. 9.2. Synoptic Weather Map for 0600 CST, July 1, 1968

Fig. 9.3. Synoptic Weather Map for 0600 CST, July 2, 1968

WEDNESDAY, JULY 3, 1968

Fig. 9.4. Synoptic Weather Map for 0600 CST, July 3, 1968

9.4.3 Air Quality and Weather during Test Period

9.4.3.1 June 30. On Sunday, June 30, when many boilers were idle or on natural gas and strong southwesterly airflow covered the city, and before the scheduled switch to maximum coal the following morning, SO_2 concentrations at all eight TAM stations were low (≤ 0.05 ppm) until about 1700 CST. In contrast to other chapters of this report, the SO_2 values shown on the time sections are those reported every 15 min and are not hourly averages. Sulfur dioxide pollution levels ≥ 0.10 ppm were observed for short periods at TAM-2, -6, and -7, as shown in Fig. 9.5. These peaks did not last long, ending before the winds veered to NW with the passage of the cold front. The three most interesting features of the diagram are (1) the similarity of the SO_2 curves for TAM-7 and -2, (2) the very rapid increase in SO_2 concentrations at TAM-2 (from 0.04 to 0.17 ppm) in 15 min, and (3) the isolated high SO_2 concentration at TAM-6 at 1900 CST.

Fig. 9.5. Time Section of SO_2 Concentrations and Wind Velocities at Selected TAM Stations, June 30, 1968. ANL Neg. No. 113-1116.

Figure 6.4 shows only one major emitter upwind of TAM-7 within the city (Plant No. 27); unfortunately, this plant did not report fuel-consumption data for June 30. This plant did submit full data starting at 0000 CST on July 1 and was burning large amounts of coal at this time. The shapes of the curves, the lower SO_2 concentration downwind, and the time lag between stations suggest (but of course do not prove) that one or a group of sources are responsible for both stations. There is no way to determine from these data whether this source is the industrial plant mentioned or one or more industries outside of the city. The Edison Company's Northwest Power Plant (power plant I on Fig. 6.4), just upwind from TAM-2, used no coal or oil on this date and cannot be the source of SO_2 observed there.

The wind-direction data at TAM-6 indicate that the source is either an unknown source within the city or one or more outside the city limits. Industrial Plant No. 17 (see Fig. 6.4) was releasing only 45-50 lb of SO_2 per hour from 1200 to 2400 CST on June 30; this plant appears to be not sufficiently upwind of the station to be its source.

Inspection of the weather data at Midway Airport and Argonne indicates that SO_2 levels returned to near zero before the light rain showers that accompanied the passage of the cold front.

9.4.3.2 July 1. Industry and the utilities were asked to switch to high-sulfur fuel between 0700 and 1100 CST on Monday, July 1. Some of the stations reported a sharp rise in SO_2 concentration at this time, as shown in Fig. 9.6. This figure shows SO_2 levels at the four reporting

Fig. 9.6

Time Section of SO_2 Concentrations and Wind Velocities at Selected TAM Stations, Rural (Argonne), Lapse Rate, Stability Index, and Period of Precipitation, July 1, 1968. ANL Neg. No. 112-9764.

stations having significant concentrations of SO_2 on July 1. Of the four remaining stations, TAM-1 and -7 recorded SO_2 levels ≤ 0.04 ppm for this entire day, while TAM-2 reported a momentary peak of 0.14 ppm at 1700. TAM-8 reported 0.10 ppm for a 1-hr period beginning at 1100. Also shown are wind speed and direction at two TAM stations, the Argonne (rural) lapse rate, a mixing-layer depth index, and the period during which the changes were scheduled to take place.

The stability index is the depth of the mixing layer as calculated from a simulated Chicago temperature sounding and observed surface temperatures. The Chicago sounding is constructed using the Green Bay and Peoria radiosonde data plus the 850- and 700-mbar charts. Units are the depth of the mixing layer in tens of millibars (a unit of pressure), except for "15," which means a layer of 150 mbar or more thick. At these temperatures, a 10-mbar layer is about 280 ft thick, and a 150-mbar layer about 4500 ft thick.

The Argonne lapse rate is the difference in temperature between the 144- and 5.5-ft levels in degrees Celsius. A positive value of this difference indicates an inversion; the dry adiabatic or neutral lapse rate for this layer is -0.42°C . In a stable atmosphere, turbulence and vertical motions are suppressed and dilution rates greatly reduced. Winds at two TAM stations are shown; airflow at the other locations is basically the same.

Figure 9.6 shows that the SO_2 concentration at Hyde Park (TAM-4) jumped from zero to 0.23 ppm in 15 min shortly after the fuel switch began. This peak and the one at 2100 CST were short in duration and accompanied by temporary changes in wind direction from WSW to WNW. Figure 6.4 shows many industrial sources plus three electrical generating plants upwind of this SO_2 monitoring station for NW and WNW winds, very few for SW and WSW winds. Figure 9.7 shows the total reported hourly SO_2 emissions from the three power plants and industry in this area. ("Reported" is underlined because many SO_2 sources in the area did not or were not asked to submit SO_2 data.) The SO_2 emission data are incomplete. Nevertheless, the parallelism of the emission and SO_2 concentrations at TAM-4 curves is striking. It is tempting to conclude from the figure that the power plants are responsible for the observed SO_2 peaks; more likely, the observed variations of SO_2 with time are due to changes of wind direction, not SO_2 production.

Also shown in Fig. 9.7 are the SO_2 concentrations at TAM-3, downwind of the industrial area for southwest winds. In general, SO_2 levels were moderate from 1100 to 1400 CST, when WSW winds were observed, and low before and after this period with W to WNW winds. This pattern is consistent with the distribution of SO_2 sources.

Fig. 9.7. SO_2 Concentrations at TAM-3 and -4 on July 1, 1968, and Reported SO_2 Emissions Upwind of Stations. ANL Neg. No. 113-1117 Rev. 1.

One should not conclude from this figure that most of the SO_2 observed at the two reporting stations was due to the power plants. True, these plants do produce more SO_2 than all other plants combined. Power-plant emissions, in general, come from taller stacks than industry and have greater plume rise, due to higher velocities and temperatures. Ground-level concentrations decrease rapidly as the effective stack height (actual elevation plus plume rise) increases and as the source-to-receptor distance increases. Except for the Fisk plant and TAM-3, the Edison stacks are further from the two reporting stations than are many industrial sources. The problem of isolating the effect on air quality of one or two specific SO_2 sources in a complex urban area is a difficult one that cannot be solved by fuel-switch tests alone. Tracer studies (see Sec. 5.4) can be used to isolate the relative contribution of single and multiple sources.

The first peak at TAM-6 on July 1 came very early, before the fuel switch was scheduled to begin. Only one major industrial source is located between 180° and 270° from this station; winds at TAM-6 indicate that this plant (No. 17 in Fig. 6.4) is too southerly to be the source of SO_2 observed.

Between 0500 and 1100 CST, this plant was releasing about 110 lb of SO_2 per hour. The pollutant observed probably originated outside the city. The source of the SO_2 observed at TAM-5 on July 1 is not known.

The early peaks at TAM-4 and -6 may have been due to a fumigation effect associated with the breakup of the nocturnal inversion; however, data from the other six stations do not support this hypothesis. If this were the cause, the times of the peaks at all stations should have been closer together.

Figure 9.8A is a computer-plotted weather and SO_2 concentration map for the Chicago area for 0600 CST on July 1, before the switch to coal/oil and the frontal passage. Figure 9.8B shows conditions at 1000 CST, during the fuel-conversion period; Fig. 9.8C at 1500 CST, when the city was on maximum use of high-sulfur fuels. Figure 9.8D shows conditions at 2100 CST, when all TAM stations but TAM-4 reported low SO_2 , despite the high emission rate of SO_2 .

The SO_2 levels plotted on all the mesometeorological charts in this chapter are hourly averages, not the 15-min values plotted on time sections (such as Fig. 9.6). A comparison of the two charts shows how averaging SO_2 levels reduce the peak values.

Plotted on Fig. 9.8 are wind direction, wind speed (nearest whole knot), and hourly average SO_2 concentration at the eight TAM stations. Also plotted are weather data at five locations: Midway, Meigs, O'Hare, Glenview Naval Air Station, and Argonne National Laboratory. (The data for Argonne and Meigs Airport are displaced; their exact locations are given by the eight-pointed stars.) Missing data are not plotted (for example, wind at TAM-6 in Fig. 9.9D); calms are shown by larger circles than usual (O'Hare and Glenview airports in Fig. 9.9D). The data are plotted around the station circle, using the layout shown in the upper right of the figure. At the TAM stations, only wind and SO_2 data are observed and plotted. The Argonne data do not include visibility, cloud cover, or ceiling heights, but do include items not measured at the four airports, such as precipitation (inches), net radiation (langley/hr), and the difference between the temperature at 144 ft and that at 5.5 ft (an index of stability; positive values are inversions). The first digit in the stability spot for Midway Airport is the Turner stability class (Turner, 1967). The TAM air-quality and wind data are averaged over a full hour (30 min before to 30 min after); the airport and Argonne wind and temperature data are for the time indicated and represent short (5- to 10-min) averages. Some of the space variations of weather elements shown in Fig. 9.8, especially those of wind speed and direction, are due to exposure problems and are not real.

9.4.3.3 July 2. The dual-fuel plants were requested to convert to low-sulfur fuels; the electrical plants were asked to stay on coal. Except

Fig. 9.8. Mesometeorological Map and SO_2 Distributions in Chicago, July 1, 1968

Fig. 9.9. Mesometeorological Map and SO_2 Distributions in Chicago, July 2, 1968

for TAM-4, the SO_2 levels at all stations dropped to and remained at very low levels (mostly ≤ 0.03 ppm) after 2200 CST on July 1 and during all of July 2. These low-pollution levels were observed until 0700 CST on July 3, despite the maximized SO_2 output. During the night of July 1-2, the mixing depth was calculated to be greater than 4500 ft. The next night, when the power plants were still on coal, pollution levels remained low at all eight stations, despite the rural surface inversion and a very shallow mixing layer (see Fig. 9.10).

Fig. 9.10. Time Section of SO_2 Concentrations and Wind Velocities at Selected TAM Stations, Rural (Argonne) Lapse Rate, and Stability Index, July 3, 1968. ANL Neg. No. 112-9765.

Wind data for July 2 show moderate (6-8 knots) SSW to W airflow before noon, stronger (10-13 knots) from WNW to NW after noon (see Fig. 9.9). The wind speeds are similar to those observed the day before. Fuel-use data show only a slightly reduced SO_2 output (the utilities were still burning coal). For example, the three Edison plants along the Stevenson Expressway release as much as 5500 lb of SO_2 in 1 hr (0800 CST).

This output may be responsible for the moderate (0.06 to 0.09 ppm) SO₂ levels at TAM-4 from 0200 to 0700 CST (see Fig. 9.9A). Sulfur dioxide production from the power plants and single-fueled industries remained large; none of the eight TAM stations reported values greater than 0.03 ppm until 2300 CST (see Figs. 9.9B, C, and D). The observed uniform and low SO₂ concentrations are rather unexpected from weather and emission factors. One possible explanation is that SO₂ from the tall power-plant stacks did not reach the ground, at least not at any of the TAM stations. The low levels on the upwind side of Chicago indicate little advective import of SO₂ from the west at this time. Figure 9.9B shows conditions in the city at 1000 CST, when dual-fueled plants were converting to natural gas. The SO₂ value at TAM-4 was 0.07 ppm at 0900 CST. Figure 9.9C shows conditions in midafternoon; all air-quality values are low. Figure 9.9D shows no buildup of SO₂ during the night.

9.4.3.4 July 3. The highest SO₂ concentrations observed during the test period were observed during the afternoon of July 3, after all plants were scheduled to revert to maximum low-sulfur fuel. These maxima were associated with a lake breeze that penetrated as far inland as O'Hare field, but not to Argonne. The highest 15-min SO₂ level measured was 0.47 ppm at TAM-6 at 1715. Unfortunately, the TAM-6 wind-direction sensor failed to operate properly, and this significant information is missing. Stream-line analyses indicate the missing winds should have been similar to those of TAM-5 and -8.

Figure 9.10 shows the time variations of SO₂ at five TAM stations and wind-velocity data for three. Also given are the calculated urban mixing depths and the Argonne lapse-rate data. The time of the scheduled fuel switch to maximum gas for the Commonwealth Edison plants is shown.

Sulfur dioxide concentrations at TAM-1, -2, and -3 were ≤ 0.04 ppm until 2200 CST on July 3. Low concentrations (≤ 0.04 ppm) were observed at seven of the eight TAM stations (all except TAM-4) during the nighttime hours of July 2-3, despite a very shallow mixing depth (280 ft or less), low wind speeds, and maximum SO₂ output from the utilities. The moderate morning SO₂ concentrations at TAM-4 (Hyde Park High School) are probably due to pollution originating in the industrial complex northwest of the station. Sulfur dioxide levels at this lakefront location dropped to zero as soon as the wind switched to easterly with the onset of the lake breeze. TAM-5 SO₂ levels were low until there was a brief period of WNW flow, bringing in polluted air.

Wind data at the TAM and airport stations show that a lake-breeze circulation was well established at the shoreline by 1000 CST; SO₂ concentrations in the air coming into the city from over the lake were very low for the duration of the wind flow.

An analysis of the data at the inland stations (TAM-1, -5, -7, and -8) does not reveal any buildup of SO_2 along the zone of convergence ahead of the lake-breeze front. TAM-5, -7, and -8 showed some buildup late in the day, as the lake breeze weakened and disappeared.

The most interesting feature of the entire test period was the SO_2 buildup at Fenger High School (TAM-6). In 1 hr, the SO_2 level went from 0.07 to 0.36 ppm. Large variations in SO_2 were recorded between 1400 and 2200. An analysis of the wind data from the other stations indicates that the buildup did not begin until some time after the winds became easterly. Figure 6.4 shows one large point source (TAM-4) 1.5 miles ESE of the receptor; this plant was on 100% gas during this period. Also upwind of this station are the many large SO_2 sources sited along the Calumet River and in the Gary-Hammond industrial area.

Figure 9.11 shows the TAM-6 SO_2 data and the total reported SO_2 output from industry and the two electrical generating plants after 1000 CST. Most of the SO_2 emissions shown are from the State Line Commonwealth Edison plant, which burned an average of 290 tons of 3.38% sulfur coal per hour between 1200 and 2300 CST. Sulfur dioxide from this plant, plus that from all the other sources in the area, was trapped in the relatively, cool, stable air moving in from the lake. Again, it is not possible to guess the relative contribution of each multiple source upwind of the station.

Fig. 9.11. SO_2 Concentration at TAM-6 on July 3, 1968 and Reported SO_2 Emissions in the Lake Calumet-Little Calumet River Industrial Area. ANL Neg. No. 113-1118.

The conclusion that diffusion rates are small in the cool, stable air associated with lake breeze is confirmed by similar data collected in other lake-breeze situations (see Chapter 5, for example).

TAM-7 and -8 reported very low SO₂ concentrations both before and for many hours after the lake-breeze circulation reached the station. Some pollution buildup was observed after 1700 CST, associated with a minor change in wind direction to more southeasterly. The large buildup of pollutants in the lake-breeze air mass was not observed at the other inland stations (TAM-1, -5, and -6).

Figure 9.12 is a series of mesometeorological charts showing how the airflow and SO₂ patterns varied over the city on July 3. Of interest is the nonuniformity of wind speed and direction over the city (calms at two airports in Fig. 9.12A, speeds up to 5 knots elsewhere), a situation frequently observed when the winds are light (≤ 5 knots) or when a lake breeze is blowing. In both situations, no single wind direction can be used to characterize the airflow over the entire city or to determine uniquely the path the plume of a given stack will follow. (Remember that the SO₂ and wind data at the TAM stations are averaged over a 60-min period; the airport data are not.)

Figure 9.12A is for 0300 CST; only TAM-4 was reporting significant SO₂ levels. By 0900, the winds were stronger and more from the NW (see Fig. 9.12B) and all SO₂ values were low. One hour later (see Fig. 9.12C), the lake breeze had begun. By 1300, the lake breeze was well established, all SO₂ values were very low. By 1400 (see Fig. 9.12D), the lake air covered all the city except Midway. The rapid buildup of SO₂ began at TAM-6 after 1415 CST; Fig. 9.12D indicates that the lake breeze had probably passed this station. Figure 9.12E shows the city at 1700, the time of maximum SO₂ at TAM-6; the SO₂ was clearly in the lake-breeze air. Four hours later (Fig. 9.12F), the lake-breeze front was still east of Argonne and the airflow over the city was from the SSE.

These charts show that significant amounts of SO₂ were generated outside the control area and were advected into the south side of Chicago with easterly flow associated with the lake breeze.

9.4.4 Summary of the 1968 Fuel-switch Tests

This experiment did accomplish its primary objectives. The air pollution abatement actions were tested in the real world, and numerous ideas were suggested to improve the strategy. Sources contributing 68% of the city's SO₂ (on an annual basis) cooperated by submitting fuel-consumption records. Much was learned about the ability of plants to switch fuels on short notice. The unfavorable weather during the second week of the exercise was valuable in that it caused a significant exercise of the communications channels between DEC and plant operating officials, the gas and electric load dispatchers, etc.

Fig. 9.12. Mesometeorological Map and SO_2 Distributions in Chicago, July 3, 1968

normal fuel for the season over the weekend of May 24 and 25. The second switch to high-sulfur fuels was made between 0700 and 1100 CST on Monday, May 26, with a second conversion to gas or other low-sulfur fuels 1 to 3 days later.

In the first two fuel-switch tests, the conversions to low-sulfur fuels were to be made by all dual-fuel industrial plants in the city on one day, with the electric utility plants converting either one day earlier or one day later (the exact date being selected on the basis of the weather forecast for the 1968 test). In the 1969 experiment, the conversions to natural gas after maximum use of coal/oil were selective. That is, the plants that were asked to change to low-sulfur fuels were selected on the basis of the calculated effect of that plant on air quality measured at one or more TAM receptors downwind, within the availability of gas and the ability of the plants to convert. The 1969 test was therefore a much more realistic "dress rehearsal" for a real pollution episode than were the earlier tests.

Observing the effect of the fuel changes on air quality requires several consecutive days of reasonably constant weather. Since very little flexibility was available for the date of the fuel changes, two separate abatement strategies were planned: one being to make the conversions using real weather conditions and observed air quality data (and forecasts of these two items); the alternate strategy being, if the actual and forecast meteorological conditions were not suitable, to make the conversions based on a "synthetic" or "fake" forecast. We decided to use the actual weather and air quality data for April 1-2, 1966 for this "synthetic" air pollution episode and to base abatement activities on these conditions. This period was selected because it was a typical spring weather situation involving high SO_2 levels (0.25-0.54 ppm) at three or more TAM stations. The use of this synthetic weather forecast would greatly reduce the ability to detect and explain changes in air quality due to the fuel switches.

DEC inspection cars were used during the test to observe the plumes from many of the cooperating companies and to see if the proper fuels were being used. One phase of this operation was to check the ability of the patrol personnel to catch noncooperators.

Two additional observational systems were scheduled to be used during the 1969 test: the National Weather Service low-level radiosondes and the DEC helicopter flight package. The balloons did yield valuable information on the wind and temperature profiles over the city and exact measurements of the depth of the mixing layer. These data were most useful in predicting diffusion rates and mixing depth as well as future weather. It was planned to use the Chicago Fire Department helicopter extensively to measure temperature and SO_2 profiles at many locations around the city, to measure temperature profiles at Midway between balloon flights, to photograph and observe plume motions and SO_2 concentrations from certain

plants, and to look for noncooperators. Unfortunately, because of poor flying weather on some days and lack of availability of the helicopter (due to various causes) on others, no useful data were collected from the air during the test period.

Because of the cool temperature and time of year, very little natural gas was available at low rates during the first week of the test. This fuel was not available for the Ridgeland Power Station (IV in Fig. 6.4), which is located in the territory of another gas supplier using a different contract. Thus, one very large SO_2 source used only coal during the entire two-week test period. Equipment failures in two large power plants further reduced the ability of the electric utility to contribute to the control actions by switching fuels and loads.

The Tabulation Prediction Technique (TPT), described in Sec. 6.3, was to be used to predict sulfur dioxide levels whenever real weather conditions were used to control the changes of fuels.

The calculated change of SO_2 at a given receptor as a consequence of a fuel switch by a given plant was estimated from a set of previously computed tables. These tables are essentially solutions to the standard plume-dispersion equation for various stack heights, wind speeds, and stabilities. The expected change of SO_2 could be rapidly estimated from these tables.

Seventy-five large SO_2 producers in the Chicago area were contacted and asked to participate in the third fuel-switch test. The response was better than for the two earlier tests: 20 out of 21 single-fuel plants, 25 of the 32 dual-fuel industrial plants, and 9 of 16 large commercial/residential sources joined the six power plants in the exercise. DEC personnel again wrote letters to all participating companies. A letter explaining the role of the gas and electric utilities in the "war game" was prepared by ANL personnel. The gas supplier was asked to supply information on the present and forecast availability of natural gas for air pollution control actions. The electrical supplier was asked to supply data on projected power demands, the status of the various generating units, and the availability of low-sulfur fuels. The utilities generate such forecasts for their own use; pollution-abatement actions called for by the DEC were based in no small measure on these data.

9.5.2 Air Quality and Weather, First Week

9.5.2.1 Synoptic Situation. All major SO_2 producers were asked to convert to maximum use of high sulfur fuels during the morning of May 20. A strong NE-SW oriented cold front passed Midway Airport at 0930 CST on this day. Moderate (6-13 knots) NE winds behind the front brought very cool air into the area for the next 72 hr. May 21 averaged 11°F below

normal; May 22, 14°F below; and May 23, 10°F below. These much-below-normal temperatures greatly curtailed the amount of natural gas available for the SO₂ abatement actions, since a high priority is given to space-heating requirements.

Moderate NE winds persisted in the area on May 21 and 22 as a rain area associated with a wave cyclone on the polar front moved from west to east to the south of the city, with 0.37 in. of precipitation (including some sleet) falling at Midway Airport between 1600 CST on May 21 and 0935 CST on May 22. On May 23, the NNE to NE flow weakened as the center of the high-pressure area crossed Illinois.

Because of these adverse weather conditions, air pollution abatement strategies for the first week were based on the "synthetic" forecast.

9.5.2.1.1 May 20. The 0500 CST low-level radiosonde at Midway Airport showed a nearly isothermal layer about 2000 ft thick, and a morning mixing depth of zero vertical extent. The 3°C urban mixing layer was 12,000 ft thick with a vector transport speed of 4 knots from 309°. The 1100 CST balloon showed an adiabatic layer to 3000 ft. The wind data at two TAM stations (Fig. 9.13) are representative of the flow over the entire city (Fig. 9.14).

Fig. 9.13. Time Section of SO₂ Concentrations and Wind Velocities at Selected TAM Stations, May 20, 1969

Fig. 9:14. Mesometeorological Map and SO_2 Distributions in Chicago, May 20, 1969.
A. and B. ANL Neg. No. 149-4206; C. and D. ANL Neg. No. 149-4207.

Unfortunately, the SO₂ sensors at TAM-1 and -7 were not operational on the morning of May 20. Three of the TAM stations (TAM-1, -2, and -7) reported SO₂ levels less than 0.10 ppm for the entire day. The highest SO₂ values were reported at TAM-4 and -5 (see Fig. 9.13). (Diagrams similar to Fig. 9.13 use wind and SO₂ values obtained from sensors every 15 min; diagrams such as Fig. 9.14 use hourly averages.) Peak SO₂ values at all reporting stations except TAM-5 occurred early in the morning: 0.11 ppm at 0800 CST at TAM-3, 0.14 ppm at 0900 CST at TAM-7, and 0.16 ppm at 0800 CST at TAM-8. Conditions at TAM-4 are shown in Fig. 9.13. These early-morning peaks are probably related to the breakup of the early-morning inversion; SO₂ values at these seven receptors fell after the switch to high-sulfur fuels was completed, due to higher winds, a deeper mixing zone, and the wind-direction change.

The SO₂ data at TAM-5 are more interesting. The reported SO₂ values were low during the morning hours, despite a trajectory from an area of known high SO₂ production. After the winds veered, the SO₂ levels increased markedly. The power plant upwind of this sensor (Plant II on Fig. 6.4) was on coal for the entire day; its average SO₂ production from 0900 to 1600 CST was 28,600 lb/hr. Upwind sources also include many small plants near the receptor as well as the Loop. Figures 9.14B and 9.14C show low SO₂ levels at TAM stations further downwind.

Figure 9.14A shows weather and SO₂ concentrations in the Chicago area for 0600 CST on May 20, before the switch to coal/oil and the frontal passage. Figure 9.14B shows conditions at 1200 CST, after the air-mass change and fuel switches. Pollution levels decreased sharply at the lake-front sites as the wind direction changed and a mixing zone 3000 ft thick developed. The large SO₂ concentration of short duration at only one station at the time of the switch to maximum coal is interesting but not easily explained.

Figure 9.14C shows conditions in midafternoon. Only TAM-5 shows a high SO₂ concentration. Figure 6.4 shows a large number of SO₂ sources upwind of this sensor. During the evening, SO₂ levels dropped to low values, despite the lack of a change of wind direction or a significant increase in SO₂ production (Fig. 9.14D). A strong nocturnal surface inversion had formed, probably preventing pollutants released from tall stacks from reaching ground level.

Figure 9.14 and others in this series show the space variability of wind, temperature, and other meteorological parameters as well as of SO₂. Some of the space variations, especially those of wind direction and speed, are due to exposure differences and are not real.

9.5.2.1.2 May 21. The 0600 CST synoptic weather chart showed that the northern part of the cold front which passed the city the previous

day was now over the Atlantic Ocean. The trailing section of the front had become stationary across the U.S. along the 35° parallel, into a warm front in Kansas. A strong high-pressure center over Sault Ste. Marie, Michigan, was dominating Chicago's weather, with NE winds over the city (see Fig. 9.15). The 0500 CST balloon flight showed a small inversion at 1800 ft. The mixing depth as measured was 660 ft; by midafternoon, the mixing depth had increased to 3000 ft.

Fig. 9.15. Time Section of SO₂ Concentrations and Wind Velocities at Selected TAM Stations, May 21, 1969

Because of the approaching warm front and associated rain area, it was decided not to declare an "air pollution episode" on May 21. Plants were expected to remain on maximum coal. Wind and SO₂ conditions at three TAM stations are shown in Fig. 9.15. The SO₂ concentrations at the other stations and hours was ≥ 0.10 ppm, despite maximum SO₂ production. In fact, the highest readings were 0.06 ppm at TAM-2 and -8, 0.04 at TAM-3 and -4, and 0.03 ppm at TAM-5. No helicopter flight was made due to poor flying weather. Rain began at Midway at 1530 CST.

Figure 6.4 shows no major sources of SO₂ NE of TAM-1 within the city. High SO₂ concentrations were observed at this location on May 21 and 22,

indicating that the pollutant had originated either in a small source near the station inside Chicago or in some plant outside the city. In either case, the abatement strategy being tested would not have been effective, since it depends on lowering emissions from major sources inside the city limits.

9.5.2.1.3 May 22. The synoptic weather chart showed that Chicago was in a large rain area associated with a wave on the polar front moving from west to east across southern Illinois. The rain ended at 0935 CST at Midway.

The 0500 CST radiosonde showed a very stable and near-saturated atmosphere to the top of the sounding at 10,000 ft. The base of a 7°F inversion was located at 4000 ft, and a 700-ft mixing depth was observed. By afternoon, the mixing depth had increased to 2500 ft. Again, no helicopter flight was made because of bad weather.

Because of the approaching weekend and despite an unfavorable weather forecast, pollution abatement actions began on May 22. The "synthetic" weather forecast procedures were used.

About 0800 CST on May 22, the Director of the DEC declared that an "air pollution episode" had begun and control actions were started. The meteorologists prepared weather and air quality forecasts for the rest of the day, copying the "synthetic" data, rather than predicting actual conditions, and gave these to the Air Pollution Control Strategist. He in turn used these forecasts and other considerations (such as precalculated SO₂ concentration estimates for point sources, location of controllable factories, and availability of natural gas) to prepare a list of companies to be asked to convert to low-sulfur fuels. This list was given to the local gas supplier who in turn informed the plants that gas was available at the proper rate.

Twenty-four plants were notified by 1110 CST. DEC engineers later called each plant to ask if the conversions had in fact been made. It turned out that some plants on the list had failed to convert to coal 48 hr earlier.

DEC air pollution patrol cars were sent to many plants in the afternoon to see if the expected fuel conversions had in fact been made. The effectiveness of this inspection system was tested on May 22; one plant, by prior agreement with DEC, deliberately did not convert to gas but reported that it had. Happily, the patrol did detect and report the "violator."

Unfortunately, weather conditions on May 22 (the high temperature for the day was only 52°F) were such that little natural gas was available for air pollution control.

Three of the power-generating plants were asked to remain on coal: State Line (VI on Fig. 6.4), Calumet (V), and Northwest (I). The Ridgeland plant (IV) of necessity remained on coal; fortunately, the winds carried its

plume away from the city. Because of mechanical failure, the coal-fired units of the Crawford (III) plant were off-line most of the week. The remaining plant, Fisk (II), has only a limited ability to burn natural gas. This plant did convert at the request of DEC and lowered its SO_2 emissions from an average of 22,000 lb of SO_2 per hour in the morning to 6000 lb/hr after 1400 CST.

All reporting stations except TAM-1 reported low (<0.10 ppm) SO_2 values until 1600 CST, despite high SO_2 production (see Fig. 9.16). The TAM-4 data show significant SO_2 levels with north to northeast winds; this station is near the lake shore with no SO_2 sources to the east. Space heating in apartments to the north and northeast must be the source of this air pollution.

Fig. 9.16. Time Section of SO_2 Concentrations and Wind Velocities at Selected TAM Stations, May 22, 1969

Sodium dioxide values at the other lakefront stations (TAM-2 and -3) were ≤ 0.04 ppm during the period. Figure 9.16 shows that SO_2 levels rose after control actions were begun.

9.5.2.1.4 May 23. The abatement actions taken on May 22 were continued, and four additional plants were asked to convert. DEC dispatched inspectors to 15 of the plants to verify their compliance. The helicopter was not made available for use by the DAPC.

On May 23, the center of the cold high-pressure area was over Illinois, moving slowly to the southeast. The winds were mostly NNW through NNE at 3-6 knots during the morning hours, becoming NE in the afternoon, as shown in Fig. 9.17.

Fig. 9.17. Time Section of SO_2 Concentrations and Wind Velocities at Selected TAM Stations, May 23, 1969

The early sounding showed a ground-based inversion. By 1000 CST, solar heating had raised the mixing height to about 4000 ft.

Seven of the eight TAM stations (all but TAM-1) showed SO_2 levels ≥ 0.10 ppm for several hours between 0500 and 0900 CST. The hourly average SO_2 data for six stations, plus wind information at four, are given in Fig. 9.17. TAM-5 reported SO_2 levels of about 0.11 ppm from 0500 to 0800 CST.

High pollution levels were measured despite the control actions taken on the previous day. This case again illustrates the point that SO_2 levels are more closely related to dispersion conditions than to SO_2 emissions.

Again, TAM-4 pollution increased sharply during a short period of north winds, reflecting the distribution of sources. The pollution pattern at TAM-8 is quite interesting. The major upwind source is a power plant (IV). The observed SO_2 pattern at TAM-8 paralleled the emissions from that station until the wind direction changed to NE. Sulfur dioxide levels at all stations dropped when the wind direction went to NE, wind speeds increased, and the mixing depth increased.

The "emergency" was declared over at 1600 CST, and this phase of the test was terminated. Plants were notified to revert to their normal fuel until 0700 CST on May 26.

After 1800 CST, the NE winds changed to S or SW at 3-6 knots, and all seven operating TAM stations (TAM-1 was not working properly) reported SO_2 values above 0.10 ppm. The highest instantaneous value was 0.44 ppm at TAM-4 at 2300 CST.

9.5.3 Air Quality and Weather, Second Week

9.5.3.1 Synoptic Situation. The second week of the test produced far more interesting and useful results than the first week.

On May 26, 1969, Chicago had moderate (4 to 8 knots) easterly flow as a result of a large high-pressure area just north of Lake Huron. This pressure center moved to the southeast and was located over New York State at 0600 CST on May 27, and over Virginia on May 28. The winds veered as the system moved, becoming southerly by 0100 CST on May 27 and then southwesterly from 1200 CST on May 27 until a cold front passed about 1200 CST on May 29. No rain fell during the period. Figures 9.18-9.21 show the 0600 CST weather charts for the test period.

On May 26, when the dual-fuel plants were scheduled to be converted to high-sulfur fuels, the winds off the lake resulted in a 6°F below-normal day.

MONDAY, MAY 26, 1969

Fig. 9.18. Synoptic Weather Map for 0600 CST, May 26, 1969

Fig. 9.19. Synoptic Weather Map for 0600 CST, May 27, 1969

WEDNESDAY, MAY 28, 1969

Fig. 9.20. Synoptic Weather Map for 0600 CST, May 28, 1969

Fig. 9.21. Synoptic Weather Map for 0600 CST, May 29, 1969

The flow on the next two days, when the plants were to be asked to convert to low-sulfur fuels, brought very warm conditions (for the season): May 27 was 13°F above normal with a high of 89°F; the next day was 14°F above with a high of 92°F. May 28 was the first plus-90°F day of the year and broke the old maximum temperature record for the date by 1°F. This widespread heat wave caused most area residents to turn off their space-heating equipment (thus curtailing SO₂ production) and to turn on their air conditioners. A near-record load was placed on the electrical system, already hurt by major mechanical troubles at two of its larger plants and lack of gas to burn in another. The power company was able to produce about 25% of its city power requirements in plants outside the city. Additional electricity was purchased from other companies, reducing SO₂ production in the city.

9.5.3.2 Air Quality and Weather Forecasts. The meteorological situation during the afternoon of May 26, 1969, indicated that an extended period (over 48 hr) of strong SW flow with no low ceilings or precipitation would occur. So it was decided to begin the pollution control actions the following morning, and to use the actual and forecast weather to select which plants were to be converted to gas.

Two of us (Carson and Klappenbach) prepared a weather forecast for the city before 0700 CST on both May 27 and 28. The forecast parameters were those needed for use with a preliminary version of the Tabulation Prediction Technique, described in Sec. 6.3: wind direction, wind speed, air temperature, ceiling below 7000 ft (yes/no), and precipitation (yes/no). The Weather Bureau radiosonde data proved to be most useful in preparing these forecasts.

Using the forecast weather data, the TPT tables, and the observed 0700 CST SO₂ concentrations, we made a forecast of SO₂ concentrations at each TAM station for every hour from 0900 until 2400 CST.

No attempt was made to measure quantitatively the accuracy of the SO₂ forecasts made using the Tabulation Prediction Technique. An examination of the forecast versus observed values showed some discrepancies. One cause was a less-than-perfect weather forecast. But more important was the fact that record or near-record high temperatures were recorded on the two days used. The data used to construct the tables were for March-April-May of 1966 and 1967, and these six months contained few data in the 80-89°F band. We were forced to use the 80-89°F data for periods whenever the forecast called for higher temperatures.

9.5.3.3 Declaration of an Air Pollution Episode. These air-quality and weather forecasts were given to Mr. Samuel G. Booras, the Air Pollution Control Strategist, before 0730 CST on both days.

On May 27, 1969, he discussed these forecasts with Mr. William J. Stanley, Director of DEC. Mr. Stanley declared at 0800 CST that an "Air Pollution Alert" situation existed, and ordered the Department to continue and intensify its air-quality monitoring program, the key word being alert. No control actions were called for at this time.

Three hours later (1100 CST), Mr. Stanley declared that an "Air Pollution Episode" had begun and requested that the control procedures called for in the "Argonne-Department of Environmental Control Episode Control Plan" be initiated. Sample press releases for both announcements were prepared but not released. The pollution-control exercise ended at 1600 CST on May 28.

9.5.3.4 Implementation of the Episode Control Plan. The Air Pollution Control Strategist, using the SO_2 and weather forecast information and the location of controllable plants, determined which of these should be converted to low-sulfur fuel in order to reduce SO_2 levels at the control points (TAM stations). This list was then compared with the total available supply of natural gas (supplied by the gas company) and the amount needed by each plant. When the total gas needed was equal to the amount available, the list was terminated. This list of 24 plants was given to the gas dispatcher, who in turn informed the plant engineers that gas was available. Unfortunately, the response by industry was again less than had been desired. The electric utility was asked to go on maximum gas by 1100 CST on May 27. The fuel changes made by this company were as great as possible, considering the near-record load and equipment failures. The Northwest (able to burn only coal) and Ridgeland (no gas available) plants were on coal the entire period. At the Crawford plant, two units were off-line for repair and only gas was burned in the remaining units on May 26-28. At the Fisk plant, the conversion to gas reduced average SO_2 output from 24,300 lb/hr during the period 1300-2300 CST on May 26 to 2500 lb/hr for the same period the following day. The reduction in SO_2 generation rates at the other two plants for the same time periods was: at Calumet, from 9750 to 4940 lb/hr; at State Line, 39,100 to 28,600 lb/hr. As much as possible of the city's load was generated by plants outside the area. In addition, power was purchased from other utilities.

9.5.3.4.1 May 26. Figure 9.18 shows the synoptic weather situation at 0600 CST on May 26; Fig. 9.19 shows conditions 24 hr later.

Surface winds from the NE quadrant brought cool air into the city until about 2200 CST (see Figs. 9.22 and 9.23). The 0500 CST low-level balloon flight showed a ground-based inversion; the temperature at 1000 ft was 11°F warmer than that at the surface. By 1000 CST, the surface inversion was replaced by an adiabatic layer 1700 ft deep; the afternoon mixing depth was estimated to be 4600 ft. Broken to overcast conditions prevailed most of the day, due to stratocumulus and altocumulus layers above 10,000 ft.

The episode-control schedule called for all dual-fuel firms plus the power stations to convert to maximum use of high-sulfur fuels by 1100 CST. Sulfur dioxide levels at four of the seven operational monitoring stations (TAM-1 was off line until 1300 CST) showed significant SO_2 levels at this time, as shown in Fig. 9.22. These peaks were reached around the time of breakup of the nocturnal inversion; the fumigation process plus increased SO_2 output could be responsible. Figure 9.23A shows the conditions in Chicago at

Fig. 9.22. Time Section of SO_2 Concentrations and Wind Velocities at Selected TAM Stations, May 26, 1969

Fig. 9.23. Mesometeorological Map and SO₂ Distributions in Chicago, May 26, 1969.
A. and B. ANL Neg. No. 149-4202; C. and D. ANL Neg. No. 149-4205.

0800 CST, the time of the early-morning peak SO_2 levels. Note the nonuniform wind currents over the city on this chart, a frequent occurrence during periods of low wind speeds. Figure 9.23B shows the wind field over the city at 1100 CST; air quality has improved due to stronger winds and the breakup of nocturnal inversion.

The three monitoring stations near the lake (TAM-2, -3, and -4) show the expected low SO_2 values associated with NNE to E surface winds (see Fig. 9.23). After the wind shift to SE late that evening, SO_2 values at these three locations plus TAM-1 and -7 rose sharply, while the value at TAM-6 fell to 0.01 ppm (see Fig. 9.23D).

Sulfur dioxide emission data upwind of TAM-5 and -8 show an average value of 50,000 lb/hr from 0800 to 2200 CST, and less than 25,000 lb/hr before and after this period. At TAM-6, the reported SO_2 production was less than 500 lb/hr until 0600 and after 2000; 50,000 lb/hr between 0700 and 1900 CST. At TAM-7, SO_2 production before 0600 was reported as 1000 lb/hr. From 0700 until 2300 CST, it averaged about 26,000 lb/hr.

The SO_2 concentration data at TAM-5, -7, and -8 do not exactly parallel these emission curves. The afternoon peak SO_2 values at TAM-6 and -8 are interesting but hard to explain. They are probably due to the small wind direction change shown in Fig. 9.22. Sulfur dioxide levels at TAM-7 were above the critical 0.11-ppm level for almost 14 hr; the figures indicate that most of the pollution could have originated in the city.

9.5.3.4.2 May 27. The synoptic weather chart for 0600 CST is shown in Fig. 9.19. Wind and SO_2 data for the three TAM stations reporting SO_2 values ≥ 0.10 ppm are shown in Fig. 9.24. The 0500 CST radiosonde indicated a mixing depth of 650 ft, capped by a 3°C inversion, with an average transport wind of 20 knots from 190° ; winds just above the inversion were from SW at 20 to 30 knots. The mixing depth increased 1400 ft by 1100 CST and 6000 ft in midafternoon. Skies were again broken to overcast above 10,000 ft.

Twelve dual-fueled plants, selected on the basis of their location with respect to TAM stations, and certain power stations were asked to convert to natural gas by 1500 CST.

Very high SO_2 levels were observed at TAM-7 during the early morning, as shown in Figs. 9.24 and 9.25A. Figure 6.4 shows only one dual-fuel plant (plant 27) upwind of this receptor. This plant was therefore requested to go to gas before 1200 CST. Naturally, we at the Pollution Control Center were pleased to see that the SO_2 fell to 0.07 ppm by 1000 CST without a change of wind direction, and to 0.05 ppm by 1300 CST. Unfortunately, the fuel-consumption record for this plant indicated that only gas was used during the entire second week of the test. The Sanitary District Plant (just east of power plant IV, not shown on Fig. 6.4) was also on gas only during

the week. The observed SO_2 must have come from the Ridgeland Power Station (plant IV) or other industries outside of Chicago to the southwest of this monitoring station. Time series of SO_2 levels at the various monitoring stations and reported SO_2 production upwind of the sensor have been prepared. Those plants in a segment of circle $\pm 30^\circ$ from the observed TAM wind direction are included in these time series. The time series for TAM-7 shows that the maximum production of SO_2 was reached between 1000 and 1200 CST after the maximum ground-level value was reached. Thus the observed SO_2 patterns reflect changes in diffusion conditions as well as changes in SO_2 emission.

Sulfur dioxide levels at TAM-3 reached 0.14 ppm before 0600 and 0.28 ppm at 0945 CST, as shown on Fig. 9.24. To "shave" this peak, the power plant just upwind of the Loop (plant II) and other dual-fuel plants in this area were asked to convert to natural gas. The SO_2 value in the downtown area dropped; the power emission was about 25,000 lb of SO_2 per hour from 0600 to 1200 CST, and only 2500 lb/hr in the afternoon. This major improvement in air quality in Chicago's Loop was the major success of this fuel switch.

Fig. 9.24. Time Section of SO_2 Concentrations and Wind Velocities at Selected TAM Stations, May 27, 1969

Fig. 9.25. Mesometeorological Map and SO_2 Distributions in Chicago, May 27, 1969.
A. and B. ANL Neg. No. 149-4201; C. and D. ANL Neg. No. 149-4204.

The afternoon cleanliness of the city is shown in Figs. 9.24 and 9.25C. TAM-3 and -4, located on the downwind edge of the city, show slightly higher SO_2 levels in the evening hours, with better air quality after 2200 CST (Figs. 9.24, 9.26, and 9.25D). TAM-7, still downwind of power station VI which was on full coal, reported low SO_2 values after 0800 CST on May 27 and all of May 28. The SO_2 from power plant IV was not affecting this station. TAM-1, -5, -6, and -8 reported low SO_2 values all day; TAM-2 had a momentary SO_2 peak (0.14 ppm) at 1000 CST.

9.5.3.4.3 May 28. Surface winds were moderate (6 to 12 knots) SW to W all day (see Fig. 9.26). The 0500 CST low-level balloon sounding showed two inversions. The lower one began at the ground and was about 700 ft thick. The base of a subsidence inversion rose from 3800 ft at the time of the early sounding to 4000 ft at 1100 CST. Winds in the zone of mixing, after the nocturnal surface inversion was destroyed by solar heating, were 250-270°,

Fig. 9.26. Time Section of SO_2 Concentrations and Wind Velocities at Selected TAM Stations, May 28, 1969

15-20 knots. The second sounding of the day showed the expected neutral layer to the base of the subsidence inversion. The strong SW flow brought in extremely warm air; a new maximum temperature record for the day (92°F) was set.

Sulfur dioxide values at the TAM stations on the upwind edge of the city--TAM-1, -7, and -8--showed low (mostly <0.05 ppm) throughout the day. TAM-7 did report 2 hr of 0.11 ppm at 0100 and 0200 CST. The low SO₂ values were reported, despite the fact that the upwind power plant was on maximum coal all day to supply electricity for the peak air-conditioning load.

All eight stations reported their highest pollution levels for the day between 0700 and 0900 CST, the time of breakup of the surface nocturnal inversion. Sulfur dioxide levels were quite low at all eight TAM stations, except TAM-2, for the rest of the day. The SO₂ level at TAM-2 rose to 0.23 ppm at 2100 CST, after the fuel test was terminated (see Fig. 9.26).

Figures 9.26 and 9.27 show the SO₂ distribution in Chicago on May 28. Figure 9.27A shows conditions at 0500 CST, before the breakup of the nighttime inversion; Fig. 9.27B shows conditions at 0800. Figure 9.27C shows conditions at noon, when the mixing layer was at least 4000 ft deep. Figure 9.27D shows the city at 1600 CST, the end of the fuel-switch test.

Since the wind and pollution patterns were similar on the two days, the control activities of May 27 were continued. Again, a major effort was made to reduce pollution levels in the Loop, as measured by TAM-3.

The Fisk Power Plant continued on maximum gas throughout the day. Sulfur dioxide production averaged about 2400 lb of SO₂ per hour from 1300 CST on May 27 to 0500 CST on May 28; the emission rose to about 8000 lb/hr after 0700 CST on May 28. This increase in the use of coal was forced by the near-record power load.

A comparison of the early-morning peak SO₂ concentrations at TAM-3 on May 27 and 28 is interesting. On May 27, before control actions were taken, the highest reading was 0.28 ppm at 0945 CST. On the following day, despite the fact that many of the upwind industrial plants had converted to low-sulfur fuels, the peak value was 0.33 ppm at 0815 CST. The total reported average SO₂ production within the sector of a circle $\pm 30^\circ$ of the TAM wind direction during the 2-hr period before the peak on May 27 was about 27,000 lb/hr. The comparable figure on May 28 was only 9000 lb/hr, with most of the reduction due to the Fisk Power Plant. Thus, a reduction of SO₂ production of 67% failed to reduce early-morning pollution values in the Loop.

The fuel-switch test was terminated at 1600 CST on May 28. All plants were notified to resume normal operations.

Fig. 9.27. Mesometeorological Map and SO₂ Distributions in Chicago, May 28, 1969.
A. and B. ANL Neg. No. 149-4200; C. and D. ANL Neg. No. 149-4203.

9.5.4 Summary of the 1969 Test

The May 1969 fuel switch was a realistic and successful test of the air pollution control strategies developed under this contract (see Sec. 8).

The conversion of the power plants and large dual-fuel plants to maximum use of high-sulfur fuels on May 20 and 26 produced high SO_2 levels in parts of Chicago. The pollution-abatement actions taken during the second week were based on present and forecast weather conditions, present air quality data, and information on fuel-use patterns; the diffusion equations were used to generate air quality forecasts on a real-time basis. These air quality forecasts, plus the availability of alternate fuels and the location of dual-fuel plants, were used to select which plants upwind of the affected area were to be converted to low-sulfur fuels.

These control actions were then imposed, and improvements in air quality were observed. The observed changes in SO_2 levels indicated that fuel switches were effective in lowering SO_2 concentrations in the affected areas, and that the decreases were consistent with those computed by the diffusion model. The forces for dealing with an actual pollution episode were identified and mobilized. During the test, 15 large-scale users of fuel within Chicago switched from high-sulfur fuels to natural gas upon being notified that a simulated pollution episode was taking place. Municipal incinerator operation was temporarily curtailed. Hospitals were alerted, and patrol cars checked potential pollution sources. Air pollution control engineers maintained hot-line contact with utilities and other major sources.

The 1969 exercise was able to test in the real world the command, control, and communications needed to implement an episode control operation.

This test showed that selective fuel switching can improve air quality in a portion of a large urban area with minimum costs and disruptions to the normal activities of the city. Several events showed that the 1969 exercise was a realistic test of the pollution-abatement strategies developed under this project. For example, the unseasonably cool weather during the first week created a severe shortage of low-cost gas for abatement actions. The record heat wave during the second week, coupled with failures of the power-generating equipment, reduced the ability of this utility to reduce SO_2 emissions by fuel and load shifting.

The freedom of the operation strategist to allocate the limited supply of natural gas to best advantage was restricted by the rate structure. The need for more natural gas at low rates for pollution control was shown:

Again, a large number of large SO_2 sources in the area were either unwilling or unable to participate. Also, a portion of the fuel data was again

unsatisfactory or incomplete. These factors reduce the usefulness of the entire test. One industry volunteered to test the ability of DEC inspectors to locate "violators" by failing to switch fuels on schedule; the patrol did detect the noncooperator. Much was learned concerning the ability of individual plants to curb SO_2 production during potentially hazardous periods. After an initial period of close involvement, the Argonne scientists who served as technical advisors were able to phase themselves out of almost all operational activities. The methods, computational techniques, and organizational structure developed at Argonne were used effectively by city employees in a real-world situation.

9.6 Summary and Conclusions

The fuel-switch test program did successfully accomplish two of its three primary objectives. The air pollution episode control plan developed by the Argonne National Laboratory in cooperation with the Chicago Department of Environmental Control was tested in the field and found to be effective and operationally sound.

The test provided considerable information on (1) the ability of various types of plants to reduce SO_2 emissions by using alternate fuels and (2) the time needed for conversion. It was found, for example, that it was easier and quicker to convert from coal or oil to natural gas than to convert to high-sulfur fuels, and that equipment failures often reduce the ability of plants to convert.

The tests also showed that the organizational and control structure of the basic plan was sound; the duties of the various personnel in the control system were identified and tested. The communication channels between the DEC office and the plant engineers, the gas and electrical load dispatchers, and the patrol cars were established, tested, and improved.

The control actions for the third test were based on selective emission controls. Only those dual-fueled sources shown to be significant contributors to high ambient SO_2 levels were asked to convert. The decision of which plants to convert was based in part on forecasts of SO_2 levels using the standard dispersion equations.

Both receptor- and source-oriented air quality forecast models were used.

These outdoor experiments also resulted in a set of high-quality hourly emission data, which have been used to improve the accuracy of emission forecasts, thus fulfilling the second objective.

The program was less successful in achieving its final objective, correlating air quality changes to SO_2 emission rates. The time variations

of SO_2 concentration at a point are the result of many parameters in addition to SO_2 emission rates upwind, such as variations of wind speed, wind direction, time of day and cloud cover (which in turn control turbulence levels), and mixing depth.

In many instances in this test, air quality changes appear to be more closely related to meteorological conditions than to fuel use. Also, air quality at a given TAM station is known to be markedly influenced by small, uncontrolled SO_2 sources near the receptor; big changes in SO_2 by large plants miles upwind are often masked by these local, unmeasured sources.

During these tests, no attempt was made to control or reduce SO_2 production from any source, whether for space heating or for industrial use. The "pulses" given to SO_2 production rates by fuel switching were sometimes only a fraction of the total SO_2 production influencing the TAM receptors.

Fuel-switch tests cannot be used to unambiguously isolate the effect of converting one or a group of sources to low-sulfur fuels on air quality. Atmospheric tracer studies, such as those discussed in Chapter 5, give air pollution control officials the ability to "see" the relative effect of a given pollution source on ambient air quality levels.

Several additional conclusions can be drawn from these field programs:

- 1) Sulfur dioxide production in the City of Chicago could be reduced by as much as 70% by fuel switching and load shifting by the electrical utility, if sufficient supplies of low-sulfur fuels are available.
- 2) Air quality in Chicago is adversely affected by large SO_2 sources outside the city limits, such as Cicero, the Gary-Hammond (Indiana) industrial area, and plants along the Illinois Ship Canal.
- 3) Air pollution control officials should take action to ensure that a large block of natural gas and other low-sulfur fuels are available at low unit prices when needed for air pollution control activities.
- 4) There is a definite need for real-time monitoring of air quality and meteorological conditions.
- 5) To uniquely relate changes in air quality to changes in SO_2 output during a fuel switch test requires a long period (say 72 hr) of constant weather conditions (wind direction and speed, stability, no precipitation, etc.), a condition not frequently observed in this area.

6) (This final conclusion is the most important one.) Without excessive costs or disruptions to normal operations, selective fuel switching can be used to abate (or lessen the severity of) air pollution episodes in any city or area in which a significant number of dual-fuel plants exist.

10. LONG-RANGE PLANNING IN AIR RESOURCE MANAGEMENT

(A. S. Cohen, E. J. Croke, A. Hurter, J. E. Norco, and J. J. Roberts)

10.1 Discussion

Long-range planning in air resource management involves the formulation, development, evaluation, and implementation of air pollution control strategies to ensure the maintenance of acceptable air quality over time. Such strategies must be flexible enough to avoid rapid obsolescence, yet stable enough to provide, for the components of the urban economic system, a base to develop its long-range plans.

The popular per-source control strategies, which include process-weight, thermal-input, potential emissions, sulfur content, control device, and stack-height control ordinances, do not, in general, have those properties. As the urban system evolves, the intensity of land-use may change drastically. This may result in increased pollution emissions over time, even if control regulations are strictly enforced. Thus the probability of violating the air quality standard in some areas will increase over time. Eventually, the control regulations will become obsolete and have to be reformulated.

This inherent obsolescence of these control strategies increases the uncertainty of the long-range planning function for the various economic activities in the control region. Because of the capital expense involved in air pollution control, an industrial firm will plan its expansion program to ensure that it will comply with control regulations over time. An increase in the uncertainty as to the severity of these regulations will decrease the probability of making economically sound decisions.

These problems of per-source controls can be avoided if regional controls are adopted. A regional control establishes well-defined emission rights associated with each parcel of land in the region. Regional emission-control regulations will be designated by a maximum uniform effective emission density E_i (mass per unit area per unit time, $\text{lb}/\text{m}^2\text{-hr}$) for each land use Class i (single-family residential, heavy industry, etc.). The maximum emissions from a given parcel of land are calculated by multiplying the land area of the parcel by the emission right of the actual or intended land use of the parcel.

Local governments throughout the region reflect the actual or intended land use within their jurisdiction through their zoning ordinances. Therefore, the air quality of a region, if it is fully developed, can be estimated by using a region-wide zoning survey which states the percentage of land zoned in each areal unit (square mile) for a specified number of zoning classes, a set of emission densities, and an atmospheric dispersion model.

The atmospheric dispersion model is used to calculate the concentration pattern $P_i(x,y)$ at every receptor point x, y in the region due to a unit emission ($1 \text{ lb/m}^2\text{-hr}$) from all areas with zoning Class i (zero emission from all other zones). For example, if 35% of the land in a particular square mile is zoned heavy industry (HI), an emission rate of 0.35 lb/hr would be assigned to that square mile in order to calculate the pattern $P_{HI}(x,y)$. These calculations are repeated, considering each zoning class separately, and result in a set of patterns $P_i(x,y)$. A representative, uniform stack height is assigned to each zoning class. A set of P_i 's is generated for both short- and long-term meteorological conditions.

The total ground-level pollutant concentration, $X(x,y)$ is then defined as

$$X(x,y) = \sum_{i=1}^N E_i P_i(x,y), \quad (10.1)$$

where N is the number of zoning (land-use) classes considered.

For both short- and long-term conditions, the values of $X(x,y)$ are compared to the air quality standards at each point (x,y) . If the standards are met, the vector of emission densities, $E = (E_1, \dots, E_N)$, is a feasible means of controlling pollution in the region. This regional control will ensure acceptable air quality over time, regardless of the intensity of land development.

The analysis, as presented, could be modified to include some special point sources such as power plants. Since the general methodology is not affected, these modifications are not discussed here.

Clearly, there are many solutions, i.e., many combinations of E_i that will satisfy the air quality standard. The set of all E_i 's that satisfy the constraints

$$\sum_{i=1}^N E_i P_i(x,y) \leq \text{air quality standard} \quad (10.2)$$

for all (x,y) is a convex polygon having one or more vertices determined by the intersections of the linear boundaries of the feasible solution for each individual dose point. Figure 10.1 is an example of such a feasible region in a two-dimensional problem.

Once established, the emission limit E_i immediately tells the operator or future operator of any source on land zoned Class i that his maximum allowable emission, $Q_{\max}$, is

$$Q_{\max} = \frac{A}{640} \times E_i, \quad (10.3)$$

where A is the number of acres associated with the plant. The regulation leaves it up to the operator to decide how compliance is to be achieved. This flexibility of control by the operator ensures that the most economical form of control will be employed by each source. The alternatives available to the operator include installations of control devices, use of cleaner fuels, reducing production, buying more land, and/or buying excess emission rights from his neighbors. The last alternative, at this point, is conjectural, but probably realistic.

Fig. 10.1

Envelope of Feasible Solutions for a Two-dimensional Emission-density Zoning Problem. ANL Neg. No. 113-1197.

In summary, the two major advantages of the regional approach are the assurance that acceptable air quality levels will be maintained over time and that the increased flexibility of control will be available to each source. Furthermore, the long-range planning function of the various components of the urban system is enhanced by eliminating uncertainty associated with control regulations.

In addition to the flexibility afforded to the sources of air pollution, the emission-right approach is amenable to simple forms of evaluation by air pollution control agencies and regional planners. This is a result of the convexity of the feasible region of admissible emission densities.

For example, the minimum perturbation solution for control can be generated using linear programming. The problem is formulated as

$$\min \sum_{i=1}^N C_i A_i (E_{iG} - E_i), \quad (10.4)$$

$$\text{st. } \sum_{i=1}^N E_i P_{ij} \leq S_j, \quad j = 1, \dots, J, \quad (10.5)$$

and

$$0 \leq E_{i\min} \leq E_i, \quad (10.6)$$

where

j = receptor points,

C_i = a weighting factor, such as land value, productivity per acre, etc., assigned to land in zoning Class i ,

A_i = total land area committed to zoning Class i ,

E_{iG} = emission density estimated for zoning Class i at the point of "natural growth,"

S_j = the air quality standard at the receptor,

and

$E_{i\min}$ = minimum possible value of E_i , based on technological limitations.

The philosophy behind this approach is that the minimum perturbation solution will cause the least disruption of the system, based on present trends, and therefore result in the least economic costs of control.

The regional approach to air resource management requires two essential inputs: a zoning inventory of the region, and projections of pollution emissions without control. The zoning is used with an atmospheric dispersion model to generate the P_i 's; the emission projections are used to determine the minimum perturbation solution.

The zoning survey, as used in the regional approach, was easily generated by using a modified Monte Carlo procedure, which is used in many land-use studies. This statistical procedure involves the superimposition of an array of dots onto a zoning map as shown in Fig. 10.2. For each areal unit, the percentage of dots falling into a particular zoning class is the estimate of the total area zoned in that class. For example, if 100 dots are used per square mile and 45 dots fall into areas zoned for manufacturing, then 45% of the square mile is considered to be zoned for manufacturing.

Future uncontrolled emissions were projected by using a simple projection model which uses only available or readily obtainable data.

A base year is selected to develop an emission inventory. (This may be a present-day inventory.) Future inventories are generated by using regional growth rates, fuel-conversion expectations, new construction plans, etc. These parameters are developed independently. Growth is assumed to occur exponentially, where appropriate capacity restrictions are imposed.

RESIDENCE DISTRICTS

- R1 SINGLE-FAMILY RESIDENCE DISTRICT
- R2 SINGLE-FAMILY RESIDENCE DISTRICT
- R3 GENERAL RESIDENCE DISTRICT
- R4 GENERAL RESIDENCE DISTRICT
- R5 GENERAL RESIDENCE DISTRICT
- R6 GENERAL RESIDENCE DISTRICT
- R7 GENERAL RESIDENCE DISTRICT
- R8 GENERAL RESIDENCE DISTRICT

BUSINESS DISTRICTS

- B1-1 TO B1-5 LOCAL RETAIL DISTRICTS
- B2-1 TO B2-5 RESTRICTED RETAIL DISTRICTS
- B3-1 TO B3-5 GENERAL RETAIL DISTRICTS
- B4-1 TO B4-5 RESTRICTED SERVICE DISTRICTS
- B5-1 TO B5-5 GENERAL SERVICE DISTRICTS
- B6-6 AND B6-7 RESTRICTED CENTRAL BUSINESS DISTRICTS
- B7-5 TO B7-7 GENERAL CENTRAL BUSINESS DISTRICTS

COMMERCIAL DISTRICTS

- C1-1 TO C1-5 RESTRICTED COMMERCIAL DISTRICTS
- C2-1 TO C2-5 GENERAL COMMERCIAL DISTRICTS
- C3-1 TO C3-7 COMMERCIAL-MANUFACTURING DISTRICTS
- C4 MOTOR FREIGHT TERMINAL DISTRICT

MANUFACTURING DISTRICTS

- M1-1 TO M1-5 RESTRICTED MANUFACTURING DISTRICTS
- M2-1 TO M2-5 GENERAL MANUFACTURING DISTRICTS
- M3-1 TO M3-5 HEAVY MANUFACTURING DISTRICT

Fig. 10.2

Array of Dots Superimposed on Zoning
Map. ANL Neg. No. 190-4 Rev. 2.

The model is divided into four major sections. These sections are designed to independently project emissions from residential, industrial/commercial point and area sources, and utility sources.

For complete details of the regional approach to air resource management, the zoning survey procedure, and the projection model, see ANL/ES-CC-008. Applications of the zoning procedure and the projection model were made, and the results are presented below.

10.2 Results of Zoning Survey

The complete 1970 zoning survey for the Northeastern Illinois Metropolitan study area is presented below. Four types of aggregation are used and are presented in the following order (see Fig. 10.3 and Table 10.1 for areal unit designation):

1. Areal units of square miles and zoning classes of limited, general, and heavy manufacturing (Table 10.2).
2. Areal units of square miles and zoning class of light and heavy manufacturing (Table 10.3).
3. Areal units of source I.D. and zoning classes of limited, general, and heavy manufacturing (Table 10.4).
4. Areal units of source I.D. and zoning classes of light and heavy manufacturing (Table 10.5).

The output lists the area source identification and the percent of the source zoned in each class (M1 = limited manufacturing, M2 = general manufacturing, M1 + M2 = light manufacturing, M3 = heavy manufacturing). In addition, when source I.D. units are used, the size of the source in square miles is also given.

For the 1970 survey, only one square mile showed an error in aggregation. Since this error was less than 5%, the computer program used to process the raw data automatically reduced each zoning class proportionally.

The final listing (Table 10.6) is the result of the 1964 zoning survey. This survey was incomplete. Two major areas not included in the survey were Will County and the City of Chicago. In addition, only two zoning classes were considered; they are M1 = light manufacturing and M2 = heavy manufacturing. The M3 class represents the portion of a source left unzoned because of the incomplete nature of the survey.

Fig. 10.3. X,Y and I.D. Grid Systems. ANL Neg. No. 190-15.

TABLE 10.1. X,Y and I.D. Mapping^a

X	Y	I.D.	X	Y	I.D.	X	Y	I.D.	X	Y	I.D.	X	Y	I.D.
46	51	10	45	51	20	44	51	30	43	51	40	42	51	50
46	50	60	45	50	70	44	50	80	43	50	90	42	50	100
46	49	110	45	49	120	44	49	130	43	49	140	42	49	150
46	48	160	45	48	170	44	48	180	43	48	190	42	48	200
46	47	210	45	47	220	44	47	230	43	47	240	42	47	250
47	46	260	46	46	270	45	46	280	44	46	290	43	46	300
42	46	310	44	54	320	42	54	330	40	54	340	44	52	350
42	52	360	40	52	370	40	50	380	40	48	390	40	46	400
46	44	410	44	44	420	42	44	430	40	44	440	48	42	450
46	42	460	44	42	470	42	42	480	40	42	490	50	39	500
50	37	510	30	87	520	20	87	530	10	87	540	0	87	550
30	77	560	20	77	570	10	77	580	0	77	590	30	67	600
20	67	610	10	67	620	0	67	630	40	61	640	35	62	650
40	62	660	20	57	670	10	57	680	0	57	690	0	57	690
40	56	700	35	57	710	30	57	720	35	52	730	30	52	740
20	47	750	10	47	760	0	47	770	35	47	780	30	47	790
35	42	800	30	42	810	20	42	820	10	42	830	0	42	840
45	37	850	40	37	860	35	37	870	30	37	880	45	32	890
40	32	900	30	27	910	20	27	920	10	27	930	45	27	940
40	27	950	45	22	960	40	22	970	30	17	980	20	17	990
10	17	1000	45	17	1010	40	17	1020	40	7	1030	30	7	1040
20	7	1050	10	7	1060	50	35	1360	50	33	1370	50	31	1380
50	29	1390	50	27	1460	50	22	1550	50	12	1590	50	2	1620

^aThe X,Y coordinate is for the lower left-hand corner of the I.D. grid. Only those grids in Illinois are listed.

TABLE 10.2. X,Y Listing of 1970 Data for Limited, General, and Heavy Manufacturing

X	Y	M1	M2	M3	TOTAL	X	Y	M1	M2	M3	TOTAL	X	Y	M1	M2	M3	TOTAL
0	40	1.	0.	0.	1.	11	45	1.	38.	0.	39.	14	52	34.	46.	0.	80.
0	42	2.	0.	0.	2.	11	47	0.	2.	6.	8.	14	53	48.	0.	0.	48.
0	49	1.	0.	0.	1.	11	48	0.	13.	1.	14.	14	54	18.	0.	0.	18.
0	90	1.	0.	0.	1.	11	49	0.	27.	0.	27.	14	57	36.	0.	0.	36.
1	42	0.	0.	4.	4.	11	52	24.	6.	0.	30.	14	58	1.	10.	30.	41.
1	46	3.	0.	0.	3.	11	53	12.	0.	0.	12.	14	59	3.	20.	67.	90.
1	63	0.	0.	1.	1.	11	57	1.	0.	6.	7.	14	60	12.	0.	4.	16.
1	91	1.	0.	0.	1.	11	58	0.	0.	6.	6.	14	61	1.	0.	0.	1.
2	44	3.	0.	0.	3.	11	59	9.	0.	21.	30.	14	63	1.	0.	0.	1.
2	46	1.	0.	0.	1.	11	60	3.	0.	0.	3.	14	73	4.	0.	0.	4.
2	50	1.	0.	0.	1.	11	61	3.	0.	0.	3.	14	74	10.	0.	0.	10.
2	51	0.	0.	5.	5.	11	62	21.	0.	17.	38.	14	76	16.	0.	0.	16.
2	54	1.	0.	0.	1.	11	63	19.	0.	0.	19.	14	82	1.	0.	0.	1.
2	58	2.	0.	0.	2.	11	64	1.	0.	0.	1.	15	6	0.	0.	2.	2.
2	64	2.	0.	0.	2.	11	65	0.	0.	2.	2.	15	16	0.	0.	40.	40.
2	65	4.	0.	0.	4.	11	66	0.	0.	13.	13.	15	17	0.	0.	100.	100.
3	51	0.	0.	8.	8.	11	67	3.	0.	15.	18.	15	18	0.	0.	61.	61.
3	61	3.	0.	0.	3.	11	70	16.	0.	0.	16.	15	19	4.	0.	16.	40.
3	65	3.	0.	0.	3.	11	71	28.	0.	18.	46.	15	20	0.	0.	7.	2.
3	71	10.	0.	6.	16.	11	72	28.	0.	0.	28.	15	21	0.	0.	4.	4.
3	82	18.	0.	6.	24.	11	73	36.	0.	0.	36.	15	22	2.	0.	5.	7.
3	83	16.	0.	0.	16.	11	74	44.	0.	0.	44.	15	24	1.	0.	0.	1.
4	61	1.	0.	0.	1.	11	75	42.	0.	0.	42.	15	25	7.	0.	0.	7.
4	69	2.	0.	0.	2.	11	76	9.	0.	0.	9.	15	30	2.	0.	0.	2.
4	70	1.	0.	0.	1.	11	83	8.	0.	0.	8.	15	31	23.	0.	0.	23.
4	71	1.	0.	6.	7.	11	91	0.	0.	6.	6.	15	32	26.	0.	0.	26.
4	79	9.	0.	0.	9.	11	92	8.	0.	10.	18.	15	33	33.	0.	0.	33.
4	80	2.	0.	0.	2.	11	93	0.	0.	4.	4.	15	36	14.	0.	0.	14.
4	81	6.	0.	0.	6.	12	41	0.	0.	1.	1.	15	37	2.	0.	0.	2.
4	91	0.	0.	7.	7.	12	42	8.	0.	29.	37.	15	38	3.	0.	0.	3.
4	92	4.	0.	0.	4.	12	43	6.	0.	17.	4.	15	42	0.	0.	62.	62.
4	93	4.	0.	0.	4.	12	44	0.	10.	8.	18.	15	43	17.	0.	24.	36.
5	50	3.	0.	0.	3.	12	45	18.	0.	17.	43.	15	44	9.	0.	0.	9.
5	56	2.	0.	0.	2.	12	48	0.	15.	8.	23.	15	45	23.	0.	0.	23.
5	69	10.	0.	0.	19.	12	49	0.	8.	31.	39.	15	49	22.	0.	0.	22.
5	70	8.	0.	8.	16.	12	50	2.	0.	0.	2.	15	50	0.	68.	0.	68.
5	71	1.	0.	0.	1.	12	52	44.	0.	0.	44.	15	51	18.	6.	0.	24.
5	78	2.	0.	0.	2.	12	53	12.	0.	0.	12.	15	52	6.	26.	0.	32.
5	79	32.	0.	0.	32.	12	57	4.	0.	40.	48.	15	56	4.	0.	0.	4.
5	80	37.	0.	0.	37.	12	58	1.	0.	4.	10.	15	57	68.	0.	0.	68.
5	81	6.	0.	0.	6.	12	59	0.	0.	32.	32.	15	58	0.	14.	0.	14.
5	84	4.	0.	0.	4.	12	60	13.	0.	8.	21.	15	59	11.	0.	0.	11.
5	91	6.	0.	0.	6.	12	61	8.	0.	0.	8.	15	60	3.	0.	0.	3.
5	92	1.	0.	1.	2.	12	62	6.	0.	0.	6.	15	72	8.	0.	0.	8.
5	93	4.	0.	0.	4.	12	63	4.	0.	0.	4.	15	73	10.	0.	0.	10.
6	40	0.	0.	12.	12.	12	66	70.	0.	5.	25.	15	88	8.	0.	0.	8.
6	42	2.	0.	0.	2.	12	67	29.	0.	17.	45.	15	89	6.	0.	1.	7.
6	48	1.	0.	0.	1.	12	68	1.	0.	16.	20.	16	10	0.	0.	23.	23.
6	50	4.	0.	0.	4.	12	71	0.	0.	14.	14.	16	11	1.	0.	10.	11.
6	59	1.	0.	0.	1.	12	73	1.	0.	0.	1.	16	16	0.	0.	70.	70.
6	69	0.	3.	0.	3.	12	74	22.	0.	22.	22.	16	17	0.	0.	84.	84.
6	78	8.	0.	0.	8.	12	75	4.	0.	0.	4.	16	18	0.	0.	82.	82.
6	79	20.	0.	0.	20.	12	77	14.	0.	0.	14.	16	19	5.	0.	23.	28.
6	91	6.	0.	0.	6.	12	78	2.	0.	0.	2.	16	20	0.	0.	65.	65.
6	92	1.	0.	0.	1.	12	79	1.	0.	0.	1.	16	21	2.	0.	24.	26.
7	40	0.	0.	54.	54.	12	80	6.	0.	0.	6.	16	22	7.	0.	3.	10.
7	62	8.	0.	0.	8.	12	81	8.	0.	2.	10.	16	24	5.	0.	0.	5.
7	63	3.	0.	2.	5.	12	83	5.	0.	0.	5.	16	25	10.	0.	0.	16.
7	65	0.	0.	2.	2.	12	85	8.	0.	0.	8.	16	27	7.	0.	0.	7.
7	66	2.	0.	4.	6.	12	86	1.	0.	0.	1.	16	30	1.	0.	4.	5.
7	68	1.	0.	0.	1.	13	92	2.	0.	0.	2.	16	31	5.	0.	56.	61.
7	75	4.	0.	0.	4.	13	3	0.	0.	9.	9.	16	32	20.	0.	40.	60.
7	92	1.	0.	0.	1.	13	4	0.	0.	47.	47.	16	33	12.	0.	23.	35.
8	40	1.	7.	63.	71.	13	5	0.	0.	30.	30.	16	34	0.	0.	6.	6.
8	41	0.	1.	6.	7.	13	6	0.	0.	37.	37.	16	35	0.	0.	7.	7.
8	44	0.	1.	2.	3.	13	16	0.	0.	2.	2.	16	36	3.	0.	4.	7.
8	45	0.	0.	19.	19.	13	27	0.	0.	6.	6.	16	47	0.	0.	40.	46.
8	48	1.	0.	0.	1.	13	42	4.	0.	72.	76.	16	43	16.	0.	10.	26.
8	50	4.	2.	0.	6.	13	44	0.	0.	42.	42.	16	45	10.	0.	0.	10.
8	52	6.	0.	0.	6.	13	49	1.	0.	0.	1.	16	52	23.	0.	0.	23.
8	62	2.	0.	0.	2.	13	57	0.	0.	7.	7.	16	72	8.	0.	0.	8.
8	66	2.	0.	0.	2.	13	58	25.	30.	1.	56.	16	79	1.	0.	0.	1.
8	77	4.	0.	0.	4.	13	59	0.	42.	8.	90.	16	81	12.	0.	0.	12.
9	40	0.	5.	2.	7.	13	60	8.	0.	8.	8.	16	88	9.	0.	0.	9.
9	41	2.	1.	23.	26.	13	61	6.	0.	6.	6.	17	10	0.	0.	14.	15.
9	42	5.	1.	15.	21.	13	67	3.	0.	0.	3.	17	11	0.	0.	1.	1.
9	43	0.	0.	22.	22.	13	63	5.	0.	0.	5.	17	18	0.	0.	0.	0.
9	44	5.	0.	14.	19.	13	66	2.	0.	0.	2.	17	19	0.	0.	18.	18.
9	45	0.	13.	5.	18.	13	67	2.	0.	0.	2.	17	20	0.	0.	100.	100.
9	48	0.	0.	7.	7.	13	69	1.	0.	4.	5.	17	21	0.	0.	67.	67.
9	49	0.	0.	11.	11.	13	72	6.	0.	6.	6.	17	22	0.	0.	72.	72.
9	50	0.	0.	28.	28.	13	73	3.	0.	0.	3.	17	23	0.	0.	36.	36.
9	52	16.	2.	10.	28.	13	74	1.	0.	47.	48.	17	25	0.	1.	1.	2.
9	53	3.	2.	0.	5.	13	75	0.	0.	14.	14.	17	30	1.	0.	18.	19.
9	60	24.	0.	0.	24.	13	81	18.	0.	3.	21.	17	31	0.	0.	70.	70.
9	61	1.	0.	0.	1.	13	82	2.	0.	0.	2.	17	32	0.	0.	56.	58.
9	63	2.	0.	0.	2.	13	83	14.	0.	0.	14.	17	33	0.	0.	62.	62.
9	91	0.	0.	7.	7.	13	89	3.	0.	0.	3.	17	34	0.	0.	41.	41.
10	39	0.	0.	8.	8.	14	3	0.	0.	20.	20.	17	35	0.	0.	3.	3.
10	40	0.	0.	8.	8.	14	4	0.	0.	90.	90.	17	36	0.	0.	3.	3.
10	41	2.	1.	0.	3.	14	7	0.	0.	8.	8.	17	43	1.	0.	1.	2.
10	42	7.	8.	18.	33.	14	11	0.	0.	40.	40.	17	46	0.	0.	1.	1.
10	43	5.	17.	10.	27.	14	13	1.	0.	0.	1.	17	47	0.	0.	4.	4.
10	44	14.	14.	21.	49.	14	16	0.	0.	6.	6.	17	52	18.	0.	0.	18.
10	45	8.	3.	14.	25.	14	17	0.	0.	29.	29.	17	57	17.	0.	0.	17.
10	47	0.	2.	17.	19.	14	18	0.	0.	7.	7.	17	60	4.	0.	0.	4.
10	48	0.	3.	10.	13.	14	19	0.	0.	27.	27.	17	87	10.	0.	0.	10.
10	49	1.	2.	0.	4.	14	20	0.	0.	8.	8.	18	7	1.	0.	0.	1.
10	50	0.	0.	7.	7.	14	21	9.	0.	4.	13.	18	13	5.	0.	0.	5.
10	52	6.	0.	0.	6.	14	22	1.	0.	10.	11.	18	14	0.	0.	16.	16.
10	53	6.	0.	0.	6.	14	25										

TABLE 10.2 (Contd.)

X	Y	M1	M2	M3	TOTAL	X	Y	M1	M2	M3	TOTAL	X	Y	M1	M2	M3	TOTAL
19 7	1.	0.	4.	5.		24 26	9.	0.	0.	9.		30 39	11.	5.	0.	0.	16.
19 8	0.	0.	8.	8.		24 34	0.	0.	53.	53.		30 52	12.	0.	0.	0.	12.
19 22	0.	0.	5.	5.		24 35	6.	0.	59.	65.		30 53	8.	7.	0.	0.	15.
19 23	0.	0.	68.	68.		24 36	17.	0.	27.	44.		30 54	0.	20.	0.	0.	20.
19 24	0.	0.	68.	68.		24 37	41.	0.	0.	41.		30 55	48.	22.	3.	0.	73.
19 25	6.	0.	0.	6.		24 43	5.	0.	0.	5.		30 56	21.	0.	0.	0.	21.
19 27	0.	1.	0.	1.		24 44	38.	0.	0.	38.		30 58	4.	28.	0.	0.	32.
19 28	3.	2.	0.	5.		24 46	16.	0.	0.	16.		30 59	62.	9.	9.	80.	
19 32	0.	0.	3.	3.		24 50	10.	0.	0.	10.		30 67	2.	0.	0.	2.	
19 33	0.	0.	44.	44.		24 51	6.	0.	0.	6.		30 68	12.	0.	0.	12.	
19 43	2.	0.	7.	9.		24 52	6.	0.	0.	6.		30 69	2.	0.	0.	2.	
19 51	19.	0.	15.	15.		24 53	20.	0.	0.	20.		30 70	18.	0.	0.	18.	
19 52	1.	0.	0.	1.		24 55	6.	0.	0.	6.		30 71	6.	0.	0.	6.	
19 54	32.	0.	0.	32.		24 56	5.	0.	0.	5.		30 72	22.	0.	0.	22.	
19 55	10.	0.	0.	10.		24 57	12.	0.	0.	12.		30 78	15.	0.	0.	15.	
19 57	25.	0.	0.	25.		24 61	17.	0.	0.	17.		31 15	1.	0.	0.	1.	
19 58	4.	0.	0.	4.		24 62	60.	0.	0.	60.		31 39	4.	38.	0.	42.	
19 63	27.	0.	0.	27.		24 63	4.	0.	0.	4.		31 49	5.	0.	0.	5.	
19 77	7.	0.	0.	7.		24 64	25.	0.	0.	25.		31 51	0.	48.	0.	48.	
19 78	10.	0.	0.	10.		24 65	5.	0.	0.	5.		31 53	6.	54.	0.	60.	
20 23	0.	0.	14.	14.		24 66	5.	0.	0.	5.		31 54	5.	45.	0.	50.	
20 24	1.	2.	16.	19.		24 73	20.	0.	0.	20.		31 55	1.	71.	11.	83.	
20 28	2.	28.	0.	30.		24 85	12.	0.	0.	12.		31 58	18.	1.	0.	19.	
20 38	4.	0.	0.	4.		25 32	4.	0.	0.	4.		31 59	16.	2.	0.	18.	
20 43	18.	0.	0.	18.		25 34	0.	0.	4.	4.		31 65	2.	56.	0.	58.	
20 44	0.	0.	1.	1.		25 35	0.	0.	11.	11.		31 66	20.	25.	0.	45.	
20 48	0.	0.	8.	8.		25 36	12.	0.	71.	83.		31 67	34.	15.	0.	49.	
20 49	0.	0.	20.	20.		NEXT (M1+M2+M3) BETWEEN 100 AND 105											
20 50	3.	0.	0.	3.		25 37	100.	0.	0.	100.		31 68	13.	0.	0.	13.	
20 51	53.	0.	0.	53.		25 38	14.	0.	0.	14.		31 69	4.	0.	0.	4.	
20 53	54.	0.	0.	54.		25 45	5.	0.	0.	5.		31 72	71.	0.	0.	71.	
20 53	26.	0.	0.	26.		25 46	22.	0.	0.	22.		31 77	14.	0.	0.	14.	
20 54	46.	0.	0.	46.		25 47	40.	0.	0.	40.		31 88	10.	0.	0.	10.	
20 55	10.	0.	0.	10.		25 51	10.	0.	0.	10.		31 92	23.	0.	0.	23.	
20 57	44.	0.	0.	44.		25 52	46.	29.	0.	74.		32 15	7.	0.	0.	7.	
20 59	2.	0.	0.	2.		25 53	14.	0.	0.	14.		32 22	14.	0.	0.	14.	
20 76	1.	0.	0.	1.		25 56	28.	0.	0.	28.		32 23	35.	0.	0.	35.	
20 78	10.	0.	0.	10.		25 57	38.	0.	0.	38.		32 27	0.	15.	0.	15.	
20 81	7.	0.	0.	7.		25 62	17.	0.	0.	17.		32 30	1.	0.	0.	1.	
20 82	9.	0.	0.	9.		25 64	8.	0.	0.	8.		32 31	17.	28.	0.	28.	
21 22	0.	0.	13.	13.		25 65	63.	0.	0.	63.		32 32	0.	34.	0.	34.	
21 23	0.	0.	11.	11.		25 65	63.	0.	0.	63.		32 39	0.	20.	0.	20.	
21 24	0.	15.	36.	51.		25 75	3.	0.	0.	3.		32 40	1.	91.	7.	91.	
21 25	0.	9.	5.	14.		25 78	2.	0.	0.	2.		32 41	0.	31.	0.	31.	
21 26	0.	4.	2.	6.		25 81	10.	0.	0.	10.		32 49	12.	0.	0.	12.	
21 27	0.	0.	10.	10.		25 82	2.	0.	0.	2.		32 51	0.	0.	0.	0.	
21 28	2.	10.	37.	49.		26 17	0.	0.	20.	20.		32 53	0.	0.	0.	0.	
21 34	0.	0.	11.	11.		26 18	5.	0.	37.	37.		32 54	0.	43.	0.	43.	
21 38	0.	0.	4.	4.		26 25	11.	0.	1.	12.		32 55	0.	51.	10.	61.	
21 39	0.	0.	10.	10.		26 36	17.	0.	40.	57.		32 59	4.	0.	0.	4.	
21 50	4.	0.	0.	4.		26 37	4.	0.	0.	4.		32 62	7.	2.	0.	9.	
21 51	38.	0.	0.	38.		26 38	4.	0.	0.	4.		32 63	9.	7.	0.	16.	
21 52	56.	0.	0.	56.		26 40	10.	0.	0.	10.		32 65	7.	0.	0.	7.	
21 53	13.	0.	0.	13.		26 41	5.	0.	0.	5.		32 66	62.	0.	3.	65.	
21 54	40.	0.	0.	40.		26 44	8.	0.	0.	8.		32 77	25.	7.	0.	28.	
21 57	26.	0.	0.	26.		26 51	6.	0.	0.	6.		32 78	15.	32.	24.	71.	
21 58	71.	0.	0.	71.		26 52	60.	13.	0.	73.		32 79	48.	2.	0.	50.	
21 70	22.	0.	0.	22.		26 53	16.	0.	0.	16.		32 80	47.	0.	0.	47.	
						26 55	2.	0.	0.	2.		32 81	26.	0.	0.	26.	
						26 62	10.	0.	0.	10.							
22 24	4.	0.	12.	20.		26 65	14.	0.	0.	14.		32 82	10.	0.	0.	10.	
22 25	0.	0.	11.	11.		27 25	0.	0.	2.	2.		32 83	15.	0.	0.	15.	
22 26	0.	1.	33.	34.		27 30	1.	0.	0.	1.		32 84	6.	0.	0.	6.	
22 27	0.	0.	92.	92.		27 36	10.	0.	30.	40.		32 85	18.	5.	29.	51.	
22 28	0.	0.	56.	56.		27 37	0.	0.	20.	20.		32 86	0.	0.	11.	11.	
22 29	0.	0.	40.	40.		27 42	4.	0.	0.	4.		33 22	3.	0.	0.	3.	
22 30	2.	0.	37.	39.		27 43	4.	0.	0.	4.		33 23	6.	0.	0.	6.	
22 31	0.	0.	29.	29.		27 50	0.	0.	7.	7.		33 26	19.	0.	0.	19.	
22 32	0.	0.	20.	20.		27 51	16.	0.	7.	18.		33 27	14.	0.	0.	14.	
22 33	0.	0.	21.	21.		27 52	30.	0.	0.	30.		33 31	17.	0.	0.	17.	
22 38	0.	0.	14.	14.		27 53	12.	0.	0.	12.		33 34	0.	0.	0.	0.	
22 39	0.	0.	50.	50.		27 55	4.	0.	0.	4.		33 40	2.	11.	0.	13.	
22 49	0.	0.	2.	2.		27 56	40.	0.	0.	40.		33 41	4.	51.	5.	60.	
22 51	3.	0.	0.	3.		27 57	4.	0.	0.	4.		33 43	0.	0.	11.	11.	
22 53	10.	0.	0.	10.		27 60	4.	0.	0.	4.		33 44	0.	0.	22.	22.	
22 54	7.	0.	0.	7.		27 61	77.	0.	0.	77.		33 45	9.	0.	0.	9.	
22 57	22.	0.	0.	22.		27 62	4.	0.	0.	4.		33 46	3.	0.	0.	3.	
22 58	31.	0.	0.	31.		27 80	20.	0.	0.	20.		33 47	5.	0.	0.	5.	
22 59	9.	0.	0.	9.		27 84	1.	0.	0.	1.		33 48	5.	0.	0.	5.	
22 62	12.	0.	0.	12.		27 87	10.	0.	0.	10.		33 50	3.	0.	0.	3.	
22 70	0.	0.	0.	0.		28 24	1.	0.	0.	1.		33 51	6.	0.	45.	51.	
22 82	2.	0.	0.	2.		28 27	0.	0.	4.	4.		33 52	2.	0.	0.	2.	
22 85	20.	0.	0.	20.		28 28	0.	0.	13.	13.		33 53	0.	0.	53.	53.	
22 92	10.	0.	0.	10.		28 36	0.	0.	3.	3.		33 54	0.	13.	0.	13.	
23 23	1.	0.	0.	1.		28 37	0.	0.	94.	94.		33 55	28.	14.	3.	45.	
23 24	4.	0.	0.	4.		28 44	2.	0.	0.	2.		33 56	31.	0.	0.	31.	
23 25	10.	20.	4.	34.		28 49	10.	0.	4.	14.		33 57	3.	0.	0.	3.	
23 26	7.	1.	26.	34.		28 50	6.	0.	2.	8.		33 59	12.	0.	0.	12.	
23 27	0.	0.	1.	1.		28 51	1.	0.	0.	1.		33 62	0.	4.	0.	4.	
23 30	4.	0.	0.	4.		28 53	25.	0.	0.	25.		33 63	0.	14.	0.	14.	
23 31	0.	0.	81.	81.		28 55	9.	0.	0.	9.		33 64	5.	0.	0.	5.	
23 32	0.	0.	84.	84.		28 56	0.	15.	0.	15.		33 65	9.	0.	0.	9.	
23 33	0.	0.	27.	27.		28 59	25.	35.	0.	61.		33 68	2.	0.	0.	2.	
23 34	0.	0.	19.	19.		28 60	29.	0.	0.	29.		33 78	12.	8.	4.	24.	
23 35	5.	0.	24.	29.		28 61	12.	0.	0.	12.		33 79	25.	25.	0.	50.	
23 36	40.	0.	2.	43.		28 63	6.	0.	0.	6.		33 80	72.	10.	0.	82.	
23 37	8.	0.	0.	8.		28 75	10.	4.	0.	14.		33 81	6.	2.	10.	18.	
23 39	0.	0.	37.	37.		28 76	0.	5.	0.	5.		33 82	5.	10.	0.	15.	
23 40	1.	0.	0.	1.		28 79	7.	0.	0.	7.		33 83	0.	41.	0.	41.	
23 44	6.	0.	0.	6.		29 23	1.	0.	0.	1.		33 84	2.	1.	0.	3.	
23 46	6.	0.	0.	6.		29 30	2.	0.	0.	2.		33 85	0.	0.	7.	7.	
23 51	5.	0.	0.	5.		29 37	17.	0.	49.	66.		33 86	0.	0.			

TABLE 10.2 (Contd.)

X	Y	M1	M2	M3	TOTAL	X	Y	M1	M2	M3	TOTAL	X	Y	M1	M2	M3	TOTAL
34 61	6.	0.	0.	0.	6.	38 42	3.	0.	70.	73.	42 61	6.	0.	0.	0.	6.	
34 62	1.	0.	0.	0.	1.	38 43	4.	0.	0.	4.	43 19	6.	0.	0.	0.	6.	
34 63	29.	0.	0.	0.	29.	38 44	3.	0.	53.	62.	43 20	1.	0.	0.	0.	1.	
34 64	3.	0.	0.	0.	3.	38 45	6.	36.	45.	89.	43 22	0.	0.	0.	0.	5.	
34 68	3.	0.	0.	0.	3.	38 47	6.	32.	0.	38.	43 27	2.	0.	0.	0.	2.	
34 77	19.	0.	0.	0.	19.	38 49	0.	8.	0.	8.	43 28	22.	7.	0.	0.	29.	
34 78	14.	2.	0.	0.	16.	38 52	26.	0.	0.	26.	43 29	5.	22.	0.	0.	27.	
34 79	0.	7.	0.	0.	7.	38 56	5.	0.	0.	5.	43 31	0.	9.	0.	0.	9.	
34 87	0.	0.	30.	0.	30.	38 57	2.	0.	0.	2.	43 32	20.	2.	0.	0.	22.	
34 90	0.	44.	0.	0.	44.	38 58	5.	0.	0.	5.	43 33	0.	27.	42.	60.	69.	
34 91	0.	7.	0.	0.	7.	38 59	45.	2.	0.	47.	43 34	12.	0.	0.	0.	12.	
35 11	6.	0.	0.	0.	6.	38 60	21.	1.	0.	22.	43 35	15.	0.	18.	33.	33.	
35 23	1.	0.	0.	0.	1.	38 64	5.	0.	0.	5.	43 36	15.	0.	0.	0.	15.	
35 25	3.	0.	0.	0.	3.	38 65	3.	0.	0.	3.	43 40	6.	0.	0.	0.	6.	
35 27	33.	0.	0.	0.	33.	39 19	3.	0.	0.	3.	43 41	15.	10.	0.	0.	25.	
35 36	5.	0.	0.	0.	5.	39 22	8.	0.	0.	8.	43 42	10.	0.	0.	0.	10.	
35 38	0.	0.	5.	0.	5.	39 23	24.	0.	0.	24.	43 43	8.	26.	0.	0.	34.	
35 41	0.	5.	0.	0.	5.	39 33	22.	0.	18.	40.	43 44	1.	18.	0.	0.	19.	
35 42	2.	5.	50.	0.	57.	39 34	15.	0.	2.	17.	43 45	0.	43.	30.	0.	73.	
35 43	19.	34.	33.	0.	86.	39 35	17.	0.	0.	17.	43 46	6.	2.	4.	0.	12.	
35 44	6.	2.	79.	0.	87.	39 36	5.	0.	0.	5.	43 47	0.	4.	60.	64.	64.	
35 45	14.	0.	11.	0.	25.	39 37	1.	0.	0.	1.	43 48	7.	24.	0.	0.	31.	
35 48	12.	0.	0.	0.	12.	39 39	8.	0.	0.	8.	43 50	17.	24.	0.	0.	41.	
35 49	61.	0.	0.	0.	61.	39 41	0.	0.	55.	55.	43 52	15.	0.	0.	0.	15.	
35 53	1.	0.	0.	0.	1.	39 42	0.	0.	70.	70.	43 53	19.	15.	0.	0.	34.	
35 54	2.	0.	0.	0.	2.	39 44	4.	9.	0.	13.	43 54	5.	0.	0.	0.	5.	
35 60	2.	0.	0.	0.	2.	39 45	0.	24.	92.	76.	43 55	9.	0.	0.	0.	9.	
35 64	28.	0.	0.	0.	28.	39 46	0.	4.	37.	41.	43 56	8.	5.	0.	0.	13.	
35 65	5.	0.	0.	0.	5.	39 47	11.	48.	2.	61.	43 58	2.	5.	0.	0.	7.	
35 68	9.	0.	0.	0.	9.	39 48	14.	43.	0.	57.	43 59	4.	0.	0.	0.	4.	
35 69	20.	8.	0.	0.	28.	39 49	18.	26.	0.	44.	43 60	2.	0.	0.	0.	2.	
35 70	8.	0.	0.	0.	8.	39 50	5.	0.	0.	4.	43 61	5.	0.	0.	0.	5.	
35 73	7.	0.	0.	0.	7.	39 51	4.	0.	0.	4.	44 16	1.	0.	0.	0.	1.	
35 81	10.	0.	25.	0.	35.	39 52	17.	1.	0.	18.	44 21	3.	16.	0.	0.	19.	
35 82	10.	0.	6.	0.	16.	39 55	6.	0.	0.	6.	44 22	2.	10.	31.	0.	43.	
35 83	2.	0.	0.	0.	2.	39 56	10.	0.	0.	10.	44 23	6.	0.	0.	0.	14.	
35 84	1.	0.	0.	0.	1.	39 57	6.	0.	0.	6.	44 24	0.	0.	0.	0.	5.	
35 85	2.	0.	0.	0.	2.	39 60	10.	0.	0.	10.	44 25	3.	0.	0.	0.	3.	
35 90	0.	4.	0.	0.	4.	39 61	10.	0.	0.	10.	44 26	5.	0.	0.	0.	5.	
35 91	14.	0.	0.	0.	14.	39 62	3.	6.	0.	9.	44 27	10.	29.	0.	0.	39.	
35 92	6.	0.	0.	0.	6.	39 63	3.	0.	0.	3.	44 28	1.	48.	0.	0.	49.	
36 10	3.	0.	0.	0.	3.	39 64	10.	0.	0.	10.	44 29	10.	15.	0.	0.	25.	
36 11	5.	0.	6.	11.	11.	40 21	2.	0.	0.	2.	44 30	0.	22.	0.	0.	22.	
36 12	4.	3.	0.	7.	7.	40 22	24.	0.	0.	24.	44 31	0.	27.	0.	0.	27.	
36 22	0.	29.	0.	29.	29.	40 23	12.	0.	0.	12.	44 32	29.	0.	0.	0.	42.	
36 23	0.	17.	0.	17.	17.	40 29	13.	0.	0.	13.	44 33	33.	33.	0.	0.	66.	
36 26	4.	0.	0.	0.	4.	40 33	15.	0.	5.	20.	44 34	5.	4.	0.	0.	9.	
36 27	51.	0.	0.	0.	51.	40 34	15.	4.	44.	63.	44 35	13.	20.	0.	0.	33.	
36 35	9.	0.	3.	11.	11.	40 35	1.	0.	3.	4.	44 36	10.	5.	0.	0.	15.	
36 36	5.	12.	2.	10.	19.	40 41	7.	43.	0.	50.	44 37	7.	6.	0.	0.	13.	
36 37	15.	8.	0.	23.	23.	40 42	18.	10.	0.	28.	44 38	1.	0.	0.	0.	1.	
36 38	7.	46.	3.	56.	66.	40 43	21.	0.	0.	21.	44 39	13.	0.	0.	0.	13.	
36 39	26.	14.	0.	40.	40.	40 44	27.	0.	0.	27.	44 40	1.	0.	0.	0.	1.	
36 40	0.	18.	0.	18.	18.	40 45	10.	60.	5.	75.	44 41	8.	5.	0.	0.	13.	
36 41	0.	24.	0.	24.	24.	40 46	0.	22.	43.	38.	44 42	0.	0.	0.	0.	0.	
36 42	0.	35.	25.	60.	60.	40 47	12.	17.	0.	29.	44 44	5.	10.	0.	0.	15.	
36 43	18.	2.	0.	20.	20.	40 48	3.	16.	3.	22.	44 45	4.	4.	84.	92.	92.	
36 44	11.	0.	17.	26.	26.	40 49	23.	14.	0.	37.	44 46	6.	11.	25.	47.	47.	
36 45	10.	0.	0.	10.	10.	40 50	21.	37.	0.	58.	44 47	9.	18.	37.	63.	63.	
36 48	5.	17.	0.	22.	22.	40 51	16.	23.	0.	39.	44 48	7.	23.	0.	0.	30.	
36 49	3.	3.	0.	6.	6.	40 52	18.	15.	0.	33.	44 49	36.	0.	0.	0.	36.	
36 53	2.	0.	0.	2.	2.	40 53	21.	8.	0.	29.	44 50	15.	35.	0.	0.	50.	
36 54	3.	0.	0.	3.	3.	40 54	17.	1.	0.	18.	44 51	0.	10.	46.	50.	50.	
36 57	1.	0.	0.	1.	1.	40 55	8.	0.	0.	8.	44 52	18.	7.	10.	64.	64.	
36 58	2.	0.	0.	2.	2.	40 56	4.	0.	0.	4.	44 53	13.	3.	0.	0.	16.	
36 64	21.	0.	0.	21.	21.	40 57	2.	17.	0.	19.	44 54	4.	0.	0.	0.	4.	
36 65	25.	0.	0.	25.	25.	40 60	4.	0.	0.	4.	45 17	2.	0.	0.	0.	2.	
36 66	12.	0.	0.	12.	12.	41 20	7.	16.	0.	23.	45 18	0.	0.	0.	0.	0.	
36 70	5.	0.	0.	5.	5.	41 23	17.	0.	0.	17.	45 19	13.	0.	0.	0.	13.	
36 71	18.	0.	0.	18.	18.	41 29	16.	0.	0.	16.	45 22	21.	14.	47.	84.	84.	
36 72	25.	0.	0.	25.	25.	41 30	21.	0.	0.	21.	45 23	0.	0.	0.	0.	0.	
36 81	0.	0.	12.	12.	12.	41 32	4.	0.	0.	4.	45 24	6.	16.	77.	90.	90.	
36 82	0.	0.	27.	27.	27.	41 33	7.	0.	18.	25.	45 25	17.	0.	11.	28.	28.	
36 83	3.	0.	20.	23.	23.	41 34	39.	0.	30.	69.	45 26	9.	6.	0.	0.	15.	
36 84	2.	0.	57.	59.	59.	41 35	4.	0.	12.	16.	45 27	0.	67.	0.	0.	67.	
36 85	6.	0.	45.	51.	51.	41 40	7.	0.	0.	7.	45 28	0.	73.	0.	0.	73.	
36 86	0.	0.	7.	7.	7.	41 41	5.	25.	0.	30.	45 29	65.	0.	0.	0.	65.	
36 88	0.	11.	0.	11.	11.	41 42	1.	0.	0.	1.	45 30	46.	0.	0.	0.	46.	
36 89	0.	15.	0.	15.	15.	41 43	3.	0.	0.	3.	45 31	16.	0.	0.	0.	16.	
36 90	0.	2.	0.	2.	2.	41 44	24.	23.	0.	47.	45 32	8.	0.	0.	0.	8.	
37 20	0.	0.	2.	2.	2.	41 45	10.	0.	60.	70.	45 33	5.	0.	0.	0.	5.	
37 26	7.	0.	0.	7.	7.	41 46	6.	0.	61.	67.	45 34	0.	1.	31.	37.	37.	
37 27	11.	0.	0.	11.	11.	41 47	4.	2.	0.	6.	45 35	4.	0.	0.	0.	4.	
37 35	19.	0.	11.	30.	30.	41 48	2.	0.	0.	2.	45 36	2.	0.	0.	0.	2.	
37 36	0.	2.	4.	6.	6.	41 49	15.	0.	0.	15.	45 37	6.	0.	0.	0.	6.	
37 37	12.	0.	0.	12.	12.	41 50	6.	0.	0.	6.	45 39	18.	11.	0.	0.	29.	
37 38	30.	0.	0.	30.	30.	41 51	10.	1.	0.	11.	45 40	37.	16.	0.	0.	53.	
37 41	0.	0.	48.	48.	48.	41 52	16.	0.	0.	16.	45 41	13.	0.	0.	0.	13.	
37 42	5.	0.	70.	75.	75.	41 53	3.	0.	0.	3.	45 42	9.	4.	0.	0.	13.	
37 43	25.	0.	0.	25.	25.	41 54	21.	0.	0.	23.	45 43	19.	0.	0.	0.	19.	
37 44	0.	37.	22.	59.	59.	41 59	0.	70.	0.	70.	45 44	46.	0.	0.	0.	46.	
37 45	9.	15.	0.	24.	24.	42 20	15.	0.	0.	15.	45 45	15.	75.	0.	0.	60.	
37 52	13.	5.	0.	18.	18.	42 21	6.	0.	0.	6.	45 46	26.	0.	0.	0.	26.	
37 53	9.	0.	0.	18.	18.	42 23	9.	0.	0.	9.	45 47	19.	10.	6.	0.	34.	
37 54	1.	0.	0.	1.	1.	42 29	4.	51.	0.	55.	45 48	3.	62.	6.	0.	71.	
37 57	2.	0.	0.	2.	2.	42 30	0.	0.	0.	0.	45 49	0.	37.	0.	0.	37.	
37 58	2.	0.	0.	2.	2.	42 32	21.	0.	0.	21.	45 50	26.	0.	0.	0.	26.	
37 59	24.	0.	0.	24.	24.	42 33	26.	14.	51.	91.	45 51	5.	4.	5.	14.	14.	
37 60	3.	0.	0.	3.													

TABLE 10.2 (Contd.)

X	Y	M1	M2	M3	TOTAL
46	42	18.	6.	0.	24.
46	43	3.	0.	0.	3.
46	44	2.	0.	0.	2.
46	45	5.	0.	0.	5.
46	47	17.	15.	0.	32.
46	48	2.	2.	0.	4.
47	22	38.	0.	0.	38.
47	23	13.	0.	0.	13.
47	24	10.	0.	0.	10.
47	25	5.	0.	0.	5.
47	27	0.	1.	0.	1.
47	28	10.	0.	0.	10.
47	29	18.	4.	0.	22.
47	30	3.	0.	0.	11.
47	32	7.	0.	21.	28.
47	33	0.	0.	28.	28.
47	34	5.	0.	30.	35.
47	35	0.	0.	30.	30.
47	36	0.	0.	14.	14.
47	37	1.	6.	72.	79.
47	38	18.	0.	52.	70.
47	39	30.	0.	0.	30.
47	40	11.	0.	0.	11.
47	41	24.	0.	0.	24.
47	42	3.	0.	0.	3.
48	23	4.	0.	0.	4.
48	28	15.	0.	0.	15.
48	29	17.	17.	0.	34.
48	30	0.	1.	0.	1.
48	31	0.	0.	2.	2.
48	32	0.	3.	52.	55.
48	33	0.	2.	32.	34.
48	34	0.	0.	84.	84.
48	35	0.	0.	58.	58.
48	36	0.	0.	57.	57.
48	37	3.	8.	83.	94.
48	38	6.	18.	24.	48.
48	39	18.	0.	0.	18.
48	40	18.	0.	0.	18.
48	41	1.	0.	0.	1.
49	13	1.	0.	0.	1.
49	27	5.	0.	0.	5.
49	23	30.	4.	0.	35.
49	28	8.	0.	0.	8.
49	29	41.	0.	0.	41.
49	31	0.	20.	16.	36.
49	32	0.	70.	8.	78.
49	33	0.	12.	30.	42.
49	34	0.	14.	28.	42.
49	35	0.	8.	73.	81.
49	36	0.	1.	99.	100.
49	37	3.	4.	65.	72.
49	38	17.	1.	27.	45.
49	39	33.	0.	1.	34.
49	40	8.	0.	0.	8.
50	23	10.	0.	0.	10.
50	31	0.	4.	10.	14.
50	32	0.	52.	2.	54.
50	33	14.	1.	5.	20.
50	34	18.	0.	0.	18.
50	35	0.	27.	28.	55.
50	36	19.	4.	12.	35.
50	37	10.	0.	1.	11.
50	38	11.	0.	21.	32.
50	39	4.	0.	62.	66.
50	40	6.	0.	54.	60.
51	58	28.	0.	0.	28.

TABLE 10.3. X,Y Listing of 1970 Data for
Light and Heavy Manufacturing

X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL
C 40	1.	0.	1.	11 43	4.	2.	6.	14 49	16.	0.	16.	18 31	0.	7.	7.	18 31	0.	7.	7.
0 42	2.	0.	2.	11 45	39.	0.	39.	14 50	92.	0.	92.	18 33	0.	54.	54.	18 33	0.	54.	54.
0 69	1.	0.	1.	11 47	2.	6.	8.	14 51	37.	0.	37.	18 34	0.	51.	51.	18 34	0.	51.	51.
C 90	1.	0.	1.	11 48	13.	1.	14.	14 52	80.	0.	80.	18 37	27.	0.	27.	18 37	27.	0.	27.
1 42	0.	4.	4.	11 49	27.	0.	27.	14 53	48.	0.	48.	18 38	6.	0.	6.	18 38	6.	0.	6.
1 46	3.	0.	3.	11 52	30.	0.	30.	14 54	18.	0.	18.	19 7	1.	4.	5.	19 7	1.	4.	5.
1 63	0.	1.	1.	11 53	12.	0.	12.	14 57	36.	0.	36.	19 8	0.	8.	8.	19 8	0.	8.	8.
1 91	1.	0.	1.	11 57	1.	6.	7.	14 58	11.	30.	41.	19 22	0.	5.	5.	19 22	0.	5.	5.
2 44	3.	0.	3.	11 58	0.	6.	6.	14 59	23.	67.	90.	19 23	0.	68.	68.	19 23	0.	68.	68.
2 46	1.	0.	1.	11 59	9.	21.	30.	14 60	12.	4.	16.	19 24	0.	68.	68.	19 24	0.	68.	68.
2 50	1.	0.	1.	11 60	3.	0.	3.	14 61	1.	0.	1.	19 25	6.	0.	6.	19 25	6.	0.	6.
2 51	0.	5.	5.	11 61	3.	0.	3.	14 63	1.	0.	1.	19 27	1.	0.	1.	19 27	1.	0.	1.
2 54	1.	0.	1.	11 62	21.	17.	38.	14 73	4.	0.	4.	19 28	5.	0.	5.	19 28	5.	0.	5.
2 58	2.	0.	2.	11 63	19.	0.	19.	14 74	10.	0.	10.	19 32	0.	3.	3.	19 32	0.	3.	3.
2 64	2.	0.	2.	11 64	1.	0.	1.	14 76	16.	0.	16.	19 33	0.	44.	44.	19 33	0.	44.	44.
2 65	4.	0.	4.	11 65	0.	2.	2.	14 82	1.	0.	1.	19 43	7.	0.	7.	19 43	7.	0.	7.
3 51	0.	8.	8.	11 66	0.	13.	13.	15 6	0.	7.	7.	19 51	19.	0.	19.	19 51	19.	0.	19.
3 61	3.	0.	3.	11 67	3.	15.	18.	15 16	0.	40.	40.	19 52	1.	0.	1.	19 52	1.	0.	1.
3 65	3.	0.	3.	11 70	16.	0.	16.	15 17	0.	100.	100.	19 54	32.	0.	32.	19 54	32.	0.	32.
3 81	10.	6.	16.	11 71	28.	18.	46.	15 18	0.	61.	61.	19 55	10.	0.	10.	19 55	10.	0.	10.
3 82	18.	6.	24.	11 72	28.	0.	28.	15 19	4.	34.	40.	19 57	25.	0.	25.	19 57	25.	0.	25.
3 83	16.	0.	16.	11 73	36.	0.	36.	15 20	0.	2.	2.	19 58	4.	0.	4.	19 58	4.	0.	4.
4 61	1.	0.	1.	11 74	44.	0.	44.	15 21	0.	4.	4.	19 63	27.	0.	27.	19 63	27.	0.	27.
4 69	2.	0.	2.	11 75	42.	0.	42.	15 22	2.	5.	7.	19 77	7.	0.	7.	19 77	7.	0.	7.
4 70	1.	0.	1.	11 76	9.	0.	9.	15 24	1.	0.	1.	19 78	10.	0.	10.	19 78	10.	0.	10.
4 71	1.	0.	1.	11 81	8.	0.	8.	15 25	7.	0.	7.	20 23	0.	34.	34.	20 23	0.	34.	34.
4 79	9.	0.	9.	11 91	0.	6.	6.	15 30	2.	0.	2.	20 24	3.	16.	19.	20 24	3.	16.	19.
4 80	2.	0.	2.	11 92	8.	10.	18.	15 31	73.	0.	73.	20 28	30.	0.	30.	20 28	30.	0.	30.
4 81	6.	0.	6.	11 93	0.	4.	4.	15 32	20.	0.	20.	20 38	4.	0.	4.	20 38	4.	0.	4.
4 91	0.	2.	2.	12 41	0.	1.	1.	15 33	33.	0.	33.	20 43	18.	0.	18.	20 43	18.	0.	18.
4 92	4.	0.	4.	12 42	8.	29.	37.	15 36	14.	0.	14.	20 44	0.	1.	1.	20 44	0.	1.	1.
4 93	4.	0.	4.	12 43	13.	4.	17.	15 37	2.	0.	2.	20 48	0.	8.	8.	20 48	0.	8.	8.
5 50	3.	0.	3.	12 44	10.	8.	18.	15 38	3.	0.	3.	20 49	0.	20.	20.	20 49	0.	20.	20.
5 56	2.	0.	2.	12 45	26.	17.	43.	15 42	0.	67.	67.	20 50	3.	0.	3.	20 50	3.	0.	3.
5 69	19.	0.	19.	12 48	15.	8.	23.	15 43	12.	24.	36.	20 51	53.	0.	53.	20 51	53.	0.	53.
5 70	8.	4.	16.	12 49	8.	31.	39.	15 44	9.	0.	9.	20 52	58.	0.	58.	20 52	58.	0.	58.
5 71	1.	0.	1.	12 50	2.	0.	2.	15 45	23.	0.	23.	20 53	26.	0.	26.	20 53	26.	0.	26.
5 78	2.	0.	2.	12 52	44.	0.	44.	15 46	22.	0.	22.	20 54	46.	0.	46.	20 54	46.	0.	46.
5 79	32.	0.	32.	12 53	12.	0.	12.	15 50	68.	0.	68.	20 55	10.	0.	10.	20 55	10.	0.	10.
5 80	32.	0.	32.	12 57	8.	40.	48.	15 51	24.	0.	24.	20 57	44.	0.	44.	20 57	44.	0.	44.
5 81	6.	0.	6.	12 58	1.	9.	10.	15 52	32.	0.	32.	20 58	2.	0.	2.	20 58	2.	0.	2.
5 84	4.	0.	4.	12 59	0.	32.	32.	15 56	4.	0.	4.	20 76	2.	0.	2.	20 76	2.	0.	2.
5 91	6.	3.	9.	12 60	13.	8.	21.	15 57	68.	0.	68.	20 78	10.	0.	10.	20 78	10.	0.	10.
5 92	1.	1.	2.	12 61	8.	0.	8.	15 58	14.	0.	14.	20 81	7.	0.	7.	20 81	7.	0.	7.
5 93	4.	0.	4.	12 62	6.	0.	6.	15 59	11.	0.	11.	20 82	9.	0.	9.	20 82	9.	0.	9.
6 40	0.	12.	12.	12 63	4.	0.	4.	15 60	3.	0.	3.	21 22	0.	13.	13.	21 22	0.	13.	13.
6 42	2.	0.	2.	12 66	20.	5.	25.	15 72	8.	0.	8.	21 23	0.	11.	11.	21 23	0.	11.	11.
6 48	1.	0.	1.	12 68	29.	16.	45.	15 73	10.	0.	10.	21 24	15.	0.	15.	21 24	15.	0.	15.
6 50	4.	0.	4.	12 71	1.	19.	20.	15 78	8.	0.	8.	21 25	9.	5.	14.	21 25	9.	5.	14.
6 59	1.	0.	1.	12 73	1.	14.	14.	15 89	6.	1.	7.	21 26	4.	2.	6.	21 26	4.	2.	6.
6 69	3.	0.	3.	12 74	22.	0.	22.	16 10	0.	23.	23.	21 27	0.	10.	10.	21 27	0.	10.	10.
6 78	8.	0.	8.	12 75	4.	0.	4.	16 11	1.	10.	11.	21 28	12.	37.	49.	21 28	12.	37.	49.
6 79	20.	0.	20.	12 76	4.	0.	4.	16 16	0.	20.	20.	21 34	0.	11.	11.	21 34	0.	11.	11.
6 91	6.	0.	6.	12 77	14.	0.	14.	16 17	0.	84.	84.	21 38	0.	4.	4.	21 38	0.	4.	4.
6 92	1.	0.	1.	12 78	2.	0.	2.	16 18	0.	82.	82.	21 39	0.	10.	10.	21 39	0.	10.	10.
7 40	0.	54.	54.	12 79	1.	0.	1.	16 19	5.	23.	28.	21 50	4.	0.	4.	21 50	4.	0.	4.
7 62	8.	0.	8.	12 80	6.	0.	6.	16 20	0.	65.	65.	21 51	38.	0.	38.	21 51	38.	0.	38.
7 63	3.	2.	5.	12 81	8.	2.	10.	16 21	2.	24.	26.	21 52	56.	0.	56.	21 52	56.	0.	56.
7 65	0.	2.	2.	12 83	5.	0.	5.	16 22	7.	3.	10.	21 53	13.	0.	13.	21 53	13.	0.	13.
7 66	2.	4.	6.	12 85	8.	0.	8.	16 24	5.	0.	5.	21 54	40.	0.	40.	21 54	40.	0.	40.
7 68	1.	0.	1.	12 86	1.	0.	1.	16 25	16.	0.	16.	21 57	26.	0.	26.	21 57	26.	0.	26.
7 75	4.	0.	4.	12 92	2.	0.	2.	16 27	7.	0.	7.	21 58	71.	0.	71.	21 58	71.	0.	71.
7 92	3.	0.	3.	13 3	0.	9.	9.	16 30	1.	4.	5.	21 70	22.	0.	22.	21 70	22.	0.	22.
8 40	8.	61.	71.	13 4	0.	47.	47.	16 31	5.	56.	61.	22 24	8.	12.	20.	22 24	8.	12.	20.
8 41	1.	5.	6.	13 5	0.	30.	30.	16 32	20.	40.	60.	22 25	9.	2.	11.	22 25	9.	2.	11.
8 44	1.	1.	2.	13 6	0.	37.	37.	16 33	12.	23.	35.	22 26	1.	33.	34.	22 26	1.	33.	34.
8 45	0.	19.	19.	13 16	0.	2.	2.	16 34	0.	6.	6.	22 27	0.	82.	82.	22 27	0.	82.	82.
8 48	1.	0.	1.	13 22	0.	9.	9.	16 35	0.	2.	2.	22 28	0.	55.	55.	22 28	0.	55.	55.
8 50	6.	0.	6.	13 42	4.	72.	76.	16 36	3.	4.	7.	22 29	0.	40.	40.	22 29	0.	40.	40.
8 52	6.	0.	6.	13 44	0.	42.	42.	16 42	6.	40.	46.	22 30	2.	37.	39.	22 30	2.	37.	39.
8 62	2.	0.	2.	13 49	1.	0.	1.	16 43	16.	10.	26.	22 31	0.	29.	29.	22 31	0.	29.	29.
8 66	2.	0.	2.	13 57	0.	7.	7.	16 45	10.	0.	10.	22 32	0.	20.	20.	22 32	0.	20.	20.
8 77	4.	0.	4.	13 58	55.	1.	56.	16 52	23.	0.	23.	22 33	0.	21.	21.	22 33	0.	21.	21.
9 40	5.	2.	7.	13 59	82.	8.	90.	16 72	8.	0.	8.	22 38	0.	14.	14.	22 38	0.	14.	14.
9 41	16.	23.	39.	13 60	8.	0.	8.	16 79	1.	0.	1.	22 39	0.	50.	50.	22 39	0.	50.	50.
9 42	1.	15.	16.	13 61	6.	0.	6.	16 81	12.	0.	12.	22 49	0.	2.	2.	22 49	0.	2.	2.
9 43	0.	22.	22.	13 62	3.	0.	3.	16 88	9.	0.	9.	22 51	3.	0.	3.	22 51	3.	0.	3.
9 44	14.	14.	28.	13 63	5.	0.	5.	17 10	0.	15.	15.	22 53	10.	0.	10.	22 53	10.	0.	10.
9 45	13.	5.	18.	13 66	5.	0.	5.	17 11	4.	1.	5.	22 54	7.	0.	7.	22 54	7.	0.	7.
9 48	0.	3.	3.	13 67	2.	0.	2.	17 18	0.	9.	9.	22 57	22.	0.	22.	22 57	22.	0.	22.
9 49	0.	11.	11.	13 69	1.	4.	5.	17 19	0.	18.	18.	22 58	21.	0.	21.	22 58	21.	0.	21.
9 50	0.	28.																	

TABLE 10.3 (Contd.)

X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL
23	87	13.	0.	13.	29	57	58.	0.	58.	34	43	34.	44.	78.	37	69	7.	0.	7.
23	88	11.	1.	12.	29	58	91.	0.	91.	34	44	0.	95.	95.	37	70	0.	0.	0.
23	89	5.	7.	12.	29	59	79.	0.	79.	34	45	2.	0.	2.	37	85	0.	43.	43.
23	91	2.	0.	2.	29	60	15.	40.	55.	34	49	7.	0.	7.	37	89	61.	0.	61.
23	92	4.	0.	4.	29	63	14.	0.	14.	34	50	22.	0.	22.	37	90	35.	0.	35.
24	23	3.	0.	3.	29	70	45.	0.	45.	34	52	4.	0.	4.	37	91	57.	0.	57.
24	25	6.	0.	6.	30	27	2.	0.	2.	34	53	0.	52.	52.	38	17	2.	0.	2.
24	26	9.	0.	9.	30	33	2.	0.	2.	34	54	25.	0.	25.	38	34	0.	7.	7.
24	34	0.	53.	53.	30	38	23.	28.	51.	34	55	38.	1.	39.	38	35	9.	95.	94.
24	35	6.	59.	65.	30	39	16.	0.	16.	34	56	7.	0.	7.	38	36	10.	17.	27.
24	36	17.	27.	44.	30	52	12.	0.	12.	34	60	3.	0.	3.	38	37	18.	0.	18.
24	37	41.	0.	41.	30	53	15.	0.	15.	34	61	6.	0.	6.	38	38	5.	0.	5.
24	43	5.	0.	5.	30	54	20.	0.	20.	34	62	1.	0.	1.	38	41	0.	55.	55.
24	44	38.	0.	38.	30	55	70.	3.	73.	34	63	29.	0.	29.	38	42	3.	70.	73.
24	46	18.	0.	18.	30	56	21.	0.	21.	34	64	3.	0.	3.	38	43	4.	0.	4.
24	50	10.	0.	10.	30	58	32.	0.	32.	34	68	3.	0.	3.	38	44	9.	53.	62.
24	51	6.	0.	6.	30	59	71.	9.	80.	34	77	19.	0.	19.	38	45	44.	45.	89.
24	52	6.	0.	6.	30	67	2.	0.	2.	34	78	16.	0.	16.	38	47	38.	0.	38.
24	53	20.	0.	20.	30	68	12.	0.	12.	34	79	7.	0.	7.	38	49	8.	0.	8.
24	55	6.	0.	6.	30	69	2.	0.	2.	34	87	0.	30.	30.	38	52	26.	0.	26.
24	56	5.	0.	5.	30	70	18.	0.	18.	34	90	44.	0.	44.	38	56	5.	0.	5.
24	57	12.	0.	12.	30	71	6.	0.	6.	34	91	7.	0.	7.	38	57	2.	0.	2.
24	61	17.	0.	17.	30	72	22.	0.	22.	35	11	6.	0.	6.	38	58	5.	0.	5.
24	62	60.	0.	60.	30	78	15.	0.	15.	35	23	1.	0.	1.	38	59	47.	0.	47.
24	63	0.	0.	0.	31	15	1.	0.	1.	35	25	3.	0.	3.	38	60	22.	0.	22.
24	64	25.	0.	25.	31	39	42.	0.	42.	35	27	33.	0.	33.	38	64	5.	0.	5.
24	65	5.	0.	5.	31	49	5.	0.	5.	35	26	5.	0.	5.	38	65	1.	0.	1.
24	66	5.	0.	5.	31	51	48.	16.	64.	35	30	0.	5.	5.	38	66	3.	0.	3.
24	73	20.	0.	20.	31	53	60.	0.	60.	35	41	8.	0.	8.	38	67	8.	0.	8.
24	85	12.	0.	12.	31	54	50.	0.	50.	35	42	7.	50.	57.	39	23	24.	0.	24.
25	32	4.	0.	4.	31	55	77.	11.	83.	35	43	6.	33.	39.	39	24	15.	0.	15.
25	34	0.	4.	4.	31	58	19.	0.	19.	35	44	8.	79.	87.	39	34	15.	2.	17.
25	35	0.	11.	11.	31	59	18.	0.	18.	35	45	14.	11.	25.	39	35	17.	0.	17.
25	36	12.	71.	83.	31	65	58.	0.	58.	35	48	12.	0.	12.	39	36	5.	0.	5.
25	37	100.	0.	100.	31	67	45.	0.	45.	35	49	61.	0.	61.	39	37	1.	0.	1.
25	38	16.	0.	16.	31	67	49.	0.	49.	35	53	1.	0.	1.	39	38	8.	0.	8.
25	45	5.	0.	5.	31	68	13.	0.	13.	35	54	2.	0.	2.	39	41	0.	55.	55.
25	46	27.	0.	27.	31	69	4.	0.	4.	35	60	2.	0.	2.	39	42	0.	70.	70.
25	47	40.	0.	40.	31	82	21.	0.	21.	35	64	28.	0.	28.	39	44	13.	0.	13.
25	51	10.	0.	10.	31	87	14.	0.	14.	35	65	5.	0.	5.	39	45	24.	52.	76.
25	52	74.	0.	74.	31	88	10.	0.	10.	35	68	8.	0.	8.	39	46	4.	37.	41.
25	53	14.	0.	14.	31	92	23.	3.	26.	35	69	28.	0.	28.	39	47	59.	2.	61.
25	56	28.	0.	28.	32	15	2.	0.	2.	35	70	8.	0.	8.	39	48	57.	0.	57.
25	57	38.	0.	38.	32	22	14.	0.	14.	35	73	7.	0.	7.	39	49	44.	0.	44.
25	62	17.	0.	17.	32	23	15.	0.	15.	35	81	0.	25.	25.	39	50	4.	0.	4.
25	64	8.	0.	8.	32	27	0.	15.	15.	35	82	10.	6.	16.	39	51	5.	0.	5.
25	65	63.	0.	63.	32	30	1.	0.	1.	35	83	2.	0.	2.	39	52	18.	0.	18.
25	75	3.	0.	3.	32	31	29.	0.	29.	35	84	1.	0.	1.	39	55	6.	0.	6.
25	78	2.	0.	2.	32	32	39.	0.	39.	35	85	7.	0.	7.	39	56	10.	0.	10.
25	81	10.	0.	10.	32	39	20.	0.	20.	35	90	4.	0.	4.	39	57	6.	0.	6.
25	82	2.	0.	2.	32	40	54.	7.	61.	35	91	14.	0.	14.	39	60	10.	0.	10.
26	17	0.	20.	20.	32	41	33.	0.	33.	35	92	6.	0.	6.	39	61	10.	0.	10.
26	18	5.	32.	37.	32	49	12.	0.	12.	36	10	3.	0.	3.	39	62	9.	0.	9.
26	25	11.	0.	11.	32	51	37.	0.	37.	36	11	5.	0.	5.	39	63	3.	0.	3.
26	36	17.	40.	57.	32	53	0.	25.	25.	36	12	7.	0.	7.	39	64	10.	0.	10.
26	37	4.	0.	4.	32	54	43.	0.	43.	36	27	29.	0.	29.	40	21	7.	0.	7.
26	38	4.	0.	4.	32	55	53.	10.	63.	36	23	17.	0.	17.	40	22	24.	0.	24.
26	40	10.	0.	10.	32	59	4.	0.	4.	36	26	4.	0.	4.	40	23	12.	0.	12.
26	41	5.	0.	5.	32	62	9.	0.	9.	36	27	51.	0.	51.	40	29	13.	0.	13.
26	44	8.	0.	8.	32	63	16.	0.	16.	36	35	4.	3.	11.	40	33	15.	0.	15.
26	51	6.	0.	6.	32	65	7.	0.	7.	36	36	17.	2.	19.	40	34	19.	44.	62.
26	52	73.	0.	73.	32	66	62.	3.	65.	36	37	23.	0.	23.	40	35	1.	0.	1.
26	53	16.	0.	16.	32	77	28.	0.	28.	36	38	53.	3.	56.	40	41	50.	0.	50.
26	55	2.	0.	2.	32	78	47.	24.	71.	36	39	40.	0.	40.	40	42	28.	0.	28.
26	62	30.	0.	30.	32	79	50.	0.	50.	36	40	19.	0.	19.	40	43	21.	0.	21.
26	65	16.	0.	16.	32	80	47.	0.	47.	36	41	24.	0.	24.	40	44	27.	0.	27.
27	25	1.	2.	3.	32	81	26.	0.	26.	36	42	39.	29.	68.	40	45	70.	5.	75.
27	30	1.	0.	1.	32	82	10.	0.	10.	36	43	20.	0.	20.	40	46	16.	22.	38.
27	36	10.	10.	20.	32	83	15.	0.	15.	36	44	11.	17.	26.	40	47	29.	0.	29.
27	37	0.	20.	20.	32	84	6.	0.	6.	36	45	10.	0.	10.	40	48	19.	3.	22.
27	42	4.	0.	4.	32	85	73.	28.	51.	36	48	22.	0.	22.	40	49	37.	0.	37.
27	43	4.	0.	4.	32	86	0.	11.	11.	36	49	6.	0.	6.	40	50	58.	0.	58.
27	50	0.	2.	2.	32	82	3.	0.	3.	36	53	2.	0.	2.	40	51	39.	0.	39.
27	51	16.	2.	18.	32	83	6.	0.	6.	36	54	3.	0.	3.	40	52	33.	0.	33.
27	52	30.	0.	30.	32	86	19.	0.	19.	36	57	1.	0.	1.	40	53	29.	0.	29.
27	53	12.	0.	12.	32	87	14.	0.	14.	36	58	2.	0.	2.	40	54	18.	0.	18.
27	55	4.	0.	4.	32	91	19.	0.	19.	36	64	21.	0.	21.	40	55	8.	0.	8.
27	56	40.	0.	40.	32	93	3.	0.	3.	36	65	25.	0.	25.	40	56	4.	0.	4.
27	57	4.	0.	4.	32	94	14.	0.	14.	36	66	17.	0.	17.	40	57	10.	0.	10.
27	60	4.	0.	4.	32	91	55.	5.	60.	36	70	5.	0.	5.	40	60	4.	0.	4.
27	61	27.	0.	27.	32	93	43.	0.	43.	36	71	18.	0.	18.	41	20	7.	0.	7.
27	62	4.	0.	4.	32	94	0.	22.	22.	36	72	25.	0.	25.	41	23	17.	0.	17.
27	80	20.	0.	20.	32	95	8.	0.	8.	36	81	0.	12.	12.	41	29	16.	0.	16.
27	84	1.	0.	1.	32	96	3.	0.	3.	36	82	0.	27.	27.	41	30	21.	0.	21.
28	23	10.	5.	15.	32	97	5.	0.	5.	36	83	3.	20.	22.	41	32	4.	0.	4.
28	24	1.	0.	1.	32	98	5.	0.	5.	36	84	2.	57.	59.	41	33	7.	18.	25.
28	27	0.	4.	4.	32	99	3.	7.	10.	36	85	6.	44.	51.	41	34	39.	10.	49.
28	28	0.	13.	13.	32	91	6.	45.	51.	36	86	0.	7.	7.	41	35	4		

TABLE 10.3 (Contd.)

X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL	X	Y	M1+M2	M3	TOTAL
42	41	52.	0.	52.	44	30	22.	0.	22.	46	19	0.	30.	30.	49	13	1.	0.	1.
42	44	36.	0.	36.	44	31	27.	0.	27.	46	20	0.	5.	5.	49	22	5.	0.	5.
42	46	30.	26.	56.	44	32	42.	0.	42.	46	22	17.	12.	74.	49	23	35.	0.	35.
42	47	24.	24.	48.	44	33	66.	0.	66.	46	23	21.	51.	72.	49	28	8.	0.	8.
42	48	35.	0.	35.	44	34	0.	0.	0.	46	24	59.	18.	77.	49	29	41.	0.	41.
42	49	19.	0.	19.	44	35	33.	0.	33.	46	25	19.	0.	19.	49	31	20.	14.	34.
42	50	67.	0.	67.	44	36	15.	0.	15.	46	30	6.	0.	6.	49	32	70.	0.	70.
42	51	3.	0.	3.	44	37	13.	0.	13.	46	31	15.	0.	15.	49	33	12.	30.	42.
42	52	2.	0.	2.	44	38	1.	0.	1.	46	32	18.	7.	20.	49	34	14.	28.	42.
42	53	17.	0.	17.	44	39	13.	0.	13.	46	33	5.	27.	32.	49	35	9.	73.	81.
42	54	44.	0.	44.	44	40	1.	0.	1.	46	34	19.	25.	40.	49	36	1.	90.	100.
42	55	3.	0.	3.	44	41	13.	0.	13.	46	35	0.	65.	65.	49	37	7.	65.	72.
42	58	3.	0.	3.	44	43	6.	0.	6.	46	36	0.	33.	35.	49	38	18.	27.	45.
42	59	9.	0.	9.	44	44	19.	0.	19.	46	37	2.	13.	15.	49	39	33.	1.	34.
42	60	21.	0.	21.	44	45	8.	84.	92.	46	38	14.	17.	31.	49	40	0.	0.	0.
42	61	6.	0.	6.	44	46	17.	25.	42.	46	39	11.	0.	11.	50	23	10.	0.	10.
43	19	6.	0.	6.	44	47	27.	34.	63.	46	41	2.	0.	2.	50	31	4.	10.	14.
43	20	1.	0.	1.	44	48	30.	0.	30.	46	42	24.	0.	24.	50	32	52.	2.	54.
43	22	0.	5.	5.	44	49	36.	0.	36.	46	43	3.	0.	3.	50	33	15.	4.	20.
43	27	2.	0.	2.	44	50	50.	0.	50.	46	44	2.	0.	2.	50	34	18.	0.	18.
43	28	29.	0.	29.	44	51	10.	46.	56.	46	45	5.	0.	5.	50	35	27.	28.	55.
43	29	27.	0.	27.	44	52	25.	30.	55.	46	47	22.	0.	22.	50	36	23.	12.	35.
43	31	0.	0.	0.	44	53	16.	0.	16.	46	48	4.	0.	4.	50	37	10.	6.	16.
43	32	22.	0.	22.	44	54	6.	0.	6.	47	22	38.	0.	38.	50	38	11.	21.	32.
43	33	27.	42.	69.	45	17	2.	0.	2.	47	23	13.	0.	13.	50	39	4.	64.	72.
43	34	12.	0.	12.	45	17	5.	0.	5.	47	24	10.	0.	10.	50	40	6.	54.	60.
43	35	15.	18.	33.	45	19	13.	0.	13.	47	25	5.	0.	5.	61	58	28.	0.	28.
43	36	15.	0.	15.	45	22	37.	47.	84.	47	27	1.	0.	1.					
43	40	6.	0.	6.	45	23	0.	73.	73.	47	28	10.	0.	10.					
43	41	25.	0.	25.	45	24	22.	77.	99.	47	29	22.	0.	22.					
43	42	10.	0.	10.	45	25	17.	11.	28.	47	30	11.	0.	11.					
43	43	34.	0.	34.	45	26	15.	0.	15.	47	32	7.	21.	28.					
43	44	16.	0.	16.	45	27	67.	0.	67.	47	33	0.	28.	28.					
43	45	43.	30.	73.	45	28	73.	0.	73.	47	34	5.	30.	35.					
43	46	8.	4.	12.	45	29	69.	0.	69.	47	35	0.	30.	30.					
43	47	4.	60.	64.	45	30	46.	0.	46.	47	36	0.	14.	14.					
43	48	31.	0.	31.	45	31	18.	0.	18.	47	37	7.	73.	80.					
43	50	41.	0.	41.	45	32	5.	0.	5.	47	38	18.	52.	70.					
43	52	15.	15.	30.	45	33	5.	0.	5.	47	39	30.	0.	30.					
43	53	38.	15.	53.	45	34	1.	34.	37.	47	40	11.	0.	11.					
43	54	5.	0.	5.	45	35	4.	0.	4.	47	41	24.	0.	24.					
43	55	9.	0.	9.	45	36	2.	0.	2.	47	42	3.	0.	3.					
43	56	13.	0.	13.	45	37	6.	0.	6.	48	23	4.	0.	4.					
43	58	7.	0.	7.	45	38	29.	0.	29.	48	28	15.	0.	15.					
43	59	4.	0.	4.	45	40	51.	0.	51.	48	29	49.	0.	49.					
43	60	2.	0.	2.	45	41	13.	0.	13.	48	30	7.	0.	7.					
43	61	5.	0.	5.	45	42	13.	0.	13.	48	31	0.	3.	3.					
44	16	1.	0.	1.	45	43	19.	0.	19.	48	32	3.	52.	55.					
44	21	10.	0.	10.	45	44	48.	0.	48.	48	33	2.	37.	34.					
44	22	12.	31.	43.	45	45	40.	0.	40.	48	34	0.	84.	84.					
44	23	6.	5.	11.	45	46	26.	0.	26.	48	35	0.	69.	69.					
44	24	0.	5.	5.	45	47	28.	0.	28.	48	36	0.	57.	57.					
44	25	3.	0.	3.	45	48	65.	0.	65.	48	37	11.	83.	94.					
44	26	5.	0.	5.	45	49	32.	0.	32.	48	38	24.	24.	48.					
44	27	39.	0.	39.	45	50	45.	0.	45.	48	39	18.	0.	18.					
44	28	49.	0.	49.	45	51	9.	0.	9.	44	40	14.	0.	14.					
44	29	25.	0.	25.	46	18	1.	15.	16.	49	41	1.	0.	1.					

TABLE 10.4. I.D. Listing of 1970 Data for Limited, General, and Heavy Manufacturing

ID	M1	M2	M3	AREA	ID	M1	M2	M3	AREA	ID	M1	M2	M3	AREA
10	0.0	0.0	0.0	1.00	580	1.10	0.0	0.05	100.00	1150	0.0	0.0	0.0	1.00
20	5.00	4.00	5.00	1.00	590	1.81	0.0	0.12	100.00	1160	0.0	0.0	0.0	1.00
30	0.0	10.00	46.00	1.00	600	2.27	0.23	0.0	100.00	1170	0.0	0.0	0.0	1.00
40	0.0	0.0	0.0	1.00	610	1.37	0.10	0.0	100.00	1180	0.0	0.0	0.0	1.00
50	3.00	0.0	0.0	1.00	620	3.61	0.0	1.47	100.00	1190	0.0	0.0	0.0	1.00
60	0.0	0.0	0.0	1.00	630	0.29	0.12	0.14	100.00	1200	0.0	0.0	0.0	1.00
70	28.00	17.00	0.0	1.00	640	0.44	0.0	0.0	25.00	1210	0.0	0.0	0.0	1.00
80	15.00	35.00	0.0	1.00	650	4.88	0.24	0.0	25.00	1220	0.0	0.0	0.0	1.00
90	17.00	24.00	0.0	1.00	660	6.16	4.37	0.12	25.00	1230	0.0	0.0	0.0	1.00
100	21.00	41.00	0.0	1.00	670	7.62	2.68	0.40	100.00	1240	0.0	0.0	0.0	1.00
110	0.0	0.0	0.0	1.00	680	4.65	1.56	2.94	100.00	1250	0.0	0.0	0.0	1.00
120	0.0	32.00	0.0	1.00	690	0.60	0.0	0.09	100.00	1260	0.0	0.0	0.0	1.00
130	36.00	0.0	0.0	1.00	700	3.04	4.32	0.0	25.00	1270	0.0	0.0	0.0	1.00
140	0.0	0.0	0.0	1.00	710	5.48	0.12	0.0	25.00	1280	0.0	0.0	0.0	1.00
150	19.00	0.0	0.0	1.00	720	5.12	1.60	0.36	25.00	1290	0.0	0.0	0.0	1.00
160	2.00	2.00	0.0	1.00	730	3.80	0.60	0.0	25.00	1300	0.0	0.0	0.0	1.00
170	3.00	62.00	9.00	1.00	740	7.12	15.80	6.32	25.00	1310	0.0	0.0	0.0	1.00
180	7.00	23.00	0.0	1.00	750	9.20	0.55	0.48	100.00	1320	0.0	0.0	0.0	1.00
190	7.00	24.00	0.0	1.00	760	3.91	3.40	0.79	100.00	1330	0.0	0.0	0.0	1.00
200	18.00	17.00	0.0	1.00	770	0.42	0.06	0.65	100.00	1340	0.0	0.0	0.0	1.00
210	17.00	15.00	0.0	1.00	780	5.56	7.08	0.08	25.00	1350	0.0	0.0	0.0	1.00
220	18.00	10.00	6.00	1.00	790	2.28	2.24	4.20	25.00	1360	4.75	7.75	10.00	4.00
230	9.00	18.00	36.00	1.00	800	5.64	8.52	25.52	25.00	1370	8.00	0.25	3.25	4.00
240	0.0	4.00	60.00	1.00	810	2.80	1.16	7.08	25.00	1380	0.0	14.00	3.00	4.00
250	8.00	28.00	24.00	1.00	820	4.33	0.0	3.13	100.00	1390	0.0	0.0	0.0	4.00
260	0.0	0.0	0.0	1.00	830	2.06	1.17	7.61	100.00	1400	0.0	0.0	0.0	4.00
270	0.0	0.0	0.0	1.00	840	0.25	0.51	2.39	100.00	1410	0.0	0.0	0.0	4.00
280	26.00	0.0	0.0	1.00	850	11.52	2.80	14.20	25.00	1420	0.0	0.0	0.0	4.00
290	6.00	11.00	25.00	1.00	860	4.68	3.76	0.0	25.00	1430	0.0	0.0	0.0	4.00
300	6.00	2.00	4.00	1.00	870	4.88	4.60	6.64	25.00	1440	0.0	0.0	0.0	4.00
310	13.00	17.00	26.00	1.00	880	1.72	8.56	1.60	25.00	1450	0.0	0.0	0.0	4.00
320	1.00	0.0	0.0	4.00	890	3.00	4.44	33.28	25.00	1460	0.0	0.0	0.0	4.00
330	9.00	6.25	0.0	4.00	900	11.72	4.92	9.52	25.00	1470	0.0	0.0	0.0	4.00
340	12.00	0.25	0.0	4.00	910	2.76	0.80	1.64	100.00	1480	0.0	0.0	0.0	4.00
350	7.75	2.50	7.50	4.00	920	1.24	0.38	9.01	100.00	1490	0.0	0.0	0.0	4.00
360	11.25	6.75	7.50	4.00	930	1.68	0.20	5.77	100.00	1500	0.0	0.0	0.0	4.00
370	14.50	5.75	0.0	4.00	940	10.56	8.28	0.76	25.00	1510	0.0	0.0	0.0	4.00
380	13.25	15.25	0.0	4.00	950	4.56	9.20	0.0	25.00	1520	0.0	0.0	0.0	4.00
390	10.75	7.50	0.75	4.00	960	10.04	4.44	11.56	25.00	1530	0.0	0.0	0.0	36.00
400	6.00	8.25	20.75	4.00	970	3.12	0.40	1.96	25.00	1540	0.0	0.0	0.0	100.00
410	1.75	0.0	0.0	4.00	980	1.43	0.46	0.02	100.00	1550	0.40	0.0	0.0	25.00
420	17.50	9.75	21.00	4.00	990	0.74	0.65	2.58	100.00	1560	0.0	0.0	0.0	25.00
430	0.75	23.25	7.50	4.00	1000	0.65	0.31	12.04	100.00	1570	0.0	0.0	0.0	25.00
440	17.75	20.75	16.25	4.00	1010	0.76	0.0	2.00	25.00	1580	0.0	0.0	0.0	25.00
450	0.0	0.0	0.0	4.00	1020	1.64	0.64	0.04	25.00	1590	0.0	0.0	0.0	100.00
460	6.00	1.50	0.0	4.00	1030	0.04	0.0	0.0	100.00	1600	0.0	0.0	0.0	100.00
470	8.50	1.00	0.0	4.00	1040	0.21	0.03	0.06	100.00	1610	0.0	0.0	0.0	100.00
480	4.50	5.50	0.0	4.00	1050	0.0	0.0	0.0	100.00	1620	0.0	0.0	0.0	100.00
490	10.75	2.50	0.0	4.00	1060	0.13	0.0	1.85	100.00	1630	0.0	0.0	0.0	100.00
500	2.50	0.0	30.50	4.00	1070	0.0	0.0	0.0	1.00	1640	0.0	0.0	0.0	100.00
510	5.25	0.0	6.75	4.00	1080	0.0	0.0	0.0	1.00	1650	0.0	0.0	0.0	25.00
520	1.11	1.92	0.33	100.00	1090	0.0	0.0	0.0	1.00	1660	0.0	0.0	0.0	25.00
530	0.22	0.23	0.08	100.00	1100	0.0	0.0	0.0	1.00	1670	0.0	0.0	0.0	4.00
540	0.46	0.0	0.21	100.00	1110	0.0	0.0	0.0	1.00	1680	0.0	0.0	0.0	1.00
550	0.31	0.0	0.08	100.00	1120	0.0	0.0	0.0	1.00	1690	0.0	0.0	0.0	1.00
560	4.27	1.48	3.37	100.00	1130	0.0	0.0	0.0	1.00					
570	1.13	0.0	0.0	100.00	1140	0.0	0.0	0.0	1.00					

TABLE 10.5. I.D. Listing of 1970 Data for
Light and Heavy Manufacturing

ID	M1+M2	M3	AREA	ID	M1+M2	M3	AREA	ID	M1+M2	M3	AREA
10	0.0	0.0	1.00	580	1.10	0.05	100.00	1150	0.0	0.0	1.00
20	9.00	5.00	1.00	590	1.81	0.12	100.00	1160	0.0	0.0	1.00
30	10.00	46.00	1.00	600	2.50	0.0	100.00	1170	0.0	0.0	1.00
40	0.0	0.0	1.00	610	1.47	0.0	100.00	1180	0.0	0.0	1.00
50	3.00	0.0	1.00	620	3.61	1.47	100.00	1190	0.0	0.0	1.00
60	0.0	0.0	1.00	630	0.41	0.14	100.00	1200	0.0	0.0	1.00
70	45.00	0.0	1.00	640	0.44	0.0	25.00	1210	0.0	0.0	1.00
80	50.00	0.0	1.00	650	5.12	0.0	25.00	1220	0.0	0.0	1.00
90	41.00	0.0	1.00	660	10.48	0.12	25.00	1230	0.0	0.0	1.00
100	62.00	0.0	1.00	670	10.30	0.40	100.00	1240	0.0	0.0	1.00
110	0.0	0.0	1.00	680	6.21	2.94	100.00	1250	0.0	0.0	1.00
120	32.00	0.0	1.00	690	0.60	0.09	100.00	1260	0.0	0.0	1.00
130	36.00	0.0	1.00	700	7.36	0.0	25.00	1270	0.0	0.0	1.00
140	0.0	0.0	1.00	710	5.60	0.0	25.00	1280	0.0	0.0	1.00
150	19.00	0.0	1.00	720	6.72	0.36	25.00	1290	0.0	0.0	1.00
160	4.00	0.0	1.00	730	4.40	0.0	25.00	1300	0.0	0.0	1.00
170	65.00	9.00	1.00	740	22.92	6.32	25.00	1310	0.0	0.0	1.00
180	30.00	0.0	1.00	750	9.75	0.48	100.00	1320	0.0	0.0	1.00
190	31.00	0.0	1.00	760	7.31	0.79	100.00	1330	0.0	0.0	1.00
200	35.00	0.0	1.00	770	0.48	0.65	100.00	1340	0.0	0.0	1.00
210	32.00	0.0	1.00	780	12.64	0.08	25.00	1350	0.0	0.0	1.00
220	28.00	6.00	1.00	790	4.52	4.20	25.00	1360	12.50	10.00	4.00
230	27.00	36.00	1.00	800	14.16	25.52	25.00	1370	8.25	3.25	4.00
240	4.00	60.00	1.00	810	3.96	7.08	25.00	1380	14.00	3.00	4.00
250	36.00	24.00	1.00	820	4.33	3.13	100.00	1390	0.0	0.0	4.00
260	0.0	0.0	1.00	830	3.23	7.61	100.00	1400	0.0	0.0	4.00
270	0.0	0.0	1.00	840	0.76	2.39	100.00	1410	0.0	0.0	4.00
280	26.00	0.0	1.00	850	14.32	14.20	25.00	1420	0.0	0.0	4.00
290	17.00	25.00	1.00	860	8.44	0.0	25.00	1430	0.0	0.0	4.00
300	8.00	4.00	1.00	870	9.46	6.64	25.00	1440	0.0	0.0	4.00
310	30.00	26.00	1.00	880	10.28	1.60	25.00	1450	0.0	0.0	4.00
320	1.00	0.0	4.00	890	7.44	33.28	25.00	1460	0.0	0.0	4.00
330	15.25	0.0	4.00	900	16.64	9.52	25.00	1470	0.0	0.0	4.00
340	12.25	0.0	4.00	910	3.56	1.64	100.00	1480	0.0	0.0	4.00
350	10.25	7.50	4.00	920	1.62	9.01	100.00	1490	0.0	0.0	4.00
360	18.00	7.50	4.00	930	1.88	5.77	100.00	1500	0.0	0.0	4.00
370	20.25	0.0	4.00	940	18.84	0.76	25.00	1510	0.0	0.0	4.00
380	28.50	0.0	4.00	950	13.76	0.0	25.00	1520	0.0	0.0	4.00
390	18.25	0.75	4.00	960	14.48	11.56	25.00	1530	0.0	0.0	36.00
400	14.25	20.75	4.00	970	3.52	1.96	25.00	1540	0.0	0.0	100.00
410	1.75	0.0	4.00	980	1.85	0.02	100.00	1550	0.40	0.0	25.00
420	27.25	21.00	4.00	990	1.39	2.58	100.00	1560	0.0	0.0	25.00
430	24.00	7.50	4.00	1000	0.96	12.04	100.00	1570	0.0	0.0	25.00
440	38.50	16.25	4.00	1010	0.76	2.00	25.00	1580	0.0	0.0	25.00
450	0.0	0.0	4.00	1020	2.28	0.04	25.00	1590	0.0	0.0	100.00
460	7.50	0.0	4.00	1030	0.04	0.0	100.00	1600	0.0	0.0	100.00
470	9.50	0.0	4.00	1040	0.24	0.06	100.00	1610	0.0	0.0	100.00
480	11.00	0.0	4.00	1050	0.0	0.0	100.00	1620	0.0	0.0	100.00
490	13.25	0.0	4.00	1060	0.13	1.85	100.00	1630	0.0	0.0	100.00
500	2.50	30.50	4.00	1070	0.0	0.0	1.00	1640	0.0	0.0	100.00
510	5.25	6.75	4.00	1080	0.0	0.0	1.00	1650	0.0	0.0	25.00
520	3.03	0.33	100.00	1090	0.0	0.0	1.00	1660	0.0	0.0	25.00
530	0.45	0.08	100.00	1100	0.0	0.0	1.00	1670	0.0	0.0	4.00
540	0.46	0.21	100.00	1110	0.0	0.0	1.00	1680	0.0	0.0	1.00
550	0.31	0.08	100.00	1120	0.0	0.0	1.00	1690	0.0	0.0	1.00
560	5.75	3.37	100.00	1130	0.0	0.0	1.00				
570	1.13	0.0	100.00	1140	0.0	0.0	1.00				

TABLE 10.6. I.D. Listing of 1964 Data

ID	M1	M2	M3	AREA	ID	M1	M2	M3	AREA	ID	M1	M2	M3	AREA
10	0.0	0.0	0.0	1.00	580	1.07	0.11	1.34	100.00	1150	0.0	0.0	0.0	1.00
20	0.0	0.0	0.0	1.00	590	1.01	0.08	3.13	100.00	1160	0.0	0.0	0.0	1.00
30	0.0	0.0	0.0	1.00	600	2.67	0.0	22.52	100.00	1170	0.0	0.0	0.0	1.00
40	0.0	0.0	0.0	1.00	610	1.04	0.0	1.77	100.00	1180	0.0	0.0	0.0	1.00
50	0.0	0.0	0.0	1.00	620	2.70	1.27	4.25	100.00	1190	0.0	0.0	0.0	1.00
60	0.0	0.0	0.0	1.00	630	0.16	0.09	3.02	100.00	1200	0.0	0.0	0.0	1.00
70	0.0	0.0	0.0	1.00	640	0.64	0.0	0.0	25.00	1210	0.0	0.0	0.0	1.00
80	0.0	0.0	0.0	1.00	650	6.16	0.0	0.0	25.00	1220	0.0	0.0	0.0	1.00
90	0.0	0.0	0.0	1.00	660	0.76	0.24	0.0	25.00	1230	0.0	0.0	0.0	1.00
100	0.0	0.0	0.0	1.00	670	5.78	3.66	0.23	100.00	1240	0.0	0.0	0.0	1.00
110	0.0	0.0	0.0	1.00	680	3.69	4.99	0.0	100.00	1250	0.0	0.0	0.0	1.00
120	0.0	0.0	0.0	1.00	690	0.45	0.01	0.0	100.00	1260	0.0	0.0	0.0	1.00
130	0.0	0.0	0.0	1.00	700	4.20	3.12	6.52	25.00	1270	0.0	0.0	0.0	1.00
140	0.0	0.0	0.0	1.00	710	5.96	0.48	0.0	25.00	1280	0.0	0.0	0.0	1.00
150	0.0	0.0	0.0	1.00	720	11.04	6.52	0.0	25.00	1290	0.0	0.0	0.0	1.00
160	0.0	0.0	0.0	1.00	730	1.08	0.0	16.12	25.00	1300	0.0	0.0	0.0	1.00
170	0.0	0.0	0.0	1.00	740	13.08	2.56	16.44	25.00	1310	0.0	0.0	0.0	1.00
180	0.0	0.0	0.0	1.00	750	3.13	0.43	1.10	100.00	1320	0.0	0.0	0.0	1.00
190	0.0	0.0	0.0	1.00	760	7.72	3.31	0.77	100.00	1330	0.0	0.0	0.0	1.00
200	0.0	0.0	0.0	1.00	770	0.52	0.32	0.0	100.00	1340	0.0	0.0	0.0	1.00
210	0.0	0.0	0.0	1.00	780	1.36	1.04	5.32	25.00	1350	0.0	0.0	0.0	1.00
220	0.0	0.0	0.0	1.00	790	1.08	2.92	19.92	25.00	1360	0.0	0.0	0.0	4.00
230	0.0	0.0	0.0	1.00	800	2.64	14.84	28.72	25.00	1370	0.0	0.0	0.0	4.00
240	0.0	0.0	0.0	1.00	810	2.88	2.94	17.24	25.00	1380	0.0	0.75	1.50	4.00
250	0.0	0.0	0.0	1.00	820	1.44	1.31	0.0	100.00	1390	0.0	0.0	0.0	4.00
260	0.0	0.0	0.0	1.00	830	1.67	7.32	1.29	100.00	1400	0.0	0.0	0.0	4.00
270	0.0	0.0	0.0	1.00	840	0.27	1.94	0.01	100.00	1410	0.0	0.0	0.0	4.00
280	0.0	0.0	0.0	1.00	850	0.0	0.0	0.0	25.00	1420	0.0	0.0	0.0	4.00
290	0.0	0.0	0.0	1.00	860	0.20	0.0	25.60	25.00	1430	0.0	0.0	0.0	4.00
300	0.0	0.0	0.0	1.00	870	4.08	3.41	19.08	25.00	1440	0.0	0.0	0.0	4.00
310	0.0	0.0	0.0	1.00	880	11.04	4.84	2.80	25.00	1450	0.0	0.0	0.0	4.00
320	0.0	0.0	0.0	4.00	890	1.54	4.09	5.44	25.00	1460	0.0	0.0	45.20	4.00
330	0.0	0.0	0.0	4.00	900	3.36	10.28	49.68	25.00	1470	0.0	0.0	0.0	4.00
340	0.0	0.0	0.0	4.00	910	2.37	2.36	3.06	100.00	1480	0.0	0.0	0.0	4.00
350	0.0	0.0	0.0	4.00	920	0.51	2.63	0.04	100.00	1490	0.0	0.0	0.0	4.00
360	0.0	0.0	0.0	4.00	930	0.0	0.0	0.0	100.00	1500	0.0	0.0	0.0	4.00
370	0.0	0.0	0.0	4.00	940	6.60	9.69	28.68	25.00	1510	0.0	0.0	0.0	4.00
380	0.0	0.0	0.0	4.00	950	3.00	3.92	33.06	25.00	1520	0.0	0.0	0.0	4.00
390	0.0	0.0	0.0	4.00	960	5.88	15.21	5.08	25.00	1530	0.0	0.0	0.0	36.00
400	0.25	4.00	20.75	5.00	970	8.00	0.29	3.84	25.00	1540	0.0	0.0	0.0	100.00
410	0.0	0.0	0.0	5.00	980	0.16	0.0	0.0	100.00	1550	2.28	0.0	1.60	25.00
420	0.0	0.0	0.0	5.00	990	0.0	0.0	0.0	100.00	1560	0.0	0.0	0.0	25.00
430	0.0	0.0	0.0	5.00	1000	0.0	0.0	0.0	100.00	1570	0.0	0.0	0.0	25.00
440	0.25	5.75	19.00	5.00	1010	0.0	0.0	0.0	25.00	1580	0.0	0.0	0.0	25.00
450	0.0	0.0	0.0	4.00	1020	0.20	0.0	0.0	25.00	1590	0.0	0.0	0.0	100.00
460	0.0	0.0	0.0	4.00	1030	0.0	0.0	0.0	100.00	1600	0.0	0.0	0.0	100.00
470	0.0	0.0	0.0	4.00	1040	0.0	0.0	0.0	100.00	1610	0.0	0.0	0.0	100.00
480	0.0	0.0	0.0	4.00	1050	0.0	0.0	0.0	100.00	1620	0.0	0.0	0.0	100.00
490	0.0	0.0	0.0	4.00	1060	0.0	0.0	0.0	100.00	1630	0.0	0.0	0.0	100.00
500	0.0	0.0	0.0	4.00	1070	0.0	0.0	0.0	1.00	1640	0.0	0.0	0.0	100.00
510	0.0	0.0	0.0	4.00	1080	0.0	0.0	0.0	1.00	1650	0.0	0.0	0.0	25.00
520	0.34	5.09	6.46	100.00	1090	0.0	0.0	0.0	1.00	1660	0.0	0.0	0.0	25.00
530	0.41	0.0	1.10	100.00	1100	0.0	0.0	0.0	1.00	1670	0.0	0.0	0.0	4.00
540	0.14	0.14	0.46	100.00	1110	0.0	0.0	0.0	1.00	1680	0.0	0.0	0.0	1.00
550	0.10	0.06	0.52	100.00	1120	0.0	0.0	0.0	1.00	1690	0.0	0.0	0.0	1.00
560	2.07	1.10	0.38	100.00	1130	0.0	0.0	0.0	1.00					
570	1.37	0.01	4.13	100.00	1140	0.0	0.0	0.0	1.00					

Because of grid-alignment errors, a meaningful comparison between the 1970 and the 1964 surveys for the area outside Will County and Chicago could not be made on a square-mile basis. Therefore, only a source I.D. comparison, including 40 sources was performed. Of these 40 sources, eight, six, and seven had changes of greater than 2%, i.e., $|M(1970) - M(1964)| > 2\%$, for light, heavy, and total manufacturing, respectively. This represents a maximum of 20% of the sources showing any change in industrial zoning. A change of greater than 2% was assumed to represent an actual change and not a statistical variation.

In addition, only 5% of the sources showed changes of greater than 10% in industrial zoning, and none showed changes greater than 15%. Since the industrial zoning in Chicago has not changed greatly over the 6-year period, the total percent changes in zoning would be even smaller.

One important assumption used while making the comparison should be mentioned. If the incomplete portion of any source in the 1964 survey could account for the difference in the two surveys, it was assumed that no change occurred.

These results indicate that a zoning inventory of this type does not become obsolete in a short period of time, even though zoning ordinances are constantly being revised. Therefore, this type of zoning inventory represents a useful tool for long-range planning.

10.3 Results of the Projection-model Application to Chicago

The projection model, a climatology code that generates frequencies of met sets for each section, and an atmospheric dispersion model are used in conjunction, as shown in Fig. 10.4 to develop future air quality data

Fig. 10.4. Flow Diagram of Air Pollution Projection and Display Model. ANL Neg. No. 190-91.

useful in long-range planning. The outputs of this planning model are emission inventories, isopleth maps, and pollution profiles. Each of two measures of air pollution are discussed below, and results from the application of the model to the City of Chicago are given.

10.3.1 Emission Inventories

The primary output of the projection model is an emission inventory, the temporal scale used depends on the intended use of the output. For example, hourly rates are given if the model is coupled with an atmospheric dispersion model. The model, however, has the capability of generating daily, monthly, seasonal, or yearly rates.

For the Chicago application, yearly estimates of SO_x emissions for 1970, 1975, and 1980 were made. It is assumed that a pollution control ordinance limiting the sulfur content of all fuels to a maximum of 1.5% is enacted before 1975 and continues through 1980. Furthermore, it is assumed this ordinance has no effect on growth rates.

TABLE 10.7. Yearly SO_x
Emission, tons

1970					
HEAVY MANUFACTURING	RESIDENTIAL	UTILITY	LIGHT INDUSTRY	COMMERCIAL	TOTAL
56,000	69,400	154,200	30,900	11,300	322,100
17 %	22 %	48 %	9 %	4 %	100 %

1975					
HEAVY MANUFACTURING	RESIDENTIAL	UTILITY	LIGHT INDUSTRY	COMMERCIAL	TOTAL
32,700	32,900	29,700	17,000	6,800	119,100
27 %	28 %	25 %	14 %	6 %	100 %

1980					
HEAVY MANUFACTURING	RESIDENTIAL	UTILITY	LIGHT INDUSTRY	COMMERCIAL	TOTAL
35,900	27,300	10,600	19,800	6,800	100,400
36 %	27 %	11 %	20 %	6 %	100 %

Table 10.7 lists estimates of total yearly emissions. The aggregate change in emissions for heavy and light manufacturing sources represents a combination of three major changes: 1) the pollution control ordinances, 2) fuel switching, and 3) growth. The first two reduce emissions; the third increases emissions. The large drop in SO_x from 1970 to 1975 can be attributed to the control ordinances, since much of the incentive for fuel switching was

created by the ordinance. The fuel switching plus the lower sulfur content resulted in the estimated reduction. Some of the gains, however, were offset by the projected growth in manufacturing activity. This is demonstrated quite clearly by comparing emissions in 1975 to those in 1980. SO_x levels are rising again, because additional fuel switching does not compensate for increased manufacturing activity.

Another interesting point concerning industrial sources is the increased percentage contribution to total city emissions made by these sources. Unless much of the manufacturing activity moves out of Chicago, this trend will continue.

The emission figures for heavy manufacturing represent 34 of the larger manufacturing firms in Chicago. Of these, 23 responded to the future fuel use survey. For the other sources, it was assumed that present fuel use patterns would continue.

The decrease in residential emissions from 1970 to 1975 can be attributed to a combination of two factors. Of course, the sulfur ordinance reduced SO_x emissions, but more importantly, the use of coal for residential space heating is on the decline. This rate of decline might be expected to increase because of the ordinance, but without any way to project this change, the assumption that past trends would continue at the same rate was applied.

The greatest change in SO_x emissions, however, cannot be attributed to any of the factors discussed thus far. The greatest change is due to "industrial migration." The migration of power generation from Chicago over the 10-year period, 1970-1980, would cut SO_x emission almost in half without using any pollution controls. (It is, however, possible that the rate of migration could be affected by the ordinance.)

Two important qualifications must be placed on these findings. First, the rate of emissions in Chicago from power generation is very sensitive to the construction timetable of the utilities. Secondly, the change in emissions does not represent a total reduction, but rather a transfer of emissions to other parts of Illinois. If the model were applied to the Chicago Air Quality Control Region, the decline in emissions from utilities would not be as sharp.

Because of a lack of data, it was assumed that there would be no change in commercial activity over the next 10 years. Thus, the change in emissions from commercial sources for 1970 to 1975 represents the effects of the control ordinance and fuel switching only. The lack of change from 1975 to 1980 is a result of the no-growth assumption.

For the entire city, emissions are expected to be reduced quite considerably in the next 5 years and are expected to remain relatively stable until 1980. Emissions will probably rise slightly after 1980, because the rate of growth in manufacturing activity is greater than the rate of decline in the use of coal in residences. However, it is not expected that emissions will ever reach the levels of 1970, provided there remains an adequate supply of low-sulfur fuels and power generation is located outside the city.

10.3.2 Isopleth Maps

The basic output mode of the planning model is the isopleth map. For the Chicago test case, the ground-level concentrations developed from the projected emissions were calculated at every node point on a 1-square-mile gridwork. This array was used by a plotting package (incorporated in the model) to plot isopleths of SO_2 on an IBM 2280 film plotter. The isopleth maps (on a continuous roll of unsprocketed film, approximately $1\frac{3}{8}$ in. wide) are projected and overlaid with the city grid to produce pictures such as those in Fig. 10.5. In all the isopleth figures, three concentration levels are

Fig. 10.5. Isopleth Maps for 1980. ANL Neg. No. 113-3438-6 Rev. 1.

Fig. 10.5 (Contd.): ANL Neg. No. 113-3438-5 Rev. 1.

Fig. 10.5 (Contd.). ANL Neg. No. 113-3438-1 Rev. 1.

Fig. 10.5 (Contd.). ANL Neg. No. 113-3438-12 Rev. 1.

Fig. 10.5 (Contd.). ANL Neg. No. 113-3438-2 Rev. 1.

Fig. 10.5 (Contd.). ANL Neg. No. 113-3438-3 Rev. 1.

Fig. 10.5 (Contd.). ANL Neg. No. 113-3438-9 Rev. 1.

Fig. 10.5 (Contd.). ANL Neg. No. 113-3438-7 Rev. 1.

Fig. 10.5 (Contd.). ANL Neg. No. 113-3438-8 Rev. 1.

depicted; 0.01, 0.05 and 0.1 ppm. A line-density scheme is incorporated to determine the levels. The middle isopleth level (0.05) is always plotted with a heavy line density, while the other two are light. This technique enables one to determine the line value at a glance. If, for example, a light line is observed within a heavy line, it is a 0.1-ppm line, or if a light line stands alone, it must be a 0.01-ppm line, and so on.

In addition to the individual met set plots, an overall expected isopleth map can be produced for each season. This is accomplished by computing at every receptor point the sum of the concentrations for all met sets weighted by their respective frequencies. Expected isopleth maps for the winter seasons are shown in Figs. 10.6-10.8. (The expected winter isopleths for 1970 and 1975 are included for comparative purposes.) The model is coded to handle and plot separately the isopleths for source classes, such as residential/commercial area sources, industrial area sources, or major point sources.

10.3.3 Pollution Profile

Up to this point, only standard types of outputs, including isopleth maps, have been discussed. However, these maps are not direct outputs of the dispersion model. Rather, they are generated from an array of ground-level concentrations, as shown in Fig. 10.9. (The outline of Chicago was superimposed onto the array by using a transparent overlay.) These data can be used for many types of analysis. For example, pollution-profile analyses are easily performed.

A profile is a means of "measuring" ground-level concentrations on an areal rather than a point scale. It generates the percentage of land area that is below any concentration level for a given set of meteorological conditions. The analysis can be performed for the entire region or for a few known trouble spots.

The approach is similar to the Monte Carlo sampling technique used in many land-use studies. The difference is that receptor points in the region are not randomly selected. Although random selection is conceptually possible, the dispersion code does not have this capability. The pollution profile is essentially a cumulative frequency distribution of ground-level concentrations in the region. If only a few areas are being analyzed, then the computations can be performed by hand, like the one demonstrated below.

The data in Fig. 10.9 were used to develop the isopleth in Fig. 10.5a. The frequency of the met set used is 3.3% or the equivalent of 72 hr during the spring months. However, because the temperature is 35°F, these conditions most likely occur in March. The profile in Fig. 10.10 shows that in 1980 about 97% of the City of Chicago will have concentrations below 0.10 ppm

Fig. 10.6. Isopleths Drawn from Frequency-weighted Concentrations for the Winter Season 1970. ANL Neg. No. 113-3438-15 Rev. 1.

Fig. 10.7. Isopleths Drawn from Frequency-weighted Concentrations for the Winter Season 1975. ANL Neg. No. 113-3438-14 Rev. 1.

Fig. 10.8. Isopleths Drawn from Frequency-weighted Concentrations for the Winter Season 1980. ANL Neg. No. 113-3438-13 Rev. 1.

Fig. 10.9. Ground-level Concentration Pattern. ANL Neg. No. 190-2.

Fig. 10.10. Pollution Profiles

whenever these met conditions hold. In addition, the profile for the 12-square-mile area on the southeast corner of the city shows that only 83% of this area is below 0.10 ppm. These percentages represent approximately 7.2 and 1.6 square miles, respectively.

The fixed number and location of receptor points reduce the accuracy of the results as the size of the area being studied is decreased. However, accuracy could be maintained by using a variable number of receptors and choosing their location within the area randomly. This is true even if a single square mile is of interest.

An expected profile and a profile of expected concentrations can also be developed. The expected profile is calculated by multiplying each individual profile by its probability of occurrence (i.e., the frequency of the associated met set) and summing over all met sets. On the other hand, the profile of the expected concentration is calculated by multiplying the concentrations at each point by the probability of its occurrence, summing over all met sets, and developing the profile of these expected values. (The expected isopleth is developed the same way.) A simple example will demonstrate the differences.

Assume the study region has four receptors and three possible met sets, as follows:

	0.01	0.02	0.12	0.10	0.03	0.05
(1)			(2)		(3)	
	0.03	0.04	0.12	0.11	0.07	0.10

with probabilities of occurrence of 0.55, 0.05 and 0.40, respectively. For this region, the expected profile is given in Fig. 10.11 and the profile of expected concentrations in Fig. 10.12.

Fig. 10.11. Expected Profile

Fig. 10.12. Profile of Expected Concentrations

As a sample calculation for developing the expected profile, consider the expected land area with concentrations equal to or less than 0.10 ppm. The individual profiles show 100, 25, and 100% of the land area in this range. Multiplying these by their associated probabilities of occurrence and summing over all met sets gives

$$0.55(100) + 0.05(25) + 0.40(100) = 95.75\%.$$

Therefore, it can be expected that 95.75% of the land area is experiencing 0.10 ppm SO_x or less at any random time.

The profile of expected concentrations is developed from the expected concentrations at each receptor. These are 0.01, 0.04, 0.05, and 0.07. Thus, 100% of the land area has expected concentrations of 0.07 ppm or less.

Note the difference in the statement of results for the two profiles. The expected profile gives results for cumulative land areas. The specific points experiencing high concentrations differ with each met set. For small areas, however, this profile is an excellent measure of air quality, since the areas of poor air quality are generally within a small distance of each other.

The profile of expected concentrations quickly indicates if any specific points consistently experience poor air quality. These points can be identified from the array of expected concentrations.

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