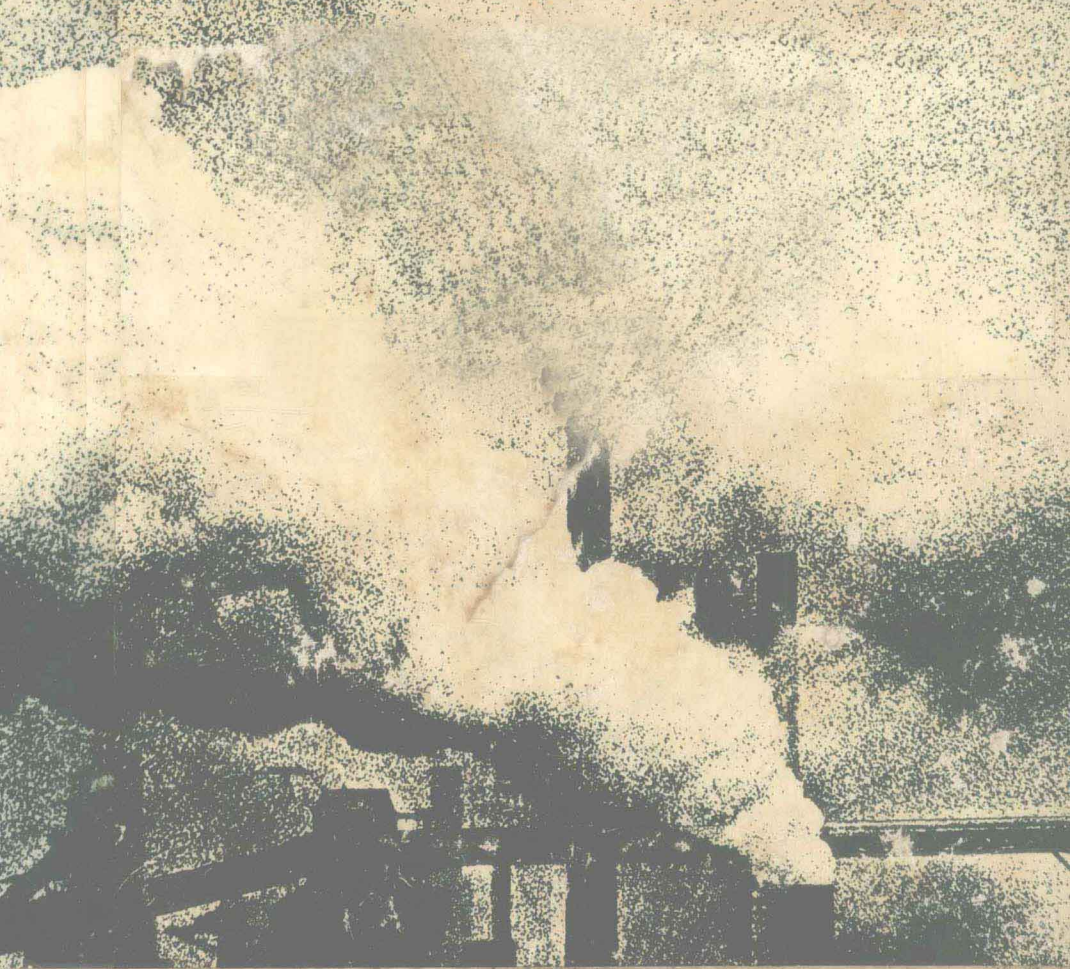


# AIR POLLUTION

Its Origin and Control

Kenneth Wark  
and Cecil F. Warner



ANOTHER QUALITY USED BOOK

# **AIR POLLUTION**

Its Origin and Control

Second Edition

Kenneth Wark

Cecil F. Warner

PURDUE UNIVERSITY

1817



**HARPER & ROW, PUBLISHERS, New York**  
Cambridge, Hagerstown, Philadelphia, San Francisco,  
London, Mexico City, São Paulo, Sydney

Sponsoring Editor: Charlie Dresser  
Project Editor: Eleanor Castellano  
Production Manager: Marion A. Palen  
Compositor: Science Typographers Inc.  
Printer and Binder: The Maple Press Company  
Art Studio: J & R Technical Services Inc.  
Cover design: Mies Hora  
(Photo credit: Johnson, De Wys)

**AIR POLLUTION: Its Origin and Control, Second Edition**

Copyright © 1981 by Kenneth Wark and Cecil F. Warner

All rights reserved. Printed in the United States of America. No part of this book may be used or reproduced in any manner whatsoever without written permission except in the case of brief quotations embodied in critical articles and reviews. For information address Harper & Row, Publishers, Inc., 10 East 53rd Street, New York, N.Y. 10022.

**Library of Congress Cataloging in Publication Data**  
Wark, Kenneth,  
Air pollution.

Includes bibliographical references and index.

I. Air-Pollution. I. Warner, Cecil Francis, joint author.

II. Title.

TD883.W28 1981 363.7'392 80-20283

ISBN 0-700-22534-X

# Preface

The first edition of this text has been modified in three broad areas. First, new material has been added in several chapters in order to improve upon the coverage of material. For example, a more thorough discussion of particulate distributions is presented, in conjunction with the material on fractional and overall collection efficiencies. A mathematical analysis of the adsorption wave and its transient behavior also has been included. Secondly, old material has been updated, or removed if no longer appropriate. A major example of this is the complete rewriting of the section on flue gas desulfurization. The chapter on mobile sources has also undergone revision that reflects changes in technology or legislation. Lastly, a considerable number of new problems have been added (and a few old ones removed). This is in keeping with the authors' general philosophy that the reader of this text should be exposed to both the quantitative and qualitative aspects of air pollution control. The data for these new problems are presented in both conventional English units and SI units. SI units are emphasized to a somewhat greater extent than in the first edition. However, a student of air pollution control must be conversant with a large set of diverse engineering units. To minimize this problem, Appendix B contains conversion tables for a number of units commonly used in the field.

It is our intent that the material be suitable for a variety of engineers who wish to gain an introduction to the field of air pollution and its control. An understanding of the fundamentals of thermodynamics is assumed, including some knowledge of chemical equilibrium for ideal-gas mixtures. The required principles of chemical kinetics, important to understand more fully the origin and persistence of numerous pollutants, is presented in the text. A review of some of the basic principles of mass transfer is also given in the text, before presenting the control methods involving absorption.

The new edition continues to present information on four broad areas of interest in the air pollution field: (1) the effects of pollutants on health and welfare, (2) the federal laws and regulations that have been promulgated in an attempt to achieve reasonable ambient air quality, (3) the modeling of atmospheric dispersion of pollutants, and (4) the general and specific approaches to the control of emissions—small- and large-scale, mobile and stationary, combustion and noncombustion. The mechanisms responsible for the effectiveness of a given control device are discussed in some depth. The

instrumentation required for the accurate and reliable monitoring of pollutants is covered briefly, since innumerable articles and books are available on the subject in the current literature. Some economic data are presented for comparative purposes. However, inflation has a large effect on construction and operating costs, so a comprehensive list of cost factors is not included.

Similar to the first edition, no attempt has been made to present a complete coverage of the air pollution control field. The space devoted to any particular topic, and the omission of other topics, is mainly a matter of the authors' choice. New methods of control and measurement are constantly being introduced; new or modified laws and regulations are continually being promulgated. Only regular perusal of the current literature will enable one to keep abreast of the developments in the area of air pollution control processes.

Kenneth Wark  
Cecil F. Warner

# Symbols

## LETTER SYMBOLS

$A$	Cross-sectional area
$a$	Absorption coefficient for light Acceleration
$B$	Magnetic field intensity
$C$	Concentration
$C_D$	Drag coefficient
$C_{oh}$	Coefficient of haze
$c_p$	Specific heat at constant pressure
$D$	Dielectric constant Mass diffusivity
$D_L$	Liquid-phase diffusion coefficient
$d$	Distance Stack diameter
$E$	Activation energy Electric field strength
$e$	Electric charge
$F$	Dimensional parameter in plume-rise evaluation Force
$G$	Gas flow rate
$g$	Gravitational acceleration
$g_c$	Gravitational constant
$H$	Effective stack height Height of gravity settling chamber
$H_t$	Height of a transfer unit
$h$	Actual stack height Enthalpy
$\Delta h$	Plume rise
$I$	Light intensity
$K$	Dust permeability Eddy diffusion coefficient Mass transfer coefficient Scattering ratio
$K_c$	Cunningham correction factor

$K_p$	Ideal-gas equilibrium constant
$k$	Boltzmann's constant
	Mass transfer coefficient
	Rate constant
	Specific heat ratio, $c_p/c_v$
$L$	Length
	Liquid flow rate
$L_v$	Limit of visibility
$M$	Molar mass (molecular weight)
$m$	Mass
	Refractive index
MB	million Btu
$N$	Mass transfer per unit time and unit area
	Number of particles per unit volume
	Number of particles under given size
$N_e$	Number of effective turns in a cyclone
$N_I$	Impaction number
$N_t$	Number of transfer units
$n$	Exponent in wind velocity profile
	Number of particles per differential size
$P$	Pressure
	Odor intensity
$p$	Pressure
$Q$	Mass emission rate, mass per unit time
	Volume flow rate
$Q_h$	Heat emission rate, energy per unit time
$q$	Electric charge
	Emission source strength per unit length
	Quantity of heat transfer
$R$	Ideal-gas constant
	Radius
	Particulate resistance
Re	Reynolds number, $DV\rho/\mu$
$r$	Radius (of particle)
$S$	Filter drag
	Odor concentration
	Separation distance
$s$	Scattering coefficient for light
$T$	Temperature
$T_{\text{frac}}$	Fractional light transmission
$t$	Time
$u$	Internal energy
	Wind speed
$V$	Velocity
	Volume
	Voltage



$\nu$	Specific volume
$W$	Mass of adsorbent
	Width
$w$	Drift velocity
	Logarithm of particle diameter
	Work interaction
$X$	Liquid-phase mole ratio
$x$	Distance or coordinate
	Mole fraction
$x_s$	Stopping distance
$Y$	Gas-phase mole ratio
$y$	Distance or direction
	Gas-phase mole fraction
$z$	Distance or direction

### GREEK SYMBOLS

$\eta$	Efficiency
$\theta$	Potential temperature
$\Gamma$	Adiabatic lapse rate
$\lambda$	Wavelength
$\mu\text{m}$	Microns (micrometers)
$\mu$	Parameter in Gaussian distribution
	Viscosity
$\rho$	Density
$\rho_e$	Electrical resistivity
$\sigma$	Extinction coefficient
	Standard deviation
$\phi$	Angle
	Equivalence ratio
$\nu$	Ion velocity

### SUBSCRIPTS

$a$	Atmosphere
$C$	Carrier gas
$G$	Gas phase
$i$	$i$ th species
$L$	Liquid phase
MM	Mass median
$m$	Molar value
NM	Number median
OG	Overall gas-phase value
OL	Overall liquid-phase value
$S$	Solvent
$s$	Stack
$x$	Based on mole fraction in liquid phase
$y$	Based on mole fraction in gas phase



# Air Pollution



# Contents

Preface	xi
Symbols	xiii

## 1. Effects and Sources of Air Pollutants 1

1-1	Introduction	1
1-2	Air Pollution Episodes	2
1-3	General Nature of Air Pollution Problems	3
1-4	Definition and General Listing of Air Pollutants	5
1-5	Particulate Matter	9
1-6	Carbon Monoxide	20
1-7	Sulfur Oxides	24
1-8	Effects of Hydrocarbons, Oxides of Nitrogen, Photochemical Oxidants, Asbestos, and Metals on Materials and Health	30
1-9	Injury to Vegetation	32
1-10	Sources of Air Pollutants	34
	QUESTIONS	36
	PROBLEMS	36
	REFERENCES	38

## 2. Federal Legislation and Regulatory Trends 41

2-1	Introduction	41
2-2	The History of Federally Enacted Laws	42
2-3	Air Quality Criteria and Ambient Air Quality Emission Standards	50
2-4	National Emission or Performance Standards	52
2-5	Implementation of and Compliance with Standards	59
	QUESTIONS	61
	PROBLEMS	62
	REFERENCES	64

## 3. Meteorology 65

3-1	Introduction	65
3-2	Solar Radiation	66

3-3	Wind Circulation	69
3-4	Lapse Rate	73
3-5	Stability Conditions	77
3-6	Wind Velocity Profile	83
3-7	Maximum Mixing Depth	86
3-8	Wind Rose	88
3-9	Turbulence	89
3-10	General Characteristics of Stack Plumes	91
3-11	Heat Island Effect	95
3-12	Global Circulation of Pollutants	95
	QUESTIONS	96
	PROBLEMS	98
	REFERENCES	100

#### 4. Dispersion of Pollutants in the Atmosphere 101

4-1	Introduction	101
4-2	The Eddy Diffusion Model	102
4-3	The Gaussian or Normal Distribution	104
4-4	The Gaussian Dispersion Model	106
4-5	Evaluation of the Standard Deviations	110
4-6	The Maximum Ground-Level In-Line Concentration	117
4-7	Calculation of the Effective Stack Height	120
4-8	Some Other Considerations Regarding Gaseous Dispersion	125
	Appendix—Development of the Gaussian-Type Dispersion	
	Equation	132
	QUESTIONS	136
	PROBLEMS	137
	REFERENCES	141

#### 5. Particulate 143

5-1	Introduction	143
5-2	Distribution and Sources of Particulate Matter	146
5-3	Particulate Collection Efficiency	151
5-4	Particulate Distributions	158
5-5	Terminal or Settling Velocity	165
5-6	Deposition of Particulates from Stacks	170
5-7	Hood and Duct Design	175
5-8	Particulate Collection Mechanisms	178
5-9	Particulate Control Equipment	179
5-10	Comparison of Particulate Control Equipment	233
	QUESTIONS	236
	PROBLEMS	237
	REFERENCES	252

**6. General Control of Gases and Vapors** **255**

- 6-1 Introduction    255
- 6-2 Adsorption    256
- 6-3 The Adsorption Wave    263
- 6-4 Transient Analysis of an Adsorption Wave    266
- 6-5 Regeneration of an Adsorption Bed    271
- 6-6 Absorption    273
- 6-7 Basic Design of a Packed Absorption Tower    280
- 6-8 Determination of an Absorption Tower Height    292
- 6-9 Fundamentals of Chemical Kinetics    302
- 6-10 Kinetics of Carbon Monoxide Formation    309
- 6-11 Carbon Monoxide Emission Control    311
- 6-12 Incineration or Afterburning    314
- 6-13 Reaction Kinetics and Catalysis in Afterburning Processes    330
  - QUESTIONS    334
  - PROBLEMS    335
  - REFERENCES    341

**7. Control of Sulfur Oxides** **343**

- 7-1 Introduction    343
- 7-2 Thermodynamics and Kinetics of Sulfur Oxide Formation    346
- 7-3 General Control Methods    349
- 7-4 Flue-Gas Desulfurization Processes    352
  - QUESTIONS    367
  - PROBLEMS    368
  - REFERENCES    369

**8. Control of Oxides of Nitrogen from Stationary Sources** **371**

- 8-1 Introduction    371
- 8-2 Sources and Concentrations of  $\text{NO}_x$     372
- 8-3 Thermodynamics of  $\text{NO}$  and  $\text{NO}_2$  Formation    375
- 8-4 Kinetics of Nitric Oxide Formation in Combustion Processes    380
- 8-5  $\text{NO}_x$  Formation from Fuel Nitrogen    389
- 8-6 Combustion Control Methods for  $\text{NO}_x$  from Stationary Sources    389
- 8-7 Flue-Gas Control Methods for  $\text{NO}_x$     397
  - QUESTIONS    401
  - PROBLEMS    402
  - REFERENCES    403

**9. Atmospheric Photochemical Reactions** **405**

- 9-1 Introduction    405
- 9-2 Thermodynamics of Photochemical Reactions    405

9-3	Monatomic Oxygen and Ozone Formation	406
9-4	Role of Oxides of Nitrogen in Photooxidation	407
9-5	Hydrocarbons in Atmospheric Photochemistry	410
9-6	Oxidants in Photochemical Smog	414
9-7	Hydrocarbon Reactivity	416
9-8	Daily History of Pollutants in Photochemical Smog	417
9-9	Oxidation of Sulfur Dioxide in Polluted Atmospheres	419
	QUESTIONS	422
	PROBLEMS	422
	REFERENCES	423

## 10. Mobile Sources

425

10-1	Introduction	425
10-2	Emission Standards for Automobiles	425
10-3	Gasoline	427
10-4	Origin of Exhaust Emissions from Gasoline Engines	429
10-5	Crankcase and Evaporative Emissions	435
10-6	Emission Reduction by Fuel Changes	437
10-7	Emission Reduction by Engine Design Changes	437
10-8	External Reactors	440
10-9	Stratified-Charge Engines	443
10-10	Rotary Combustion Engines	445
10-11	Alternative Vehicle Power Sources	446
10-12	Diesel Engine Emissions	448
10-13	Turbojet Engine and Gas Turbine Emissions	452
10-14	Alternative Fuels and Their Utilization	461
	QUESTIONS	463
	PROBLEMS	464
	REFERENCES	465

## 11. Odor Control

469

11-1	Introduction	469
11-2	The Sense of Smell and Theories of Odor	470
11-3	Physical Properties of Odorous Substances	471
11-4	Odor Measurement Techniques	473
11-5	Odor Threshold Values	477
11-6	Applications of Odor Measurements	478
11-7	Odor Control Methods	481
	QUESTIONS	484
	PROBLEMS	485
	REFERENCES	485

<b>Appendix A. Instrumentation</b>	<b>487</b>
A-1 Introduction	487
A-2 Sampling Train	487
A-3 Particulate Analysis	488
A-4 Gas Analysis	490
A-5 Monitoring of Carbon Monoxide and Hydrocarbons	498
A-6 Monitoring Methods for Sulfur Dioxide	499
A-7 Monitoring for Oxides of Nitrogen	500
A-8 Monitoring of Photochemical Oxidants	501
REFERENCES	501
<b>Appendix B. Measurement Quantities</b>	<b>503</b>
B-1 Conversion Factors	503
B-2 Universal Gas Constant and Gravitational Acceleration	504
B-3 Properties of Air	504
B-4 Molar Masses of Various Substances, $M$	504
B-5 Values of the Error Function, $\text{erf } x$	505
B-6 Ideal-Gas Enthalpy of Air	506
<b>Answers to Odd-Numbered Problems</b>	<b>507</b>
<b>Index</b>	<b>513</b>

The use of coal in the generation of energy was a major factor in the Industrial Revolution, which formed the basis of our current technological society. Unfortunately, intimately associated with the benefits of our technological society is the fouling and degrading of our environment. One of the earliest legal attempts to control air pollution in the United States appears to be an 1895 ordinance making illegal the "showing of visible vapor" as exhaust from steam automobiles.

Such natural processes as forest fires, decaying vegetation, dust storms, and volcanic eruptions have always contaminated the air. Although the total global production of many gases and particulate matter recognized as pollutants is much greater from natural sources than from man-made sources, global distribution and dispersion of those pollutants result in low average concentrations. By precipitation, oxidation, and absorption into the oceans and the soil, the atmosphere can cleanse itself of all known pollutants given sufficient time [2, 3]. On the other hand, man-generated pollutants are usually concentrated in small geographic regions; hence most air pollution is truly man-made. In the United States alone, over 200 million tons of gaseous, solid, and liquid waste products are discharged annually into the atmosphere. Currently the rate at which pollutants are discharged into the atmosphere in highly populated regions at time exceeds the cleansing rate of the atmosphere.

## 1-2 AIR POLLUTION EPISODES

Although limited air pollution was experienced as early as 1272, it has become a major problem only in relatively recent years, considering man's total history. In December, 1930, a heavily industrialized section of the Meuse Valley, in Belgium, experienced a severe 3-day fog during which hundreds of people became ill and 60 died—more than 10 times the normal number. Shortly afterward, during a thick 9-day fog in January, 1931, 592 people in Manchester and Salford area of England died—again a large jump in the death rate. In 1948, in Donora, Pennsylvania, a small mill town dominated by steel and chemical plants, a 4-day fog made almost half of the 14,000 inhabitants sick. Twenty persons died. Ten years later, Donora residents who had been acutely ill during that episode were found to have a higher rate of sickness and to die at an earlier age than the average for all the townspeople. During a fog in London as far back as 1873, 268 unexpected deaths from bronchitis were reported. It was not until a great fog blanketed London in 1952 that the sinister potential of air pollution became fully apparent. That fog lasted from December 5 to December 8, and 10 days later it was learned that the total number of deaths in Greater London during that period exceeded the average by 4000. The statistics indicated that almost all those who died unexpectedly had records of bronchitis, emphysema, or heart trouble, and that people in the last category were most vulnerable. Again in January, 1956, 1000 extra deaths in London were



1956  
 blamed on an extended fog. In that year, Parliament passed a Clean Air Act and Britain embarked on a program to reduce the burning of soft coal [4]. The smog conditions of Los Angeles, New York City, Chicago, and other large cities of the United States are widely publicized in today's press.

The misuse of air resources in the USSR is not very different from that in this country. Despite the fact that Russia's current yearly production of cars is one-tenth that of the United States, most Soviet cities experience varying degrees of air pollution. Cities situated in valleys or hilly regions are especially likely to experience dangerous levels of air pollution. In the hilly cities of Armenia, for example, the established health standards for carbon monoxide are often exceeded. Similarly, Magnitogorsk, Alma Ato, and Chelyabinsk, with their metallurgical industries, are frequently covered with a layer of dark blue haze. Like Los Angeles, Tbilisi, the capital of the Republic of Georgia, has smog almost 6 months of the year. Leningrad has 40 percent fewer clear daylight hours than the nearby town of Pavlovsk [5].

### 1-3 GENERAL NATURE OF AIR POLLUTION PROBLEMS

Only a finite amount of air, land, and water resources exist, and as population increases, the portion available for each person decreases. From the beginning of time until 1900, the population of the world increased to 1.7 billion. By 1974 world population had reached 3.9 billion, and the awesome figure of 7 billion is estimated by the year 2000. The population of the United States has followed a similar trend. In addition, technological advances in the field of agriculture have greatly reduced the number of jobs in rural areas. As in other developed countries, today two-thirds of the population lives in urban areas comprising about 1 percent of the land. Suburban growth and superhighways have made it possible for more people to travel greater distances and thus to converge faster on our cities. Hence an increasing population combined with a high standard of living has led to a drastically intensified output and concentration of air pollutants in localized areas.

COUNTRY	GROSS NATIONAL PRODUCT (\$/CAPITA)	COMMERCIAL ENERGY CONSUMPTION (MILLION Btu/CAPITA)	GNP ENERGY
India	50	5	10
Chile	450	20	22
Japan	600	30	20
USSR	900	70	13
West Germany	1450	85	17
United Kingdom	1500	117	13
Canada	1900	130	15
United States	2850	180	16

During a recent time period in which the population of the United States doubled, there was an eightfold increase in the gross national product (GNP) and an increase in the production of electrical energy by a factor of 1.3. For developed or developing countries, there appears to be a close relationship between the gross national product per capita (economic level) and energy consumption per capita. This is illustrated by data for selected countries taken from Cook's study of the flow of energy in an industrialized society [6]. All values in the table (see page 3) are approximate.

These data indicate that the quantity of goods and services enjoyed by a citizen is closely related to the quantity of energy consumed (directly or indirectly) by that citizen. In other words, the availability and use of energy is a requisite for a high standard of living. It is striking to translate the American experience into global terms. An increase in energy demand per capita in the developing countries, similar to that experienced in West Germany and the United States, in combination with the increase in global population could result in uncontrolled emissions of air pollutants in catastrophic proportions.

In the past, industry, agriculture, and individual polluters have found it more economical to discharge waste products into the atmosphere than to exercise waste control. In general the organization or activity causing the pollution did not suffer the consequences of the pollution; likewise, those who benefited from a reduction in air pollution resulting from the installation of control equipment did not directly bear the cost of the equipment. In recent years, as the public has become increasingly concerned with environmental problems, air has come to be regarded as a resource within the public domain. Hence air pollution is considered a public problem, a concern not only of those who discharge the pollution, but also of those who may suffer as a result. Thus the laws in some countries now permit an individual or group of private individuals to sue directly an organization or company which is polluting that particular part of the public domain.

The rational control of air pollution rests on four basic assumptions [7].

1. *Air is in the public domain.* Such an assumption is necessary if air pollution is to be treated as a public problem, of concern not only to those who discharge the pollution but also to those who may suffer as a result.

2. *Air pollution is an inevitable concomitant of modern life.* There is a conflict between man's economic and biologic concerns; in the past, this conflict was recognized only after air pollution disasters. We need a systematic development of policies and programs to conserve the atmosphere for its most essential biological function.

3. *Scientific knowledge can be applied to the shaping of public policy.* Information about the sources and effects of air pollution is far from complete, and a great deal of work must be done to develop control devices and methods. Nevertheless, sufficient information is now available to make possible substantial reductions in air pollution levels. Man does not have to abandon either his technology or his life, but he must use his knowledge.