Disclaimer

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Preface

In 1971, the U.S. Environmental Protection Agency (EPA) promulgated National Ambient Air Quality Standards (NAAQS) to protect the public health and welfare from adverse effects of photochemical oxidants. In 1979, the chemical designation of the standards was changed from photochemical oxidants to ozone (O_3). This document focuses primarily on the scientific air quality criteria for O_3 and, to a lesser extent, on those for other photochemical oxidants such as hydrogen peroxide and the peroxyacyl nitrates.

The EPA promulgates the NAAQS on the basis of scientific information contained in air quality criteria issued under Section 108 of the Clean Air Act. The previous O_3 criteria document, *Air Quality Criteria for Ozone and Other Photochemical Oxidants*, was released in August 1986 and a supplement, *Summary of Selected New Information on Effects of Ozone on Health and Vegetation*, was released in January 1992. These documents were the basis for a March 1993 decision by EPA that revision of the existing 1-h NAAQS for O_3 was not appropriate at that time. That decision, however, did not take into account some of the newer scientific data that became available after completion of the 1986 criteria document. The purpose of this revised air quality criteria document for O_3 and related photochemical oxidants is to critically evaluate and assess the latest scientific data associated with exposure to the concentrations of these pollutants found in ambient air. Emphasis is placed on the presentation of health and environmental effects data; however, other scientific data are presented and evaluated in order to provide a better understanding of the nature, sources, distribution, measurement, and concentrations of O_3 and related photochemical oxidants and their precursors in the environment. Although the document is not intended to be an exhaustive literature review, it is intended to cover all pertinent literature available through 1995.

This document was prepared and peer reviewed by experts from various state and Federal governmental offices, academia, and private industry and reviewed in several public meetings by the Clean Air Scientific Advisory Committee. The National Center for Environmental Assessment (formerly the Environmental Criteria and Assessment Office) of EPA's Office of Research and Development acknowledges with appreciation the contributions provided by these authors and reviewers as well as the diligence of its staff and contractors in the preparation of this document at the request of the Office of Air Quality Planning and Standards.

Air Quality Criteria for Ozone and Related Photochemical Oxidants

Table of Contents

Volume I

1. Executive Summary 1-1

2. Introduction 2-1

3. Tropospheric Ozone and Its Precursors 3-1

4. Environmental Concentrations, Patterns, and Exposure Estimates 4-1

Appendix A: Abbreviations and Acronyms A-1

Volume II

5. Environmental Effects of Ozone and Related Photochemical Oxidants 5-1

Appendix A: Abbreviations and Acronyms A-1

Appendix B: Colloquial and Latin Names B-1

Volume III

6. Toxicological Effects of Ozone and Related Photochemical Oxidants . . . 6-1

7. Human Health Effects of Ozone and Related Photochemical Oxidants . . . 7-1

8. Extrapolation of Animal Toxicological Data to Humans 8-1

9. Integrative Summary of Ozone Health Effects 9-1

Appendix A: Abbreviations and Acronyms A-1

Table of Contents

Page

List of Tables . . . . II-xii
List of Figures . . . . II-xvi
Authors, Contributors, and Reviewers . . . . II-xxi
U.S. Environmental Protection Agency Science Advisory Board, Clean Air Scientific Advisory Committee . . . . II-xxv
U.S. Environmental Protection Agency Project Team for Development of Air Quality Criteria for Ozone and Related Photochemical Oxidants . . . . II-xxvii

5. ENVIRONMENTAL EFFECTS OF OZONE AND RELATED PHOTOCHEMICAL OXIDANTS 5-1
 5.1 INTRODUCTION 5-1
 5.2 METHODOLOGIES USED IN VEGETATION RESEARCH . . . 5-5
  5.2.1 Fumigation Systems 5-5
   5.2.1.1 Methodologies Discussed in the Air Quality Criteria for Ozone and Other Photochemical Oxidants 5-5
   5.2.1.2 Methodologies Referenced Since the Air Quality Criteria for Ozone and Other Photochemical Oxidants 5-8
  5.2.2 Experimental Design and Data Analysis 5-13
  5.2.3 Mechanistic Process Models 5-15
  5.2.4 Summary 5-16
 5.3 SPECIES RESPONSE/MODE OF ACTION 5-18
  5.3.1 Introduction 5-18
  5.3.2 Ozone Uptake 5-19
   5.3.2.1 Ozone Uptake by Plant Canopies 5-19
   5.3.2.2 Ozone Absorption by Leaves 5-22
  5.3.3 Resistance Mechanisms 5-24
   5.3.3.1 Stomatal Limitation 5-24
   5.3.3.2 Detoxification 5-26
  5.3.4 Physiological Effects of Ozone 5-27
   5.3.4.1 Carbohydrate Production and Allocation 5-30
   5.3.4.2 Compensation 5-32
  5.3.5 Role of Age and Size Influencing Response to Ozone . . 5-32
   5.3.5.1 Summary 5-34
 5.4 FACTORS THAT MODIFY PLANT RESPONSE 5-35
  5.4.1 Modification of Functional and Growth Responses 5-35
  5.4.2 Genetics 5-36
  5.4.3 Environmental Biological Factors 5-47

Table of Contents (cont'd)

Page

5.4.3.1 Oxidant-Plant-Insect Interactions 5-47
5.4.3.2 Oxidant-Plant-Pathogen Interactions 5-51
5.4.3.3 Oxidant-Plant-Symbiont Interactions 5-56
5.4.3.4 Oxidant-Plant-Plant Interactions—Competition 5-56
5.4.4 Physical Factors 5-57
5.4.4.1 Light 5-58
5.4.4.2 Temperature 5-58
5.4.4.3 Humidity and Surface Wetness 5-60
5.4.4.4 Drought and Salinity 5-60
5.4.5 Nutritional Factors 5-65
5.4.6 Interactions with Other Pollutants 5-67
5.4.6.1 Oxidant Mixtures 5-67
5.4.6.2 Sulfur Dioxide 5-68
5.4.6.3 Nitrogen Oxides, Nitric Acid Vapor, and Ammonia 5-69
5.4.6.4 Hydrogen Fluoride and Other Gaseous Pollutants 5-73
5.4.6.5 Acid Deposition 5-73
5.4.6.6 Heavy Metals 5-77
5.4.6.7 Mixtures of Ozone with Two or More Pollutants 5-77
5.4.7 Interactions with Agricultural Chemicals 5-78
5.4.8 Factors Associated with Global Climate Change 5-79
5.4.9 Summary—Environmental Factors 5-82
5.5 EFFECTS-BASED AIR QUALITY EXPOSURE INDICES 5-84
5.5.1 Introduction 5-84
5.5.1.1 Biological Support for Identifying Relevant Exposure Indices 5-84
5.5.1.2 Historical Perspective on Developing Exposure Indices 5-85
5.5.2 Developing Exposure Indices 5-89
5.5.2.1 Experimental Design and Statistical Analysis . . 5-89
5.5.2.2 Studies with Two or More Different Patterns of Exposure 5-91
5.5.2.3 Combinations of Years, Sites, or Species: Comparisons of Yield Losses with Different Exposure Durations 5-95
5.5.2.4 Comparisons of Measures of Exposure Based on Reanalysis of Single-Year, Single-Species Studies 5-105

Table of Contents (cont'd)

Page

5.5.2.5 Comparison of Effects on Vegetation of Cumulative "Peak" Versus "Mid-Level" Ozone Exposures 5-117
5.5.3 Summary 5-136
5.6 EXPOSURE-RESPONSE OF PLANT SPECIES 5-137
5.6.1 Introduction 5-137
5.6.2 Summary of Conclusions from the Previous Criteria Documents 5-137
5.6.3 Information in the Published Literature Since 1986 5-142
5.6.3.1 Effects of Ozone on Short-Lived Species 5-144
5.6.4 Effects of Ozone on Long-Lived Plants 5-163
5.6.4.1 Perennial Agricultural Crops 5-164
5.6.4.2 Effects of Ozone on Deciduous Shrubs and Trees 5-165
5.6.4.3 Effects of Ozone on Evergreen Trees 5-173
5.6.5 Assessments Using Ethylene Diurea as a Protectant 5-180
5.6.6 Summary 5-184
5.7 EFFECTS OF OZONE ON NATURAL ECOSYSTEMS 5-185
5.7.1 Introduction 5-185
5.7.2 Ecosystem Characteristics 5-186
5.7.3 Effects of Exposure to Ozone on Natural Ecosystems . . 5-188
5.7.3.1 The San Bernardino Forest Ecosystem— Before 1986 5-188
5.7.3.2 The San Bernardino Forest Ecosystem— Since 1986 5-193
5.7.3.3 The Sierra Nevada Mountains 5-196
5.7.3.4 The Appalachian Mountains—Before 1986 . . . 5-202
5.7.3.5 The Appalachian Mountains and the Eastern United States—Since 1986 5-206
5.7.3.6 Rhizosphere and Mycorrhizal-Plant Interactions 5-210
5.7.4 Ecosystem Response to Stress 5-215
5.7.4.1 Introduction 5-215
5.7.4.2 Forest Ecosystems 5-219
5.7.5 Summary 5-225
5.8 EFFECTS OF OZONE ON AGRICULTURE, FORESTRY, AND ECOSYSTEMS: ECONOMICS 5-227
5.8.1 Introduction 5-227
5.8.2 Agriculture 5-228
5.8.2.1 Review of Key Studies from the 1986 Document 5-228
5.8.2.2 A Review of Post-1986 Assessments 5-231

Table of Contents (cont'd)

Page

5.8.2.3 Limitations and Future Research Issues 5-233
5.8.3 Forests (Tree Species) 5-234
5.8.4 Valuing Ecosystem Service Flows 5-235
5.8.4.1 Background 5-235
5.8.4.2 Nonmarket Valuation: Implications for Ecosystem Service Flows 5-236
5.8.4.3 Challenges in Linking Valuation Techniques to Ecosystem Service Flows 5-237
5.8.4.4 Valuing Ecosystem Service Flows: Summary 5-237
5.8.5 Summary 5-238
5.9 SUMMARY AND CONCLUSIONS FOR VEGETATION AND ECOSYSTEM EFFECTS 5-238
5.9.1 Introduction 5-238
5.9.2 Methodologies 5-240
5.9.3 Species Response/Mode of Action 5-241
5.9.3.1 Exposure Dynamics 5-242
5.9.3.2 Age and Size 5-243
5.9.4 Factors That Modify Plant Response to Ozone 5-243
5.9.4.1 Genetics 5-243
5.9.4.2 Environmental Factors 5-244
5.9.5 Effects-Based on Air Quality Exposure Indices 5-245
5.9.6 Exposure Response of Plant Species 5-248
5.9.6.1 Introduction 5-248
5.9.6.2 Predicted Crop Yield Losses 5-249
5.9.6.3 Predicted Biomass Changes in Trees 5-249
5.9.7 Effects of Ozone on Natural Ecosystems 5-250
5.9.8 Economic Assessments 5-252
5.10 EFFECTS OF OZONE ON MATERIALS 5-253
5.10.1 Introduction 5-253
5.10.2 Mechanisms of Ozone Attack and Antiozonant Protection 5-253
5.10.2.1 Elastomers 5-253
5.10.2.2 Textile Fibers and Dyes 5-255
5.10.2.3 Paint 5-256
5.10.3 Exposure-Response Data 5-257
5.10.3.1 Elastomer Cracking 5-257
5.10.3.2 Dye Fading 5-264
5.10.3.3 Fiber Damage 5-271
5.10.3.4 Paint Damage 5-274
5.10.3.5 Cultural Properties Damage 5-276

Table of Contents (cont'd)

Page

5.10.4 Economics 5-279
5.10.4.1 Introduction 5-279
5.10.4.2 Methods of Cost Classification and Estimation 5-279
5.10.4.3 Aggregate Cost Estimates 5-280

5.10.5 Summary and Conclusions 5-282
REFERENCES 5-285

APPENDIX 5A: ABBREVIATIONS AND ACRONYMS A-1

APPENDIX 5B: COLLOQUIAL AND LATIN NAMES B-1

List of Tables

Number		Page
5-1	Comparison of Fumigation Systems for Ozone Exposure-Plant Response Studies	5-17
5-2	Examples of Intraspecific Variation of Foliar Symptoms in Ozone Response	5-37
5-3	Examples of Intraspecific Variation in Growth Responses Following Ozone Exposures	5-38
5-4	Mortality of Three Ozone Sensitivity Classes of Eastern White Pine Trees During 1971 to 1986	5-44
5-5	Examples of Ozone Effects on Pollen Germination and Tube Elongation	5-46
5-6	Ozone Effects on Insect Pests	5-49
5-7	Ozone-Plant-Pathogen Interactions	5-52
5-8	Field Studies of Ozone-Drought Stress Interactions in Crop Species	5-62
5-9	Ozone-Soil Nutrient Interactions	5-66
5-10	Some Statistical Models of Combined Ozone and Sulfur Dioxide Responses	5-70
5-11	References to Reports of Interaction or No Interaction Between Ozone and Acid Rain or Acid Fog	5-74
5-12	A Summary of Studies Reporting the Effects of Ozone for Two or More Exposure Patterns on the Growth, Productivity, or Yield of Plants	5-94
5-13	A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Plants for Two or More Replicate Studies Having Equal Total Exposures and Either Varying or Similar Durations	5-97

List of Tables (cont'd)

Number		Page
5-14	Summary of Ozone Exposures That Are Closest to Those Predicted for 20 Percent Yield Reduction per SUM06 Exposure Response Models Used by Lee et al. (1991) in Selected National Crop Loss Assessment Network Experiments	5-107
5-15	Summary of Percentiles for Ozone Monitoring Sites in 1989 with a Maximum Three-Month SUM06 Value Less Than 24.4 ppm per Hour but with a Second Hourly Maximum Concentration Greater Than or Equal to 0.125 ppm	5-109
5-16	Summary of Percentiles for Ozone Monitoring Sites in 1989 with a Maximum Three-Month SUM06 Value Greater Than or Equal to 24.4 ppm per Hour but with a Second Hourly Maximum Concentration Less Than 0.125 ppm	5-110
5-17	Ozone Concentrations for Short-Term Exposures That Produce 5 or 20 Percent Injury to Vegetation Grown Under Sensitive Conditions	5-119
5-18	A Summary of Studies Reporting Effects of Peaks or Mid-Range Concentrations	5-120
5-19	Estimates of the Parameters for Fitting the Weibull Model Using the Seven-Hour Seasonal Mean Ozone Concentrations	5-140
5-20	Summary of Ozone Exposure Indices Calculated for Three- or Five-Month Growing Seasons from 1982 to 1991	5-145
5-21	Comparison of Exposure-Response Curves Calculated Using the Three-Month, 24-Hour SUM06 Values for 54 National Crop Loss Assessment Network Cases	5-146
5-22	Comparison of Exposure-Response Curves Calculated Using the 24-Hour W126 Values for 54 National Crop Loss Assessment Network Cases	5-149
5-23	The Exposure Levels Estimated to Cause at Least 10 Percent Crop Loss in 50 and 75 Percent of Experimental Cases	5-152
5-24	SUM06 Levels Associated with 10 and 20 Percent Yield Loss for 50 and 75 Percent of the National Crop Loss Assessment Network Crop Studies	5-153

List of Tables (cont'd)

Number		Page
5-25	A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Annual Plants Published Since U.S. Environmental Protection Agency (1986)	5-154
5-26	A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Perennial Crop Plants Published Since U.S. Environmental Protection Agency (1986) . . .	5-161
5-27	A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Deciduous Shrubs and Trees Published Since U.S. Environmental Protection Agency (1986) . . .	5-166
5-28	Exposure-Response Equations That Relate Total Biomass to 24-Hour SUM06 Exposures Adjusted to 92 Days	5-169
5-29	SUM06 Levels Associated with 10 and 20 Percent Total Biomass Loss for 50 and 75 Percent of the Seedling Studies	5-171
5-30	A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Evergreen Trees Published Since U.S. Environmental Protection Agency (1986)	5-174
5-31	Effects of Ethylene Diurea on Ozone Responses	5-181
5-32	San Bernardino Forest—Status 1972	5-189
5-33	Ecosystem Response to Pollutant Stress	5-192
5-34	Growing Season Summary Statistics for Ozone Monitoring Sites in or Near Forests for the Period 1980 through 1988	5-197
5-35	Interactions of Ozone and Forest Tree Ectomycorrhizae	5-213
5-36	Interaction of Air Pollution and Temperate Forest Ecosystems Under Conditions of Intermediate Air Contaminant Load	2-219
5-37	Properties of Ecological Systems Susceptible to Ozone at Four Levels of Biological Organization	2-221
5-38	Recent Studies of the Economic Effects of Ozone and Other Pollutants on Agriculture	5-230

List of Tables (cont'd)

Number		Page
5-39	Studies of the Economic Effects of Ozone and Other Pollutants on Forests	5-235
5-40	Laboratory and Field Studies on Effects of Ozone on Elastomers	5-258
5-41	Protection of Tested Rubber Materials	5-261
5-42	Effect of Ozone and Humidity on Interply Adhesion	5-263
5-43	Laboratory and Field Studies of the Effects of Ozone on Dye Fading	5-265
5-44	Laboratory and Field Studies of the Effects of Ozone on Fibers	5-272
5-45	Laboratory and Field Studies of the Effects of Ozone on Architectural/Industrial Paints and Coatings	5-275
5-46	Laboratory Studies of the Effects of Ozone on Artists' Pigments and Dyes	5-277
5-47	Summary of Damage Costs to Materials by Oxidants	5-281

List of Figures

Number		Page
5-1	Leaf absorption and possible functional changes that may occur within the plant	5-3
5-2	Uptake of ozone from the atmosphere	5-20
5-3	Movement of gases into and out of leaves is controlled primarily by the stomata	5-23
5-4	Simulation of the effects of diurnal variation in stomatal aperture and in ozone concentration on ozone uptake: diurnal ozone concentrations, simulated conductance, and ozone uptake	5-25
5-5	Effects of ozone absorption into a leaf	5-28
5-6	Effect of ozone on plant function and growth	5-29
5-7	The average injury index for visible foliar injury after exposure of one-year-old seedlings to 50 pphm ozone for 7.5 hours	5-40
5-8	Frequency distribution showing the variability in ozone response within one half-sib family of loblolly pine exposed to increasing levels of ozone under chronic-level field conditions over several growing seasons	5-41
5-9	Distribution pattern showing the number of ozone concentrations within specified ranges for the 1983 winter wheat proportional-addition experiment for the 1.4 times ambient air and 1.8 times ambient air treatments and for San Bernardino, California, in 1987	5-92
5-10	Comparison of the Weibull exposure-response functions and its predicted relative yield loss curves using the seven-hour mean exposure and daytime SUM06 for replicate years of National Crop Loss Assessment Network Program's data for cotton, wheat, kidney bean, and potato, respectively	5-100

List of Figures (cont'd)

Number | Page

5-11 Predicted relative yield losses for Acala SJ-2 cotton for four sites and multiple years (1981, 1982, 1988, and 1989) relative to 0.01 ppm for the seven-hour mean exposure, 0.035 ppm for the second highest daily maximum concentration, 0 ppm per hour for SIGMOID, and 0 ppm per hour for SUM06, which correspond to typical levels in the charcoal-filtered chambers 5-101

5-12 Relative effect of ozone on growth and yield of spring wheat cultivars from two growing seasons 5-102

5-13 Weibull exposure-response curves for the relative effect of ozone on grain yield of spring wheat for three years, individually and combined 5-103

5-14 Quadratic exposure-response curves for the relative effect of ozone on grain yield of spring wheat in 1989 and 1990, using four different exposure indices 5-104

5-15 Percent reduction in net photosynthesis of pines and agricultural crops in relation to total ozone exposure, for several ranges of peak concentrations 5-111

5-16 Percent reduction in net photosynthesis and biomass growth of coniferous species in relation to total exposure and estimated total ozone uptake 5-112

5-17 Percent reduction in net photosynthesis and biomass growth of hardwood species in relation to total exposure and estimated total ozone uptake 5-113

5-18 Percent reduction in net photosynthesis and biomass growth of agricultural crops in relation to total exposure and estimated total ozone uptake 5-114

5-19 Percent reduction in biomass growth of tree seedlings in relation to total exposure 5-115

5-20 Reduction in volume production of loblolly pine seedlings in relation to four exposure indices 5-116

List of Figures (cont'd)

Number | Page

5-21 A comparison between the resulting cumulative frequencies for the exposure parameters, sum of all hourly average concentrations and the sigmoidally weighted integrated exposure index, W126 5-117

5-22 Fumigation schedule of uniform and simulated ambient ozone concentration distributions at two equivalent dose levels 5-123

5-23 Fumigation schedule of uniform and simulated ambient ozone concentration distributions at two dose levels 5-124

5-24 Experimental ozone exposure profiles 5-125

5-25 Ozone exposure profiles for 1983 season 5-127

5-26 Mean foliar injury on tobacco Bel W3 and mean ozone concentrations for the years 1979 to 1988, mean foliar injury on tobacco Bel W3 and ozone concentrations for weekly exposures during the 1988 growing season, maximal foliar injury on tobacco Bel W3 in relation to ozone concentrations for 1988, and mean foliar injury on subterranean clover cv. Geraldton and mean ozone concentrations for two weekly exposures during the 1988 growing season 5-129

5-27 Maximum foliar injury on tobacco Bel W3 in relation to ozone concentrations expressed in classes of 10 $\mu g/m^3$ for 1979 to 1983, and maximum foliar injury on two bean cultivars in relation to ozone concentrations for 1982 and 1983 5-130

5-28 Summary hourly ambient ozone concentrations during nine weeks of experimentation (1990) at Montague-Amherst, Massachusetts, and summary hourly ambient ozone concentrations during nine weeks of experimentation (1990) at Mount Equinox 5-133

List of Figures (cont'd)

Number		Page
5-29	Box-plot distribution of biomass loss predictions from Weibull and linear exposure-response models that relate biomass and ozone exposure as characterized by the 24-hour SUM06 statistic using data from 31 crop studies from the National Crop Loss Assessment Network and 26 tree seedling studies conducted at U.S. Environmental Protection Agency's Environmental Research Laboratory in Corvallis, Oregon; Smoky Mountains National Park, Tennessee; Michigan; Ohio; and Alabama	5-160
5-30	Effects of ozone on plant function and growth	5-187
5-31	Total oxidant concentrations at Rim Forest in Southern California during May through September, 1968 through 1972	5-190
5-32	Total basal area for each species as percent of the total basal area for all species in 1974 and 1988 on plots with severe to moderate damage, plots with slight damage, and plots with very slight damage or no visible symptoms	5-194
5-33	Impact of a reduced supply of carbon to the shoot, or water and nitrogen to the roots, on subsequent allocation of carbon	5-211
5-34	Carbon uptake through photosynthesis is made available to a general pool of carbohydrates used in construction and maintenance of various tissues	5-217
5-35	Organizational levels at which air pollutants have been shown to affect the growth-related process of forest trees	5-218
5-36	Effects of environmental stress on forest trees are presented on a hierarchial scale for leaf, branch, tree, and stand levels of organization	2-222
5-37	Postulated mechanism for damage to elastomers by ozone	5-254
5-38	Reaction of anthraquinone dyes with ozone and with nitrogen oxides	5-256
5-39	Relative decrease in stress with time as a function of ozone concentration for polyisoprene vulcanizate	5-261

List of Figures (cont'd)

Number Page

5-40 Relaxation of rubber compounds in ozone is affected by the combination of rubber formulation and type of ozone protection 5-262

Authors, Contributors, and Reviewers

Chapter 5. Environmental Effects of Ozone and Related Photochemical Oxidants

Principal Authors

Dr. Richard M. Adams—Department of Agriculture and Resource Economics, Oregon State University, Corvallis, OR 97331

Dr. Christian Andersen—Environmental Research Laboratory, U.S. Environmental Protection Agency, 200 SW 35th Street, Corvallis, OR 97333

Dr. J.H.B. Garner—National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Dr. Beverly A. Hale—Department of Horticultural Science, University of Guelph, Guelph, Ontario, N1G 2W1, Canada

Dr. William E. Hogsett—Environmental Research Laboratory, U.S. Environmental Protection Agency, 200 SW 35th Street, Corvallis, OR 97333

Dr. David F. Karnosky—School of Forestry and Wood Products, Michigan Technological University, Houghton, MI 49931

Dr. John Laurence—Boyce Thompson Institute for Plant Research at Cornell University, Tower Road, Ithaca, NY 14853

Dr. E. Henry Lee—ManTech Environmental Technology, Inc., 1600 W. Western Boulevard, Corvallis, OR 97333

Dr. Allen S. Lefohn—A.S.L. & Associates, 111 Last Chance Gulch, Suite 4A, Helena, MT 59601

Dr. Paul Miller—Pacific Southwest Forest and Range Experiment Station, USDA-Forest Service Fire Lab, 4955 Canyon Crest Dr., Riverside, CA 92507

Mr. Doug Murray—TRC Environmental Corporation, 5 Waterside Crossing, Windsor, CT 06095

Dr. Victor Runeckles—Department of Plant Science, University of British Columbia, Vancouver, British Columbia, V6T 1Z4, Canada

Authors, Contributors, and Reviewers (cont'd)

Dr. James A. Weber—Environmental Research Laboratory, U.S. Environmental Protection Agency, 200 SW 35th Street, Corvallis, OR 97333

Dr. Ruth D. Yanai—Boyce Thompson Institute for Plant Research at Cornell University, Tower Road, Ithaca, NY 14853

Reviewers

Ms. Vicki Atwell—Office of Air Quality Planning and Standards (MD-12), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Dr. Glen R. Cass—Environmental Engineering Science Department, Mail Code 138-78, California Institute of Technology, Pasadena, CA 91125

Dr. Arthur Chapelka—Auburn University School of Forestry, Auburn, AL 36849-4201

Dr. Robert Goldstein—Electric Power Research Institute, 3412 Hillview Ave., Palo Alto, CA 94303

Dr. Marcia Gumpertz—Department of Statistics, North Carolina State University, Raleigh, NC 27695

Dr. Allen Heagle—U.S. Department of Agriculture, ARS, 1505 Varsity Drive, Raleigh, NC 27606

Dr. Robert Heath—Dept. of Botany and Plant Science, University of California, Riverside, CA 92521

Dr. Thomas M. Hinckley—School of Forest Resources, University of Washington, Seattle, WA 98195

Dr. Robert Kohut—Boyce Thompson Institute, Cornell University, Tower Road, Ithaca, NY 14853-1801

Dr. Virginia Lesser—Department of Statistics, Oregon State University, Corvallia, OR 97333

Dr. Fred Lipfert—23 Carll Ct., Northport, NY 11768

Dr. Patrick McCool—SAPRC, University of California, Riverside, CA 92521

Dr. Delbert McCune—Boyce Thompson Institute, Cornell University, Tower Road, Ithaca, NY 14853-1801

Authors, Contributors, and Reviewers (cont'd)

Dr. Robert Musselman—U.S. Department of Agriculture, Forestry Service, Rocky Mountain Experiment Station, 240 West Prospect Road, Fort Collins, CO 80526

Dr. Eva Pell—Pennsylvania State University, Department of Plant Pathology, 321 Buckhout Laboratory, University Park, PA 16802

Dr. Phillip Rundel—Laboratory of Biomedical and Environmental Science, University of California, LA, 900 Veterans Ave., Los Angeles, CA 90024

Dr. Jayson Shogren—School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511

Dr. James Shortle—Department of Agricultural Economics, Pennsylvania State University, Armsby Building, 208C, University Park, PA 16802-5502

Dr. John Skelly—Pennsylvania State University, 108 Buckhout Laboratory, University Park, PA 16802

Dr. Boyd Strain—Department of Botany, 136 Biology Science Building, Duke University, Durham, NC 27708

Dr. George E. Taylor, Jr.—Biological Sciences Center, Desert Research Institute, 7010 Dandini Blvd., Reno, NV 89512

Dr. Patrick Temple—Statewide Air Pollution Research Center, University of California, Riverside, CA 92521-0312

Dr. David Tingey—U.S. Environmental Protection Agency, Environmental Research Laboratory, 200 SW 35th Street, Corvallis, OR 97333

Dr. Michael Unsworth—Department of Atmospheric Sciences, Oregon State University, Corvallis, OR 97333

Dr. David Weinstein—Boyce Thompson Institute, Cornell University, Tower Road, Ithaca, NY 14853-1801

Dr. John Yocom, 12 Fox Den Road, West Simsbury, CT 06092

U.S. Environmental Protection Agency
Science Advisory Board
Clean Air Scientific Advisory Committee

Ozone Review

Chairman

Dr. George T. Wolff—General Motors Corporation, Environmental and Energy Staff, General Motors Bldg., 12th Floor, 3044 West Grand Blvd., Detroit, MI 48202

Members

Dr. Stephen Ayres—Office of International Health Programs, Virginia Commonwealth University, Medical College of Virginia, Box 980565, Richmond, VA 23298

Dr. Jay S. Jacobson—Boyce Thompson Institute, Tower Road, Cornell University, Ithaca, NY 14853

Dr. Joseph Mauderly—Inhalation Toxicology Research Institute, Lovelace Biomedical and Environmental Research Institute, P.O. Box 5890, Albuquerque, NM 87185

Dr. Paulette Middleton—Science & Policy Associates, Inc., Western Office, Suite 140, 3445 Penrose Place, Boulder, CO 80301

Dr. James H. Price, Jr.—Research and Technology Section, Texas Natural Resources Conservation Commission, P.O. Box 13087, Austin, TX 78711

Invited Scientific Advisory Board Members

Dr. Morton Lippmann—Institute of Environmental Medicine, New York University Medical Center, Long Meadow Road, Tuxedo, NY 10987

Dr. Roger O. McClellan—Chemical Industry Institute of Toxicology, P.O. Box 12137, Research Triangle Park, NC 27711

Consultants

Dr. Stephen D. Colome—Integrated Environmental Services, University Tower, Suite 280, 4199 Campus Drive, Irvine, CA 92715

U.S. Environmental Protection Agency
Science Advisory Board
Clean Air Scientific Advisory Committee
(cont'd)

Dr. A. Myrick Freeman—Department of Economics, Bowdoin College, Brunswick, ME 04011

Dr. Allan Legge—Biosphere Solutions, 1601 11th Avenue, NW, Calgary, Alberta T2N 1H1, CANADA

Dr. William Manning—Department of Plant Pathology, University of Massachusetts, Amherst, MA 01003

Dr. D. Warner North—Decision Focus, Inc., 650 Castro Street, Suite 300, Mountain View, CA 94041

Dr. Frank E. Speizer—Harvard Medical School, Channing Lab, 180 Longwood Avenue, Boston, MA 02115

Dr. George E. Taylor—Department of Environmental and Resource Sciences, 130 Fleischmann Agriculture Bldg. 199, University of Nevada, Reno, NV 89557

Dr. Mark J. Utell—Pulmonary Disease Unit, Box 692, University of Rochester Medical Center, 601 Elmwood Avenue, Rochester, NY 14642

Designated Federal Official

Mr. Randall C. Bond—Science Advisory Board (1400), U.S. Environmental Protection Agency, 401 M Street, SW, Washington, DC 20460

Staff Assistant

Ms. Lori Anne Gross—Science Advisory Board (1400), U.S. Environmental Protection Agency, 401 M Street, SW, Washington, DC 20460

U.S. Environmental Protection Agency Project Team for Development of Air Quality Criteria for Ozone and Related Photochemical Oxidants

Scientific Staff

Mr. James A. Raub—Health Scientist, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Dr. A. Paul Altshuller—Physical Scientist, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Mr. William G. Ewald—Health Scientist, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Dr. J.H.B. Garner—Ecologist, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Dr. Judith A. Graham—Associate Director, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Ms. Ellie R. Speh—Secretary, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Ms. Beverly E. Tilton—Physical Scientist, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Technical Support Staff

Mr. Douglas B. Fennell—Technical Information Specialist, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Mr. Allen G. Hoyt—Technical Editor and Graphic Artist, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Ms. Diane H. Ray—Technical Information Manager (Public Comments), National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

U.S. Environmental Protection Agency
Project Team for Development of Air Quality Criteria
for Ozone and Related Photochemical Oxidants
(cont'd)

Mr. Richard N. Wilson—Clerk, National Center for Environmental Assessment (MD-52), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

Document Production Staff

Ms. Marianne Barrier—Graphic Artist, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Mr. John R. Barton—Document Production Coordinator, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. Lynette D. Cradle—Word Processor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. Shelia H. Elliott—Word Processor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. Sandra K. Eltz—Word Processor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. Jorja R. Followill—Word Processor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. Sheila R. Lassiter—Word Processor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. Wendy B. Lloyd—Word Processor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. Carolyn T. Perry—Word Processor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. Cheryl B. Thomas—Word Processor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Mr. Peter J. Winz—Technical Editor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

U.S. Environmental Protection Agency
Project Team for Development of Air Quality Criteria
for Ozone and Related Photochemical Oxidants
(cont'd)

Technical Reference Staff

Mr. John A. Bennett—Bibliographic Editor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709

Ms. S. Blythe Hatcher—Bibliographic Editor, Information Organizers, Inc., P.O. Box 14391, Research Triangle Park, NC 27709

Ms. Susan L. McDonald—Bibliographic Editor, Information Organizers, Inc., P.O. Box 14391, Research Triangle Park, NC 27709

Ms. Carol J. Rankin—Bibliographic Editor, Information Organizers, Inc., P.O. Box 14391, Research Triangle Park, NC 27709

Ms. Deborah L. Staves—Bibliographic Editor, Information Organizers, Inc., P.O. Box 14391, Research Triangle Park, NC 27709

Ms. Patricia R. Tierney—Bibliographic Editor, ManTech Environmental Technology, Inc., P.O. Box 12313, Research Triangle Park, NC 27709