Air Pollution at the Single-Particle Level: Integrating Atmospheric Measurements with Mathematical Models

Thesis by

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Appendix A

Cass Research Group

A.1 Introduction

This dissertation is dedicated to the memory of Dr. Glen Cass, who had the vision and provided the motivation for conducting the research work described in the preceding chapters. Glen served as my doctoral advisor for nearly three years before his death on July 30, 2001. Since that time, several articles have been written about his professional accomplishments, scientific contributions, personal integrity, and inspiring personality [1–4]. In one article, it was noted that Glen's greatest contribution may be found in the generation of researchers to whom he transmitted his enthusiasm for air pollution studies [5]. This appendix provides an account of the Cass research group members, all of whom have benefitted from Glen's supervision and leadership in one form or another.

A.2 Group Members

A.2.1 Ph.D. Students

A substantial fraction of the research conducted in the Cass group can be found in the Ph.D. dissertations written by Glen's former students. Table A.1 lists all of the doctoral theses published in the group. Students are listed chronologically in the order they began graduate studies at Caltech.

Table A.1: Ph.D. dissertations published under the supervision of Dr. Glen Cass.

Name	Title	Dept[a]
H. Andrew Gray	Control of Atmospheric Fine Primary Carbon Particle Concentrations	ENV
Armistead G. Russell	Formation and Control of Atmospheric Aerosol Nitrate and Nitric Acid	ME
Susan E. Fuhs	Studies of Inertial Deposition of Particles onto Heat Exchanger Elements	ME
Susan M. Larson	A Study of Summer Midday Low-Visibility Events in the Los Angeles Area	ENV
Lynn M. Hildemann	A Study of the Origin of Atmospheric Organic Aerosols	ENV
William W. Nazaroff	Mathematical Modeling and Control of Pollutant Dynamics in Indoor Air	ENV
Robert A. Harley	Mathematical Modeling of Gas-Phase Organic Air Pollutants	ENV
Wolfgang F. Rogge	Molecular Tracers for Sources of Atmospheric Carbon Particles: Measurements and Model Predictions	ENV
Annmarie Eldering	Alternative Models for Air Pollutant Effects on Visibility	ENV
Christos Christoforou	Control of Air Exchange and Particle Deposition within the Buddhist Cave Temples of Yungang, China	ME
Darrell A. Winner	Long-term Modeling of Regional Ozone Concentrations and Control Strategies	ENV
Michael P. Hannigan	Mutagenic Particulate Matter in Air Pollutant Source Emissions and in Ambient Air	ENV
Matthew P. Fraser	Measuring and Modeling the Concentrations of Individual Organic Compounds in the Urban Atmosphere	ENV
Christopher G. Nolte	Polar Organic Compounds in Fine Particulate Matter Sources and in the Urban Atmosphere	ENV
James J. Schauer	Source Contributions to Atmospheric Organic Compound Concentrations: Emissions Measurements and Model Predictions	ENV
Michael J. Kleeman	Source Contributions to the Size and Composition Distribution of Urban Particulate Air Pollution	ENV
Lara S. Hughes	Evolution of Atmospheric Aerosols Along Trajectories Crossing the Los Angeles Basin	ENV
Phil M. Fine	The Contribution of Biomass Combustion to Ambient Fine Particle Concentrations in the United States	ENV
Zohir Chowdhury	Fine Particle Characterization in South Asia[b]	EAS
Prakash V. Bhave	Air Pollution at the Single-Particle Level: Integrating Atmospheric Measurements with Mathematical Models	ENV

[a]Department where degree was completed. ENV = Environmental Engineering and science, Caltech. ME = Mechanical Engineering, Caltech. EAS = Earth and Atmospheric Sciences, Georgia Tech.

[b]Tentative thesis title

H. Andrew Gray joined the Cass group in the summer of 1979 after receiving an undergraduate degree from Carnegie Mellon University. His thesis work involved the development of an inventory of primary particulate carbon emissions in the Los Angeles basin, the measurement of carbonaceous aerosol concentrations at ten southern California sites throughout the 1982 calendar year, and the quantitative evaluation of various control strategies for reducing fine primary carbon particle concentrations in Los Angeles. After completing his thesis in November 1985, Dr. Gray worked at the South Coast Air Quality Management District where he served as the program manager for PM_{10} and visibility. He later worked at Systems Applications, Inc. for eight years before starting his own consulting company in San Rafael, California. He currently manages Gray Sky Solutions, an air pollution research consulting firm specializing in particulate matter and visibility issues.

Armistead (Ted) G. Russell came to the Cass group in the fall of 1979 with a bachelors degree in mechanical engineering from Washington State University. His thesis work included the development of a mathematical model for the formation and transport of ammonium nitrate aerosol, the measurement of aerosol nitrate, sulfate, ammonium, and their precursors during an intensive 1982 southern California field study, and the evaluation of his model for predicting atmospheric ammonium nitrate concentrations. In January 1985, Dr. Russell became the first Ph.D. student to finish under Glen's supervision. He was appointed to an assistant professor position at Carnegie Mellon University, where he worked until 1996. Currently, he is a distinguished professor of environmental engineering at Georgia Tech. His research group studies numerous aspects of ambient air pollution, with a focus on air quality model development. To date, nine students have received Ph.D. degrees under Dr. Russell's supervision.

Susan E. Fuhs joined the Cass group after receiving a bachelors degree in mechanical engineering from Caltech in 1980. As a graduate student, she examined the mechanisms of particle deposition on the gas-side external surface of compact heat exchanger elements. This type of fouling is commonly found in combustion systems such as coal or oil fired boilers, gas turbines, and diesel enginers. Dr. Fuhs completed her thesis in October 1987, and has worked for several private corporations in the southern California area. Recently, she served as the manager of new business development in the Engines and Systems group of Allied Signal, and she is currently the general manager of the Hybrid Power Generation Systems group in the General Electric Company.

Susan M. Larson received bachelors degrees in physics and German at Washington University before joining the Cass group in 1981. Her Ph.D. thesis involved the study of image processing based visibility models, the measurement of aerosol concentrations at five southern California sites throughout the 1984 summer, and the development and application of a modeling approach that allows the causes of regional visibility problems to be characterized quantitatively. After finishing her thesis in October 1987, Dr. Larson became an assistant professor at the University of Illinois at Urbana-Champaign (UIUC) and is a recipient of the Presidential Young Investigator award. She is currently an associate professor of environmental engineering and the director of the Women in Engineering program at UIUC. Her research group conducts laboratory-based experiments, air pollution field studies, and develops and evaluates the performance of air pollution control devices. To date, four students have received Ph.D. degrees under Dr. Larson's supervision.

Lynn M. Hildemann joined the Cass group in 1982, after earning a bachelors degree in biology from Caltech. Her thesis involved measuring the size distribution, inorganic chemical composition, and speciated organic composition of particulate matter emitted from seventeen different source categories. In order to simulate real-world combustion conditions, she designed a dilution stack sampler which has been replicated and used by numerous researchers around the world. Dr. Hildemann completed her thesis in September 1989, and was appointed to an assistant professor position at Stanford University. She is currently an associate professor of environmental engineering and science and an associate editor of *Environmental Science & Technology*. Dr. Hildemann is a recipient of the Presidential Young Investigator award and the American Association of Aerosol Research's Kenneth T. Whitby award. Her research group studies the sources and size distributions of indoor particulate matter as well as the hygroscopic properties of organic aerosols. To date, six students have received Ph.D. degrees under Dr. Hildemann's supervision.

William W. Nazaroff had received a bachelors degree in physics and a masters degree in electrical engineering from UC Berkeley before joining the Cass group in 1984. His thesis research focused on mathematically modeling the reactivity and transport of indoor air pollutants. He also assisted in the measurement of aerosol concentrations at five southern California museums during 1987–1988, in an effort to study and control the deposition of aerosols on works of art. Dr. Nazaroff was the fastest Ph.D. student in Cass group history, finishing his thesis in four years. He became an assistant professor at UC Berkeley in 1988, and is now a distinguished professor. Dr. Nazaroff is a recipient of the Presidential Young Investigator award and an elected member of the International Academy of Indoor Air Sciences. He is an associate editor of the *Journal of Air & Waste Management Association* and a past associate editor of *Health Physics*. He recently coauthored a textbook entitled, *Environmental Engineering and Science*, with Lisa Alvarez-Cohen. Dr. Nazaroff's research group focuses on indoor air quality and exposure analysis. To date, ten students have received Ph.D. degrees under his supervision.

Robert A. Harley joined the Cass group in 1987 with a bachelors degree in engineering science from the University of Toronto. At Caltech, his research focused on mathematically modeling the concentrations of ozone, volatile organic compounds, and toxic organic air pollutants. He also developed a speciated organic gas emissions inventory for the Los Angeles area which was used for several subsequent air quality modeling studies. After completing his thesis in December 1992, Dr. Harley became an assistant professor at UC Berkeley and is now a full professor. He is a recipient of the National Science Foundation's CAREER development award and on the editorial advisory board of *Atmospheric Environment*. His research group researches mobile sources of air pollutant emissions and conducts air quality modeling studies. To date, four students have received Ph.D. degrees under Dr. Harley's supervision.

Wolfgang F. Rogge also came to the Cass group in 1987, after receiving a diplom ingenieur from Technische Universitat Berlin. As a graduate student, he conducted a detailed analysis of particle-phase individual organic compounds emitted from all major sources of fine organic aerosols in the urban environment. The results of these studies are reported in a series of nine papers published in *Environmental Science & Technology* between 1991 and 1998. Dr. Rogge was appointed to an assistant professor position at Florida International University after completing his thesis in May 1993. His research group studies numerous aspects of atmospheric pollutants, with an emphasis on the measurement and source apportionment of individual organic compounds in atmospheric aerosols. He is currently an associate professor.

Annmarie Eldering joined the Cass group in 1988 after earning a bachelors degree in chemical engineering from Cooper Union. Her thesis describes the development and application of four mathematical models for determining the effects of air pollution on visibility. The models include a Lagrangian source-oriented air quality model, an image processing based model, and a model based on satellite-generated landscape data. After completing her thesis in March 1994, Dr. Eldering became an assistant professor at the University of Iowa, where she supervised seven masters degree students. In 1997, she moved back to southern California to work at the University of California, Los Angeles (UCLA). Currently, Dr. Eldering conducts research at the Jet Propulsion Laboratory and holds an adjunct assistant professor position at UCLA. Her current research focuses on the radiative impacts of aerosols and clouds.

Christos S. Christoforou also joined the Cass group in 1988, after obtaining an undergraduate degree in mechanical engineering from Rice University. His graduate research was focused on the air pollutants inside Buddhist cave temples at the Yungang Grottoes in China. He conducted air pollution measurement campaigns at the Grottoes in the spring of 1991, and used mathematical models to develop strategies for controlling the air exchange and reducing particle deposition to the cave walls. After finishing his thesis in May 1995, Dr. Christoforou did two years of service in his home country of Cyprus before joining the faculty at Clemson University in South Carolina. He is currently an assistant professor of environmental engineering and science at Clemson. His research group studies various aspects of air pollution control.

Darrell A. Winner joined the Cass group in 1989 after earning a bachelors degree in chemical engineering from Carnegie Mellon University. His thesis describes efficient methods for mathematically modeling regional ozone concentrations over periods of a year or longer. He applied these methods to determine the effect of emission control strategies on long-term ozone concentration distributions. He left Caltech in February 1996 to fulfill service obligations in the United States Air Force and finished his thesis in June 1998. Dr. Winner currently serves as a science advisor to regulatory staff at the EPA. He is a project officer in the EPA Center for Global Change, where he plans and implements solicitations for future research in atmospheric science, air quality engineering, and global change. In addition, Dr. Winner is the program manager of the Experimental Program to Stimulate Competitive Research (EPSCoR) within the EPA's National Center for Environmental Research.

Michael P. Hannigan joined the group in 1990 after obtaining a bachelors degree in mechanical engineering from Southern Methodist University. As a graduate student, he determined the bacterial and human cell mutagenicity of aerosols in emissions source and atmospheric samples. He also assisted in the measurement of atmospheric aerosols at five southern California sites throughout the 1993 calendar year. After completing his thesis in May 1997, Dr. Hannigan did postdoctoral research at MIT and Colorado State University, Fort Collins. He was a member of the University of Denver faculty for a couple of years before moving to the University of Colorado, Boulder. He is currently a research associate in the mechanical engineering department at Boulder. He focuses on urban and remote air pollutant characterization and recently has begun studying air pollution sampler development and current trends in energy use.

Matthew P. Fraser came to the Cass group in 1991 with a bachelors degree from Carnegie Mellon University. His thesis work involved the measurement of individual atmospheric organic compounds at five southern California sites during the 1993 summer. By sampling air in the Van Nuys tunnel, he determined the motor vehicle emission rates of 221 vapor-phase, semivolatile, and particle-phase organic compounds. He used these data to evaluate a mathematical model for calculating the concentrations of individual organic compounds in the Los Angeles atmosphere. Dr. Fraser completed his thesis in January 1998 and joined the faculty at Rice University. He is currently an assistant professor at Rice, where his research group studies organic air pollutants in source and ambient samples, as well as air pollution problems specific to the Houston metropolitan area.

Christopher G. Nolte joined the Cass group in 1992 after earning a bachelors degree in physics at Stanford University. His thesis research elucidated the concentrations of polar organic aerosol compounds in source and atmospheric samples. He also determined the atmospheric concentrations of numerous carboxylic acids in the Los Angeles atmosphere and helped collect samples during several field studies. After completing his thesis in February 2001, Dr. Nolte began working at Silicon Age, a small software company in San Francisco.

James (Jamie) J. Schauer held a bachelors degree from the Colorado School of Mines and a masters degree from UC Berkeley before joining the Cass group in 1993. At Caltech, he measured the concentrations of individual gas-phase and aerosol-phase organic compounds emitted from eight major air pollutant emission source categories. To date, the results of these studies constitute a five-paper series published in *Environmental Science & Technology* between 1999 and 2002. He also measured the atmospheric concentrations of individual organic compounds at three sites in central California during the 1995 Integrated Monitoring Study and used these data in combination with his source characterization data for receptor-oriented source apportionment calculations. Dr. Schauer joined the faculty at the University of Wisconsin, Madison after finishing his thesis in March 1998. Dr. Schauer is currently an assistant professor at Wisconsin and a recent recipient of the Health Effects Institute's Rosenblith Young Investigator Award. His research group investigates the origin of air pollutants as well as their impact on human health and the ecosystem.

Michael J. Kleeman also joined the group in 1993, after receiving a bachelors degree in mechanical engineering from the University of Waterloo. His thesis research involved the development and application of an air quality model in which the atmospheric aerosol is represented as a source-oriented external mixture. He measured the size-resolved chemical composition of aerosols emitted from six major combustion source categories and used those data as input to the air quality model. After completion of his thesis in October 1998, Dr. Kleeman joined the faculty at UC Davis. His research group studies urban and regional air quality problems with an emphasis on the size and composition of atmospheric particles and gas-to-particle conversion processes.

Lara S. Hughes earned a bachelors degree from Washington University before joining the Cass group in 1994. As a graduate student, she conducted two major field sampling experiments in the Los Angeles area, and helped conduct an experiment in the Indian Ocean. Her southern California experiments were conducted in 1996 and 1997, and involved measurements of the pollutant mixture within single air parcels at multiple ground-based locations as the parcels were advected across the Los Angeles basin. In addition to these trajectory studies, Lara reported the first comprehensive data set on the chemical composition of ultrafine ($D_a < 0.1$ μm) particles. She got married soon after completing her thesis in September 2000 and is now Dr. Lara Gertler. She was a postdoctoral fellow at UC Riverside, and currently works for the Ashworth Leininger Group, an environmental consulting firm in Thousand Oaks, California.

Phil M. Fine completed a bachelors degree in mechanical engineering from UC Berkeley and worked as an environmental consultant before joining the Cass group in 1995. His doctoral work involved determining the emission rates of over 250 individual organic compounds generated from the combustion of 22 species of North American wood. He used these data to quantify the contributions of biomass combustion particles to the atmospheric aerosol in various regions of the United States. After completing his thesis in January 2002, Dr. Fine conducted postdoctoral research at the University of Southern California (USC). He is currently a research assistant professor of environmental engineering at USC.

Zohir Chowdhury joined the Cass group in 1997 after earning a bachelors degree from Montana Tech. As a graduate student, he measured atmospheric aerosol properties in Maldives during the 1999 intensive field phase of the Indian Ocean

Experiment and characterized aerosols emitted from a variety of combustion source categories unique to the Indian subcontinent. After receiving a masters degree from Caltech, Zohir transferred to Georgia Tech with Dr. Cass in 2000. He conducted an aerosol characterization study at four megacities in the Indian subcontinent during each season of the 2001 calendar year, with the goal of apportioning the sources of fine particles at each site. Zohir will complete his thesis under the supervision of Ted Russell at Georgia Tech by the end of 2003, and plans to pursue a career at the World Bank.

Prakash V. Bhave was the last graduate student to join the Cass research group, after receiving a bachelors degree in environmental engineering from UC Berkeley in 1998. His thesis compares the properties of individual atmospheric particles with the single-particle properties calculated using a source-oriented externally mixed aerosol air quality model. After completing his thesis in March 2003, Dr. Bhave was appointed as a physical scientist in the Atmospheric Modeling division of the National Oceanic and Atmospheric Administration's Air Resources Laboratory in Research Triangle Park, North Carolina. He is responsible for developing the aerosol components of EPA's CMAQ model.

A.2.2 Postdoctoral Researchers

During his career, Dr. Cass hired eight postdoctoral researchers who each brought unique skills to the group. These individuals propelled the group into new areas of research, such as artwork degradation, organic compound speciation, and heterogenous atmospheric chemistry. Postdoctoral researchers also played instrumental roles in a number of field experiments.

Paul M. Whitmore worked in the Cass research group from 1984–1986 after completing a Ph.D. in chemistry from UC Berkeley and a postdoctoral research fellowship in Caltech's chemistry department. In the Cass group, Dr. Whitmore methodically studied the fading of a variety of artwork colorants due to reactions with ozone and nitrogen dioxide. After leaving Caltech, Dr. Whitmore worked in the conservation department of the Harvard University art museums. Since 1988, he has directed the Research Center on the Materials of the Artist and Conservator at the Carnegie Mellon Research Institute in Pittsburgh, Pennsylvania.

Paul A. Solomon joined the Cass group in December 1984 after finishing a Ph.D. in analytical and environmental chemistry at the University of Arizona. During the 1986 calendar year, he conducted a major field sampling program at nine southern California sites. This data set has been used by several investigators to map out the spatial and temporal distributions of PM_{10}, organic acid, and inorganic acid concentrations in the Los Angeles atmosphere. After leaving Caltech in 1988, Dr. Solomon worked for ten years as an environmental scientist at Pacific Gas and Electric company in San Ramon, California, before joining the U.S. EPA's National Exposure Research Laboratory. He is currently a senior research scientist at the EPA office in Las Vegas, Nevada, where he plans and implements regional field measurement and modeling programs aimed at developing cost effective control strategies for $PM_{2.5}$, PM_{10}, ozone, and related pollutants.

Monica A. Mazurek joined the Cass research group in February 1986 after completing her Ph.D. in geochemistry at UCLA. Her research at Caltech focused on interpreting gas chromatography/mass spectrometry (GC/MS) data acquired from atmospheric aerosols and emissions source samples. These studies laid much of the groundwork for future efforts aimed at quantifying the concentrations of individual organic compounds in source and ambient aerosol samples. Dr. Mazurek worked at the environmental chemistry division at Brookhaven National Laboratory from 1989 to 1995, before moving to Rutgers University. She is currently an associate research professor and the director of academic initiatives at Rutgers. Her research activities include studying the sources, distributions, and fates of carbonaceous aerosol particles. Dr. Mazurek is currently a member of the National Science Foundation advisory board, and was previously serving on the *Aerosol Science & Technology* editorial advisory board.

Mary P. Ligocki worked in the Cass group from March 1987 to July 1989. She coordinated sampling campaigns at five southern California museums during the summer of 1987 and winter of 1988. She passed away in 1996.

Jonathan O. Allen received a Ph.D. degree in chemical engineering from MIT before joining the Cass group in 1997. During his three years at Caltech, Dr. Allen helped manage the 1997 trajectory experiments and analyzed single-particle data collected using ATOFMS instruments. As a postdoc, he developed the YAADA software toolkit for ATOFMS data analysis and continues to maintain and update it. Dr. Allen worked briefly at Aerodyne Research, Inc. before joining the faculty of Arizona State University in 2001. His research group studies the formation and evolution of atmospheric aerosols with an emphasis on organic constituents. He is currently an assistant professor.

William S. Barney did postdoctoral work in the Cass group from 1999–2001 after receiving a Ph.D. degree in chemistry from UC Irvine. While in the group, Dr. Barney spent most of his time conducting experiments at Aerodyne Research, Inc., in Massachusetts. His research focused on heterogenous reactions between ozone and organic aerosols. He currently works at the TIAX corporation in Cambridge, Massachusetts.

Ann M. Dillner joined the Cass group at Georgia Tech after completing her Ph.D. in environmental engineering at UIUC in 2000. As a postdoc, she conducted field measurement campaigns in Houston, Beijing, and southern California, aimed at characterizing the chemical composition of atmospheric ultrafine particles. In 2001, Dr. Dillner joined the faculty of Arizona State University, where she is currently an assistant professor. Her research group studies various aspects of air pollution aerosols with a focus on ambient field measurements.

Mei Zheng received her Ph.D. degree in oceanography from the University of Rhode Island before joining the Cass group in 2000. She spent the first part of her postdoctoral appointment working at the University of Wisconsin with Jamie Schauer and the latter portion at Georgia Tech. As a postdoc, Dr. Zheng conducted applied receptor-oriented models to determine the contributions of different emissions sources to $PM_{2.5}$ concentrations in the southeastern United States and Beijing, China. She is currently a research scientist at Georgia Tech.

A.2.3 Research Staff

Dr. Cass employed a considerable number of staff scientists to ensure long-term continuity of the group's efforts. This continuity and constant staff support enabled his graduate students and postdoctoral researchers to conduct world-class research while maintaining a high rate of productivity.

Kenneth F. McCue joined the Cass group in 1983 with a Ph.D. degree in social sciences from Caltech. He brought a strong statistics background to the group, and helped analyze data from the 1982 and 1984 field studies. Primarily, he was responsible for administering the group's computer hardware and extensive air pollution data bases. While working from Glen, Dr. McCue founded Pactech Data and Research Incorporated, and split his time between both responsibilities until July 2002. He is currently a staff scientist in the applied and computational mathematics department at Caltech.

Shohreh Gharib volunteered her time in the Cass group in the early 1980's and worked as a staff scientist in the early 1990's. She developed an ammonia emission inventory for the southern California area and assisted with the 1982 and 1993 field studies. She has retired from her professional career.

Theresa Fall joined the Cass research group in 1984, after working as a draftsperson in Caltech's Environmental Quality Laboratory. She played significant roles during the 1986 basinwide field study and the southern California museum studies in 1987–1988. Theresa left the group in 1988 and is currently working in the Energy and Geoscience Institute at the University of Utah, Salt Lake City.

Lynn G. Salmon joined the Cass group in September 1986 after earning a bachelors degree from MIT and a masters degree from UCLA. Lynn either participated in or analyzed samples from nearly every atmospheric field campaign, source characterization study, and indoor air quality experiment conducted by the research group between 1986–2002. She coordinated the global ozone passive monitoring project in March and August 1999, in which ozone concentrations were determined at more than 400 locations worldwide. In addition, Lynn was primarily responsible for operation and maintenance of all laboratory equipment in the Cass research group. She continues to collect air pollution samples and conduct chemical analyses as a staff scientist in the Hoffman research group at Caltech.

Ann G. Miguel received a Ph.D. degree in biophysics from the Federal University of Rio de Janeiro in 1981. She was an associate professor at the University of Rio de Janeiro and the University of Sao Paulo before joining the Cass group in April 1994. From 1994–2002, Dr. Miguel characterized the allergens in airborne particulate matter and investigated their relationship with asthma incidences. She continues to study these subjects as a staff scientist in the Flagan research group at Caltech.

Paul R. Mayo worked in the Cass group from 1997–2002. During that time, he participated in several field studies and helped prepare and analyze air pollution samples. Paul is currently a scientist at UCLA in the Southern California Particle Center and Supersite.

Julie Saxton worked on the global ozone passive monitoring project while in the Cass group from 1999–2000. She is currently pursuing graduate studies in England.

A.2.4 Other Contributors

In addition to the investigators mentioned above, a very large number of undergraduate students contributed to research efforts in the Cass group. An exhaustive record of these individuals is not readily available, so only those who authored or were acknowledged in published work are listed here. Mari Peterson and Barbara Turpin assisted with the 1982 field study. Philip Lin, Barbara Turpin, and Frank Vasquez, helped with the 1984 summer visibility studies. Cynthia Shaver Atherton, C. Pamela De Moor, Kaitlin Drisko, Nathan Frei, Heather Mason, Cynthia Whitman, and Christine Tiller, contributed to the research on artwork deterioration. Betsy Andrews, Sandra Blumhorst, David Cole, Nancy Drehwing, Doug Gray, Michael Jones, Philip Lin, Harvey Liu, and Frank Vasquez helped with the 1986 field study. Christopher Hance analyzed data from the 1986 field study. Michael Jones helped with source characterization experiments in the 1980's. Mark Adams, Michael Jones, Harvey Liu, and Timothy Ma, assisted with museum sampling campaigns. Heather and Michael Masonjones (previously, Heather Mason and Michael Jones) collected measurements in August 1989 at the Grand Canyon and managed the high resolution gas chromatography data base. Nathan Frei and Timothy Gerk helped with the 1991 Yungang Grottoes experiments. Claudine Butcher prepared samples for the 1993 southern California field experiment. Robert Johnson helped with the 1996 trajectory study and conducted extensive analyses of the allergens found in ambient aerosols. Megha Deshpande assisted with an Atlanta field study in 2001.

Martha Conklin, Susan Hunts, Luiz Palma, Yun Ye, Steve Dutton, Brian King, and Kimberly Mertz, were graduate research assistants in the group, but did not complete doctoral degrees under Glen's supervision for a variety of reasons. Leon Bellan authored an artwork deterioration study as a high school student at the Polytechnic School.

Although not contributing directly to scientific research in the group, several administrative assistants worked for Dr. Cass. These include Pat Houseworth, Christina Conti, Dixie Fiedler, Shirley Anderson, and Laurel Martin at Caltech, and Rita Bryan and Susan Ryan at Georgia Tech. Pat Rankin, Fran Matzen, and Laura Cederquist helped manage Glen's research accounts.

A.3 Miscellaneous Notes

Dr. Cass expected his group members to conduct high quality research and encouraged his students to pursue fairly ambitious projects. Under these conditions Glen's students, on average, managed to finish their graduate work in less time than the Caltech average. The frequency distribution of time required to complete a Ph.D. degree in the Cass research group is shown in Figure A.1. The mean and median of this distribution are 6.1 years. On average, students whose research work was primarily computational (Russell, Nazaroff, Harley, Eldering, Winner, Kleeman, and Bhave) finished in 5.5 years (σ = 1.5), whereas the remaining students, whose research work included a substantial experimental component, required 6.4 years on

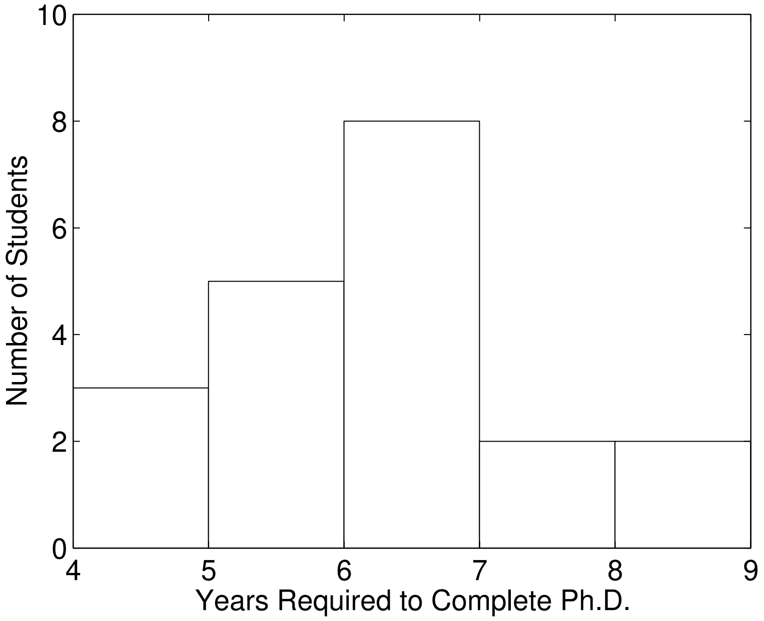

Figure A.1: Frequency distribution of time required to complete a Ph.D. degree in the Cass research group.

average ($\sigma = 0.9$).

Dr. Cass supported his students unconditionally in their search for employment as they neared completion of their doctoral work. This support helped launch all of his Ph.D. students into successful careers in either academic, governmental, or industrial sectors. Figure A.2 displays the distribution of careers that Glen's Ph.D. students pursued after graduating from Caltech. The numbers in parentheses indicate the number of students who pursued a career in the indicated sector. Dr. Gray did substantial work in both governmental and industrial sectors, so a half unit is attributed to each sector. The career path of Zohir Chowdhury is uncertain and, therefore, is excluded from Figure A.2.

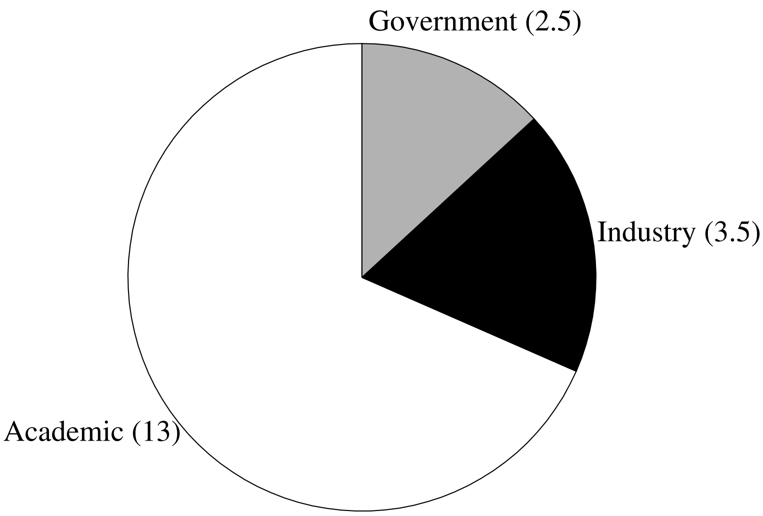

Figure A.2: Careers pursued by former Ph.D. students in the Cass research group.

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