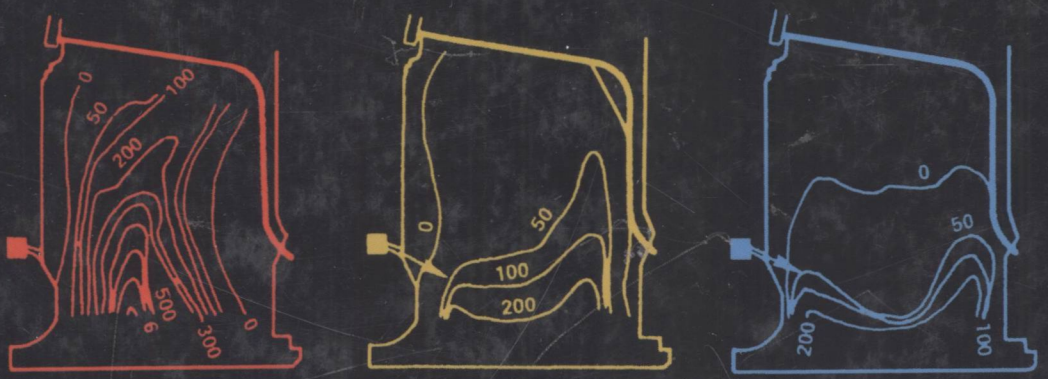
FOURTH EDITION

COMBUSTION AND INCINERATION PROCESSES

APPLICATIONS IN ENVIRONMENTAL ENGINEERING



WALTER R. NIESSEN
P. E., B.C.E.E.

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COMBUSTION AND INCINERATION PROCESSES

I dedicate this book to my precious wife, Dorothy Anne, my partner and friend for 50 years. Her love, encouragement, and support have been the foundation of my professional and personal life.

Preface

The fourth edition of *Combustion and Incineration Processes* was prepared, most importantly, to incorporate technology updates comprising the "conversion technologies" of the early 21st century. Also, additional details were added on waste and residue characteristics, combustion and air pollution control, process evaluation, design, and operations. Further, the scope was expanded to include additional details, data, and graphics regarding the design and operational characteristics of municipal and industrial waste incineration systems and numerous refinements in associated air pollution control. Several additional computer-based tools have been added to the enclosed CD.

The 21st century did not see the end of the weak markets for incineration-based waste management technologies in the United States. As in the last decade of the 20th century, new plant construction has been essentially stopped. This is due, in part, to the reduced landfill demand through recycling efforts, the opening of new landfills, some depression in landfilling costs and softening in the revenue from electricity generated by waste-to-energy plants. However, the most powerful influence has been the anxiety of the public. Citizens have been stirred by political rhetoric and frightened by worries over the health effects of air emissions (especially emission of heavy metals and a spectrum of organic compounds grouped as "air toxics"). Increasing pressure on municipal budgets has further weakened the resolve of city leadership to move away from landfills as long as they were available. The spike in diesel oil costs in 2008, however, raised the cost and anxiety in cities dependent on distant landfills, leading to a reconsideration of volume-reducing technologies.

The situation in Europe and, increasingly, in Asia has been different. Many of the countries of the European Community have passed legislation that greatly restricts the quantity and quality of materials that can be consigned to landfills. In Asian cities, burgeoning populations and movements to "throwaway" concepts have greatly increased the burden on city governments to handle solid wastes. Nearby landfills are rapidly filling and hauling to remote sites is costly.

The growing net waste generation rates within U.S. metropolitan centers, increasing transportation costs for waste hauling, and the burgeoning political interest in "zero waste" concepts coupled with the enticement of increases in electrical revenues from "green power sources" have renewed interest in thermal processing. It has become clear that the achievement of true zero waste (no landfilling) will require some kind of thermal processing to economically extract the last ultimate useful value from the material remaining after waste minimization, reuse and recycling: energy recovery. This final step must include use of furnace residues for road beds and other low-technology applications. With this realization has emerged interest in the new class of thermal processing technologies: the "conversion technologies" described in Chapter 12. Many of these technologies are seen to generate a clean fuel or synthesis gas intermediate and can often produce a slagged residue with essentially zero heavy metal leaching potential. However, selection and procurement of these advanced system concepts are not straightforward (see Chapter 15) and care must be taken to ensure that the commitments made will and can be fulfilled. The "mass burn" technologies of the 1970s and 1980s may still be seen as the gold standard: able to achieve (and usually beat) all state and federal air standards; produce enviable on-line availability, safety, and capacity records; and operate as good neighbors in communities throughout the world.

This book is an attempt to help those cities, consulting engineers, industrial firms, and academics working in this challenging and complex field to continue their evolution of this fascinating, interdisciplinary technology.

Walter R. Niessen, P.E., B.C.E.E.

Preface to the Third Edition

The third edition of *Combustion and Incineration Processes* was prepared to incorporate technology updates and additional details on combustion and air pollution control, process evaluation, design, and operations from the 1990s. Also, the scope was expanded to include (1) additional details and graphics regarding the design and operational characteristics of municipal waste incineration systems and numerous refinements in air pollution control, (2) emerging alternatives using refuse gasification technology, (3) lower-temperature thermal processing applied to soil remediation, and (4) plasma technologies as applied to hazardous wastes. Additional computer tools have been added to the enclosed diskette.

The 1990s have been difficult for incineration-based waste management technologies in the United States. New plant construction has slowed or stopped due to the anxiety of the public, fanned at times by political rhetoric, about the health effects of air emissions, including a focus on emissions of "air toxics" (heavy metals and a spectrum of organic compounds), softening of the selling price of electricity generated in waste-to-energy plants, reduced pressure on land disposal as recycling programs emerged, the opening of several new landfills, and some depression in landfilling costs. Also, the decade saw strong attention paid to the potential hazards of incinerator ash materials (few hazards were demonstrated, however). These factors have reduced the competitive pressures that supported the burgeoning incinerator growth of the previous decade.

Chapters 13 and 14 of this book, most importantly, give testimony to the great concern that has been shown to air emissions from municipal solid waste combustors (MWCs). This concern has often been expressed as a strong adversarial response by some individuals in potential host communities that slowed or ultimately blocked the installation of new facilities and that greatly expanded the required depth of analysis and intensified regulatory agency scrutiny in the air permitting process. Further, the concern manifested itself in more and more stringent air emission regulations that drove system designers to incorporate costly process control features and to install elaborate and expensive trains of back-end air pollution control equipment. A comparative analysis suggests that MWCs are subject to more exacting regulations than many other emission sources [506]. Not that those environmental improvements are without merit, but, perhaps, in this instance the higher costs to the taxpayers and/or the dogmatic elimination of a useful option for solid waste management may not be justified by the actual benefits realized.

The situation in Europe has been quite different. Many of the countries of the European Community have passed legislation that greatly restricts the quantity and quality of materials consigned to landfills. In Germany, for example, the Closed Cycle Economy Law, refining the Waste Act of 1986, raised energy recovery from waste incineration to a level equal to materials recycling in the "hierarchy" of preference in waste management alternatives. Further, their Technical Directive for Residual Waste severely restricted the loss of ignition of waste destined for landfills to less than 5% and the total organic carbon to less than 3%. The combination of these factors makes incineration almost a requirement. It must be said, however, that European air emission requirements are equal to or more stringent than their counterparts in the United States, and, therefore, the increased use of incineration will come at a very high cost.

The incineration community has responded well to these technical, political, and economic challenges. Over the past 40 years, incineration technology and its embodiment in processing plants have moved from its primitive early days as a "bonfire in a box" to sophisticated, energy recovery combustion systems with effective process control capped with broad spectrum and highly efficient

air pollution control systems capable of meeting stringent emission standards. The improvements and enhancements still continue to emerge. This book is an attempt to help those engineers and scientists working in this challenging and complex field to continue their evolution of this fascinating, interdisciplinary technology.

Walter R. Niessen, P.E., B.C.E.E.

Preface to the Second Edition

The second edition of *Combustion and Incineration Processes* was prepared as an update and as a substantial extension of the first edition. However, the underlying philosophy of the first edition has been retained: a focus on the fundamentals of incineration and combustion processes rather than on specific equipment. There have been many technical advances in the 15 years since this book first reached store shelves. The application of incineration to the hazardous waste area has required new levels of process control and better and more reliable combustion performance. There is now a profound and pervasive impact of state and federal environmental regulations and guidelines on design and operation. Consequently, air pollutant emission issues have assumed a dominant position in shaping system configuration.

The topics concerned with basic waste combustion processes (atomization, chemical kinetics of pyrolysis and oxidation, mixing, etc.) have been expanded. Applications relevant for hazardous wastes and their incineration systems are presented. Analysis methods and discussions of key design parameters for several additional incinerator types (especially for those burning sludges, liquids, and gases) have been significantly enlarged.

The section of the book dealing with techniques for waste data analysis and waste characterization has been substantially expanded. This reflects the strong influence of waste composition on the incineration process and the increased regulatory attention paid to emissions of toxic, carcinogenic, and otherwise environmentally significant trace elements and compounds found in wastes ("air toxics").

The first edition of *Combustion and Incineration Processes* (1978) focused on the incineration of *municipal* solid wastes. At that time "resource recovery" (energy recovery) was emerging as the only incineration concept that made economic sense for large plants. Inflation had greatly increased capital and operating costs. An offset from electrical revenue had become critical to viability. Technology that fed as-received refuse to the furnace ("mass burn") was competing for attention with facilities that first processed waste to a "refuse-derived fuel" (RDF). Still, as the research supporting the text for the first edition was prepared, few facilities of either type were operating in the United States. Data were scant and much was to be learned. This technology has matured since then.

The Clean Air Act had been long passed by 1978. Its provisions were fully implemented regarding the control of municipal incinerators. However, only total particulate emissions were regulated. Investigators in the Netherlands had recently reported the presence of "dioxin" in collected particulates of their local refuse incinerators. Acid gas, heavy metal, or NO_x controls were not incorporated into any municipal plant. However, over the past 15 years, regulatory actions (public hearings, permits, approvals, mandated designs, operating guidelines, etc.) have assumed a dominant role in the design, cost, performance objectives, and implementation schedules of incineration facilities. Consequently, additional and updated methodologies are presented to estimate pollutant emission rates. Also (but modestly and in keeping with the primary focus on the incineration system), a discussion of air pollution control technology has been included.

The attention of the public and the political and regulatory establishments were just beginning to focus on "hazardous wastes." The Resource Conservation and Recovery Act (RCRA) that mandated the structured and rigorous management of hazardous wastes was new. Its full scope and requirements were still uncertain. Public Law 96-510, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), better known as the "Super-fund Act," dealing with abandoned

hazardous waste sites, had not yet been written. The challenges to incineration of RCRA and CERCLA applications are significant. Emission mitigation using both sophisticated combustion control and back-end control equipment is of great interest to both regulators and the public.

I would like to acknowledge the support extended by Camp Dresser & McKee Inc. (CDM) in underwriting the preparation of many of the graphics incorporated in this edition and for their forbearance during the many months of manuscript preparation and refinement. I thank the many clients for whom I have worked over the years for their confidence and, importantly, for their support as together we addressed their problems and learned more about incineration technology. Finally, I want to thank the many colleagues I have worked with over the years . . . both inside and outside my employer's firm. Their professional support and help have been a constant source of stimulation.

Walter R. Niessen, P.E., B.C.E.E.

Preface to the First Edition

Purification by fire is an ancient concept, its applications noted in the earliest chapters of recorded history. The art and the technology of combustion (incineration) and pyrolysis as applied to environmental engineering problems draw on this experience, as well as the results of sophisticated contemporary research. To many engineers, however, combustion systems still hold an unnecessary mystery, pose unnecessary questions, and generate unnecessary mental barriers to their full exploitation as tools to solve tough problems. This book was written in an earnest attempt to thin the clouds of mystery, answer many of the questions (those for which answers are available), and provide a clearer way for the engineer to analyze, evaluate, and design solutions to environmental problems based on combustion.

The book describes combustion and combustion systems from a process viewpoint in an attempt to develop fundamental understanding rather than present simplistic design equations or nomographs. In large part, this approach was selected because combustion systems are complex and not readily susceptible to "cookbook" design methods. Consequently, considerable space is devoted to the basics: describing the chemical and physical processes that control system behavior.

In an effort to make the book as comprehensive as possible, a large number of topics have been dealt with. Specialists in particular fields may perhaps feel that the subjects they are interested in have received inadequate treatment. This may be resolved in part by exploring the noted references, an activity also recommended to the newcomer to the field.

The publication of this book appears timely since current trends in environmental awareness and regulatory controls will prompt increases in the use of combustion technology as the preferred or only solution. In light of escalating construction costs, the soaring expense and diminishing availability of fossil fuels used as auxiliary energy sources (or the growing value of recovered energy), and the ever more stringent regulatory insistence on high performance regarding combustion efficiency and/or air pollutant emissions, the "black box" approach is increasingly unacceptable to the designer and to the prospective owner.

This book was prepared to meet the needs of many: students; educators; researchers; practicing civil, sanitary, mechanical, and chemical engineers; and the owners and operators of combustion systems of all types—but particularly those dealing with environmental problems. To serve this diverse audience, considerable effort has been expended to provide reference data, correlations, numerical examples, and other aids for a fuller understanding and use.

Last (but of the greatest significance to me, personally), the book was written because I find the study and application of combustion to be an exciting and mind-stretching experience: ever fascinating in its blend of predictability with surprise (though sometimes, the surprises are cruel in their impact). Combustion processes are and will continue to be useful resources in solving many of the pressing environmental problems of modern civilization. I sincerely hope that my efforts to share both contemporary combustion technology and my sense of excitement in the field will assist in responding to these problems.

In the preparation of this book, I have drawn from a broad spectrum of the published literature and from the thoughts, insights, and efforts of colleagues with whom I have been associated with throughout my professional career. I am particularly grateful for the many contributions of my past associates at Arthur D. Little, Inc. and at the Massachusetts Institute of Technology, whose inspiration and perspiration contributed greatly to the substance of the book. Also, the many discussions and

exchanges with my fellow members of the Incinerator Division (now the Solid Waste Processing Division) of the American Society of Mechanical Engineers have been of great value.

I must specifically acknowledge Professor Hoyt C. Hottel of MIT who introduced me to combustion and inspired me with his brilliance, Mr. Robert E. Zinn of ADL who patiently coached and taught me as I entered the field of incineration, and Professor Adel F. Sarofim of MIT whose technical insights and personal encouragement have been a major force in my professional growth.

I would like to acknowledge the support given by Roy F. Weston Inc. and Camp Dresser & McKee Inc. in underwriting the typing of the text drafts and the preparation of the artwork. Particularly, I would thank Louise Miller, Bonnie Anderson, and Joan Buckley, who struggled through the many pages of handwritten text and equations in producing the draft.

Walter R. Niessen, P.E., B.C.E.E.

Author

Walter R. Niessen, president of Niessen Consultants (Andover, Massachusetts), is an internationally recognized consultant in process analysis, design, impact assessment, planning and start-up, and operations assistance drawing on 50 years of experience in applied combustion technology; air pollution control; and solid, sludge, liquid, and gaseous waste management. He has prepared over 95 technical papers, contributed chapters to nine environmental engineering books, and authored the definitive text and reference *Combustion and Incineration Processes*. He has been involved in numerous solid waste and biosolids management planning studies and implementation projects for industry and for small jurisdictions through larger cities and regions, and in numerous international assignments in the Caribbean, Europe, Africa, and Asia.

Niessen received his BS (1960) and MS (1961) in chemical engineering from the Massachusetts Institute of Technology. He is a board certified environmental engineer in the American Academy of Environmental Engineers (AAEE) in both solid waste and air pollution control and a member of the American Society of Mechanical Engineers (ASME), the American Institute of Chemical Engineers, Sigma Xi research honorary, and the Air and Waste Management Association (AWMA). He is a registered professional engineer in Massachusetts and New Hampshire. Among his honors, he received the Pioneer Award of ASME and the IT3 in 2008 for his lifetime educational and research efforts in incineration and waste management. He was a senior vice president with Camp Dresser & McKee Inc. (CDM) from 1976 to 1997, where he still functions as a senior consultant. Prior affiliations were with the U.S. Air Force, Arthur D. Little Inc., Bolt, Beranek & Newman, and Roy F. Weston Inc.

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