Perspectives in Chemical Engineering

Research and Education

Edited by

Clark K. Colton

Advances in
Chemical Engineering
Volume 16

Perspectives in Chemical Engineering

Research and Education

ADVANCES IN CHEMICAL ENGINEERING

Volume 16

ADVANCES IN CHEMICAL ENGINEERING

Volume 16

Editor-in-Chief

JAMES WEI

Department of Engineering
Princeton University
Princeton, New Jersey

Editors

JOHN L. ANDERSON

Department of Chemical Engineering
Carnegie-Mellon University
Pittsburgh, Pennsylvania

KENNETH B. BISCHOFF

Department of Chemical Engineering
University of Delaware
Newark, Delaware

JOHN H. SEINFELD

Department of Chemical Engineering
California Institute of Technology
Pasadena, California

Perspectives in Chemical Engineering

Research and Education

Edited by

CLARK K. COLTON

Department of Chemical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

ACADEMIC PRESS, INC.
Harcourt Brace Jovanovich, Publishers
Boston San Diego New York
London Sydney Tokyo Toronto

This book is printed on acid-free paper. ♾

ACADEMIC PRESS, INC.
1250 Sixth Avenue, San Diego, CA 92101

United Kingdom Edition published by
ACADEMIC PRESS LIMITED
24–28 Oval Road, London NW1 7DX

Library of Congress Catalog Card Number: 56–6600

ISBN 0–12–008516–X (alk. paper)

Printed in the United States of America
91 92 93 94 9 8 7 6 5 4 3 2 1

CONTENTS

PREFACE

A century has passed since the field of chemical engineering became formalized as an academic discipline. To mark this occasion, the Department of Chemical Engineering at the Massachusetts Institute of Technology sponsored a celebration on October 5–9, 1988 consisting of a Centennial Symposium of Chemical Engineering and an Alumni Convocation. This volume is a permanent record of all of the presentations and discussions at the symposium together with several papers presented at the convocation.

The symposium was divided into nine sections. The first eight covered topical areas of chemical engineering: fluid mechanics and transport; thermodynamics; kinetics, catalysis, and reactor engineering; environmental protection and energy; polymers; microelectronic and optical materials; bioengineering; and process engineering. Two important areas of chemical engineering, separations and surface and colloidal phenomena, were not explicitly included as separate topics but are nonethless included implicitly within several of the topical areas. The last section contained a self-examination of our identity as a profession. For each topical area, one symposium participant was asked to author a major review that included its historical development, current and future research directions, and role in education. It was to be aimed not at the expert but rather the broadly trained and well educated chemical engineer. Drafts of these manuscripts were made available to participants prior to the symposium. In addition, for each topical area one or two participants were asked to serve as discussants to critique the papers and add new material from their own perspective. The authors were given opportunity to edit and update their manuscripts, and final drafts from authors and discussants were received after the symposium. The discussants graciously accepted their role, as reflected in their shorter papers in this volume. A general discussion amongst all participants took place after the presentations in each area. These discussions, which were taped and subsequently transcribed and edited, are also included in this volume. Three papers presented at the convocation are included in Section I, most notably the masterful treatise by Skip Scriven on the intellectual roots and early evolution of chemical engineering.

The 23 chapters in sections II through IX attest to the extraordinary diversity of activities that characterizes chemical engineering today. Although these papers deal primarily with research, they also reflect the mutually reinforcing interaction between research and education—the creation

of new knowledge and the infusion of that knowledge into a continuously evolving curriculum. By contrast, the general discussions at the end of each section are concerned to a greater degree with education. This is not surprising, since, as noted by Jim Wei in the discussion of the last section, the educational process is the glue that binds the profession together.

A wide variety of problems and issues are considered in this volume. One that arises repeatedly is the diversification and increased specialization we are now undergoing. This puts increased demands for incorporation of new subject matter into an already overburdened curriculum. Furthermore, some express concern that this diversification is leading to fragmentation and loss of collegiality. Others are less concerned, recognizing that these pressures are simply the irritants that are the source of evolution.

The stresses and strains we observe are certainly not unique to chemical engineering. Any vibrant profession has the capacity to leave its main stream and form new branches. Our sister professions have faced the same problems that we have, as illustrated by the following quotation:

> "How to keep education sound in an environment of continued change brought about by scientific and technological progress is one of the themes of this volume.... Periodically, as the field has grown and become too diversified, it has been necessary to hammer out new underlying unities, new core curricula, new paradigms to keep the field together and to keep pace with change. The participants in these struggles were concerned with how to keep the field open-ended and the educational process vital and relevant; they were concerned with how to educate students for the long term, since students and educators alike are always in danger of being out paced by events."

This quotation, which so aptly applys to chemical engineering today, is from a volume by K. L. Wildes and N. A. Lindgren prepared for the Centennial of MIT's Department of Electrical Engineering and Computer Science in 1982!

The tapes of the discussions were transcribed and edited, along with the manuscripts, in Cambridge. The entire book was entered electronically and made ready for publication in Cambridge. A project of this scope requires the cooperation of many individuals, and I would like to thank several people who made it possible. Ms. Barbara Driscoll helped in preparations for the symposium. Mr. Scott Anthony of Academic Press provided needed help in final formatting of the manuscript. Last, but not least, my editorial assistant, Ms. Jane Ewing, played an invaluable role in all aspects of this adventure at the frontiers of electronic publishing, including tape transcription and editing of the entire manuscript. Without her tireless efforts this book would not have been possible.

Lastly, I acknowledge my family—Ellen, Jill, Jason, Michael, and Brian—for their continued love, support, and patience through projects such as this.

Clark K. Colton
Cambridge, Massachusetts

This Page Intentionally Left Blank

PARTICIPANTS

Professor Andreas Acrivos, *The Levich Institute of PCH, The City College of CUNY, New York, New York 10031*

Professor James E. Bailey, *Department of Chemical Engineering, California Institute of Technology, Pasadena, California 91125*

Professor Alexis T. Bell, *Department of Chemical Engineering, University of California, Berkeley, Berkeley, California 94720*

Professor Stuart W. Churchill, *Department of Chemical Engineering, University of Pennsylvania, Philadelphia, Pennsylvania 19104*

Professor Stuart L. Cooper, *Department of Chemical Engineering, University of Wisconsin, Madison, Wisconsin 53706*

Professor H. Ted Davis, *Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota 55455*

Professor Morton M. Denn, *Department of Chemical Engineering, University of California, Berkeley, Berkeley, California 94720*

Professor James M. Douglas, *Department of Chemical Engineering, University of Massachusetts, Amherst, Amherst, Massachusetts 01003*

Professor Thomas F. Edgar, *Department of Chemical Engineering, University of Texas, Austin, Texas 78712*

Professor Keith E. Gubbins, *Department of Chemical Engineering, Cornell University, Ithaca, New York 14853*

Dr. L. Louis Hegedus, *W.R. Grace & Company-Conn., Washington Research Center, Columbia, Maryland 21044*

Professor Arthur E. Humphrey, *Center for Molecular Bioscience and Biotechnology, Lehigh University, Bethlehem, Pennsylvania 18015*

Dr. Sheldon E. Isakoff, *Engineering Research and Development Division, DuPont Company, Newark, Delaware 19714-6090*

Dr. James R. Katzer, *Mobil Research and Development Corp., Paulsboro Research Laboratory, Paulsboro, New Jersey 08066*

Professor L. Gary Leal, *Department of Chemical and Nuclear Engineering, University of California, Santa Barbara, Santa Barbara, California 93106*

Professor Edwin N. Lightfoot, *Department of Chemical Engineering, University of Wisconsin, Madison, Wisconsin 53706*

Professor Dan Luss, *Department of Chemical Engineering, University of Houston, Houston, Texas 77004*

Professor Manfred Morari, *Department of Chemical Engineering, California Institute of Technology, Pasadena, California 91125*

Dr. J.R. Anthony Pearson, *Schlumberger Cambridge Research, Cambridge CB3 0EL, England*

Professor John M. Prausnitz, *Department of Chemical Engineering, University of California, Berkeley, Berkeley, California 94720*

Professor Channing R. Robertson, *Department of Chemical Engineering, Stanford University, Stanford, California 94305*

Professor Eli Ruckenstein, *Department of Chemical Engineering, State University of New York at Buffalo, Buffalo, New York 14260*

Professor William B. Russel, *Department of Chemical Engineering, Princeton University, Princeton, New Jersey 08544*

Professor T.W. Fraser Russell, *Department of Chemical Engineering, University of Illinois, Urbana, Illinois 61807*

Professor William R. Schowalter, *Dean of the School of Engineering, University of Illinois, Urbana, Illinois 61807*

Professor L.E. Scriven, *Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota 55455*

Professor John H. Seinfeld, *Department of Chemical Engineering, California Institute of Technology, Pasadena, California 91125*

Professor Reuel Shinnar, *Department of Chemical Engineering, City College of New York, New York, New York 10031*

Dr. Larry F. Thompson, *AT&T Bell Laboratories, Murray Hill, New Jersey 07974*

Professor Matthew V. Tirrell, *Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota 55455*

Professor Arthur W. Westerberg, *Engineering Design Research Center, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*

From the Department of Chemical Engineering at the Massachusetts Institute of Technology:

Professor Robert C. Armstrong
Professor Janos M. Beer
Professor Daniel Blankschtein
Professor Howard Brenner
Professor Robert A. Brown
Professor Robert E. Cohen
Professor Clark K. Colton
Professor Charles L. Cooney
Professor William M. Deen
Professor Lawrence B. Evans
Professor Karen K. Gleason
Professor T. Alan Hatton
Professor Hoyt T. Hottel
Professor Jack B. Howard
Professor Marcus Karel
Professor Mark A. Kramer
Professor Robert S. Langer
Professor John P. Longwell
Professor Herman P. Meissner
Professor Edward W. Merrill
Dr. C. Michael Mohr
Professor Adel F. Sarofim
Professor Charles N. Satterfield
Professor Herbert H. Sawin
Professor George Stephanopoulos
Professor Gregory Stephanopoulos
Dr. Maria-Flytzani Stephanopoulos
Professor Jefferson Tester
Professor Preetinder S. Virk
Professor Daniel I.C. Wang
Professor James Wei
Professor Glenn C. Williams

Professor Kenneth A. Smith, *Associate Provost and Vice President for Research*

Professor Gerald L. Wilson, *Dean of Engineering*

This Page Intentionally Left Blank

SECTION I
Historical Perspective and Overview

This Page Intentionally Left Blank

1

On the Emergence and Evolution of Chemical Engineering

L. E. Scriven
Department of Chemical Engineering and Materials Science
Institute of Technology
University of Minnesota
Minneapolis, Minnesota

I. Introduction

The Industrial Revolution opened technological continents that engineering soon radiated into from its military and civil origins. In the 19th century, while military and civil engineering themselves evolved rapidly, the needs of proliferating growth industries selected for vigorous mutations and hybrids that became established as mining and mechanical engineering. Electrical engineering followed, then metallurgical and chemical engineering, and later aeronautical engineering. From these early forms have descended today's major engineering species and the many related subspecies that fill narrower niches.

This paper deals with chemical engineering as a dynamic, evolving discipline and profession and highlights what I have learned, or surmised, or wondered about chemical engineering. Most of that was in three episodes. One was nearly 30 years ago when, with several years of industrial experience (pilot plants, design, research) and certification in the engineering science movement (interfacial phenomena, fluid mechanics, transport and reaction processes), I was readying to take over as lead professor in team teaching the first course in chemical engineering that undergraduates at

ADVANCES IN CHEMICAL ENGINEERING, VOL. 16