



# SOLVENT EXTRACTION and LIQUID MEMBRANES

Fundamentals and Applications  
in New Materials

Edited by  
Manuel Aguilar  
José Luis Cortina

 CRC Press  
Taylor & Francis Group

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and LIQUID  
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## *Dedication*

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*We dedicate this book to our esteemed colleague  
Abraham Warshawsky who passed away  
during the preparation of his chapter.*



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# Foreword

The International Solvent Extraction Conferences (ISECs) have been held every 3 years since 1971 in various countries around the world. The 1999 conference (ISEC99) was held in Barcelona, Spain. It was organized under the concept of being a “good soup,” so the best ingredients were combined both to have a good taste and to provide the best healthy nutrition to grow on solvent extraction fundamentals and applications. Under this concept the Organizing Committee decided to cook ISEC99 with a special ingredient by preceding the conference with a Summer School addressing the principles and applications of solvent extraction for the benefit of students and newcomers to this widely used technique in separation science. Although this idea of providing short courses on topics related to the main conference is an established practice elsewhere, this was the first time such a course was offered as part of an ISEC. The aim of the course organizers was to provide a fairly comprehensive overview of the fundamental and practical applications of solvent extraction, so they contacted a number of internationally recognized experts to talk about their particular fields of interest.

As a result, this publication represents a good recipe to feed the present and future newcomers to the solvent extraction community. Thus, the text presents the perspectives of solvent extraction (SX) in the twenty-first century, a new focus of fundamentals of solvent extraction, renewed topics of calculations on extraction equilibria, liquid membranes, and industrial applications. The book also introduces topics of new materials and solid sorbents for solvent extraction including the improved and developing topic of solvent impregnated resins. The content of this publication, presented with a tutorial focus, will benefit the understanding of solvent extraction for today’s practice.

**Michael Cox**  
**Manuel Valiente**



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# Preface

Following the activities of the first School in Solvent Extraction in Barcelona in 1986, and coincident with the 1999 International Solvent Extraction Conference (ISEC), the second International Solvent Extraction School (ISES) was held in Bellaterra, Spain. The school gathered senior and young scientists and engineers with the main idea of discussing the fundamentals and practice of solvent extraction (SX) and liquid membranes (LM) and to grow the new ideas and trends to contribute to the best understanding of applications of SX and LM in the future. The lecturers were leading experts in solvent extraction and liquid membranes.

One of the conclusions from the International Solvent Extraction Committee was to recommend to the authors of this book and the chairs of the ISES to produce a reference book by converting the lectures into written material.

The different uses of liquid–liquid extraction, liquid membranes, and solvent impregnated materials make the subject important for university students of chemistry, metallurgy, hydrometallurgy, and chemical and mineral processing technology. Some universities offer special courses on separation processes in which those techniques are minor topics in more comprehensive courses. Laboratory experiments on liquid–liquid and liquid membranes are common in chemical and mineral processing engineering curricula. Because of the breadth of the subject, the treatment in such courses is often scarce, and more comprehensive text is difficult to find in a form suitable for use directly with students.

To meet this demand, and to answer the request of the ISEC, we initiated this project to develop a simple text suitable not only for students but also for scientists and engineers in the field. However, no single scientist or engineer can be an expert in all parts of the field. Therefore, it seemed that the best idea was to develop this book as a joint project among many expert authors, each of whom has in many cases years of experience in research, teaching, or industrial development. The result is an international book at a high scientific and technical level.

In this context, we would like to point out that this book represents the effort to bring together the key important topics dealing with thermodynamics, kinetics, interfacial behavior, process and plant applications, including chemical and engineering aspects of new extraction systems based on synthetic materials by the leading experts at the school. The book is directed toward third- to fourth-year undergraduate and postgraduate chemistry and chemical engineering students as well as toward researchers and developers in the chemical industry, the mining and mineral processing industry, and the waste treatment industry. The book is also intended for chemical, metallurgical, mineral processing, and waste treatment engineers who already use this technique but have a desire to understand better or to solve existing process problems. Furthermore, the book should be useful for researchers in solvent extraction who wish to learn about its applications in areas other than their own.

So, after an introduction to SX and LM in the perspective of the twenty-first century (Chapter 1), the following two chapters (Chapters 2 and 3) present the physical principles (thermodynamics and kinetics) in SX processes and the tools for computation of the equilibrium and kinetic parameters. They are followed by three chapters of various industrial applications and process experience on SX and LM (Chapters 4 through 6), including optimization and modeling tools. The three final chapters (Chapters 7 through 9) focus on new materials in SX and LM science and technology, including functionalized organic and inorganic solid sorbents and solid impregnated sorbents, indicating the research frontiers and future developments in new materials.

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We the editors want to express our gratitude to the contributors, who made this book possible through their helpful suggestions and extensive efforts. Professor Michael Cox, Professor Josef Havel, Dr. Karel Jeřábek, Professor Vadim Korovin, Dr. Anil Kumar Pabby, Professor Immaculada Ortiz Uribe, Professor Angel Irabien, Dr. Jun S. Lee, Dr. Sergio Gomez Salazar, Professor Ana María Sastre, Dr. Yuri Shestak, Dr. Kathryn C. Sole, Professor Lawrence L. Tavlarides, Professor Hitoshi Watarai, Dr. Yuri Pogorelov, and Professor Abraham Warshawsky worked hard and successfully on their chapters and provided us much valuable help. The success of this book belongs to our distinguished authors.

We thank Nita Lekhwani and David Russell on the initial editorial staff at Marcel Dekker and to David Fausel and Barbara Glunn and the new staff at Taylor & Francis for their invaluable editorial assistance.



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# About the Editors

**Manuel Aguilar, Ph.D.**, was born in Spain in 1943. He achieved his licentiate studies in chemistry at the University of La Laguna in Tenerife, Spain with a main focus in analytical chemistry. From 1965 to 1969 he was assistant lecturer at the University de Los Andes in Venezuela. From 1970 through 1976 he was research assistant at the Royal Institute of Technology in Stockholm, Sweden, where he completed his Ph.D. studies under the supervision of Professor E. Hogfeldt. In 1976 he returned to Spain and was assistant professor of inorganic and analytical chemistry at the Universidad Autonoma in Barcelona. Since 1977, he has been professor of chemistry in the Department of Chemical Engineering at the Universitat Politècnica de Catalunya. Dr. Aguilar has been active in chemical research for many years, with a main interest in the field of ionic equilibrium and solvent extraction, and he has published more than 100 papers in this field. He has also been involved in the field of education, in which he has published different books and compendia on ionic equilibrium and has directed two international solvent extraction schools and diverse postgraduate courses in Spain and South America. Dr. Aguilar has been active in equilibrium analysis and computers, participating in the production of various programs for treatment of hydrochemical systems and in the program of virtual laboratory for experimental laboratory teaching for basic chemistry courses.

**José Luis Cortina, Ph.D.**, was born in Ligüerrre de Cinca, Spain, in 1964. He has been professor of chemical engineering at the Universitat Politècnica de Catalunya in Barcelona, Spain, since 2001 and project research technical director at the Water Technology Center (CETaqua) since 2007. Dr. Cortina received B.Sc., D.Sc., and Ph.D. degrees from the University of Barcelona in Spain. He has been a visiting scientist at the Polymer Chemistry Department at the Weizmann Institute of Science in Rehovot, Israel, and at the Center for Process Analytical Chemistry at the University of Washington in Seattle at the Fiber Optical Chemical Laboratory. Dr. Cortina has been active in chemical technology research for many years, with a main interest in the field of treatment and separation processes for industrial and environmental applications using solvent extraction and ion exchange, and he has published more than 70 papers in this field. During the last several years his research has been centered on the treatment technologies for soil and groundwater remediation. He has been a member of the International Committee on Ion Exchange since 2004.



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# 1 Liquid–Liquid Extraction and Liquid Membranes in the Perspective of the Twenty-First Century

*Michael Cox*

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