



Treatise on  
Process Metallurgy

# Volume 2: Process Phenomena

Editor-in-Chief  
Seshadri Seetharaman

Co-Editors-in-Chief  
Alexander McLean  
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VOLUME 2

# TREATISE ON PROCESS METALLURGY

## Process Phenomena

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VOLUME 2

TREATISE ON  
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This book is dedicated to the Memory of former Chief Co-editor Professor Masanori Iwase, Kyoto University, Japan



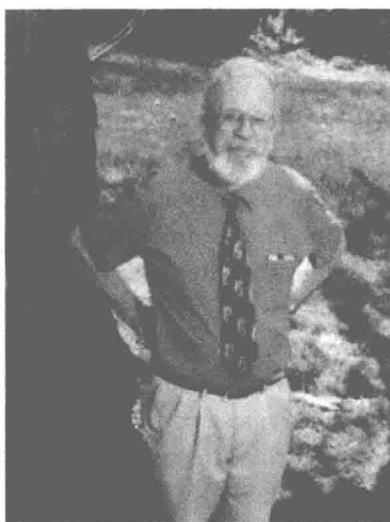
January 10, 1948 to September 29, 2011

**Professor Masanori Iwase**, known to his friends as “Masa,” was a beacon of knowledge with respect to the thermochemistry of metallurgical systems. He graduated from Kyoto University with his Bachelor’s Degree in 1971, obtained his Master’s Degree in 1973, and his Doctor of Engineering Degree in 1979, by which time he had already published 14 papers. From 1979 through 1981, he was a Post-Doctoral Fellow with Professor Alexander McLean’s Group within the Department of Metallurgy and Materials Science at the University of Toronto. He was appointed Associate Professor in the Department of Ferrous Metallurgy, now the Department of Energy Science and Technology, at Kyoto University in 1985 and became Full Professor in 1996. On several occasions he served as Department Chair. He held visiting Professorships at the University of Toronto, the University of New South Wales, and the Royal Institute of Science and Technology in Stockholm and was granted the title of Honorable Professor by North Eastern University in China. He was a member of the International Editorial Board of “Transactions of the Iron and Steel Society of AIME” and “High Temperature Materials and Processes.” He presented numerous courses on metallurgical chemistry to steelmaking engineers and researchers in Japan and countries overseas. He published over 200 technical papers and 2 books and obtained over 30 patents. He had a strong interest in the development of electrochemical sensors for the measurement of the chemical potentials of species in

molten copper as well as in molten iron and steel and steelmaking slags. He was the inventor of a “Silicon Sensor” and an “FeO Activity Determinator” both of which are manufactured commercially and currently utilized by a number of steel companies in different parts of the world. In the area of slags, he made a number of major contributions by combining excellent experimental measurements with a sound knowledge of thermodynamics. During his later years, he was deeply engaged in the environmental problems associated with the metallurgical industries and conducted studies on waste incineration in the blast furnace. His research findings on the reduction of steelmaking slag volume and fluorspar consumption have been applied within several steel plants in Japan. In recognition of his many achievements, he received the Silver Medal Award from the Japan Institute of Metals in 1991 and the Nishiyama Memorial Award from the Iron and Steel Institute of Japan in 1993. During his last days, he was Co-Editor-in-Chief for this Treatise on Process Metallurgy. May it serve as a tribute to his numerous contributions.

**David R. Gaskell, (1940 – 2013)**

**A Memorial Tribute**



**David Robert Gaskell** was born in Glasgow, Scotland where he attended Glasgow University and The Royal College of Science and Technology. He received his B.Sc. and A.R.C.S.T. with First Class Honors in Metallurgy and Technical Chemistry in 1962 after which he spent two years working in England with the chemical industry. He married Sheena Morrow in 1964 and they had three children, Sarah, Claire and Drew. Shortly after their marriage they immigrated to Hamilton, Canada where David

conducted graduate studies at McMaster University under the supervision of Professors R. G. Ward and A. McLean. His Ph.D. degree was awarded in 1967 with a thesis entitled: "The Densities of Liquid Silicates Containing Iron Oxide at 1410°C." Following his Doctoral studies, David joined the University of Pennsylvania as an Assistant Professor where he worked closely with Professor Geoff Belton. In 1982 he moved to Purdue University as a Professor of Metallurgical Engineering. During his career, Dr. Gaskell served as a Visiting Professor working with Dr. Charles Masson at the Atlantic Regional Laboratory of the National Research Council of Canada in Halifax, Nova Scotia (1975–1976) and as a Visiting Professor at the G.C. Williams Co-operative Research Centre for Extraction Metallurgy at the University of Melbourne (1995).

Professor Gaskell was gifted with an exceptional combination of intellect and curiosity and particularly enjoyed his teaching, his research and his discussions with students. He served as thesis advisor for numerous graduate students as well as faculty mentor for dozens of undergraduate student projects. He was the recipient on several occasions of the Schuhmann Best Teaching Award in Materials Engineering. Dr. Gaskell was a prolific writer with numerous publications in journals and conference proceedings. He was known internationally for his classic textbooks "Introduction to Metallurgical Thermodynamics", "An Introduction to the Thermodynamics of Materials", and "An Introduction to Transport Phenomena in Materials Engineering". He was also involved in professional activities, including the Metallurgical Society of AIME, Alpha Sigma Mu (President, 1985–1986) and the Iron and Steel Society Transactions International Advisory Board. In 1977 Dr. Gaskell was named a Distinguished Alumnus of McMaster University and in 2000 was the recipient of the John F. Elliott Memorial Lectureship Award from the Iron and Steel Society of AIME. At the time of his death, David was serving as one of four distinguished reviewers for this Treatise on Process Metallurgy. He will be remembered with great fondness by many friends around the world not only for his intellectual achievements, and they were many, but also for his laughter, his sense of fun and his ability to play the bagpipes.





## PREFACE

This book, “Treatise on Process Metallurgy”, consisting of three volumes, aims to provide a comprehensive work that is intended to be a reference source for industrial and academic researchers and to provide material for teachers of process metallurgy. This effort was inspired by the successful series on Treatise for Physical Metallurgy by Robert Cahn and Peter Haasen published by Elsevier that has become a standard text found on the shelves of most academics and industrial metallurgists. We hope to mirror this success in the field of Process Metallurgy. This work is intended to provide the most pertinent contemporary developments within process metallurgy and offer a single complete collection of information on metal extraction processes from atomic level to industrial production.

The book is an important milestone in the development of technologies in metal extraction and refining that have evolved over the past millennia. After humans discovered fire and started using this energy source for metal extraction, the field of process metallurgy has grown from an art to an area of advanced technology. Growth has been significant over the past 200 years, and over the past five decades it has been exponential. Although there are books available describing well-defined aspects of the subject, it is rather surprising that we do not yet have a comprehensive volume which covers the broad spectrum of topics that constitute “process metallurgy”. The current endeavor is aimed at addressing this deficiency.

An important phenomenon that has happened over the years is the separation of the subject of process metallurgy into ferrous and non-ferrous extraction processes. While the underlying principles are the same for both areas, the enormous impact of iron and steel on human civilization has given ferrous metallurgy a special place. Process design in the case of non-ferrous metals such as copper, lead and zinc, has often lagged behind that in iron and steelmaking. Over the course of time, the synergistic effects of the interactions between these two major areas of process metallurgy were lost. The present work is designed to bridge this knowledge gap.

Another development, which has manifested itself especially in Europe, is the division between “Theoretical Process Metallurgy” and “Applied Process Metallurgy”. Fortunately, this division is not encountered to the same extent within Northern America. This division between theory and practice can be attributed in large part to the eagerness of industry to solve their immediate problems within tightly defined conditions and within the shortest possible time frame. As a consequence, in the absence of proper theoretical foundations, the solutions tend to be empirical in character and of limited applicability. In this context, it is worth emphasizing that no solution is generally applicable without proper theory, and no theory is particularly helpful, if it cannot be applied.

Another objective of this Treatise therefore, is to provide a bridge between fundamental concepts and practical applications.

The current work aims to present a comprehensive overview of the broad field of process metallurgy, bridging the above-mentioned gaps. It begins with a historical perspective of the development of metal extraction processes from the earliest of times to today's state-of-the art. There are thirteen chapters with about twenty five editors and eighty specialists, who have contributed to particular subject areas within which they

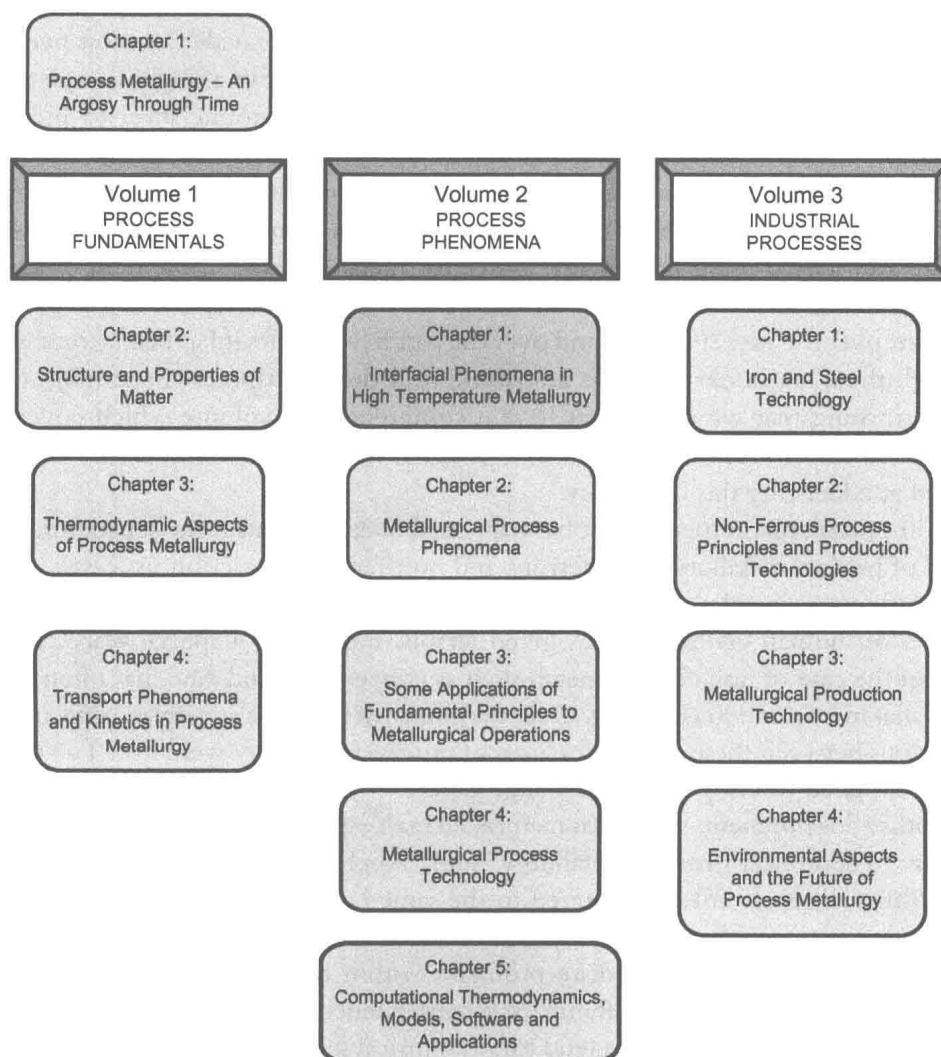


Figure. The flowchart of chapters in the Treatise. (For color version of this figure, the reader is referred to the online version of this chapter.)

are recognized experts. The development of the subject through these chapters is outlined in the following flow-chart.

The book is divided into three main streams. Following the first chapter which presents a birds-eye view of the history of metal extraction from stone-age to modern times, Chapters 2–4 present the process fundamentals. The second group of chapters on Process Phenomena, *viz.* Chapters 1–5, link the micro-modeling of process phenomena to macro-modeling of industrial processes, reactor technologies and computational models for process simulations. The third group deals with Industrial Processes. Chapters 1 and 2 present details of modern industrial practice for the extraction and refining of ferrous and non-ferrous metals respectively. Chapter 3 describes the design of metallurgical plants including the logistics, economics, intellectual property rights, upscaling and some case studies. The last chapter, Chapter 4, addresses the environmental problems existing today and the directions we should take for a better future. All chapters use the same nomenclature and symbols so that the reader can more readily see the links between related areas.

As the subject area is broad, the Treatise was designed as a multi-author work. The editors were asked to choose their contributors so that one red-thread passed through any particular chapter. While the potential problem of different schools of thought in each area had to be resolved, the editors took care that, where necessary, other schools of thought were presented, without causing confusion. The editors and contributors are from all parts of the world and formed a virtual forum of noted metallurgists who have worked in harmony for a period of more than two years. As the Board of Editors-in-Chief, it has been a distinct privilege to bring these leading members of the process metallurgy community together. We were also fortunate to obtain four world-famous metallurgists to review the chapters, so that their views could be implemented before the manuscripts were printed.

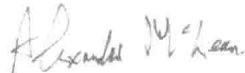
The publication of this Treatise is timely, as many of the present younger generation do not perceive Process Metallurgy as a “high-tech” area compared to more recent technologies, such as electronic-, bio- and nano-materials. The work is intended to show to the coming generations that Process Metallurgy is a continuously evolving subject area, like a flowing river, collecting tributaries from adjoining areas: sensor developments, signal processing, physical and mathematical modeling, automation, robotics and business management. It can be said, without exaggeration, that Process Metallurgy has had a major impact on the development of human civilization, and will continue to exert a powerful influence on metals production and the generation of advanced materials, for many decades to come.

The Board of Editors-in Chief expresses its deep gratitude to Staff Members at Elsevier who proposed the concept of a treatise on Process Metallurgy and who encouraged and assisted it throughout this activity. The generous support of Chief Editor, Seshadri Seetharaman, by the Swedish Steel Producers Association is also greatly

appreciated. Finally, the Editors-in-Chief express their sincere thanks to the chapter editors, contributors and reviewers, for providing their valuable time and expertise, in order to bring this endeavor to a successful conclusion.



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Alexander McLean  
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Roderick Guthrie  
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Seetharaman Sridhar  
Warwick

## EDITOR IN CHIEF



**Seshadri Seetharaman** received his Ph.D. degree in Metallurgy from Indian Institute of Science, Bangalore, India, in the year 1971. He joined the Royal Institute of Technology, Stockholm, in 1973 as Senior Research Associate and became Associate Professor in 1981. Dr. Seetharaman was installed in the Chair of Theoretical Metallurgy in 1990 and he retired from this position at the end of 2010. Professor Seetharaman has about 350 peer-reviewed publications in leading journals in Metallurgy, about 150 conference presentations, and 10 patents. His major scientific interests are the fundamentals of Process Metallurgy that covers thermodynamics, transport phenomena, thermophysical properties of high temperature systems, and interfacial phenomena. He was also involved in the teaching of the above subjects.

Professor Seshadri Seetharaman has been nominated eight times as the best teacher in Materials Design teaching program at the Royal Institute of Technology. He has been awarded the President's Award in 1994 for meritorious contributions in teaching. He was selected as the best teacher of the Royal Institute of Technology in 2004.

Professor Seshadri Seetharaman has been awarded the Brimacombe Prize for the year 2010. He is an Honorary member of the Iron and Steel Institute of Japan, Honorary doctor at the Aalto University in Finland, Honorary Professor at the Metallurgical Academy of Ukraine as well as at The University of Science and Technology Beijing. He also received the Distinguished Alumni Award of the Indian Institute of Science, Bangalore, in the year 2013.

## CO-EDITORS-IN-CHIEF



**Alexander McLean**

Following graduation with degrees in Applied Chemistry and Metallurgy from the Royal College of Science and Technology and the University of Glasgow, Dr. McLean spent 5 years at McMaster University before moving to Jones and Laughlin Steel Corporation in Pittsburgh. He joined the University of Toronto in 1970, and in 1984 the Ferrous Metallurgy Research Group was formed with Professor McLean as Director. He served as Department Chair from 1992 through 1997 and was appointed Professor Emeritus in 2002. He is an Honorary Member and elected Fellow of several organizations including AIME, The Iron and Steel Institute of Japan, the Royal Society of Canada, and the Canadian Academy of Engineering. He is a recipient of the Queen Elizabeth II Diamond Jubilee Medal and received Honorary Doctorates from the University of Miskolc and the University of Strathclyde. He has published extensively in the areas of iron and steelmaking and materials processing.



**Roderick Guthrie**

**Roderick I.L. Guthrie**, Ph.D. (Imperial College), ARSM, Eng., is the Macdonald Professor of Metallurgy and Director of the McGill Metals Processing Centre. An Honorary Member of ISIJ, Distinguished Member of AIST, Fellow of the Canadian Institute of Mining and Metallurgy, Fellow of the Royal Society of Canada, and Fellow of the Canadian Academy of Engineering, he is the author of two text books concerning *Engineering in Process Metallurgy* and *The Physical Properties of Liquid Metals*. The winner of the 2006 Killam Prize for Engineering, he was co-inventor of the successful LiMCA process for detecting inclusions in liquid metals, and also of the HSBC process for casting steel and aluminum alloy sheets. As a researcher, he has been keenly interested in the application of fluid flow, heat, and mass transfer phenomena in the description of metallurgical processes. A long-time consultant to the steel industry, Dr. Guthrie has worked in all segments of an integrated steelplant, from blast furnaces through steelmaking and hot rolling mills, to annealing and finishing lines.





**Seetharaman Sridhar** is currently the Tata Steel/RAEng Joint Chair for Research into Low Carbon Materials Technology. He was until recently the POSCO Professor of Steelmaking at Carnegie Mellon University and the co-director of the Industry–University Consortium, Center for Iron and Steelmaking Research (CISR) of which Tata is a member. He received his Ph.D. from the Massachusetts Institute of Technology and his undergraduate degree from the Royal Institute of Technology in Sweden.

His research and teaching interests lie in the physical chemistry of metal processing. He has published over 125 journal papers in the areas of secondary refining, casting and mold slags, coal gasification, oxidation, and hot-shortness. He has received the following best paper awards: Marcus Grossman Award from ASM, the Herty Award from ISS, The Spriggs Phase Equilibria Award from ACERS, and the Jerry Silver Award from AIST. He has also received the Friedrich Wilhelm Bessel Research Prize from the Alexander Von Humboldt Foundation and the NSF Career Award, both for his general contributions in research. As a teacher, he was recognized by the Benjamin Teare Teaching Award by Carnegie Institute of Technology, the Philbrook Prize by the MSE Department at CMU, and he was the recipient of the 2011 J.F. Elliott Lecturer Award for AIST. He is the editor for *AIST Transactions* and an associate editor for *Metallurgical and Metals Transactions A, B, and E*. He is also on the International Advisory Board for *Steel Research International* and *ISIJ International*.