

Energy Technology 2016

Carbon Dioxide Management and Other Technologies

Edited by

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Energy Technology 2016

Carbon Dioxide Management and Other Technologies

Proceedings of the
**Energy Technologies and Carbon Dioxide
Management Symposium,**
sponsored by the Energy Committee of the
Extraction & Processing Division (EPD) and
the Light Metals Division (LMD) of The Minerals, Metals &
Materials Society (TMS).

Additional papers have been contributed
by the following symposia:

High-Temperature Systems for Energy Conversion and Storage

Sponsored by the Energy Conversion and
Storage Committee of the Functional
Materials Division (FMD)

All symposia were held during

TMS2016
145th Annual Meeting & Exhibition

FEBRUARY 14-18 DOWNTOWN NASHVILLE,
TENNESSEE MUSIC CITY CENTER

Edited by:

**Li Li, Donna Post Guillen, Neale R. Neelameggham, Lei Zhang,
Jingxi Zhu, Xuan Liu, Soumendra N. Basu, Nawshad Haque,
Tao Wang, Dirk E. Verhulst, and Amit Pandey**

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Library of Congress Cataloging-in-Publication Data is available.

ISBN 978-1-119-22577-5

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

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145th Annual Meeting & Exhibition

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New proceedings volumes from the TMS2016 Annual Meeting:

- 7th International Symposium on High-Temperature Metallurgical Processing
- CFD Modeling and Simulation in Materials Processing 2016
- Characterization of Minerals, Metals, and Materials 2016
- Energy Technology 2016: Carbon Dioxide Management and Other Technologies
- EPD Congress 2016
- Light Metals 2016
- Magnesium Technology 2016
- Rare Metal Technology 2016
- REWAS 2016
- Shape Casting: 6th International Symposium
- TMS 2016 Supplemental Proceedings

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PREFACE

This volume is a collection of papers primarily from the Energy Technologies and Carbon Dioxide Management Symposium presented at the TMS 2016 Annual Meeting & Exhibition in Nashville, Tennessee. Selected papers from the symposium of High-Temperature Systems for Energy Conversion and Storage are also included. This book is focused on addressing the issues, complexities, and challenges relating to mass and energy flow in the chemical and process engineering industry and impacts to the environment.

Topics on CO₂ sequestration and reduction in greenhouse gas emissions from process engineering and materials for clean energy are covered. Papers addressing sustainable technologies in extractive metallurgy, materials processing, and manufacturing industries with reduced energy consumption and CO₂ emission are also included, as well as those on industrial energy efficient technologies including innovative ore beneficiation, smelting technologies, recycling, and waste heat recovery. The book also carries contributions from all areas of non-nuclear and non-traditional energy sources, including renewable energy sources such as solar, wind, biomass, etc. The book also emphasizes novel mineral beneficiation, processing, and extraction techniques leading to waste minimization of critical rare-earth materials utilized in energy systems (e.g., magnets, display and lighting devices).

This book provides a reference for materials scientists/engineers and metallurgists to stay abreast of innovative energy technologies and novel energy materials processing. We hope this book will be helpful in your investigation of sustainability and energy efficiency related issues. We appreciate the support from the TMS Energy Committee and those who have helped us during the production of this book.

Energy Technologies and Carbon Dioxide Management Symposium Organizers:

Li Li

Donna Post Guillen

Neale R. Neelameggham

Lei Zhang

Jingxi Zhu

Xuan Liu

Soumendra N. Basu

Nawshad Haque

Tao Wang

Dirk E. Verhulst

EDITORS



Li Li is an Advisory Scientist in Semiconductor Research & Development Center in IBM. He served as the Senior Research Associate in Department of Materials Science and Engineering of Cornell University between 2013 and 2014. He received his Ph.D. degree in Materials Science and Engineering from Carnegie Mellon University (CMU) in 2012; two master degrees from CMU and Harbin Institute of Technology (HIT); and a bachelor degree from HIT. Dr. Li is a talented materials scientist with expertise in metallurgical and metal oxide materials processing, as well as their applications in solar energy conversion, energy

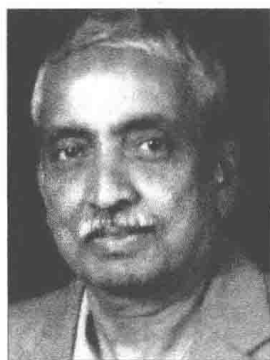
storage, microelectronics fabrications, etc. He has authored more than 40 technical journal papers and is a Key Reader for *Metallurgical and Materials Transactions*. He has frequently organized and chaired symposia at TMS and MRS annual meetings (MRS 2012; TMS 2013, 2014, and 2015) and served as the board chair for the Best Paper Award Sub-committee of the TMS Energy Committee. Because of his contribution to materials science, he was the recipient of 2015 EPD Young Leaders Professional Development Award and was selected to represent TMS at the Emerging Leaders Alliance Conference in 2014. His paper published in RSC journal *Nanoscale* was selected as one of the “Top 20 Most Accessed Articles” in 2014.



Donna Post Guillen is a Distinguished Research Engineer and Group Lead in the Advanced Process & Decision Systems Department at the Idaho National Laboratory (INL). Dr. Guillen earned a B.S. in Mechanical Engineering from Rutgers University, an M.S. in Aeronautics from Caltech, and a Ph.D. in Engineering and Applied Science from Idaho State University. She is a registered Professional Engineer in Mechanical Engineering in the State of Idaho. She has served as Principal Investigator for several multidisciplinary research projects on the topics of waste heat recovery, synthetic fuels production, nuclear reactor

fuels and materials experiments, and waste glass processing. The focus of her research is on multiphase computational fluid dynamics (CFD) and thermal hydraulics for sustainable energy technologies. She applies numerical modeling techniques to provide understanding of a wide variety of complex systems, from greenhouse gas generation/sequestration for dairies to waste vitrification for the Hanford Waste Treatment Plant. Dr. Guillen is especially interested in materials as they relate to heat transfer and fluid flow phenomena. She is experienced with irradiation testing and thermal hydraulic analysis for irradiation experiments and serves as Principal

Investigator/Technical Lead for the Nuclear Science User Facilities (NSUF) Program. She is the lead inventor on two patents related to the development of a new composite material to produce a fast reactor environment within a pressurized water reactor, such as ATR. She actively mentors students, routinely chairs and organizes technical meetings for professional societies, serves in leadership capacity for the American Nuclear Society (Thermal Hydraulics Executive and Program Committees, Book Publishing Committee), The Minerals, Metals & Materials Society (Energy Committee Chair), and the American Society of Mechanical Engineers (Thermal Hydraulics and CFD Studies Track Chair), provides subject matter reviews for proposals and technical manuscripts, has published more than 100 conference papers, reports and journal articles, and written/edited three books.



Neale R. Neelameggham is ‘The Guru’ at IND LLC, involved in technology marketing and international consulting in the field of light metals and associated chemicals (boron, magnesium, titanium, lithium and alkali metals), rare earth elements, battery and energy technologies, etc. He was a visiting expert at Beihang University of Aeronautics and Astronautics, Beijing, China. He was a plenary speaker at the Light Metal Symposium in South Africa – on low carbon dioxide emission processes for magnesium.

He has over 38 years of expertise in magnesium production and was involved in process development of its startup company NL Magnesium through to the present US Magnesium LLC, UT from where he retired in 2011. He is developing thiometallurgical processes – a new concept of using sulfur as the reductant and/or fuel. He has published a heat transfer model for global anthropogenic warming based on thermal emissions independent of energy conversion source.

Dr. Neelameggham holds 16 patents and patent applications, and has published several technical papers. He has served in the Magnesium Committee of LMD since its inception in 2000, chaired it in 2005, and in 2007 he was made a permanent co-organizer for the Magnesium Symposium. He has been a member of the Reactive Metals Committee, Recycling Committee, Titanium Committee, and Programming Committee Representative of LMD and the LMD Council.

Dr. Neelameggham was the inaugural chair when the LMD and EPD created the Energy Committee in 2008, and has been a co-editor of the Energy Technology proceedings through the present. He received the LMD Distinguished Service Award in 2010. While he was the chair of Hydro- & Electrometallurgy Committee he initiated the Rare Metal Technology symposium in 2014. He is co-editor for the

symposia proceedings *Magnesium Technology 2016*, *Energy Technology 2016*, *Rare Metal Technology 2016*, and the light metals section of *REWAS 2016*.



Lei Zhang obtained her Ph.D. degree in Materials Science and Engineering from Michigan Technological University in 2011 and is currently an Assistant Professor in the department of Mechanical Engineering at the University of Alaska Fairbanks (UAF). Prior to joining UAF in 2013, Dr. Zhang worked as a postdoctoral associate in the department of Chemical and Biomolecular Engineering at the University of Pennsylvania. Her research is focused on the design and investigation of the properties of porous materials and nanostructure-based films for energy and environmental applications. Her current research mainly focuses on the synthesis of metal-organic frameworks (MOFs) and MOF-based nanocomposites, and the manipulation of their properties and applications in gas storage, separation, and water treatment, development and characterization of anti-corrosion coatings, and characterization of magnesium alloys used for biodegradable implants.



Jingxi Zhu is currently an Assistant Professor of the SYSU-CMU Joint Institute of Engineering of Sun Yat-sen University (SYSU) located in Guangzhou, China. She received her B.E. degree in Metallurgical Engineering from University of Science and Technology Beijing, China in 2003 and an M.E degree in Metallurgical Physical Chemistry from Central Iron & Steel Research Institute, Beijing, China in 2006. She earned a M.Sc. degree and Ph.D. degree in Materials Science and Engineering from Carnegie Mellon University (CMU) in 2009 and 2011, respectively.

During her postdoctoral research associate appointment at CMU, she has been a main participant in a number of research projects in collaboration with CMU's Center for Iron and Steel Research and the Data Storage System Center as well as National Energy Technology Laboratory of the U.S. DOE and the DARPA, U.S. Army. Her research interests include novel energy application-related electronic devices enabled by a wide range of functional materials, including electronic, magnetic and multiferroic metals, and ceramics. She also specializes in advanced characterization with electron microscopy and micro/nano fabrication processing techniques.

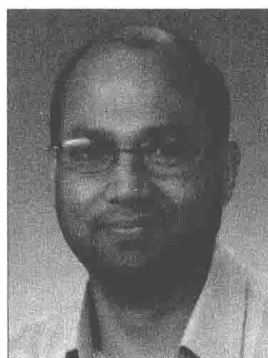


Xuan Liu is currently an applications scientist working for NanoMEGAS USA. She received her B.E. degree in Chemical Engineering at Xi'an Jiaotong University, China in 2009. She received her M.Sc. and Ph.D. degrees in Materials Science and Engineering, Carnegie Mellon University in 2011 and 2014, respectively.

Xuan Liu's Ph.D. research in Carnegie Mellon University focused on high throughput precession electron diffraction based metrology of nanocrystalline materials. Her current work includes orientation, phase, and strain mapping of ultrafine featured materials with small spatial resolution and high sensitivity. She has been in collaboration with many research and industrial partners including Semiconductor Research Corporation (SRC), Columbia University, and Los Alamos National Laboratory. She has published more than 25 articles in several publications, including *Acta Materialia*, *Scripta Materialia*, and *Scientific Report* (Nature publishing group).



Soumendra N. Basu is a professor of mechanical engineering and the Associate Division Head of the Division of Materials Science and Engineering at Boston University. Professor Basu is also a member of Photonics Center at Boston University. His research interests include high-temperature coatings; thin films for energy, photonic, and electronic applications; processing of optical fibers for mid-IR transmission, environmental degradation of materials at elevated temperatures; structure and stability of interfaces; and characterization of structure and phase transformations in materials using electron microscopy techniques. After receiving his Ph.D. in Materials Science and Engineering from MIT, Professor Basu was a postdoctoral researcher at Los Alamos National Laboratory, prior to joining Boston University. Professor Basu has 125 peer-reviewed publications. He is the Principal Editor for the book *Surface Engineering 2004 – Fundamentals and Applications*. Professor Basu is a member of a team that won the silver medal at the 2014 TECO Green Tech International Contest in Taiwan. He has consulted with several companies on a variety of materials issues, and has been on the Organizing/International Advisory Committees of several international conferences. He has also delivered numerous invited presentations at international conferences including keynote and plenary talks.



Nawshad Haque is a Senior Scientist and Team Leader at the Australian national research agency CSIRO. He is leading a range of projects that evaluates technology for mining industries for saving energy, water, and operating costs. Dr. Haque joined CSIRO Mineral Resources as a Research Scientist (Process Modelling) in 2007. His current research focuses on process, project, and technology evaluation applying life cycle assessment (LCA) methodology and techno-economic capabilities using various tools, software, and databases. He has contributed to developing a number of novel technologies and flowsheets for 'Mine to Metal' production at CSIRO. His publications and industry reports are widely used internally and externally and assist in decision making both in Australia and internationally. Dr. Haque completed his doctorate with the Department of Chemical Engineering at the University of Sydney on process modeling, simulation, and optimization in 2002. He commenced work as a materials scientist at New Zealand Forest Research Institute (Scion) and later seconded to CSIRO at Clayton to conduct research on drying process simulation and technology evaluation for industries. He is an active leader in professional societies such as TMS, the Australian Life Cycle Assessment Society, and AusIMM for events such as conferences and meetings. Dr. Haque supervised undergraduate and Ph.D. students. He has coordinated and offered mineral processing and life cycle assessment courses and workshops at universities. He has a number of international collaborations with the universities and publicly funded research laboratories on mineral and metal processing and sustainability.



Tao Wang is currently Castrip Metallurgical Engineer at Nucor Steel. He is one of the lead engineers in process and product research and development areas. Dr. Wang's current focus is to develop and modify a novel thin strip casting technology which uses up to 90% less energy than conventional casting methods to process liquid steel into hot rolled steel sheets. Dr. Wang has rich experience in metallurgical thermodynamics, thermal energy storage and transfer, steelmaking, metal solidification and casting, and metal corrosion. Dr. Wang obtained his Ph.D and M.S. from the University of Alabama; and he received his B.S. from Xi'an Jiao Tong University in China. In his areas of research, Dr. Wang has published multiple papers and patents which led to breakthroughs in thermodynamic modeling, high efficiency thermal energy transfer medium development, and thin strip metal casting technology.

Dr. Wang received the 2013 LMD Best Energy Paper Award - Student and is the TMS 2016 EPD Young Leaders Professional Development Award winner. Dr. Wang also serves on several technical committees including the Energy Committee and the Pyrometallurgy Committee in TMS; and the Metallurgy-Steelmaking & Casting Technology Committee and the Continuous Casting Technology Committee, Southeast Chapter in AIST.



Dirk E. Verhulst spent the last 40 years in practical process-metallurgy research on both sides of the Atlantic, bringing a number of projects from the laboratory to the pilot scale, and a few to industrial implementation. He is presently an independent consultant in process metallurgy and energy efficiency.

Until the end of 2008, he was Director of Research at Altairnano in Reno, Nevada. He participated in the development of the Altair Lithium-ion Battery, and was involved in the design and procurement of the manufacturing

plant for the ceramic materials. Over the period 2003-2008, he put a lot of effort into the Altair Hydrochloride TiO_2 Pigment Process and the operation of its pilot plant. The complex flow sheet included both hydrometallurgical and pyrometallurgical steps. Optimization of energy use was a key factor to make this new approach competitive.

From 1995 to 2000, Verhulst worked as Senior Development Engineer in BHP's Center for Minerals Technology at the same location in Reno. It is at BHP that the development of the Hydrochloride TiO_2 pigment process was initiated. Other BHP projects included novel processes for nickel, cobalt, zinc and copper.

Prior to 1995, he worked for 17 years in the research department of Umicore in Hoboken, Belgium. He was active in lead refining and in the hydrometallurgy of minor metals (indium, tellurium, selenium), but was mostly involved in the introduction of electric furnaces in lead smelting and slag-cleaning. He tackled mathematical models and lab-scale experiments, ran pilot plants and participated in the start-up of industrial operations.

Dr. Verhulst has a doctor of engineering science degree in extractive metallurgy from Columbia University, and a chemical engineering degree from the Free University of Brussels. He wrote and presented publications in the areas of hydrometallurgy, pyrometallurgy, nanomaterials and environmental science. He holds several patents and patent applications.

HIGH-TEMPERATURE SYSTEMS FOR ENERGY CONVERSION AND STORAGE



Amit Pandey is working as a development lead in reliability at Rolls Royce LG Fuel Cell Systems, Inc., in Ohio. He started working in the field of thermal barrier coatings at Johns Hopkins University as a postdoctoral fellow in the department of mechanical engineering. Later he was awarded the research fellowship at the Oak Ridge National Laboratory in the Materials Science and Technology Division. During his time at ORNL he used microscale testing techniques to study the thermo-mechanical response of porous and microcracked ceramics systems.

Dr. Pandey has published aggressively and has received various awards showing his academic excellence and exemplary leadership ability. He has also been involved as an organizing chair and co-chair of symposia for high temperature materials in particular in the area of functional ceramics for energy conversion and storage. Dr. Pandey received his B.S. (2003) in mining engineering from Indian Institute of Technology (IIT- BHU) Varanasi, India. He later received his M.S. (2005) in civil engineering from University of Arizona and Ph.D. (2009) in mechanical engineering from University of Maryland.

SESSION CHAIRS

ENERGY TECHNOLOGIES AND CARBON DIOXIDE MANAGEMENT

Session I

Neale R. Neelameggham, IND LLC

Nawshad Haque, CSIRO

Jingxi Zhu, Carnegie Mellon University

Session II

Cong Wang, Northeastern University

Zuotai Zhang, Peking University

Xuan Liu, Carnegie Mellon University

Session III

Li Li, Cornell University

Lei Zhang, University of Alaska
Fairbanks

Ziqi Sun, Queensland University of
Technology

Session IV

Donna Post Guillen, Idaho National
Laboratory

Soumendra N. Basu, Boston University

Dirk E. Verhulst, Consultant, Extractive
Metallurgy

Tao Wang, Nucor Steel

HIGH-TEMPERATURE SYSTEMS FOR ENERGY CONVERSION AND STORAGE

Ceramic Reliability I

Amit Pandey, Rolls Royce LG Fuel Cell
Systems Inc.

Amit Shyam, Oak Ridge National
Laboratory

Recent Advancements in Solid Oxide Fuel Cell Technology I

Paul Ohodnicki, National Energy
Technology Laboratory

Kathy Lu, Virginia Tech

Recent Advancements in Solid Oxide Fuel Cell Technology II

Vikram Jayaram, Indian Institute of
Science

Prabhakar Singh, University of
Connecticut

Ceramic Reliability II

Joseph Gladden, University of
Mississippi

Jeffrey Fergus, Auburn University

Systems for Energy Conversion and Storage I

Ritesh Sachan, Oak Ridge National
Laboratory

Swathi Manivannan, University of
Hyderabad

Systems for Energy Conversion and Storage II

Jung Pyung Choi, Pacific Northwest
National Laboratory

William Chueh, Stanford University

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