



Molten Salt Reactors and Thorium Energy

Edited by Thomas J. Dolan

Woodhead Publishing Series in Energy

Molten Salt Reactors and Thorium Energy

Edited by

Thomas J. Dolan



WP

WOODHEAD
PUBLISHING

An imprint of Elsevier

Woodhead Publishing is an imprint of Elsevier

The Officers' Mess Business Centre, Royston Road, Duxford, CB22 4QH, United Kingdom

50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

The Boulevard, Langford Lane, Kidlington, OX5 1GB, United Kingdom

Copyright © 2017 Elsevier Ltd. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-08-101126-3 (print)

ISBN: 978-0-08-101243-7 (online)

For information on all Woodhead Publishing publications
visit our website at <https://www.elsevier.com/books-and-journals>



Working together
to grow libraries in
developing countries

www.elsevier.com • www.bookaid.org

Publisher: Joe Hayton

Acquisition Editor: Maria Convey

Editorial Project Manager: Charlotte Kent

Production Project Manager: Debasish Ghosh

Designer: Matt Limbert

Typeset by MPS Limited, Chennai, India

Molten Salt Reactors and Thorium Energy

Related titles

Handbook of Small Nuclear Reactors

(ISBN: 978-0-85709-851-1)

Molten Salts Chemistry: From Lab to Applications

(ISBN: 978-0-12-398538-5)

Small Modular Reactors: Fad or Future

(ISBN: 978-0-08-100252-0)

Vision

We envision a world where almost every country has affordable molten salt reactors burning thorium, uranium, and spent fuel actinides, producing electricity, hydrogen, and desalinized water with no serious accidents.

List of Contributors

Michel Allibert Centre national de la recherche scientifique, Paris, France

Charalampos Andreades University of California, Berkeley, CA, United States

A.S. Bakai National Academy of Sciences of Ukraine, Kharkiv, Ukraine

Stephen Boyd Aufbau Laboratories, LLC, Blue Point, NY, United States

Wayne Boyes Steenkampskraal Thorium Limited, Centurion, South Africa

Mariya Brovchenko Institut de Radioprotection et de Sûreté Nucléaire, France

Antonio Cammi Polytechnic University of Milan, Milan, Italy

Konrad Czerski Institute for Solid-State Nuclear Physics, Berlin, Germany; University of Szczecin, Szczecin, Poland

Zhimin Dai Shanghai Institute of Applied Physics (SINAP), Shanghai, China

Alexey M. Degtyarev NRC “Kurchatov Institute”, Moscow, Russia

Sylvie Delpech Centre national de la recherche scientifique, Paris, France

Lindsay Dempsey Generation Solutions, Auckland, New Zealand

Leslie Dewan Transatomic Power Corporation, Cambridge, MA, United States

Valentino Di Marcello Polytechnic University of Milan, Milan, Italy; Karlsruhe Institute of Technology—KIT, Karlsruhe, Germany

Elling Disen Norwegian Reactor facility at Halden, Norway

Thomas J. Dolan University of Illinois at Urbana-Champaign, Champaign, IL, United States

I.V. Dulera Bhabha Atomic Research Centre, Mumbai, Maharashtra, India

Victor Dykin Chalmers University of Technology, Gothenburg, Sweden

Lyndon Edwards Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, Australia

L. Berrin Erbay Eskişehir Osmangazi University, Eskişehir, Turkey

Yu S. Fedorov Petersburg State Technological Institute (Technical University), St. Petersburg, Russia

Charles Forsberg Massachusetts Institute of Technology, Cambridge, MA, United States

Kazuro Furukawa High Energy Accelerator Research Organization, ITMSF, Tsukuba, Japan

Stephan Gottlieb Institute for Solid-State Nuclear Physics, Berlin, Germany

Sophie Grape Uppsala University, Uppsala, Sweden

Eduardo D. Greaves Simón Bolívar University, Caracas, Venezuela

Carl Hellesen Uppsala University, Uppsala, Sweden

Fabian Herrmann Institute for Solid-State Nuclear Physics, Berlin, Germany

Daniel Heuer Centre national de la recherche scientifique, Paris, France

Yasuo Hirose Retired, the former Institute of Research and Innovation, Kashiwa, Chiba-ken, Japan

Zara Hodgson National Nuclear Laboratory, Warrington, United Kingdom

Boris Hombourger Paul Scherrer Institute (PSI), Villigen, Switzerland; Laboratory for Reactor Physics and Systems Behaviour, EPFL Lausanne, Switzerland

Armin Huke Institute for Solid-State Nuclear Physics, Berlin, Germany

Ahmed Hussein Institute for Solid-State Nuclear Physics, Berlin, Germany; University of Northern British Columbia, Prince George, BC, Canada

Yongjin Jeong Ulsan National Institute of Science and Technology, Ulsan, Republic of Korea

Lars Jorgensen ThorCon Energy, Stevenson, WA, USA

Motoyasu Kinoshita The University of Tokyo, Tokyo, Japan; International Thorium Molten-Salt Forum, Yokohama, Japan

Esben Klinkby Seaborg Technologies, Copenhagen, Denmark

Jan L. Kloosterman On behalf of the SAMOFAR consortium Delft University of Technology, Delft, The Netherlands

Jiří Křepel Paul Scherrer Institute (PSI), Villigen, Switzerland

John Kutsch Thorium Energy Alliance, Harvard, IL, United States

Vince Lackowski Thorium Energy Alliance, Harvard, IL, United States

Axel Laureau Centre national de la recherche scientifique, Paris, France

David LeBlanc Terrestrial Energy, Inc., Oakville, ON, Canada

Deokjung Lee Ulsan National Institute of Science and Technology, Ulsan, Republic of Korea

A.A. Lizin State Research Centre—Research Institute of Atomic Reactors, Dimitrovgrad, Russia

Lelio Luzzi Polytechnic University of Milan, Milan, Italy

Mark Massie Transatomic Power Corporation, Cambridge, MA, United States

Elsa Merle Centre national de la recherche scientifique, Paris, France

Andrey A. Myasnikov NRC “Kurchatov Institute”, Moscow, Russia

Sergii Nichenko Paul Scherrer Institute (PSI), Villigen, Switzerland

Andreas Pautz Paul Scherrer Institute (PSI), Villigen, Switzerland; Laboratory for Reactor Physics and Systems Behaviour, EPFL Lausanne, Switzerland

Imre Pázsit Chalmers University of Technology, Gothenburg, Sweden

Thomas J. Pedersen Copenhagen Atomics, Denmark

Alessandro Pini Polytechnic University of Milan, Milan, Italy

Leonid I. Ponomarev A.A. Bochvar High Technology Research Institute of Inorganic Materials, Moscow, Russia

Michael Prasser Paul Scherrer Institute (PSI), Villigen, Switzerland; Laboratory of Nuclear Energy Systems, ETH Zürich, Switzerland

Magdi Ragheb University of Illinois at Urbana-Champaign, Champaign, IL, United States

A. Rama Rao Bhabha Atomic Research Centre, Mumbai, Maharashtra, India

Andrei Rineiski Karlsruhe Institute of Technology, Germany

Sean Robertson Transatomic Power Corporation, Cambridge, MA, United States

Cyril Rodenburg Terrestrial Energy, Inc., Oakville, ON, Canada

Götz Ruprecht Institute for Solid-State Nuclear Physics, Berlin, Germany

Laszlo Sajo-Bohus Universidad Simón Bolívar, Caracas, Venezuela

Raluca Scarlat University of Madison-Wisconsin, Madison, WI, United States

Troels Schönfeldt Seaborg Technologies, Copenhagen, Denmark

Ian Scott Moltex Energy, London, United Kingdom

Yoichiro Shimazu University of Fukui, Fukui, Japan

R.K. Sinha Bhabha Atomic Research Centre, Mumbai, Maharashtra, India

Stephen Smith Transatomic Power Corporation, Cambridge, MA, United States

Christopher Taylor DNV GL, Oslo, Norway

SAMOFAR consortium Delft University of Technology, Delft, The Netherlands

S.V. Tomilin State Research Centre—Research Institute of Atomic Reactors, Dimitrovgrad, Russia

Jan Uhlíř Research Centre Řež, Husinec - Řež, Czech Republic

Evgeny P. Velikhov Kurchatov Institute, Moscow, Russia

P.K. Vijayan Bhabha Atomic Research Centre, Mumbai, Maharashtra, India

Abdul Waris Bandung Institute of Technology, Bandung, Indonesia

Daniel Weißbach Institute for Solid-State Nuclear Physics, Berlin, Germany

Ritsuo Yoshioka International Thorium Molten-Salt Forum (ITMSF), Yokohama, Japan

Preface

There is growing awareness that nuclear energy is needed to complement intermittent energy sources and to avoid pollution from fossil fuels. Light-water reactors are complex, expensive, and vulnerable to core melt, steam explosions, and hydrogen explosions, so better technology is needed. Thorium energy and molten salt reactors could make nuclear energy safer and less expensive, so this book describes the current state of the art. It has the following sections:

- Motivation—why are we interested?
- Technical issues—reactor physics, thermal hydraulics, materials, environment, etc.
- Generic designs—thermal, fast, solid fuel, liquid fuel, etc.
- Specific designs—aimed at electrical power, actinide incineration, thorium utilization, etc.
- Worldwide activities in 23 countries.
- Conclusions.

This book is a collaboration of many authors from around the world. It can serve as a reference for engineers and scientists, and it can be used as a textbook for graduate students and advanced undergrads. We hope that leaders of governments and industry will recognize the great potential benefits and provide appropriate research support. Appendix A provides a list of about 450 abbreviations used in this field, since technical readers often suffer from excessive use of abbreviations (EUA). I am grateful to Professor Ritsuo Yoshioka, International Thorium Molten Salt Forum, for guidance in organizing and writing the book.

Thomas J. Dolan



Contents

List of Contributors	xvii
Preface	xxiii
1 Introduction	1
<i>Thomas J. Dolan</i>	
1.1 Need for MSR	1
1.2 MSR origin and research curtailment	2
1.3 MSR activities	3
1.4 Fissile fuels	4
1.5 Thorium fuel advantages	5
1.6 Liquid fuel MSR	6
1.7 Advantages of liquid fuel MSR	7
1.8 MSR development issues	10
1.9 Tritium issues	11
References	12
2 Electricity production	13
<i>Lindsay Dempsey, Charles Forsberg and Thomas J. Dolan</i>	
2.1 Heat engines	13
2.2 Rankine cycles	15
2.3 Helium Brayton cycles	16
2.4 Supercritical CO ₂ Brayton cycles	18
2.5 Metal vapor combined cycles	20
2.6 Nuclear air Brayton power cycles	20
2.7 Summary	27
References	27
3 Chemical fundamentals and applications of molten salts	29
<i>Stephen Boyd and Christopher Taylor</i>	
3.1 Introduction	30
3.2 Fundamental physicochemical properties of molten salts	30
3.3 Remote power sources	45
3.4 Heat exchangers and materials embrittlement challenges	55
3.5 High-temperature commercial applications	60
3.6 Actinide burning	68
3.7 Medical isotopes	73

3.8	Desalination	74
3.9	Optical applications	80
3.10	Summary and conclusions	80
	Acknowledgment	82
	References	82
	Further Reading	90
4	Reactor physics of MSR	93
	<i>Yoichiro Shimazu</i>	
4.1	Introduction	93
4.2	Interaction of neutrons with matter	93
4.3	Multiplication factor of chain reactions	95
4.4	Cross-sections	95
4.5	Reaction rate	96
4.6	Neutron energy distribution and maxwell—bolzmann distribution	96
4.7	Transport and diffusion of neutrons	98
4.8	Criticality equation	101
4.9	Kinetic equations	104
4.10	Monte Carlo method	107
4.11	Conclusion	108
	References	109
5	Kinetics, dynamics, and neutron noise in stationary MSRs	111
	<i>Imre Pázsit and Victor Dykin</i>	
5.1	Introduction	111
5.2	The MSR model	113
5.3	The static equations	114
5.4	Space—time-dependent transient during start-up	125
5.5	Dynamic equations in the frequency domain: neutron noise	140
5.6	The point kinetic approximation and the point kinetic component	148
5.7	The neutron noise in an MSR, induced by propagating perturbations	159
5.8	Conclusions	164
	Acknowledgment	164
	References	164
6	Thermal hydraulics of liquid-fueled MSRs	167
	<i>Lelio Luzzi, Antonio Cammi, Valentino Di Marcello and Alessandro Pini</i>	
6.1	Introduction	167
6.2	Preliminary approach to thermo-hydraulics of internally heated molten salts	168
6.3	Heat transfer and pressure losses	173
6.4	Effects of internal heat generation on natural circulation stability	178
6.5	Conclusions	184
	Acknowledgments	184