ASTM INTERNATIONAL
Selected Technical Papers

Zirconium in the Nuclear Industry: 19th International Symposium

STP 1622

Editors:
Arthur T. Motta
Suresh K. Yagnik

ASTM INTERNATIONAL

SELECTED TECHNICAL PAPERS
STP1622

Editors: Arthur T. Motta and Suresh K. Yagnik

Zirconium in the Nuclear Industry: 19th International Symposium

ASTM STOCK #STP1622
DOI: 10.1520/STP1622-EB

ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959
Printed in the U.S.A.

Library of Congress Cataloging-in-Publication Data

ISBN: 978-0-8031-7690-4

ISSN: 1050-7558

Peer Review Policy
Each paper published in this volume was evaluated by two peer reviewers and at least one editor. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM International Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of the peer reviewers. In keeping with long-standing publication practices, ASTM International maintains the anonymity of the peer reviewers. The ASTM International Committee on Publications acknowledges with appreciation their dedication and contribution of time and effort on behalf of ASTM International.

Citation of Papers
When citing papers from this publication, the appropriate citation includes the paper authors, "paper title," in *STP title*, book editor(s) (West Conshohocken, PA: ASTM International, year), page range, paper doi, listed in the footnote of the paper. A citation is provided on page one of each paper.

Printed in Eagan, MN
July, 2021

Foreword

THIS COMPILATION OF Selected Technical Papers, STP1622, *Zirconium in the Nuclear Industry: 19th International Symposium*, contains peer-reviewed papers that were presented at a symposium held May 19–23, 2019, in Manchester, United Kingdom. The symposium was sponsored by ASTM International Committee B10 on Reactive and Refractory Metals and Alloys and Subcommittee B10.02 on Zirconium and Hafnium.

Symposium Chairs and STP Editors:

Arthur T. Motta
Penn State University
University Park, PA, USA

Suresh K. Yagnik
Electric Power Research Institute (EPRI)
Palo Alto, CA, USA

Contents

Overview

This Selected Technical Papers (STP) publication contains papers presented at the *19th International Symposium on Zirconium in the Nuclear Industry*, which was held in Manchester, United Kingdom from May 19 to 23, 2019.

The 2019 symposium had 147 participants from 16 countries with representation from around the world. The symposium featured 40 platform presentations in addition to a poster session with 25 contributions. This STP contains 37 peer-reviewed papers, including the three papers from the winners of the William J. Kroll Zirconium Medal for 2016, 2017, and 2018. We were happy to note the increasing participation of young researchers and students at the symposium, some of whom presented their work, either as oral presentations or posters. A total of 26 students attended the conference, which represents a welcome and continuing trend toward formation of the new generation of researchers in the field.

For almost 53 years this symposium series has been recognized as the premier forum for researchers who work in zirconium technology as applied to the nuclear industry. Researchers often save their most noteworthy work for presenting at the upcoming symposium and subsequent publication in the STP, following a rigorous peer and editorial review process. The first symposium of this series was in 1968 with subsequent symposia held every two to three years at various locations in Europe, North America and Asia. The proceedings of each symposium in the series constitute significant contributions to the understanding and development of zirconium alloys for application in nuclear power reactors and have been consistently documented in STP publication series. This symposium's sessions are held in series, making it possible for all the attendees to hear every presentation, which is often followed by stimulating discussions, prompted by questions from the audience. As in past symposia, these questions are included at the end of each paper of this volume, along with written responses by the authors. This is a unique and valuable feature of this STP series, allowing the attendees to often provide different perspectives on the work while providing the authors a chance to further clarify their research.

During this symposium, the William J. Kroll Zirconium Medals for the years 2016-2018 were presented. The recipient for 2016 was Peter Rudling, whose citation was "For contributions to the scientific, technological and commercial aspects of the metallurgy of zirconium through the development of ZIRAT (ZIRconium Alloy Technology) Program, providing continuing education and consultation to the international nuclear industry." With membership currently consisting of nearly

75 organizations from 21 countries, ZIRAT offers a series of annual review seminars and comprehensive topical reports by acknowledged subject matter experts to numerous nuclear materials professionals around the world. The 2017 recipient was Bruce Kammenzind, whose citation was "For his influential role in the mechanistic interpretation of experimental research on the long-term in-reactor corrosion, hydriding and hydrogen migration in Zircaloy-4." He and his co-workers at Bettis have provided some unique and fundamental research insights on core and structural material behaviors, which has spawned new directions of investigations by other researchers. The 2018 recipient was Michael Preuss, whose citation was "For establishing and developing the Zirconium Technology Group at the University of Manchester, UK and his research leadership in mechanistic understanding of irradiation damage in zirconium alloys and their oxides." His group provided a strong foundation for zirconium alloy research at a group of UK universities through application of advanced modeling and micro-analytical techniques, with several papers in these areas which were key contributions in this STP as well as the previous one (STP1597).

For the second time in the symposium series a "Best Poster Award" was selected from the contributions in the poster session by a group of judges encompassing various areas of expertise. The winning poster selected by this group of judges was entitled "Diffusion path comparison of the hydrogenated species in the oxide layers formed on Zircaloy-4 and M5 in PWR conditions," and was authored by M. Jublot, K. Colas, M. Tupin, and C. Bisor, from the CEA in France. The award was presented to the authors at the end of the symposium.

The winner of the John H. Schemel Best Paper Award based on technical excellence, relevance to the nuclear industry, and 'groundbreaking' research, was based on a deliberate selection process by seeking inputs from peers and experts representing a breadth of experience. The entire process avoided any direct or indirect conflict of interest. More specifically, during the symposium, votes from all session chairs were taken and tallied in nominating five most deserving platform papers from among all papers presented at the symposium. Following the symposium, the feedback comments of anonymous peer reviewers to the question of award quality caliber of the submitted manuscripts were tallied up from the ScholarOne review stages. These two considerations formed the basis of selecting three top ranking papers. Finally, a panel of five judges, having no conflict of interests were polled to rank these top three papers, again using the aforementioned selection criteria. Accordingly, the winner of the award was the paper entitled "Zirconium Hydride Precipitation and Dissolution Kinetics in Zirconium Alloys" by Evrard Lacroix, Arthur Motta, Pierre-Clement Simon, and Jonathan Almer. We offer our sincere congratulations to the winners. The award will be presented at the next symposium to be held in Ottawa, Canada in 2022.

The papers included in this STP volume are divided into the following seven categories, each being a separate session at the symposium:

- Fabrication and Alloy Development
- Mechanical Behavior
- In-reactor Behavior and Irradiation Effects
- Corrosion
- Hydrogen Effects
- Hydrides in Zirconium Alloys
- High Temperature Transients and Modeling of Process or Phenomenon

These broad categories encompass the range of challenges that are relevant to the nuclear community and which are currently being addressed in research being conducted in industry, universities, and national laboratories. In the following paragraphs, we summarize a few key observations on the papers being published in this STP.

Over a dozen papers in two different sessions of the symposium deal with hydrogen effects and hydrides in zirconium alloys. This field of research seems to have overtaken issues related to thermal performance of zirconium alloy core components—mostly the past focus on cladding corrosion per se as being a design limitation. The current research interests in hydrogen are clearly driven by the structural performance and cladding integrity concerns, in addition to the data needs and regulatory concerns of long-term storage of used fuel assemblies.

Except for a review paper on experiences from commercial BWRs, the papers on in-reactor behavior were limited to test reactor studies. Three papers at the symposium were based on test reactor experiments and monitoring. Test reactors offer the flexibility of controllable irradiation conditions and in situ instrumentation, ideally suited to examine neutron irradiation effects in zirconium alloy core components. Testing of such fidelity is often not possible in commercial reactors, where the overarching goal is production of electricity. However, the available test reactor facilities are on the decline worldwide. Most notably, the closure of the Halden test reactor in 2018 with its unique in-pile instrumentation capabilities affects our ability to conduct such tests. An alternate approach to neutron irradiation is the use of ion irradiation to simulate in-reactor effects. Ion irradiation clearly allows one to separate out some of the many effects that are occurring simultaneously under in-reactor conditions and can partially alleviate expensive in-reactor testing and post neutron irradiation evaluations, as well as declining availability of test reactor facilities around the world for neutron irradiation research. However, care must be taken to ensure that the accelerated and highly localized irradiation damage rates from ion irradiations are indeed reproducing the sought after in-reactor neutron irradiation effects meaningfully.

Three of the papers in the high temperature session were devoted to multiple length scale advanced modeling capabilities to describe performance of zirconium

alloys under both normal and accident conditions. Such advanced modeling attempts to understand and deconvolute various complex phenomena that are occurring under irradiation and temperature transients, is a growing trend in this symposium series, in part due to advances in software as well as hardware computational capabilities. The fact that multi-scale advanced modeling can provide guidance to experimental research programs and vice-versa, the optimum mix of the future research direction between the two approaches will depend on the interests and needs of the research that the nuclear industry and governmental agencies are willing to fund.

Except for a single paper on additive manufacturing, there was a notable absence of papers discussing new alloy development at this symposium. This is not coincidental—the past work on new alloy development was driven by the desire to increase fuel assembly lifetime and improving fuel reliability. With the advent of alloys, beyond traditional Zircaloys, that are already in wide use (M5, ZIRLO, Zr-2.5Nb, and E110 for PWRs and Zircaloy-2 with modern manufacture schedules for BWRs), new alloy development has slowed down somewhat.

As in the recent past, the session on corrosion included papers on fundamental aspects, modeling, characterizations of oxide and metal matrix. One paper experimentally examined the behavior of Zircaloy-4 in LiOH coolant conditions, in the absence of H_3BO_3, under a thermal gradient and in two-phase flow regime with the stated application in a small modular reactor design.

With the heightened interest in accident tolerance of fuel since the Fukushima accident in 2011, there were several papers on coating technologies and high temperature transients. Most common coating technology appears to be chromium-based, applied to the outer surface of the fuel cladding. This coating concept for accident tolerance is not too different from that of the duplex cladding manufactured through co-extrusion of an outer alloy layer with better corrosion performance. While the duplex cladding has been used in several PWRs in reload quantities, the current coating technologies for accident tolerance is mainly focused on adherence and stability of the coatings under normal and accident conditions. These technologies still face significant challenges to achieve extended periods of testing under irradiation and regulatory acceptance before their full-scale demonstration and implementation in commercial reactors. Nevertheless, it appears that the Fukushima accident has made its mark on the future direction of research, including in the papers presented at this symposium series. Similarly, growing trends and capabilities in multi length scale modeling and ion irradiation testing, combined with the advances in microstructural and microchemical characterization are very exciting in that they offer promise in allowing more accurate extrapolation of the limited and expensive in-reactor data, as well as the possibility to make faster advances in understanding, performance model development, and material improvements.

In looking through the overviews written by previous editorial chairs, many of the important issues that are now of concern to the industry had been identified previously and were being studied in the prior symposia. Knowledge has thus been accruing in many of the session topics of interest to the community and this symposium provides continuity of research and a chance for discussion and resolution with the best experts in the world. We are happy to see that this STP can contribute to this continuous process of scientific discovery, mechanistic understanding, and technology development to further improve the performance of zirconium in the nuclear industry.

Arthur T. Motta
Suresh K. Yagnik