

# Preface

Zirconium alloys are widely used in nuclear reactors, their most challenging applications being as cladding for nuclear fuel in Pressurized and Boiling Water Reactors (PWR and BWR, respectively) and as pressure tubes in CANDU<sup>TM</sup> and Pressurized Heavy Water (PHW) reactors. The possible failure of these components has consequences to the safe and economic operation of these reactors. Data and understanding to prevent any such failures is, therefore, of great importance to the nuclear industry. It was recognized early on in the development of the design of nuclear reactors that these alloys have an affinity for absorbing hydrogen both during their manufacture and operation. When the hydrogen solubility limit in these alloys is exceeded, their excess amount results in the formation of zirconium hydride precipitates. These precipitates have been shown to be less ductile than the surrounding zirconium alloy matrix. In the 1960s when the first commercial nuclear reactors were being designed and built, the initial concern regarding the presence of these precipitates was their potential for decreasing the fracture toughness of zirconium alloy components. This led to an initial intensive study of the physical and mechanical properties of zirconium hydride in its bulk form and as precipitates uniformly distributed in the alloys. Somewhat later, in the early 1970s, as a result of leaks found in some over-rolled pressure tubes in two of the earliest commercial CANDU reactors, a time-dependent failure mechanism associated with hydrogen and hydrides in the pressure tube alloy was discovered and subsequently extensively studied. This time-dependent failure mechanism was initially referred to by a variety of different names but is now universally called Delayed Hydride Cracking (DHC). A vast body of knowledge has since appeared in the open literature and in internal reports on this topic including some review articles. To acquaint oneself with this knowledge, however, a thorough review of the literature can be an arduous and sometimes confusing task since models, measurement methods, and data have changed over the years, been revised or updated, taking on different forms over time.

This book, then, is an attempt to provide the reader with a more coherent account of this topic than is obtainable through a reading of the extant literature. Emphasis in this book is placed on showing how the fundamental aspects of DHC

have informed the methods—and provided the underpinning—for its practical applications. In so doing, the book provides more detailed descriptions of the current theoretical and experimental foundations of the properties and behavior of hydrogen, hydrides, and DHC in zirconium and its alloys than is usually found in individual papers in the literature. Although emphasis is on zirconium alloys, this book has been presented in such a way that it could also serve as a basis for the treatment of other hydride forming metals. In fact, it is noted that the reverse has frequently been the case with the knowledge produced concerning the properties and behavior of hydrogen and hydrides in other hydride forming material providing starting points for quantifying and understanding these in zirconium alloys.

The book is not meant to be an exhaustive source of the documented work involving DHC. Nevertheless, the author has attempted to give as complete an account of the present state of knowledge of this field as possible. To make the derivations of the theoretical models reproduced in this book more understandable, background information is provided to show how these derivations follow from the general theories of the diffusion of atoms in crystalline solids, the macroscopic theory of irreversible thermodynamics, thermodynamics of coherent misfitting phases in crystalline solids containing mobile interstitial atoms, self and interaction energies of point and line defects in crystalline solids, and continuum fracture and solid mechanics. This book could also be useful as a teaching tool in that it provides an illustration of a specific application of these general theories to a practical engineering problem. Although the primary emphasis in this book is on zirconium alloys used in pressure tubes of CANDU and other PHW reactors, the treatment is sufficiently general for applications to other zirconium alloys and components used in nuclear reactors, particularly those for nuclear fuel cladding.

<http://www.springer.com/978-1-4471-4194-5>

The Effect of Hydrogen and Hydrides on the Integrity of  
Zirconium Alloy Components

Delayed Hydride Cracking

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2012, XXXII, 452 p., Hardcover

ISBN: 978-1-4471-4194-5