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Applications of neutron radiography for the nuclear power industry

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Abstract

The World Conference on Neutron Radiography (WCNR) and International Topical Meeting on Neutron Radiography (ITMNR) series have been running over 35 years. The most recent event, ITMNR-8, focused on industrial applications and was the first time this series was hosted in China. In China, more than twenty new nuclear power plants are under construction and plans have been announced to increase the nuclear capacity by a factor of three within fifteen years. There are additional prospects in many other nations. Neutron tests were vital during previous developments of materials and components for nuclear power applications, as reported in the WCNR and ITMNR conference series. For example a majority of the 140 papers in the Proceedings of the First WCNR are for the benefit of the nuclear power industry. Many of those techniques are being utilized and advanced to the present time. Neutron radiography of irradiated nuclear fuel provides more comprehensive information about the internal condition of irradiated nuclear fuel than any other non-destructive technique to date. Applications include examination of nuclear waste, nuclear fuels, cladding, control elements, and other critical components. In this paper, applications of neutron radiography techniques developed and applied internationally for the nuclear power industry since the earliest years are reviewed, and the question is asked whether neutron test techniques, in general, can be of value in development of the present and future generations of nuclear power plants world-wide.

Peer-review under responsibility of the organizing committee of ITMNR-8

Keywords: neutron radiography, post-irradiation examination, nuclear fuel

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1. Introduction

Understanding the behavior of nuclear fuels during irradiation and under transient conditions contributes to development of safer and more-efficient nuclear reactors. Neutron radiography (NR) of irradiated nuclear fuel and other critical components provides more comprehensive information about the internal condition of irradiated nuclear fuel than any other non-destructive technique to date. This international conference series, including the World Conference on Neutron Radiography (WCNR) and International Topical Meeting on Neutron Radiography (ITMNR), has been running over 35 years. Examinations using NR were vital during previous developments of materials and components for nuclear power applications. The value of neutron radiography in development of reactor materials and components was evident in the significant number of publications on the topic in the 1970s and 1980s. For example, a majority of the 140 papers in the Proceedings of the First WCNR (Barton and von der Hardt, 1981) are for the commercial nuclear power industry. Included in those proceedings are reviews of the diverse techniques being applied in Europe (Domanus and von der Hardt, 1981), Japan (Kobayashi et al., 1981), the United States (DeVolpi, 1981), and at many other centers. However, the number of publications in the WCNR and ITMNR conference series on nuclear power applications waned through the 1990s, with only a modest resurgence since the mid-2000s.

There are a number of review papers discussing the application of neutron examination techniques to nuclear applications (Ross, 1977; Ashraf and Kahn, 1992; Vogel, 2013; Parker and Joyce, 2015; International Atomic Energy Agency, 2015; de Beer, 2015) and NR in general (Brenizer, 2013). In this paper, the techniques developed and applied internationally for the nuclear power industry since the earliest years are reviewed briefly, and particular emphasis is given to evaluate trends and lessons learned. Drawing from these perspectives, the question is asked to what extent neutron examination techniques will continue being of value in development of the present and future generations of nuclear power plants worldwide. Neutron radiography plays an important role in development of safer and more efficient nuclear power plants by providing valuable information for development of new fuels, cladding, and other reactor materials, which is discussed in the following section.

2. Nuclear Applications of Neutron Examinations

The earliest neutron radiographs were produced in 1935 by Kallmann, with only modest progress through the 1950s, and only four NR programs worldwide in 1964 (Brenizer, 2013). A facility specifically built for NR at the 200 kW Juggernaut reactor provided the first application of NR to study irradiated nuclear fuel (Berger and Beck, 1963). Fifteen years later, by 1977, there were over sixteen facilities in Europe dedicated to NR for irradiated nuclear fuel, and a review paper cites 154 references to related work worldwide (Ross, 1977).

Neutron radiography of irradiated nuclear fuel and other critical components provides more comprehensive information about the internal condition of irradiated nuclear fuel than any other non-destructive technique to date. Neutron examination techniques have been applied to study fuel swelling and cracking (Chichester and Harp, 2016; Sun et al., 2016), pellet-clad interactions, hydridization of Zircaloy cladding (Yasuda et al., 2002; Grosse et al., 2011; Agrawal et al., 2012), cladding microstructural properties (Kruželová et al., 2012), fuel pellet fragmentation during transient conditions (Richards et al., 1982; Grosse et al., 2012; Jenssen et al., 2014), central void formation in fuel, burn-up and enrichment variations, pellet-clad and pellet-pellet gaps (Notea et al., 1983; Sim et al., 2013), evidence of fuel melting, and migration of material (Rice et al., 2015). Neutron radiography also provides post-irradiation analysis of highly-radioactive lead target rods from proton-accelerator neutron sources (Vontobel et al., 2006). Many of the same radioactive material inspection techniques developed in the early years of NR are still being utilized and advanced to the present time (Jenssen and Oberländer, 2002; Vontobel et al., 2006; Craft et al., 2015). Applications of neutron examination techniques to nuclear waste containers (Hausladen et al., 2007; McGlinn et al., 2010; Bücherl et al., 2017) will become increasingly important as nuclear waste storage concerns continue to grow. Additionally, NR enables analysis of two-phase flow experiments that provide insights into the coolant behavior of boiling water reactors and provides data for validation of computational models (Takenaka et al., 1996).

Neutron scattering applications to nuclear materials is probably one of the most promising fields of neutron examination techniques for nuclear materials in the future, as is indicated by the more than 200 references in recent