Development of a PCI-Mandrel Test System for I-SCC Evaluation at the KAERI Post-Irradiation Examination Facility

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1. Introduction

The Post Irradiation Examination Facility (PIEF) at KAERI is expanding its experimental capabilities for safety and performance assessment of irradiated nuclear fuel. One of the systems under development is a PCI-mandrel apparatus for reproducing the mechanical and environmental conditions associated with pellet-cladding interaction and iodine-induced stress corrosion cracking (I-SCC). The system design has been completed, and fabrication is in progress to enable controlled testing of zirconium alloy cladding under prescribed hoop loading, temperature, and iodine exposure.

2. PCI-Mandrel Test System

The system consists of a mechanical loading unit, electric heater, iodine supply and exhaust lines, shielding, and control and data-acquisition units. As shown in Fig. 1, axial movement of a stainless-steel conical spike expands a Zr intermediate sheath and a longitudinally slitted Al_2O_3 sleeve in the test section. The radial expansion of these components imposes radial displacement and hoop stress on the surrounding cladding specimen. Load, spike displacement, and specimen temperature will be recorded during testing. Nonlinear contact analysis will also be performed to establish the relationship between the spike displacement and the local hoop stress at the cladding inner surface and to define repeatable loading conditions.

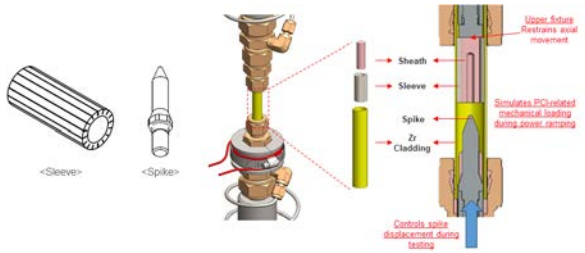


Fig. 1. Hoop-stress generation mechanism of the PCI-mandrel assembly

3. Iodine Delivery and Monitoring

I-SCC failure time is sensitive not only to stress and temperature but also to the iodine condition at the cladding surface [1]. Therefore, the iodine exposure should be defined using a measured quantity rather than solely by the initially charged iodine mass. The preliminary iodine delivery and monitoring arrangement is shown in Fig. 2. The planned loop generates iodine vapor in a temperature-controlled bath and transports it with Ar carrier gas through a heated PTFE line. Molecular iodine is monitored using optical absorption spectroscopy near its characteristic absorption region around 520 nm, while a downstream scrubber controls the exhaust. Commissioning tests will quantify the effects of iodine-bath temperature, carrier-gas flow rate, transfer-line temperature, and stabilization time. These tests will also establish the relationship between the measured optical signal and the iodine partial pressure delivered to the cladding specimen.

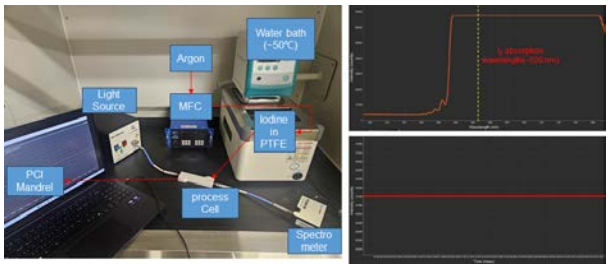


Fig. 2. Preliminary iodine delivery and optical absorption monitoring arrangement

4. Time-to-Failure Model

The Shann-Olander model describes the time to failure of zirconium alloy cladding under iodine environments as a function of hoop stress, temperature, and iodine partial pressure [2]. Constant-condition tests will therefore be conducted using the PCI-mandrel system to develop a TTF correlation based on the following threshold-modified form:

$$t_f = A \cdot (\sigma - \sigma_{\text{th}})^{-n} \cdot P_{I_2}^{-m} \cdot \exp\left(\frac{Q}{RT}\right)$$

where A, n, m, Q, and threshold stress σ_{th} are calibration parameters. A preliminary fitting of 21 literature test results produced approximate values of A = 3, n = 2, Q/R = 3,500 K, and σ_{th} = 240 MPa when an iodine exponent near unity was assumed. As shown in Fig. 3, the threshold-modified model reproduced the increase in failure time near the low-stress limit. The model parameters and applicable ranges will be further determined using PCI-mandrel test results under controlled stress, temperature, and iodine conditions.

5. Future Work

Future work will focus on mechanical calibration of the PCI-mandrel assembly, commissioning of the iodine delivery and monitoring system, and constant-condition failure tests under selected combinations of hoop stress, temperature, and iodine partial pressure. These test results will be used to calibrate the parameters of the TTF model described in Section 4 and to evaluate its applicability under controlled test conditions.

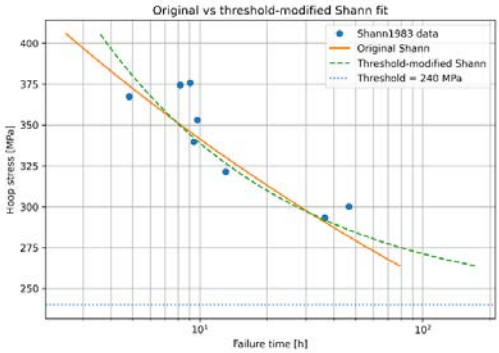


Fig. 3. Preliminary fit of the threshold-modified Shann-Olander relation to literature data

The calibrated TTF model will then be applied to conditions in which stress, temperature, and iodine level vary with time. As shown in Fig. 4, the failure time calculated for each condition will be combined with its exposure duration to evaluate cumulative damage and remaining life. Interrupted tests using cladding specimens with prescribed prior stress histories will also be considered to assess cumulative-damage and loading-sequence effects.

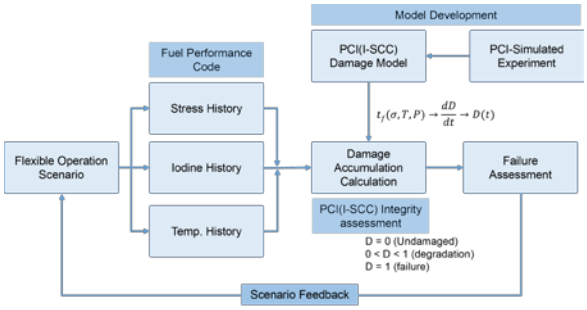


Fig. 4. Proposed test-modeling framework for PCI(I-SCC) assessment under variable operating histories

6. Conclusions

A PCI-mandrel test system is being developed at the KAERI PIEF to evaluate the I-SCC behavior of zirconium alloy cladding under controlled mechanical, thermal, and iodine conditions. The system combines mandrel-based hoop loading with an iodine delivery and optical monitoring system to control and quantify the major parameters affecting failure time.

The resulting test data will be used to develop a TTF model as a function of hoop stress, temperature, and iodine partial pressure. The model is expected to support cumulative-damage and remaining-life assessments under variable operating conditions.

ACKNOWLEDGEMENT

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