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Shutdown-induced tensile stress in monolithic miniplates as a possible cause of plate pillowing at very high burnup

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ABSTRACT

Post-irradiation examination of RERTR-12 miniplates showed that in-reactor pillowing occurred in at least 4 plates, rendering performance of these plates unacceptable. To address in-reactor failures, efforts are underway to define the mechanisms responsible for in-reactor pillowing, and to suggest improvements to the fuel plate design and operational conditions. To achieve these objectives, the mechanical response of monolithic fuel to fission and thermally induced stresses was modeled using a commercial finite element analysis code. Calculations of stresses and deformations in monolithic miniplates during irradiation and after the shutdown revealed that the tensile stress generated in the fuel increased from 2 MPa to 100 MPa at shutdown. The increase in tensile stress at shutdown possibly explains in-reactor pillowing of several RERTR-12 miniplates irradiated to the peak local burnup of up to 1.11×10^{22} fissions/cm^3. This paper presents the modeling approach and calculation results, and compares results with post-irradiation examinations and mechanical testing of irradiated fuel. The implications for the safe use of the monolithic fuel in research reactors are discussed, including the influence of fuel burnup and power on the magnitude of the shutdown-induced tensile stress.

1. Introduction

RERTR-12 miniplate irradiation experiment was conducted at the Idaho National Laboratory in the Advanced Test Reactor with an objective to investigate performance of the monolithic U-10Mo fuel to the burnup up to 1×10^{22} fissions/cm^3. The test included 56 monolithic U-10Mo miniplates whose operating conditions enveloped those expected in the US high power research reactors (Perez et al., 2011, 2012). Post irradiation examination of the RERTR-12 experiment is in progress, and has revealed that most of the plates demonstrated acceptable performance, up to the average burnup of 7×10^{21} fissions/cm^3. However, the higher-burnup plates L1P754, L1P759, L1P785, and L1P7A0 exhibited pillows over a part of the fuel region, rendering performance of these plates unacceptable (Robinson et al., 2013). Despite the presence of pillows, no fission product release into the reactor coolant was detected. To illustrate the pillowing phenomenon, the appearance of a pillowed plate L1P785 is shown in Fig. 1.

To address the in-reactor failures, efforts are underway to define the mechanisms responsible for the in-reactor pillowing, and to suggest improvements to the fuel plate design and operational conditions. To achieve these objectives, the mechanical response of monolithic fuel to fission and thermally induced stresses was modeled using a commercial finite element analysis code.

This paper presents the modeling approach and calculation results, and compares results with post-irradiation examinations and mechanical testing of irradiated fuel. The implications for the safe use of the monolithic fuel in research reactors are discussed, including the influence of fuel burnup and power on the magnitude of the shutdown-induced tensile stress.

2. Modeling approach

To investigate the mechanical response of monolithic fuel to fission and thermally induced stresses, a commercial finite element analysis code ABAQUS was utilized. A fully coupled three-dimensional model of a monolithic miniplate with a capability to evolve mechanical and thermal properties of the constituent materials with irradiation time and burnup was developed. The model uses plate geometry, power history, coolant conditions as an input. The model output includes temperature, stress and deformation history in the fuel, cladding and zirconium diffusion barrier (Miller and Ozaltun, 2012; Ozaltun et al., 2013). The behavior models include fission heat source, swelling due to solid and gaseous fission products (Kim and Hofman, 2011), irradiation induced creep (Kim et al., 2013), elasticity, thermal expansion, plasticity, and cladding hardening due to the fast neutron fluence. The fuel swelling model is coupled with the thermal conductivity model to

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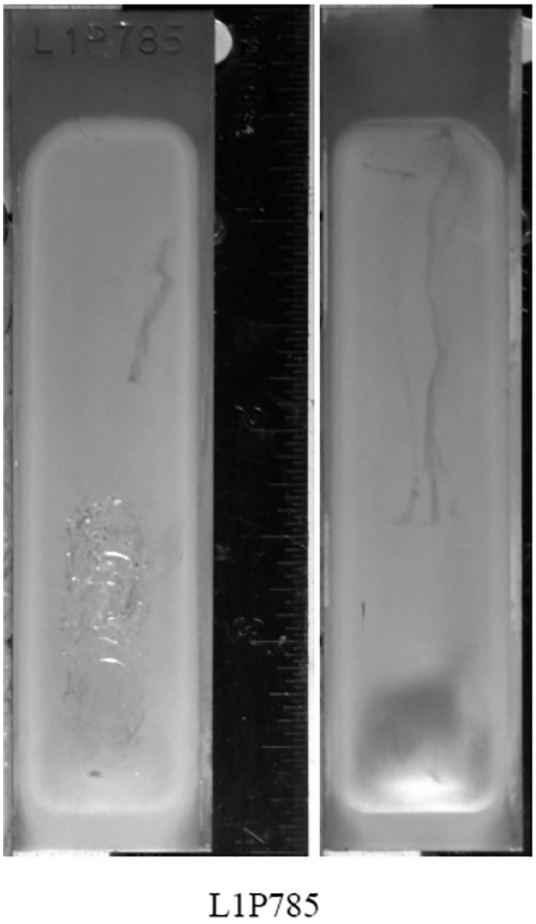

Fig. 1. Post irradiation appearance of a pillowed plate L1P785.

account for the degradation of the thermal conductivity due to the formation of fission gas bubbles (pores) in the fuel during irradiation. As most of the physical and mechanical properties of irradiated U-10Mo are unknown, the modeling results are regarded as qualitative.

3. Plate power history and spatial power distribution

While the detailed description of the experiment conditions are given elsewhere (Perez et al., 2011), the power history and spatial power distribution in plates L1P785, L1P7A0, L1P756 analyzed in this study are shown in Fig. 2. Spatial power distribution plots reveal power variations in the plate and highlight the high power regions. High power regions attain higher burnup and operate at higher temperatures.

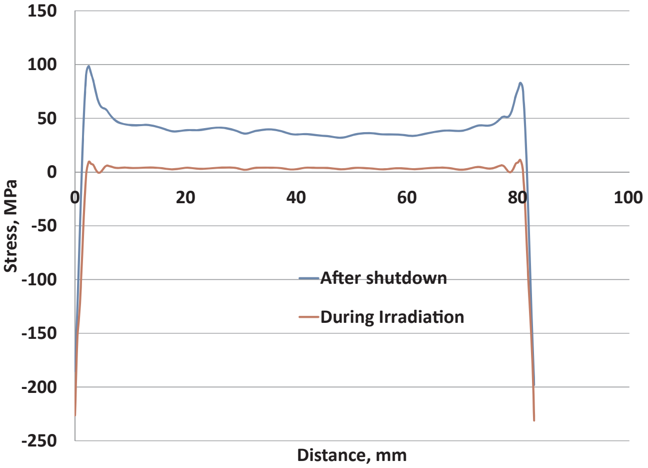

Fig. 3. Comparison of the calculated values of maximum principal stress during irradiation and after the shutdown.

4. Results

4.1. Shutdown-induced tensile stress in the fuel

The focus of the present paper is on the discovery of the tensile stress that develops in the fuel foil after the shutdown. In an event of a reactor shutdown, the plate power instantly reduced from its current value to zero and the temperature is instantly reduced to the reactor coolant temperature. The existence of this stress is demonstrated by comparing stress patterns in the fuel before and after the shutdown. For the plate L1P785, this comparison is provided in Fig. 3, where the calculated values of maximum principal stress during irradiation and after the shutdown are plotted along the length of the fuel. As evident from Fig. 3, a shutdown results in a nearly 10-fold increase of the maximum principal stress in the bottom region of the plate. It should be noted, that the positive sign of the stress value is indicative of the tensile stress.

The neutron radiography image of the plate L1P785, the contour plot of the calculated maximum principal stress at the mid-plane of the fuel after the shutdown, and pre-shutdown fuel temperature are shown in Fig. 4. Examination of Fig. 4 and Fig. 1 reveals that the pillow is found on the bottom of the plate where the maximum principal stress is the highest. This observation establishes a possible correlation between

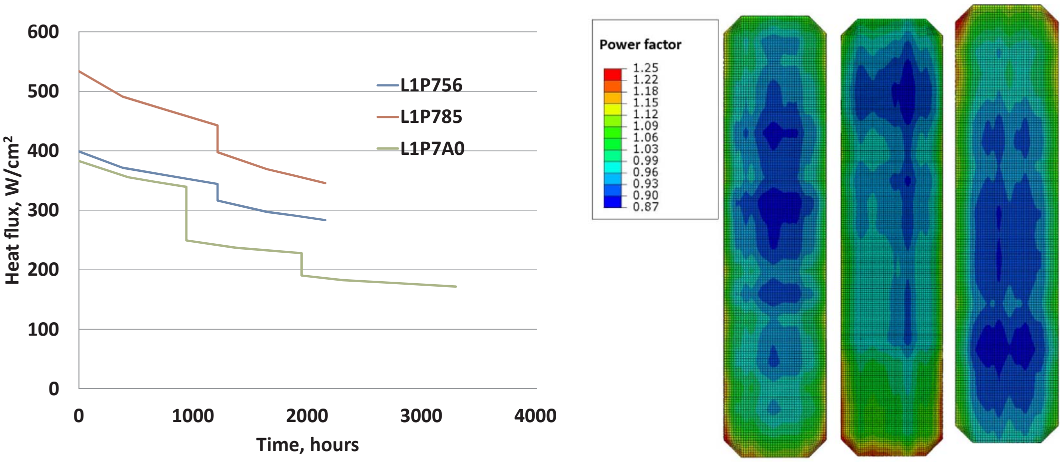

Fig. 2. Power history and spatial power distribution in plates L1P785, L1P7A0, L1P756 (left to right).