INL/CON-13-30701
PREPRINT

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RRFM 2014

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April 2014

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

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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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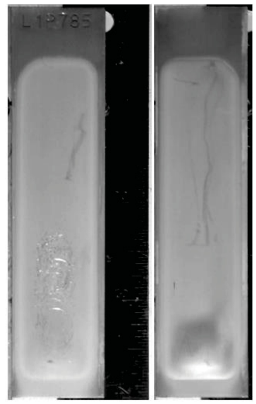
ABSTRACT

Post-irradiation examination of Reduced Enrichment for Research and Test Reactors (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

The RERTR-12 miniplate irradiation experiment was conducted at the Idaho National Laboratory (INL) 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 U.S. high power research reactors [1,2]. 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 [3]. 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 Figure 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.



L1P785

Figure 1. Post-irradiation appearance of a pillowed plate L1P785.

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, and coolant conditions as input. The model output includes temperature, stress and deformation history in the fuel, cladding and zirconium diffusion barrier [4,5]. The behavior models include fission heat source, swelling due to solid and gaseous fission products [6], irradiation-induced creep [7], 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 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 is given elsewhere [1,2], the power history and spatial power distribution in plates L1P785, L1P7A0, L1P756, analyzed in this study are shown in Figure 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.

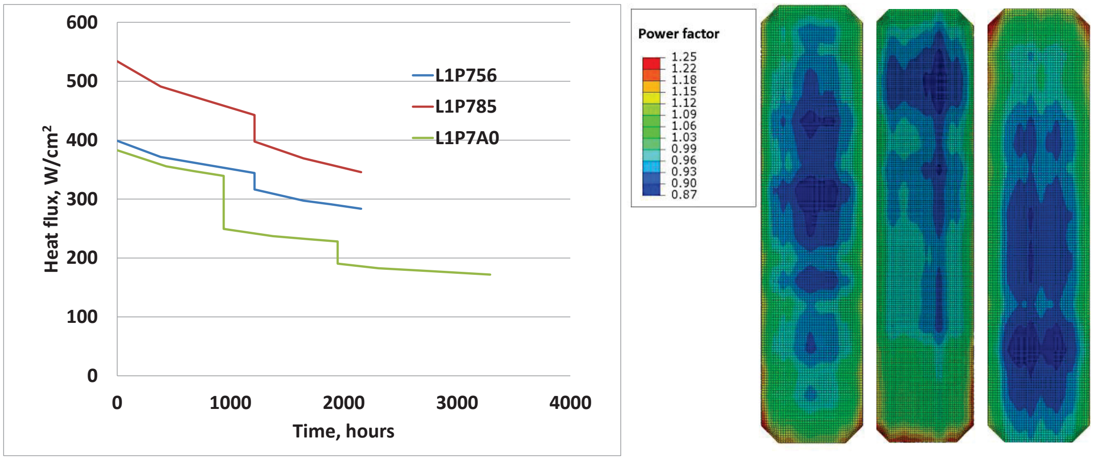


Figure 2. Power history and spatial power distribution
in plates L1P785, L1P7A0, L1P756 (left to right).

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 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 Figure 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 Figure 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.

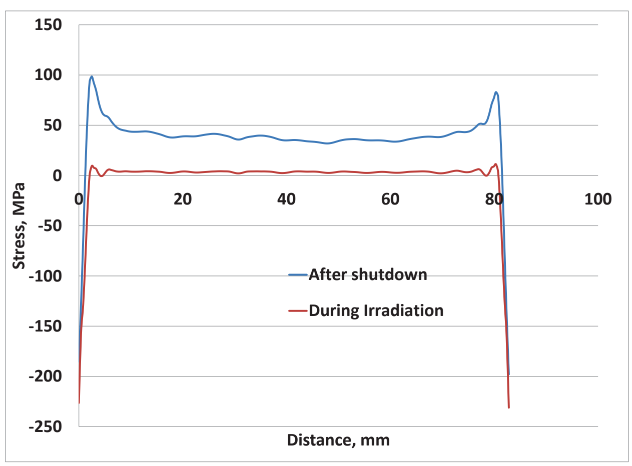


Figure 3. Comparison of the calculated values of maximum principal stress
during irradiation and after the shutdown.

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 Figure 4. Examination of Figure 4 and Figure 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 the plate pillowing and high tensile stress in the fuel observed after the shutdown.

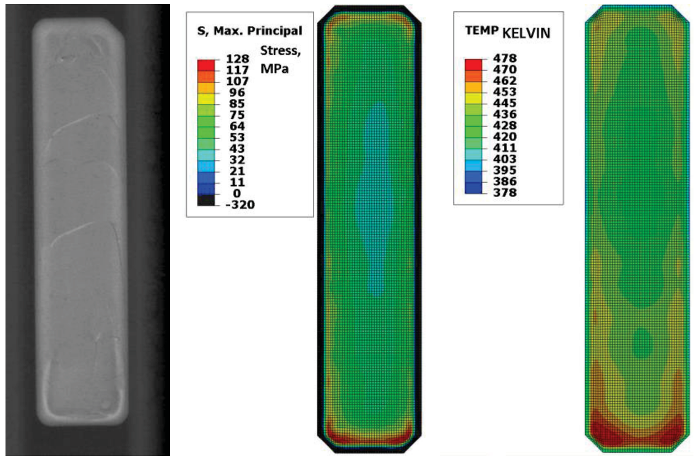


Figure 4. Left: neutron radiography image,
Center: contour plot of the maximum principal stress at the fuel mid-plane,
Right: the pre-shutdown fuel temperature.

Examination of the pre-shutdown fuel temperature contour shown in Figure 4, suggests that the peak stress is occurring at the peak temperature locations, which leads to a conclusion that the stress is due to thermal effects in the fuel. The temperature gradients are explained by the power gradients and by a more efficient cooling of the fuel edges. During the thermal transient occurring on the shutdown, the thermal strain, being a product of a thermal expansion coefficient and a temperature change, is greater in the locations of the fuel that operate at higher temperatures.

4.2 Comparison of the shutdown-induced tensile stress with the fuel strength

According to the maximum stress failure criterion, a material failure is expected if the maximum principal stress in the material exceeds its uniaxial tensile strength. Therefore, it is of interest to compare the values of maximum principal stress in the fuel with the fuel strength. Results of the bending strength measurements [8] performed at the INL on fuel foil samples taken from irradiated AFIP-3 plates are shown in Table 1.

Sample ID	Bending strength, MPa	Burnup, fissions/cm^3
3BZ-3	156.5	2.42x10^{21}
3BZ-4	114.9	2.03x10^{21}
3TT-3	25.2	5.24x10^{21}
3TT-4	84.1	5.39x10^{21}

Table 1. Bending strengths and fission densities of irradiated U-10Mo fuel.

The values of the fuel foil strength shown in Table 1 range from 25.2 MPa to 156.5 MPa, and a decrease of strength with burnup is evident. The peak value of maximum principal stress calculated in plate L1P785 is 128 MPa. Recognizing that plate L1P785 peak burnup is 1.1x10^{22} fissions/cm^3, which is nearly twice the burnup of the AFIP-3 plates subjected to fuel strength measurements, it is concluded that the stress plate L1P785 has most likely exceeded the fuel foil strength resulting in fuel failure manifested by cracking.

4.3 Porosity interconnection and fission gas release

It has been postulated that gaseous fission products generated in the U-10Mo fuel form fission gas bubbles (pores) that contribute to the fuel swelling [6]. It is also well known [9,10] that, when fission gas induced swelling in metal fuel reaches 33% (which corresponds to a porosity of 24%), the porosity begins to interconnect, and the fission gas is released. To demonstrate the likelihood of porosity interconnection and fission gas release in plate L1P785, the calculated values of fuel porosity are mapped in Figure 5. Also shown in Figure 5, are the locations where porosity interconnection and fission gas release is expected. As evident from Figure 5, porosity interconnection and fission gas release are expected in the corners and edges of the fuel foil, with the bottom region of the foil being affected the most. The location of the most pronounced porosity interconnection and fission gas release coincides with the location of the pillow shown in Figure 1. Therefore, the formation of the pillow at the bottom of the fuel foil may be explained by the porosity interconnection and fission gas release in that fuel region.

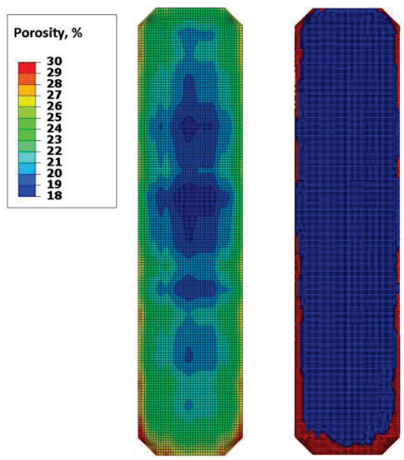


Figure 5. Left: map of fission gas porosity in the fuel;
Right: locations where porosity interconnection
and fission gas release are expected (shown in red).

4.4 Comparison with plates L1P7A0 and L1P756

To uncover possible fuel performance trends, the calculated values of temperature, stress, burnup, and porosity were compared among plates L1P785, L1P7A0, L1P756 listed in Table 2. Among the compared plates, plate L1P756 was the only plate that did not form a pillow. Examination of the data in Table 2 reveals that unlike the other two plates, plate L1P756 did not reach the 24% porosity threshold necessary for fission gas bubble interconnection and fission gas release. This observation may link plate pillowing to porosity interconnection and fission gas release. Recognizing that the fuel strength decreases with an increase of porosity, it is noted that the fuel strength would be the highest in plate L1P756, thus rendering it more resistant to the shutdown-induced stress. It appears that plate pillowing could be attributed either to the porosity interconnection, or to the shutdown-induced stress, or to both phenomena occurring simultaneously. Similar analysis for additional plates from the RERTR-12 experiment should be performed to better understand causes of pillowing. In addition, post-irradiation examinations seeking the evidence of porosity interconnection and fission gas release are needed.

Plate	Pre-shutdown temperature, C	Maximum principal stress after shutdown, MPa	Burnup, fissions/cm^3	Fission gas porosity, %	Plate pillowed?
L1P785	205	128	1.1×10^{22}	30	Yes
L1P7A0	135	73	1.0×10^{22}	27	Yes
L1P756	171	86	9.2×10^{21}	23	No

Table 2. Calculated peak values of temperature, stress, burnup, and porosity for plates L1P785, L1P7A0, L1P756.

4.5 Implications for the safe use of the monolithic fuel in research reactors

Based on the findings documented in this paper, the conditions for a destructive shutdown-induced stress are: (1) high pre-shutdown fuel temperature and (2) highly porous fuel featuring low strength. Because the maximum burnup expected in the low-enriched uranium (LEU) research reactor fuel is approximately 8×10^{21} fissions/cm^3, the maximum attainable fission gas porosity is 18.5%, as estimated using the methodology developed by Kim [6]. Maximum attainable fission gas porosity in LEU fuel is less than the porosity interconnection and fission gas release threshold (24%) and is less than the values calculated for plates L1P785, L1P7A0, L1P756 (23-30%). Therefore, the LEU fuel is not expected to reach porosity levels calculated in the pillowed RERTR-12 plates. Furthermore, LEU fuel operating at high burnup is unable to sustain high fission power necessary to achieve high fuel temperature. As shown in Figure 6, LEU fuel operating in a constant neutron flux exhibits a rapid power decrease due to the depletion of the fissile material. This is in contrast to the 70% enriched fuel used in RERTR-12 test capable of sustaining a heat flux of 300 W/cm^2 while having attained a burnup of 1×10^{22} fissions/cm^3. Indeed, due to lack of power generation, the temperature of the LEU fuel that has reached burnup of 8×10^{21} fissions/cm^3 is expected to be nearly equal to the coolant temperature, and development of significant shutdown-induced stresses in high-burnup LEU fuel does not seem possible. As the RERTR-12 experiment utilized highly-enriched uranium (HEU) fuel to achieve high fission rates in the available neutron flux, the power history of the RERTR-12 fuel was not prototypic of the LEU fuel; therefore, the fuel behavior observed in this experiment is also not prototypic of the LEU fuel. Nevertheless, the experiment has elucidated a new fuel failure mode and a definition of fuel operational limits.

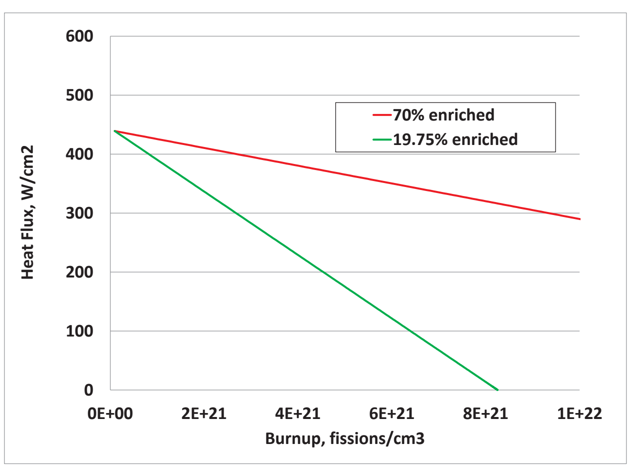


Figure 6. Heat flux in HEU and LEU fuels exposed to a constant neutron flux.

5 Conclusions

Based on the results of the thermo-mechanical analysis, pillowing in several RERTR-12 plates irradiated to a very high burnup has been attributed to a shutdown-induced stress in the fuel and/or to the fission gas release caused by interconnection of the fission gas porosity. These phenomena occurred because the fuel continued to operate at a considerable power while having attained burnup in excess of $1x10^{22}$ fissions/cm^3. Such a combination of burnup and power ensued because of high (70%) fuel enrichment used in the RERTR-12 experimental fuel plates.

The failure mode discussed in the present paper is not likely to occur in the LEU fuel, because the LEU fuel is not only unable to reach the burnup attained in RERTR-12 plates, but also unable to sustain the power necessary for development of shutdown-induced stress at the end of irradiation. Nevertheless, the experiment and modeling results yielded to a definition of operational limits of U-10Mo monolithic fuel.

Similar analysis for additional plates from RERTR-12 experiment should be performed to confirm the findings of this study. In addition, post-irradiation examinations seeking the evidence of porosity interconnection and fission gas release are needed. Finally, the calculations should be updated as better mechanical and thermal property data for the U-10Mo fuel become available.

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