DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Deployment and In-Reactor Test of an Instrument for Real-Time Monitoring Thermal Conductivity Evolution of Nuclear Fuels

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ABSTRACT:

The thermal conductivity of nuclear fuels is a critical physical property directly tied to reactor efficiency and safety. Low or reduced thermal conductivity in current fuels may cause unexpected, local temperature spikes that are directly related to the long-term fuel performance. In designing advanced nuclear fuels, targeting higher thermal conductivity will lead to the reduction of temperature gradients in the fuels. High conductivity can lower central fuel temperatures in current systems, reducing fission gas transport, or enable new system considerations such as increased coolant temperatures, raising the thermodynamic efficiency of electricity generation.

The accumulation of defects in reactor operation brings about a continual degradation of thermal conductivity. Coupled effects of high temperature and high neutron fluxes, and the induced multiple feedback mechanisms, further increase the complexity of defect accumulation and interaction, leading to continuous temporal and spatial variations of thermal conductivity in fuels over their lifecycle. Current studies and prediction of irradiation-induced thermal conductivity reduction and the underlying defect microstructure in fuels during their lifetime rely on nuclear fuel performance codes, whose experimental validation is primary through post-irradiation examination (PIE). Computational material scientists have speculated for years that in-reactor thermal conductivity can be significantly different from that measured after irradiation. The primary contribution to the reduction in thermal conductivity comes from the accumulation of point defect caused by irradiation. However, their elevated populations are only in equilibrium while displacement damage is taking place under high neutron fluxes. The majority of the small-scale defects will anneal or cluster into larger defects prior to PIE. Thus, the ability to monitor the thermal conductivity of fuels in real-time, in reactor, is necessary for a complete understanding of a nuclear reactor systems. This technical gap still exists primarily due to the extreme, high temperature and high radiation in-reactor environments.

Photothermal radiometry (PTR) is an ideal candidate to meet this challenge. In this method, thermal conductivity is measured through locally heating a sample surface and measuring the transient temperature response by collecting infrared (IR) black-body radiation at specific positions. This approach has unique advantages over other measurement techniques and is well suited to in-reactor environments. As a laser-and-fiber-optic-based instrument, the local heating and signal collection are accomplished in a non-contact and remote way. This approach differs from other laser-based techniques as it requires only single-sided access and does not require surface preparation. Rough surfaces and high temperature environments, common challenges for other measurement techniques, boost the accuracy of the PTR instrument due to an increase in surface emissivity and the scaling of radiant flux associated with black-body radiation.

This project will deploy a recently-developed fiber-optic-based PTR instrument in the MIT Research Reactor (MITR) to perform in-reactor thermal conductivity measurements of nuclear fuels. This instrument is capable of performing thermal conductivity measurement in a temperature range commensurate with reactor operation in a remote and non-contact manner, and is highly tolerant to environmental noise and fuel surface deterioration. The MITR is the ideal collaborative facility to validate the in-reactor performance of this PTR instrument as programs for in-core testing of advanced ultrasonic and fiber-optic sensors for high temperature use are ongoing. The high technical readiness of the equipment combined with the extensive personnel expertise will be key to the success of this work.