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Changing the World's Energy Future

Matilda Aberg Lindell, Brian Durtschi, David Kamerman, Travis Labossiere-Hickman

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Matilda Åberg Lindell, Brian Durtschi, David Kamerman, Travis Labossiere-Hickman

Idaho National Laboratory, 1955 N. Fremont Avenue, Idaho Falls, ID 83415, Matilda.AbergLindell@INL.gov

INTRODUCTION

Background

In the wake of the Fukushima Daiichi nuclear power plant accident in 2011, the accident tolerant fuels (ATF) program was initiated to enhance the safety of light-water reactor fuels [1], placing significant emphasis on cladding. A crucial step for the broad implementation of ATF in commercial reactors involves irradiation testing of the fuel designs.

ATF-2D, the latest experiment in the ATF series, is slated to undergo irradiation in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). ATF-2D is a joint effort of the INL with industry partners General Electric Global Research; Framatome; General Atomics; the Japan Atomic Energy Agency; Hitachi-GE Nuclear Energy, Ltd; Global Nuclear Fuel-Japan Co., Ltd; Nippon Nuclear Fuel Development Co., Ltd; and Mitsubishi Heavy Industries, Ltd [2].

The ATF-2D test train design consists of four tiers, each housing six rodlets. The device will be inserted in Loop 2A within the central flux trap of the ATR (see Figure 1), and is anticipated to undergo irradiation throughout three 60-day cycles. Typical pressurized water reactor conditions will be emulated during the irradiation.

Objective

The objective of the work presented here is to dimension neutron-absorbing hafnium (Hf) components surrounding the fuel rodlets, such that the axial power profile is flattened, while simultaneously ensuring that the total fission power output of the entire test train remains below 200 kW. Three criteria are defined for the linear heat generation rates (LHGRs), all of which assume segments with a maximum height of 2 cm:

(1) The maximum LHGR on the top or bottom segment of the fuel stack shall not exceed the LHGR of adjacent segments by more than 10%,

(2) the segment local-to-maximum total fission heat rate in each specimen shall be ≥ 70%, and

(3) LHGRs for PWR sized pins enriched to 4.95% shall target a maximum in the span 440-485 W/cm.

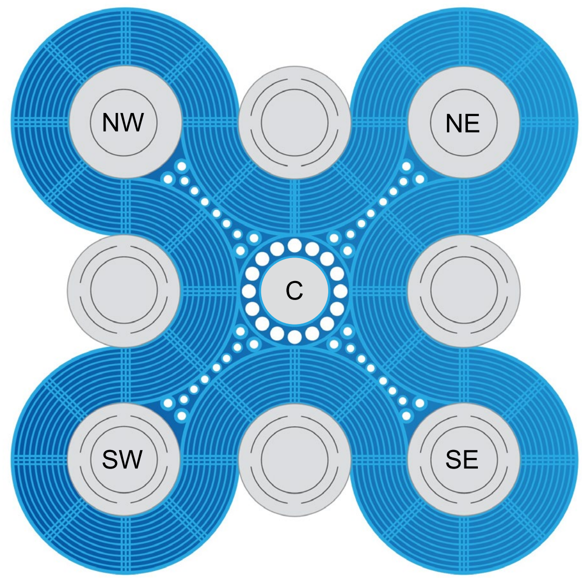

Fig. 1. Overview of the ATR core with its five lobes. The ATF-2D experiment will be placed in the central flux trap, inside the center lobe.

METHODOLOGY

Experiment configuration and modeling assumptions

The experiment configuration is presently in the design phase, undergoing incremental refinement to align with both safety requirements and programmatic goals. To accommodate customer flexibility, operational adaptability, and last-minute modifications, the experiment configuration incorporates bounding assumptions. For instance, treating all fuel as fresh 4.95% enriched uranium enables the replacement of these rodlets and pellets within the safety calculation framework. Furthermore, the fuel volume is conservatively overestimated, and the loop moderator is modeled without its boron content.

The rodlets in Tiers 1 (bottom), 3, and 4 (top), are modeled as standard PWR fuel with a pellet diameter of 8.2 mm and 0.57 mm thick zirconium alloy cladding, whereas the Tier 2 rodlets represent BWR fuel with a pellet diameter of 9.5 mm and zirconium alloy cladding thickness of 0.35 mm. The length of the uranium fuel stack is consistently 170 mm in every rodlet.

Each tier has a holder containing the rodlets. Three thin shroud components are located in each holder, surrounding the fuel, see Figure 2. These are (a) the *main shroud*, which is an approx. 20 cm tall, hollow cylinder covering the entire length of the rodlets, (b) the *lower shroud*, which surrounds the bottom of the rodlets up to approx. 1.9 cm, and (c) the *upper shroud* – a 3.8 cm tall piece which surrounds only the upper part of the rodlets. Thicknesses are varied in the scope of this work.

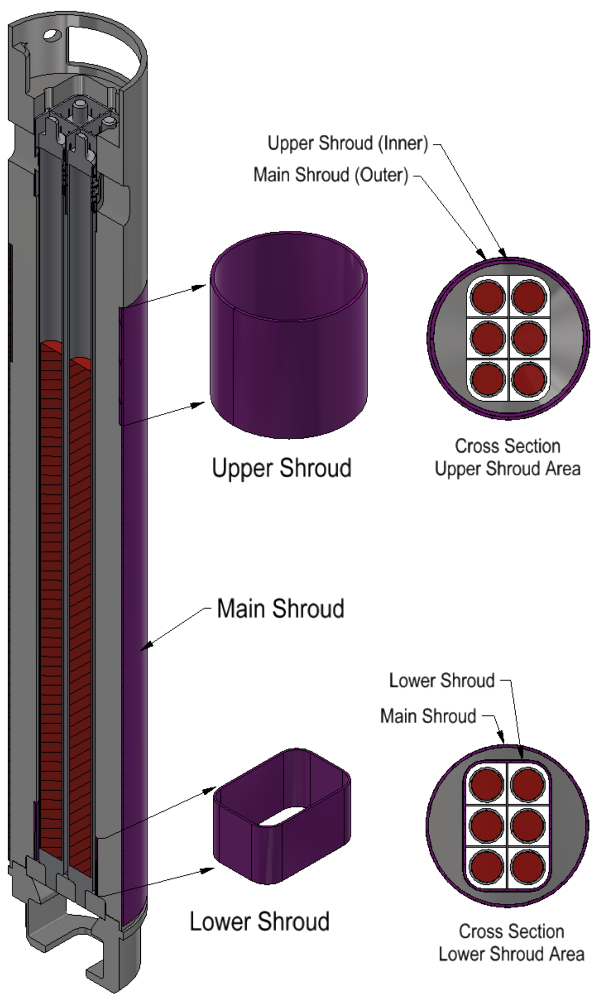

Fig. 2. Cross-sectional views of holder including six rodlets (red) and three shroud components (purple).

Code

Neutron transport calculations were conducted utilizing MCNP6.3 [3] and performed at the INL High Performance Computing Center.

Normalization method

To transform tally results per source particle into absolute neutron fluxes and reaction rates, normalization is required based on the average neutrons per fission (ν), average energy per fission (ε), and core power observed by the lobe, known as lobe-adjusted total core power (LATCP). The ATR comprises five lobes – northwest, northeast, center, southwest, and southeast – largely but not entirely independent of one another. LATCP serves to normalize reaction rates within a specific lobe (L), accounting for the overall lobe power distribution. Refer to Eq. 1 for the LATCP calculation, considering planned lobe power (Q_L), fission energy deposition tally result $(f7{:}n)_L$ for the lobe's driver fuel, and tally mass (m_L).

$$LATCP_L = \frac{Q_L}{(f7{:}n)_L \times m_L} \sum_{i=1}^{5} (f7{:}n)_i \times m_i \qquad (1)$$

Heating rate calculations

Heating rates in the experiment fuel were calculated using the MCNP fission energy deposition tallies of type 'f7'. Heat generation values (Q) in units of W were calculated using Eq. 2. For thermal fission in ^{235}U, ν/ε is here conservatively assumed to be 0.01215 fission neutrons per MeV [4].

$$Q = \frac{\nu}{\varepsilon}\,(LATCP)(f7{:}n) \times m \qquad (2)$$

CASE DESCRIPTIONS AND RESULTS

Several cases have been iteratively investigated in order to arrive at a satisfactory shroud configuration. This section provides a brief overview of each investigated case along with the corresponding calculation results. Figure 3 illustrates the LHGRs for cases 1-3, while Figure 4 shows the results for cases 4-7.

Case 1 – Zirconium only

The first case, serving as a baseline, does not include any Hf shrouds. Instead, the shroud cells in the MCNP model are filled with zirconium (Zr). Nominally, the thicknesses of the main, lower, and upper shrouds, respectively, are 28 mil (1 mil = 25.4 μm), 26 mil, and 36 mil.

Case 2 – Hafnium only

Case 2 has the same shroud dimensions as Case 1, but the material in all shroud components is Hf. The absorbing properties of the Hf substantially lower the LHGR in all tiers.

Case 3 – Hafnium/zirconium combined

For Case 3, the shroud pieces utilize the materials outlined in Table I. This configuration flattens the Tier 1 and Tier 4 profiles without excessively reducing the power. The main shroud thickness for Tiers 2 and 3 is decreased to 20 mil.

TABLE I. Case 3 shroud material configuration.

Tier	Lower shroud	Main shroud	Upper shroud
1 (bottom)	Zr	Zr	Hf
2	Hf	Hf	Hf
3	Hf	Hf	Hf
4 (top)	Hf	Zr	Zr

Case 4 – Split main shrouds

In Case 4, a divided main shroud is featured in Tiers 1 and 4, with one half composed of Hf and the other half of Zr. The Hf sections are oriented towards the core axial center plane, where neutron absorption is needed the most. The impact on the power profile is notable, surpassing the intended objective of achieving a flat profile.

Case 5 – Hafnium disks

In Case 5, the shroud configuration remains consistent with that of Case 4. However, to mitigate end-effects in each rodlet, Hf disks with a thickness of 1/16 in. (approx. 1.6 mm) are introduced at both the top and bottom of every fuel stack. The radius of the disks corresponds to that of the fuel pellets. The disks clearly and effectively mitigate the end-effects.

Case 6 – Final configuration, no hafnium disks

The final iteration of the shroud optimization includes adjustments to the shroud thickness, according to Table II. Additionally, the Tier 2 holder containing BWR rodlets is made from stainless steel instead of Zr. Hf disks are absent in this configuration, making it the most conservative setup intended for safety calculations.

Case 7 – Final configuration with hafnium disks

The shroud arrangement in Case 7 mirrors that of Case 6, but the Hf disks are present. This case is used in the evaluation of programmatic requirements.

Conclusion

The programmatic goals (1)-(3) concerning axial distribution of LHGR are fulfilled when the Case 7 configuration is adopted. The total fission power in Case 6 is 192 kW when accounting for both an 8.5% uncertainty in the lobe power indication system and a 5% increase in LHGR to account for fabrication uncertainties. Consequently, the safety limit of 200 kW total fission power is met. The inclusion of Hf disks in the test train slightly reduces the overall fission power, but they are not required from a safety perspective.

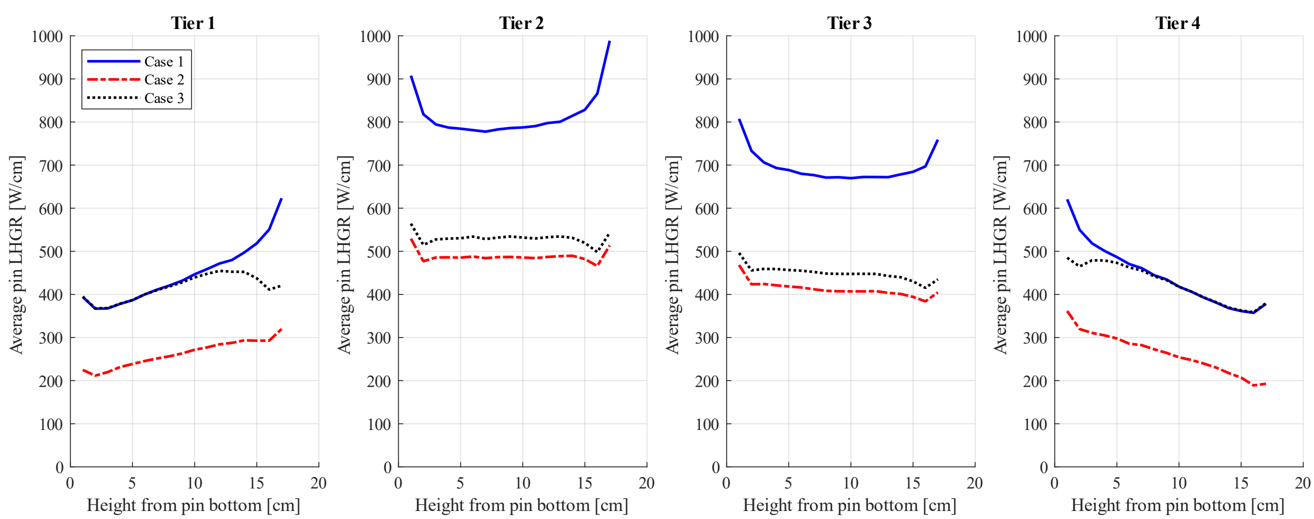

Fig. 3. Average LHGRs for Cases 1-3. Note that the axial power profile over the entire test train roughly follows the cosine-shaped power profile of the ATR reactor.

TABLE II. Final configuration of the ATF-2D shroud components.

	Lower shroud		Main shroud, bottom		Main shroud, top		Upper shroud	
Tier	Material	Thickness	Material	Thickness	Material	Thickness	Material	Thickness
1 (bottom)	Zr	26 mil	Zr	10 mil	Hf	10 mil	Hf	36 mil
2	Hf	26 mil	Hf	20 mil	Hf	20 mil	Hf	36 mil
3	Hf	36 mil	Hf	20 mil	Hf	20 mil	Hf	26 mil
4 (top)	Hf	36 mil	Hf	10 mil	Zr	10 mil	Zr	26 mil

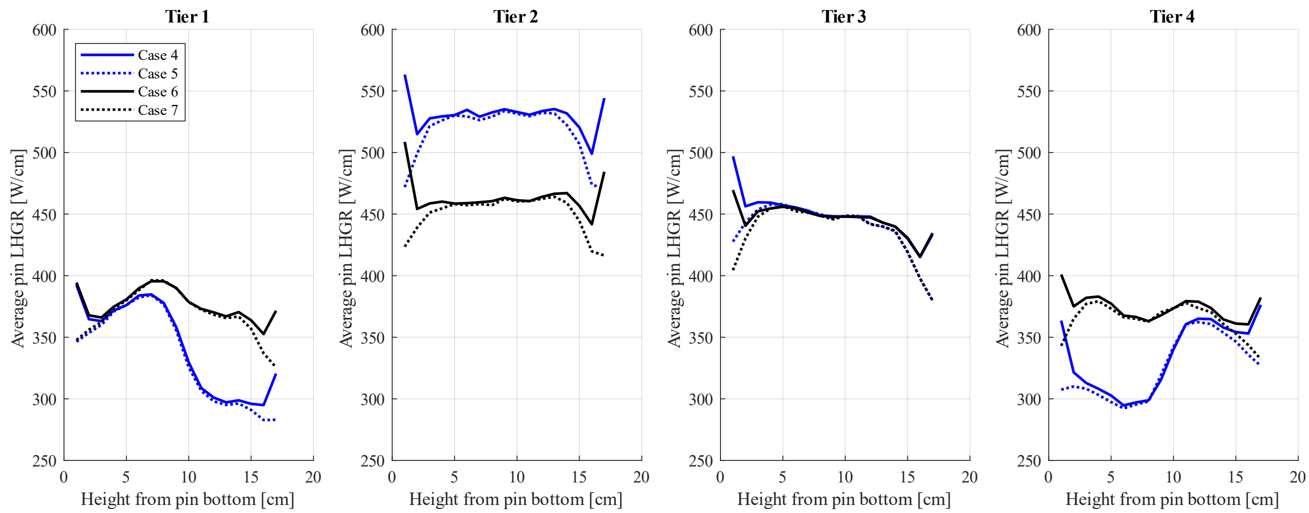

Fig. 4. Average LHGRs for Cases 4-7. The presence of Hf disks at the top and bottom of each fuel stack (Cases 5 and 7) efficiently counteracts end-effects at the respective extremities of the rodlets.

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