INL/CON-24-78167-Revision-0

Refining Absorber Shroud Geometry to Maximize Power Output and Reduce Power Peaking in ATF Test Train

June 2024

Changing the World's Energy Future

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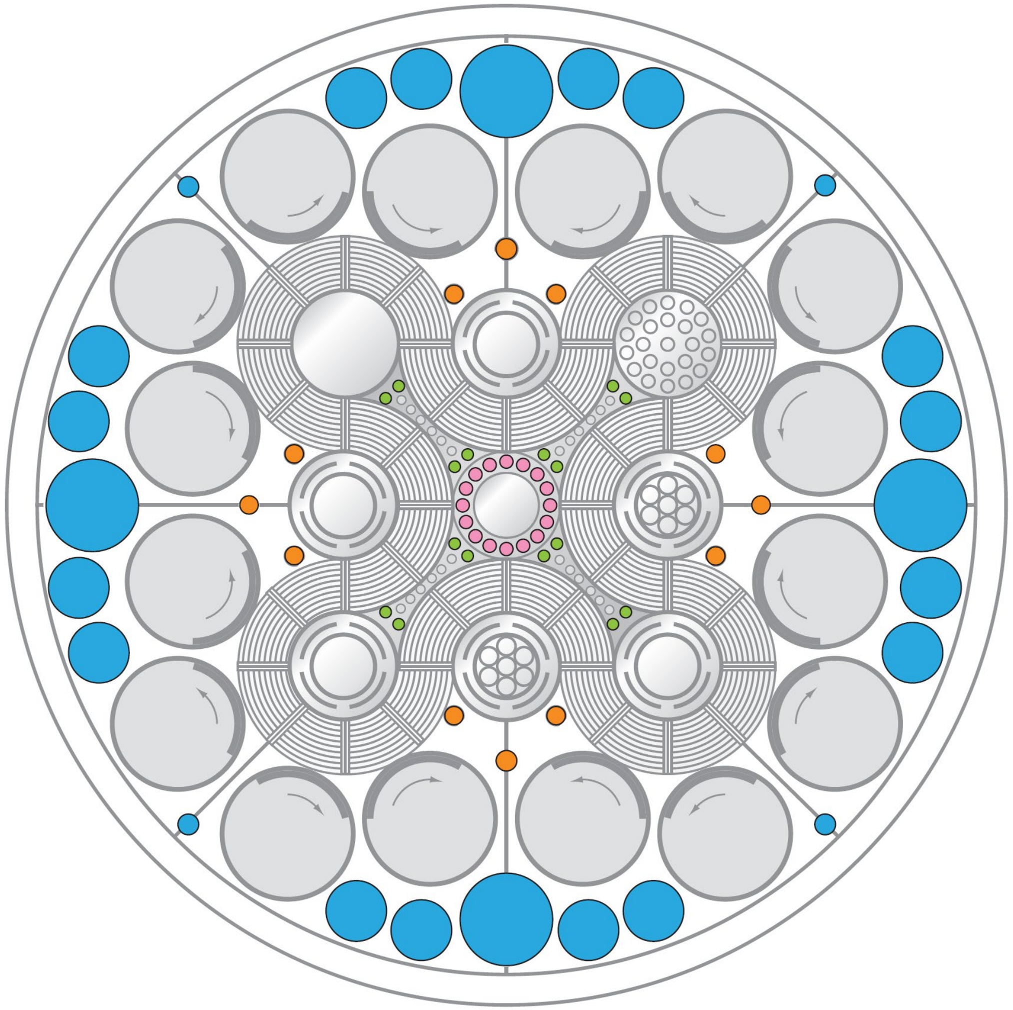
The Accident Tolerant Fuels (ATF) Program

- Initiated by **DOE-NE** following the 2011 Fukushima accident.
- Focused on developing nuclear fuels and claddings with enhanced accident tolerance.
- **ATF definition: Fuels that can tolerate loss of active cooling in the reactor core for a considerably longer time period in comparison with the standard UO_2 – Zircaloy system.**
- Potentially important attributes:
  - Reduced hydrogen generation (resulting from cladding oxidation),
  - Enhanced fission product retention under severe accident conditions,
  - Reduced cladding reaction with high-temperature steam, and
  - Improved fuel-cladding interaction for enhanced performance under extreme conditions.

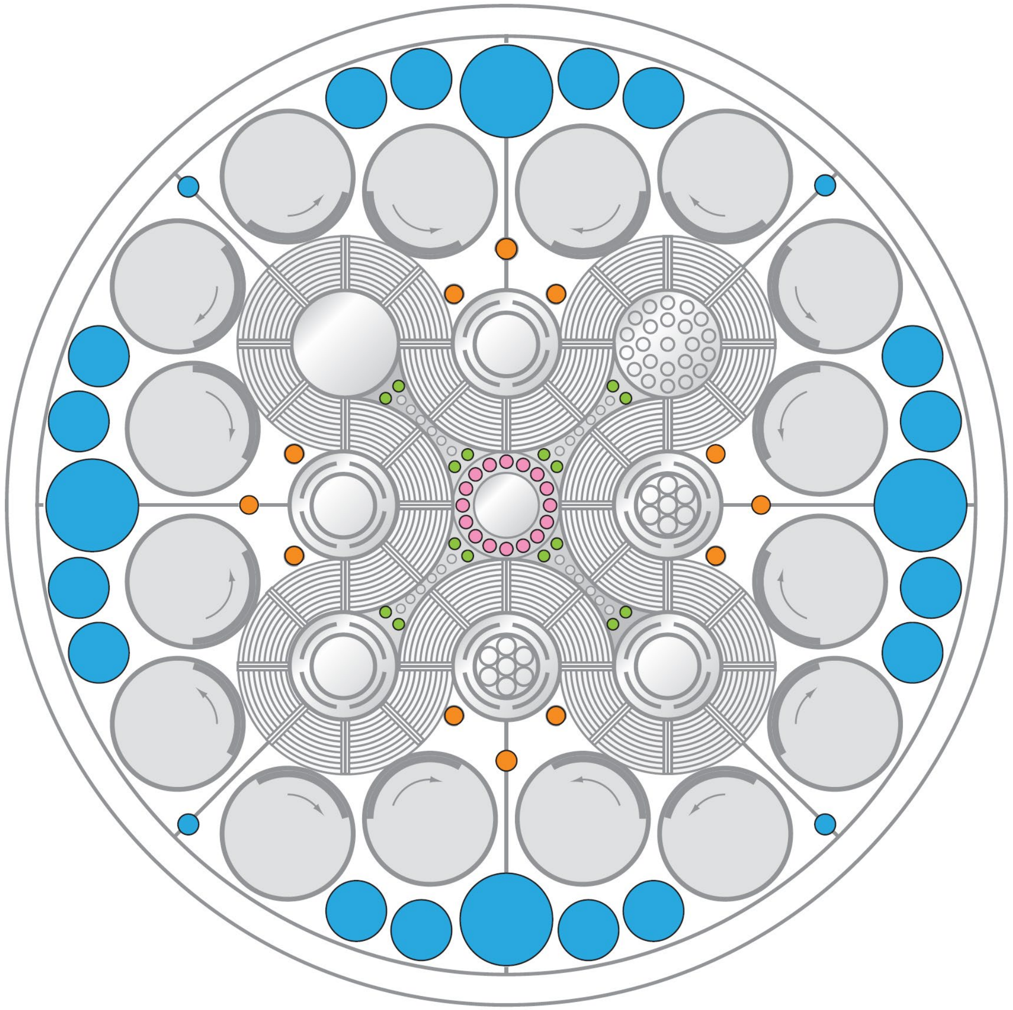
Advanced Test Reactor (ATR)

- One-of-a-kind pressurized water test reactor.
- ATR thermal power
  - Maximum: 250 MW_{Th}
  - Typical operation: 110 MW_{Th}
- Regular cycles last approx. 60 days.
- Corner lobes can be independently operated at different power levels, making it possible to conduct multiple simultaneous experiments under different testing conditions.
- 77 test positions available.
- Peak flux in Center Flux Trap at 110 MW_{Th}
  - Thermal: 4.4×10^{14} n/cm^2-s
  - Fast: 2.2×10^{14} n/cm^2-s



The ATF-2D Experiment

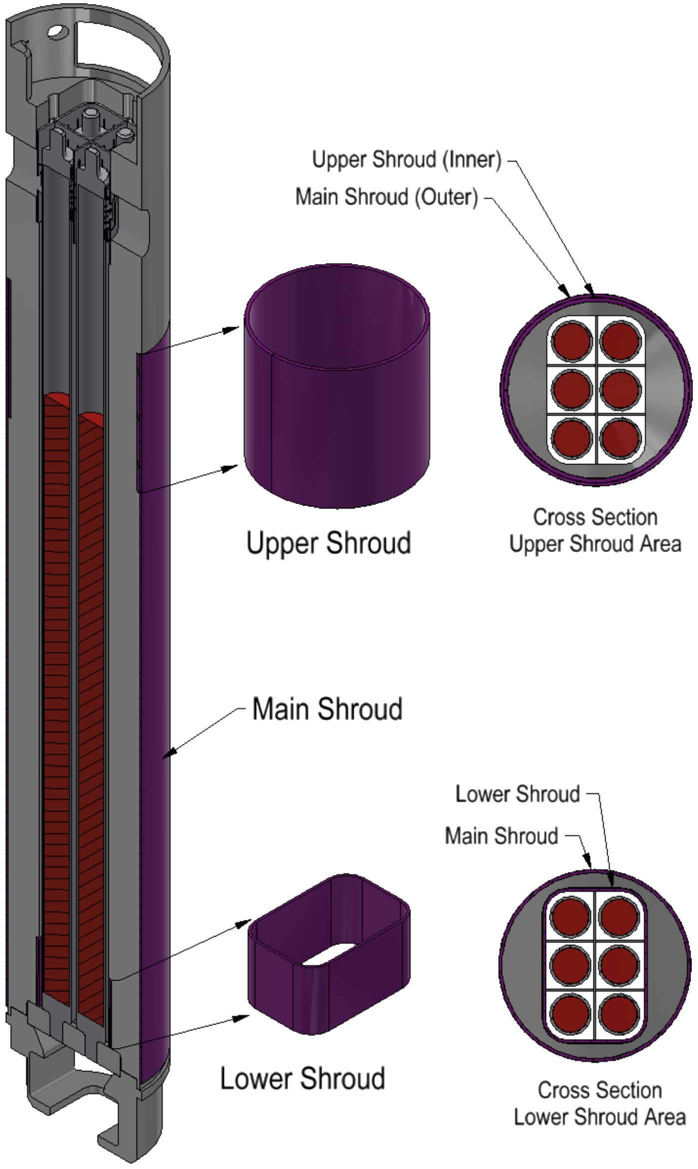
- ATF-2D is the latest experiment in the ATF series.
- Joint effort of the INL with industry partners (mainly fuel vendors).
- Irradiation in the ATR Center Flux Trap tentatively starting in June 2025.
- Closed loop with typical PWR conditions.
- Experiment design not yet finalized.



Experiment Design

- 4 holders (Zr or SS-316), vertically stacked in test train.

- Each holder houses 2×3 array of rodlets.
- Modeled rodlet dimensions
  - Fuel stack length: 17 cm
  - Pellet diameter: 8.2 mm and 9.5 mm.
- UO_2 fuel with varying enrichments, some Cr-doped. All modeled as UO_2 with 4.95% ^{235}U.
- Cladding materials: Zircaloy-4, SiC, FeCrAl, and M5 with and without coating. All modeled as Zirc-4 here.
- Upper, Main and Lower shrouds in each holder.



Power Output and Profile Criteria

Safety criterion:

1. Total fission power output of the entire test train **≤ 200 kW**

Programmatic criteria (assuming max. 2 cm segments):

1. Max. LHGR in the top or bottom segment shall not exceed the LHGR of adjacent segments by more than **10%**
2. The segment local-to-maximum fission heat rate shall be **≥ 70%**
3. Max. LHGR for PWR pins shall be in the span **440-485 W/cm**

Calculations

- **MCNP 6.2** used for neutron transport and reaction rates.

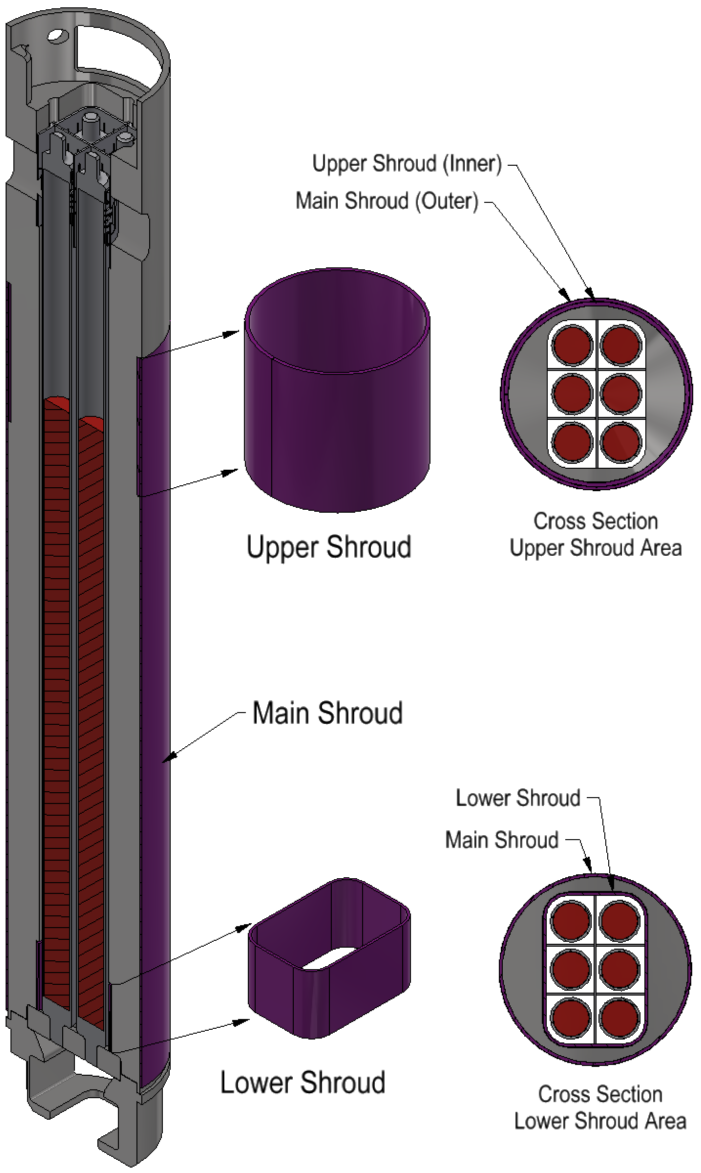
- MCNP tally results (per particle) normalized to absolute neutron fluxes and reaction rates based on
  - average neutrons per fission,
  - average energy per fission,
  - total core power, and
  - power split between the five ATR lobes.

- Calculations performed using INL's High Performance Computing systems.

Shroud Design #1 and #2

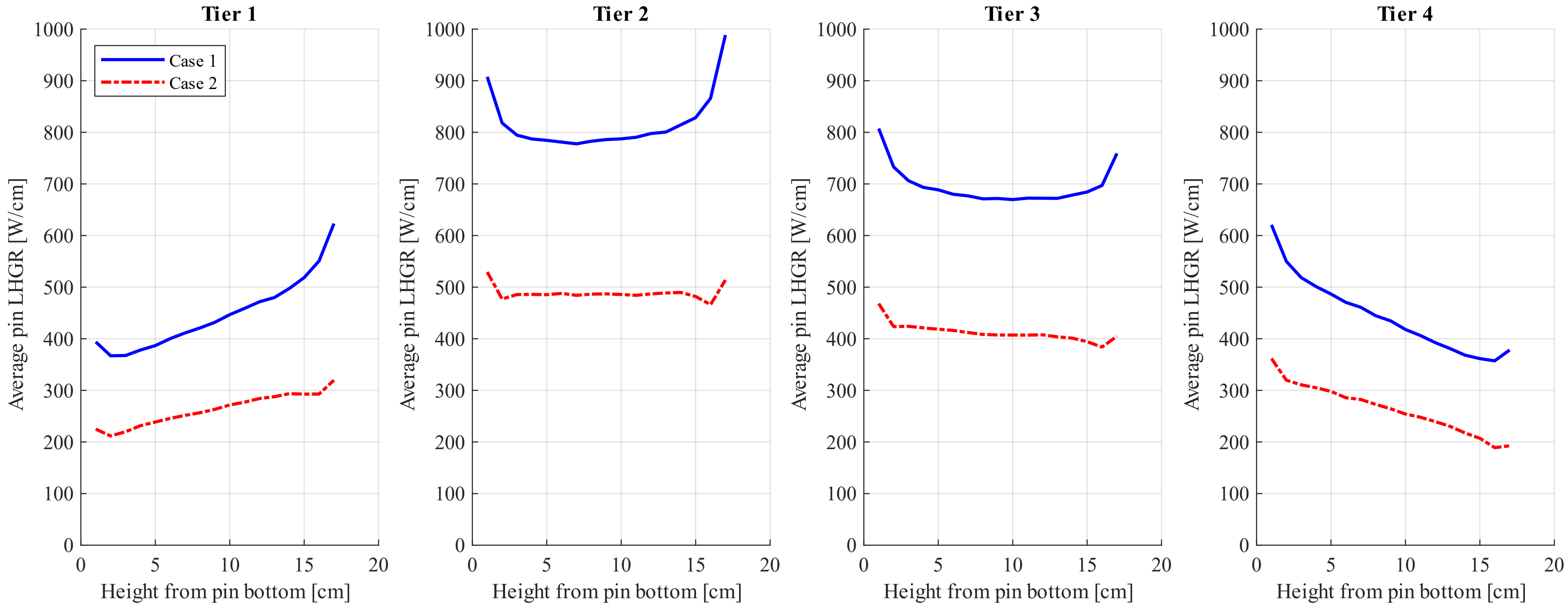
- **Case 1: Zirconium only**
  - Baseline
  - Thickness for Upper, Main, and Lower shrouds: 36 mil, 28 mil, and 26 mil.
  - All holders modeled as Zr.

- **Case 2: Hafnium only**
  - Same thicknesses



Shroud Design #1 and #2

- **Case 1: Zirconium only** Total power: 279 kW (< 200 kW)
- **Case 2: Hafnium only** Avg. LHGR reduction ~60%

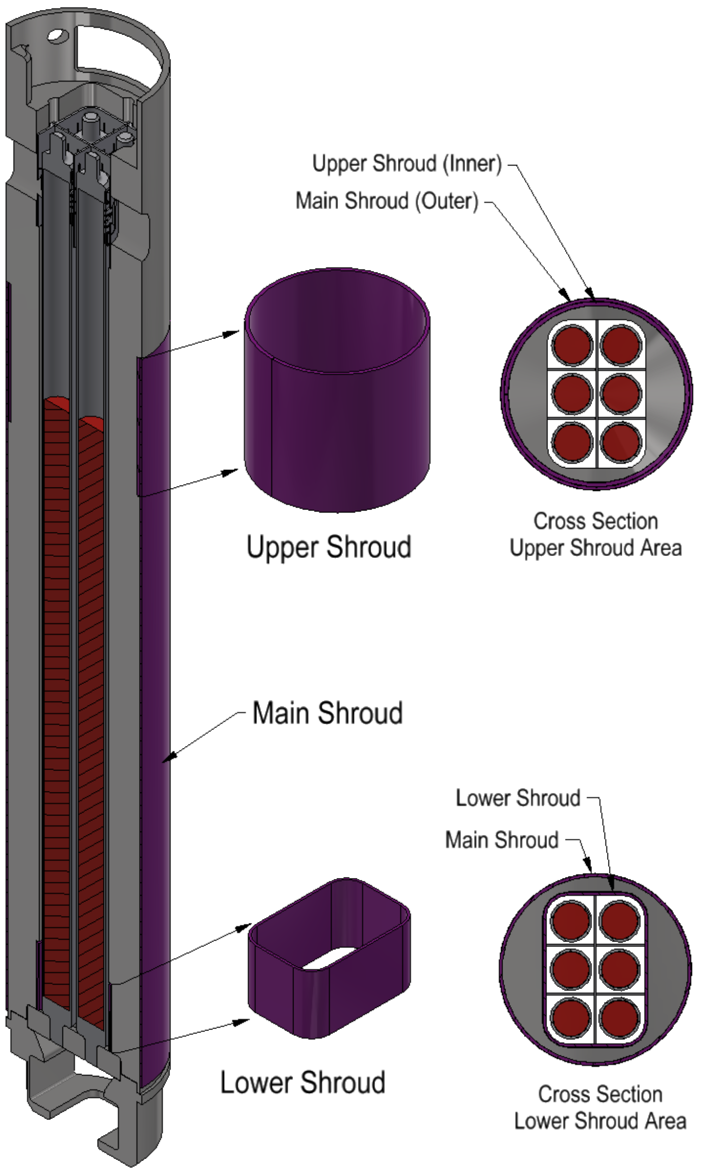


Shroud Design #3

- **Case 3: Hafnium/zirconium combined**
  - Most shrouds made from Hf.
  - Shrouds at top/bottom of test train made from Zr

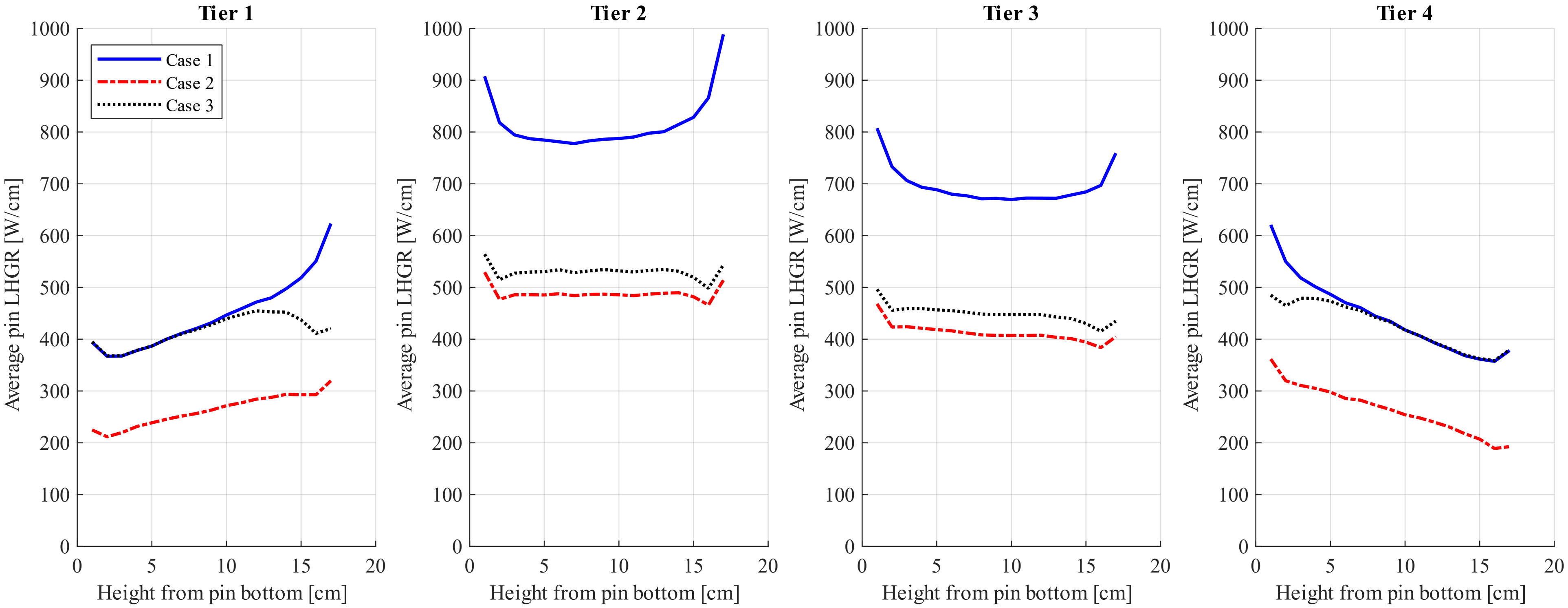
Tier	Lower shroud	Main shroud	Upper shroud
1 (bottom)	Zr	Zr	Hf
2	Hf	Hf	Hf
3	Hf	Hf	Hf
4 (top)	Hf	Zr	Zr

  - Main shroud thickness for Tiers 2 and 3 reduced to 20 mil.



Shroud Design #3

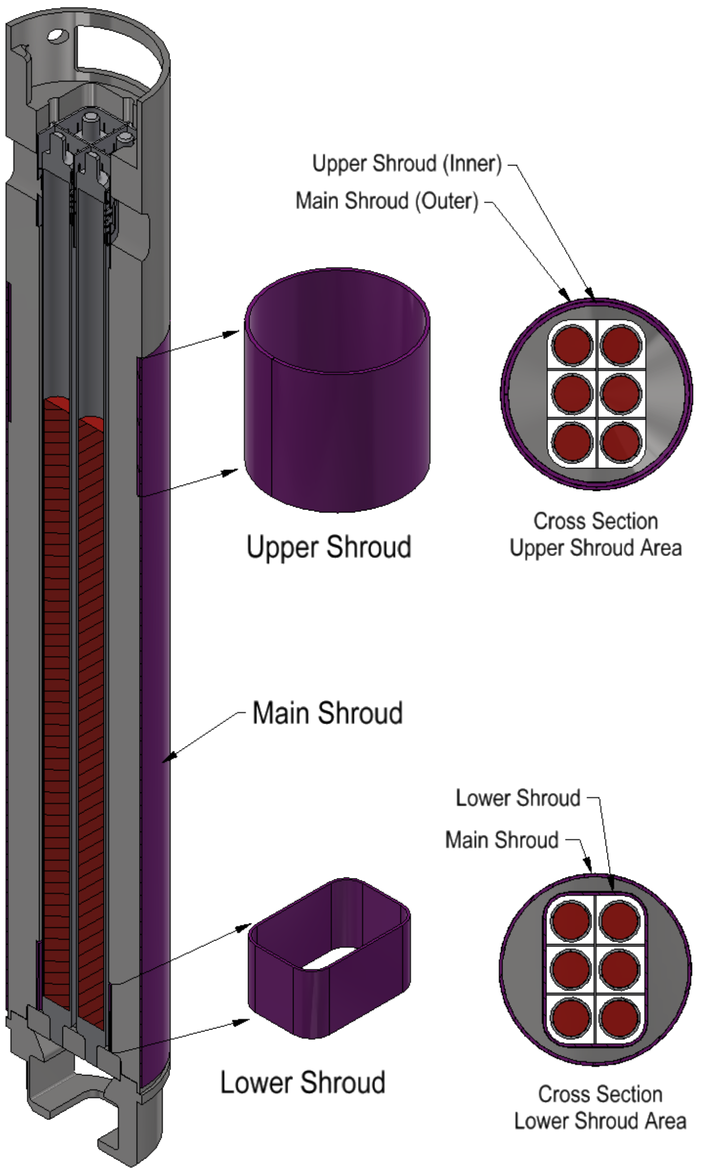
- **Case 3: Hafnium/zirconium combined**
  - Tiers 1 and 4 somewhat flattened.
  - Total power: 211 kW



Shroud Design #4 and #5

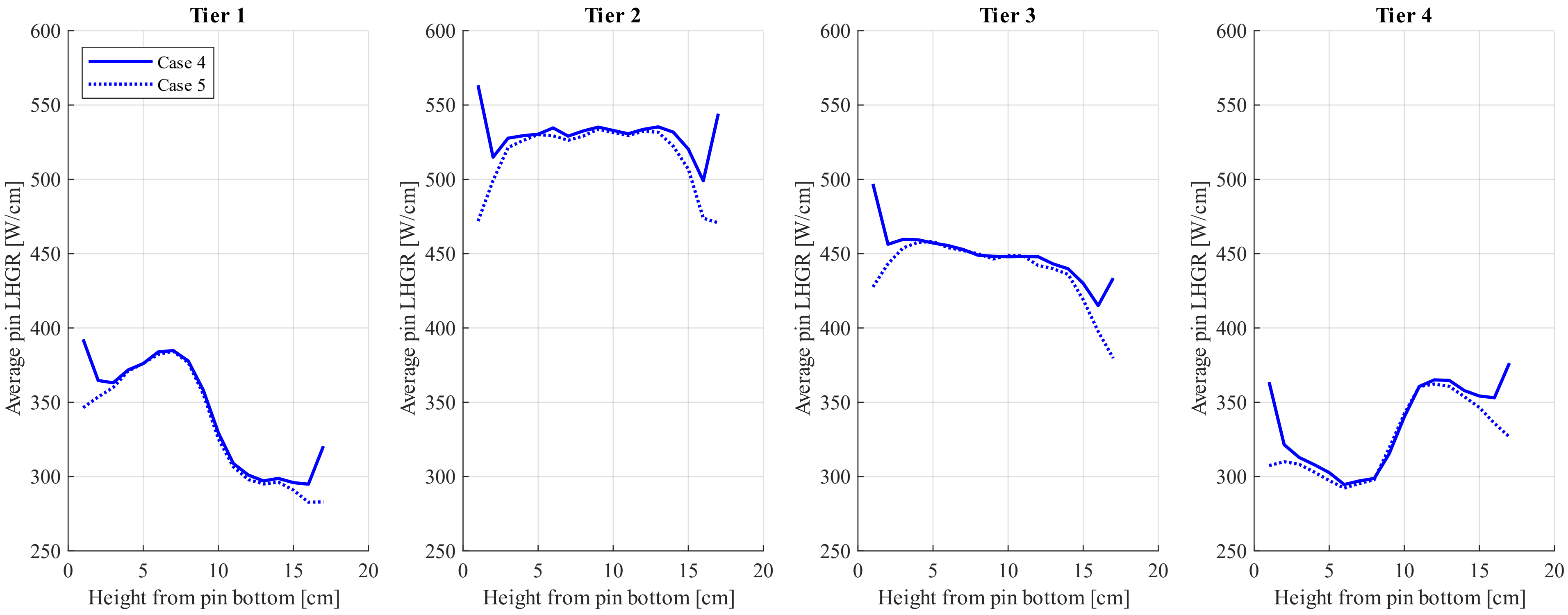
- **Case 4: Split Main shrouds**
  - Like Case #3 but Tiers 1 and 4 Main shrouds split in half. Hafnium closest to axial core center plane, zirconium away from center plane.

- **Case 5: Hafnium disks**
  - Like Case #4 but has 1/16-inch hafnium disks at both the top and bottom of every fuel stack.



Shroud Design #4 and #5

- **Case 4: Split Main shrouds** — T1 and T4 have too much Hf – not flat!
- **Case 5: Hafnium disks** — End-effects suppressed



Shroud Design #6 and #7

- **Case 6: Final configuration, no hafnium disks**
  - Thinner shrouds in T1 & T4
  - T2 holder modeled as stainless steel
  - Used in preliminary safety evaluations

Tier	Lower shroud		Main shroud, bottom		Main shroud, top		Upper shroud	
	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

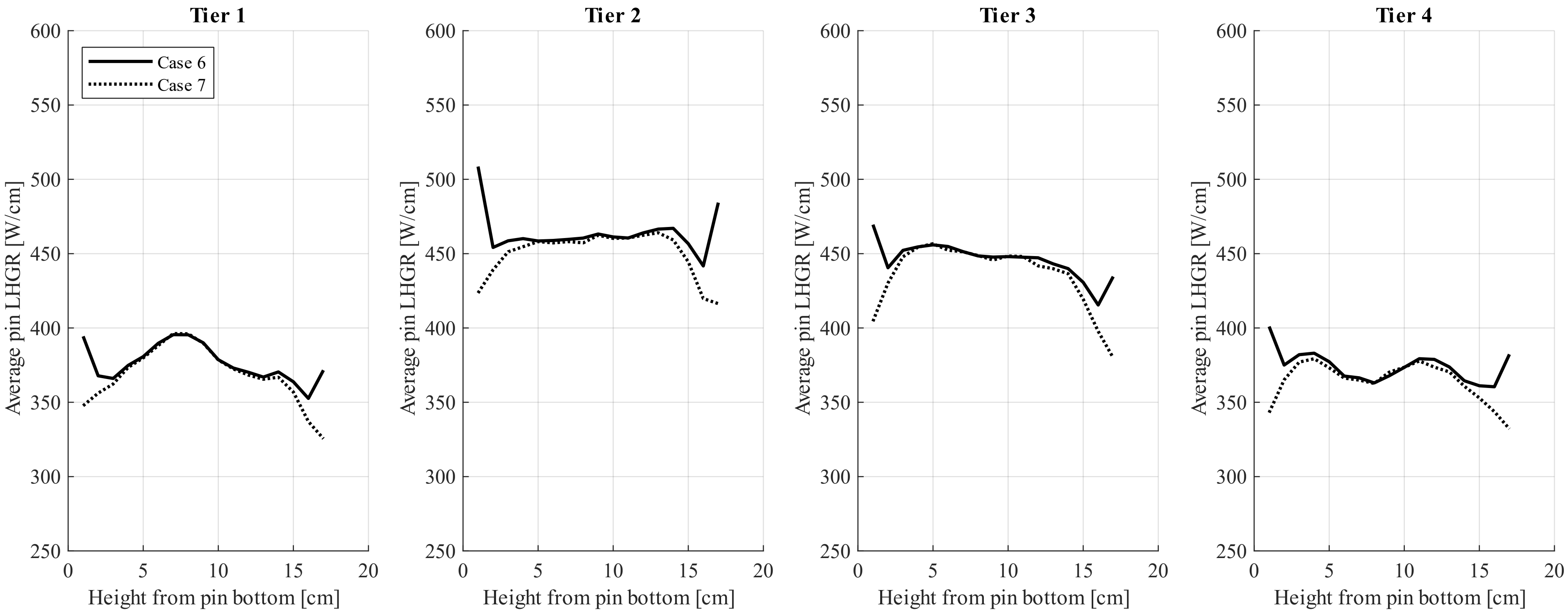
- **Case 7: Final configuration with hafnium disks**
  - Used in preliminary programmatic evaluations

Shroud Design #6 and #7

- **Case 6: Final configuration, no hafnium disks**
- **Case 7: Final configuration with hafnium disks**

Total power: 193 kW

All requirements met!



Future Work to Prepare for Irradiation

- **Establish final design**
  - Based on customer requests and INL's analyses
  - May require multiple iterations
  - Model a conservative safety case and a best-estimate case

- **Calculations to ensure requirements met:**
  - Total fission power
  - Programmatic LHGR requirements
  - Reactivity worths (experiment vs. backup, and multiple accident scenarios)
  - 3-cycle projection calculations, incl. decay heat and radioactivity source terms
  - Driver fuel axial perturbation
  - Thermal and structural analyses downstream from neutronics calculations
  - etc.

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