INL/CON-24-81996-Revision-0

ANS Winter 2024 Slides: Optimizing the ATF-2Ramp Power Profile

November 2024

Travis J Labossiere-Hickman, Brian P Durtschi, David W Kamerman

Changing the World's Energy Future

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Idaho Falls, Idaho 83415

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517, DE-AC07-05ID14517, DE-AC07-05ID14517

November 19, 2024

Travis J. Labossiere-Hickman
Brian Durtschi, David Kamerman

Optimizing the ATF-2Ramp Power Profile

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

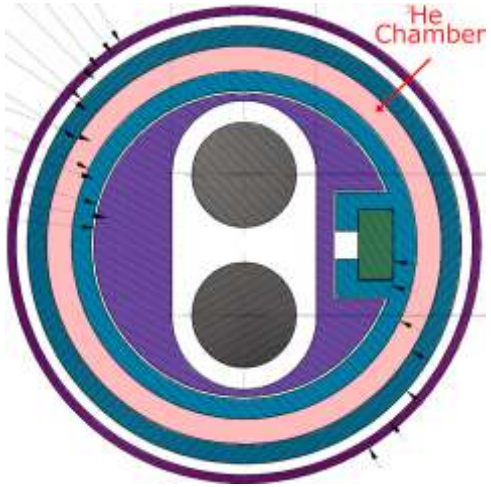
Idaho National Laboratory

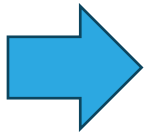
Background

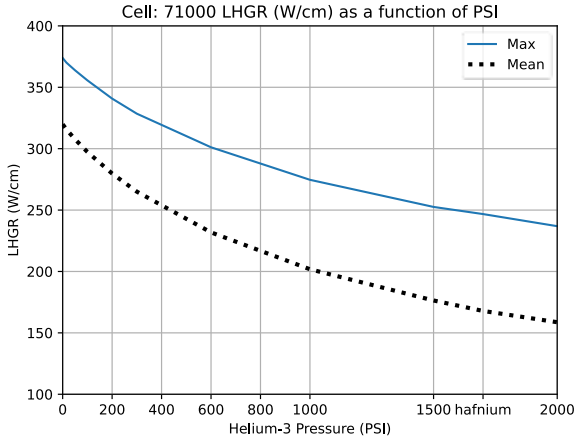
Motivation

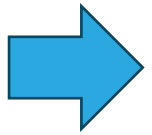
- Following the closure of the Halden Boiling Water Reactor in 2018, it became important to develop new in-reactor power ramp testing capacity.
- Ramp testing is important to the Accident Tolerant Fuel (ATF) program to study the effects of pellet-cladding interactions.
- ATF-2Ramp is a proposed irradiation experiment to be placed in the in the center flux trap (CFT) of the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) during powered axial locator mechanism (PALM) cycles.
- The objective of this work is design and optimize a test train (TT) for ATF-2Ramp so that it achieves a peak pin linear heat generation rate (LHGR) power ramp of 250-600 W/cm.

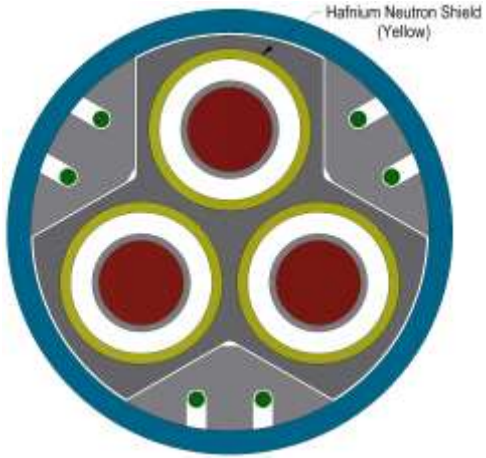
Previously…

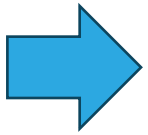

He
Chamber

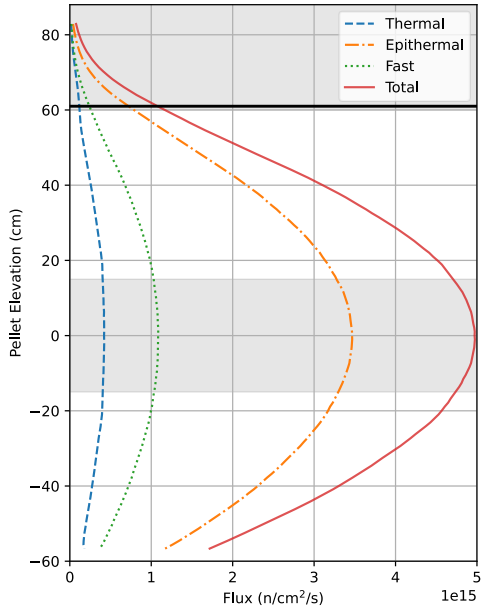


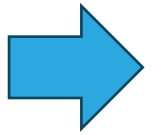

Cell: 71000 LHGR (W/cm) as a function of PSI
Max
Mean
LHGR (W/cm)
Helium-3 Pressure (PSI)
1500 hafnium




Hafnium Neutron Shield
(Yellow)




Thermal
Epithermal
Fast
Total
Pellet Elevation (cm)
Flux (n/cm²/s)
1e15



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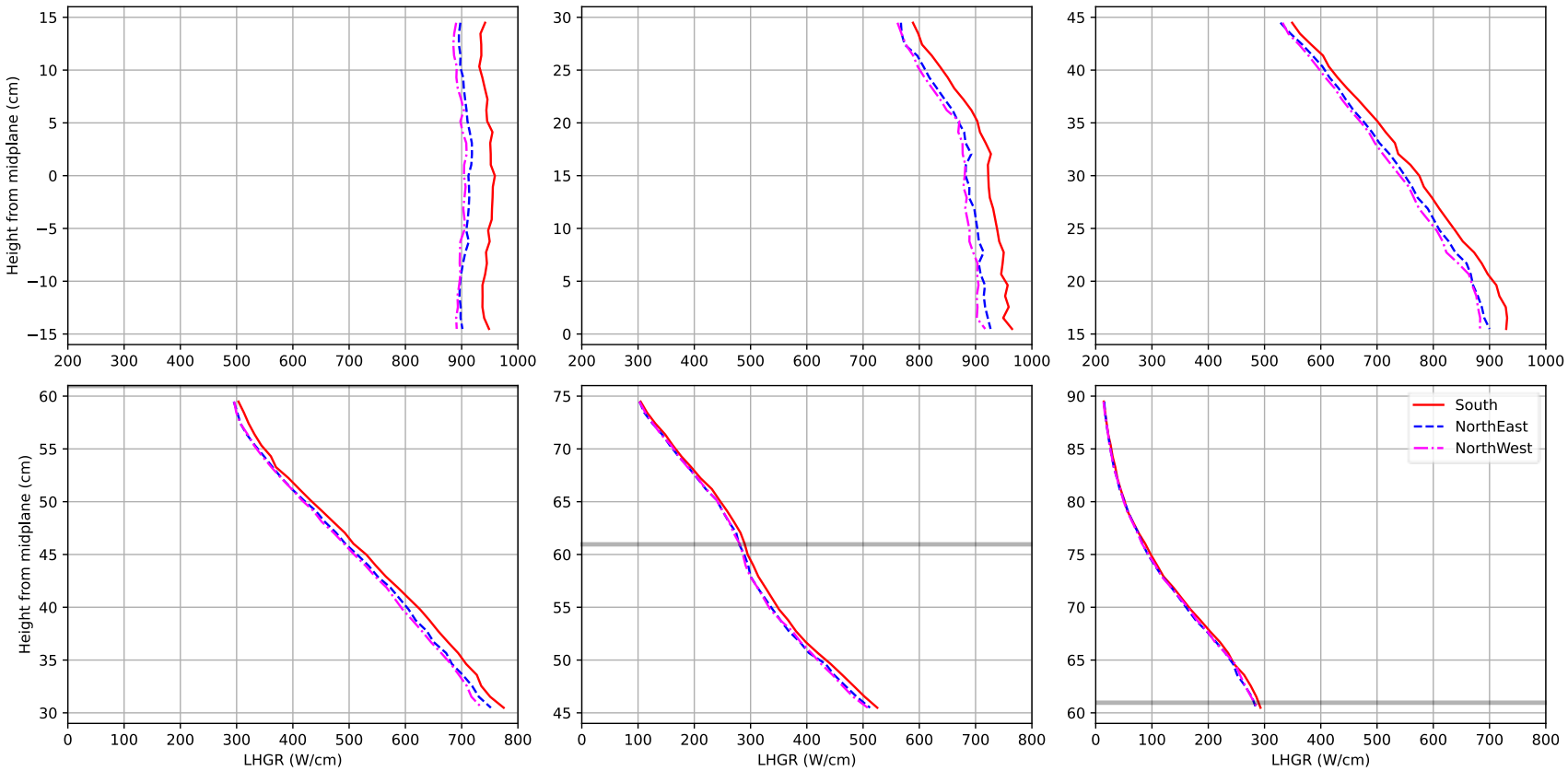
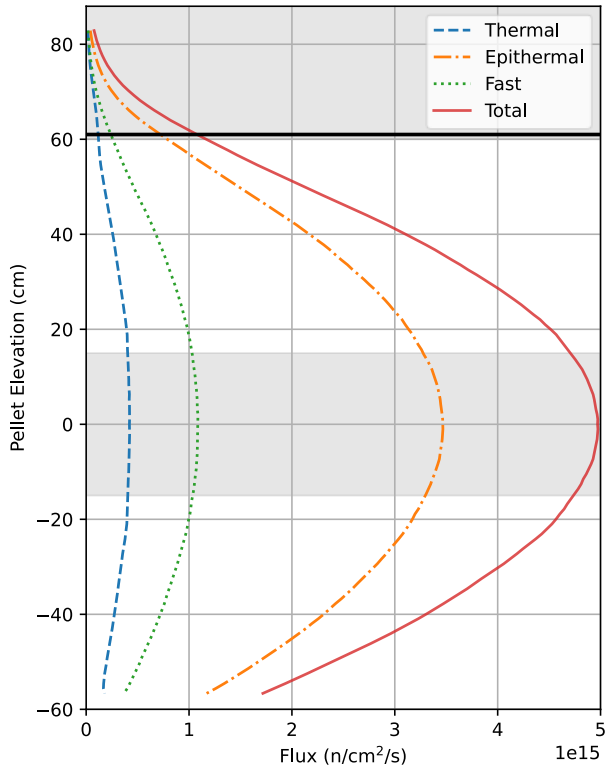
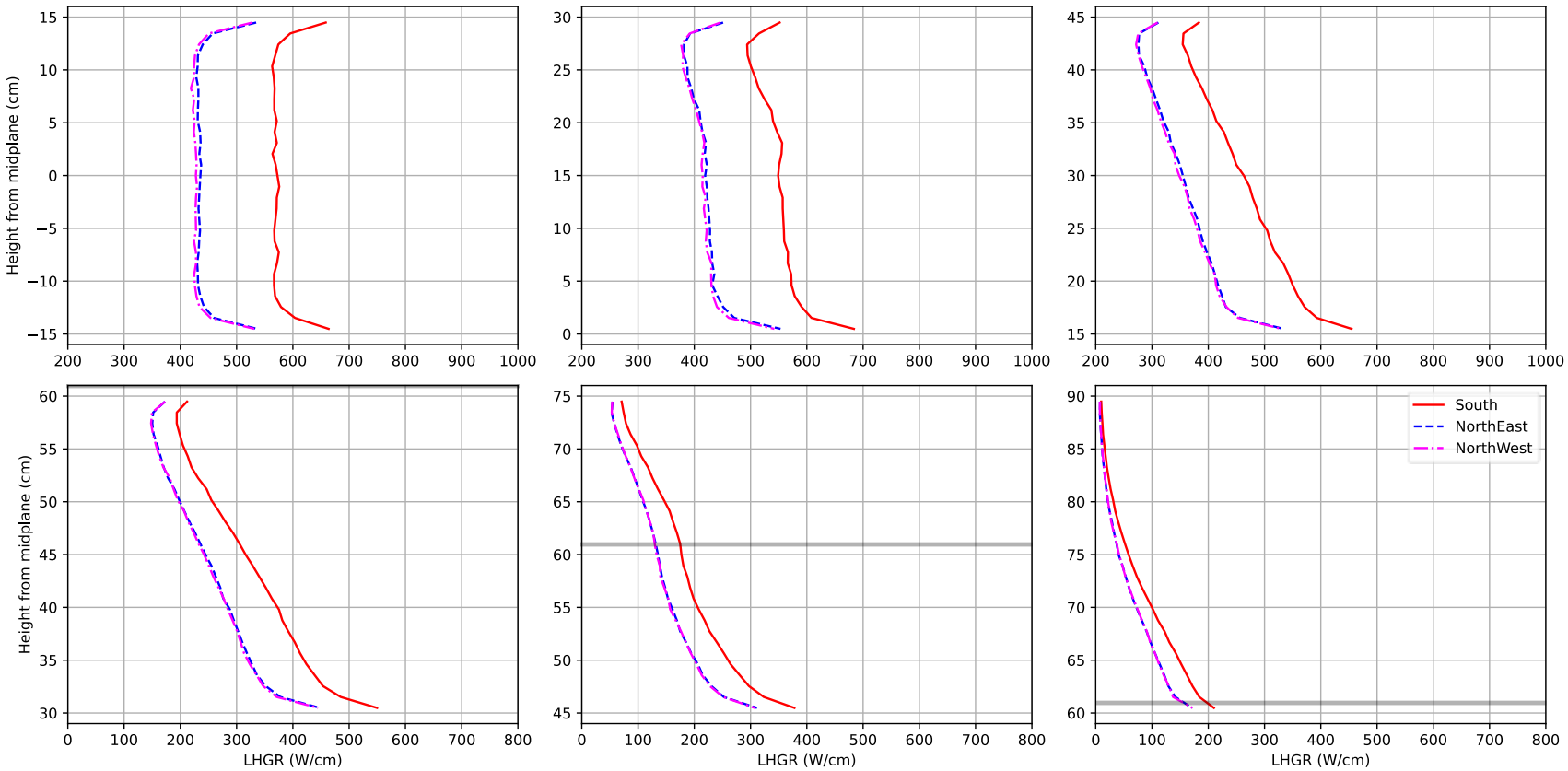
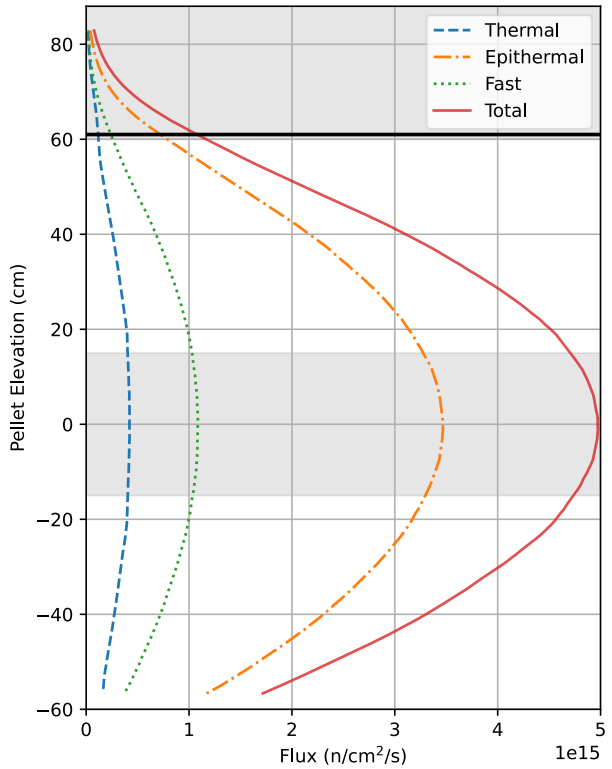




Objective: Refine minishroud thicknesses to obtain optimal profile.

Previously (continued)…



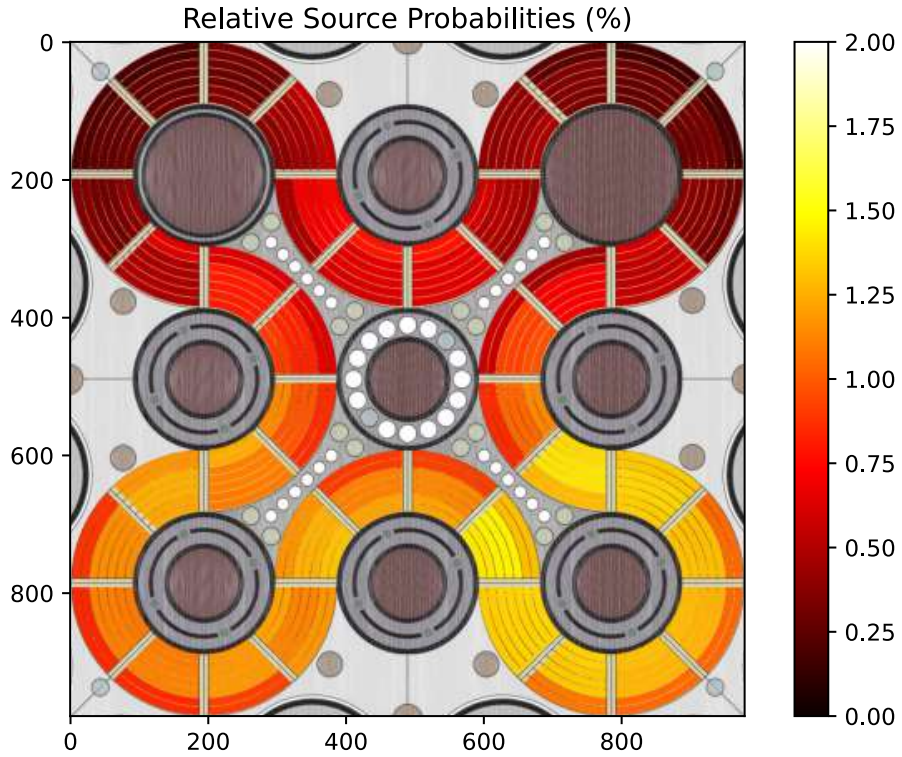


Objective: Refine minishroud thicknesses to obtain optimal profile.

Methodology

Monte Carlo Model

- Fixed-source model using MCNP 6.2
- Source distribution based on Cycle 167A-PALM
  - Center lobe power: 36.7 MW
  - Lobe-adjusted total core power: 170 MW
  - Strong flux tilt toward the south
- Generate surface source model (`RSSA`)
  - Source around CFT, outside H-positions (assume cobalt targets)
  - Generated assuming TT bottom at midplane
  - Accurate to ±1%



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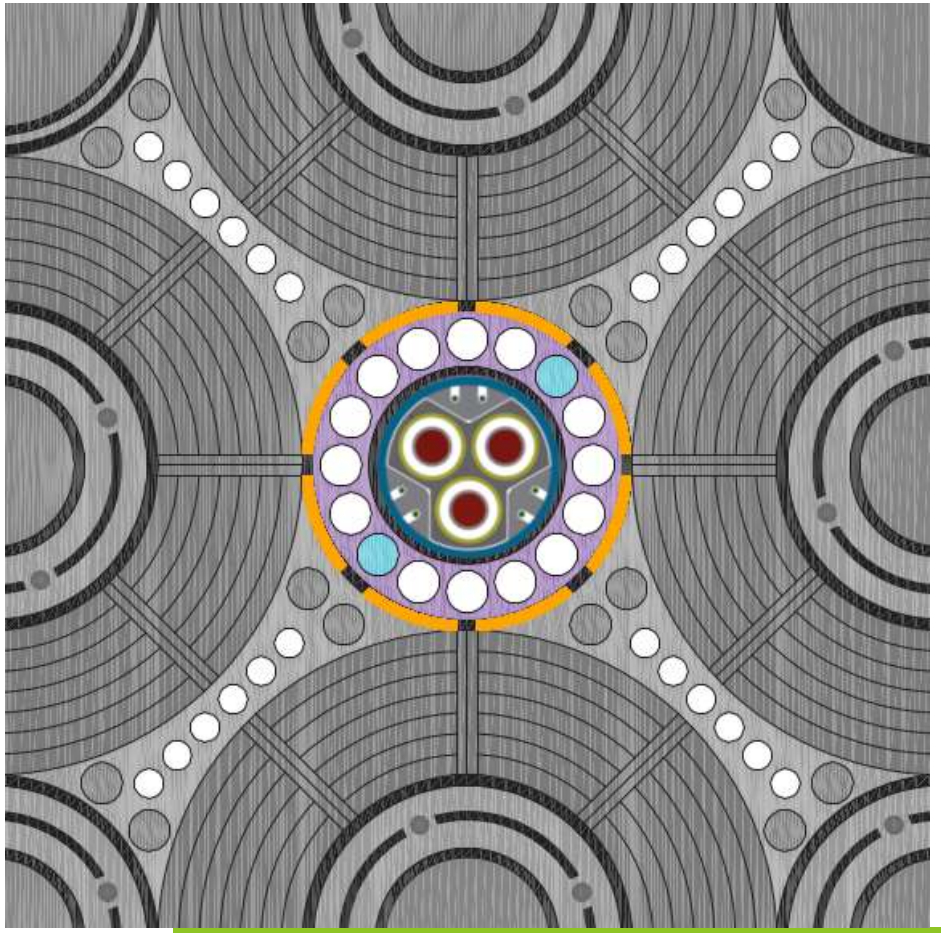


Experiment Parameters

- Vary the thickness of the hafnium of the three pins' minishrouds
  - Keep in mind that the south (S) pin naturally has a higher power than the northeast (NE) and northwest (NW) pins due to flux tilt
- Allow variation from 0.6868 to 0.7864 cm hafnium outer radius
  - Hafnium thickness: 0 to 40 thousandths of an inch (thou)
- Discretize axially, approximately every two pellets
- Place the bottom of the TT at 15 cm above the ATR core midplane
- Attempt to achieve the target of a flat 650-W/cm LHGR profile
  - This leads to our objective function for the optimization

Initial Optimization

- Initially, optimize the three pins' minishrouds together
- Minimize a penalty function based on root mean square (RMS)
- After some trial and error:
  - RMS from target value (30%) → achieve target
  - RMS from mean value (70%) → achieve flat profile
  - End zones 3× RMS → penalize end effects
  - Cubic penalty on bottom two pellets → severely penalize bottom peaking
- Using this penalty function, optimize hafnium thickness using Dakota 6.18
- Try a single-objective genetic algorithm (SOGA)

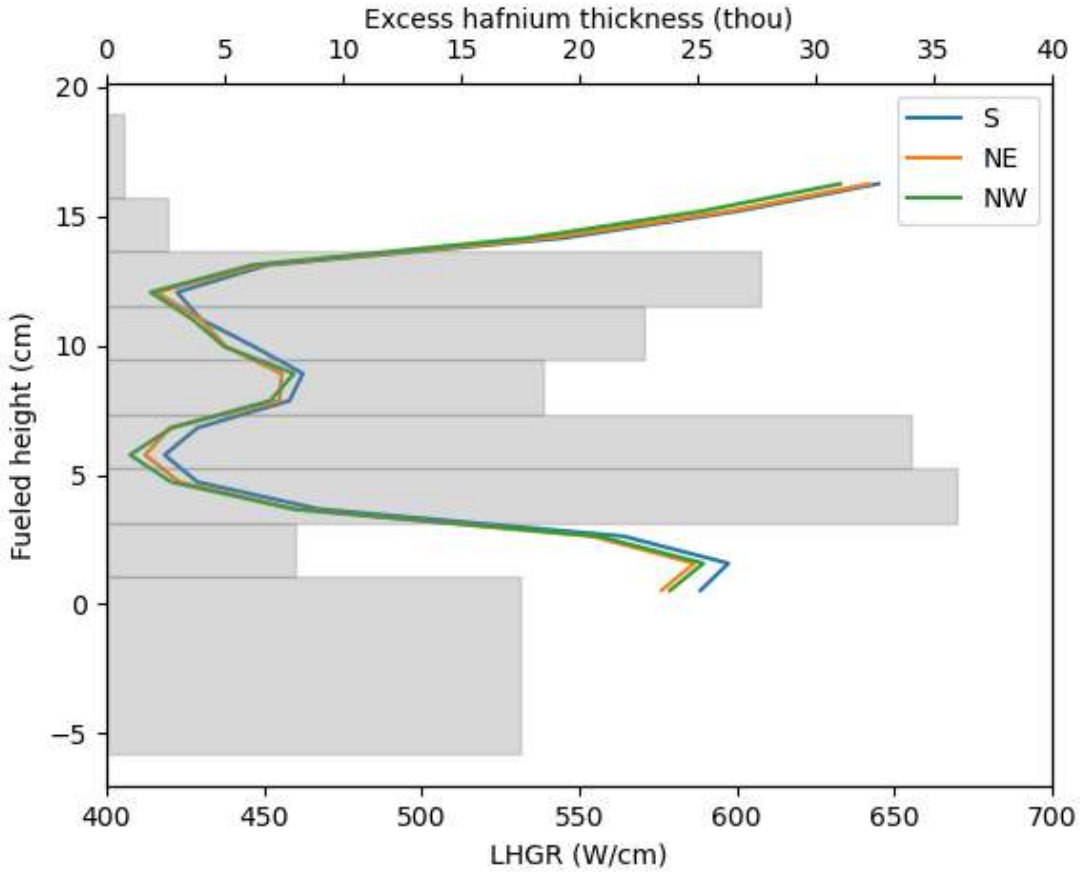
Dakota Input

```
method

    soga
        max_iterations = 512
        max_function_evaluations = 10000
        convergence_tolerance = 0.001
        population_size = 32
        crossover_type = shuffle_random
            num_parents = 2
            num_offspring = 2
        mutation_type = bit_random
            mutation_rate = 0.05
```

Preliminary Optimization Study

Sample 1


Excess hafnium thickness (thou)
0
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Fueled height (cm)
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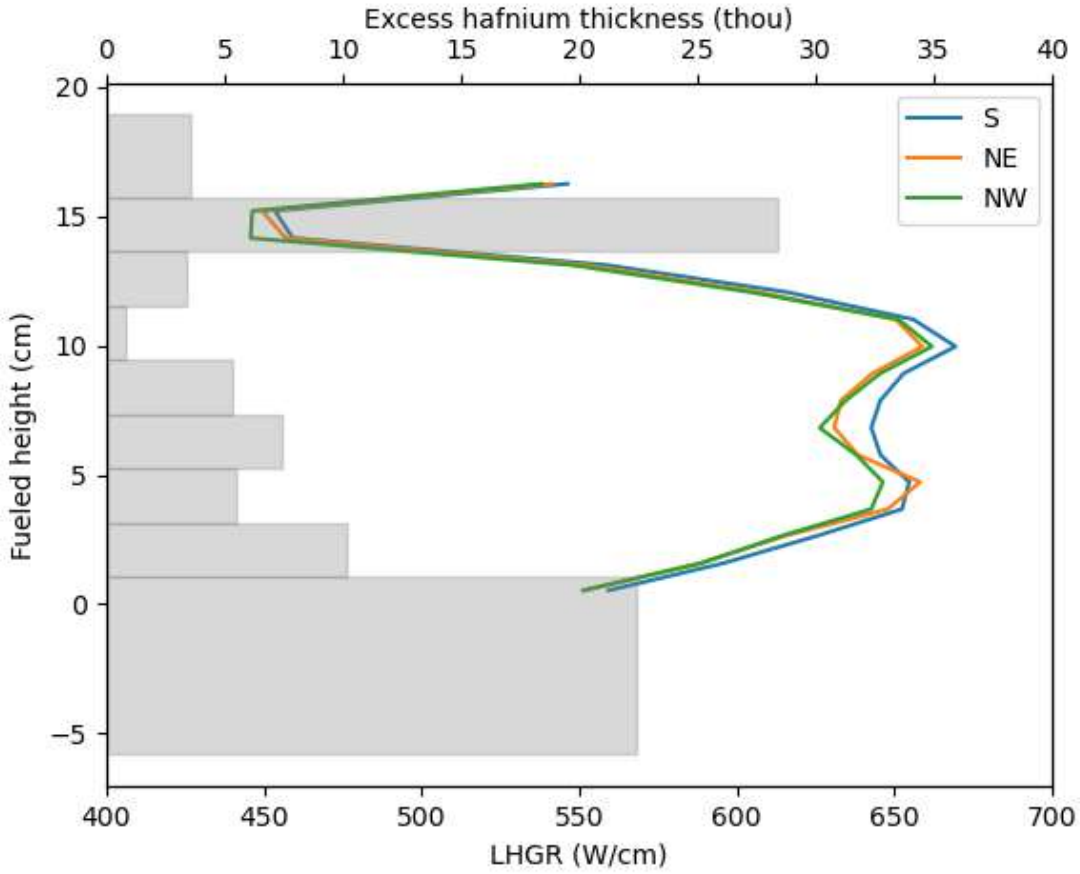
650
700
LHGR (W/cm)

Sample 148


Excess hafnium thickness (thou)
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Fueled height (cm)
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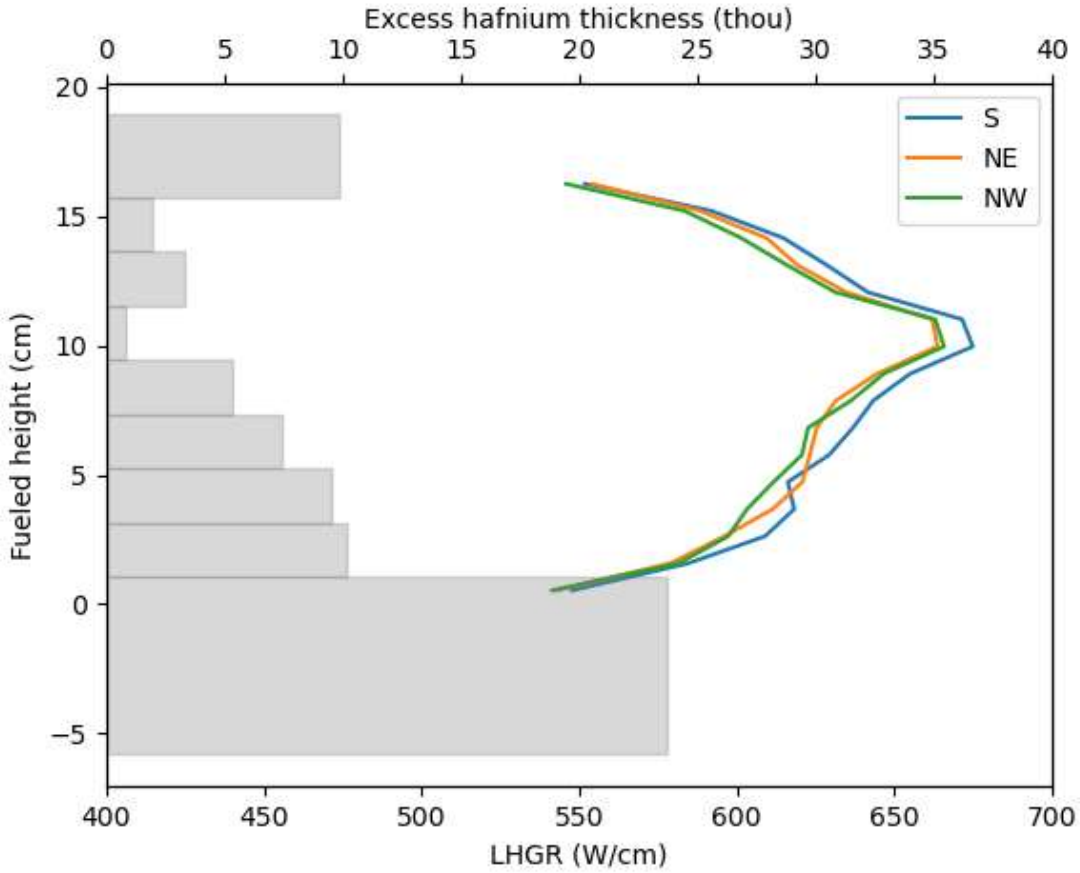
700
LHGR (W/cm)

Sample 256


Excess hafnium thickness (thou)
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Fueled height (cm)
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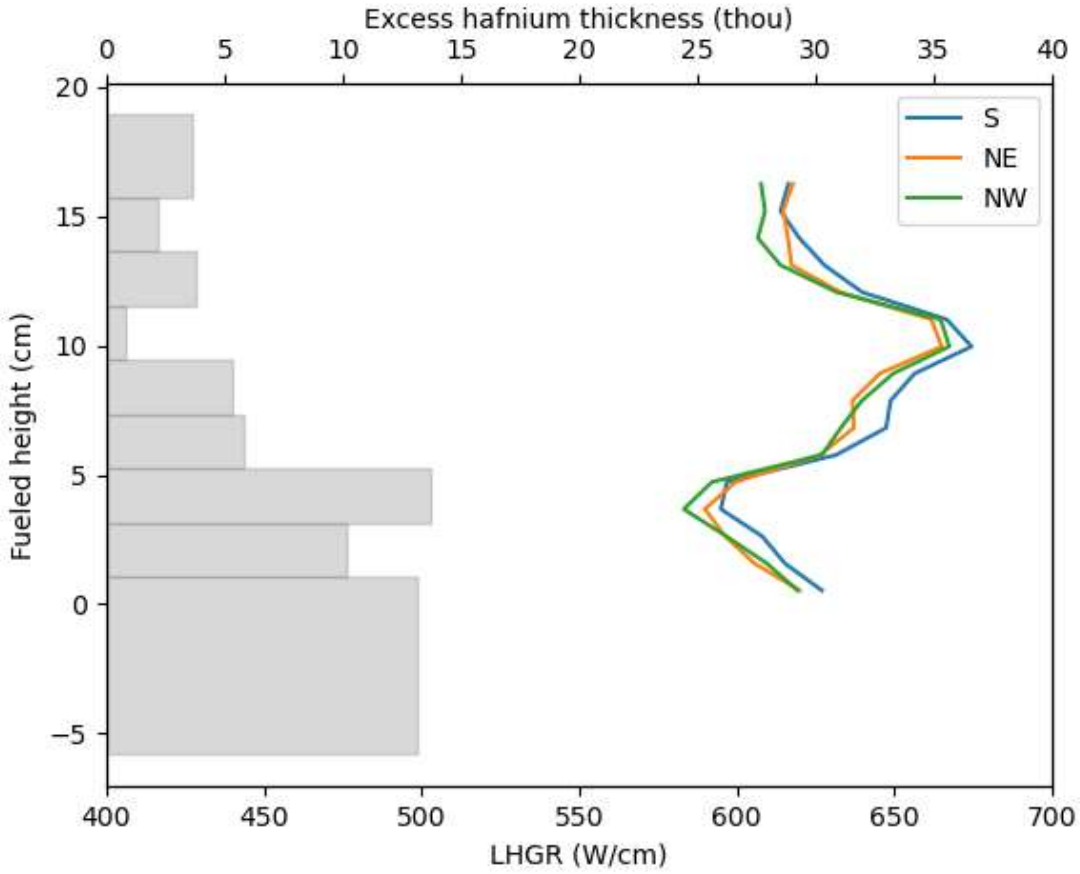
LHGR (W/cm)

Sample 517


Excess hafnium thickness (thou)
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Fueled height (cm)
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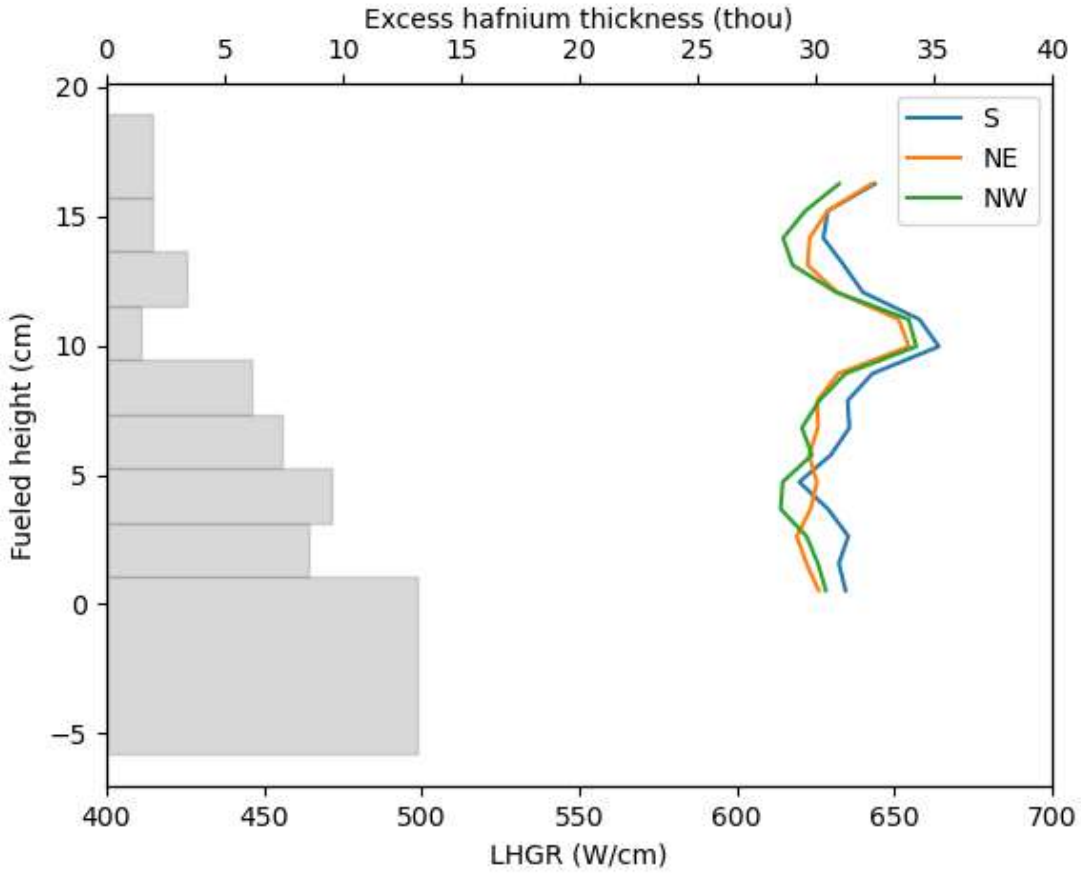
LHGR (W/cm)

Sample 880


Excess hafnium thickness (thou)
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Fueled height (cm)
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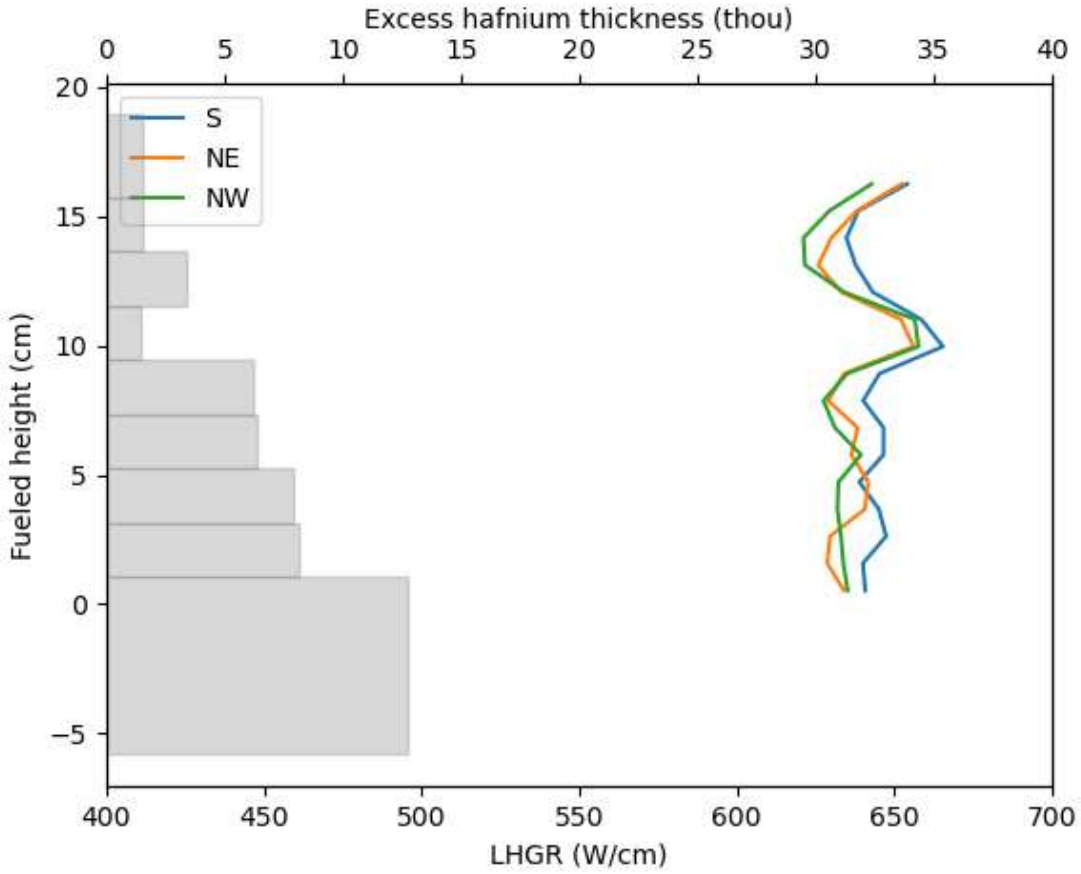
LHGR (W/cm)

Sample 1646


Excess hafnium thickness (thou)
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Fueled height (cm)
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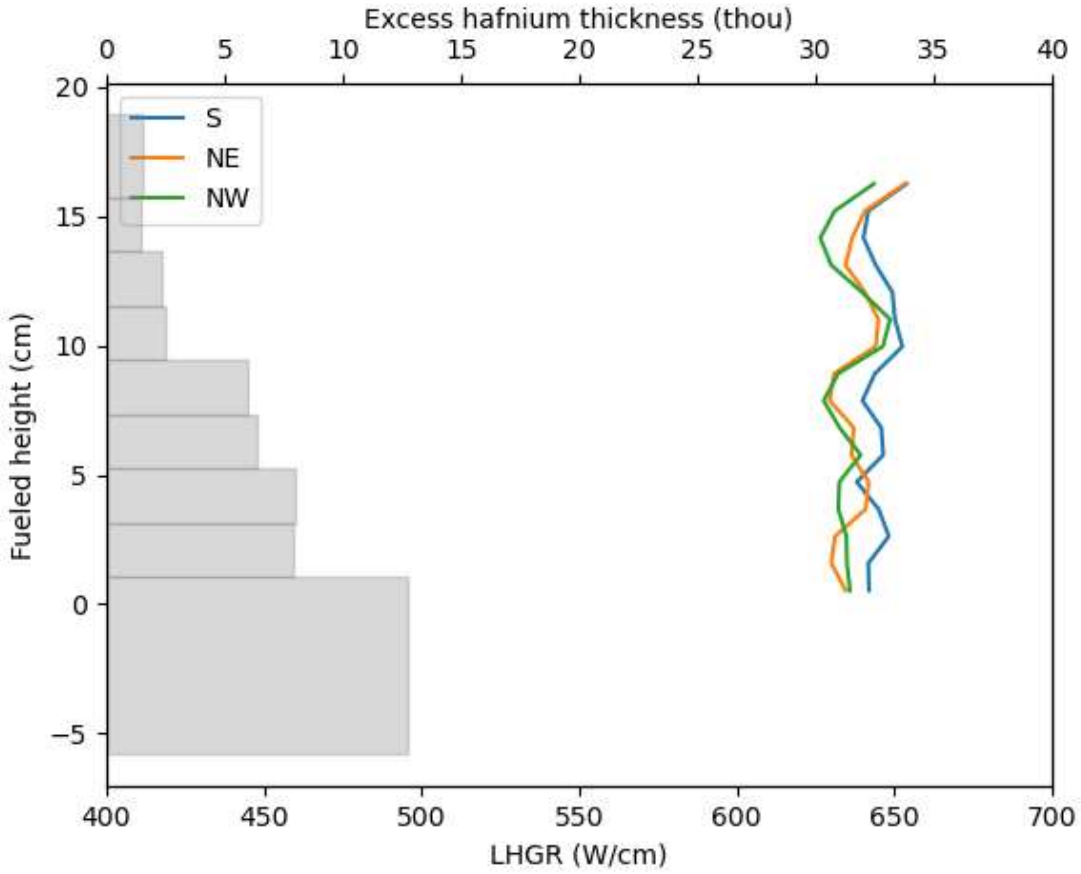
LHGR (W/cm)

Sample 2116


Excess hafnium thickness (thou)
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Fueled height (cm)
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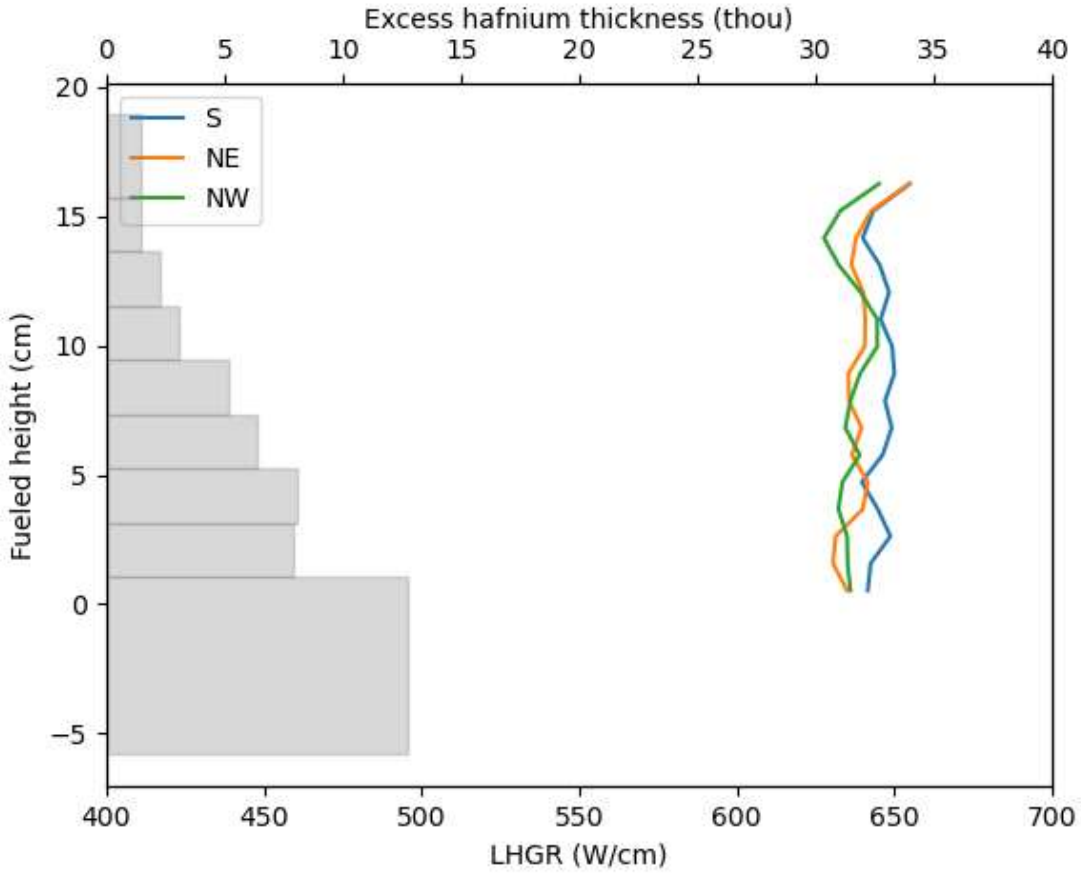
LHGR (W/cm)

Sample 4519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Fueled height (cm)
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LHGR (W/cm)

Next Steps

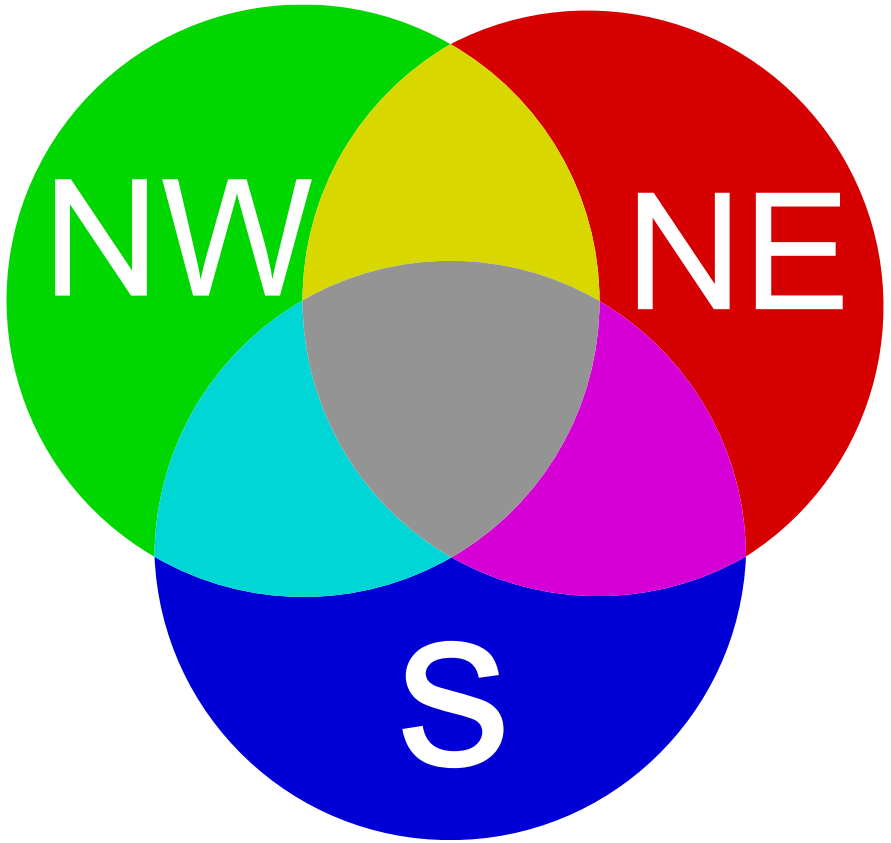
- Start from this optimization result
- Update TT axial geometry to latest mechanical design, reducing the extent of the minishrouds below the fuel and structural mass above the fuel
- Use thickness increments of **10 thou**
- Try to the separate the pin LHGR profiles by about 50 W/cm at the peak
- Allow to peak somewhere in the middle; perhaps cosine-like

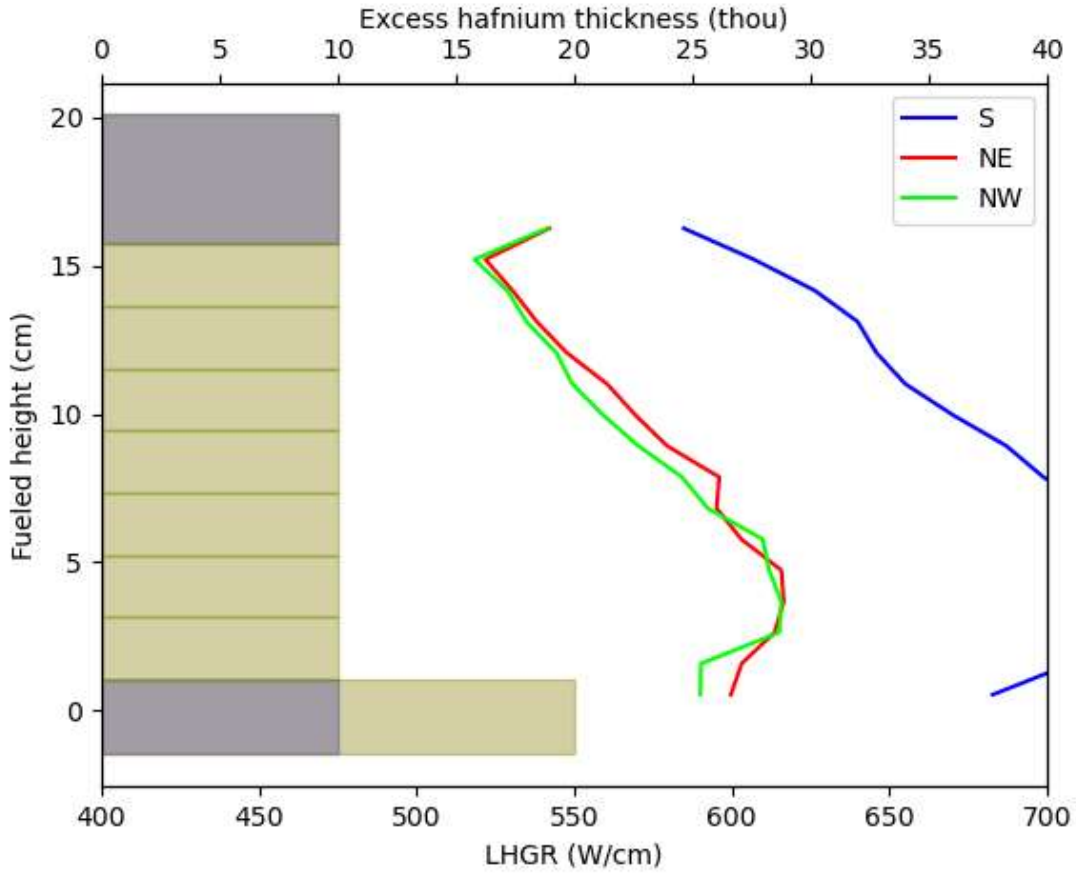
Separate Pin Profile Study

South Pin

Color Scheme Explanation

- The plots on the next several slides show the hafnium thickness by pin.
- Additive color model:
  - **Green:** NW
  - **Yellow:** NW + NE
  - **Gray:** NW + NE + S

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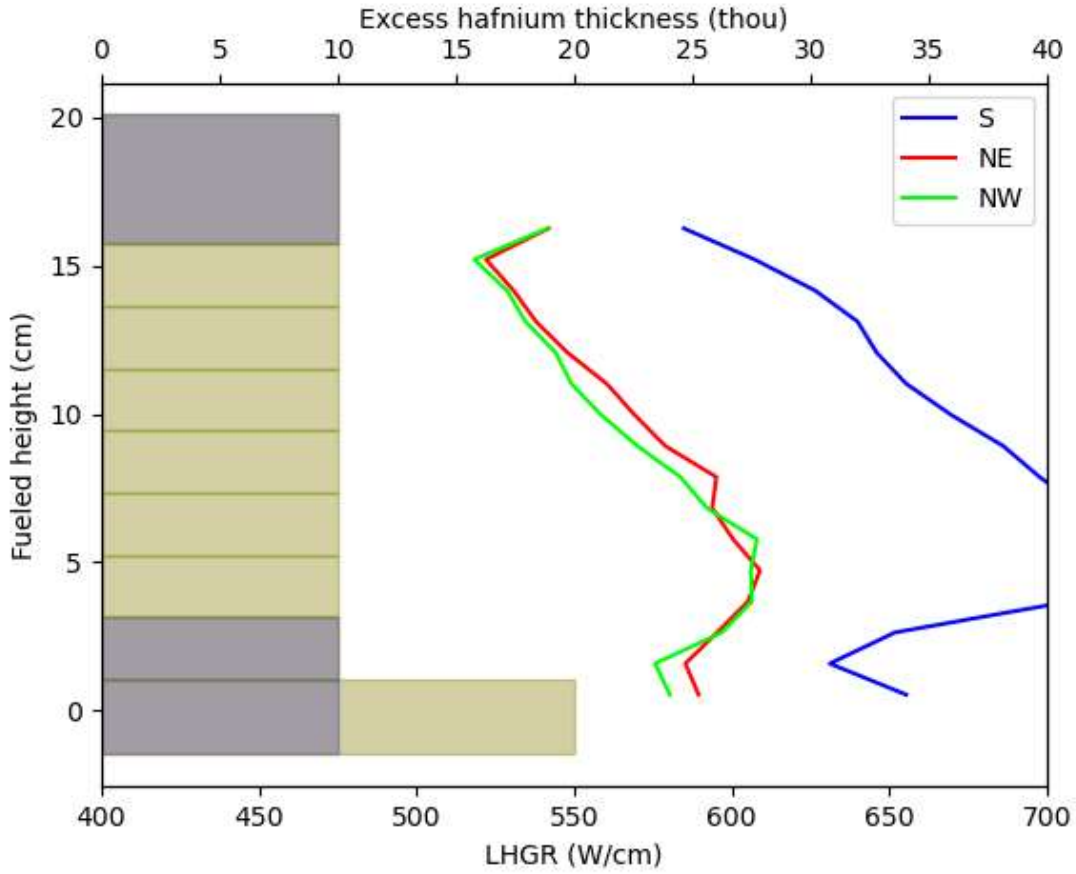
LHGR (W/cm)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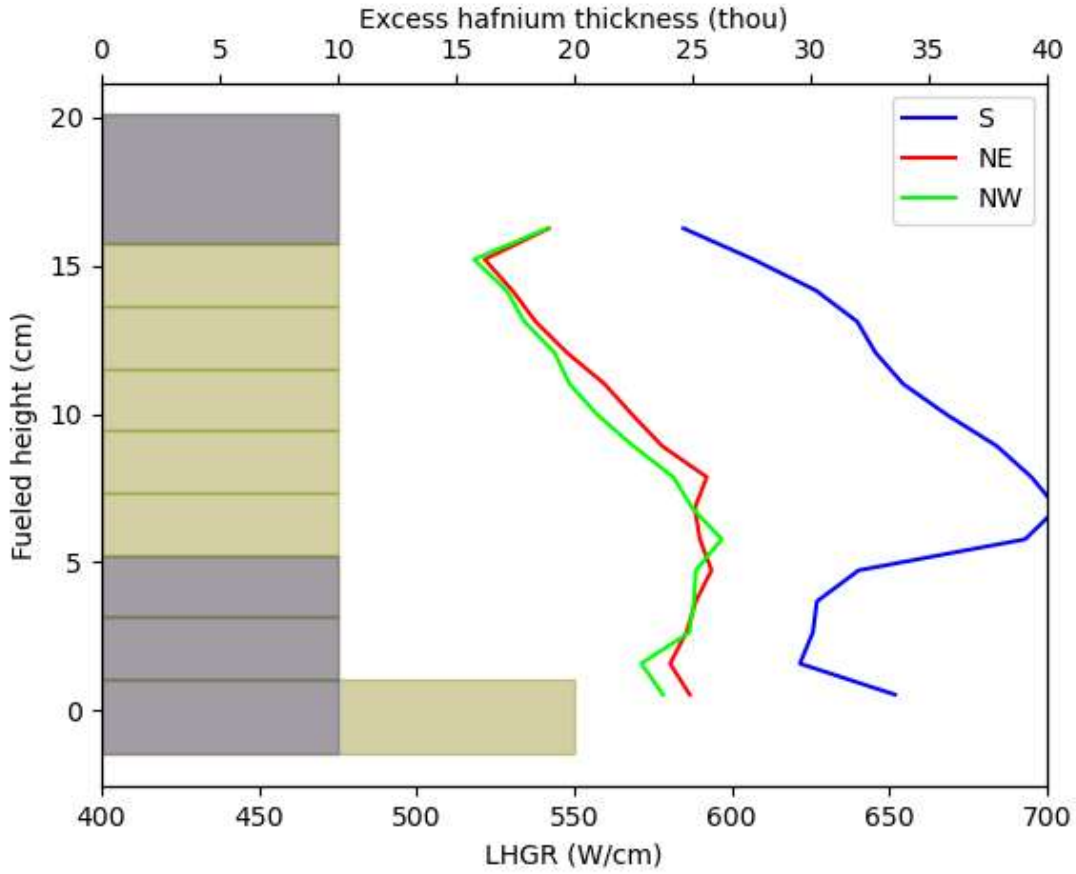
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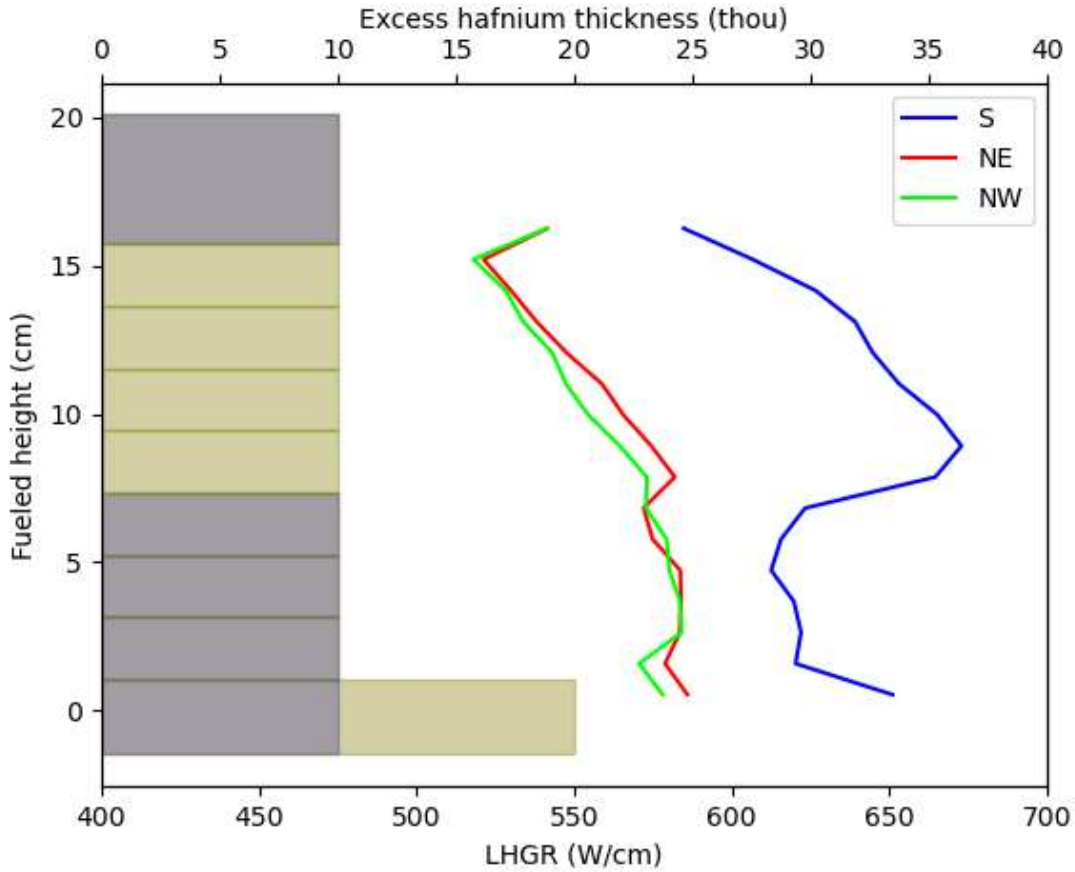
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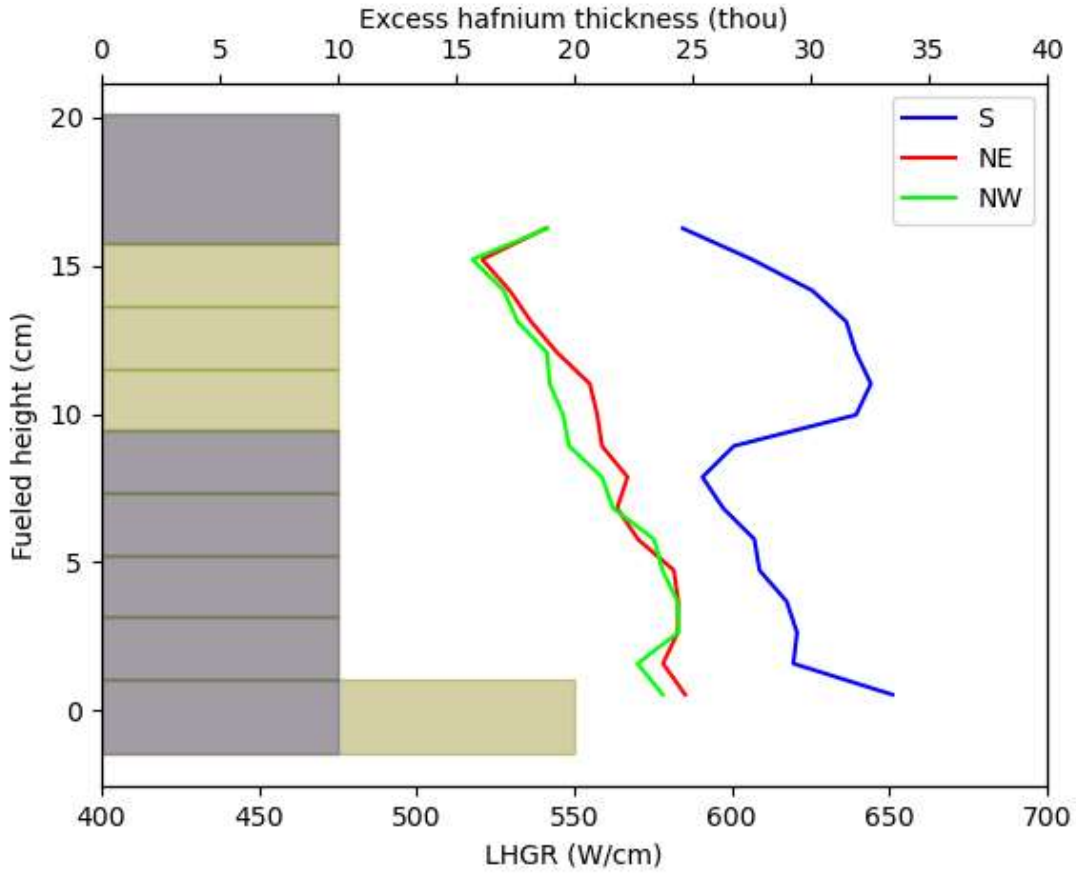
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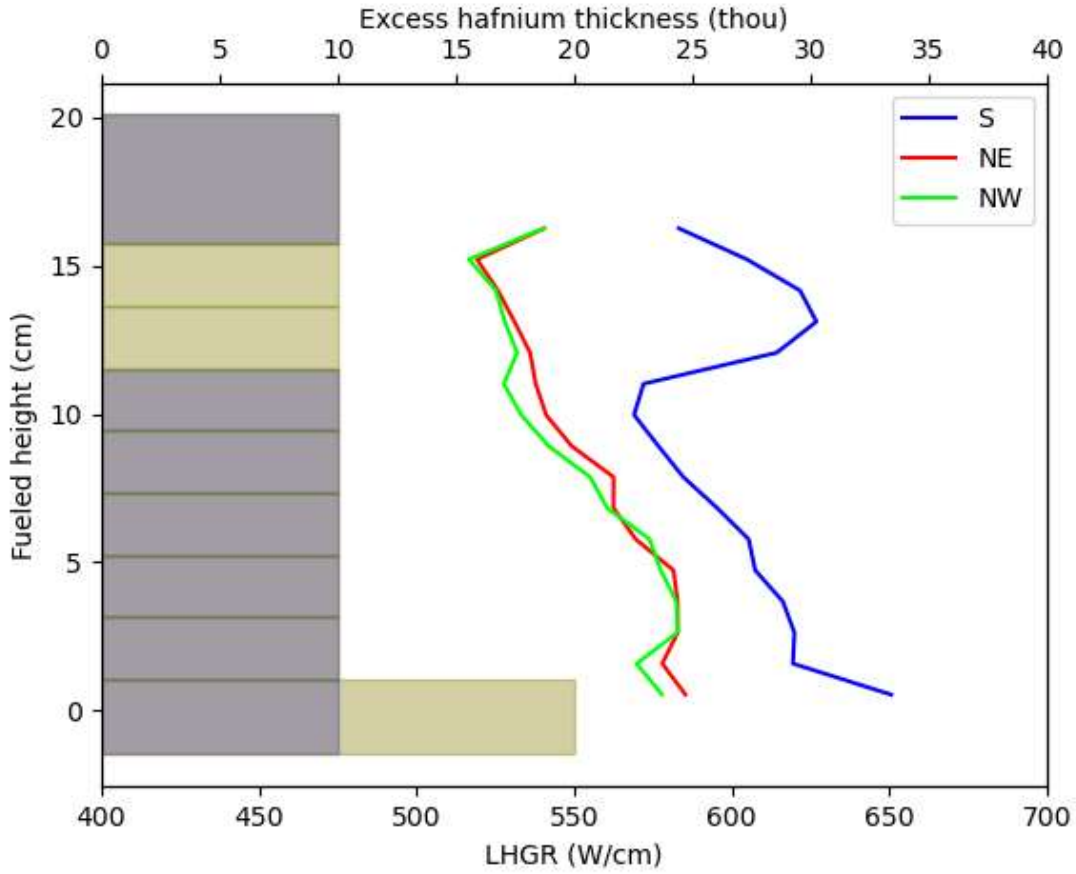
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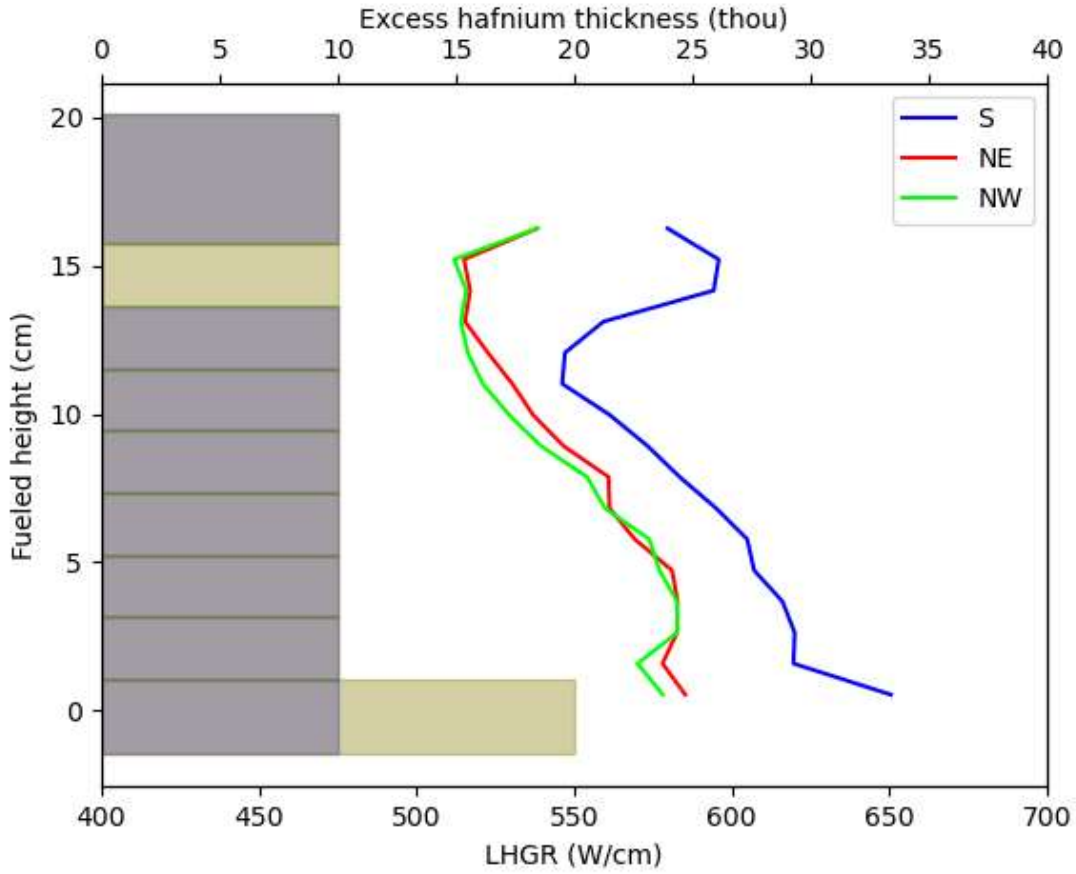
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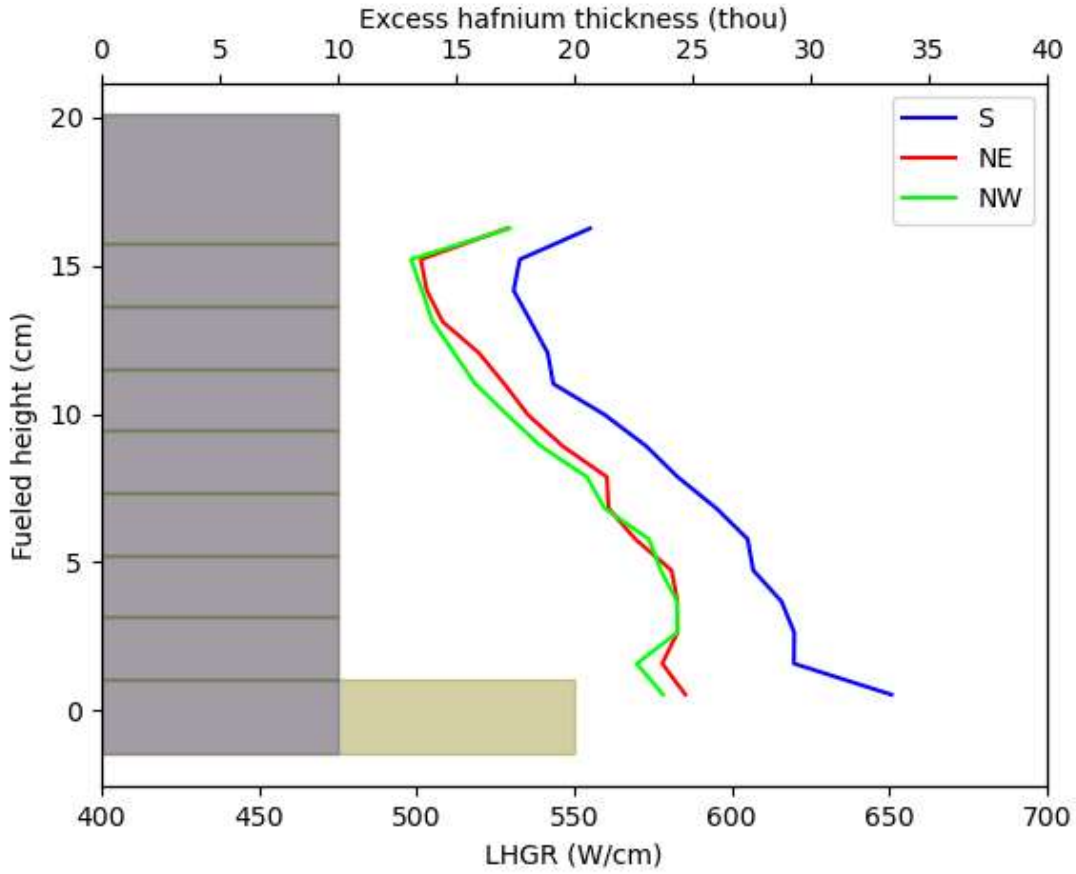
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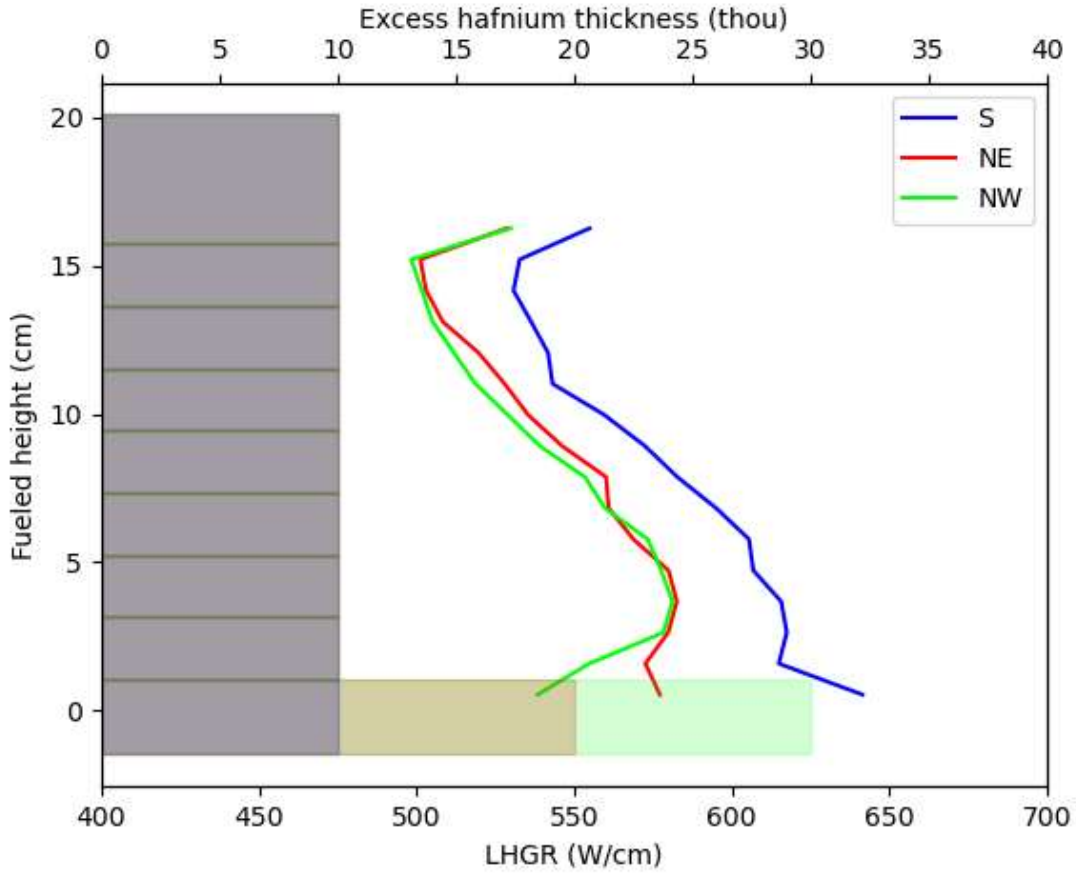
LHGR (W/cm)

Separate Pin Profile Study

Northwest + South Pins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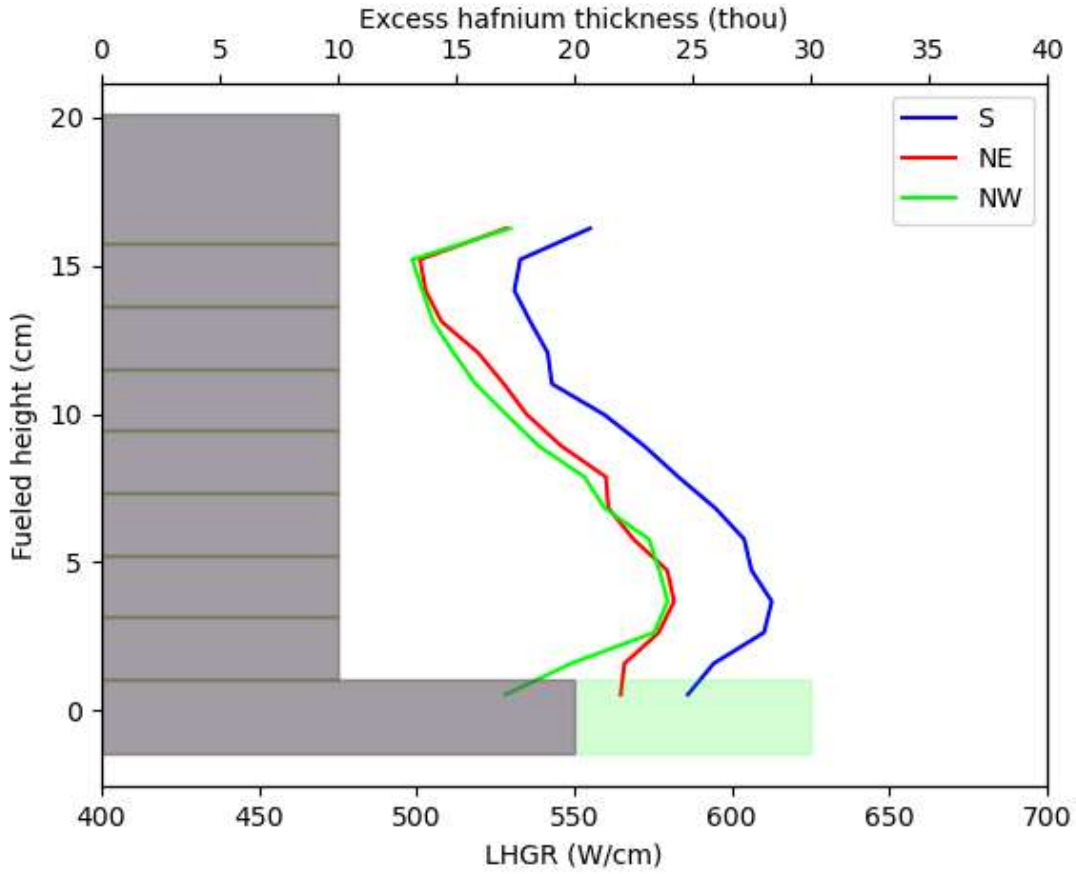
LHGR (W/cm)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Fueled height (cm)
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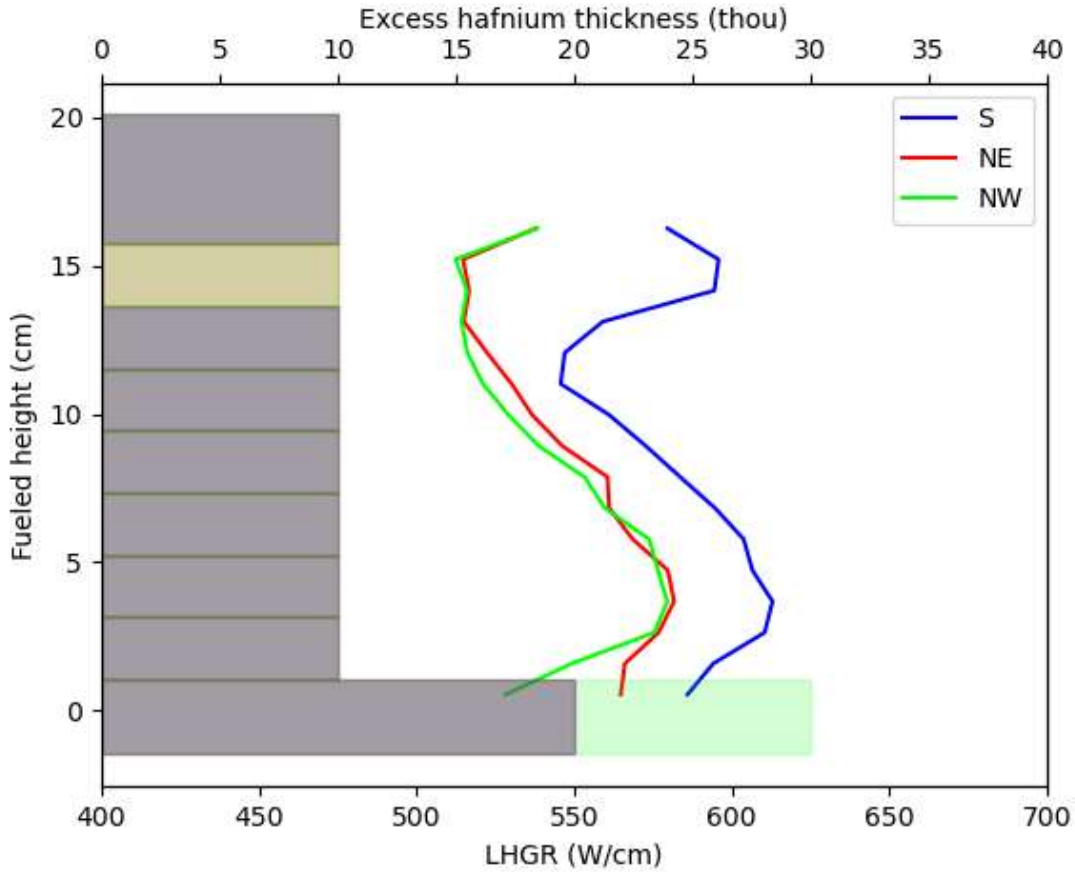
LHGR (W/cm)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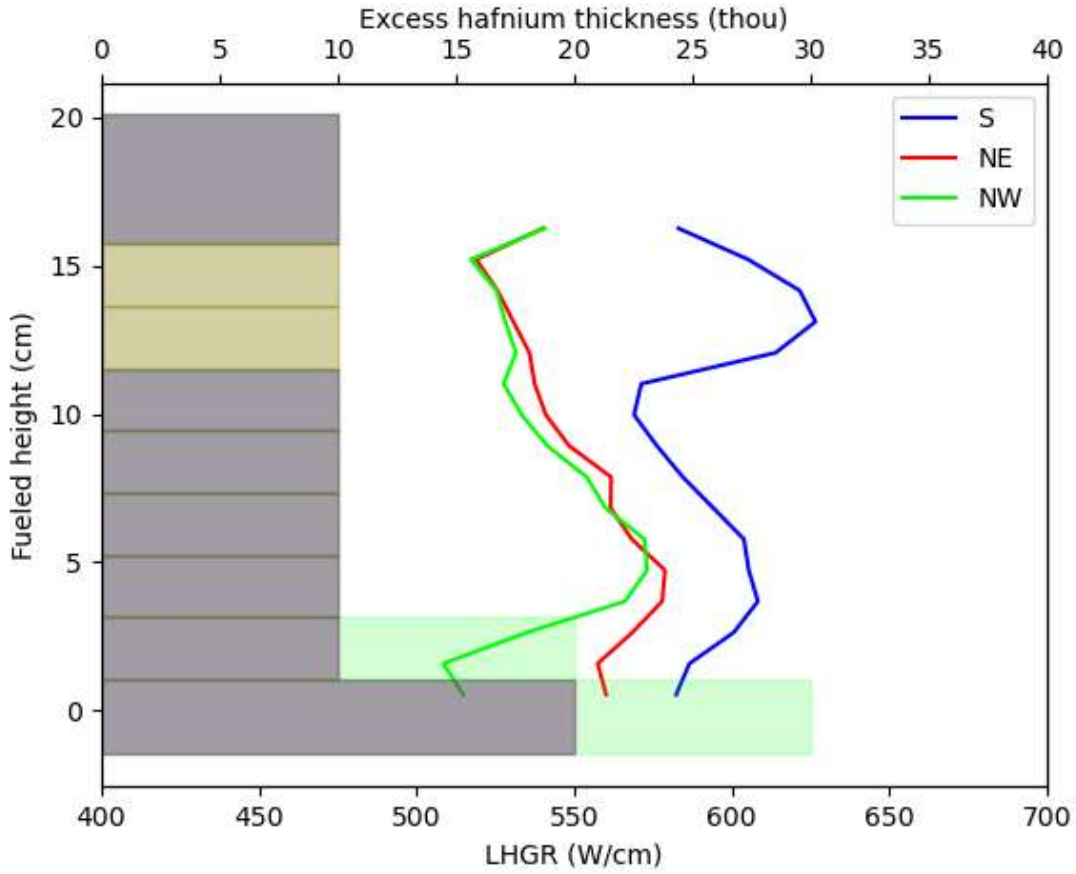
700
LHGR (W/cm)


Excess hafnium thickness (thou)
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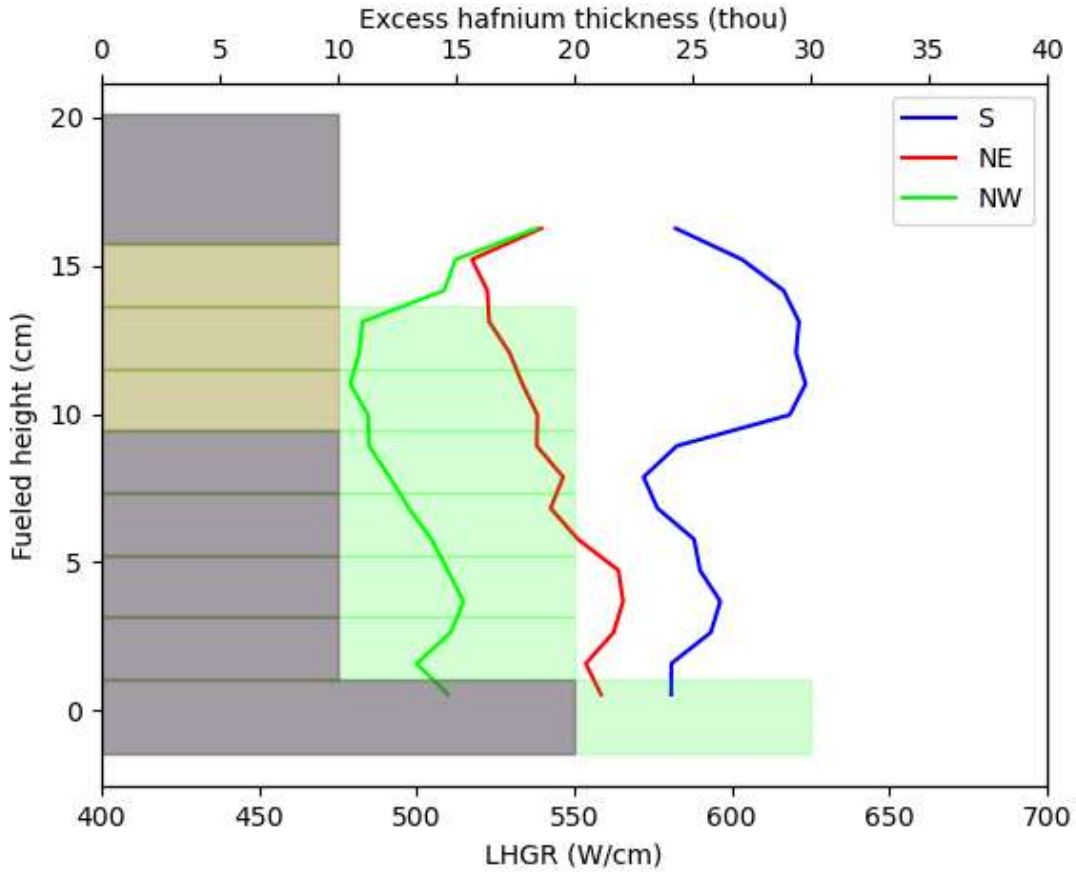
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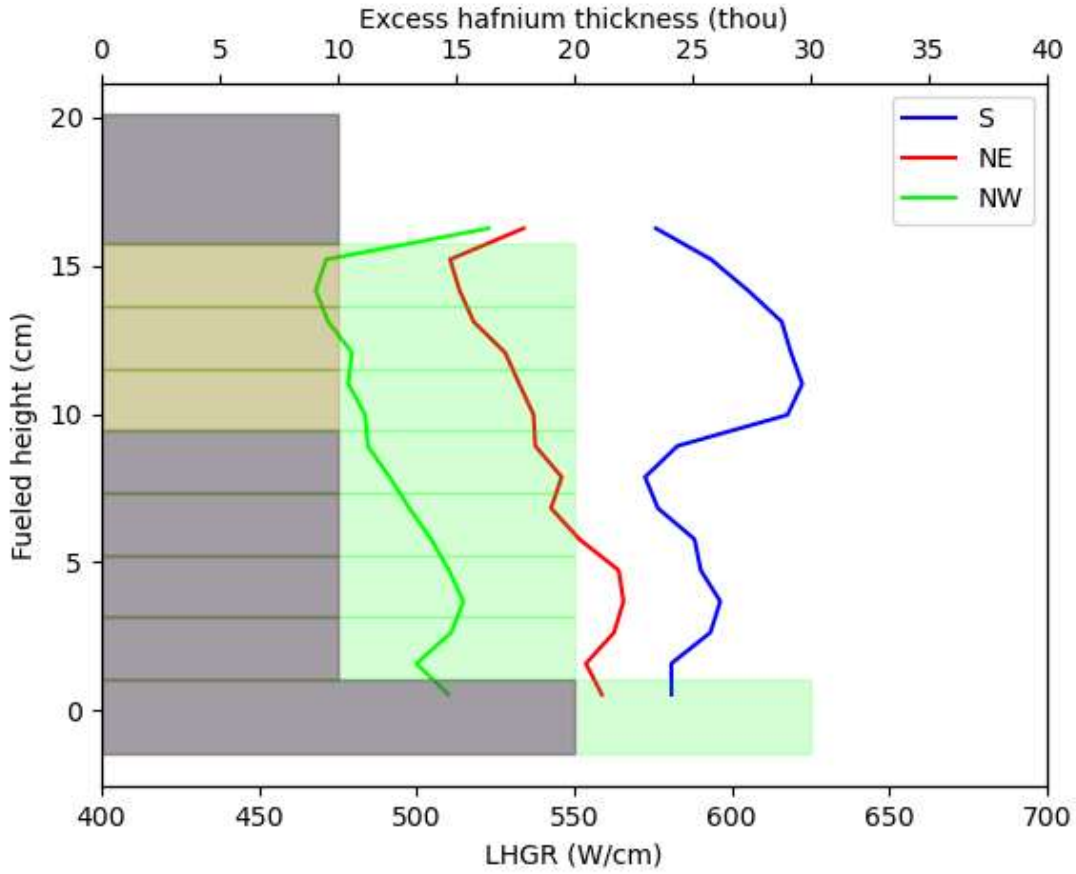
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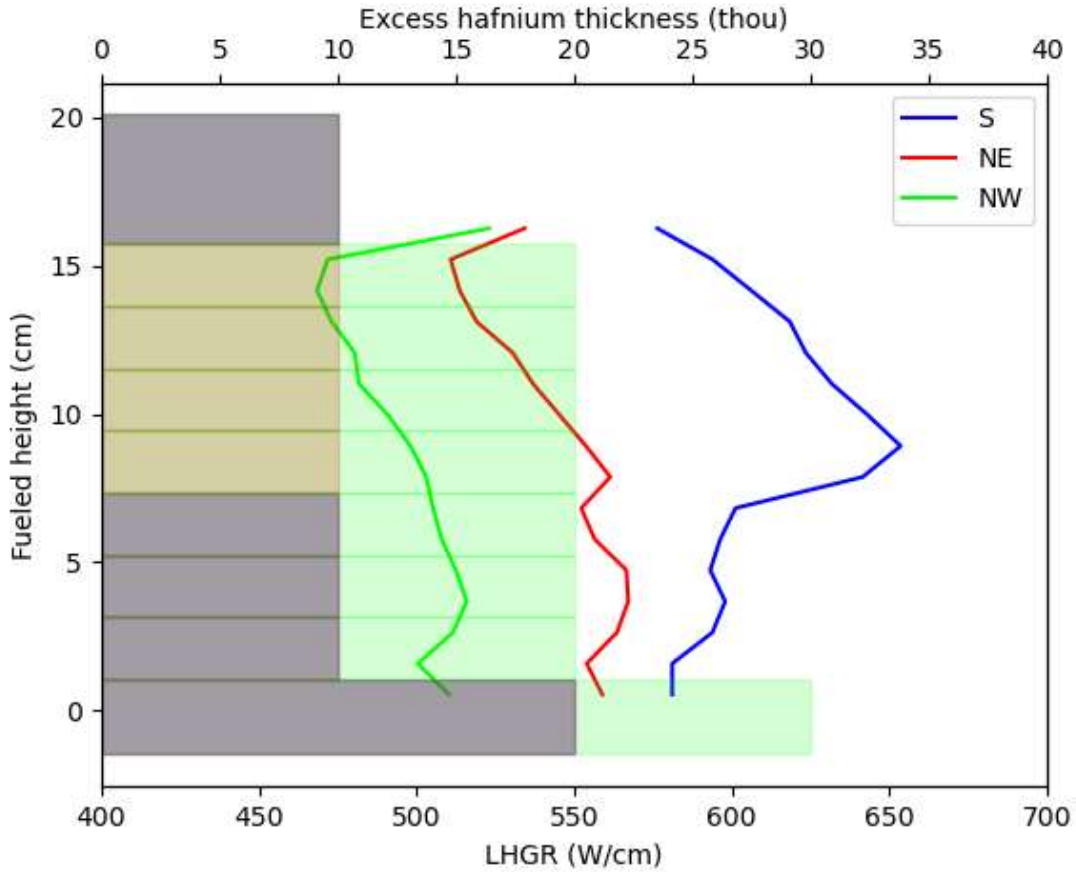
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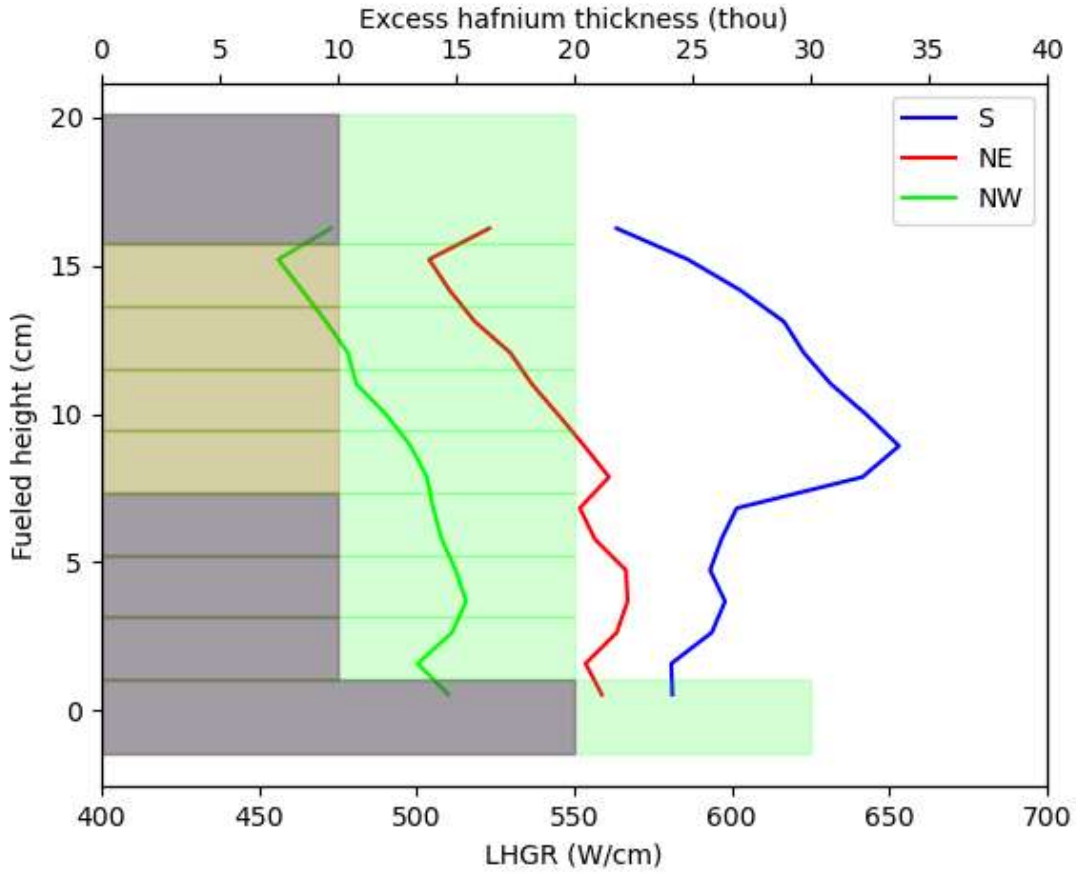
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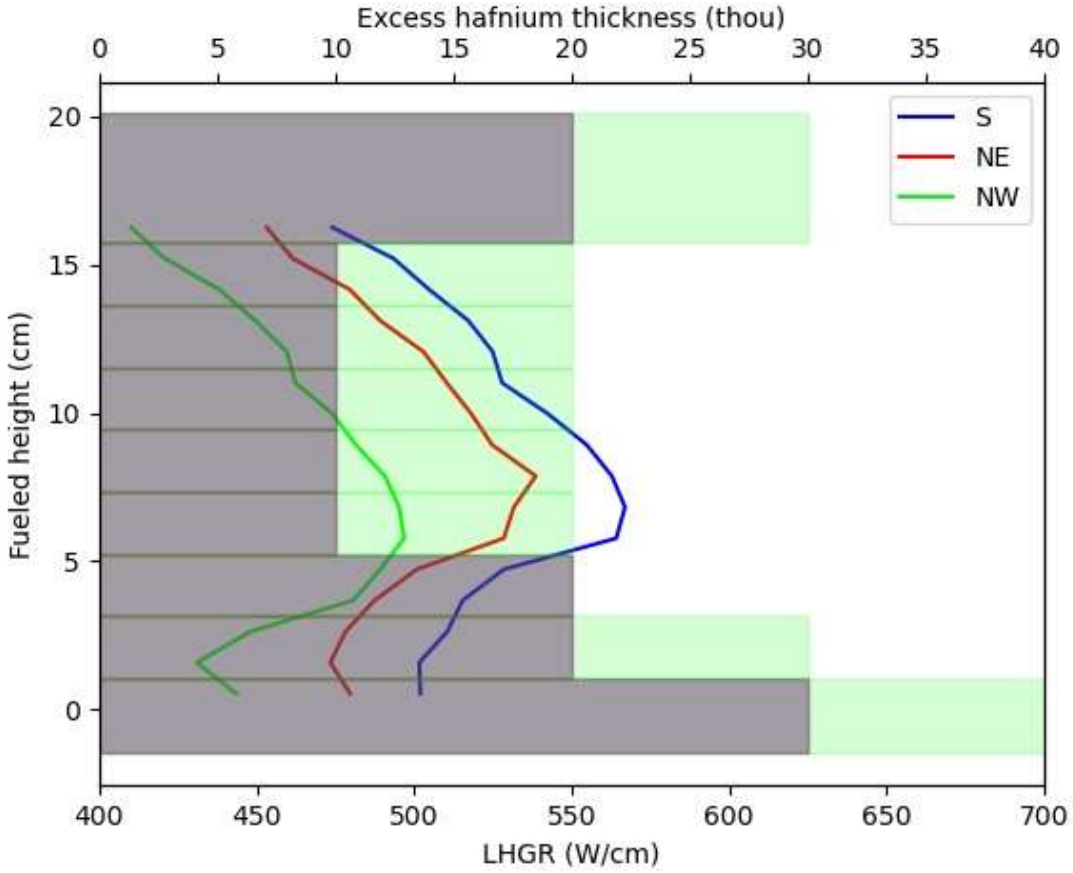
LHGR (W/cm)

Finishing Touches

Manually Tweak the Profile

- The power profile is shaping up nicely.
- The natural power tilt on the S pin and the thicker hafnium on the NW pin are starting to give us separate power profiles.
- Let us make some manual adjustments at the ends.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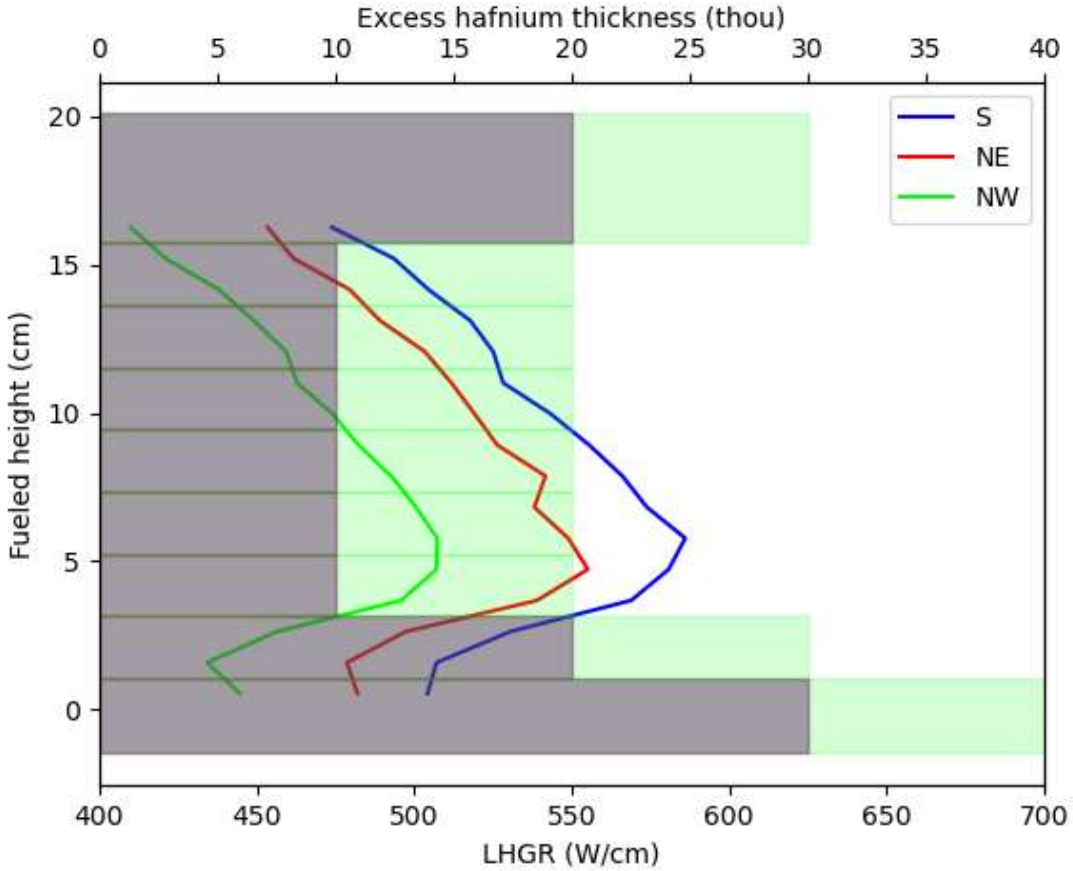
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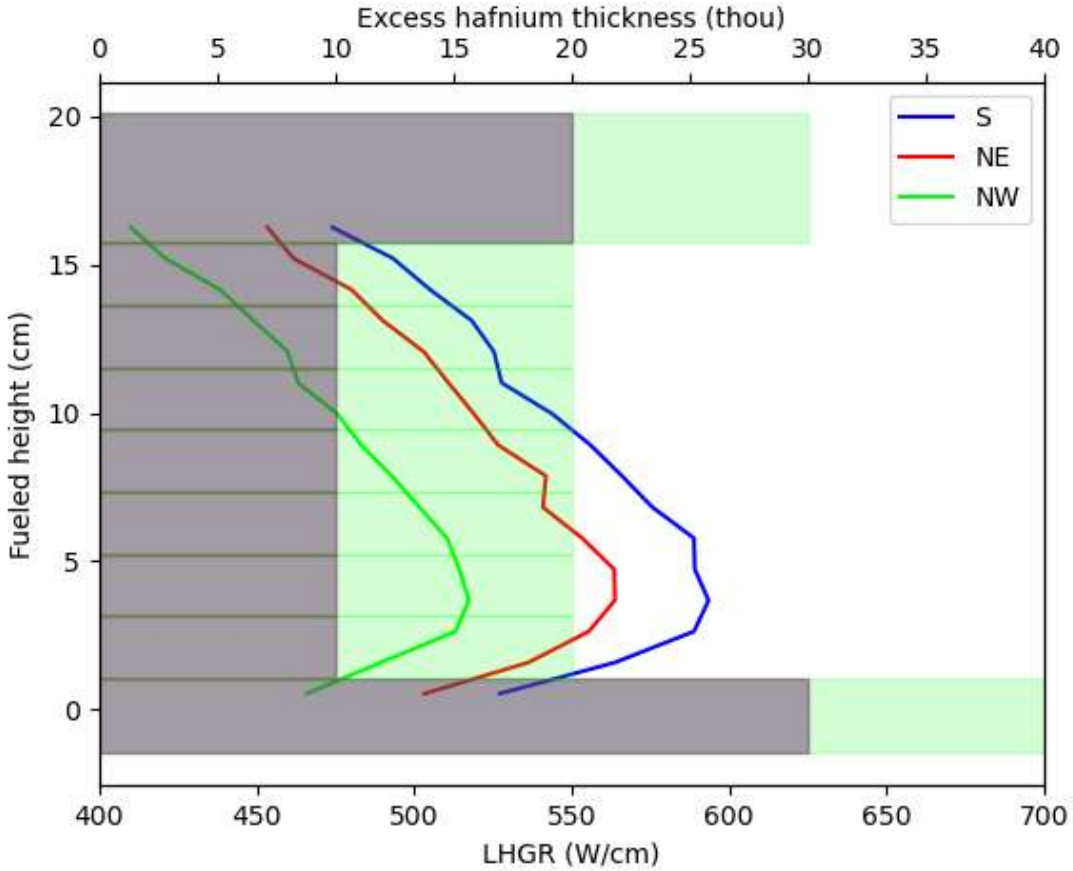
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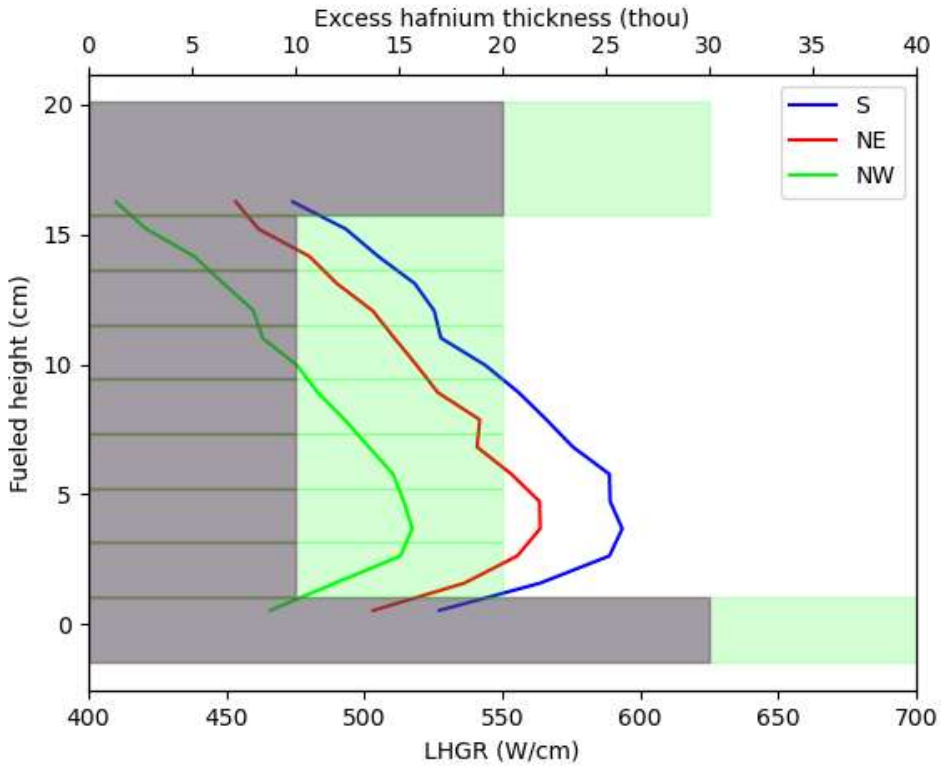
LHGR (W/cm)

Conclusion

Results

- Pros:
  - The power shape is satisfactory.
  - The power separation between pins is satisfactory.
- Cons:
  - The power magnitude is low.
  - Thickness of only 10 thou will be challenging to fabricate.



Future Work

- Find ways to reduce hafnium mass without reducing thickness
  - Drill horizontal holes
    - Model as reduced hafnium density
    - Determine required mass removal from optimal density
  - Use a hafnium alloy
    - Blend with zircaloy
    - Use zirconium with natural hafnium impurities
- Tailor the ends further
  - Insert hafnium wafers below bottom pellet and above top pellet
  - Use a natural uranium pellet at the bottom
- Improve the selection of or hyperparameters of the optimization algorithm

Acknowledgments

- This research made use of the resources of the High Performance Computing Center at Idaho National Laboratory, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517.
- This work was supported through the U.S. Department of Energy Advanced Fuels Campaign under DOE Idaho Operations Office Contract DE-AC07-05ID14517. Accordingly, the U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

Idaho National Laboratory

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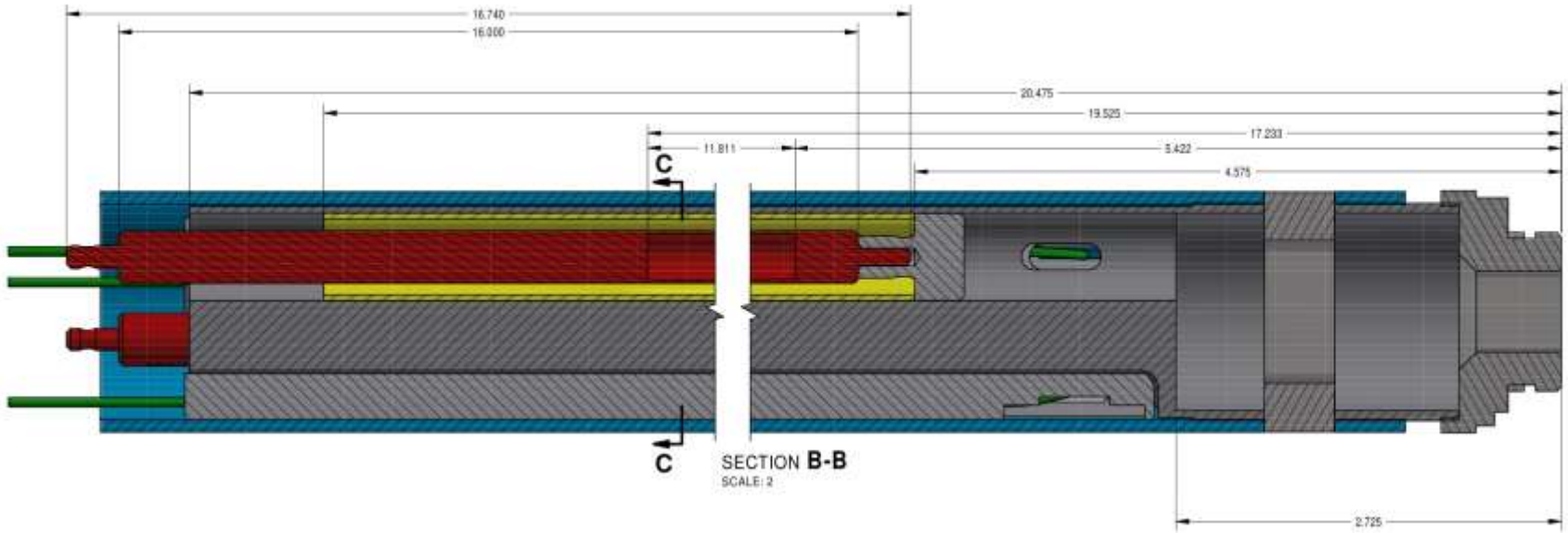
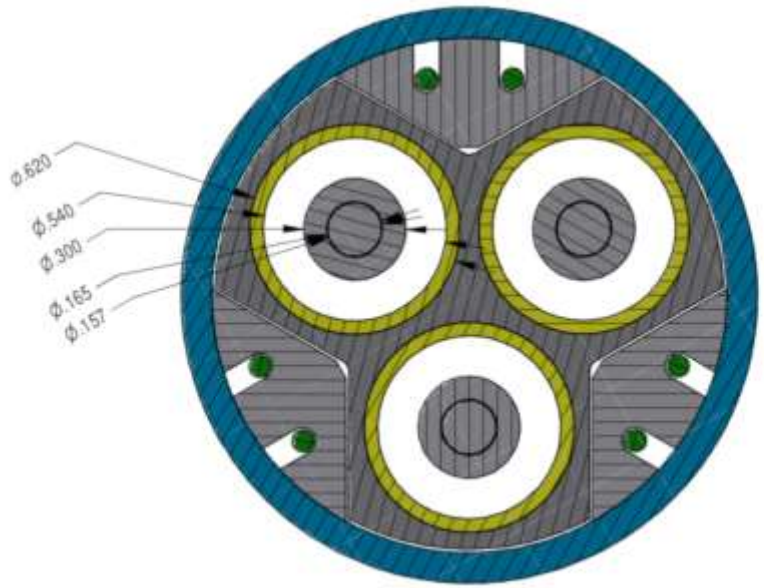
Questions?

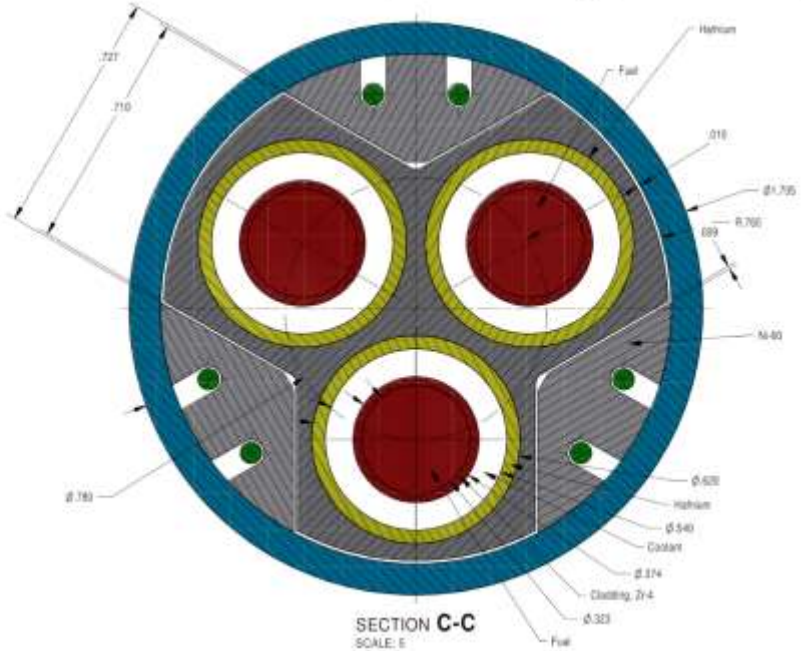
Travis.LabossiereHickman@INL.gov

Backup Slides

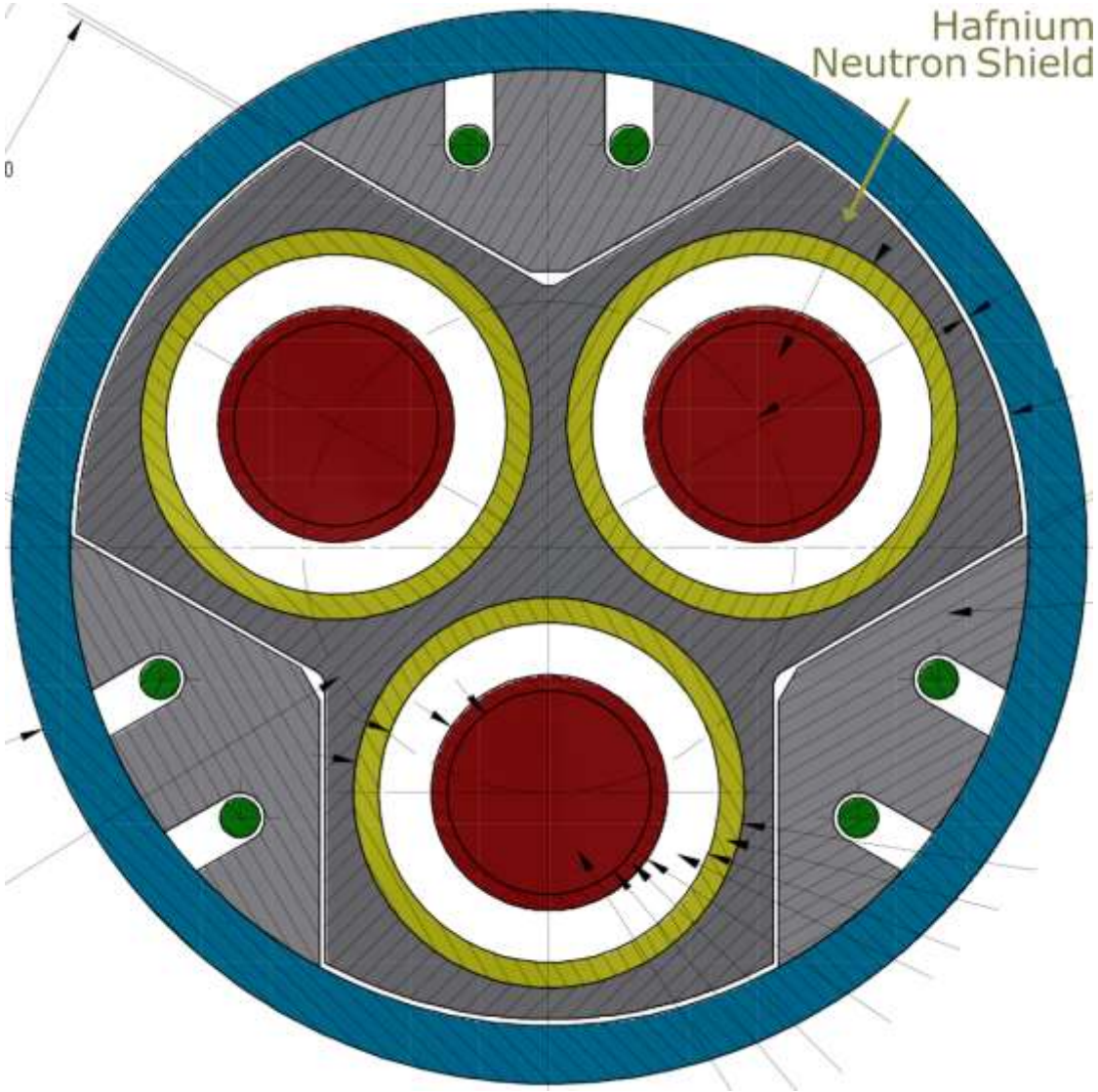
Trefoil Device





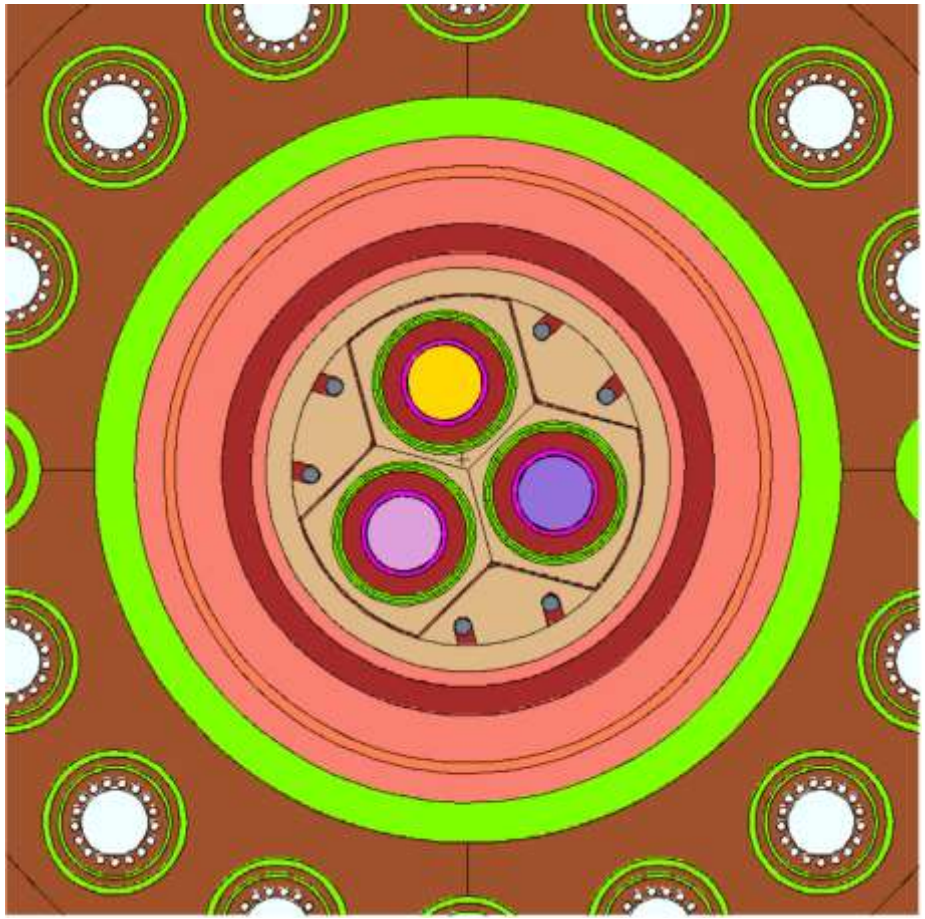


Trefoil Device



Trefoil Device (continued)

- Three-pin TT concept with separate flow channels in symmetric layout
- Power ramp controlled by axial location, using PALM device
- Minishrouds:
  - Layer on outside of each pin's water channel
  - Made of Zirc/Hf
  - Radial variation and axial variation possibilities
    - *Pictured:* three equal-volume radial regions



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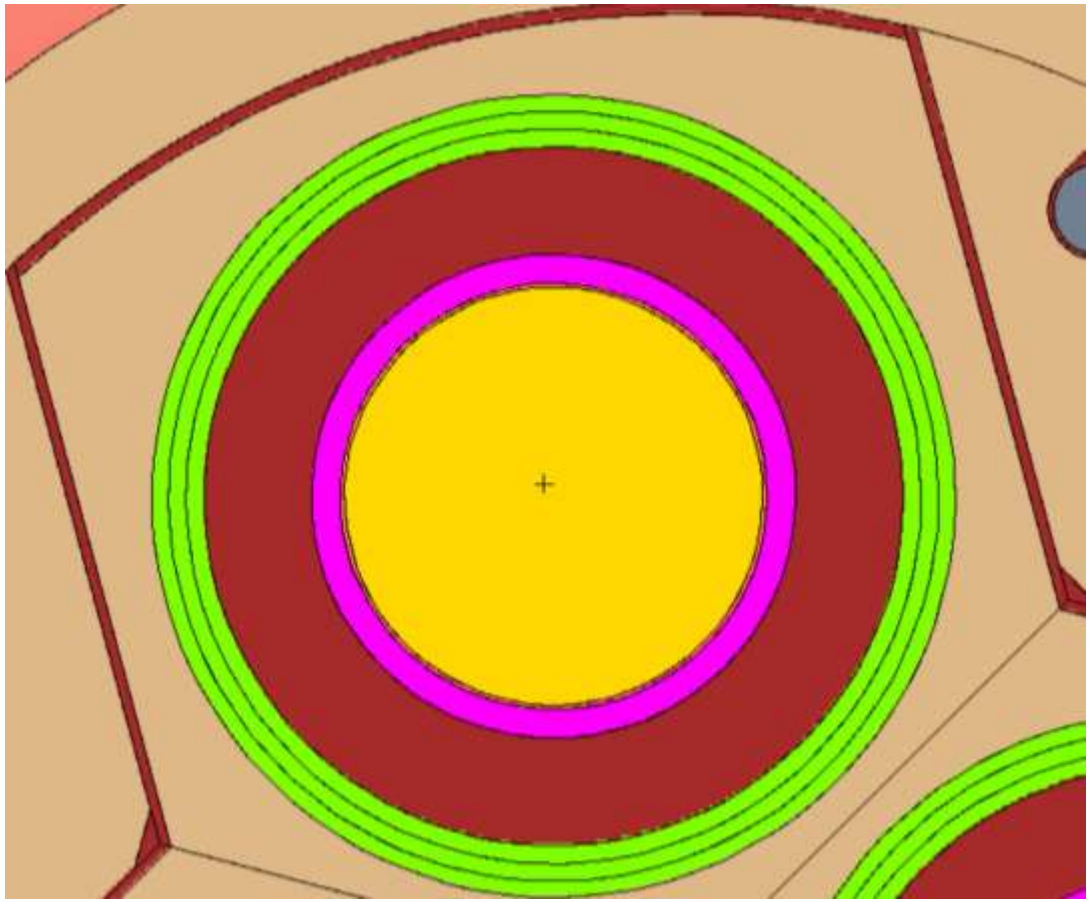
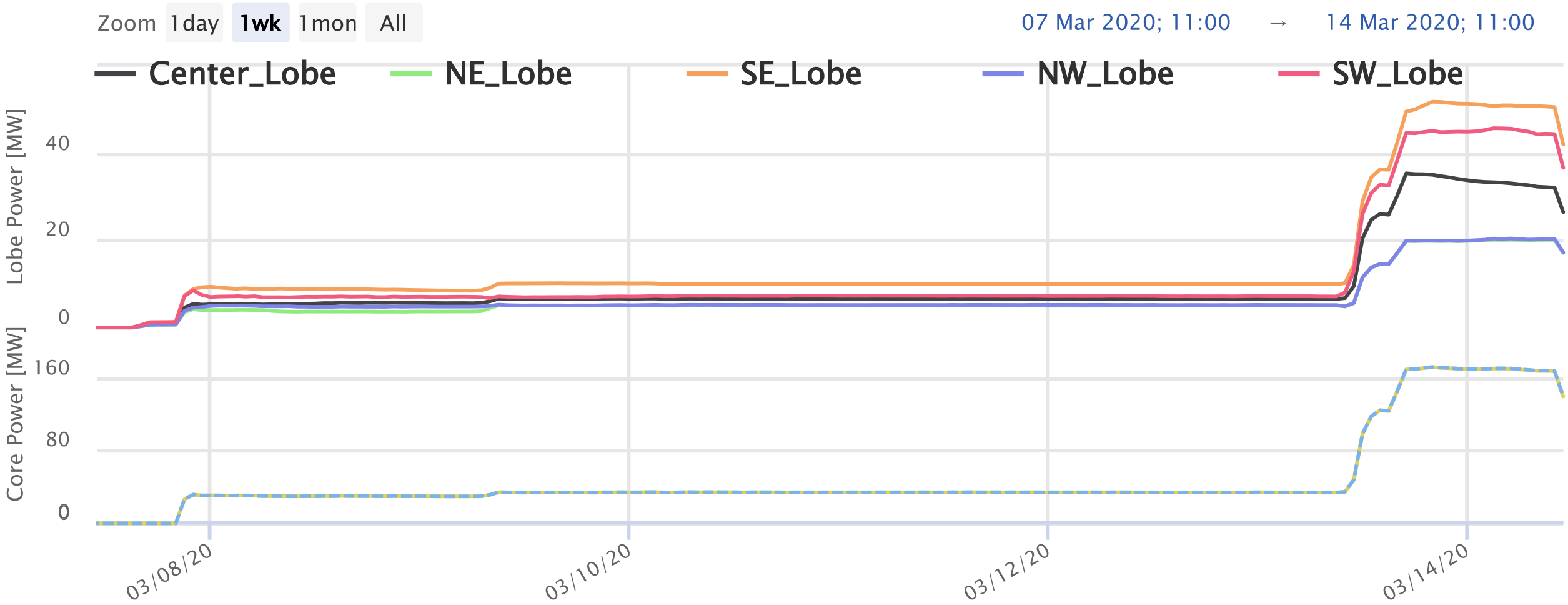
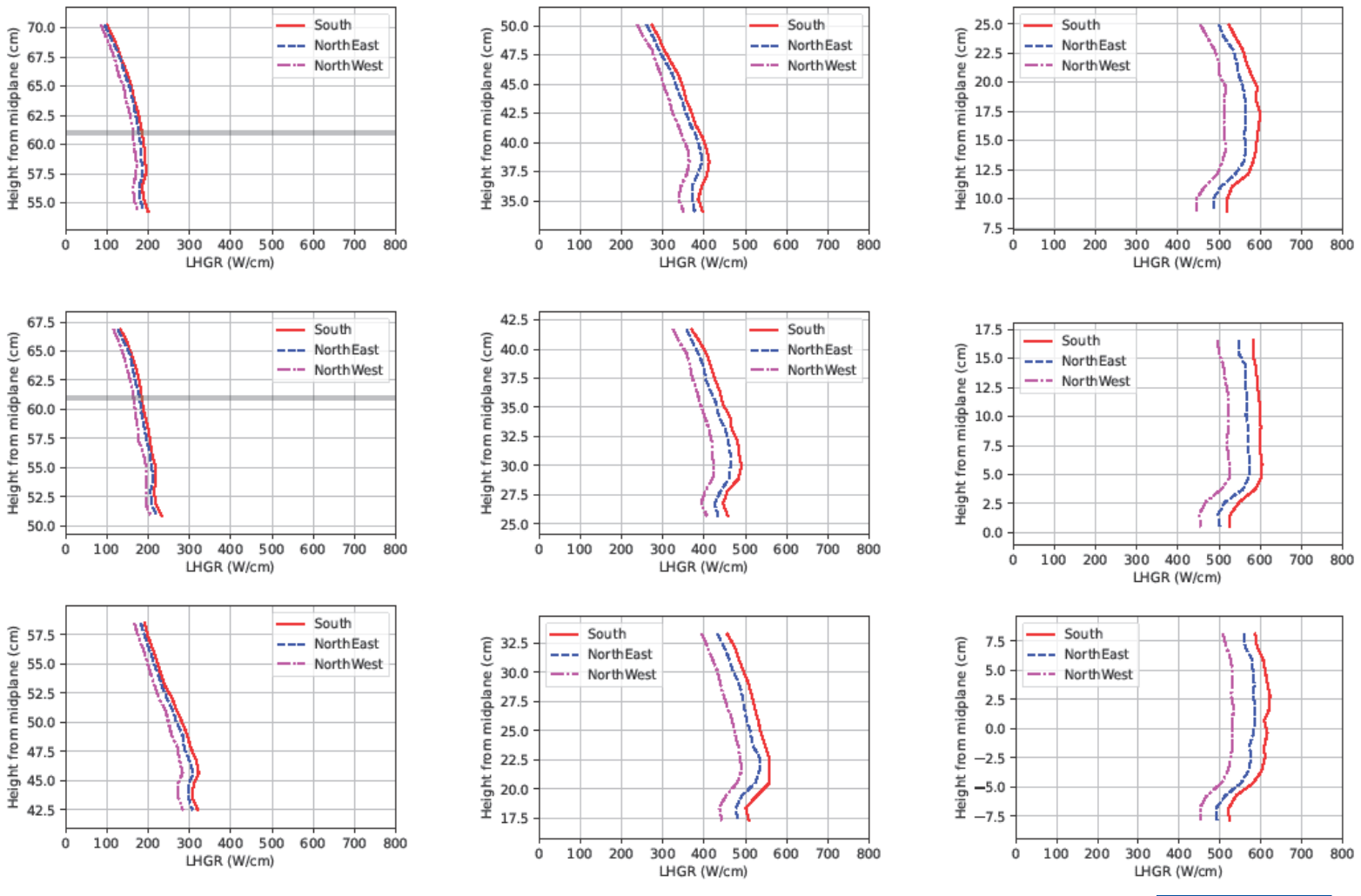


Cycle 167A-PALM Power History



Axial Power Profiles of Near-Optimal ATF-2Ramp Design



Methods: Reaction Rate Normalization

- Heat Generation Rate:

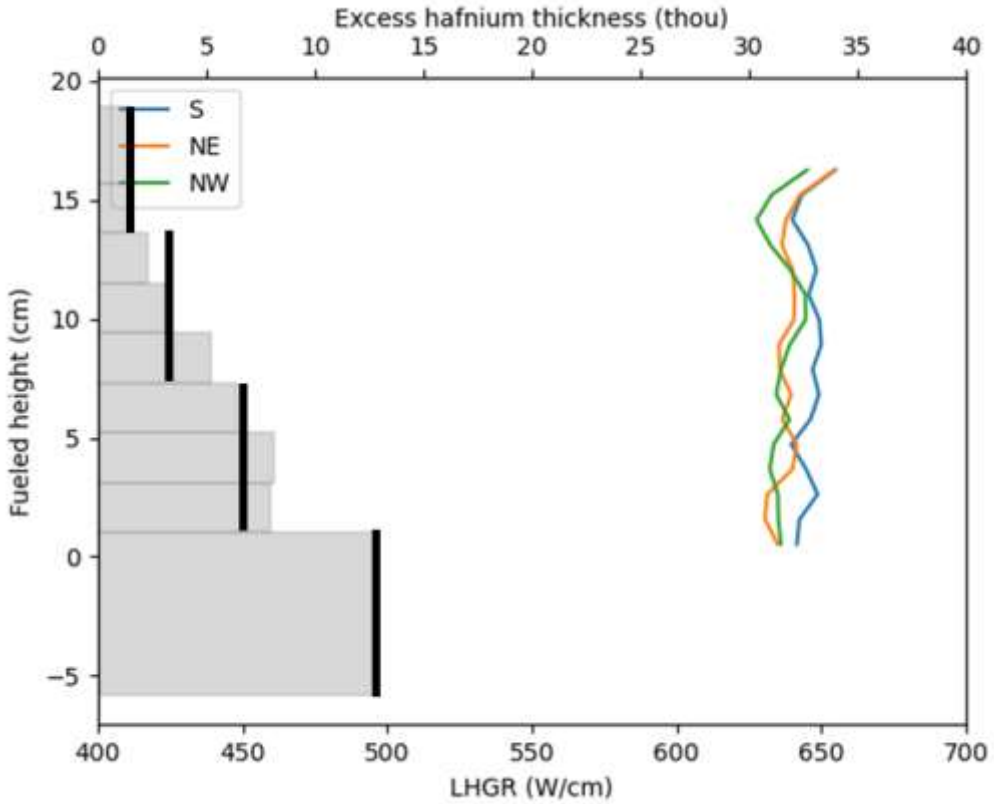
$$Q_{cell} = \frac{\nu}{\varepsilon}(LATCP)(\mathtt{f7:n}) \times m$$

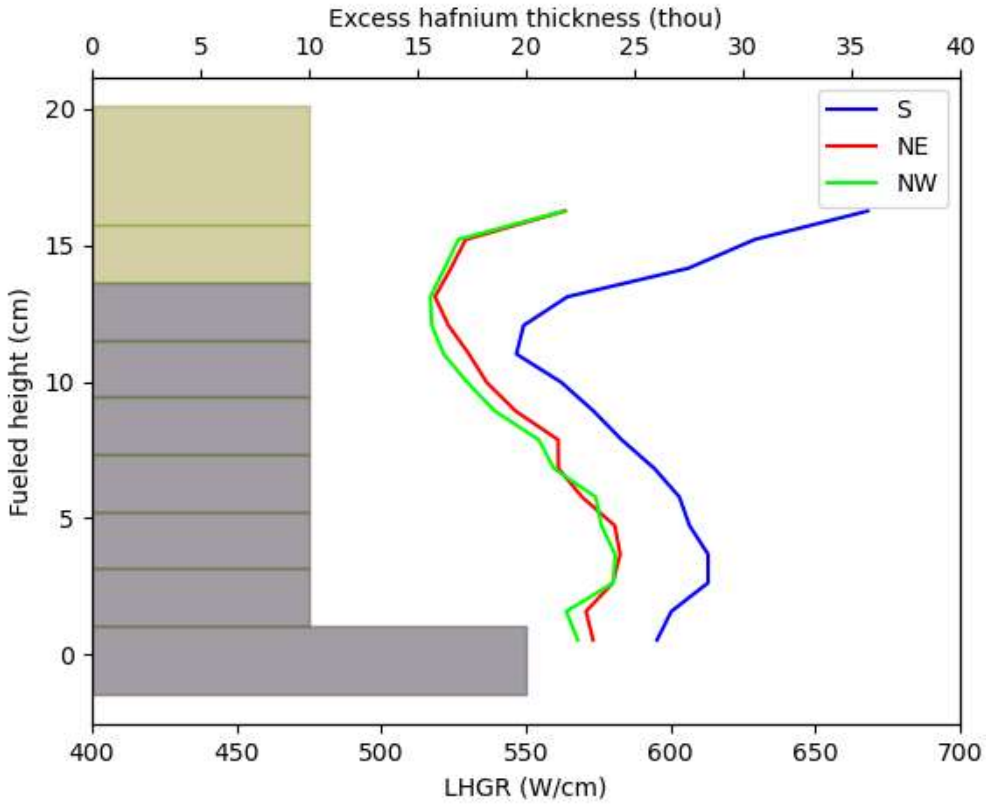
- Normalized to Lobe-Adjusted Total Core Power (LATCP)
  - Tally fission heating (MeV/g) in the 5 lobes (NW, NE, C, SW, SE)
  - Multiply by the ratio of *planned* lobe power (Q_L) to *tallied* lobe power ($f7{:}n)_L$

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

- Reaction rates scale linearly with Q_L.

Proposed Change #1





Proposed Change #2