INL/CON-23-75394-Revision-0

Conceptual Neutronics Scoping for Ramp Testing in the Advanced Test Reactor

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Changing the World's Energy Future

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Conceptual Neutronics Scoping for Ramp Testing in the Advanced Test Reactor

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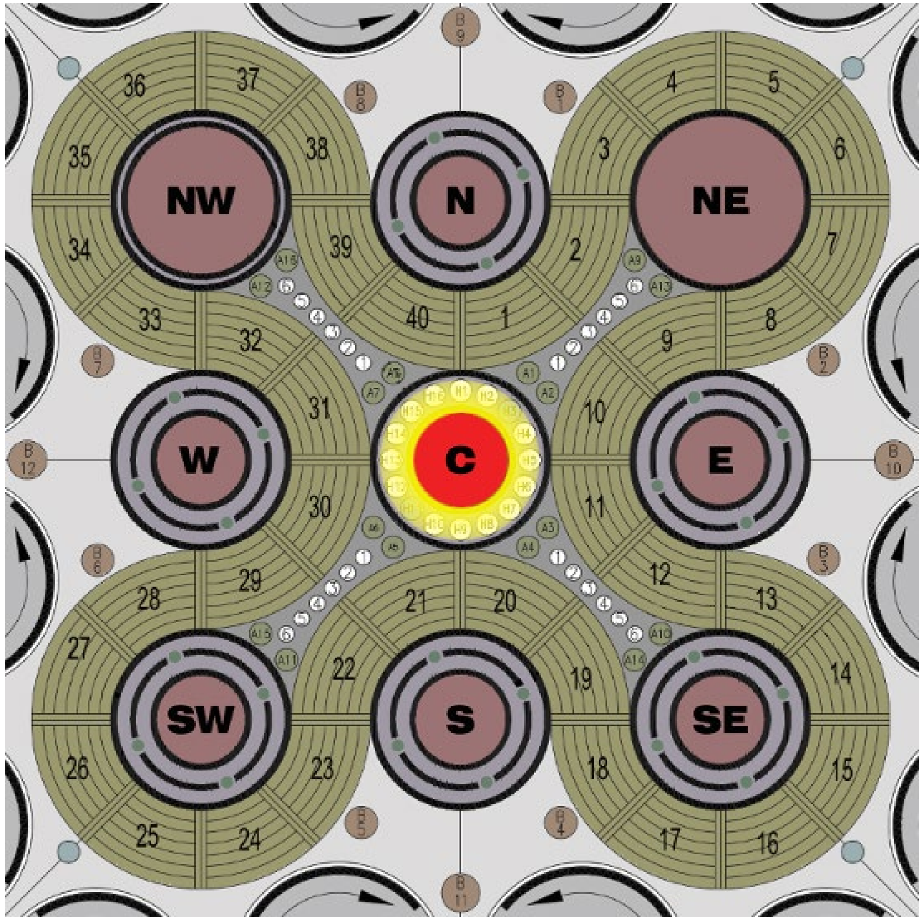
Idaho National Laboratory

Background

- “Ramp” testing is essential for studying pellet cladding interaction (PCI).
  - Experiment power is ramped up and down to stress the fuel.
- With the closure of the Halden Boiling Water Reactor in 2018, capacity for in-reactor power ramp testing was lost.
- It is of interest to the US Accident Tolerant Fuel (ATF) Program to find new facilities for PCI ramp testing.
- Three options at Idaho National Laboratory were considered:
  - Transient Reactor Test Facility (TREAT) in a Transient Water Irradiation System in TREAT (TWIST) capsule
  - Advanced Test Reactor (ATR) in an I-Loop (*up next – Worrall et. al.*)
  - **ATR Center Flux Trap (CFT) in Loop-2A**
- This presentation examines conceptual neutronic design of the proposed Loop-2A experiment “**ATF-2Ramp**.”

Advanced Test Reactor Layout

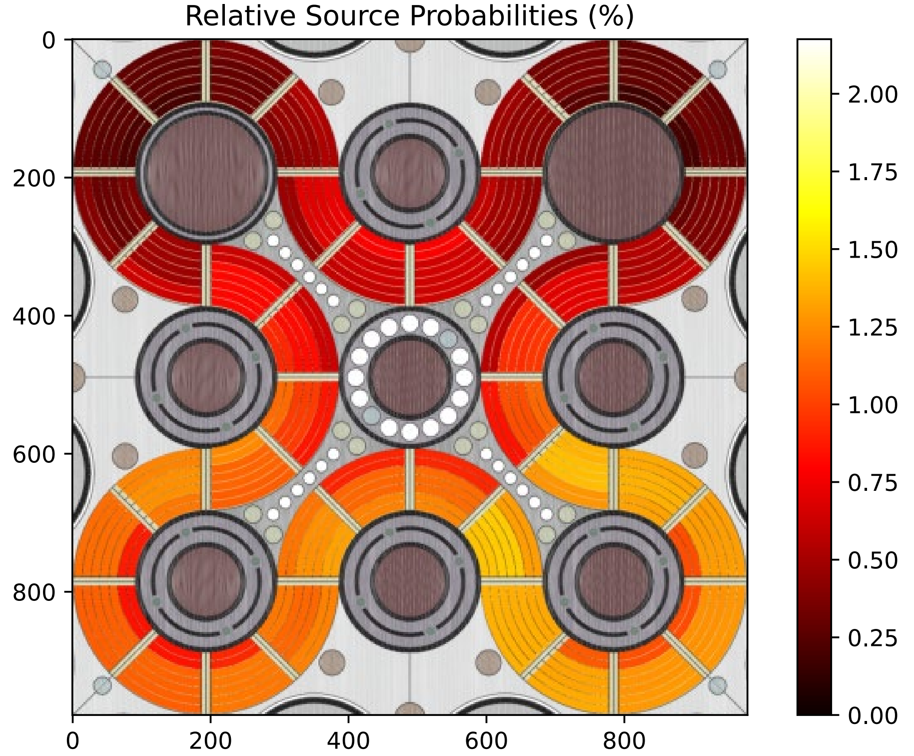


Typical Fluxes

Location	Diameter (inches)	Thermal Flux (n/cm^2-s)	Fast Flux (n/cm^2-s)
North Flux Trap	3.250	4.4E+14	9.7E+13
West Flux Trap	3.250	4.4E+14	9.7E+13
East Flux Trap	3.250	4.4E+14	9.7E+13
South Flux Trap	3.250	4.4E+14	9.7E+13
Center Flux Trap	**3.160**	**4.4E+14**	**9.7E+13**
Northwest Flux Trap	5.375	4.4E+14	2.2E+14
Northeast Flux Trap	5.375	4.4E+14	2.2E+14
Southwest Flux Trap	3.250	4.4E+14	9.7E+13
Southeast Flux Trap	3.250	4.4E+14	9.7E+13
Small B-Position	0.875	2.5E+14	8.1E+13
Large B-Position	1.500	1.1E+14	1.6E+13
Inner-A Position	0.625	1.9E+14	1.7E+14
Outer-A Position	0.500/0.625	2.0E+14	2.3E+14
H-Hole	0.625	1.9E+14	1.7E+14
Small I-Position	1.500	8.4E+13	3.2E+12
Medium I-Position	3.250	3.4E+13	1.3E+12
Large I-Position	5.000	1.7E+13	1.3E+12

PALM Cycles in ATR

- The ATR CFT is normally occupied by steady-state ATF-2 experiments.
- ATR periodically operates short, high-powered cycles for powered axial locator mechanism (PALM) experiments.
  - Characterized by core power changes and a strong flux tilt, conventionally South lobes > North lobes.
- Assumed: Cycle 167A-PALM lobe power distribution from near EOC.

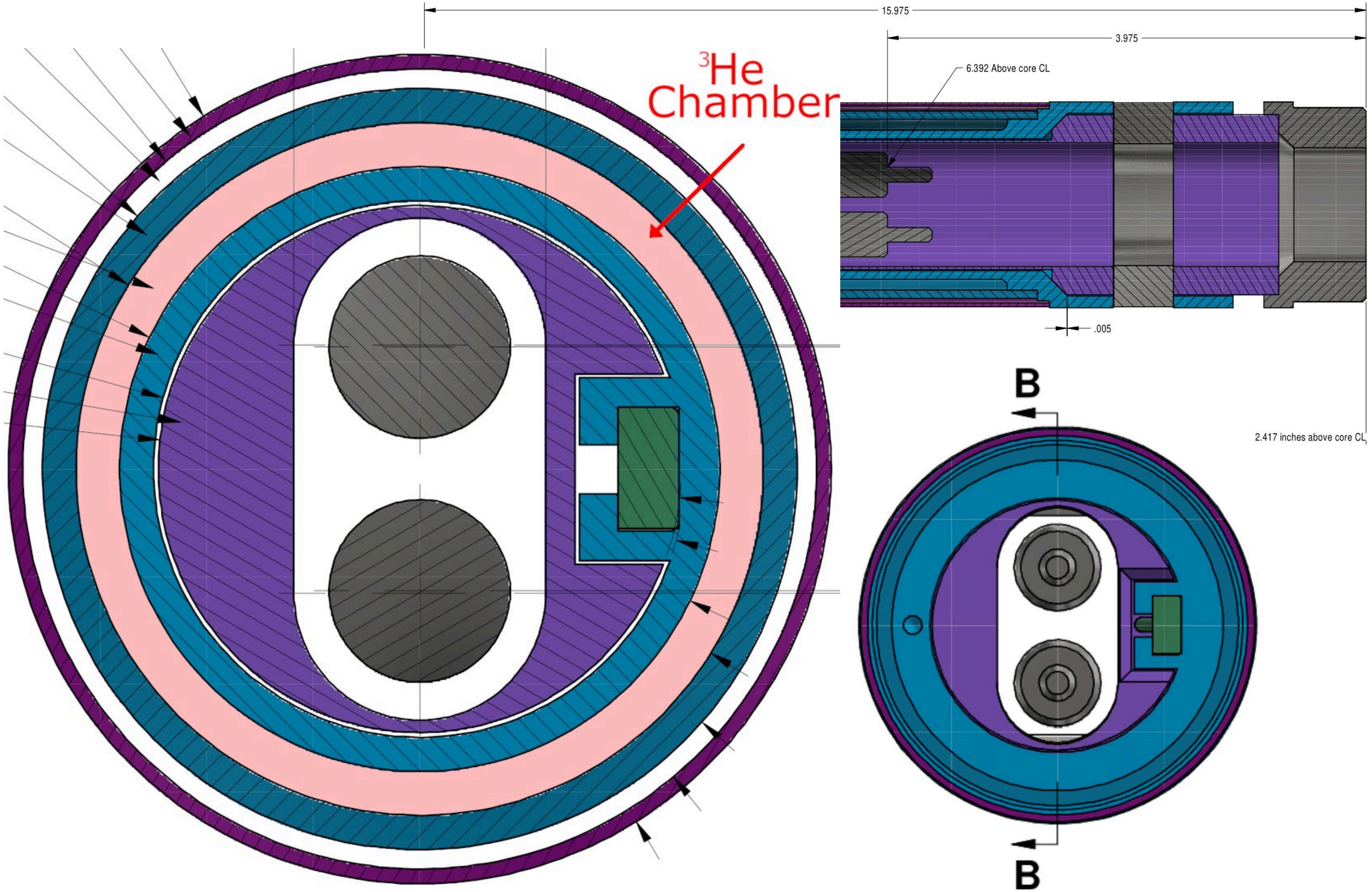


Lobe	NE	SE	SW	NW	C
Power (MW)	16.86	51.31	44.90	18.44	36.71

ATF-2Ramp Objectives

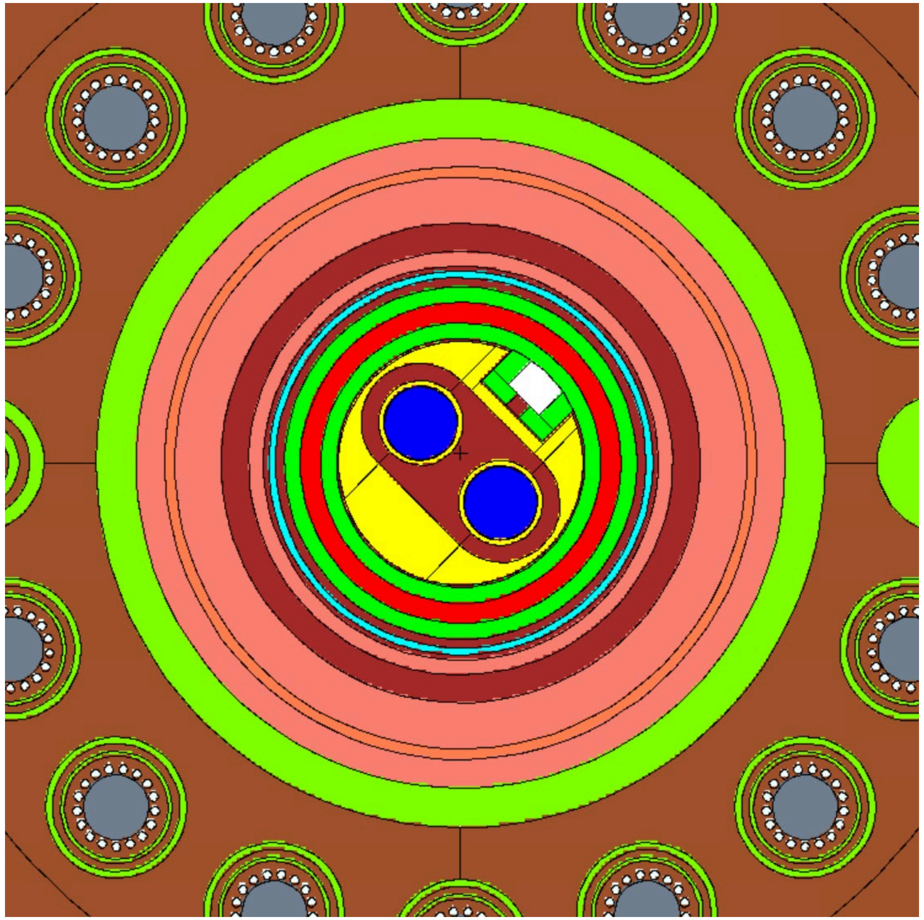
- Operate at peak ATR PALM cycle power
- Irradiate 2-3 pins under pressurized water reactor (PWR) conditions
  - Standard PWR radius, 30 cm length
  - Coolant around 15 MPa, 300°C, 1000 ppmb
- Achieve power ramp of 250 W/cm to >600 W/cm peak pin LHGR
  - i.e., a “ramp height” of 2.4
- To meet these objectives, two test train (TT) concepts were examined.

Helium Chamber Device

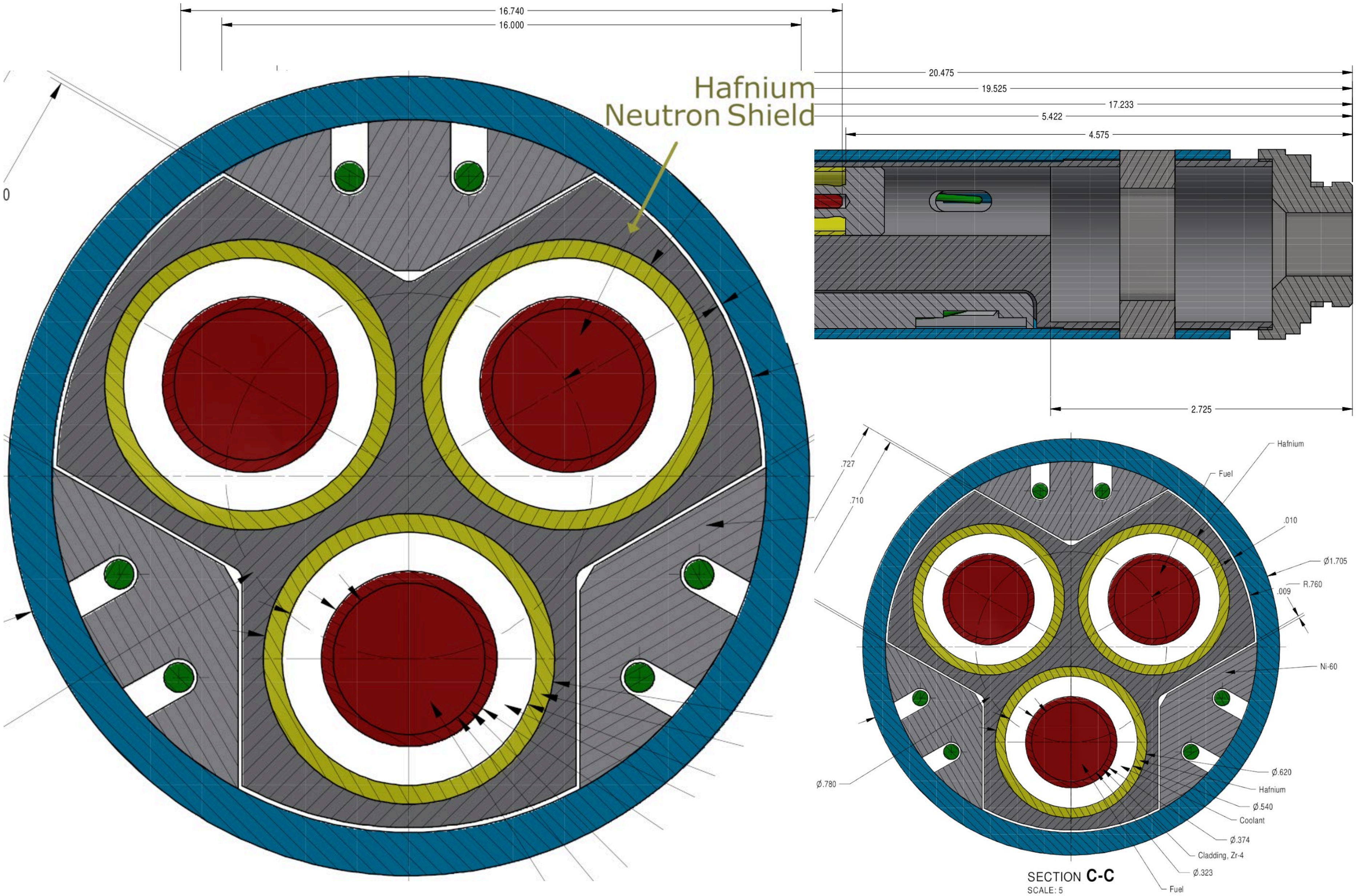


Helium Chamber Device

- Two-pin TT with shared flow channel
- Surrounded by ^{3}He chamber (red)
- Power ramp controlled via helium pressure - pumping ^{3}He in/out.
- Optional external hafnium shroud

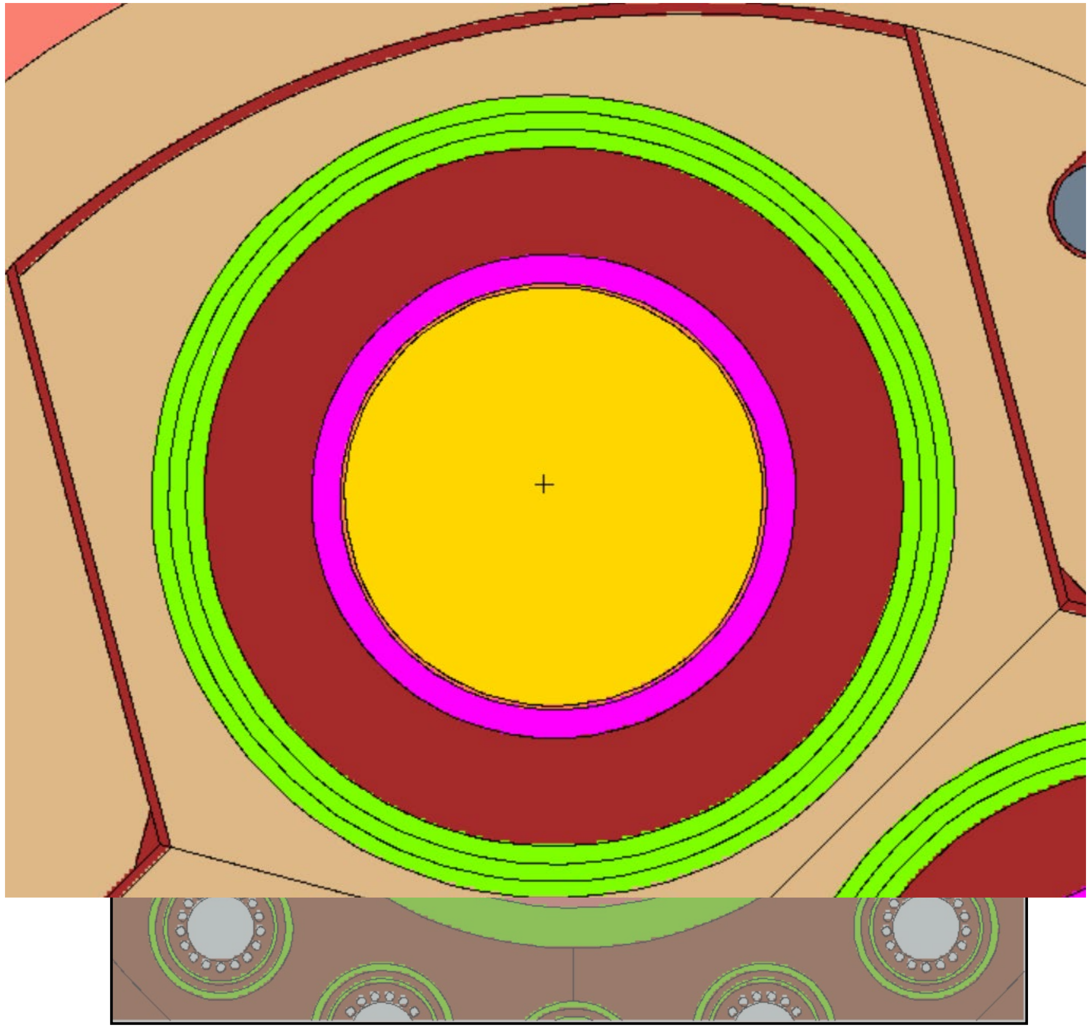


Trefoil Device

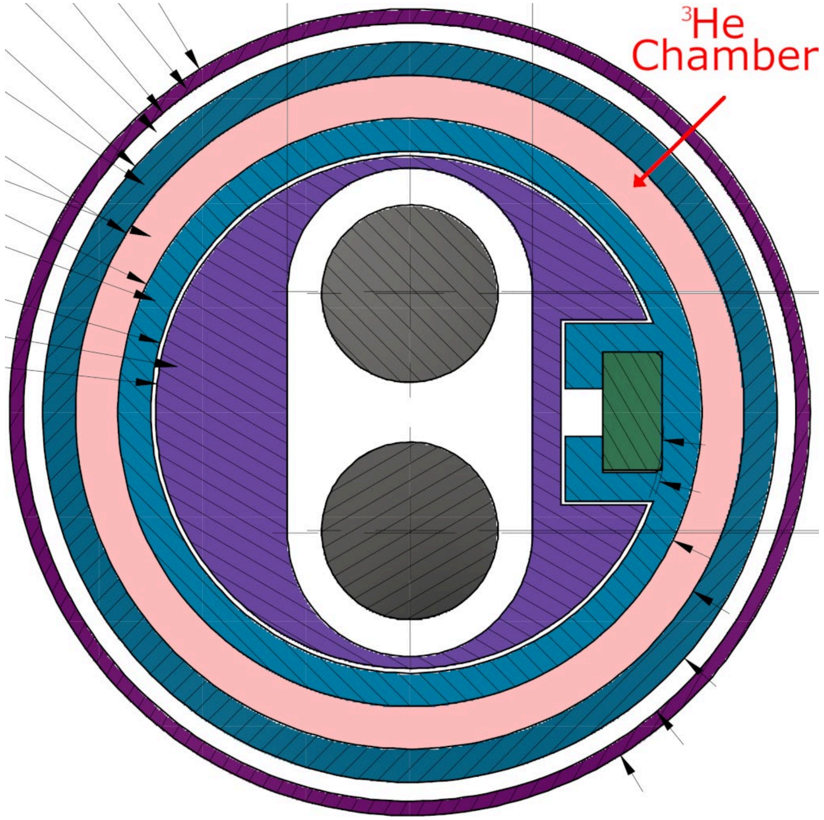


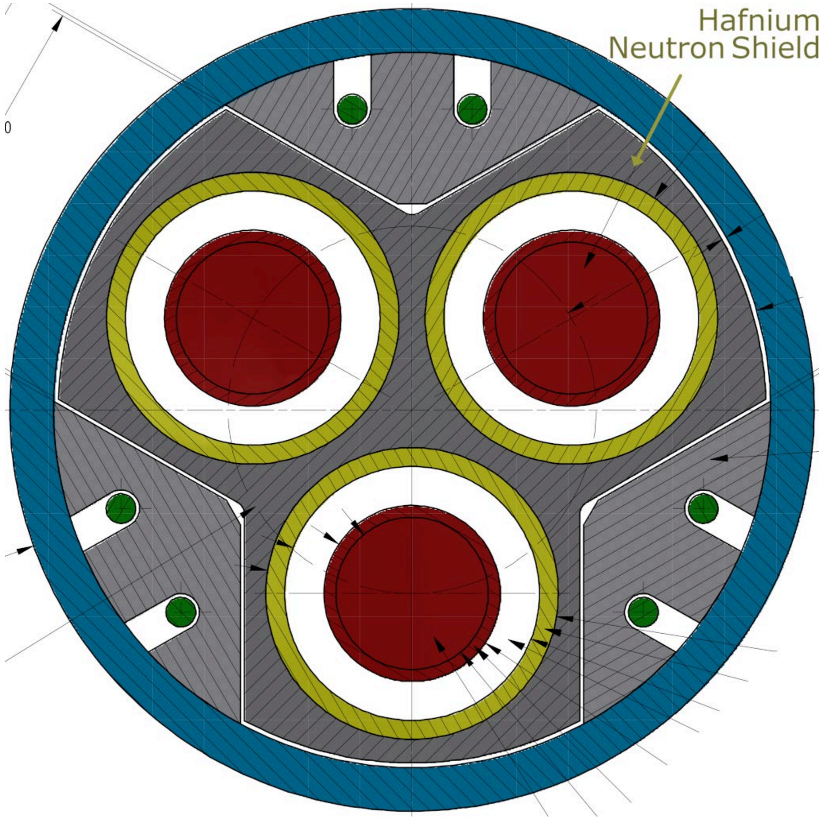
Trefoil Device

- 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: 3 equal-volume radial regions



Side-by-side



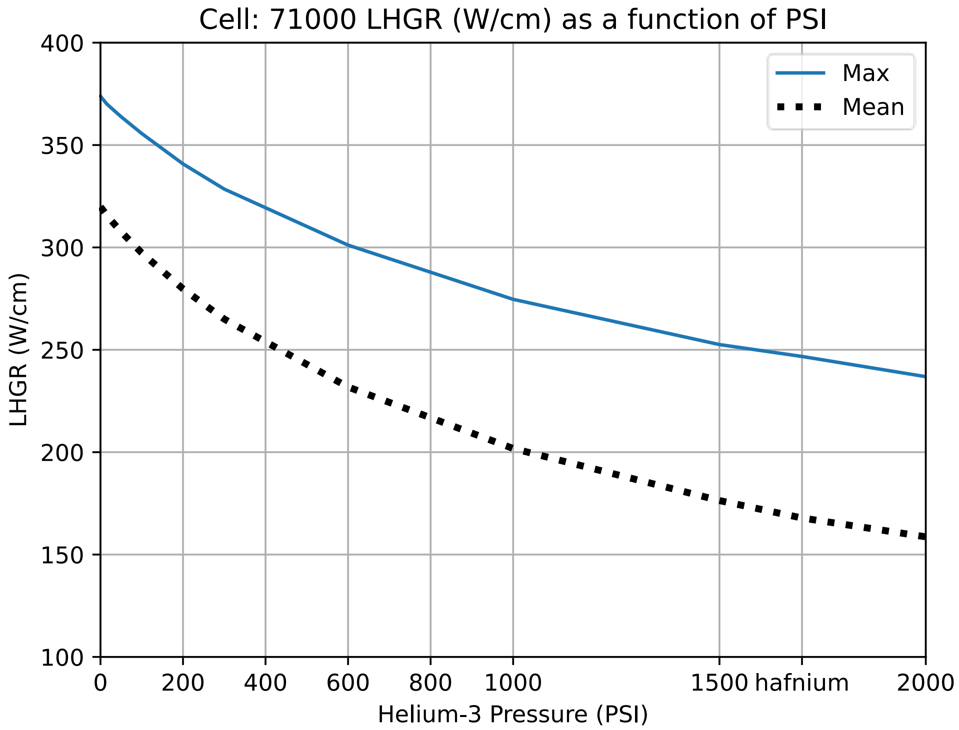


Methodology

- Monte Carlo neutron transport calculation with MCNP6 (Monte Carlo N-Particle Transport Code)
- Same fixed-source definition applied across all cases
- Tally fission power in fuel pellets
- Calculate feasible power ramps from both ATF-2Ramp concepts
- Helium chamber device:
  - Vary ^{3}He pressure from 0 (void) to 2000 psi
  - Calculate number density: $PV = nRT \rightarrow N = \frac{n}{V} = \frac{P}{RT}$
- Trefoil device:
  - Vary axial location from ATR core midplane to withdrawal above core
  - Additionally study power shaping using minishrouds

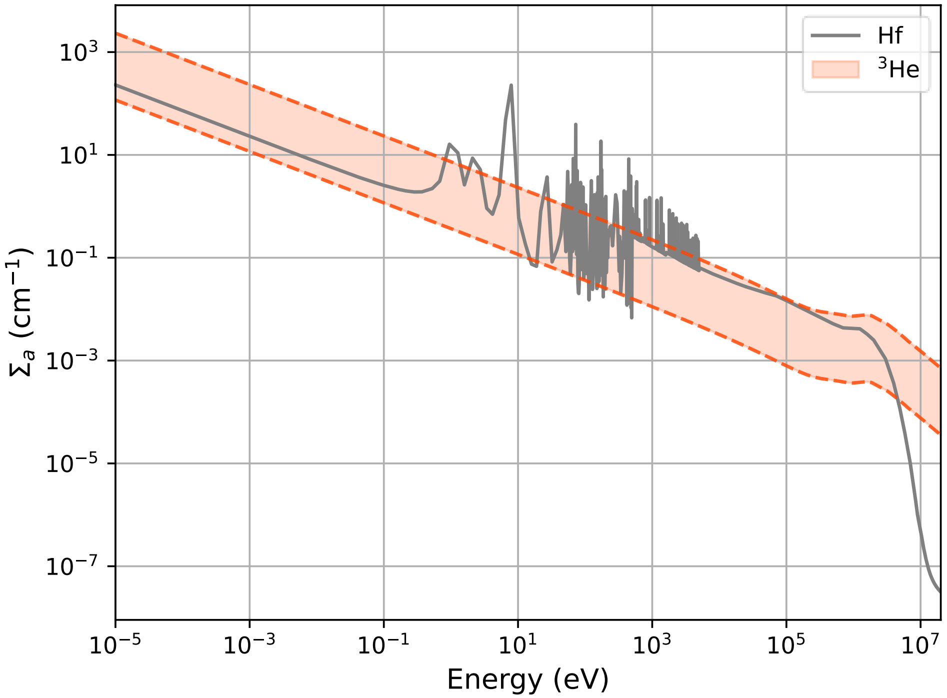
Results: Helium Chamber

- Test train placed just above core midplane (fuel: +4 to +28 cm)
- The ^{3}He control mechanism offers a certain degree of control of power, but not as much as needed.
- A mean ramp height of 2× requires pressures in excess of 2000 psi.

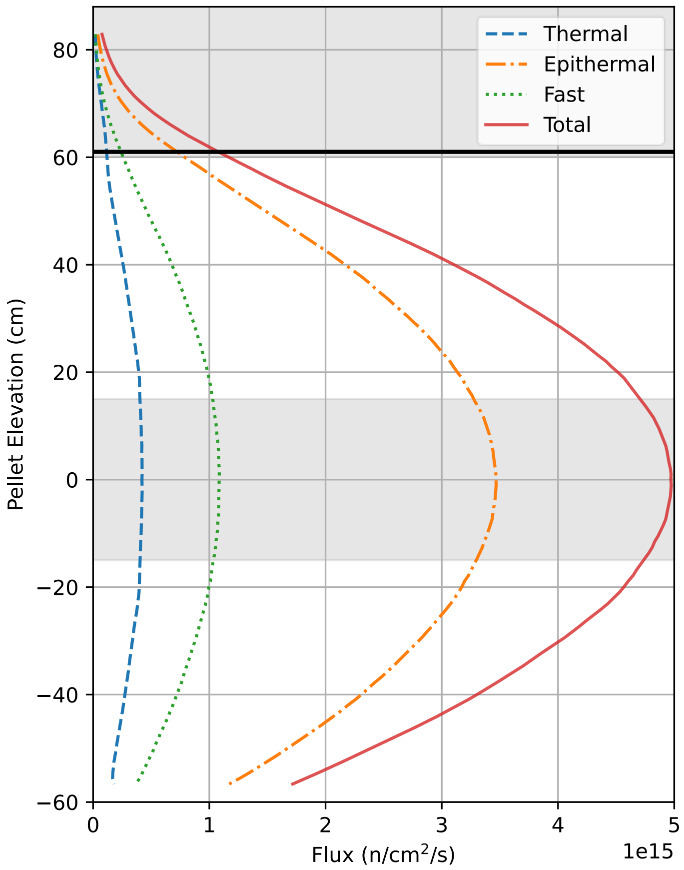


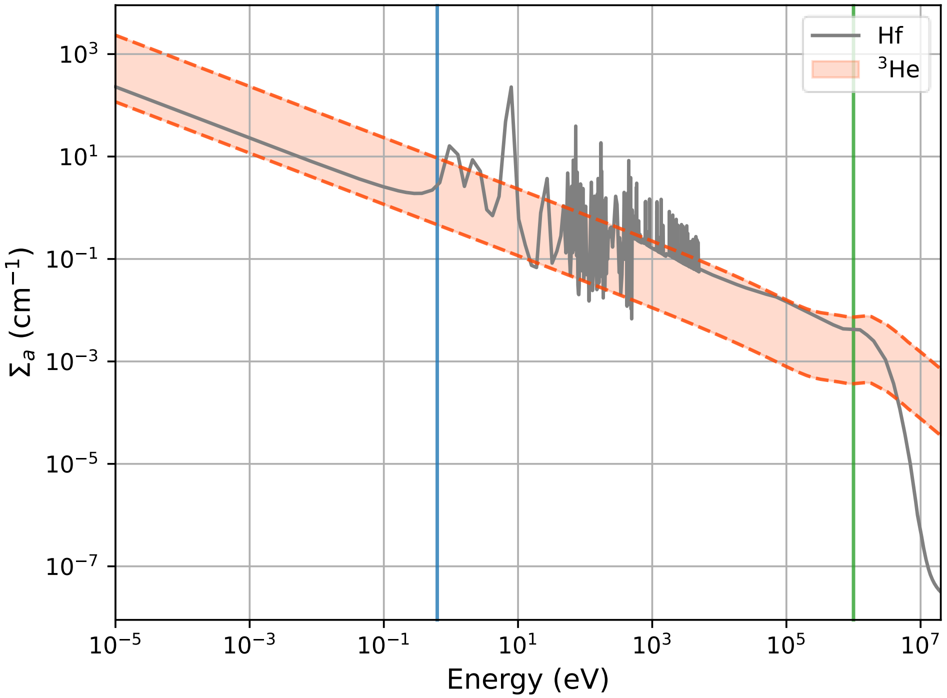
Results: Effectivity of Helium-3 vs. Hafnium

- ^3He is not as effective as Hf for controlling power in this position.
  - Right: macroscopic absorption cross section for 100-2000 psi
- To have the same effect as an equal volume of hafnium, a helium pressure of 1700 psi is required.
- Why is this?

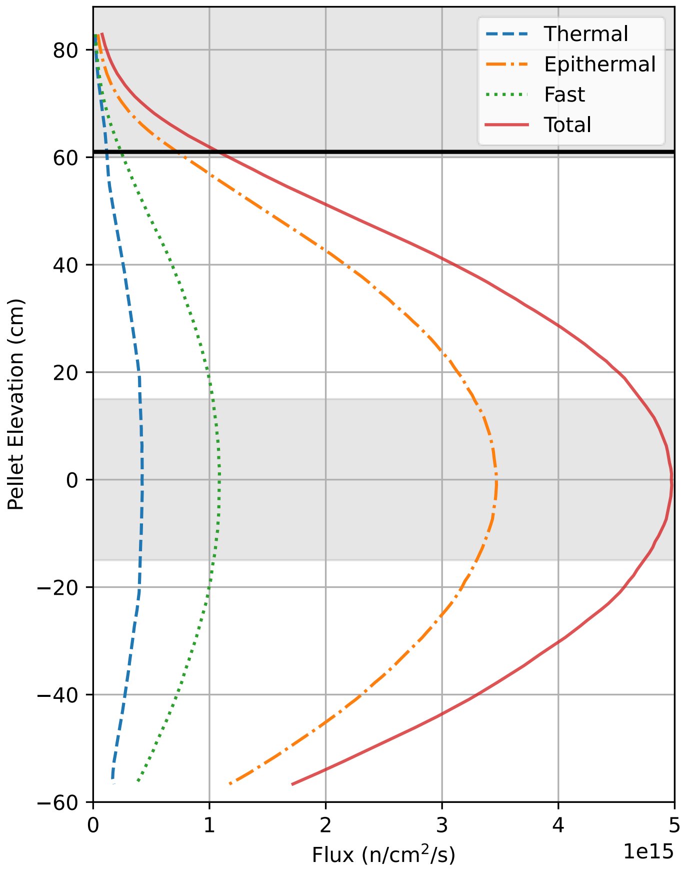


CFT Flux Spectrum is Unsuitable for ^{3}He Control





Axial Location May Outperform ^{3}He Control



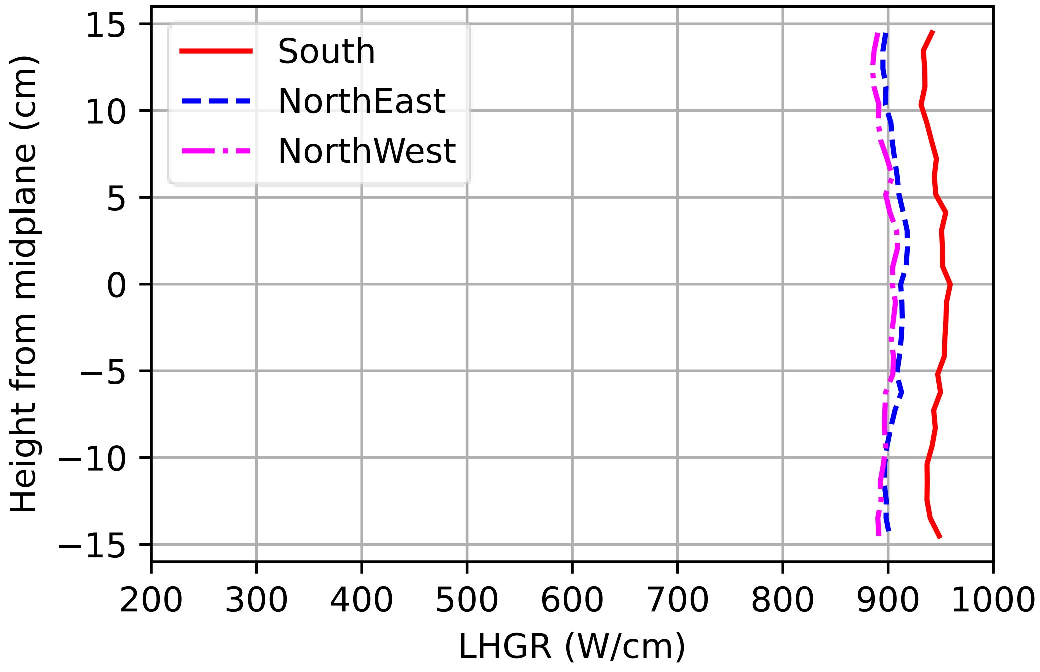
- Left: Flux profile for extruded generic ATF-2 test train w/ core at 100 MW (*this morning – Rogers et. al.*)
- Flux spectrum is too "hard" for effective ^{3}He control.
- Can achieve much better ramp using natural flux profile.
- Shaded regions indicate the minimum and maximum power test positions.

Axial Elevations for Trefoil Device

Case	Description	Δz of Fuel Bottom from Core Midplane
01	Centered at core midplane	–15.0
02	Bottom at core midplane	± 0.0
03	Centered 30 cm above midplane	+15.0
04	Top at core top	+30.0
05	Centered around core top	+45.0
06	Bottom around core top	+60.0

Results: Trefoil Device: Maximum Power

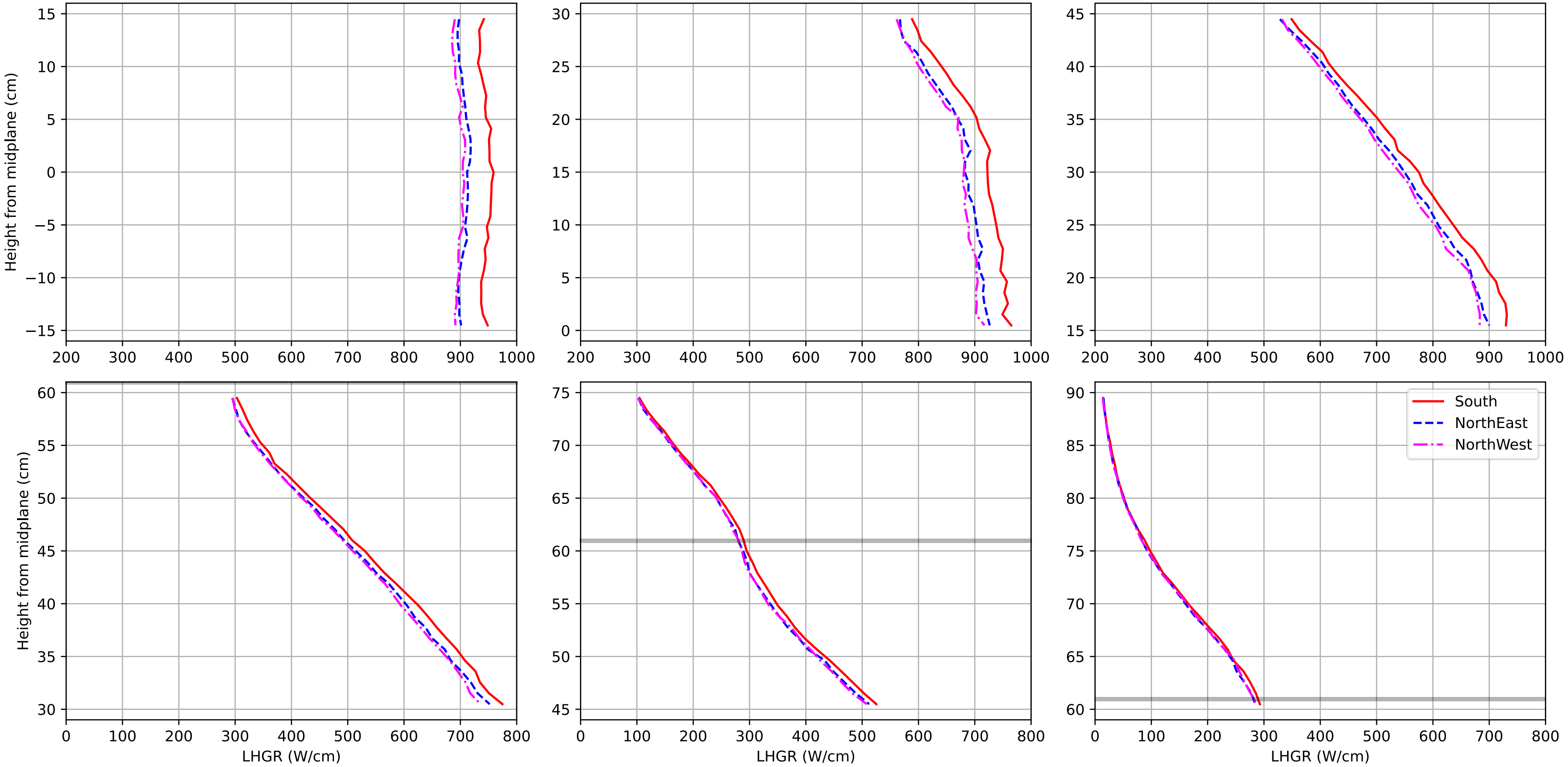
- Zircaloy minishrouds results in maximum rodlet heating.
- Left: all-Zr case at core midplane
- Flux tilt-induced pin separation:
  - S rodlet peaks at 965 W/cm
  - NE rodlet around 915 W/cm
  - NW rodlet around 910 W/cm
  - An approximate 5% North-South split is maintained across identical rodlets in all cases.
- Very hot. Power can be reduced with Hf minishrouds or higher elevations.



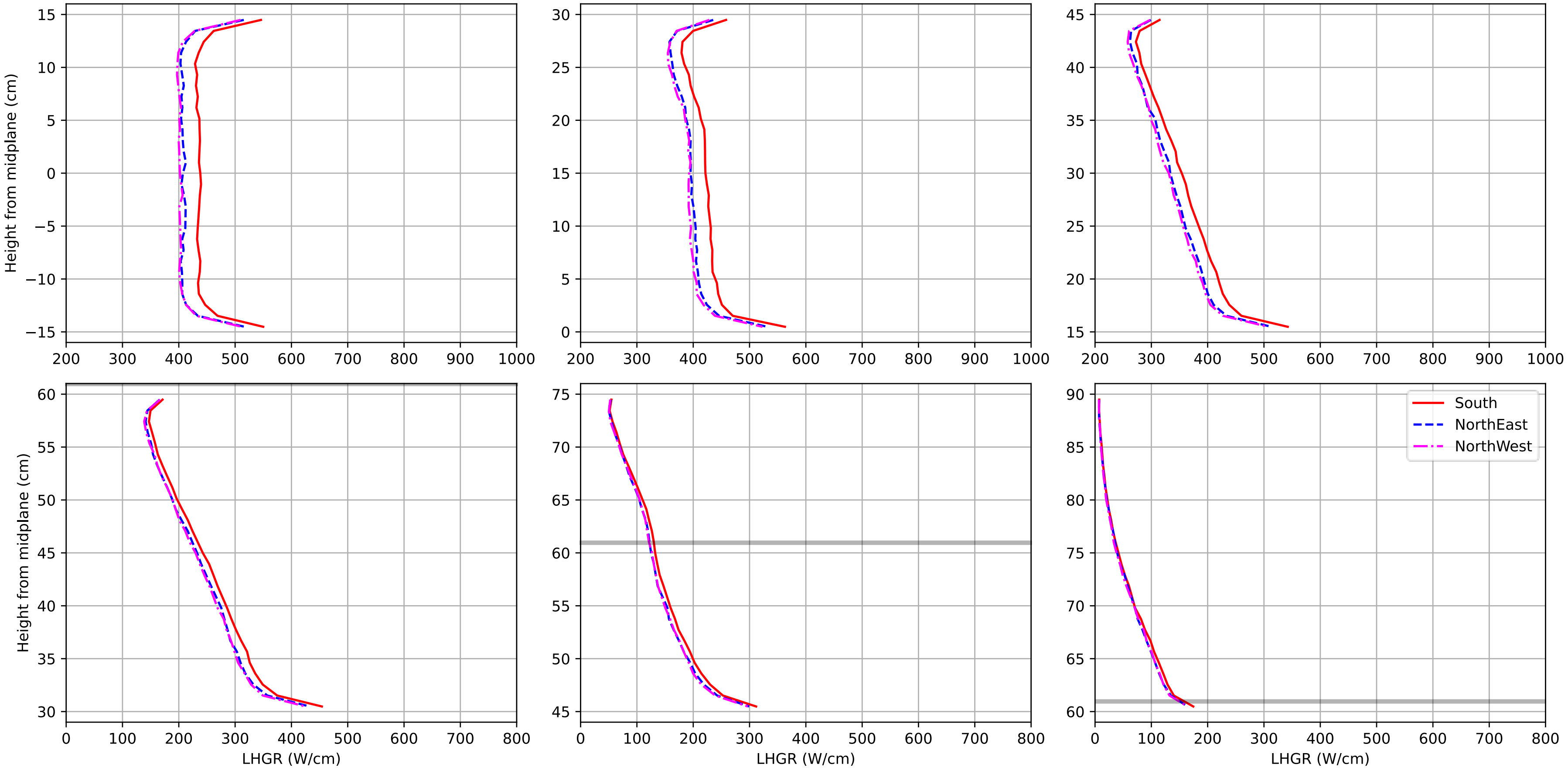
Results: Trefoil Device: Configurations

- Calculations for numerous minishroud configurations were performed.
- Minishrouds can be varied along several axes:
  - Independently by rodlet, to engineer separation
  - Radially (with concentric layers of Hf and Zr), to control power magnitude
  - Axially, to shape the experiment power profile
- Results of scoping study illustrate the ATF-2Ramp design space.

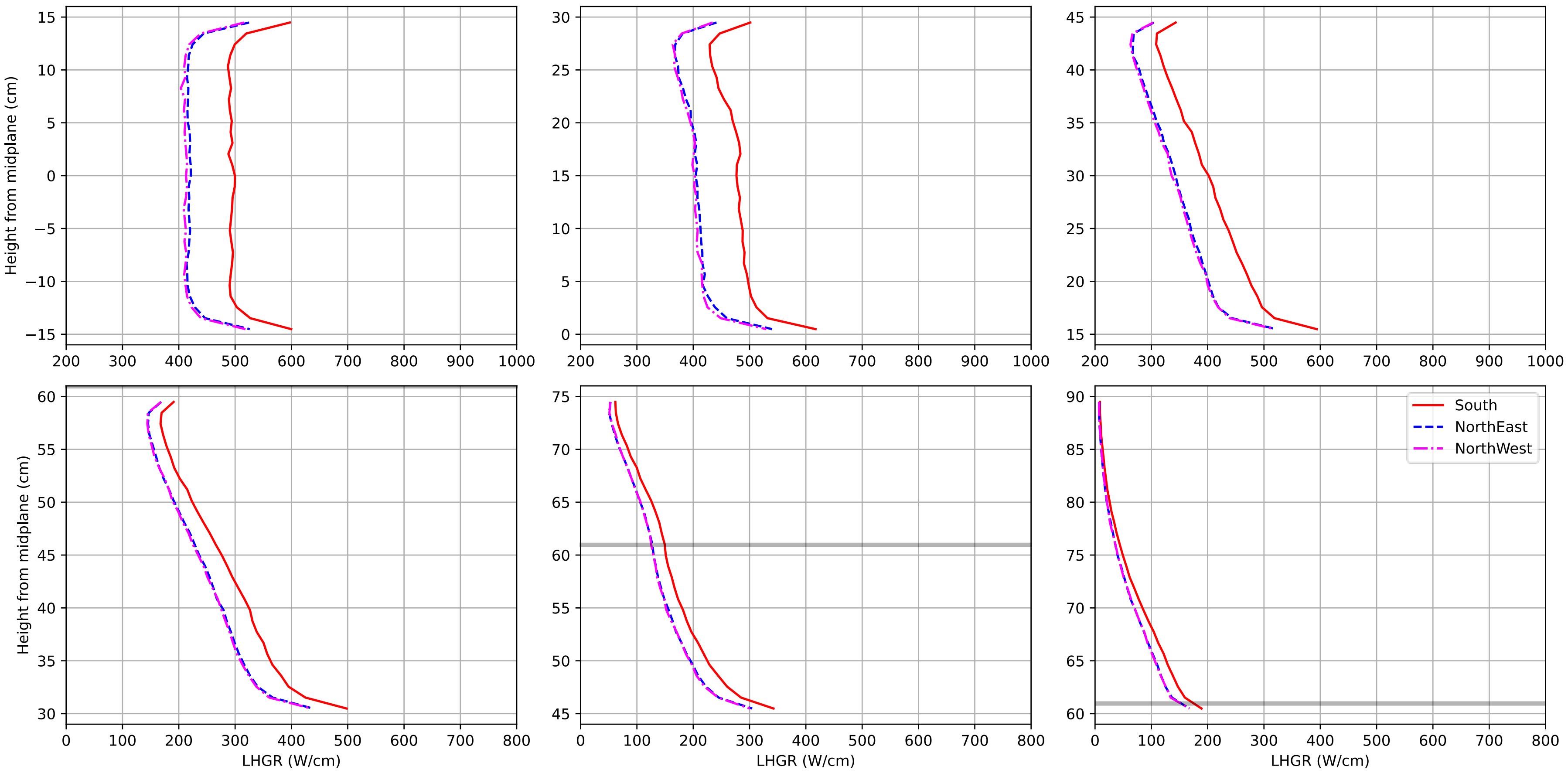
All Minishrouds as Zr



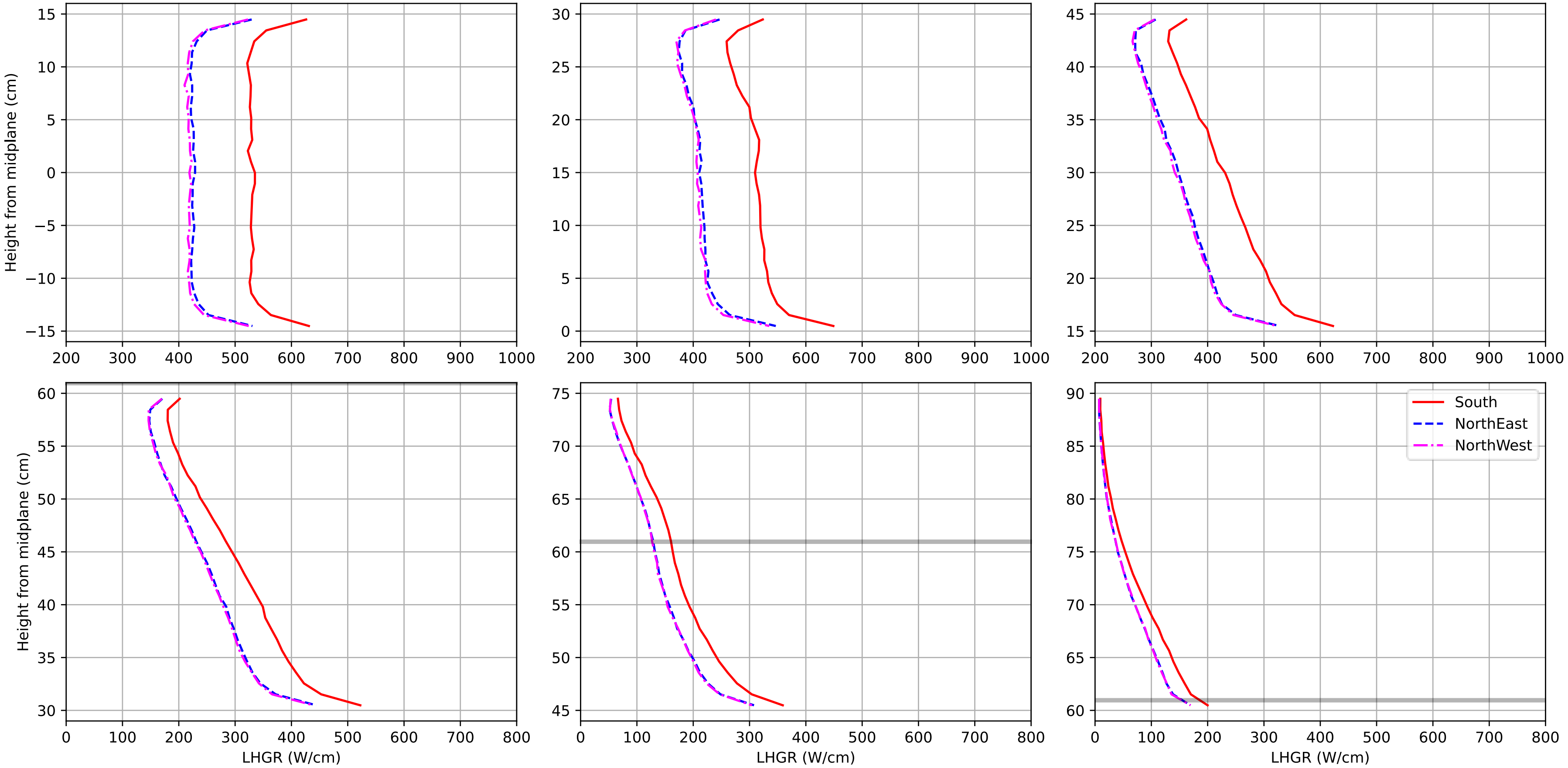
All Minishrouds as Hf



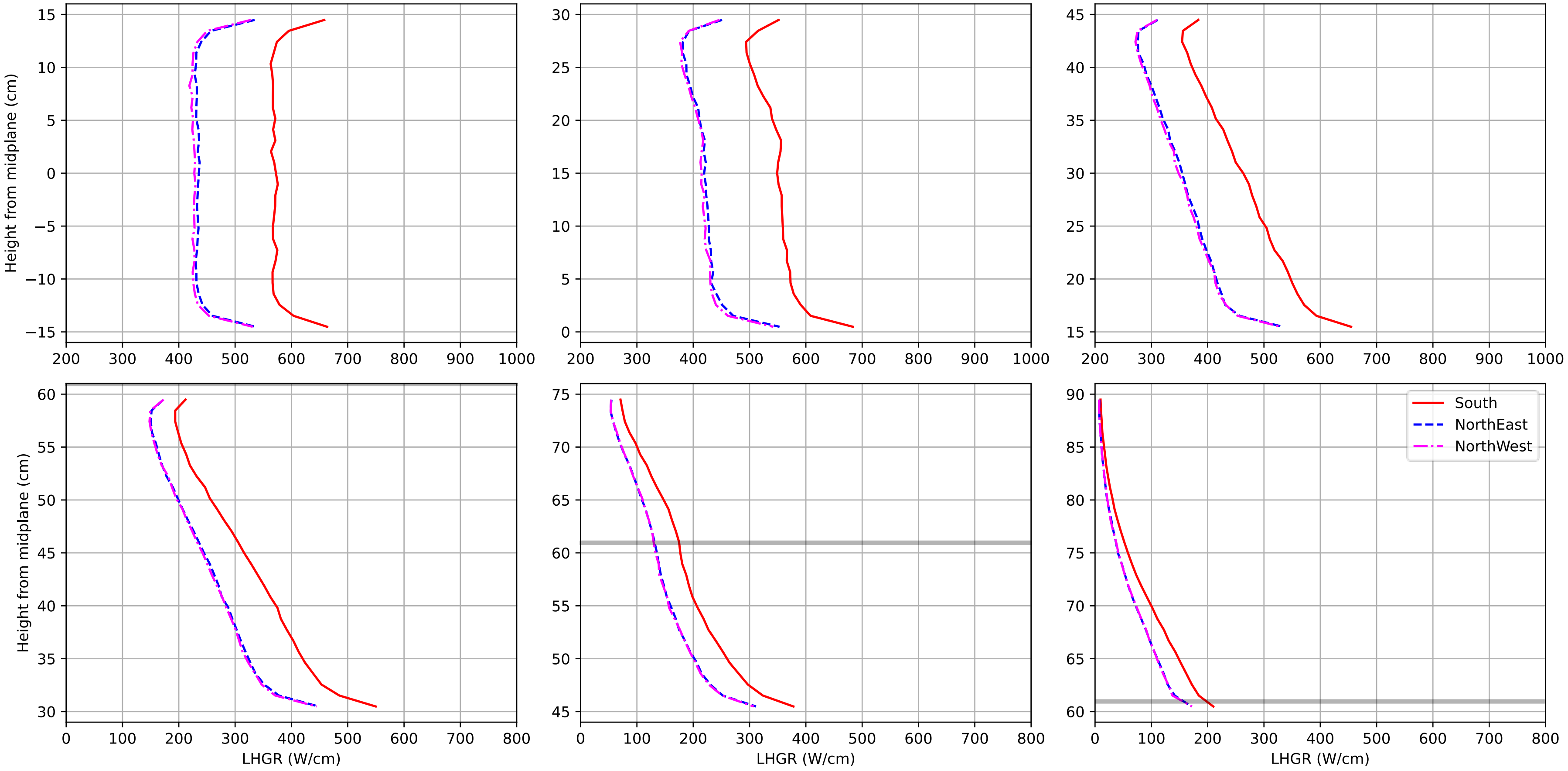
S as $^{2}/_{3}$ Hf; NW and NE as Hf



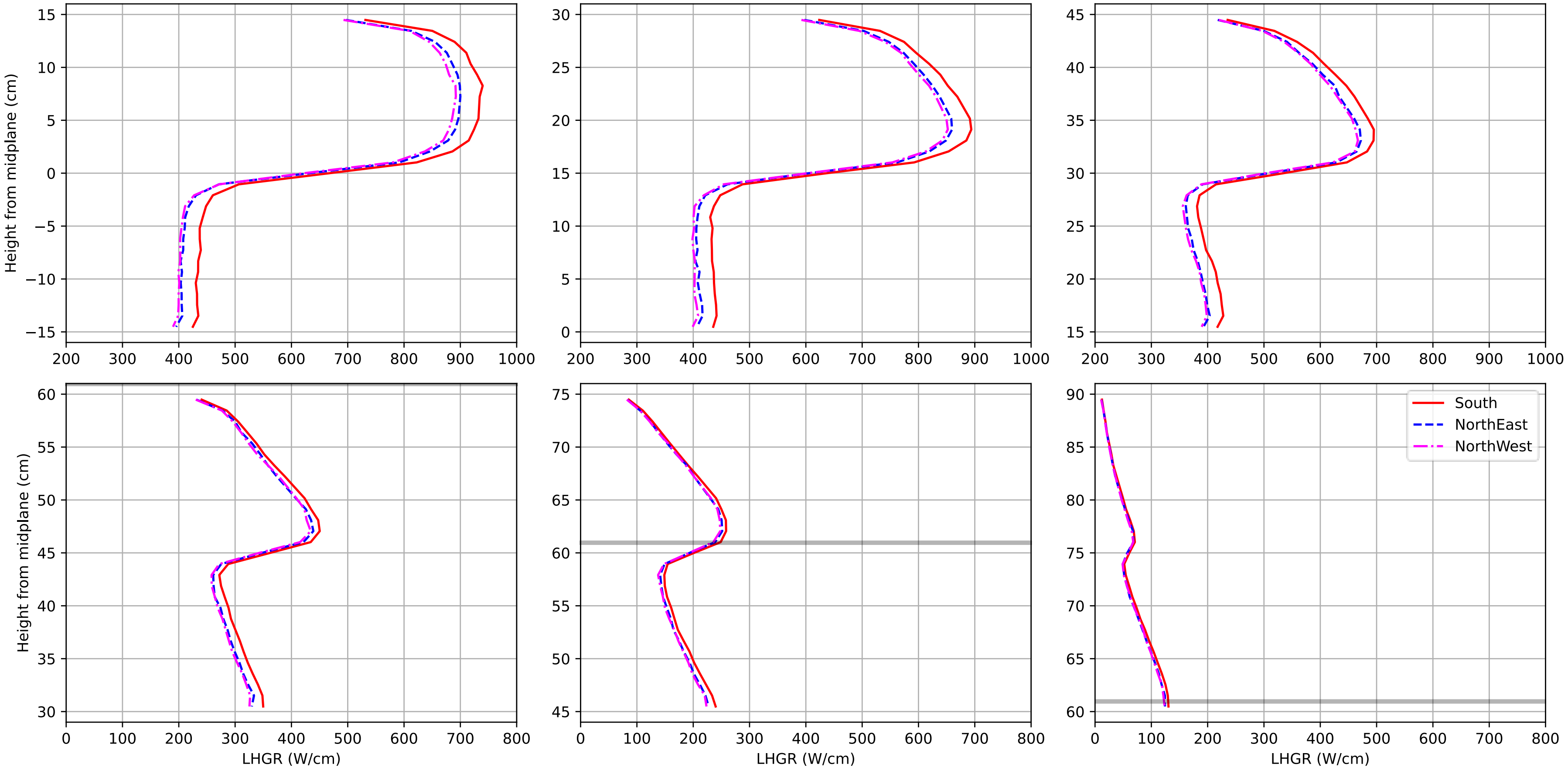
S as $^1/_3$ Hf; NW and NE as Hf



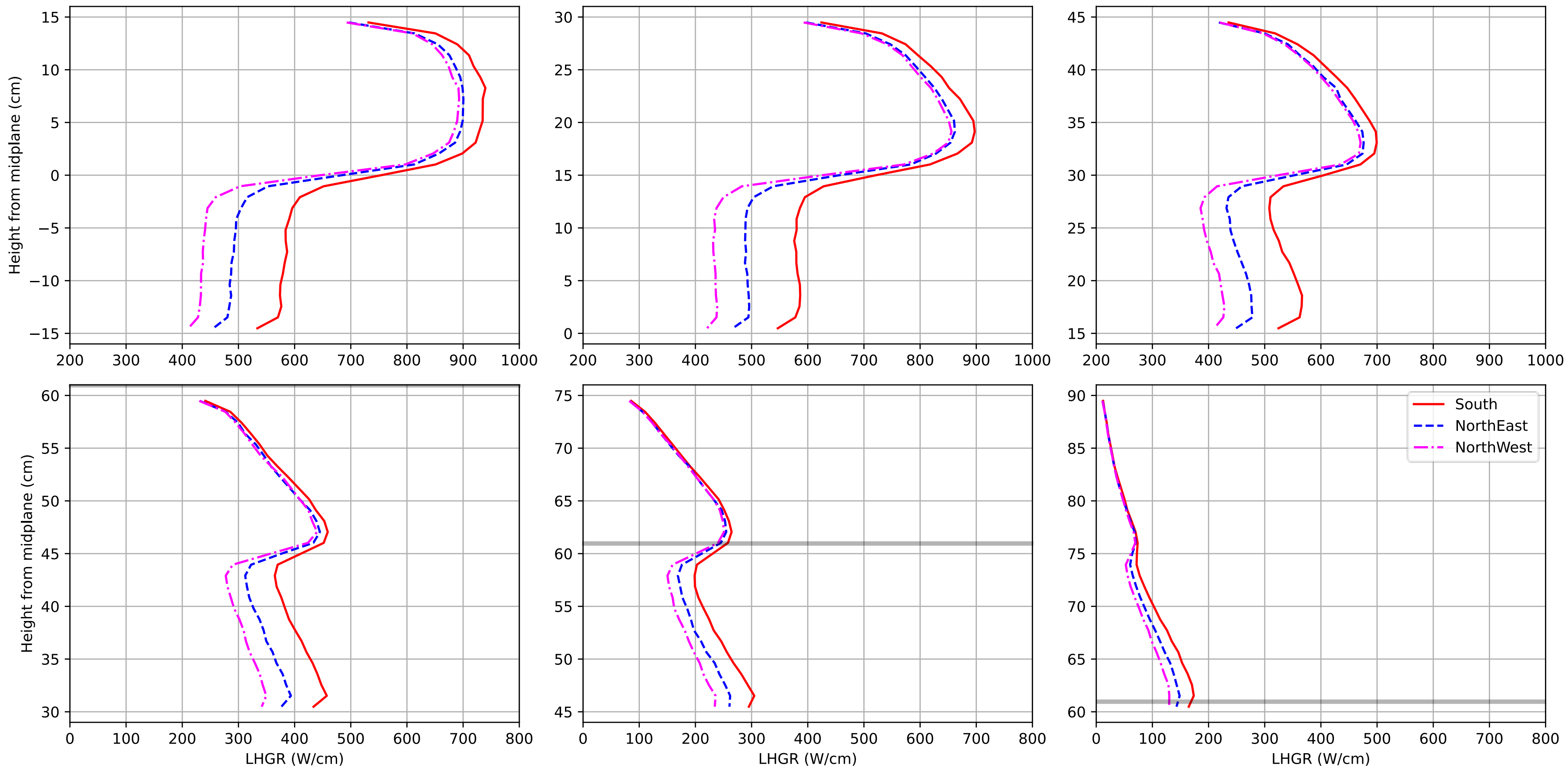
S as Zr; NW and NE as Hf



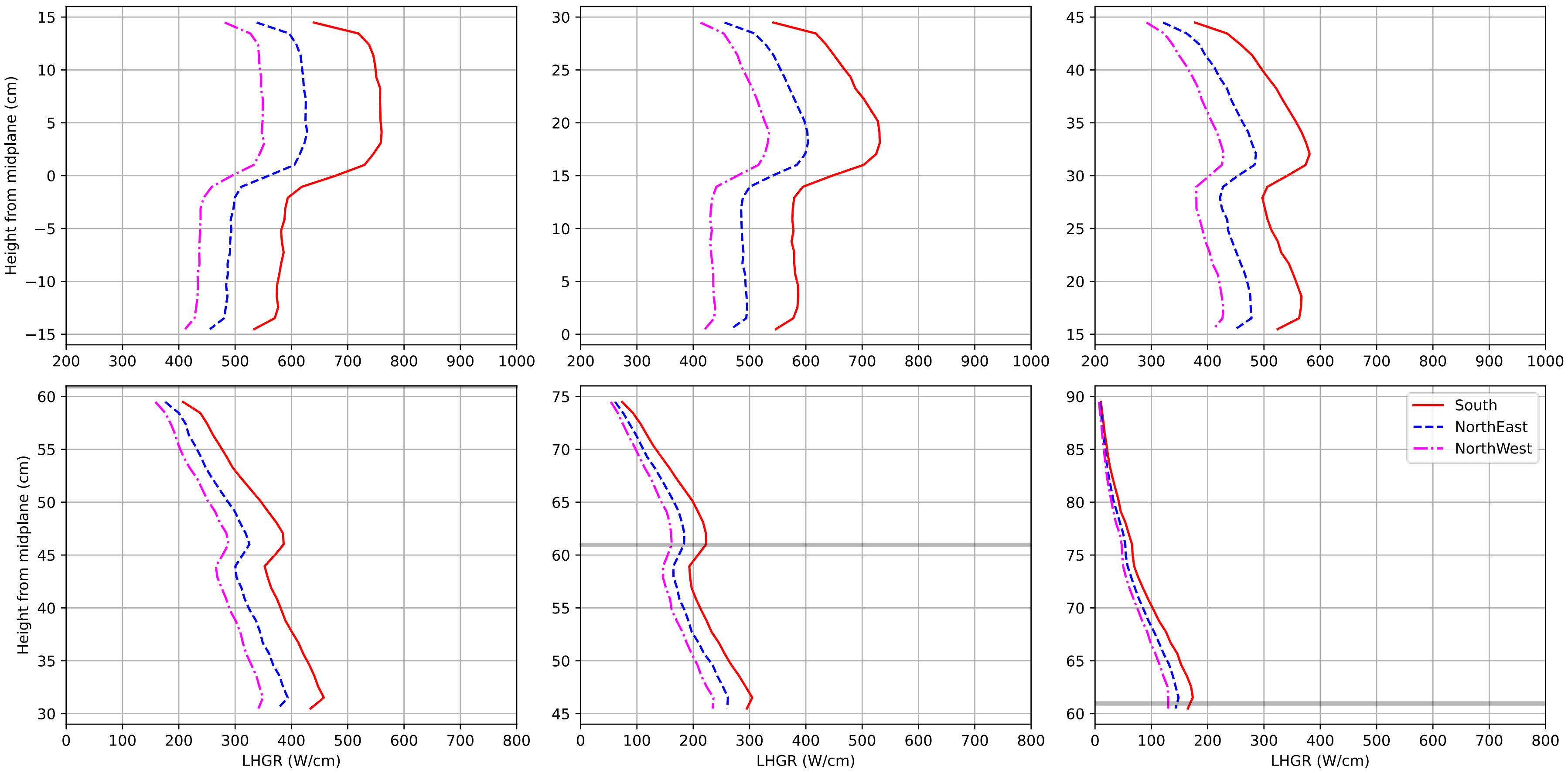
Lower Zones as Hf



Lower Zones as Decreasing Thirds of Hf



Upper Zones: S as all Zr, NE as $^1/_3$ Hf, NW as $^2/_3$ Hf
Lower Zones: S as $^1/_3$ Hf, NE as $^2/_3$ Hf, NW as all Hf



Conclusions

Helium Chamber Device

- Ramp height of < 2.0
- Irradiates 2 rodlets
- Similar powers for both rodlets
- Impractical pressures required

Trefoil Device

- Ramp height of > 5.0
- Irradiates 3 rodlets
- Can vary power between rodlets
- More challenging to fabricate
- Requires PALM device acquisition

Future Work

- Adjust test train size for consistency with ATF-2D (upcoming experiment)
- Optimize minishrouds for programmatic objectives
  - Flatten power profile in upper core
  - Resolve end peaking
  - Achieve different LHGR in all 3 rodlets
- Perform rigorous safety analysis
  - Fission power limit, reactivity, accident scenarios
  - Cycle projection depletion, dose consequence, radioisotope source term
  - Inputs to thermal and structural engineering
- Quantify sensitivity to adjacent experiments

Acknowledgements

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Questions?

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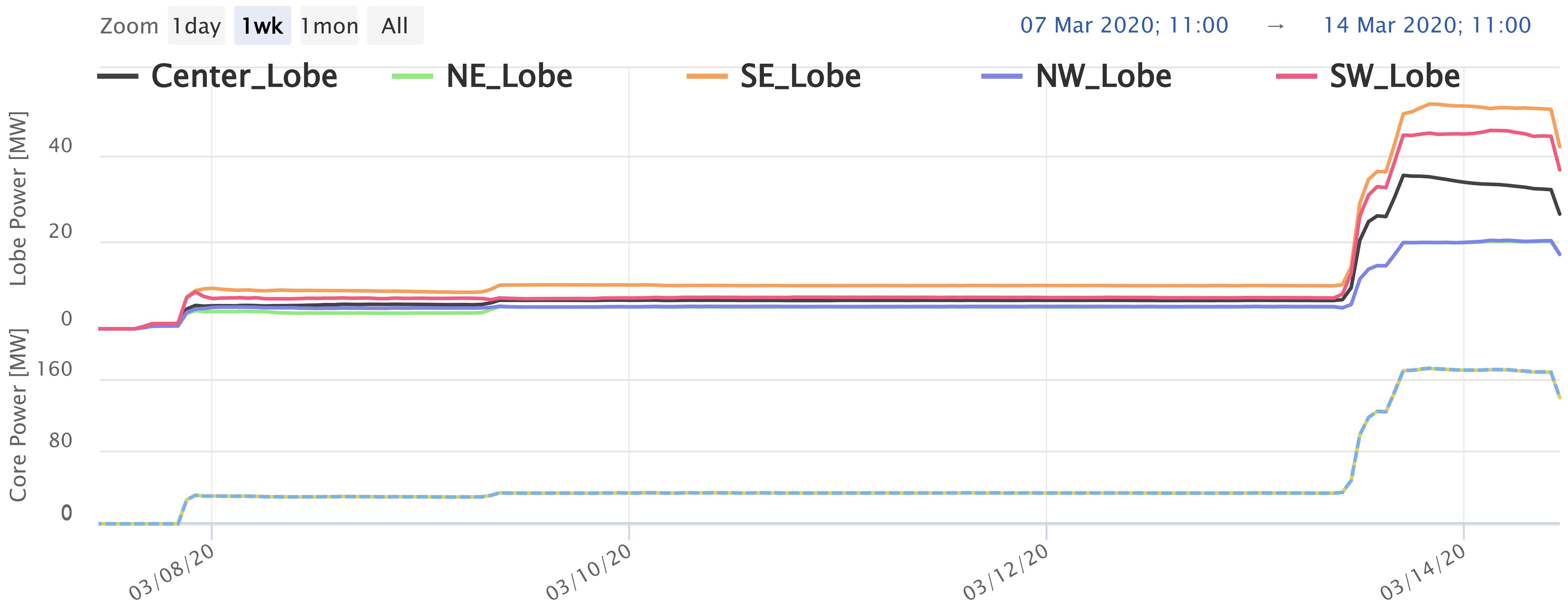
Backup Slides

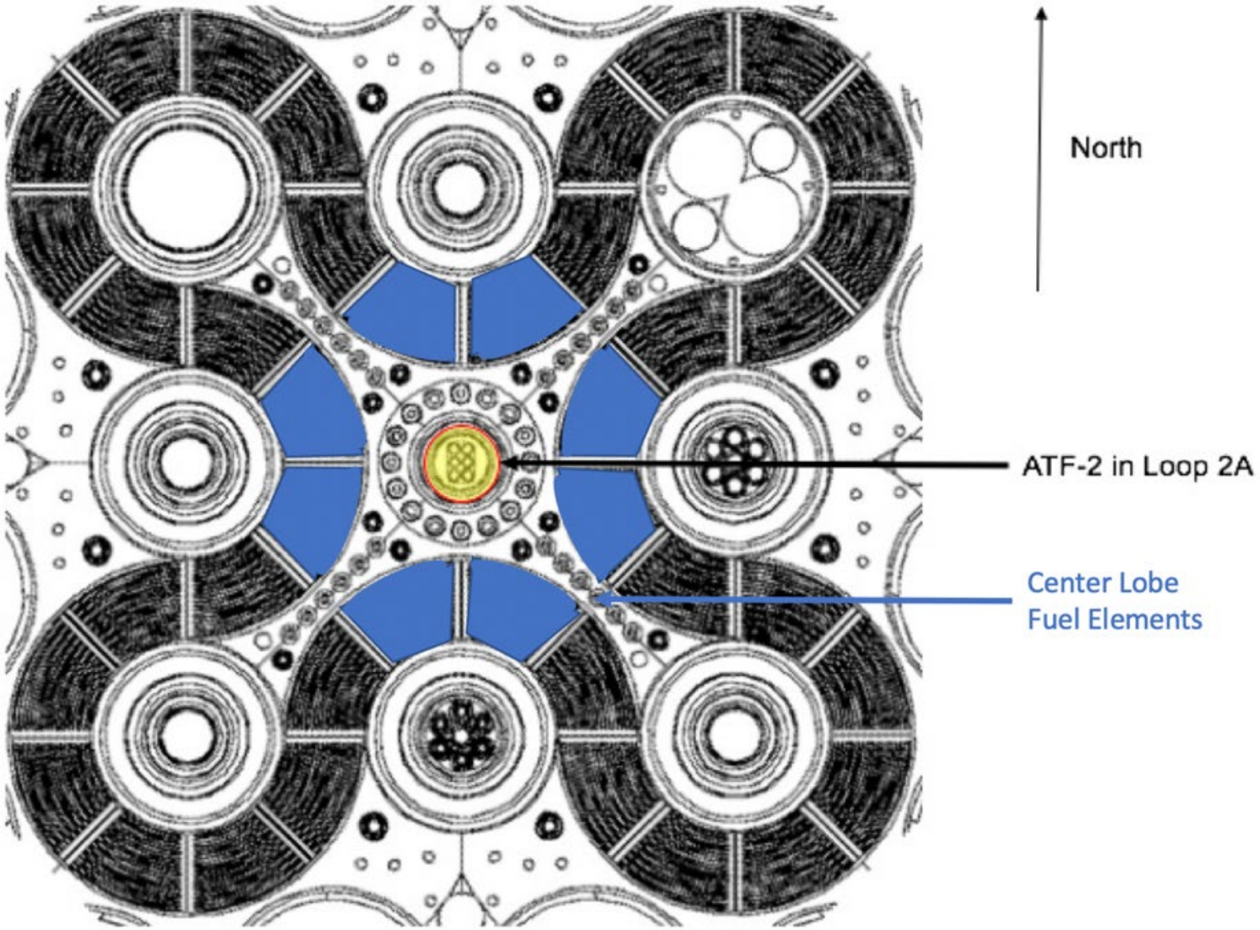
See Also:
ATF-2 Testing

- "Pellet Cladding Interaction In-Reactor Ramp Testing in a World Without the Halden Boiling Water Reactor," Woolstenhulme et al., TopFuel 2022.
- "Feasibility of Power Ramp Testing in the Advanced Test Reactor," Worrall et al., ANS Winter Meeting 2023.
- "ATF-2Ramp Conceptual Design Report," Kamerman et al., INL, 2023.
- "ATF-2C Physics Safety and Scoping Analysis," Labossiere-Hickman et al., ANS Winter Meeting 2022.
- "The Accident Tolerant Fuels' Neutronics Scoping Study (ATF-2Pert)," Rogers et al., ANS Winter Meeting 2023.

Cycle 167A-PALM Power History



Normal Steady-State Test Conditions



- The Test Train is placed into Loop 2A in the CFT of ATR.
- Loop 2A is configured to simulate PWR conditions.
  - ≈ 2250 psi (15.5 MPa)
  - ≈ 530-580°F (265-290°C)
  - ≈ 48 gpm (3 L/s)
  - ≈ 1200 ppmb
- Center Lobe typically has a power of 20-25 MWt.

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 $(f7{:}n)_L$

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

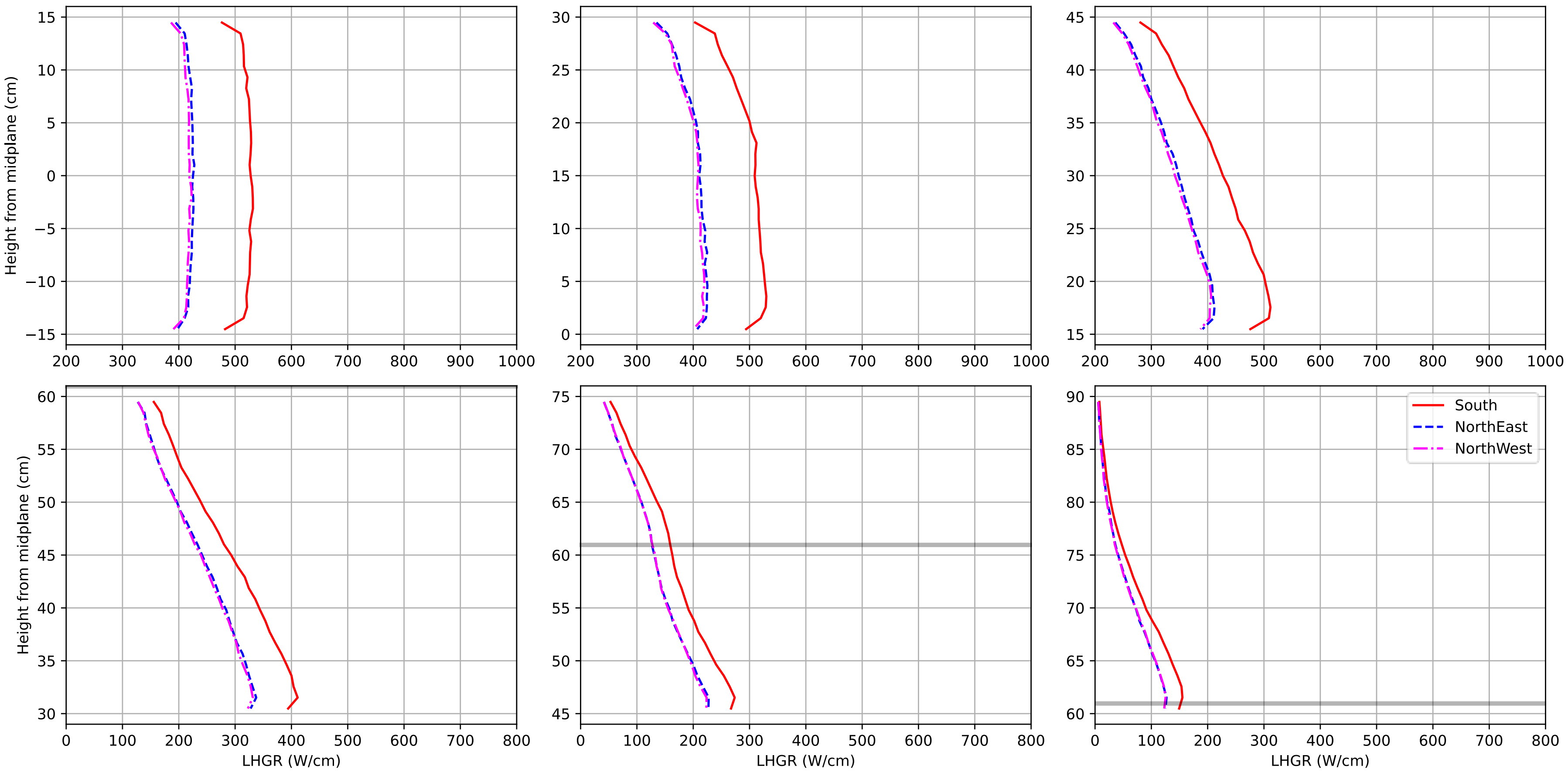
- Reaction rates scale linearly with Q_L.

Uncertainty

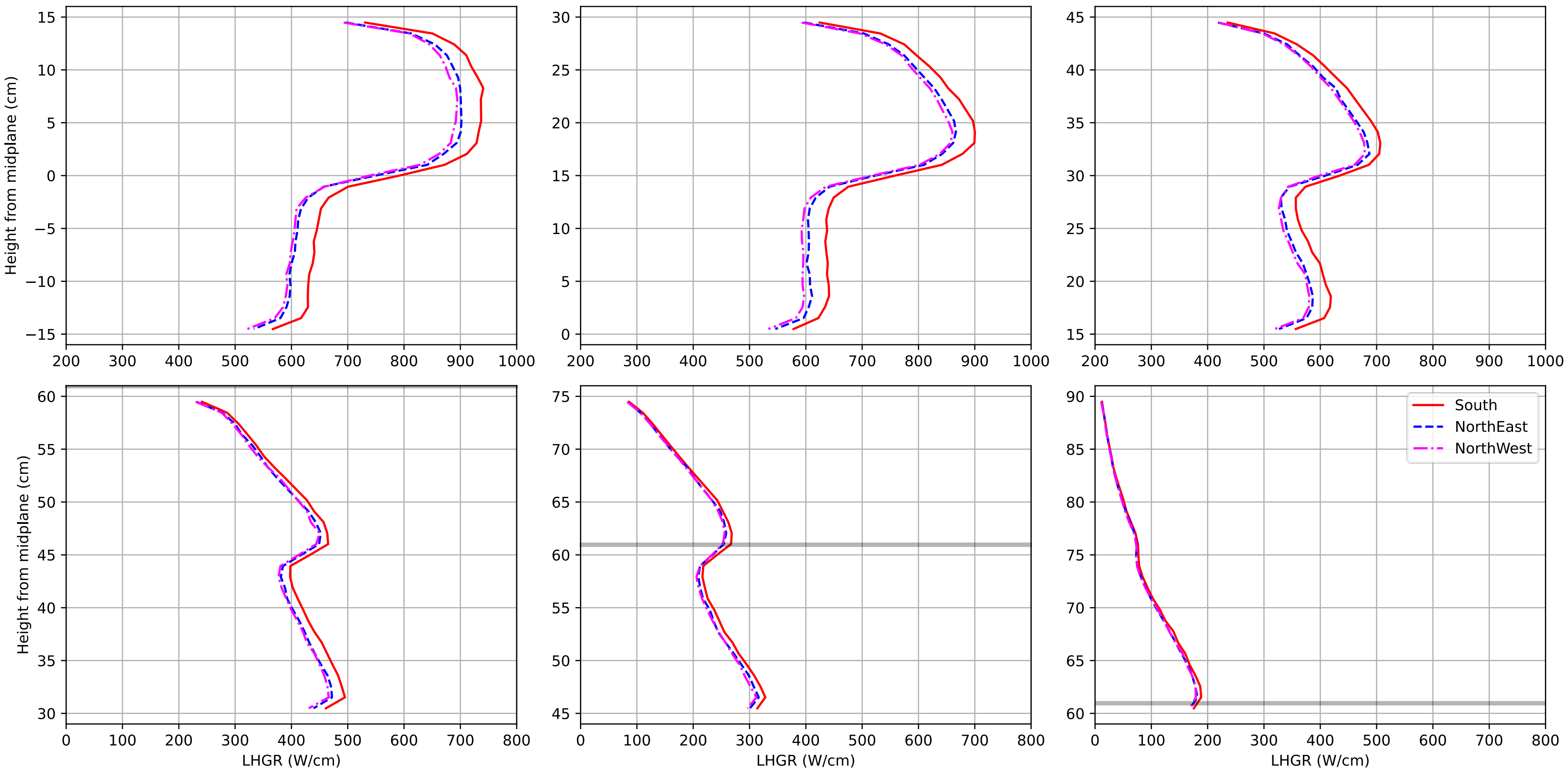
- 2σ lobe power uncertainty of ±5.4%
  - assuming worst-case high-power water power calculator uncertainty
- Monte Carlo tally uncertainty of ±1%
- Total heating rate uncertainty is ± 5.5%

$$2\sigma_{tot} = \sqrt{5.4^2 + 1^2} = 5.5\%$$

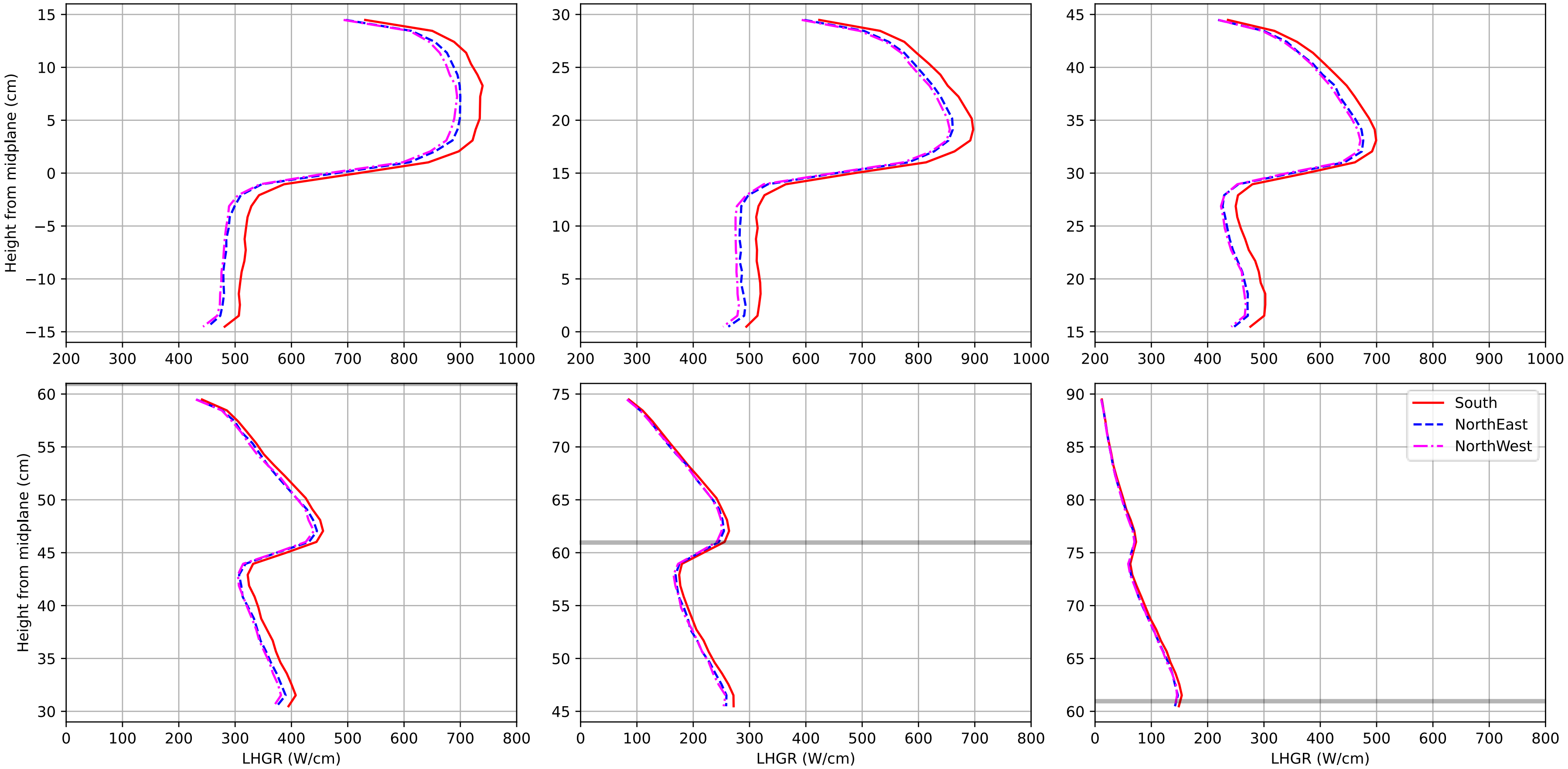
+1cm Hf Buffer zone added



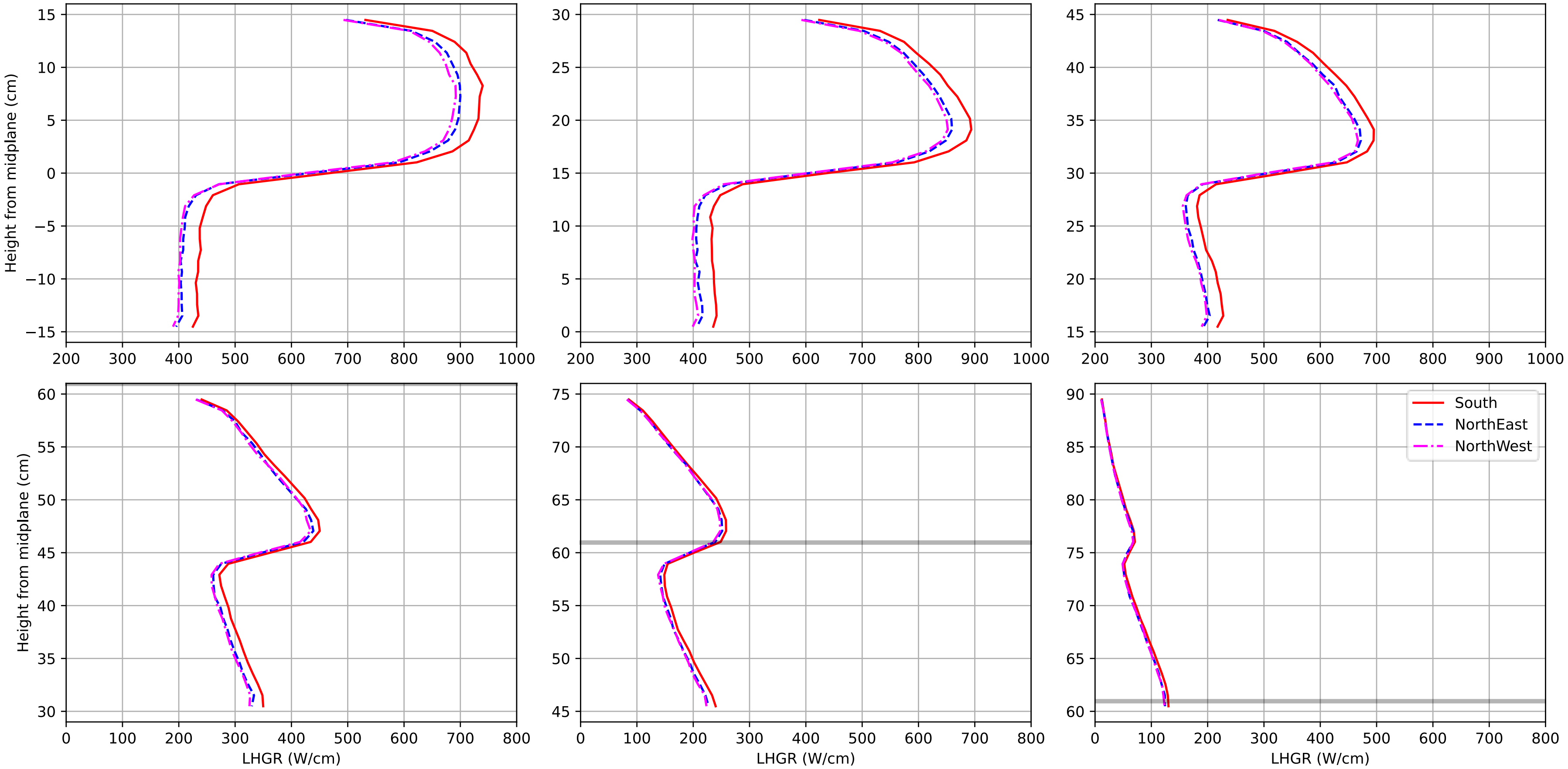
Upper Zones as Zr, Lower Zones as $^{1}/_{3}$ Hf



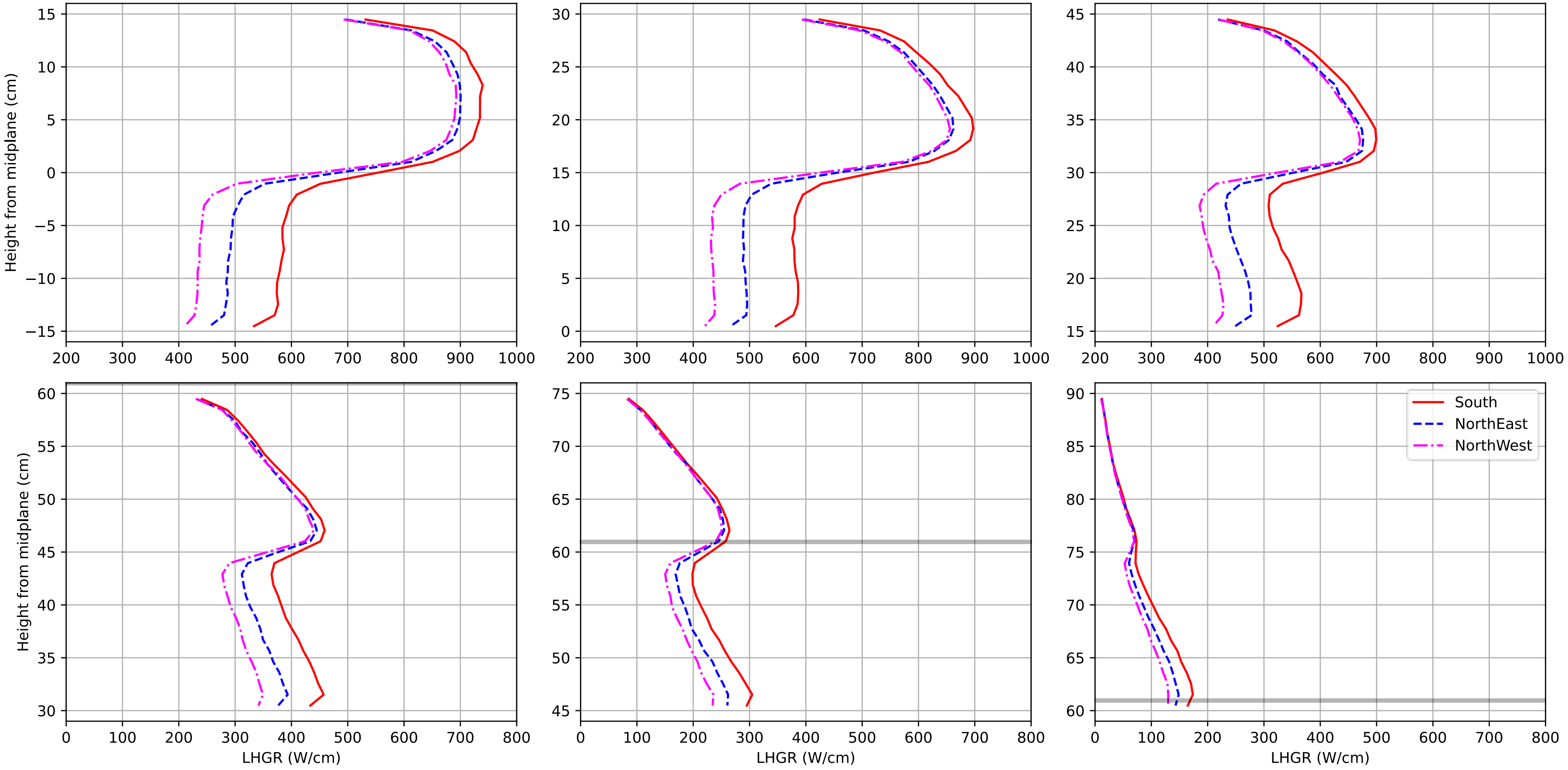
Upper Zones as Zr, Lower Zones as $^{2}/_{3}$ Hf



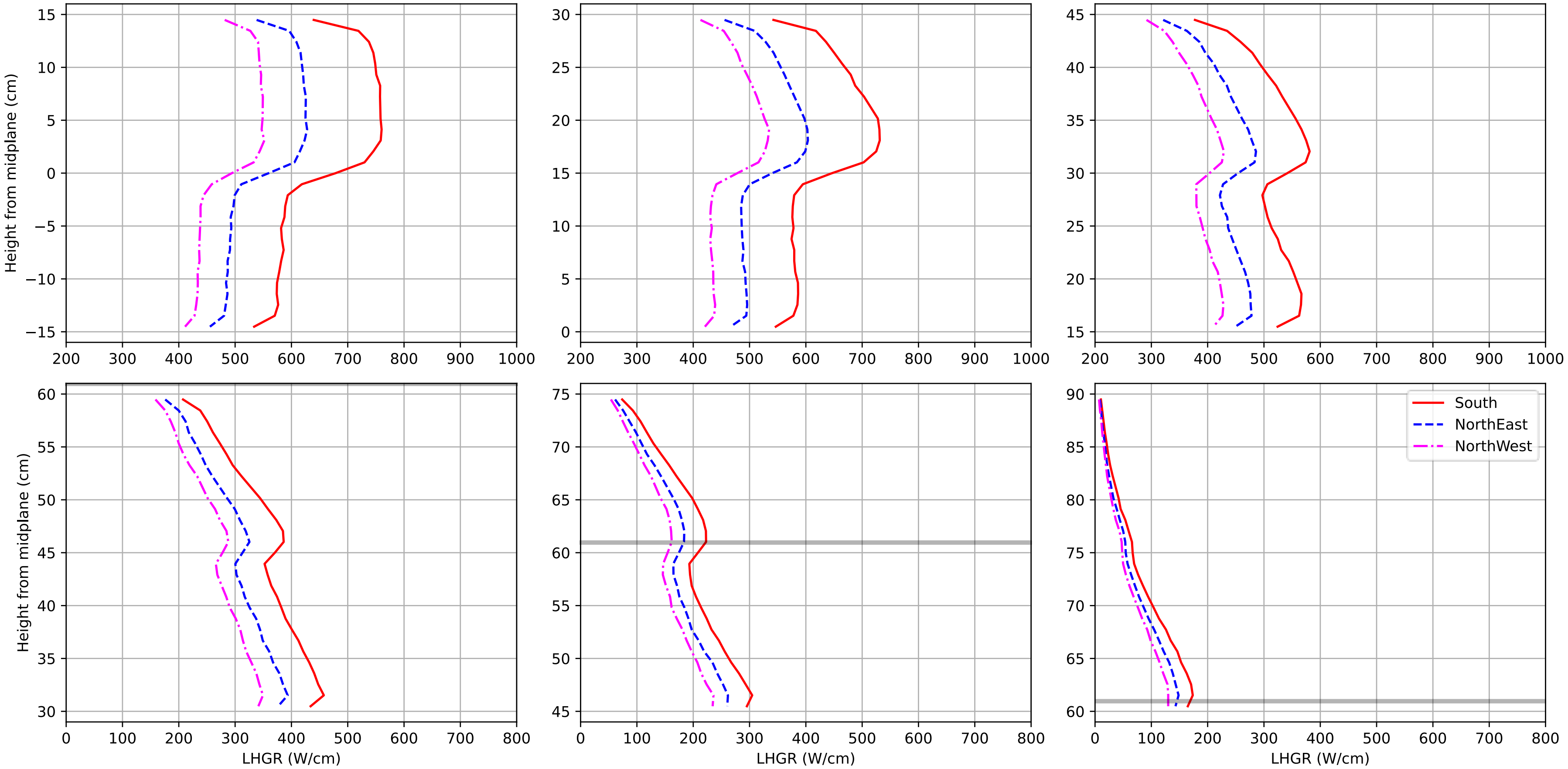
Upper Zones as Zr, Lower Zones as $^{3}/_{3}$ Hf



Upper Zones as Zr,
Lower Zones as Increasing Thirds of Hf



Upper Zones as $^{0}/_{3}$, $^{1}/_{3}$, $^{2}/_{3}$ Hf
Lower Zones as $^{1}/_{3}$, $^{2}/_{3}$, $^{3}/_{3}$ Hf



Upper Zones as $^0/_3$, $^1/_3$, $^2/_3$ Hf; Lower Zones as $^1/_3$, $^1/_3$, $^2/_3$ Hf