Transformational Challenge Reactor: Agile Core Design with Advanced Modeling and Simulation

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SCALE User's Group

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Agile Core Design Process

Overall Design Requirements and Initialization

- Leverage scientific advancements to design a reactor
  - Operate safely for less than 1 day at full power
  - Exploring configurations enabled by additive manufacturing in the *core neutronic and thermofluidic design* is the focus
  - Target elevated temperatures relative to light water reactors
- Design activities span 2 years to support deployment in 2023
- Collect data from embedded and conventional instrumentation during testing and operation
- No specific design or application was selected or targeted
  - Assessed materials, core designs, system configurations, power levels
  - Safety analyses included in all design phases

Design Progressed Rapidly Through Conceptual Phases

- Initial preconceptual core designs were fast reactors
  - High-assay LEU availability limited fuel mass
- Incorporating moderators led to larger core sizes
  - Rapid advancement in YH manufacturing process enabled its selection as a moderator
- Scoping analyses examining maximum temperatures in postulated events favored TRISO in SiC fuel
  - Rapid advancement in TRISO in SiC fuel element manufacturing process
- YH moderator must be encapsulated
  - Steel encapsulation matured most rapidly

Design Progress

Thermal core designs

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YH-moderated designs

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TRISO in SiC fuel elements

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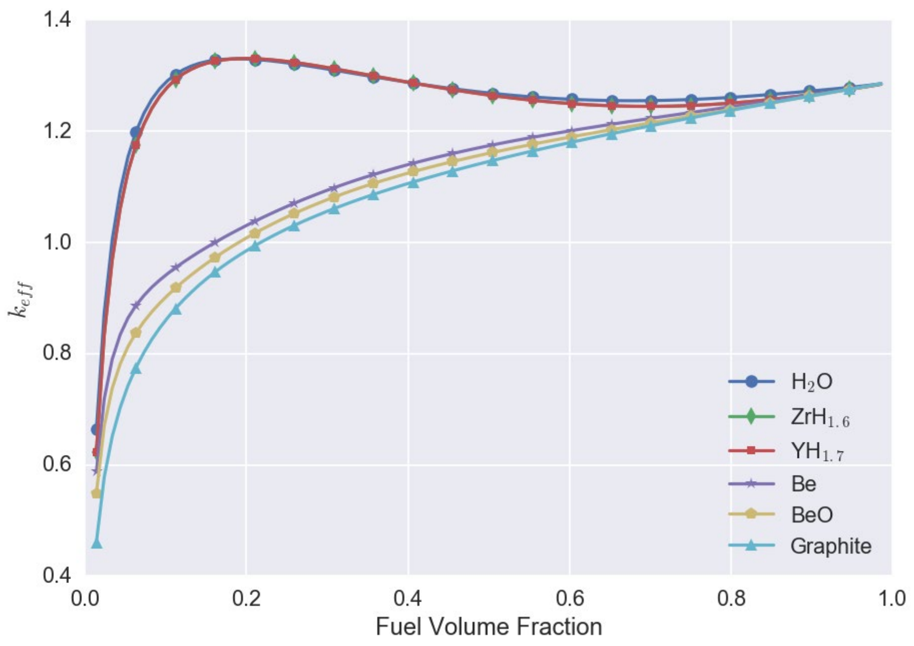
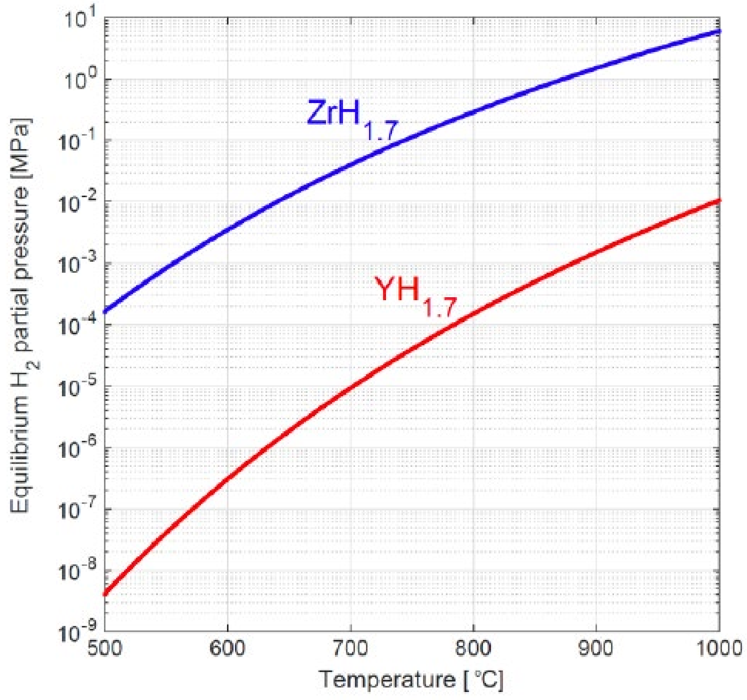
Steel YH encapsulation

TCR moderator form consists of YH rods encapsulated in stainless steel tubing

- Hydrogenous moderators are uniquely efficient volumetrically
  - Provides for a small core and low fuel mass
  - YH_x provides for higher temperatures than ZrH_x





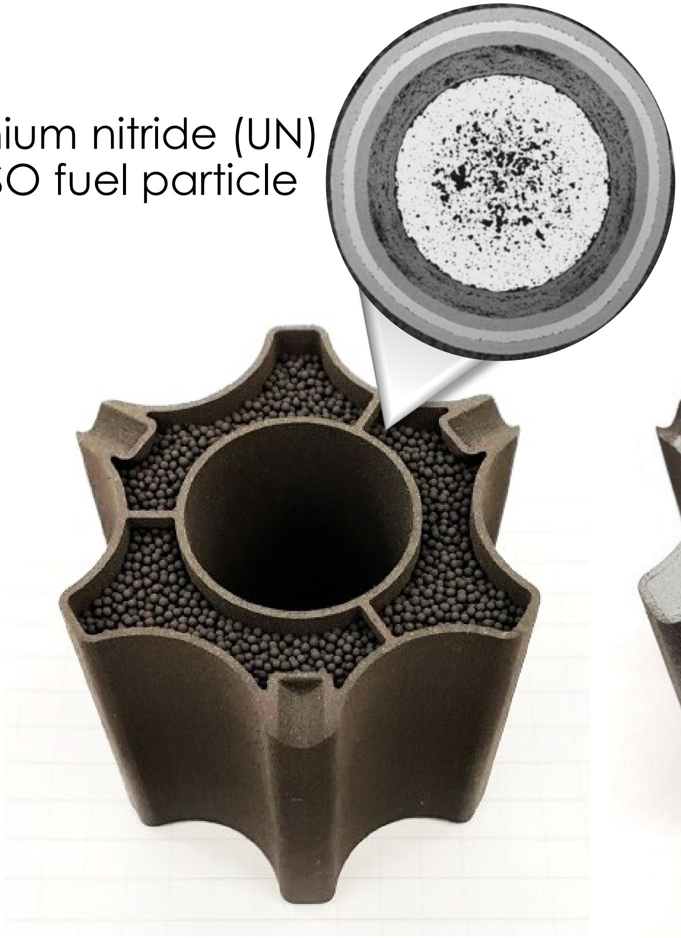
Yttrium hydride slug

TCR fuel form consists of UN TRISO particles embedded in a 3D-printed SiC matrix

Design flexibility

Printed shell

Uranium nitride (UN) TRISO fuel particle



Filled with UN TRISO

High fuel density

Filled with SiC

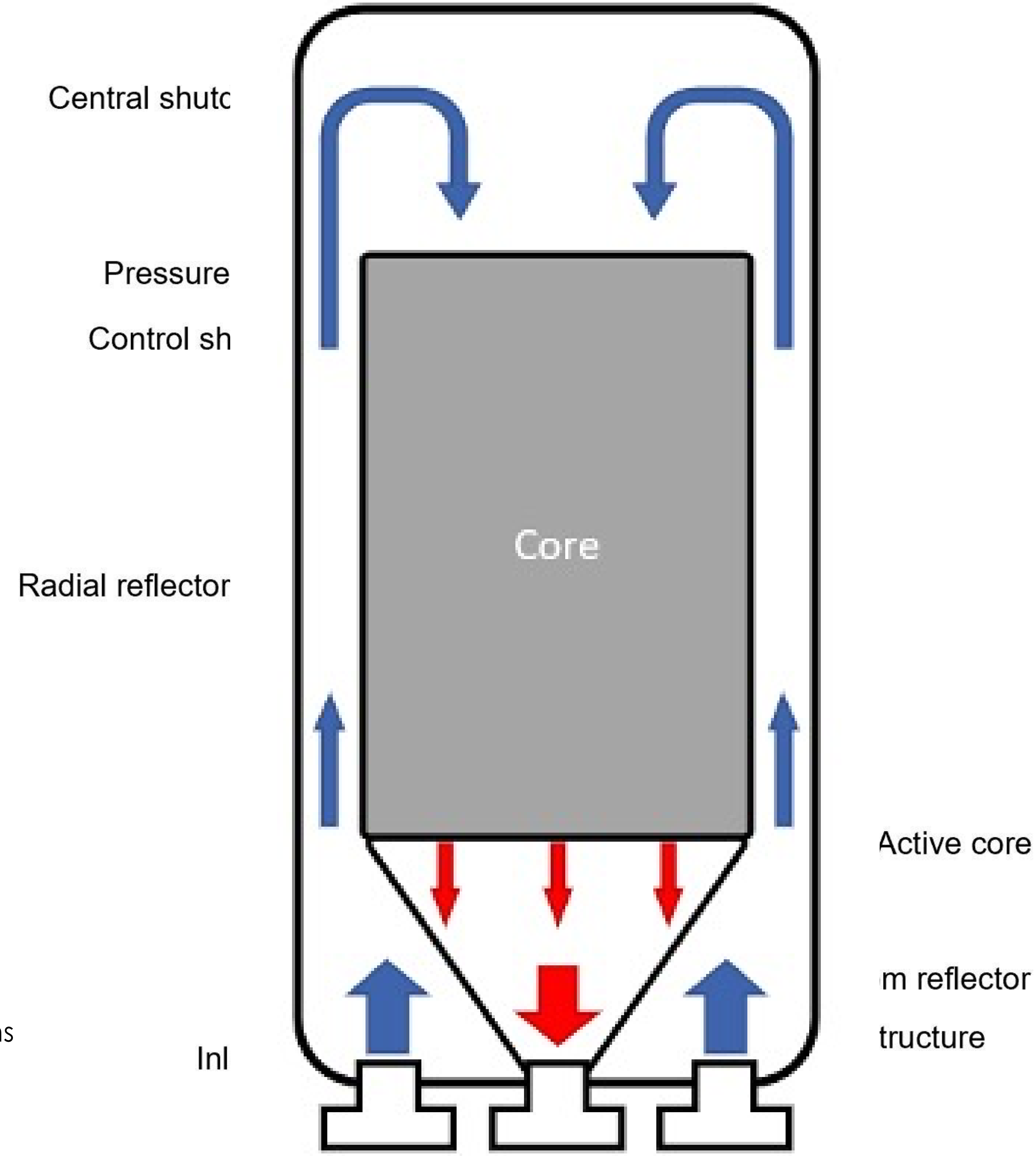
Fully densified and assembled

TCR fuel form consists of UN TRISO particles embedded in a 3D-printed SiC matrix

Reactor Design

Attribute	Value
Total power	3 MWt
Outlet coolant temperature	500°C (773 K)
Inlet coolant temperature	300°C (573 K)
Fuel	UN TRISO
Fuel element type	TRISO in SiC
Moderator	Yttrium hydride
Moderator encapsulation	316L stainless steel
Coolant flow direction	Downward
Coolant type	Helium
Coolant pressure	5 MPa
Pressure vessel	304H stainless steel
Primary loops	One
Confinement	Vented
Operational duration	< 24 hours at full power*
Heat removal	Air cooler with heat rejection

*Full 24 hour operation used to generate bounding radiological source terms
**TCR fits the definition of a microreactor
***Approximately 50 in-vessel subcomponents



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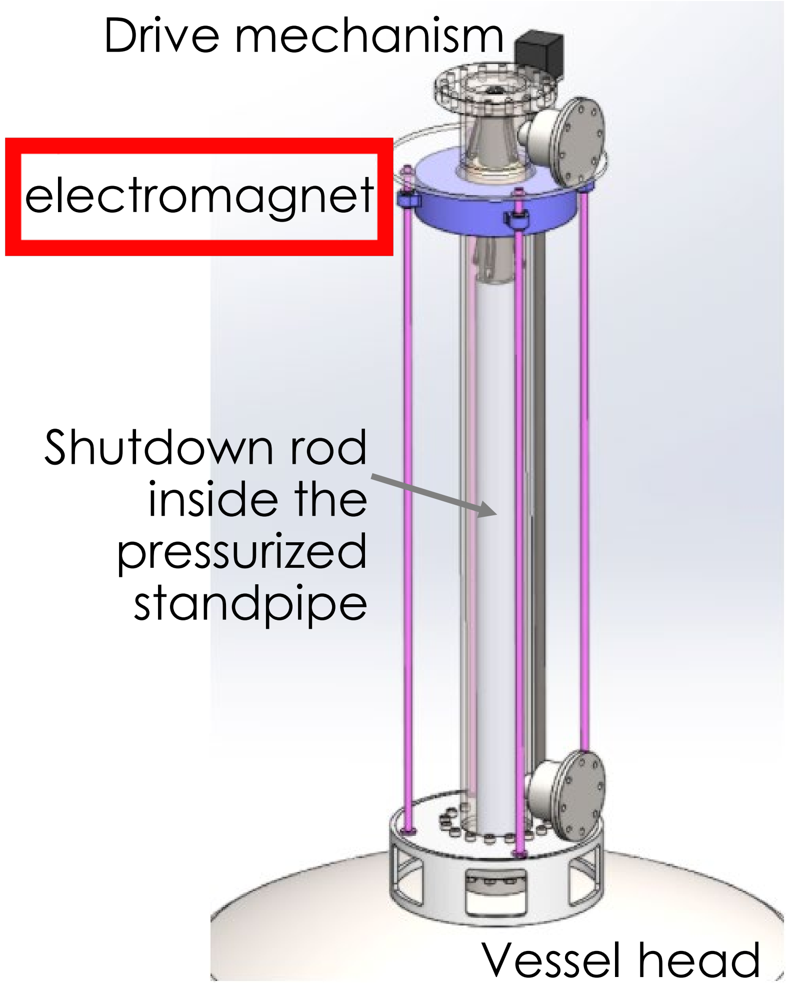
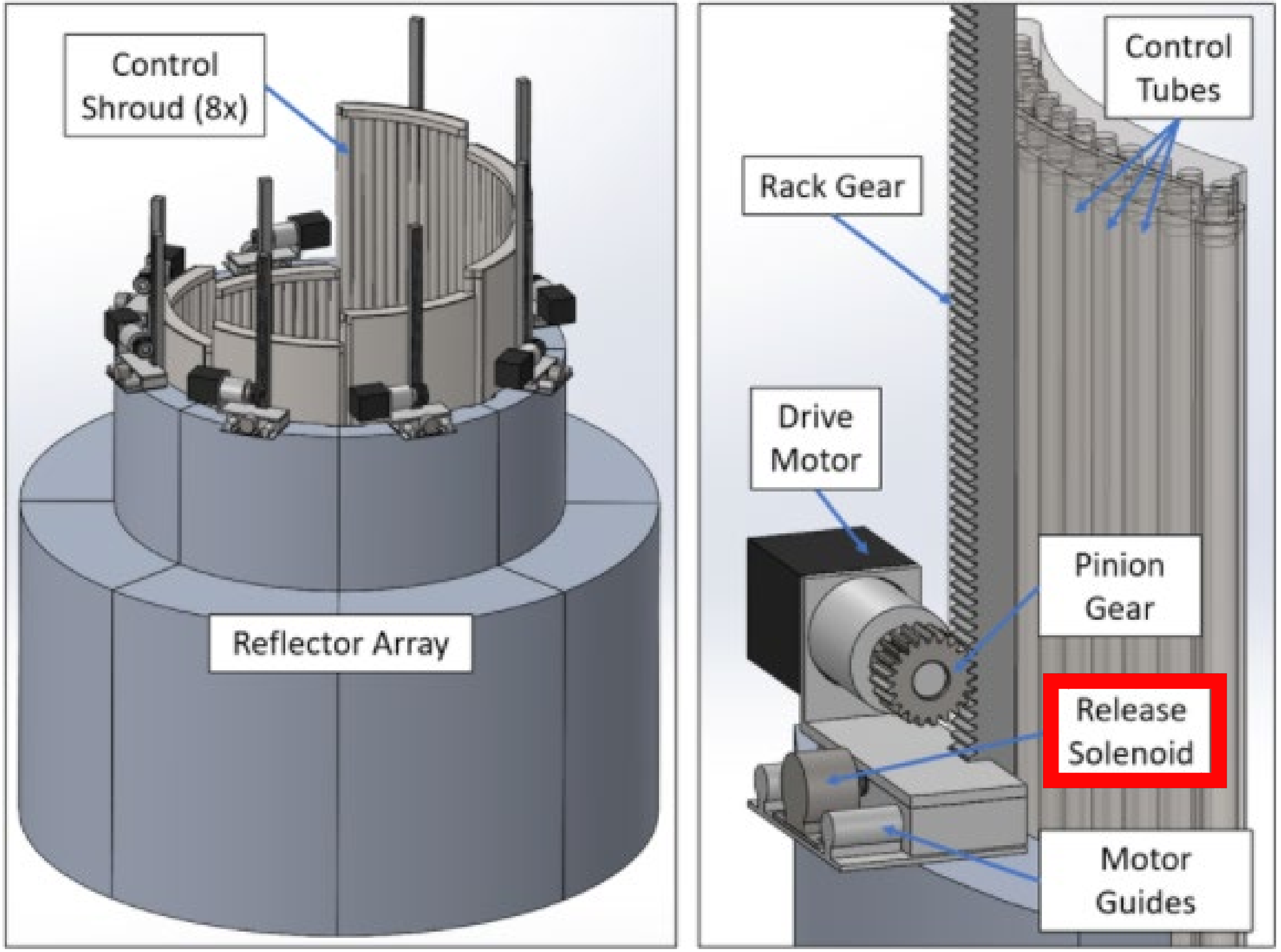
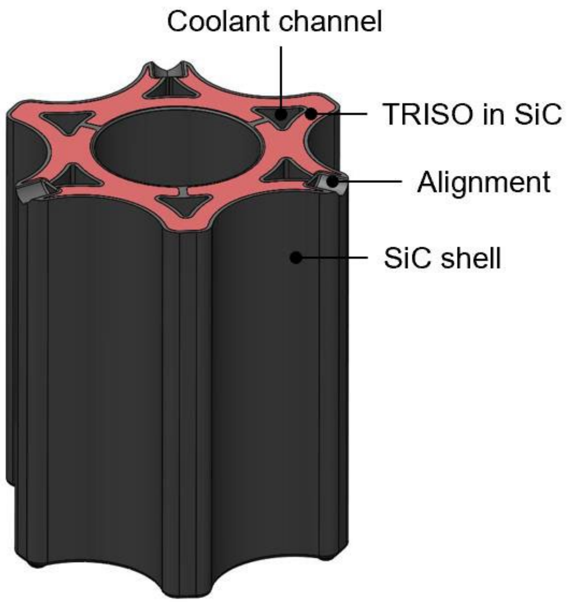
A Central Shutdown Rod for Protection, Eight External Shrouds for Fine Power Control

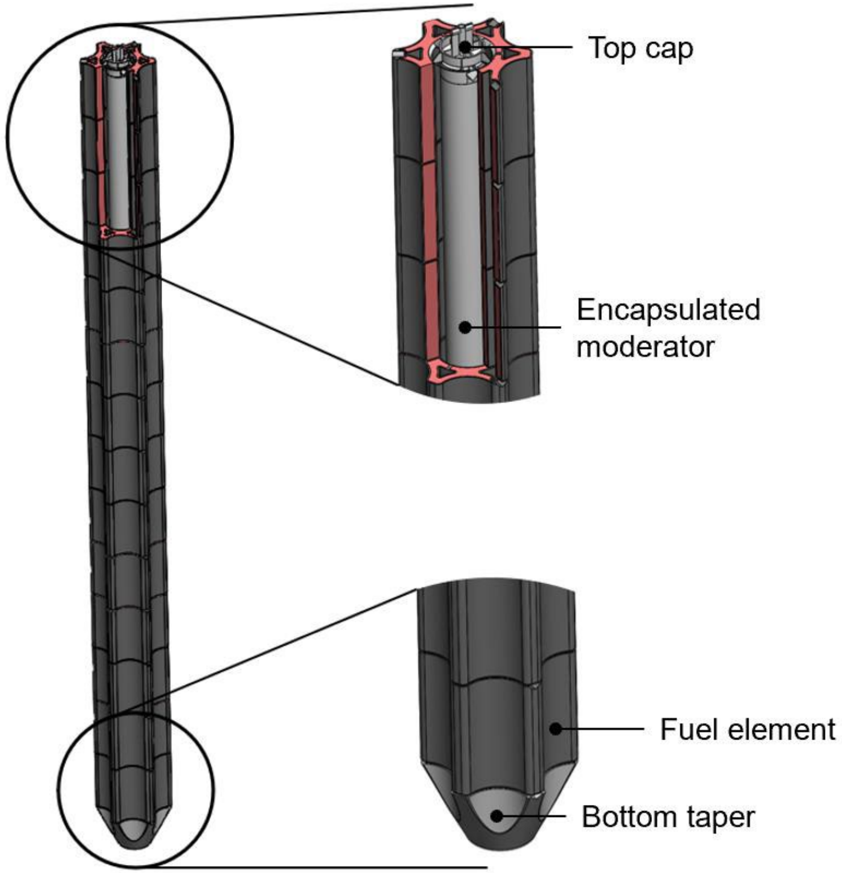


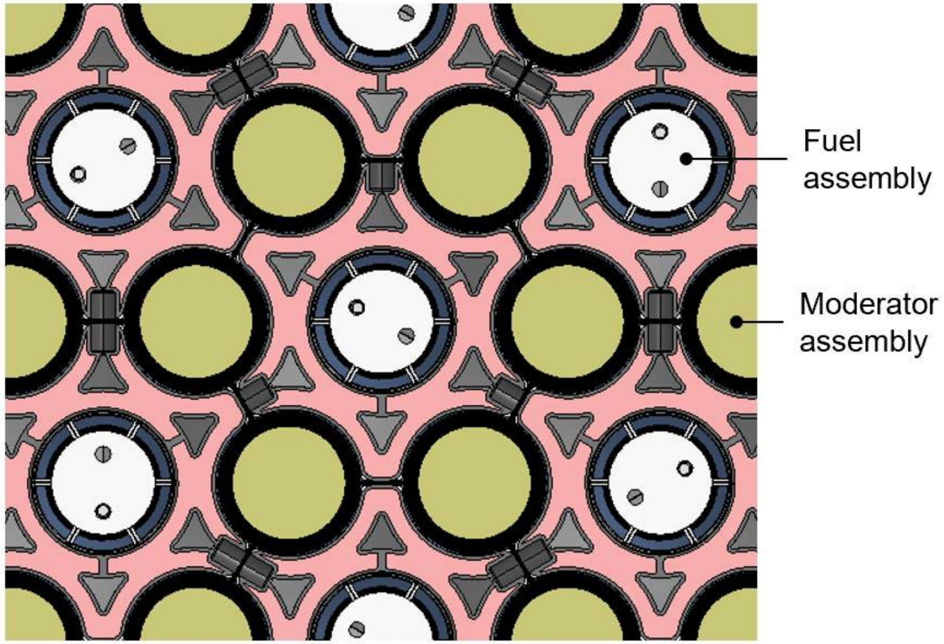


Core is a Hexagonal Arrangement of Assemblies

- Separate fuel and moderator assemblies loaded into the core
- Select components will have embedded instrumentation







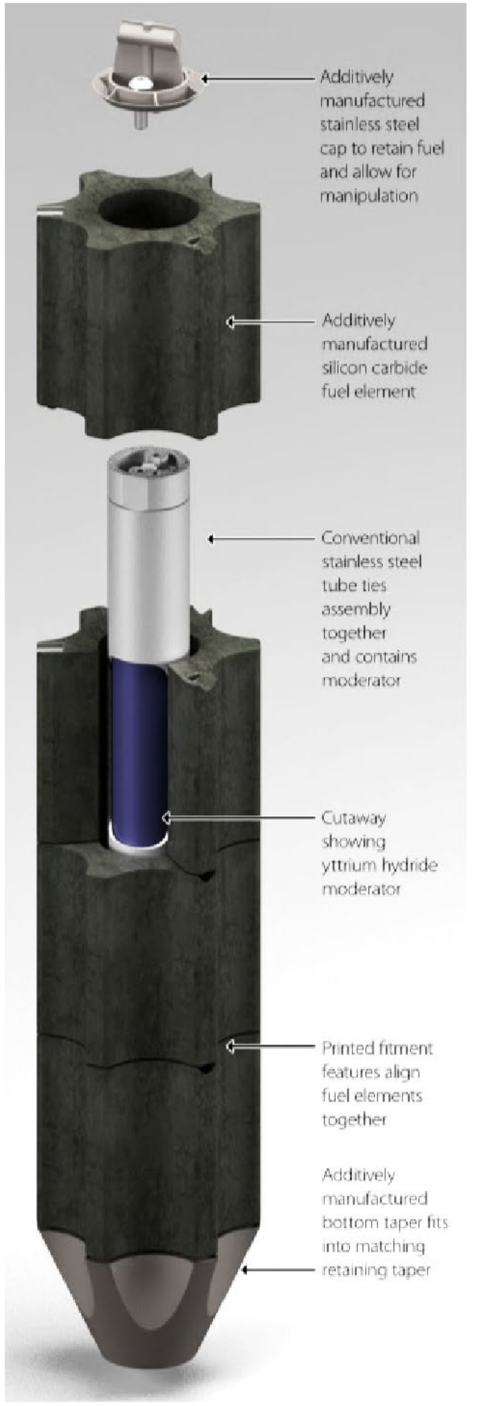
Manufacturing and Handling are Key in the Agile Design Process

- Fuel with multiple inherent barriers to radionuclide release and is encapsulated in refractory and oxidation resistant SiC
- H-bearing moderator with highest known thermal stability
- Additively and conventionally manufactured Grade 316 stainless steel as the hydride sheath and assembly structure
- Assembly design reduces parasitic steel and assembly count while meeting technical performance requirements

Uranium nitride TRISO

TCR SiC fuel block during manufacturing

Yttrium hydride slugs



Modeling and Simulation Tools for Reactor Analysis

- Neutron transport: MCNP, SCALE, Shift, Serpent
- Systems: RELAP, TRACE
- Depletion and source terms: SCALE, Shift
- Multiphysics: COMSOL, STAR-CCM+
- Thermomechanical analysis: ANSYS, BISON, ABAQUS
- Sensitivity & Uncertainty: SCALE, RAVEN
- Variance reduction: ADVANTG
- Software Quality Assurance required for reactor safety calculations, must be applied to applicable tools

Core Design

Design Requirements: Neutronics

- **Excess reactivity** – at room temperature conditions the reactor must have enough excess reactivity to account for negative reactivity feedback during operation
  - Change in temperature between cold and operating conditions, fission product buildup and fuel depletion, dimensional changes, uncertainties, and design applicable margins.
- **Shutdown margin** – The control mechanisms provides a reactor shutdown margin of more than 0.01 $\Delta k/k$ provided failure of the highest worth element.
- **Reactivity insertion rate** – The maximum reactivity insertion rate is limited to prevent any sudden power excursions that impair the integrity of the core.
- **Reactivity coefficient** – The core geometry, fuel assemblies, and fuel-to-moderator ratio is designed so that the overall temperature coefficient of reactivity is negative.
- **Power distribution** – The core is designed to reduce axial and radial power peaking.
- **Stability** – The core is designed to prevent major oscillation of the power distribution or power level.

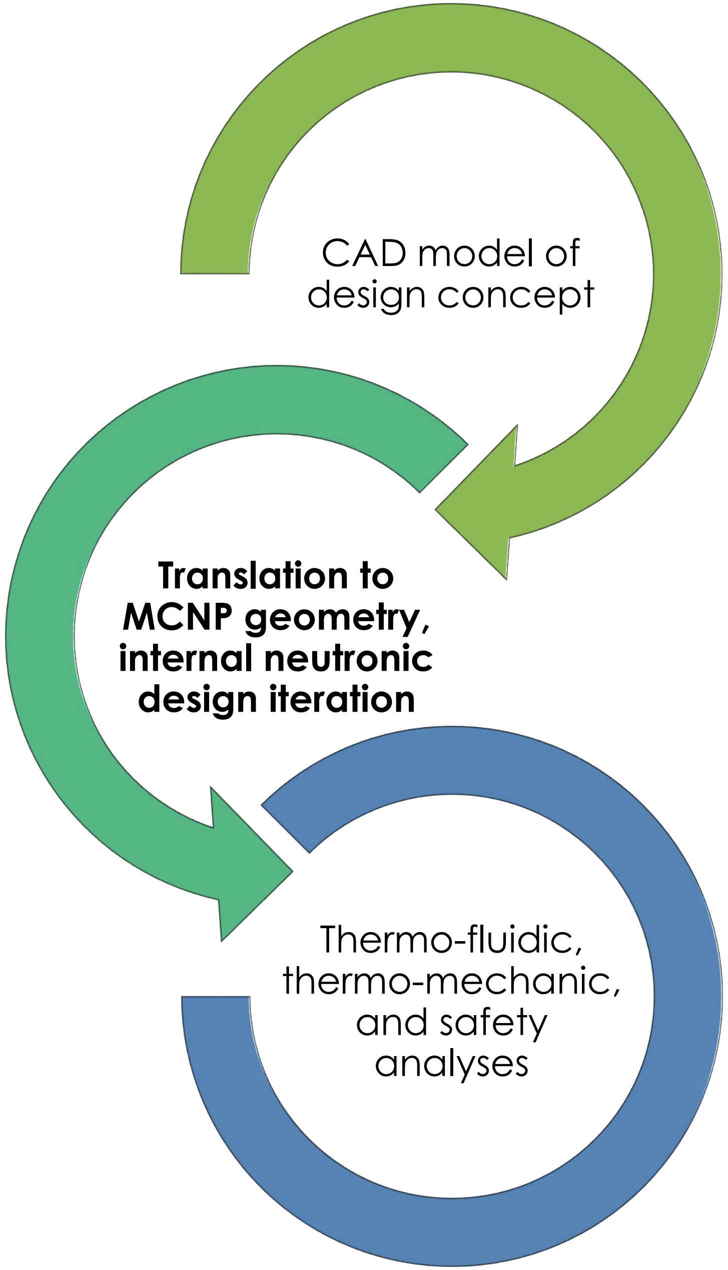
- <u>Constraints</u>
  - Core should contain less than 250 kg HALEU
  - Core should occupy a volume of less than 1.0 m^3

Core Analysis Methods

- Nuclear data
  - Continuous energy: ENDF/B-VII.1 modified with ENDF/B-VIII.0 YH thermal scattering data
  - Multigroup: ENDF/B-VII.1 252-group library distributed with SCALE 6.2.3
- Continuous energy Monte Carlo methods are leveraged as the primary core design tools
  - *Shift* – ORNL-developed modern Monte Carlo tool used for design scoping. Fast and memory-efficient neutron transport and tally capabilities. Uses MCNP geometry.
  - *MCNP* – Legacy Monte Carlo tool with very flexibly geometry and tally capability. Long history of QA. Used for all QA-level design calculations. Also used for heat depositions and neutron kinetics parameters.
  - *MCNP/ADVANTG* - Continuous-energy Monte Carlo transport with automated variance reduction
- Multigroup transport methods
  - *SCALE/TRITON (2D)* – Legacy QA-level multigroup transport method with extensive depletion validation basis
  - *SCALE/TSUNAMI (3D)* – Legacy QA-level multigroup sensitivity and uncertainty analysis tool

Agile Core Analysis Design Approach

- Neutronic design scoping models driven using Python scripting
  - Automates generation of models with needed perturbations
  - Includes temperature changes and associated thermal expansion
  - Analysis of output semi-automated in Python
- Neutronic design portion includes internal iteration to ensure high level requirements and constraints are met
  - HALEU requirements, reactivity coefficients, control shroud and shutdown rod worth, excess reactivity, etc.
- From scoping analyses, a single design is chosen
  - Final dimensions are passed back to mechanical design team for refinement, finalization, manufacturing and assembly trials
  - Neutronic results are fed to other teams for follow-on analyses

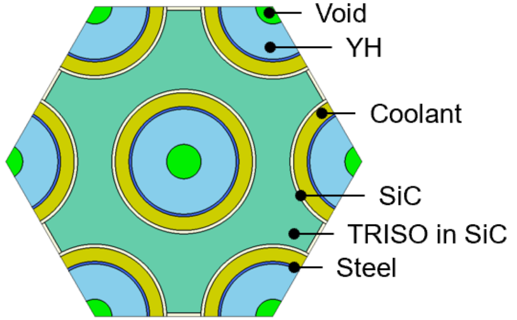


Core Analysis Models

- All core level models contain detailed representation of the active core
- Approximate representation of the core vessel, axial and radial reflectors, coolant flow geometry, etc.
- Axial reflectors composed of SiC
- Radial reflector composed of steel
- Control shroud and central shutdown rod composed of 96% enriched B_4C clad in steel

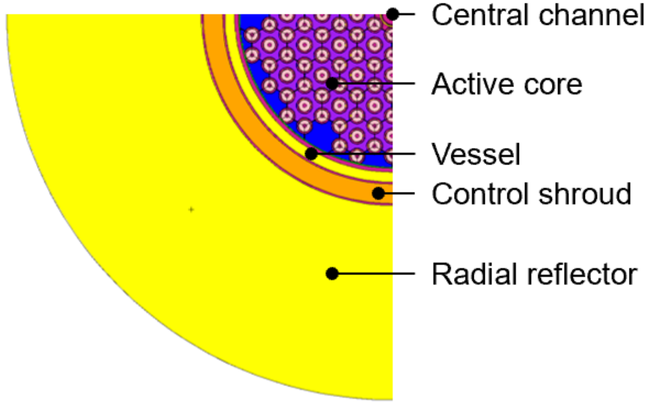
2D SCALE Models

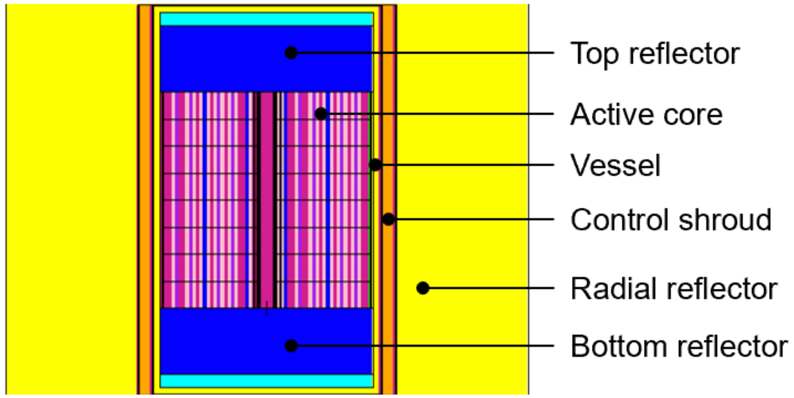
- Decay heat
- Source term
- Sensitivity and uncertainty analysis



3D Full core MCNP Models

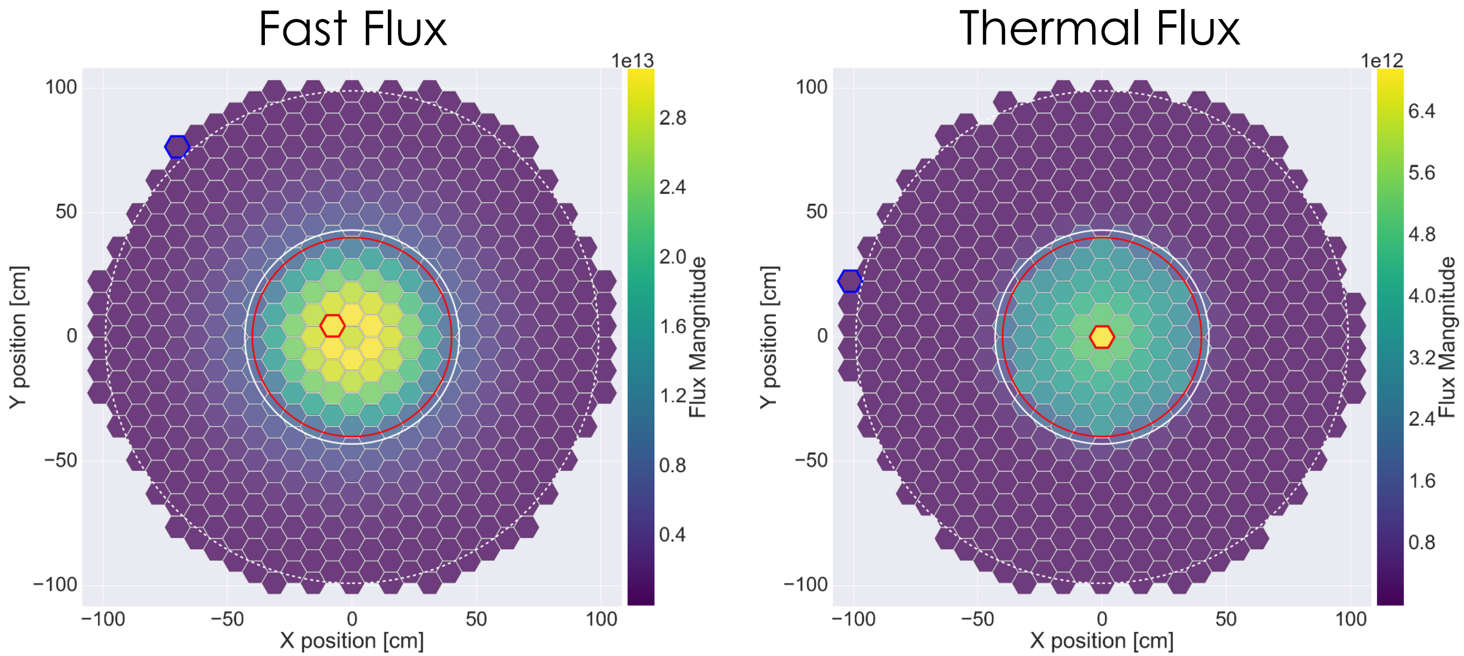
- Excess reactivity
- Reactivity coefficients
- Control and shutdown mechanism worth
- Power distribution
- Heat generation
- Neutron/gamma flux
- Kinetics parameters

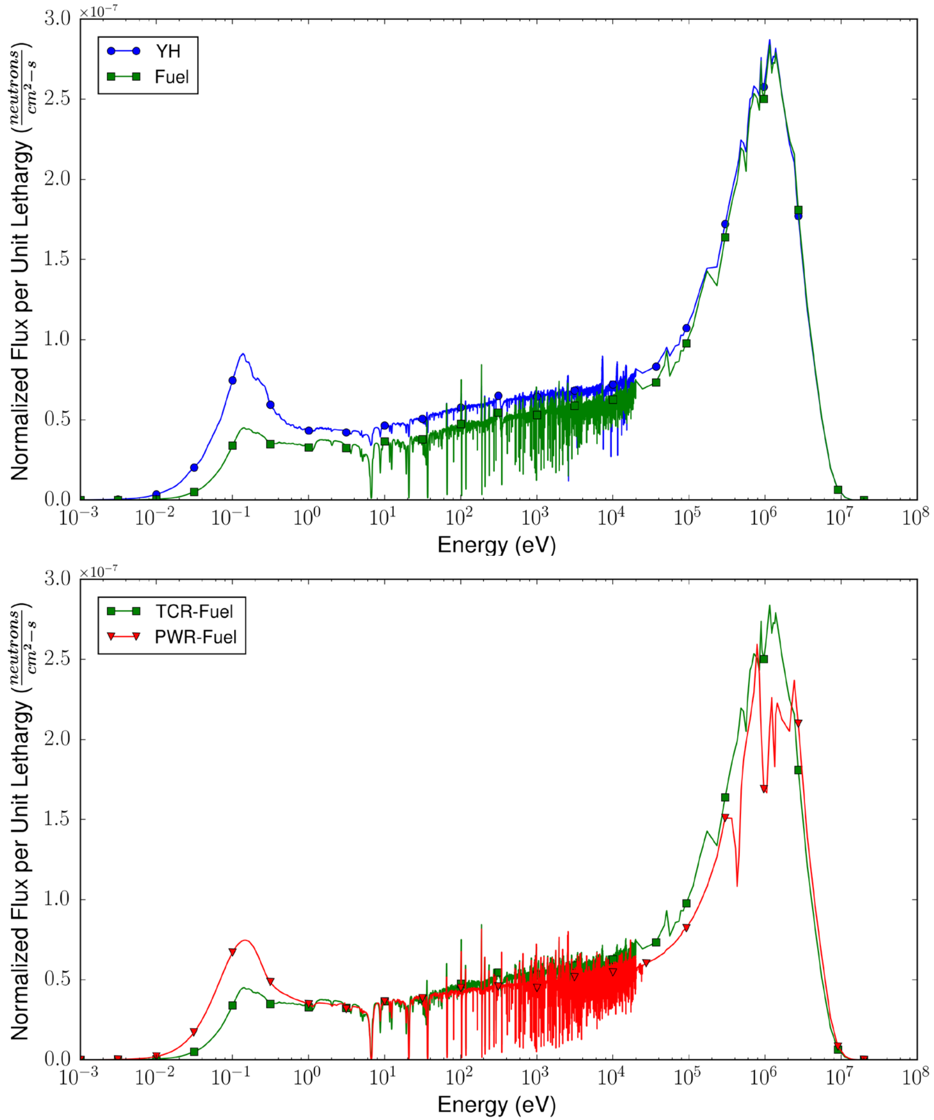




Neutron Spectra and Flux

- Flux spectra in the fuel is slightly harder (more fast neutrons) than a typical PWR
- Thermal flux peaks in the shutdown rod tube, leading to large reactivity worth of the rod





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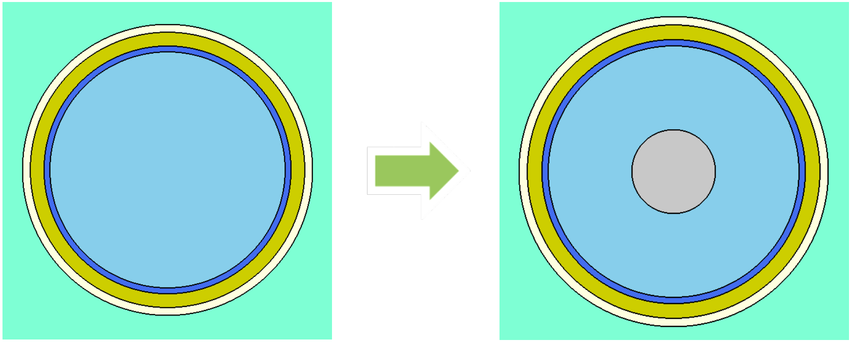
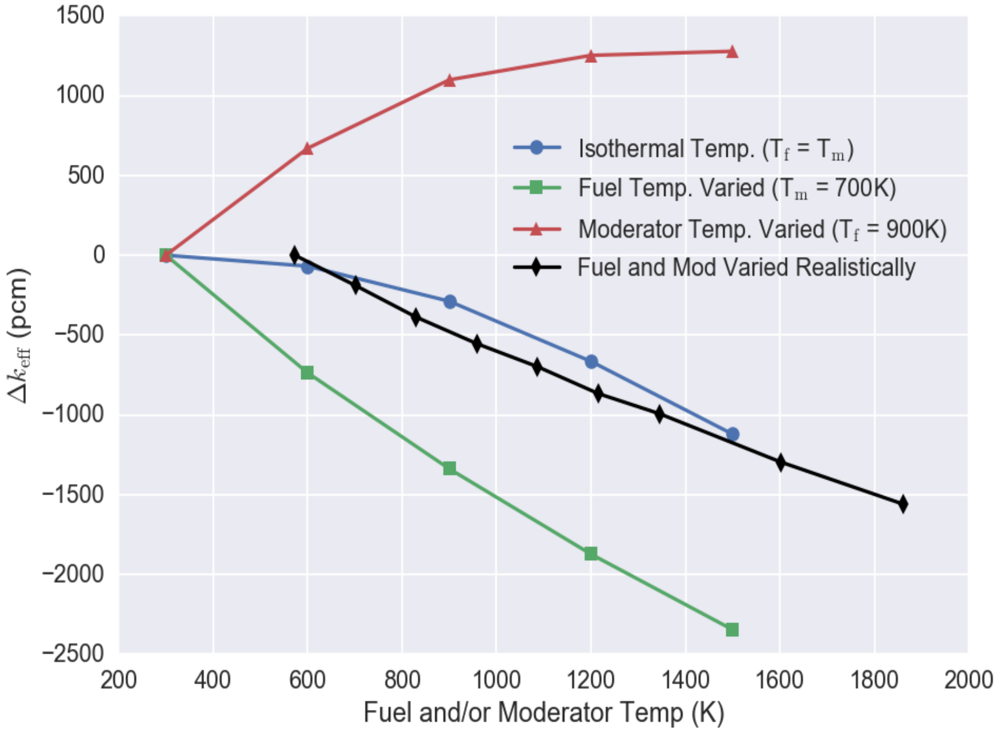
Reactivity Coefficients

- Reactivity coefficients for TCR as assessed using four assumptions
  - Fuel temperature only (negative)
  - Moderator temperature only (positive)
  - Isothermal fuel and moderator (negative)
  - Realistic fuel and moderator (negative)
- TCR fuel and moderator size/shape are specifically chosen to ensure adequate negative reactivity feedback for applicable transients
  - Effects are more complex than just the fuel to moderator ratio – the layout between fuel and moderator, and especially the size of the moderator element has a significant impact
  - Relatively large absorption in yttrium leads to positive moderator coefficient that can outweigh negative fuel coefficient is moderator element is large (same issue with ZrH)

Characteristic	Value
Fuel temperature	-2.03 pcm/K
Moderator temperature	1.07 pcm/K
Isothermal temperature	-0.98 pcm/K
Power temperature	-1.25 pcm/K
Coolant void	24 pcm
Hydrogen loss	-71 pcm/%H

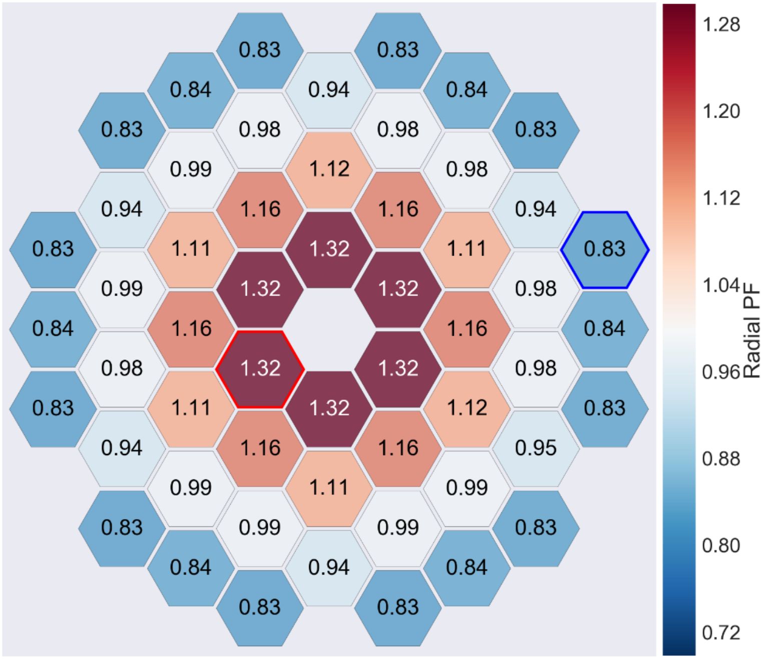




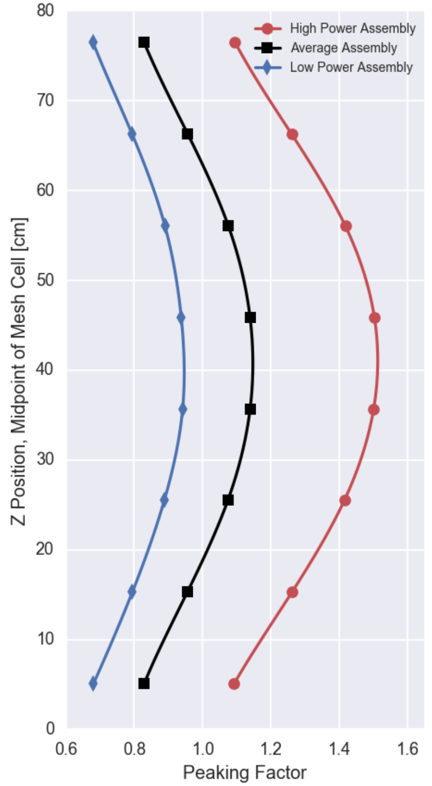
Power Distribution

- 3D power distribution computed for each for cog, assuming fresh fuel, no control shroud insertion
- Maximum power peaking factor: **1.5**
- Current power peaking expected to be conservative; ongoing design optimization will reduce power peaking

Radial Peaking Factor



Axial Peaking Factor



Heat Deposition

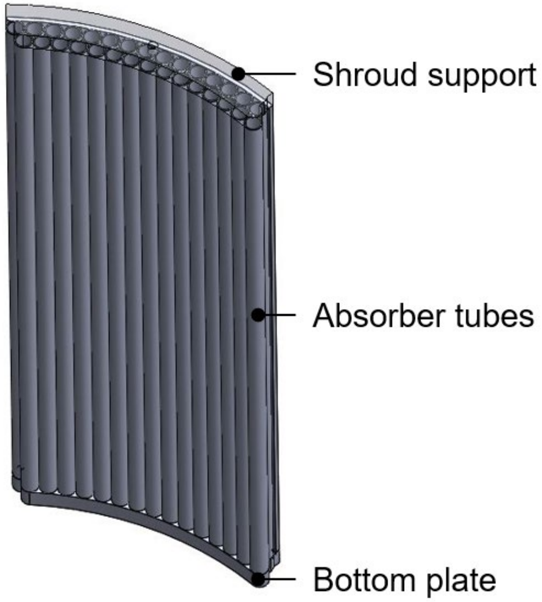
3000 kW inside the vessel
80 kW in the pressure vessel
58 kW in the reflector

Characteristic	Value
Average core power density	7.62 W/cm^3
Average fuel power density	31.02 W/cm^3
Average power per fuel particle	42.23 mW
Radial peaking factor	1.32
Axial peaking factor	1.14

Control Mechanisms

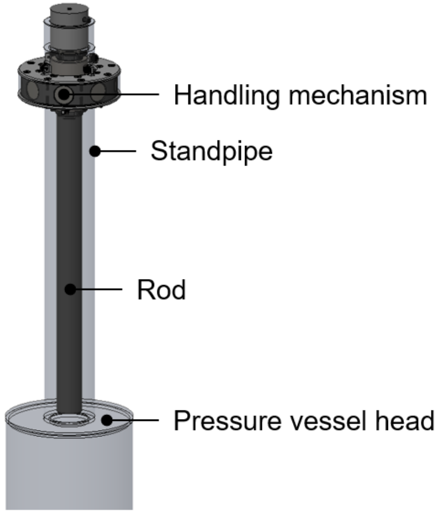
Control Shroud

- Primary function: reactor control up to and down from power
- 96% enriched B_4C contained in a stainless steel tube bundle
- Split into 8 azimuthal plates
- Total worth: ~3,700 pcm
- Plate worth: ~470 pcm



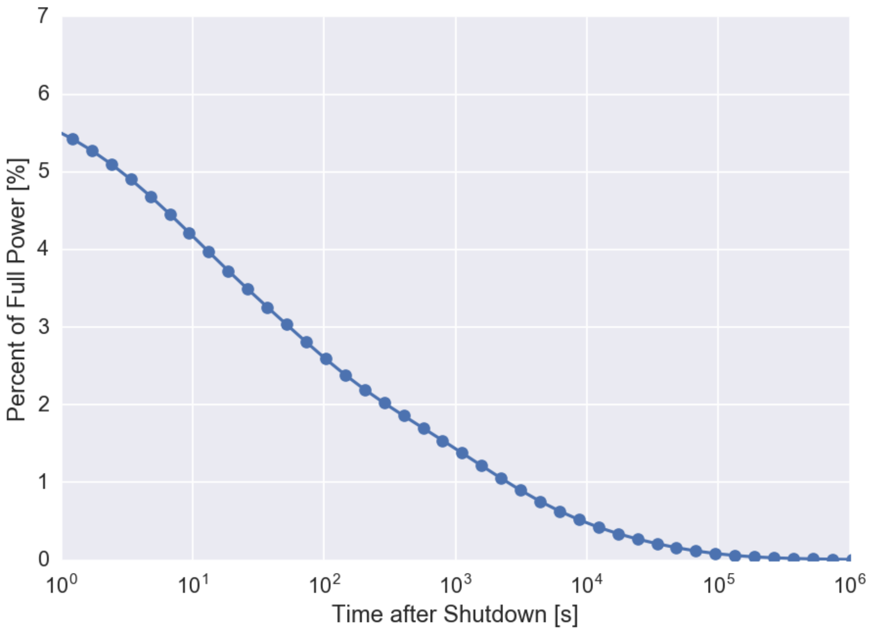
Shutdown Rod

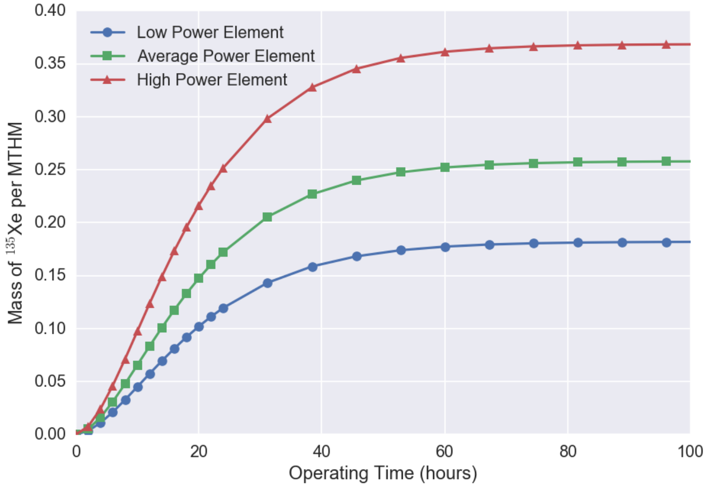
- Primary function: emergency reactor shutdown (scram)
- 96% enriched B_4C contained in a stainless steel tube
- Total worth: ~4,500 pcm



Decay Heat and Source Term

- Decay heat calculated using SCALE
  - "Average" fuel element is assumed to operate for 24 hours
- Relatively low decay heat with quick decay due to very low burnup fuel after the short operation
- Source term generated using the same calculation
- Planned operation will not reach Xe equilibrium concentration





Time after shutdown	Total decay heat (kW)	Decay heat per assembly (kW)
0.1 second	180.31	3.34
1 second	165.09	3.06
1 minute	88.41	1.64
1 hour	25.38	0.47
4 hours	11.59	0.21
12 hours	5.31	0.10
24 hours	2.82	0.05
10 days	0.26	< 0.01
100 days	0.02	< 0.0001

Radial Power Variation Leads to Only Small Increase in Stress

- Shift Monte Carlo code used to generate detailed power distribution for full-core TCR model
  - 1 mm x-y mesh cells on full core
  - 0.25 mm x-y mesh cell on selected cog
  - Power tilt of ~40% from hottest to coolest cog tip
- Bison used to determine impact on stress and element failure probability using the calculated power tilt
  - Two different candidate cog designs used (worst and best cases from stress perspective)
  - Uniform vs. profile power density used
  - Maximum stress increase less than 10% in both cases

Radial power profile at core midplane