High Flux Isotope Reactor Low-Enriched Uranium Conversion Activities – 2022 Status Update

2022 Reduced Enrichment Research and Test Reactor (RERTR) Meeting

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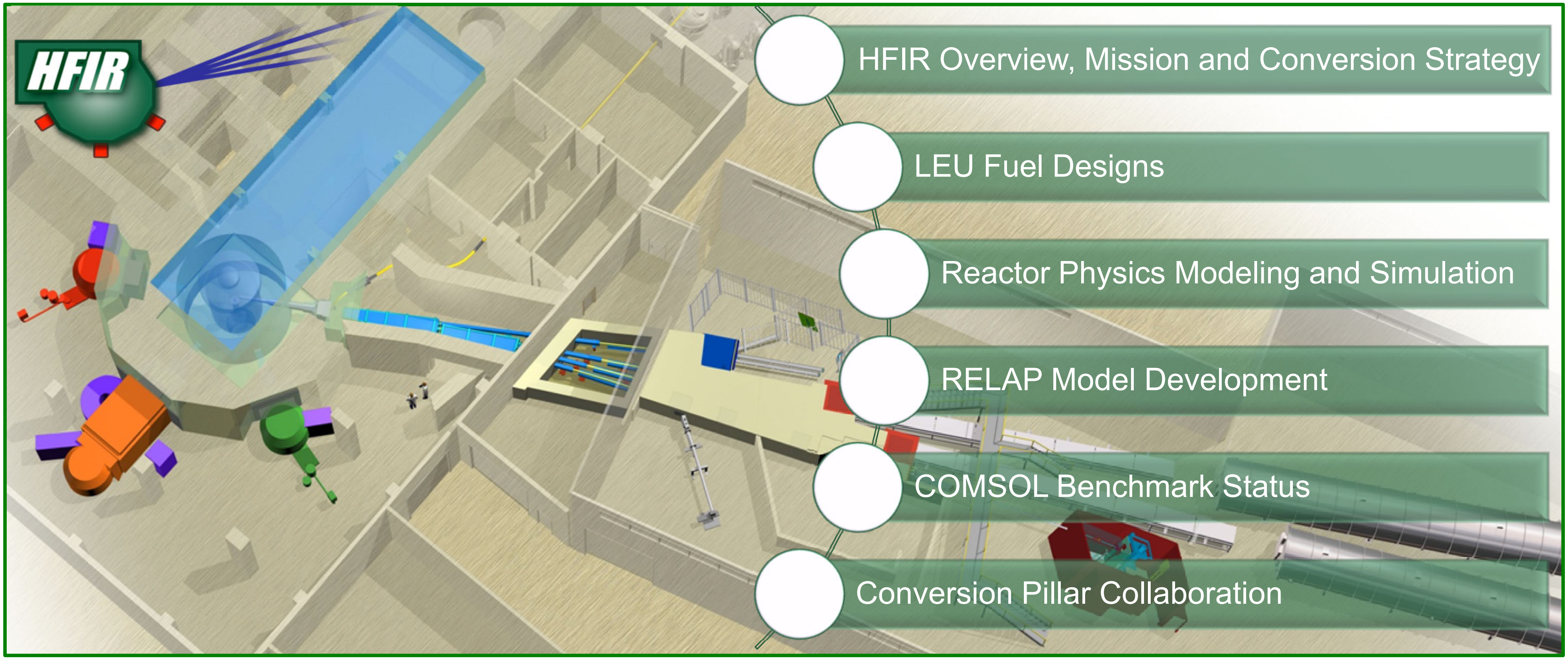
Oak Ridge National Laboratory

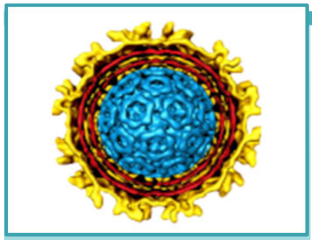
Outline



- HFIR Overview, Mission and Conversion Strategy
- LEU Fuel Designs
- Reactor Physics Modeling and Simulation
- RELAP Model Development
- COMSOL Benchmark Status
- Conversion Pillar Collaboration

HFIR is a versatile, multi-mission research reactor

HFIR’s neutron science capabilities serve a variety of high-impact missions located at Oak Ridge National Laboratory



Neutron scattering

Cold/thermal neutrons to study structure and dynamics of materials

- Physics
- Chemistry
- Materials science
- Engineering
- Biology

Radioisotope production

For use in energy, industry, security, medicine

- ^{252}Cf
- ^{238}Pu
- ^{225}Ac
- ^{188}W
- ^{75}Se
- ^{63}Ni

Materials irradiation

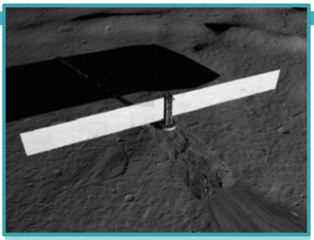
≤14 dpa/year

- Accident tolerant fuels
- Fuel cladding
- Advanced alloys
- Fusion reactor materials
- Tensile testing
- Post-irradiation examinations

Activation analysis

2 pneumatic tubes

- Nuclear forensics
- Criminal forensics
- Impurity analysis
- Geology
- Environment
- Nonproliferation



Gamma irradiation

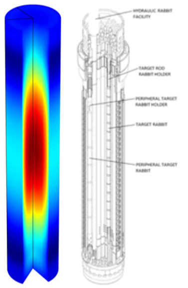
- Used fuel
- Up to 10^8 rad/h
- Radiological damage studies
- NASA material tolerance
- Resin for ^{137}Cs removal in waste
- Insulators
- Wear resistance

Neutrino research

- Pure ^{235}U spectrum
- Neutrino spectrum and oscillations
- Short baseline
- Reactor monitoring
- Nuclear safeguards

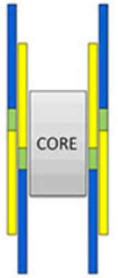
HFIR has a unique geometry for experiment flexibility

Flux trap target region



- 37 vertical target positions
- Isotope production
- Materials irradiation
- Hydraulic tube

Control element region

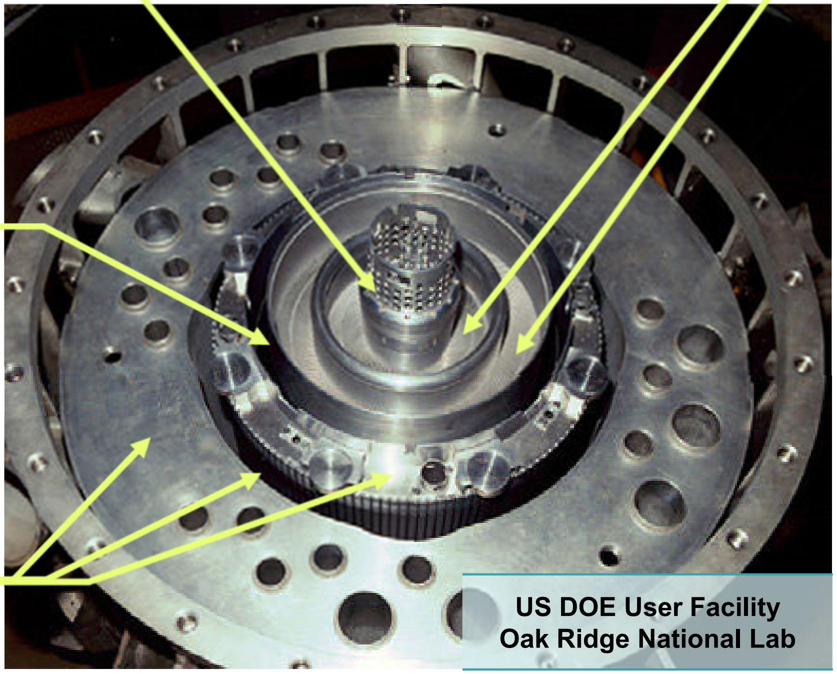


- 2 concentric cylinders
- Outer control element (OCE) for safety and regulation
- Inner control element (ICE) for regulation
- Eu, Ta, Al

Beryllium reflectors

- 4 beam tubes for scattering
- 42 vertical experiment facilities
- 2 pneumatic tubes for NAA

85 MW (1.7 MW/L average)
2.5×10^{15} n/cm^2-s peak thermal
23-26-day cycle lengths

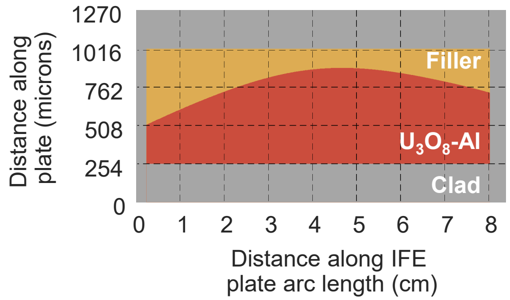


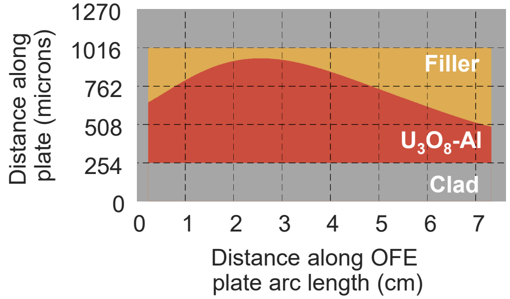
US DOE User Facility
Oak Ridge National Lab

Light water cooled and moderated
16,000 GPM primary coolant flow (120°F 468 psig)

Fuel assembly: Inner fuel element (IFE) Outer fuel element (OFE)

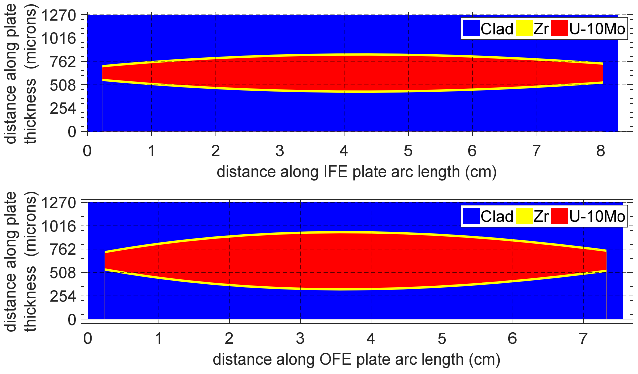
- Involute-shaped Al clad plates
- 171 IFE plates
- 369 OFE plates
- HEU$_3$O$_8$-Al dispersion fuel
- 9.4 kg ^{235}U and 2.7 g ^{10}B



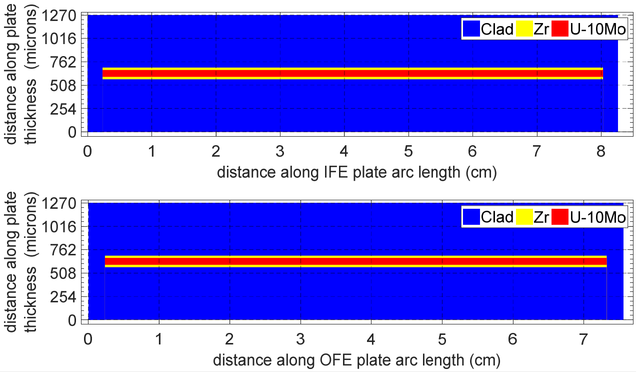


HFIR Conversion History

- ORNL has been evaluating conversion to an LEU fuel product since 2005.
- Initial studies explored U-10Mo monolithic alloy fuel, but as the U-10Mo designs to meet HFIR performance and safety metrics are complex, it was not clear they could be economically manufactured.
- HFIR re-baselined to a uranium-silicide dispersion fuel (U_3Si_2-Al) in 2019.
- HFIR conversion currently scheduled for 2030s



Uppermost 47.80 cm of fuel zone



Bottommost edge of fuel zone
(axial contour profile interpolated over 3-cm zone)

U-10Mo “utilization” design had borated side plates and an axial contour

HFIR Conversion Strategy

HFIR conversion currently scheduled for mid-2030s

1. Develop analytical tools, propose fuel designs, and demonstrate feasibility of HFIR conversion
2. Demonstrate operation of HFIR at increased power with HEU fuel
3. Conduct low-power testing of LEU lead test core in vessel
4. Conduct high-power testing of LEU lead test core in vessel with PIE
5. Demonstrate operation of HFIR with production LEU fuel at increased power

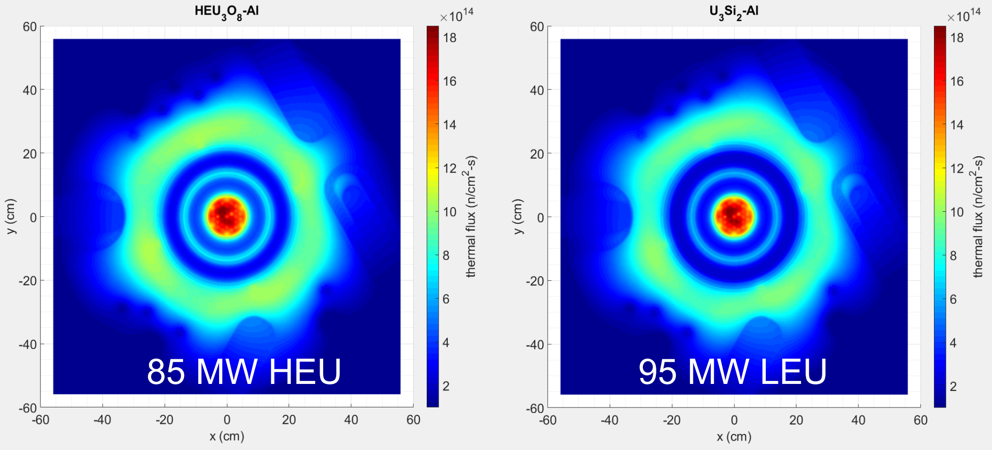
- Five-phase approach is in M^3 schedule with summary-level activities

Maintaining HFIR performance and mission capabilities

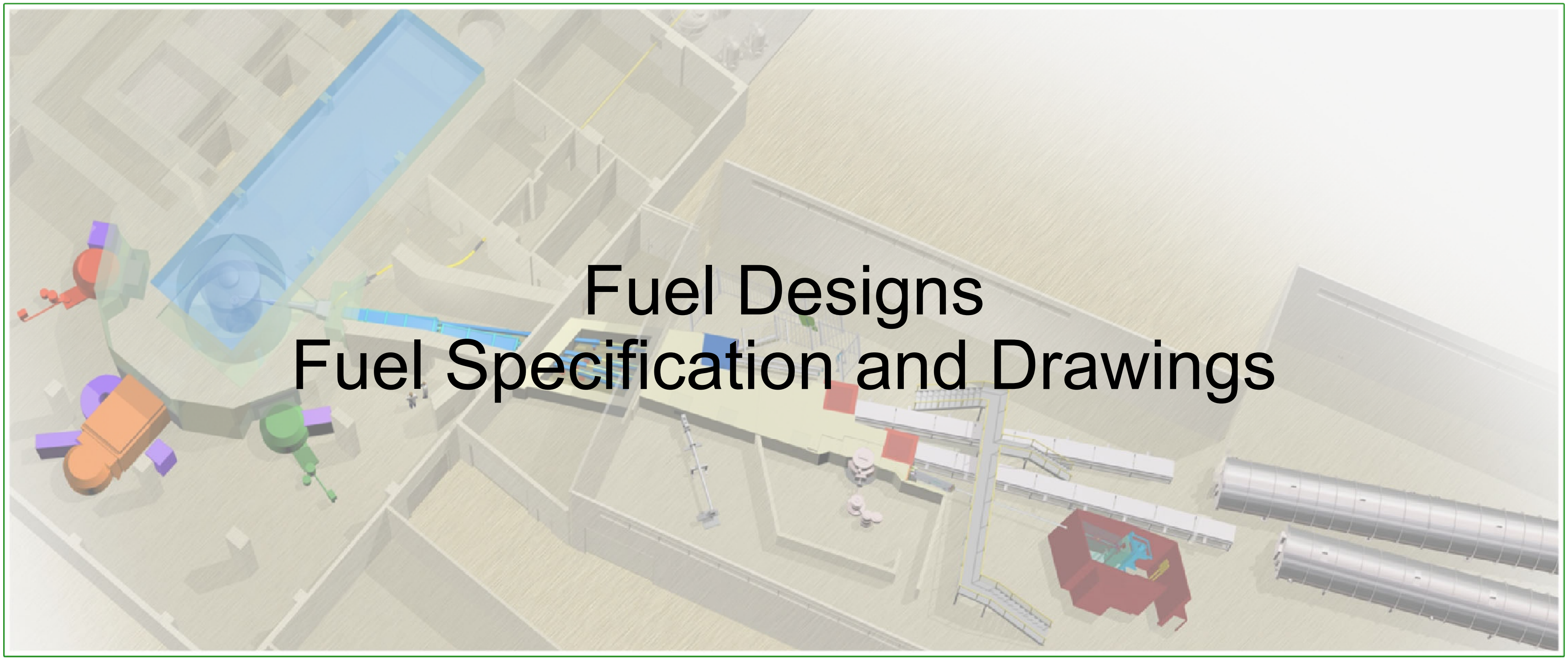
Key performance metrics have been established for design studies

Key performance metrics, defined as a means of capturing data essential for primary missions	Cold and thermal neutron flux at cold source moderator vessel
	^{252}Cf production
	Thermal neutron flux in ^{252}Cf targets in flux trap
	Fast neutron flux in flux trap targets
	Fast neutron flux in reflector
	Cycle length
	Margin to burnout

X-Y thermal flux distribution on core midplane



More detailed performance and safety assessments are performed on promising design(s)



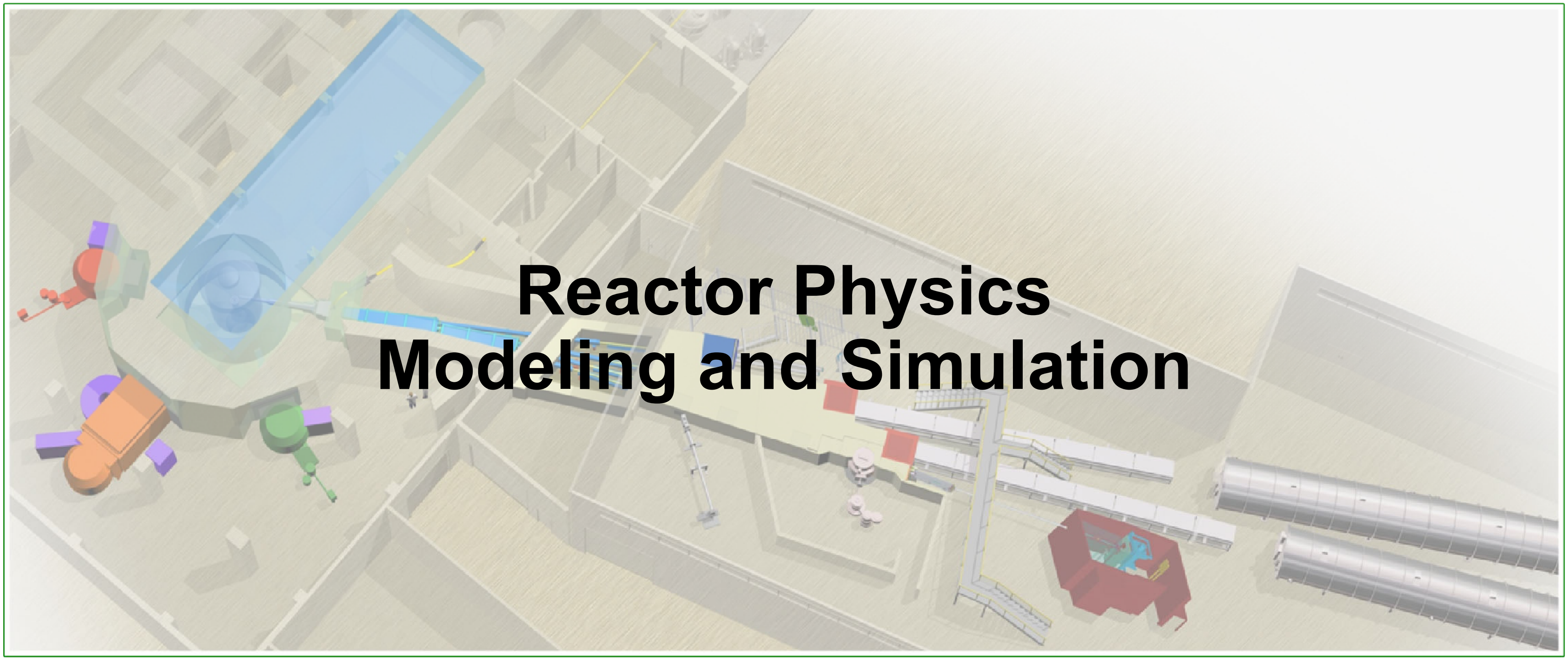
Fuel Designs
Fuel Specification and Drawings

LEU Fuel Specification

- HFIR Specification CDS-60.200-002, “Working Specification for High Flux Isotope Reactor Low Enriched Uranium Fuel Elements” Rev. 0 issued November 12, 2021.
  - New specification comparable in scope to existing HEU fuel specification.
  - Technical content based on most recent LEU design reports (ORNL/TM-2020/1798, ORNL/TM-2020/1799, and ORNL/TM-2021/1964) and ad hoc input from stakeholders.
  - Structured as a working document to be incrementally refined as the LEU fuel design and fabrication process mature.

LEU Fuel Drawings

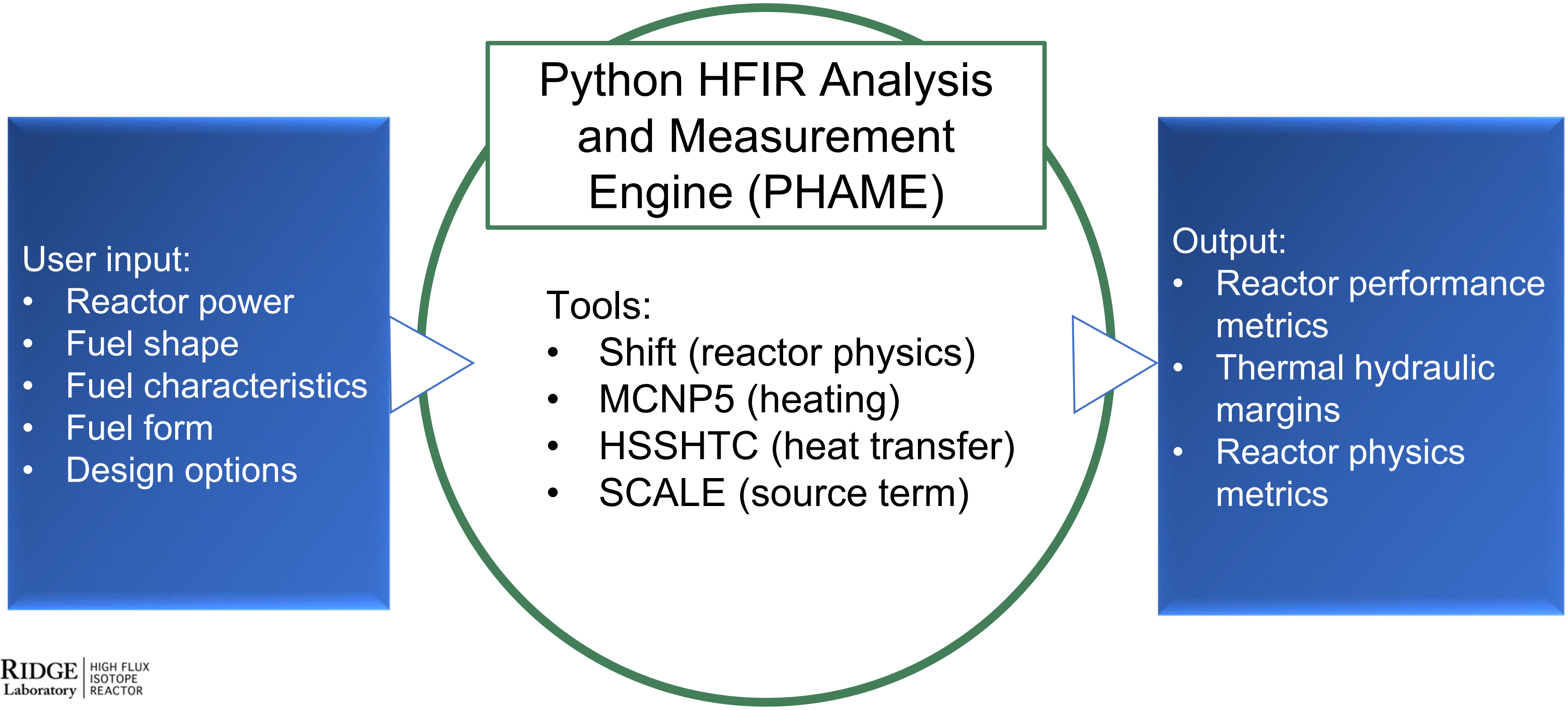
- HFIR Drawing D-42114A, “HFIR Inner Fuel Element LEU Development Fuel Plate Loading Details”, Rev. 2 issued November 8, 2021.
  - Provides detailed dimensions of flat fuel plates including fuel core and filler geometry.
  - Drawings will be revised in tandem with fuel specification.
  - Drawings contain three concept inner fuel element fuel plate details representing the principal variations under consideration



Reactor Physics Modeling and Simulation

Python HFIR Analysis and Measurement Engine (PHAME) for generation and analysis of potential fuel designs

- Allows for analyses of several designs further along in the process



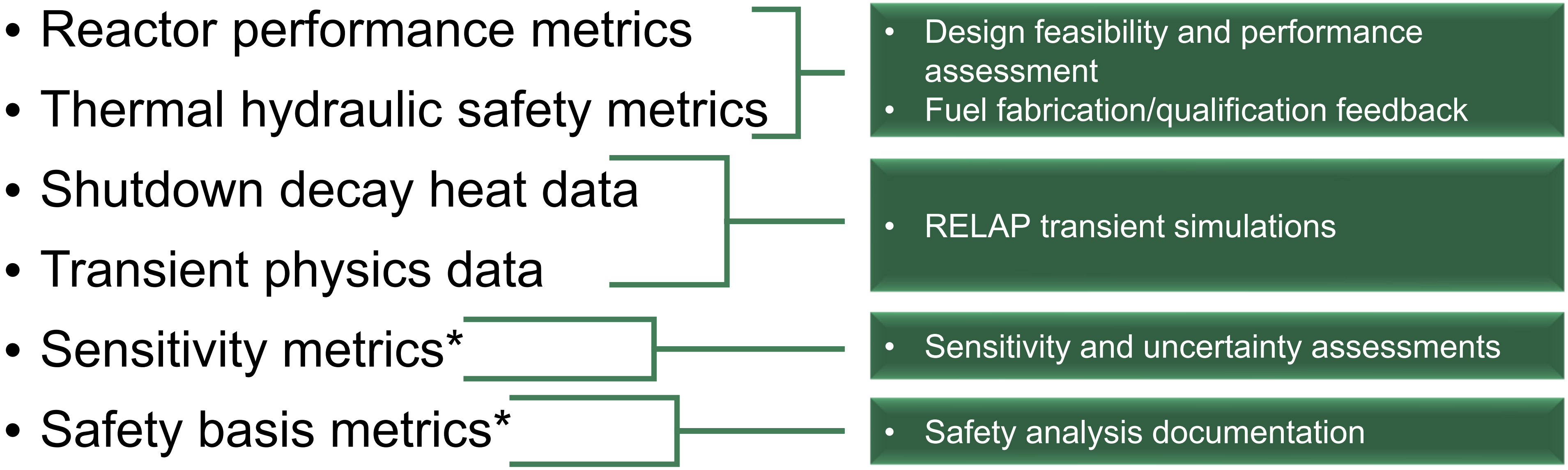
User input:
- Reactor power
- Fuel shape
- Fuel characteristics
- Fuel form
- Design options

Python HFIR Analysis and Measurement Engine (PHAME)

Tools:
- Shift (reactor physics)
- MCNP5 (heating)
- HSSHTC (heat transfer)
- SCALE (source term)

Output:
- Reactor performance metrics
- Thermal hydraulic margins
- Reactor physics metrics

Continuously expanded the PHAME simulation toolset to include physics metrics for many follow-on analyses



- Reactor performance metrics
- Thermal hydraulic safety metrics
- Shutdown decay heat data
- Transient physics data
- Sensitivity metrics*
- Safety basis metrics*
- Improved reactor performance metrics*

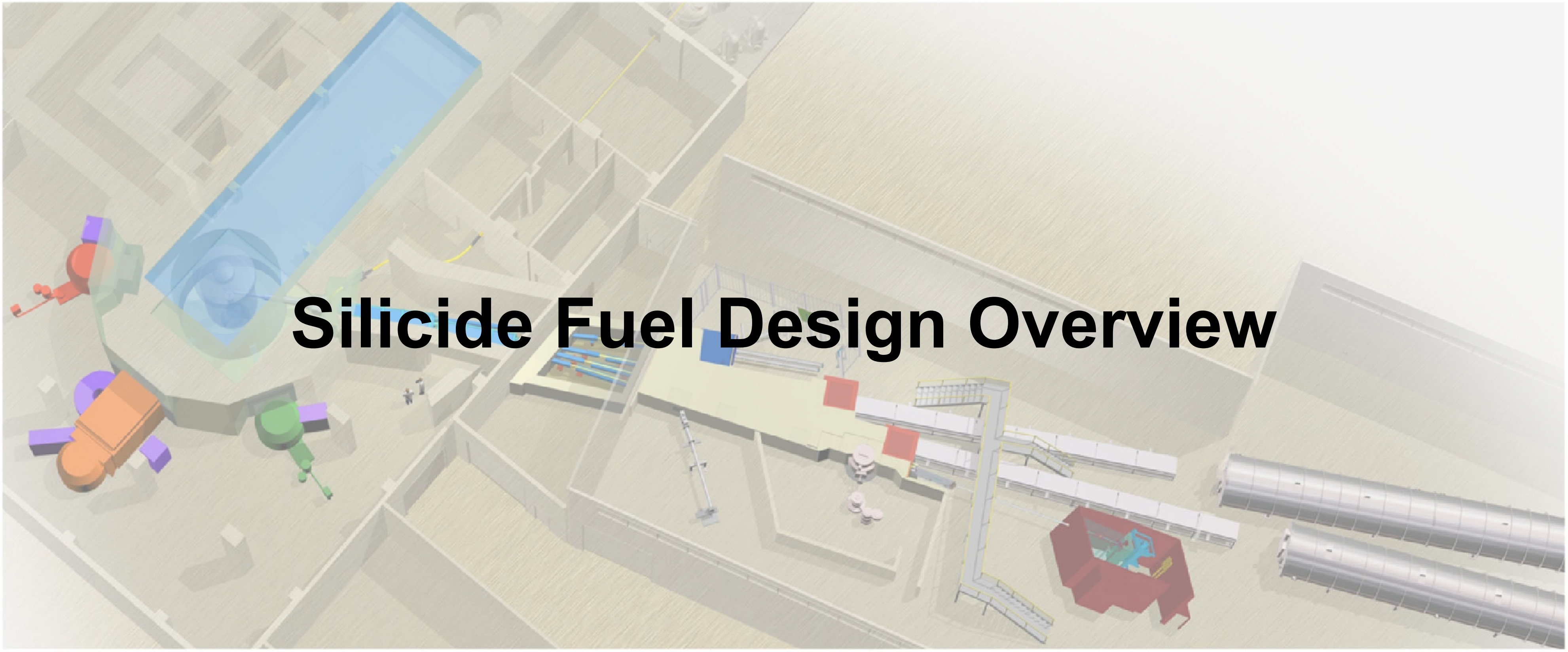
- Design feasibility and performance assessment
- Fuel fabrication/qualification feedback

- RELAP transient simulations

- Sensitivity and uncertainty assessments

- Safety analysis documentation

*capability to generate these metrics are still being incorporated in PHAME

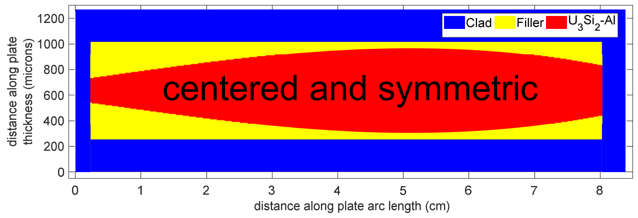


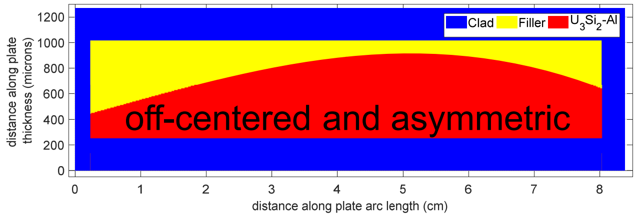
Silicide Fuel Design Overview

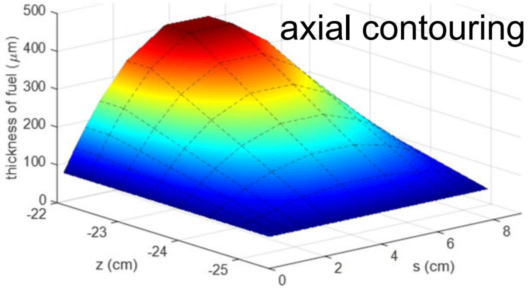
Design Variables and Challenges

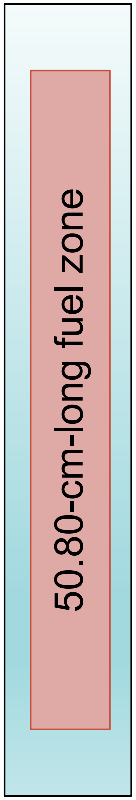
Fuel shape dictates mass, cycle length, fission rate distribution

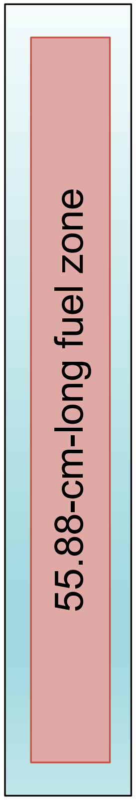
- Fuel system
- Reactor power
- Fuel shape
  - Mass and mass split between IFE and OFE
  - Radial contouring profile (across plate)
  - Centered & symmetric (eliminated off-centered & asymmetric)
  - Fuel zone length (50.80–55.88 cm)
  - Axial contouring (bottom 1–3 cm)
- Burnable poison
  - Type (e.g., B, Gd)
  - Amount
  - Location (e.g., filler, clad, side plates)



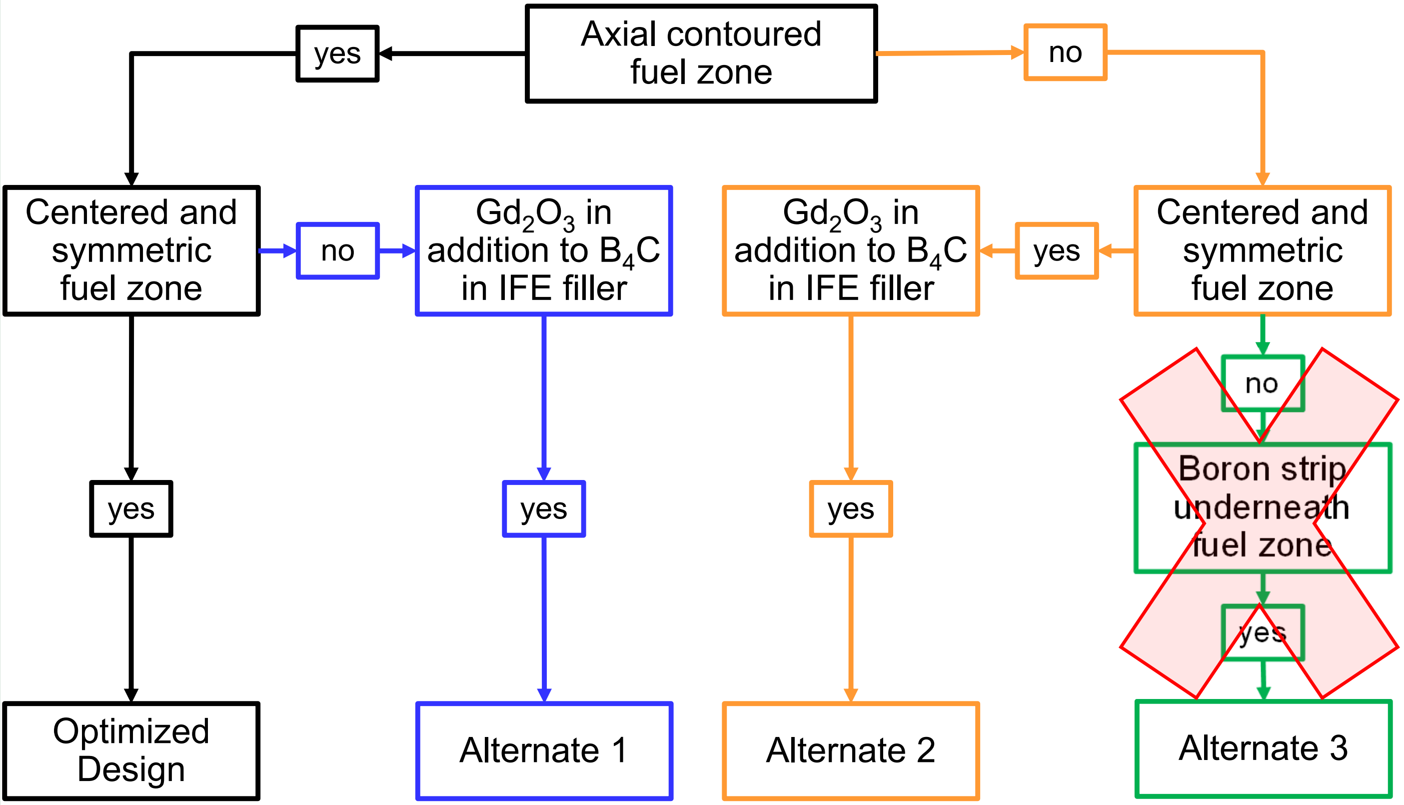








Design features for candidate low-density silicide fuel designs with 10 mil cladding



Axial contoured fuel zone

yes

no

Centered and symmetric fuel zone

no

Gd_2O_3 in addition to B_4C in IFE filler

Gd_2O_3 in addition to B_4C in IFE filler

yes

Centered and symmetric fuel zone

~~no~~

~~Boron strip underneath fuel zone~~

~~yes~~

yes

yes

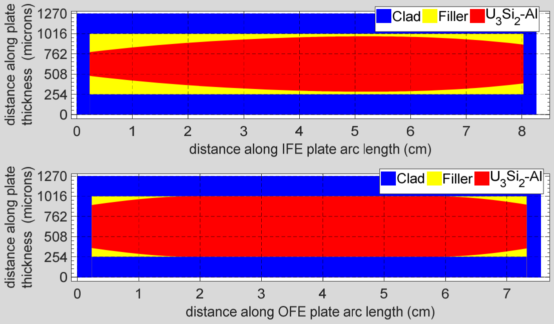
yes

Optimized Design

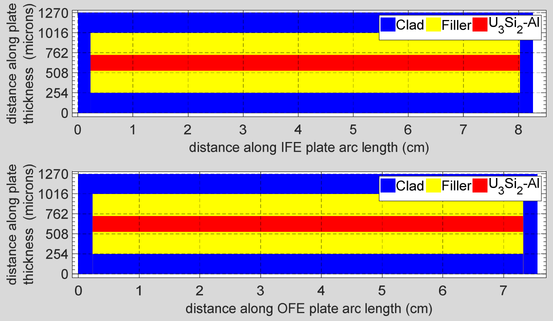
Alternate 1

Alternate 2

Alternate 3



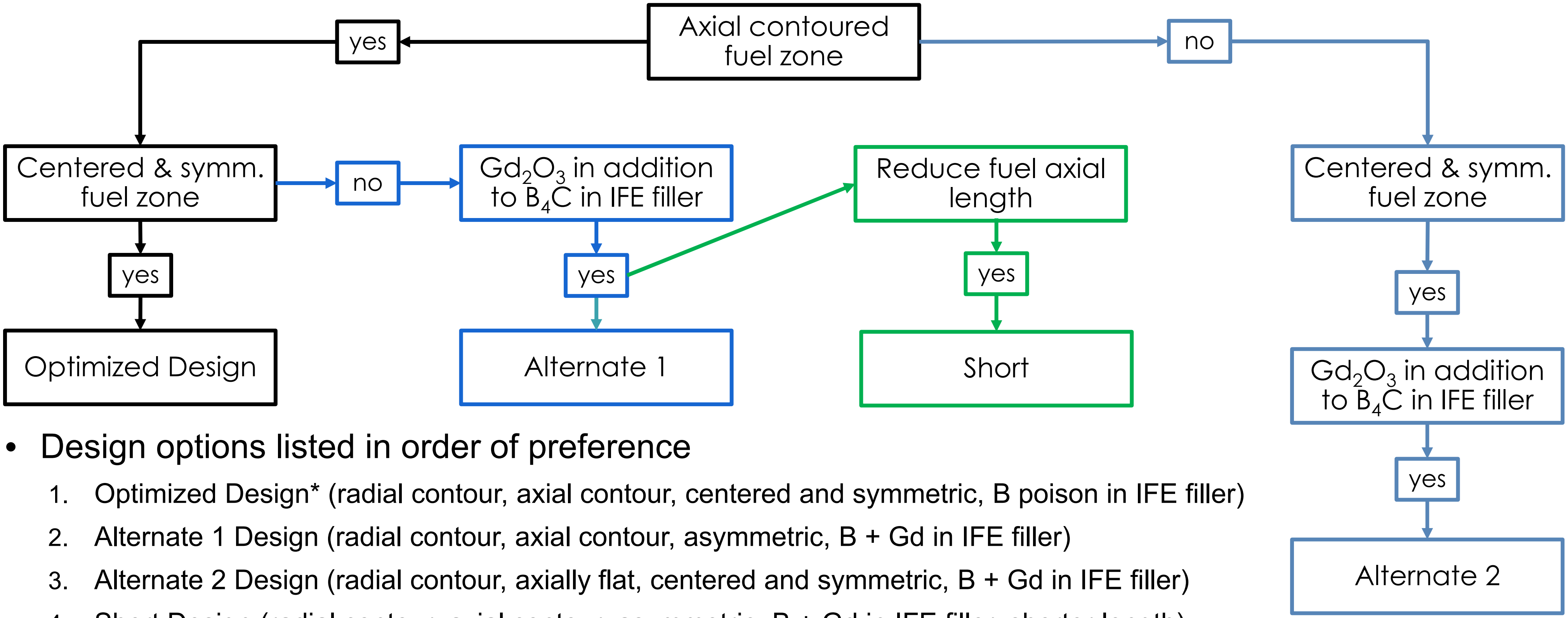
Uppermost 54.88 cm of fuel zone



Bottommost edge of fuel zone
(axial contour profile interpolated over 1-cm zone)

Optimized Design

Design features for candidate high-density silicide fuel designs with 10 mil cladding



Axial contoured fuel zone

yes

no

Centered & symm. fuel zone

no

Gd_2O_3 in addition to B_4C in IFE filler

Reduce fuel axial length

Centered & symm. fuel zone

yes

yes

yes

yes

Optimized Design

Alternate 1

Short

Gd_2O_3 in addition to B_4C in IFE filler

yes

Alternate 2

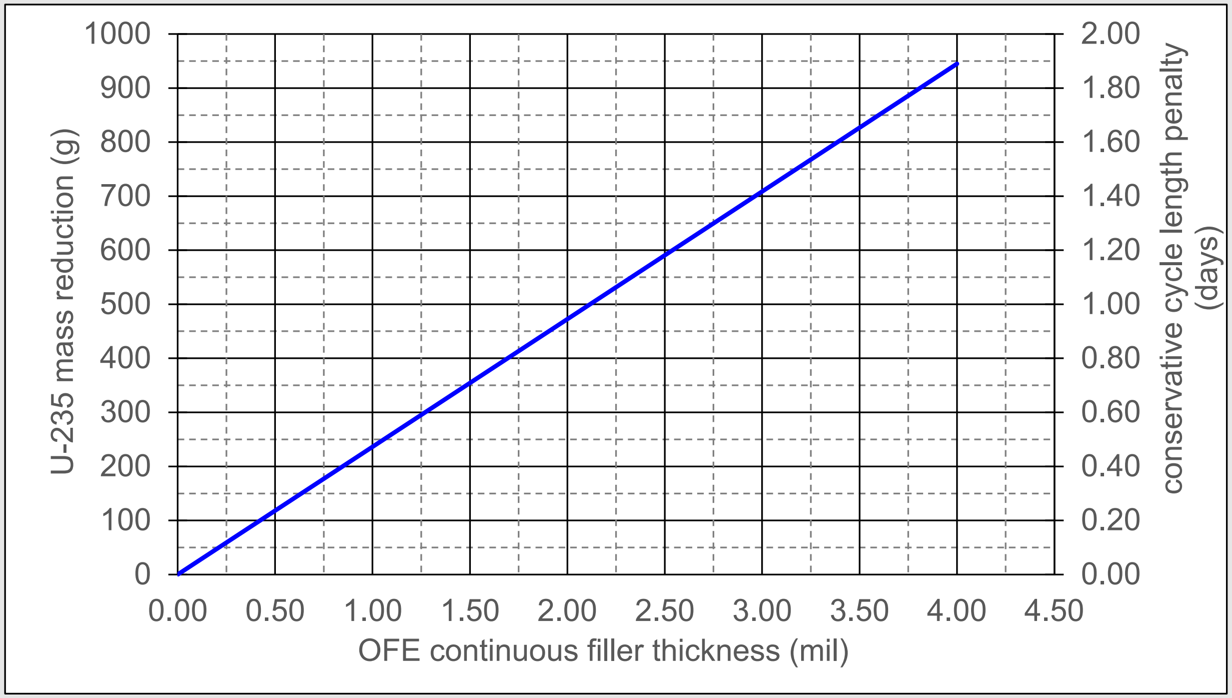
- Design options listed in order of preference
  1. Optimized Design* (radial contour, axial contour, centered and symmetric, B poison in IFE filler)
  2. Alternate 1 Design (radial contour, axial contour, asymmetric, B + Gd in IFE filler)
  3. Alternate 2 Design (radial contour, axially flat, centered and symmetric, B + Gd in IFE filler)
  4. Short Design (radial contour, axial contour, asymmetric, B + Gd in IFE filler, shorter length)

*newest design is a thick cladding variant of this optimized design

Higher U densities in LEU silicide dispersion fuel provide for less complex and higher performing designs

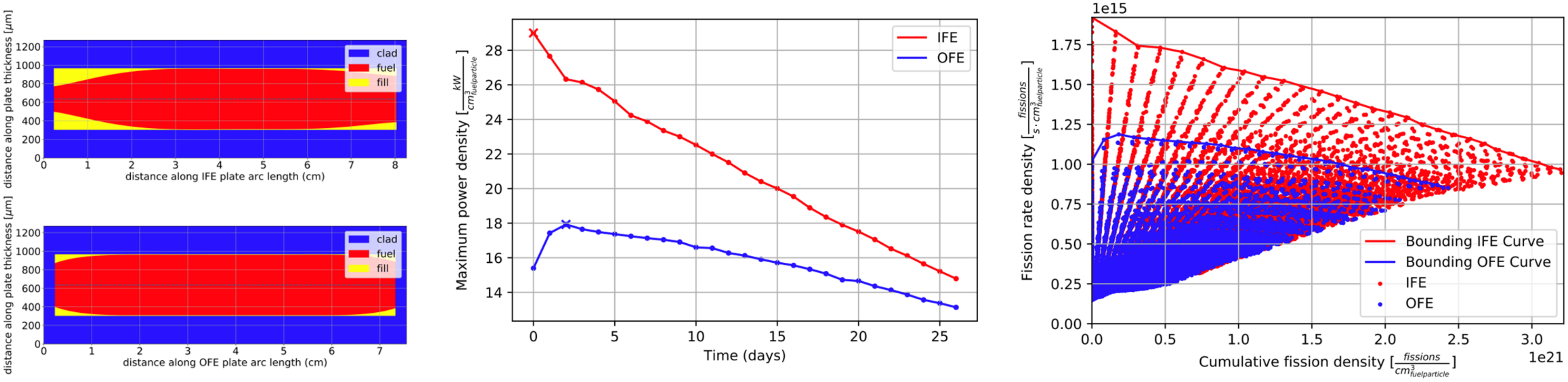
- Continuous filler
- Possible elimination of other complex design features
- Possible reduction of fuel zone length (20” < L < 22”)
- Potential increase in performance metrics
- Maintain or exceed HEU thermal safety margin
- More flexibility in fuel shape
- Enables thicker cladding

Minimum allowable filler thickness has an impact on mass loading and therefore cycle length. Additionally, reducing the “continuous” filler thickness pushes power into the radial flux peaks and therefore reduces thermal safety margin.



Continuously generated design performance metrics for low- and high-density silicide designs

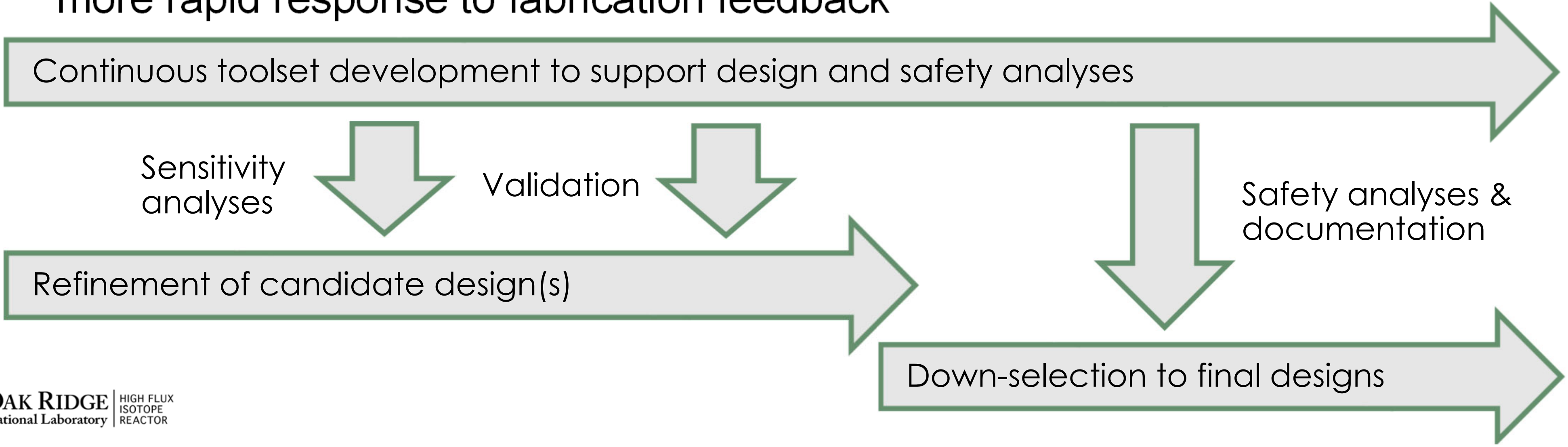
- Low-density silicide fuel (ORNL/TM-2020/1798)
- High-density silicide fuel (ORNL/TM-2020/1799)
- High-density silicide fuel with thick cladding (ORNL/TM-2021/1964)
- U-10Mo fuel for completeness (ORNL/TM-2021/2315)



High-density silicide fuel with thick cladding

Improving the understanding of the sensitivities of proposed designs relative to current fuel design

- While waiting for design feedback from fuel fabrication, assess the robustness of designs to fabrication constraints
  - Determine if the design subject to large changes in performance given small changes in design parameters
  - This assesses impacts of uncertainties in reactor simulations and allows for more rapid response to fabrication feedback



Continuous toolset development to support design and safety analyses

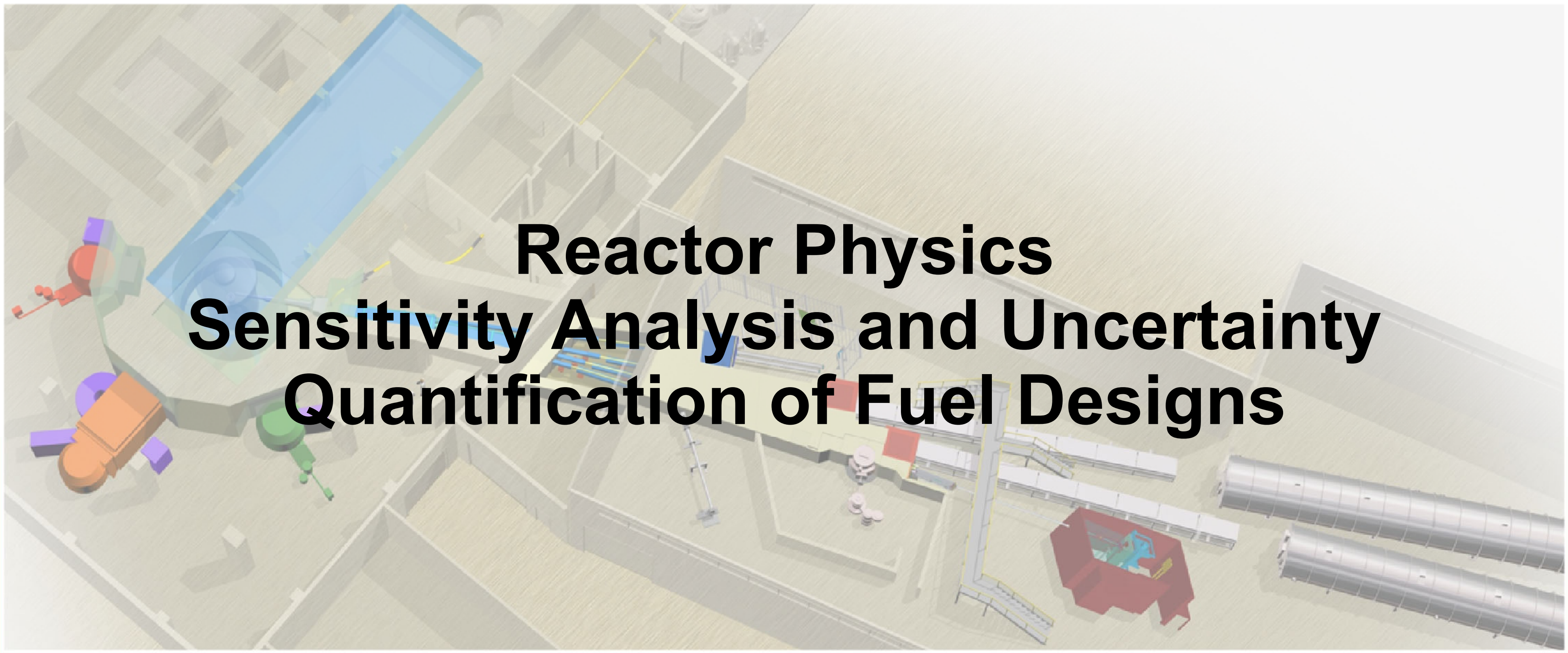
Sensitivity analyses

Validation

Safety analyses & documentation

Refinement of candidate design(s)

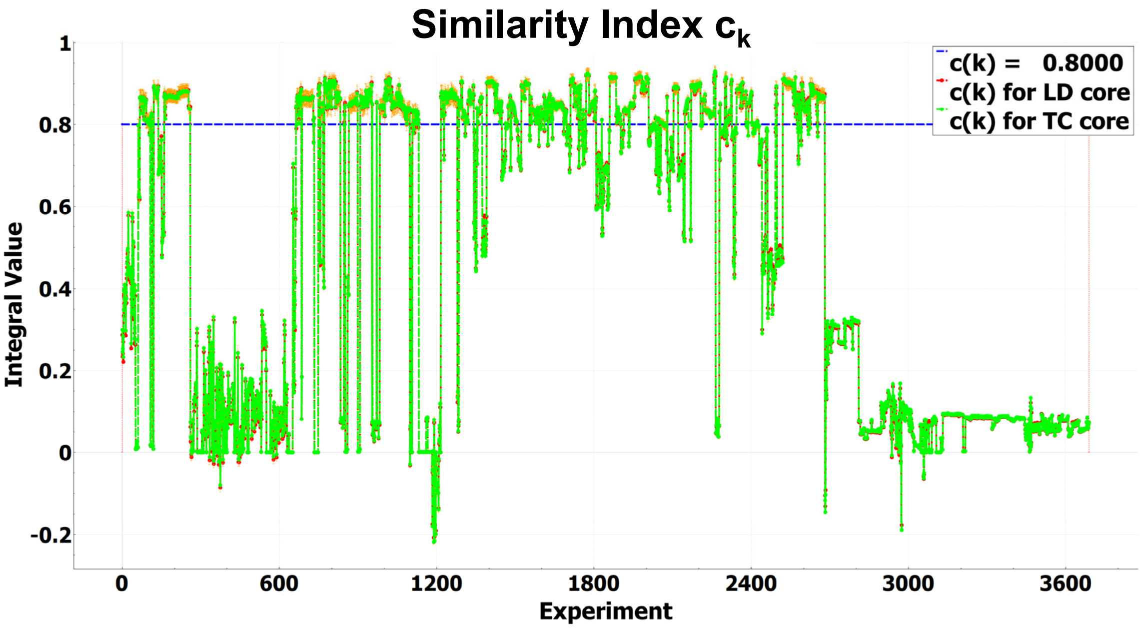
Down-selection to final designs



Reactor Physics
Sensitivity Analysis and Uncertainty Quantification of Fuel Designs

Silicide fuel designs have more similar sensitivities to more known experiments than alternate fuel systems (U-10Mo)

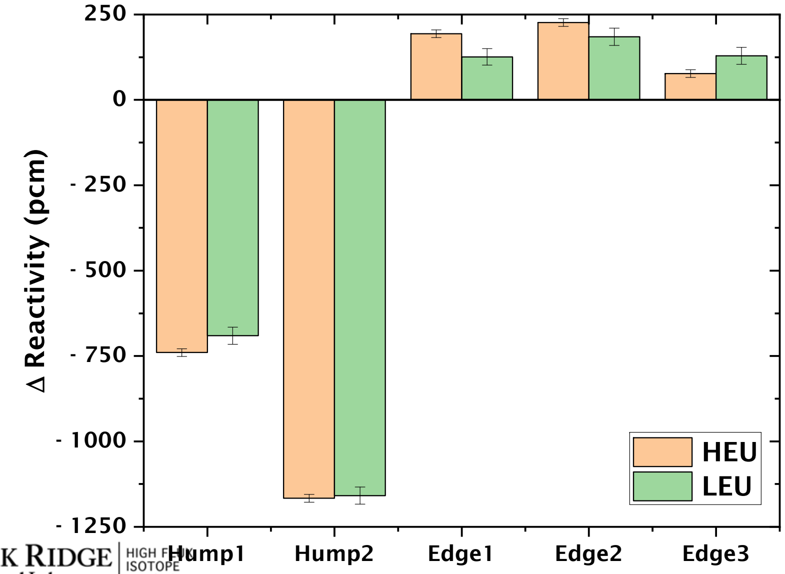
- U_3Si_2 low density (LD) core:
  - $c_k \geq$ 0.8: 1511
  - Highest c_k value: 0.9273 ± 0.0131
- U_3Si_2 thick clad (TC) core
  - $c_k \geq$ 0.8: 1516
  - Highest c_k value: 0.9306 ± 0.0129
- Most similar critical experiments:
  - LEU-COMP-THERM-066
  - LEU-COMP-THERM-029

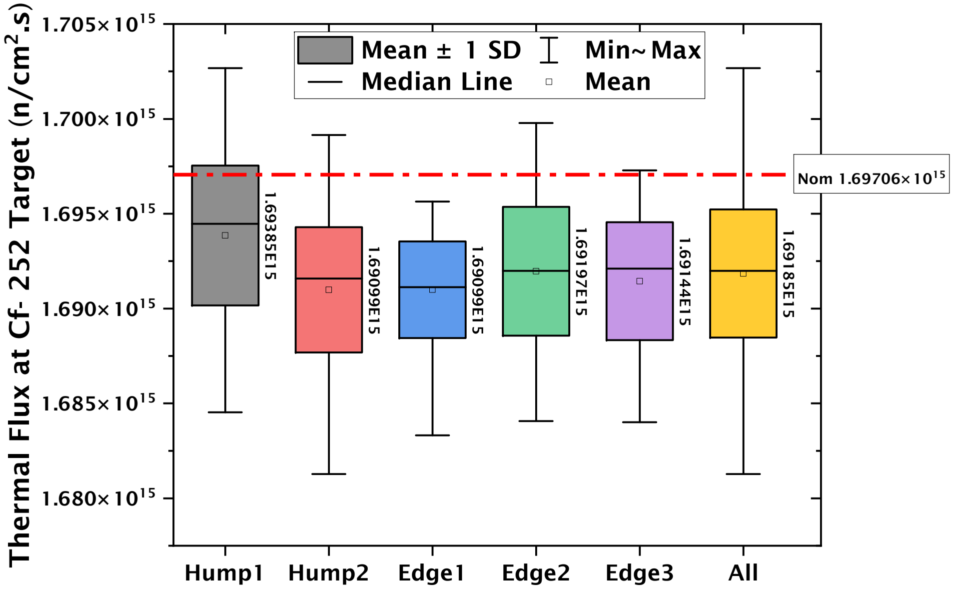


- Important isotopes affecting the uncertainty of k-eff:
  - HEU core: U-235, Al-27, H-1
  - LEU core: U-235, Al-27, U-238, H-1

Silicide fuel designs are no more sensitive to effective fuel inhomogeneity than the current HEU fuel design

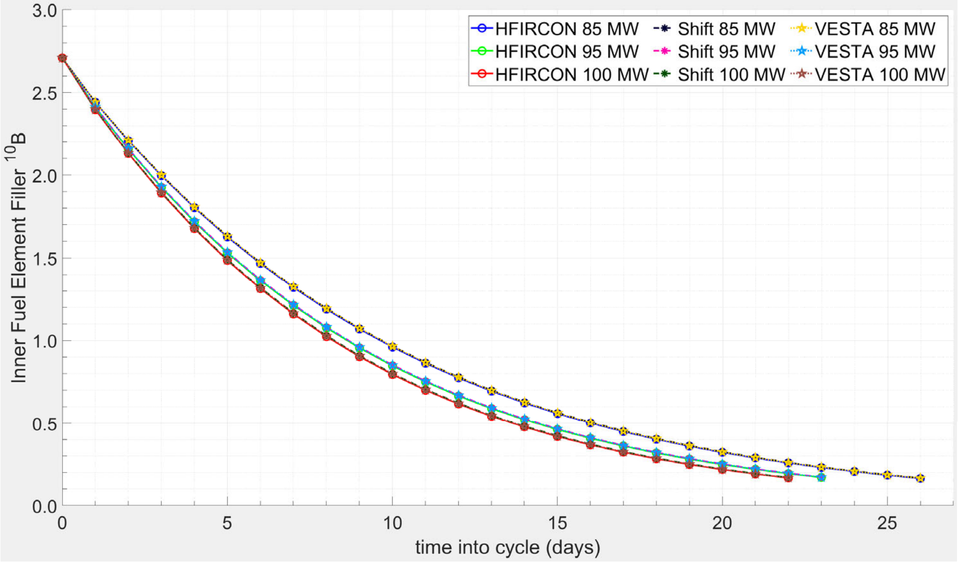
- Generated sets of measurement-informed effective inhomogeneity profiles (hump and edge profiles)
- The relative changes in the flux at several target locations between the HEU and LEU cores are negligible

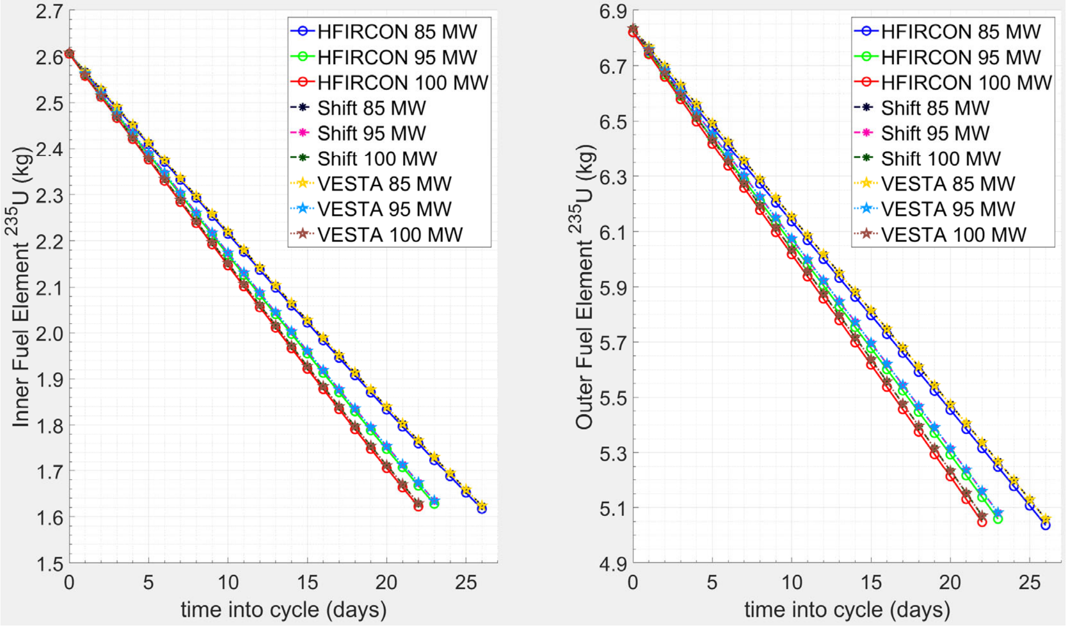




In-practice modeling and simulation suites confirm key calculated parameters for LEU fuel designs

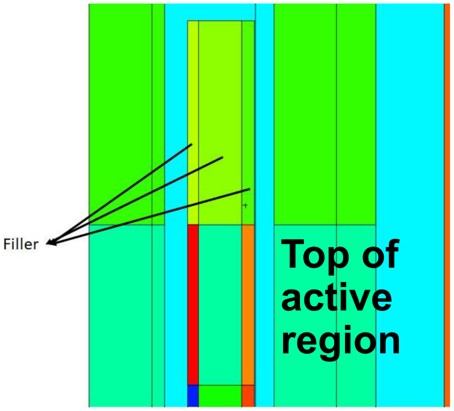
- Verification of results from VESTA (former safety basis depletion code), HFIRCON (current safety basis depletion code), and Shift (current scalable design tool)



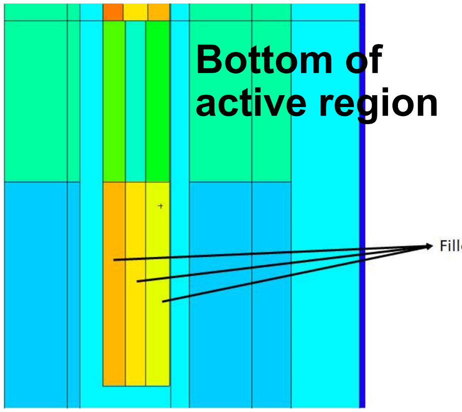


Filler extensions in silicide fuel designs encompass edges with burnable poisons, reducing localized power peaks

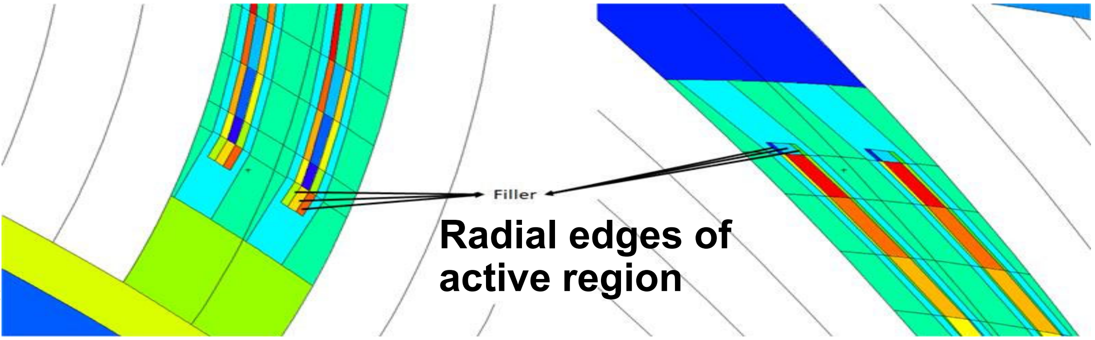
- Generated explicit models of extended filler regions in the inner fuel element plates
  - Conserving boron concentration (increasing loading)
  - Reducing boron concentration (conserving loading)
- Expecting reduced peaking at edges without fuel design changes
  - Fuel shape changes likely required to maintain consistent performance



Top of active region

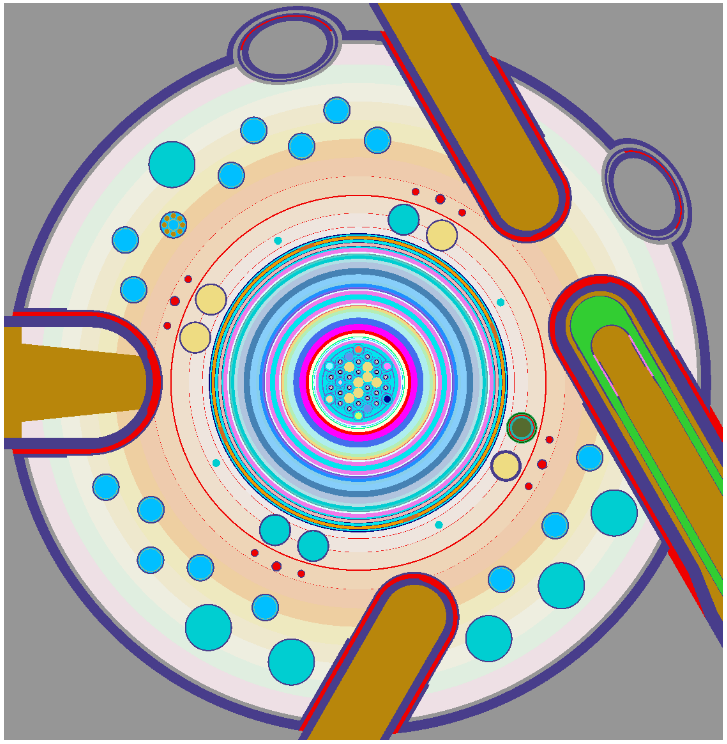


Bottom of active region

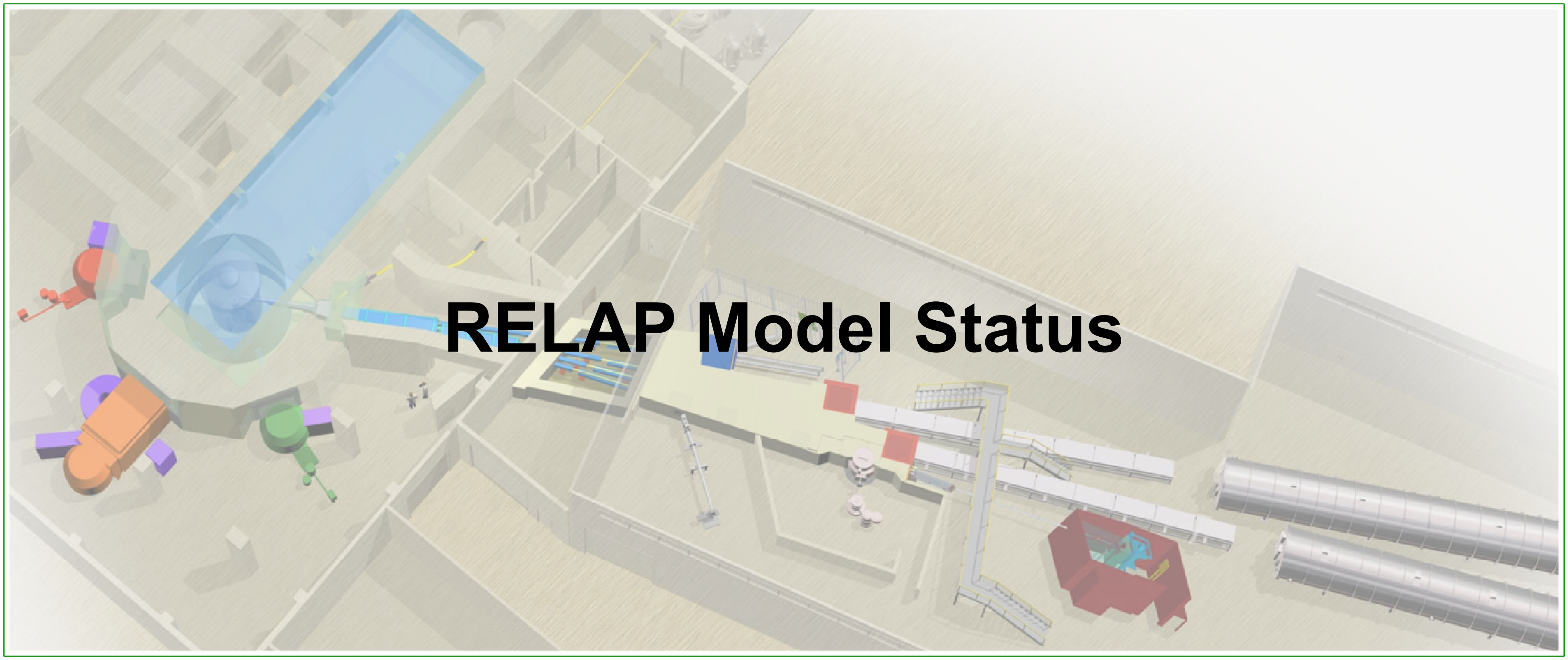


Radial edges of active region

These recent activities build a basis for validation studies on key performance metrics with uncertainties



- Continue incorporating design feedback in targeted studies to build capabilities to analyze geometries and constraints
- Leverage existing activities to improve our understanding of performance predictions of LEU fuel designs with uncertainties
- Incorporate improved calculation approaches at the appropriate level of fidelity for fuel design assessments
  - Multicycle irradiation of key isotopes
  - Improved metrics for materials irradiation



RELAP Model Status

Transient Analysis with RELAP HFIR Model

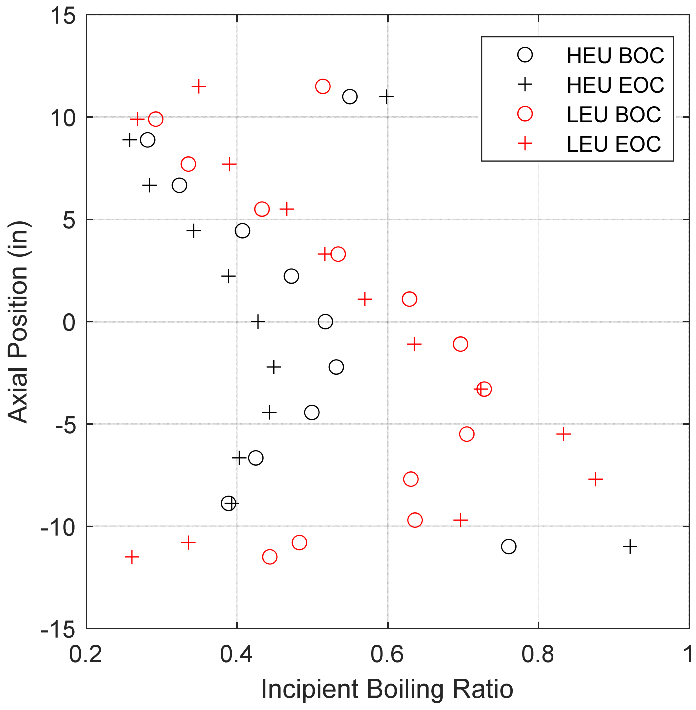
- Chapter 15 of the HFIR Safety Analysis Report (SAR) presents consequences for various accident scenarios modeled in RELAP, which will be evaluated to prove LEU fuel design acceptability
- Current SAR transients use various base plant models. All transients will be standardized to the HFIR Consolidated Model Version 14 and use HFIR-specific RELAP5/Mod3.3-Patch04
- Near-term goals: Establish a baseline HEU core configuration (HEU Representative Model) and directly compare to LEU Silicide designs for bounding events that challenge the relevant safety margins:
  - Loss of Off-Site Power (LOOP) and Small Break Loss of Coolant Accident (SBLOCA) - cases without kinetics (i.e. decay heat cases)
  - Control Cylinder Ejection (CCE) and Optimum Void in Target Region - active kinetics cases
  - Any additional cases to be added as needed

Status of LEU conversion RELAP model development

- HEU Representative Model: Provides comparison to proposed LEU core designs
  - Safety calculations (2+) in draft or review
  - Internal ORNL TM and publication to follow

Parameter	Time	LEU	HEU
Hot channel gap (mil)	BOC	39.3	38.72
	EOC	38.02	36.95
U_{25} factor extension length (in)		0.265	0.530

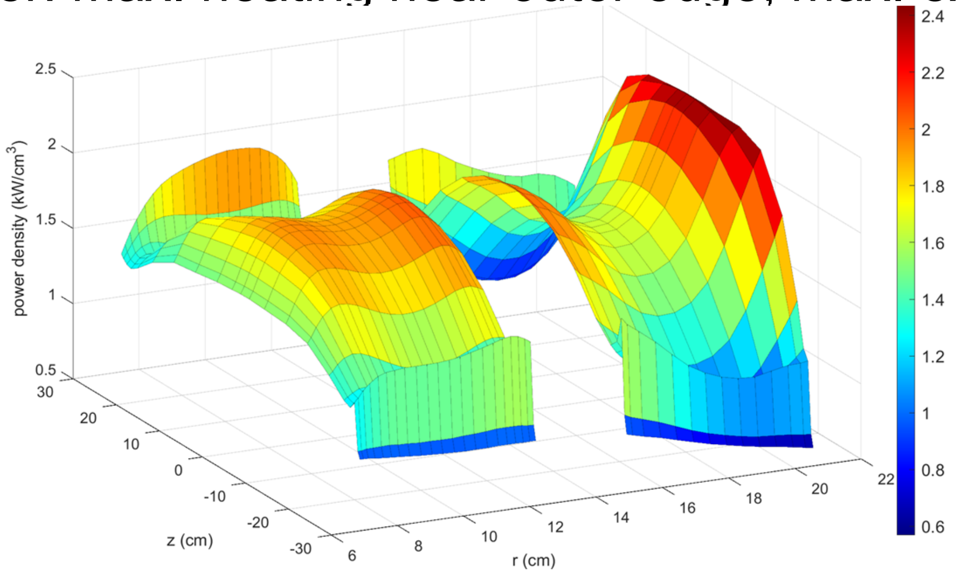
- LEU LD optimized U_3Si_2-Al Model
  - Draft publication (ORNL/TM-2021/2204) complete, currently in ORNL's publication approval process
  - Inputs (see misc. table right), model, and therefore all model results are preliminary
  - Parametric analysis shows limiting axial location (example figure right, SBLOCA @OFE)

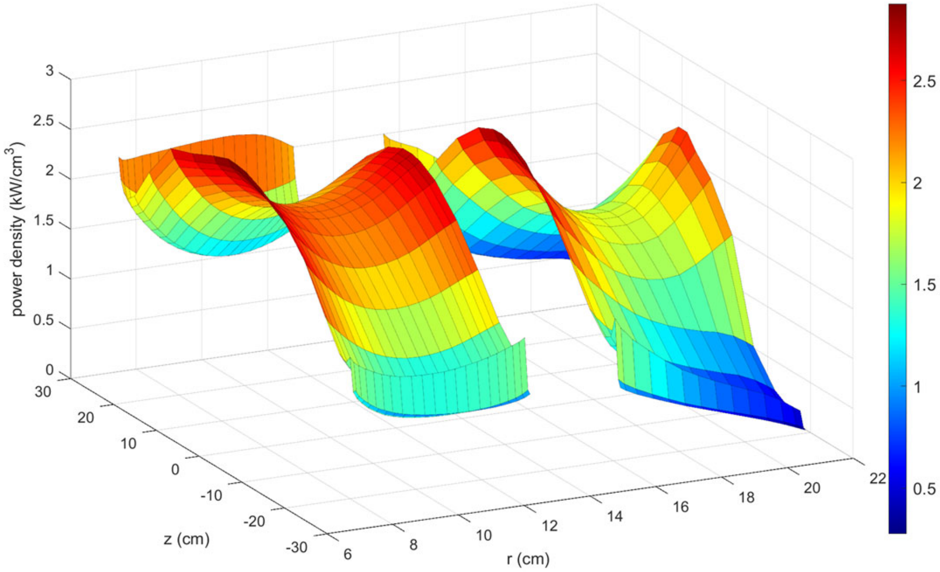


- LEU HD optimized U_3Si_2-Al Model
  - Preliminary reactor physics inputs are available for incorporation
  - Publication (ORNL/TM-2022/2396) to be submitted in 2022

LEU LD Optimized U_3Si_2-Al vs HEU: Heat Deposition

- BOC (left, fuel power densities) limiting radial locations near radial inner edge
- EOC (right) limiting radial locations differ: max. heating near outer edge, max. exit heat flux near inner edge
- Increase in LEU BOC IFE heat deposition fraction appears notable



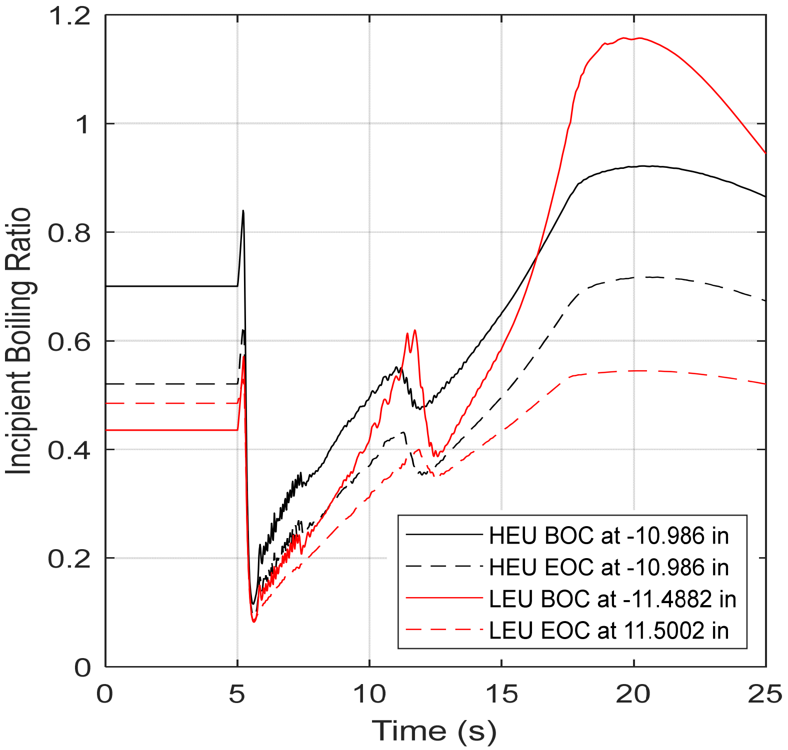


Region	Percent of Total Power			
	HEU		LEU	
	BOC	EOC	BOC	EOC
Inner Fuel Element	36.0%	31.5%	38.7%	32.8%
Outer Fuel Element	58.2%	62.0%	56.8%	61.9%
Fuel	94.2%	93.6%	95.5%	94.7%
Non-Fuel	5.6%	6.4%	4.5%	5.3%

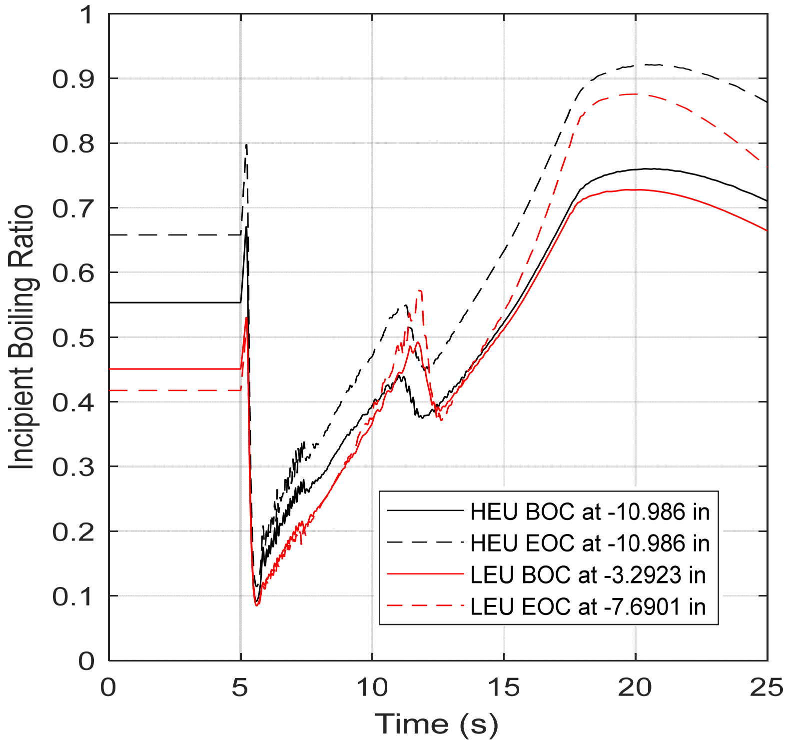
LEU LD Optimized U_3Si_2-Al vs HEU: Worst-case SBLOCA

- Small-break LOCA defined as break size that does not result in fuel damage
- Parameter: Incipient Boiling (IB) ratio, applicable low vel. (e.g. pony motor flow)

- IFE (left) LEU values at BOC at IB>1.0
- OFE and IFE EOC bounded by HEU results and above channel exit



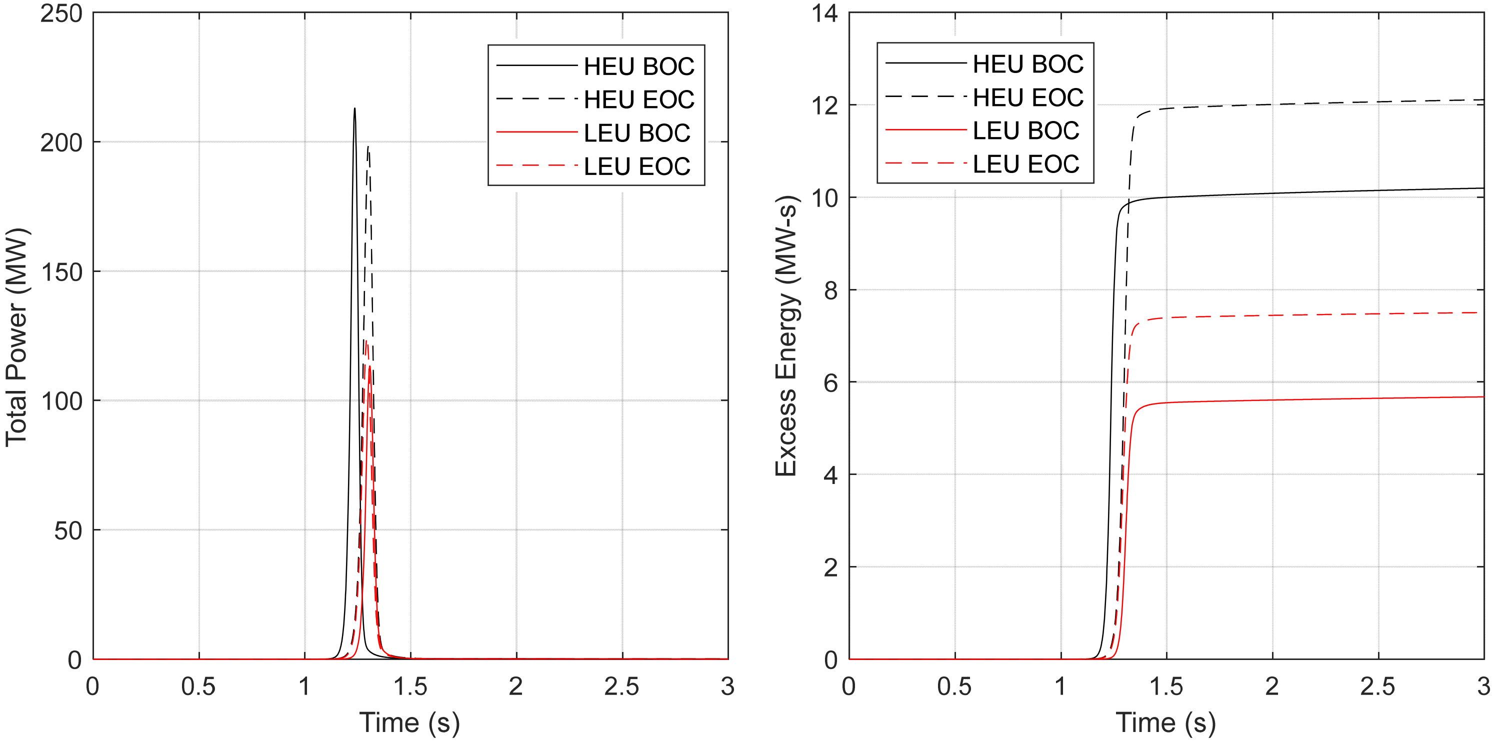
IFE



OFE

LEU LD Optimized U_3Si_2-Al vs HEU: Control Cylinder Ejection

- Control cylinder ejection is the bounding limiting frequency event in the reactivity-initiation accident transient category
- Parameters: Peak Power & Excess Energy
- LEU design shows significant improvement, as driven primarily by ^{238}U Doppler broadening



LEU LD Optimized U_3Si_2-Al vs HEU: Results Summary

- Comparison cases generated for 5 accident transients
  - Three primary coolant accidents (SBLOCA, LOOP, and ATWS LOOP)
  - Two reactivity-initiated accidents (RIA) (CCE & Optimum Void)
- RIA results show LEU silicide designs provide improvement in safety margins
- BOC IFE: there is a notable loss in minimum thermal margin in hot channels
- Overall nominal channels lose thermal margin

Hot channel heat flux ratios

	Time	IFE			OFE		
		LOOP[1]	SBLOCA[1]	ATWS LOOP[2]	LOOP[1]	SBLOCA[1]	ATWS LOOP[2]
HEU	BOC	0.539	0.922	0.490	0.430	0.760	0.484
	EOC	0.413	0.717	0.468	0.524	0.921	0.654
LEU	BOC	0.483	1.158	0.922	0.411	0.728	0.428
	EOC	0.385	0.545	0.166	0.418	0.876	0.269
Δ%	BOC	-5.6%	**23.6%**	**43.2%**	-1.9%	-3.2%	-5.6%
L-H	EOC	-2.8%	-17.2%	-30.2%	-10.6%	-4.5%	-38.5%

[1] Heat flux ratio for LOOP and SBLOCA is the MFIBHF during pony motor flow

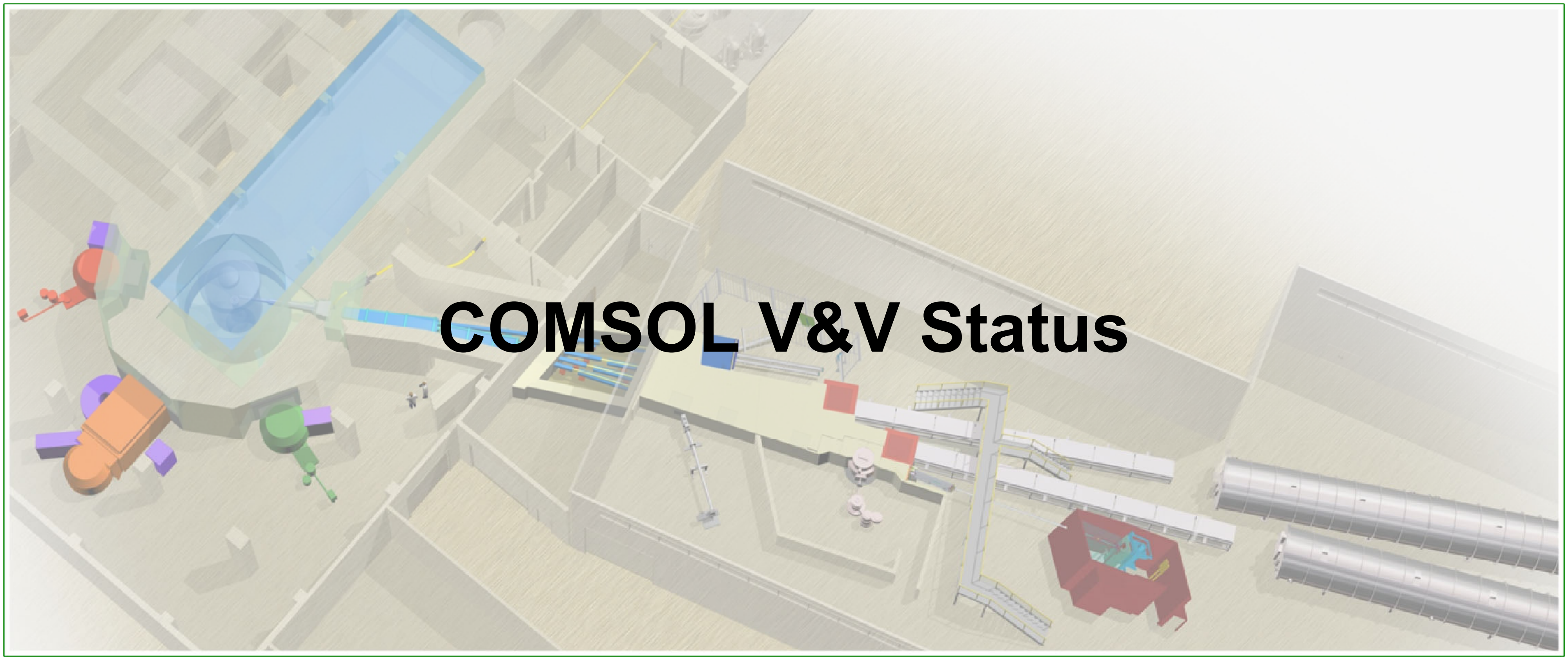
[2] Heat flux ratio for ATWS LOOP is the maximum Costa flow excursion heat flux ratio

Power excursion parameters

	Time	Peak Power (MW)		Excess Energy (MW-s)	
		CCE	Optimum Void	CCE	Optimum Void
HEU	BOC	213.031	320.677	10.336	22.905
	EOC	198.878	311.185	12.231	23.858
LEU	BOC	113.340	241.844	5.764	18.353
	EOC	124.162	239.413	7.577	18.805
Δ%	BOC	-47%	-25%	-44%	-20%
(L-H)/H	EOC	-38%	-23%	-38%	-21%

Nominal channel heat flux ratios

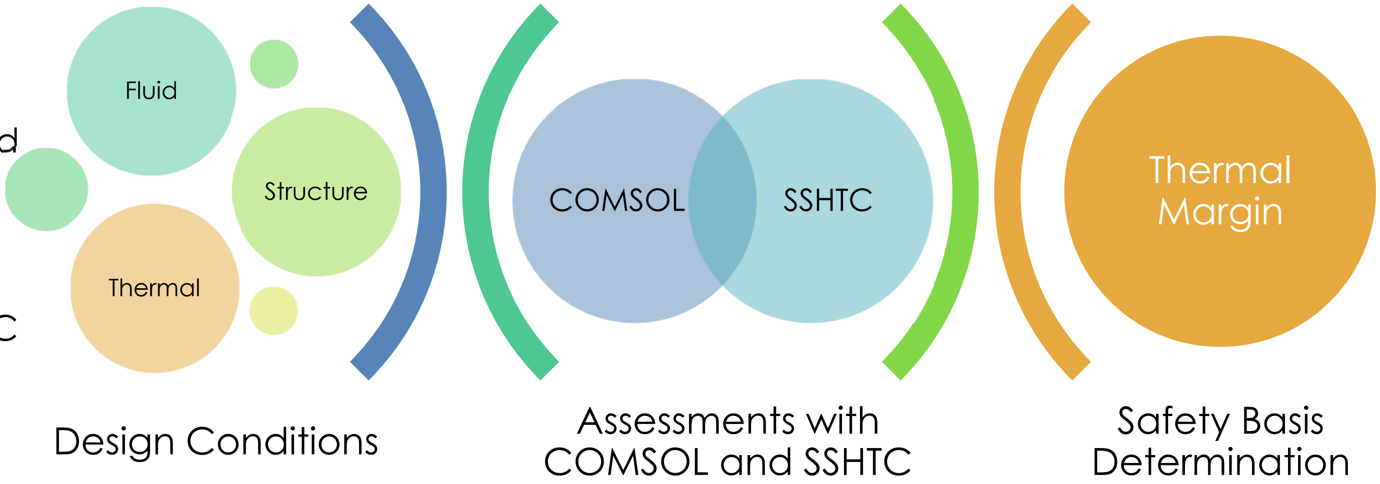
	Time	IFE			OFE		
		LOOP	SBLOCA	ATWS LOOP	LOOP	SBLOCA	ATWS LOOP
HEU	BOC	0.140	0.203	0.349	0.130	0.188	0.325
	EOC	0.113	0.163	0.293	0.118	0.170	0.305
LEU	BOC	0.174	0.260	0.368	0.148	0.218	0.313
	EOC	0.137	0.203	0.309	0.139	0.205	0.312
Δ%	BOC	3.4%	5.7%	1.9%	1.8%	3.0%	-1.2%
L-H	EOC	2.4%	4.0%	1.6%	2.1%	3.5%	0.7%



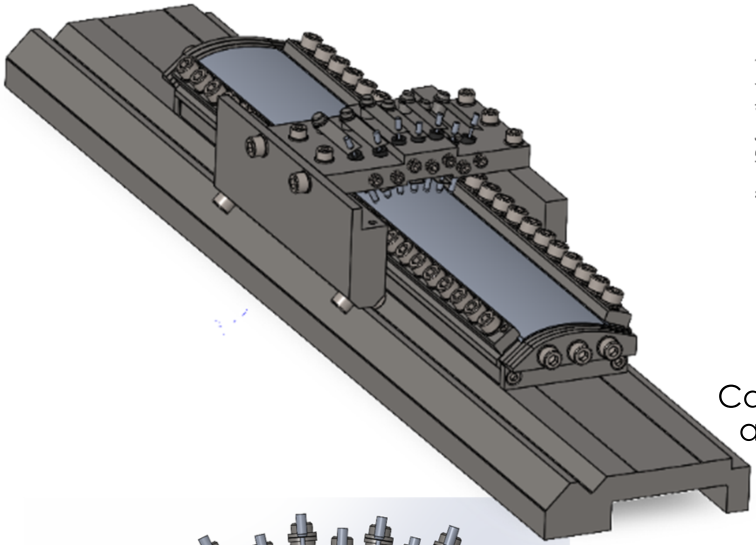
COMSOL V&V Status

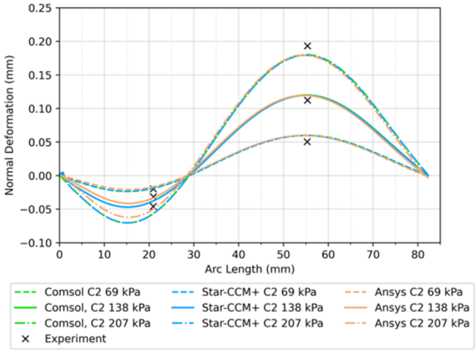
Purpose of V&V COMSOL for use in LEU conversion

- The Steady State Heat Transfer Code (SSHTC) evaluates steady state thermal hydraulic core conditions to define TSR safety limits and limiting control settings.
- COMSOL for the same purpose can reduce unnecessary analysis conservatisms and increase reported safety margins.
  - Provides detailed solutions.
  - Allows for the simulation of additional physics that the SSHTC does not.
  - Increases design space with the potential to reduce design complexity.
- Verification and Validation (V&V) of COMSOL provides the regulator with assurance that the code can accurately predict HFIR Safety Basis Conditions.

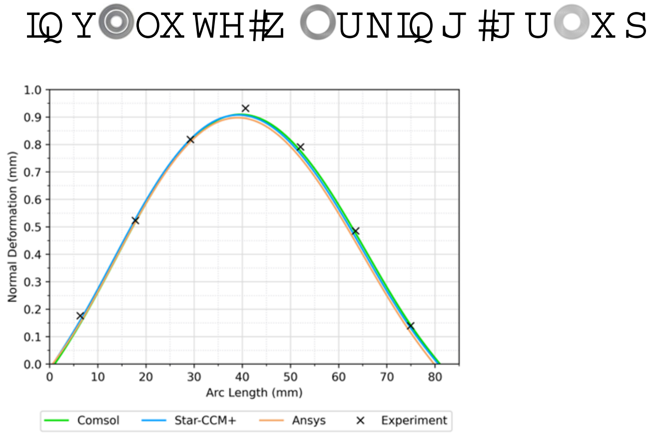


V&V Results for the Cheverton-Kelley Benchmark

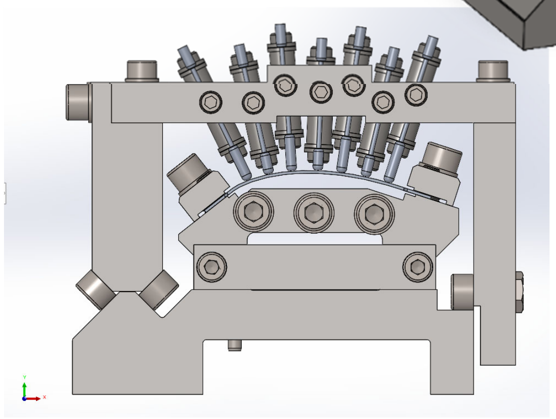


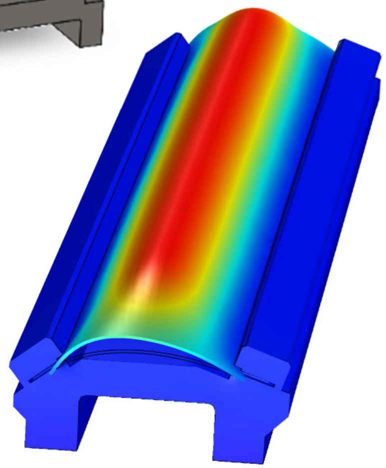


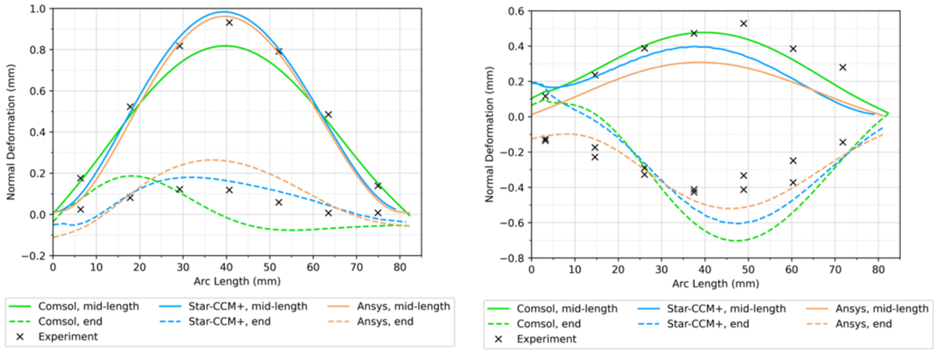
Case 2 results: normal displacements at the mid-length of the fuel plate.



Case 5 results: normal displacements at the mid-length of the plate.



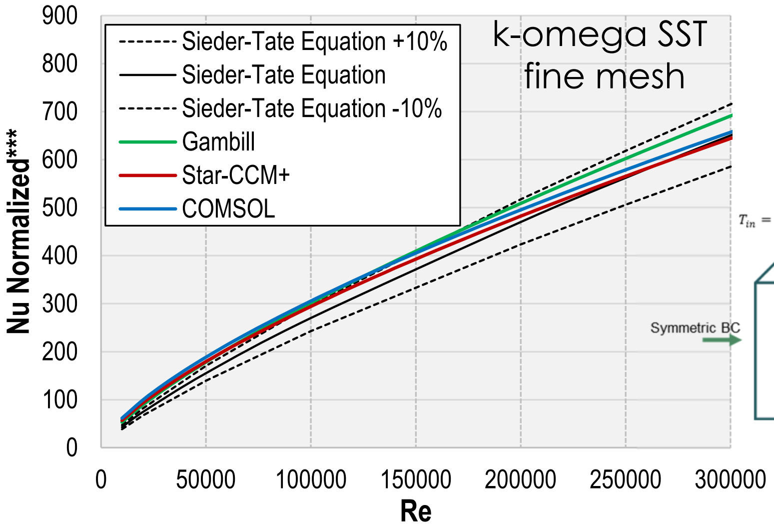


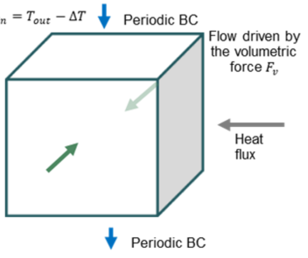


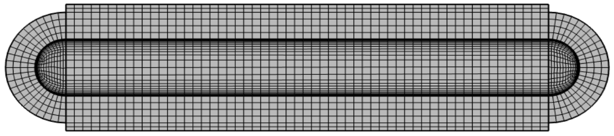
Case 6-7 results: normal displacements at the ends, and the mid-length of the plate mounted in (a) solid, and (b) split base.

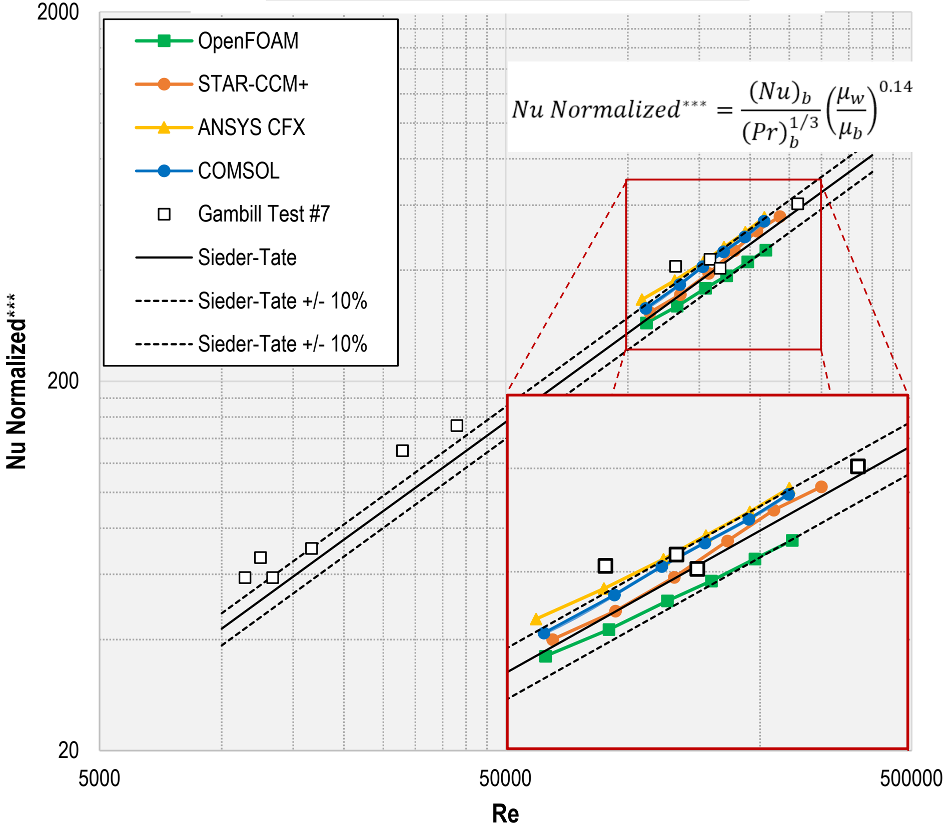
Journal manuscript in preparation to elevate the C-K problem as an international benchmark

V&V Results for the Gambill-Bundy Benchmark

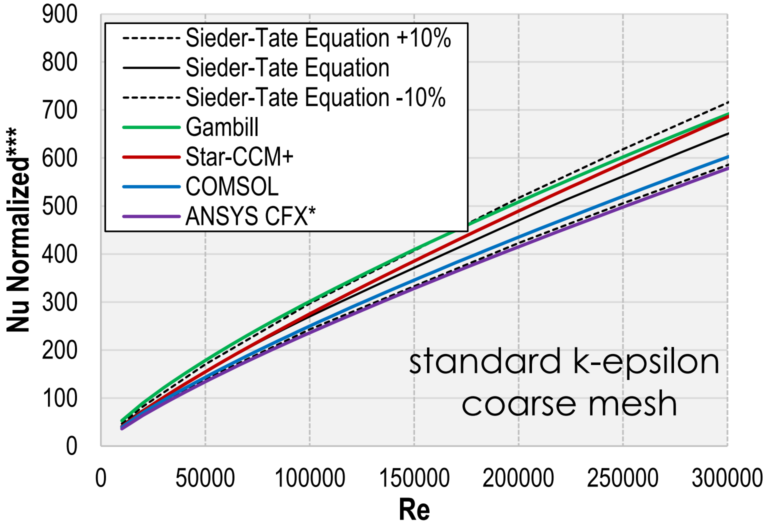






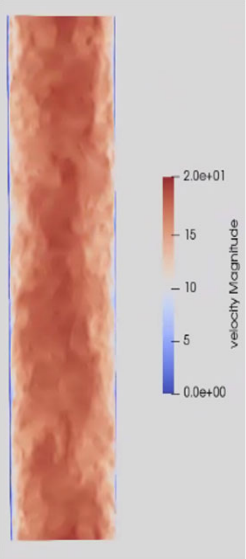


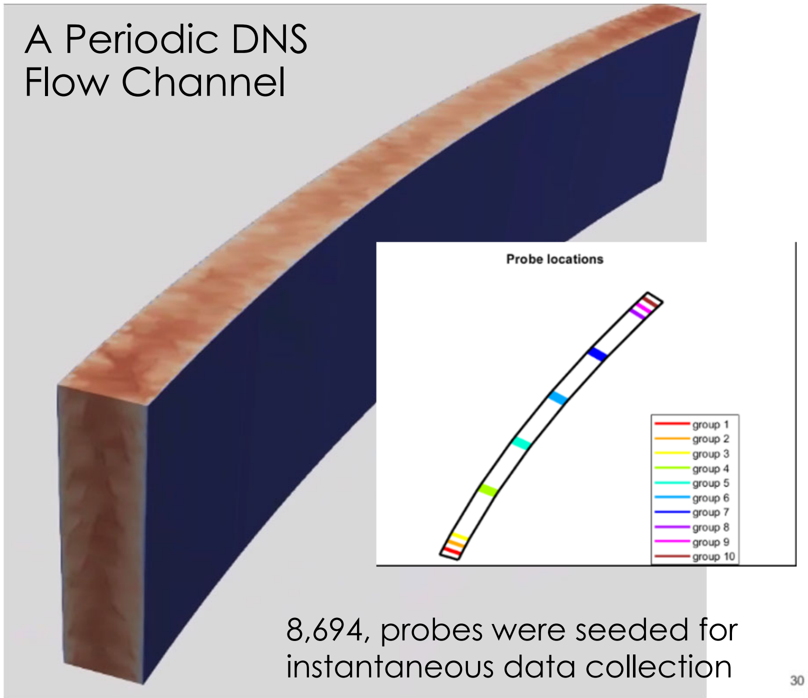
$$Nu\ Normalized^{***} = \frac{(Nu)_b}{(Pr)_b^{1/3}} \left(\frac{\mu_w}{\mu_b}\right)^{0.14}$$



COMSOL results are in an excellent agreement with the other CFD codes and the experimental data.

DNS Results for the HFIR Flow Central Subchannel

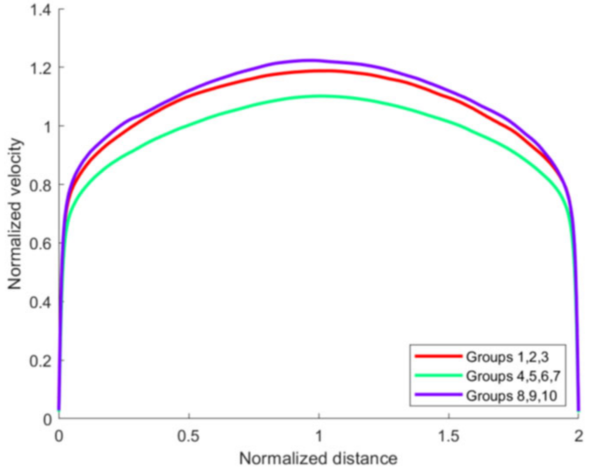



A Periodic DNS Flow Channel

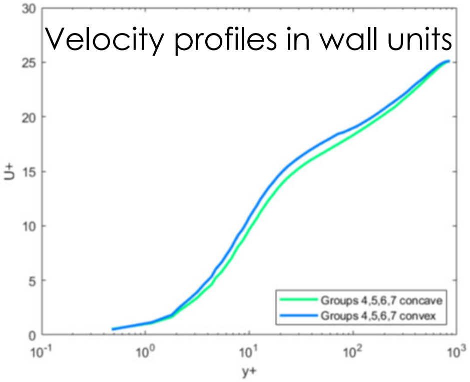
8,694, probes were seeded for instantaneous data collection

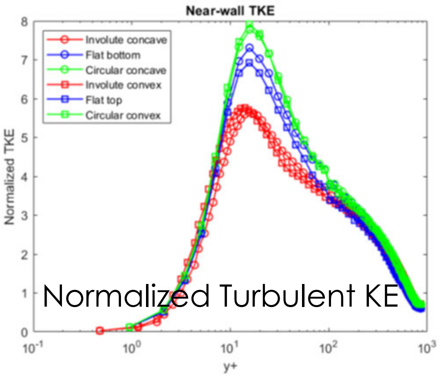
IQ Y◎OX WH#Z ○UNIQ J #J U○X S

Aggregate mean velocity plot. Groups 1, 2, and 3 are at the lower curvature side, and groups 8, 9, and 10 are on the high curvature side of domain. Central groups are 4, 5, 6, and 7.

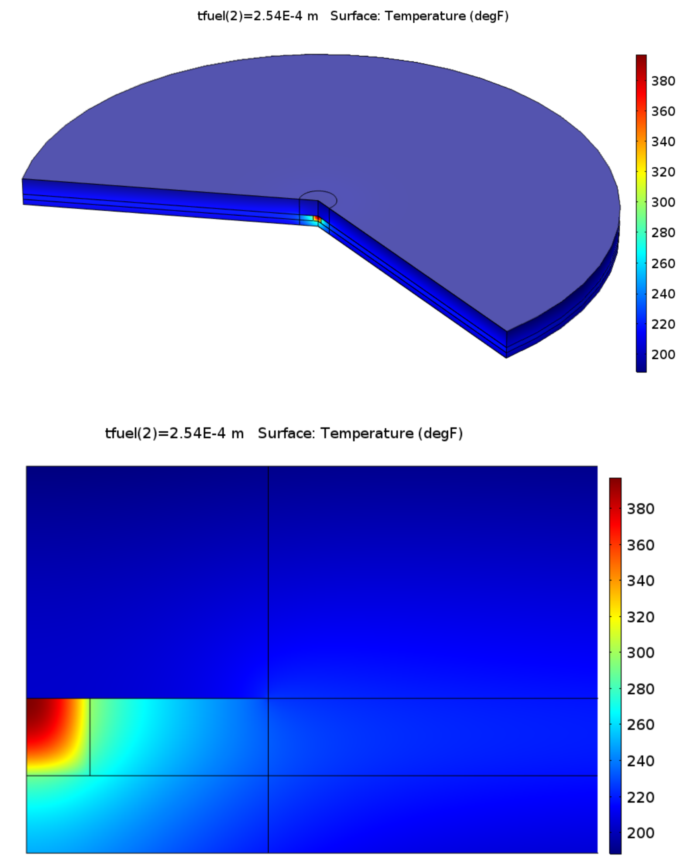


- Stable solution was produced during several (>20) flow residence times
- Mesh size: 3.2 billion elements
- Runs on HPC platform CORI on 16,384 processes
- Right: entire flow domain, flow from top to bottom
- Left: vertical central cross section

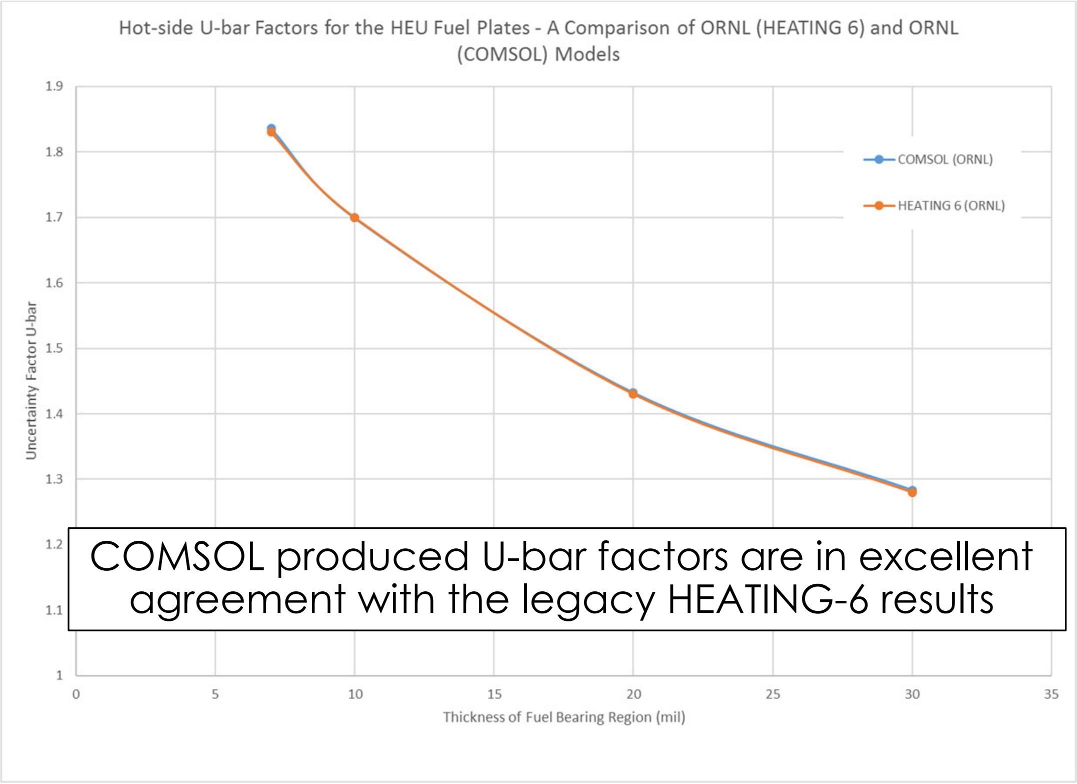

Velocity profiles in wall units


Normalized Turbulent KE

COMSOL Hot Spot Modeling for the HEU and LEU Silicide Fuel

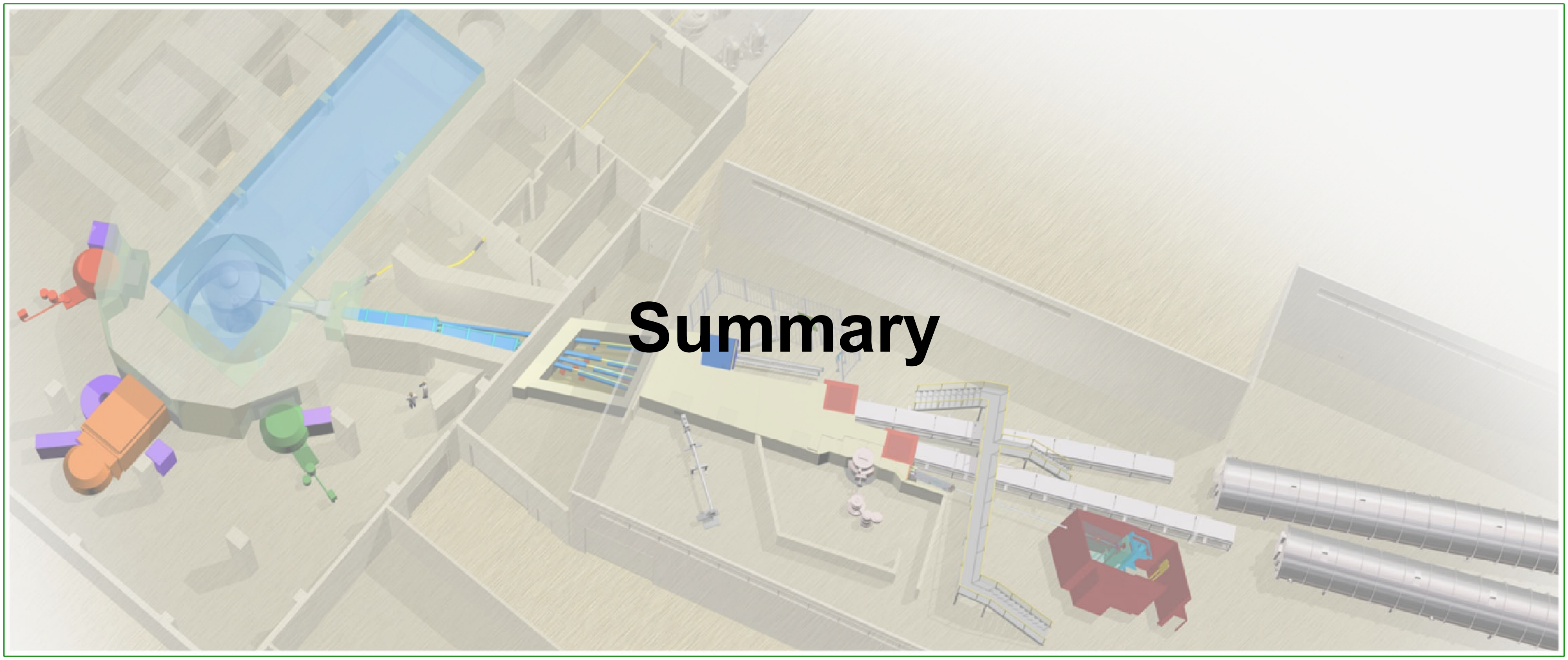


85 MW HEU Hot Spot COMSOL Model



COMSOL produced U-bar factors are in excellent agreement with the legacy HEATING-6 results

Hot-Spot models for the LEU Silicide fuel are currently being developed in COMSOL Multiphysics



Summary

Technical Papers issued in FY22

PHYSOR Reactor Physics, ANS/ATH DNS paper, DNS Letter Report

PHYSOR

Reactor Physics Characteristics of High Flux Isotope Reactor Core Designs with Low-Enriched Uranium Fuels

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space for DOI

ABSTRACT

Ongoing efforts to convert the High Flux Isotope Reactor from highly enriched uranium (HEU) to low-enriched uranium (LEU) fuel are focused on refining the design characteristics and reactor physics analyses of selected candidate fuel designs with a silicide dispersion fuel. In design optimization studies, designs are assessed for key performance and safety metrics. As the designs are further refined, reactor physics metrics are generated for additional supporting analyses such as transient simulations. Current high-fidelity tool sets are extended to support the rapid generation of these characteristics in such a way that allows candidate designs to progress further along in the design process. Development of this workflow is critical to ensuring a quick response to future experimental outcomes on potential fuel designs. Relative to the HEU design, the increase in ^{238}U in candidate LEU fuel designs hardens the neutron spectrum, driving a shorter neutron generation time and reducing the reactivity impact from coolant density changes. However, increased resonance absorption in the fuel drives a more negative fuel temperature feedback coefficient as compared to the HEU design. The addition of molybdenum in the uranium-molybdenum candidate LEU fuel hardens the spectrum further; the silicide-fueled candidate design represents a more incremental change from the current HEU fuel design. Despite the changes in these reactor physics parameters, the fuel designs are still expected to perform safely throughout additional reactor analyses.

KEYWORDS: High Flux Isotope Reactor, low-enriched uranium, conversion, core design, high-fidelity modeling

1. INTRODUCTION

The Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR) is a high power density research reactor currently operating at 85 MWth [1]. HFIR supports a variety of scientific missions, including cold and thermal neutron scattering science, isotope production, and materials irradiation. Efforts to convert the current highly enriched uranium (HEU)–fueled core to low-enriched uranium (LEU) have incorporated

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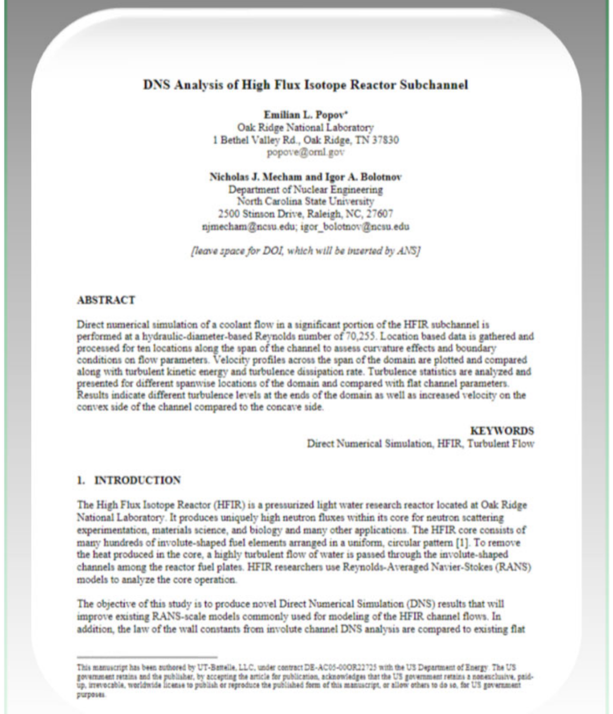
ANS / ATH Direct Numerical Simulation (DNS)



DNS Analysis of High Flux Isotope Reactor Subchannel

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ABSTRACT

Direct numerical simulation of a coolant flow in a significant portion of the HFIR subchannel is performed at a hydraulic-diameter-based Reynolds number of 70,255. Location based data is gathered and processed for ten locations along the span of the channel to assess curvature effects and boundary conditions on flow parameters. Velocity profiles across the span of the domain are plotted and compared along with turbulent kinetic energy and turbulence dissipation rate. Turbulence statistics are analyzed and presented for different spanwise locations of the domain and compared with flat channel parameters. Results indicate different turbulence levels at the ends of the domain as well as increased velocity on the convex side of the channel compared to the concave side.

KEYWORDS
Direct Numerical Simulation, HFIR, Turbulent Flow

1. INTRODUCTION

The High Flux Isotope Reactor (HFIR) is a pressurized light water research reactor located at Oak Ridge National Laboratory. It produces uniquely high neutron fluxes within its core for neutron scattering experimentation, materials science, and biology and many other applications. The HFIR core consists of many hundreds of involute-shaped fuel elements arranged in a uniform, circular pattern [1]. To remove the heat produced in the core, a highly turbulent flow of water is passed through the involute-shaped channels among the reactor fuel plates. HFIR researchers use Reynolds-Averaged Navier-Stokes (RANS) models to analyze the core operation.

The objective of this study is to produce novel Direct Numerical Simulation (DNS) results that will improve existing RANS-scale models commonly used for modeling of the HFIR channel flows. In addition, the law of the wall constants from involute channel DNS analysis are compared to existing flat

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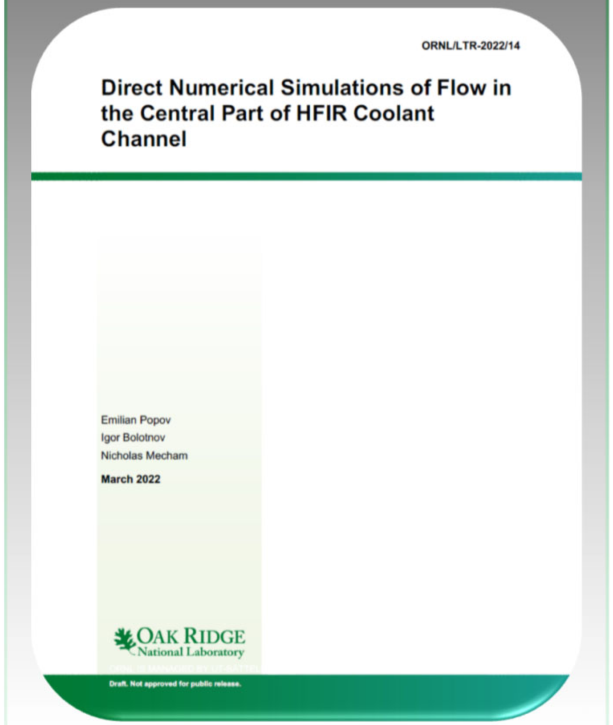
ORNL/LTR-2022/14, DNS Letter Report



ORNL/LTR-2022/14

Direct Numerical Simulations of Flow in the Central Part of HFIR Coolant Channel

Emilian Popov
Igor Bolotnov
Nicholas Mecham

March 2022

Oak Ridge National Laboratory

Draft. Not approved for public release.

Technical Papers co-authored in FY22

HFIR Silicide Fuel Qualification Plan, Updates from the Involute Working Group

HFIR Silicide Fuel Qualification Plan

INL/EXT-21-63534

High Flux Isotope Reactor: Silicide Fuel Qualification Plan

February 2022

Project 25228

Carla Miller, Tamara Shokes, and James I. Cole
Idaho National Laboratory

Carol Sizemore and David Cook
Oak Ridge National Laboratory

Laura Jamison and David Jaluvka
Argonne National Laboratory

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IWG RRFM 2022 Updates

UPDATES FROM THE INVOLUTE WORKING GROUP

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ABSTRACT

The High Flux Isotope Reactor, High Flux Reactor, and Research Neutron Source Heinz Maier-Leibnitz reactors represent a particular class of research and test reactors that provide some of the most intense and continuous neutron fluxes for science, industry, and medical applications. These high-performance reactors have achieved compact cores by operating with highly enriched uranium (HEU) fuel ($^{235}U/U \geq 20$ wt %) and using fuel plates curved as an involute. Because of the proliferation risks, the international community aims to reduce or eliminate, when possible, the use of HEU fuel in civilian facilities by converting them to a low-enriched uranium (LEU) fuel ($^{235}U/U < 20$ wt %). Converting these reactors without significantly compromising their performance or safety is a challenging endeavour that can tremendously benefit from advanced computational tools and thus eliminate unnecessary conservatism to ensure sufficient thermal margins. Therefore, models are being developed via modern computational fluid dynamics and computational structural mechanics software to evaluate the steady-state safety margins of various LEU designs instead of relying on more traditional, conservative methods. To gain the confidence and acceptance of high-fidelity modelling by nuclear regulators, Argonne National Laboratory and the involute reactors have formed an informal scientific group: the Involute Working Group (IWG). The IWG facilitates interorganizational collaboration on experimental benchmarking, code-to-code comparisons, and verification and validation. This paper describes some of the recent IWG efforts in validating software against the existing experimental data, as well as code-to-code comparisons of different software that the IWG members use.

1. Introduction

Three research reactors have fuel plates curved as a circle involute (i.e., a spiral generated around a circle):

- the Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR) located in Oak Ridge, Tennessee, USA [1],

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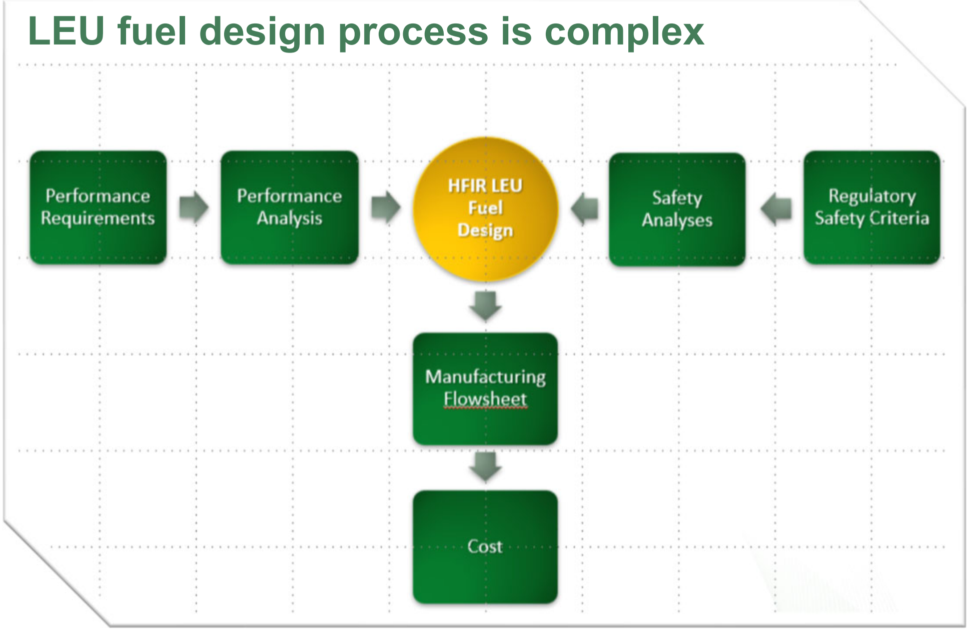
HFIR LEU Fuel Type and Design Down-Selection

Must be a balanced, multivariate, quantitative process

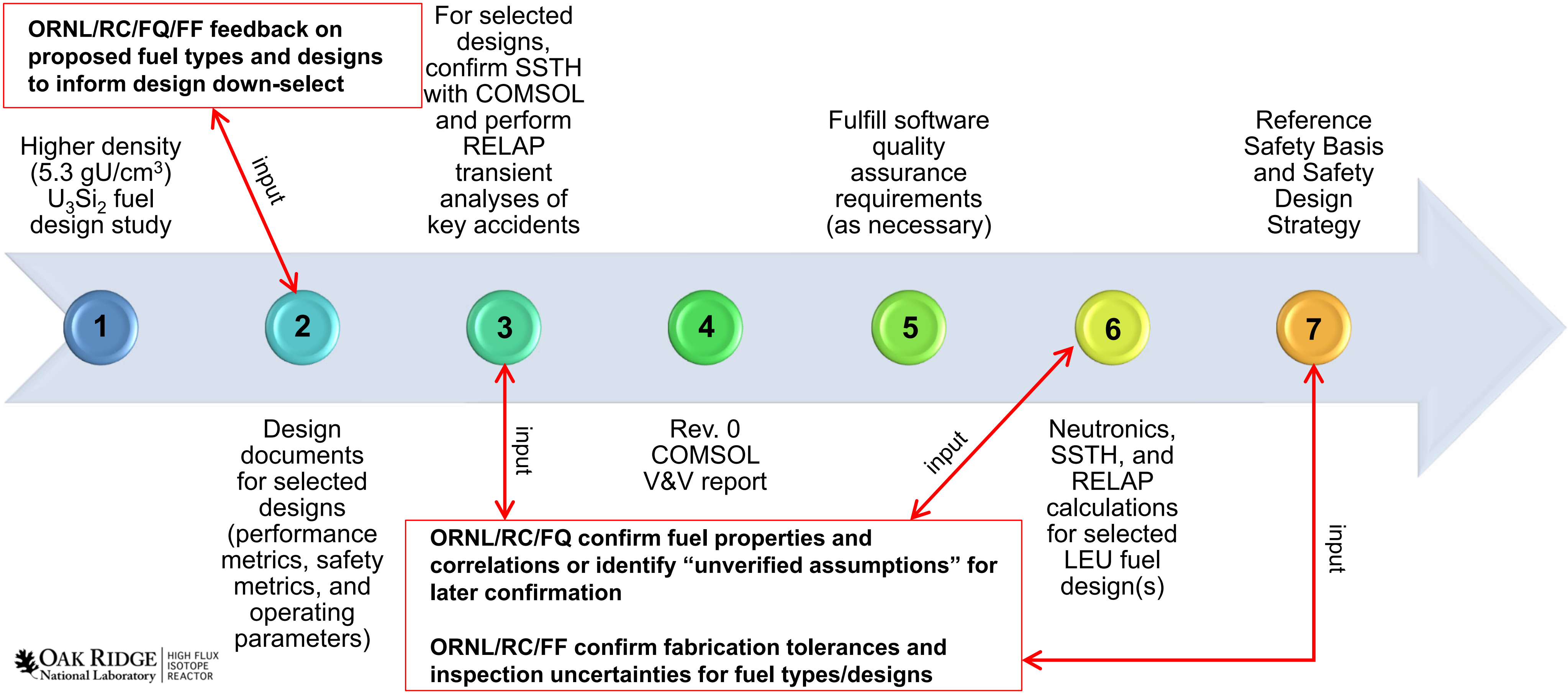
- Performance – ORNL calculates performance metrics
- Safety – ORNL calculates safety metrics
- Cost
  - FF estimates cost of manufacturing
    - Initial
      - R&D (e.g., contoured fuel zone, borated filler, Gd in filler, and centered-symmetric fuel zones)
      - Process equipment
    - Unit
  - FQ estimates cost of qualification
- Uranium utilization
  - ORNL calculates for fuel cycle
  - FF estimates yields for fuel manufacturing
- Time
  - For each fuel type, RC, FQ, FF, and CC create activities and ensure linkages to estimate time



LEU fuel design process is complex

Next Steps in Design Process

ORNL and pillars need to continue to work together to move forward



ORNL/RC/FQ/FF feedback on proposed fuel types and designs to inform design down-select

1. Higher density (5.3 gU/cm^3) U_3Si_2 fuel design study
2. Design documents for selected designs (performance metrics, safety metrics, and operating parameters)
3. For selected designs, confirm SSTH with COMSOL and perform RELAP transient analyses of key accidents
4. Rev. 0 COMSOL V&V report
5. Fulfill software quality assurance requirements (as necessary)
6. Neutronics, SSTH, and RELAP calculations for selected LEU fuel design(s)
7. Reference Safety Basis and Safety Design Strategy

ORNL/RC/FQ confirm fuel properties and correlations or identify “unverified assumptions” for later confirmation

ORNL/RC/FF confirm fabrication tolerances and inspection uncertainties for fuel types/designs

Interfaces Between RC Analyses and FQ Qualification Testing

Key for successful conversion of HFIR

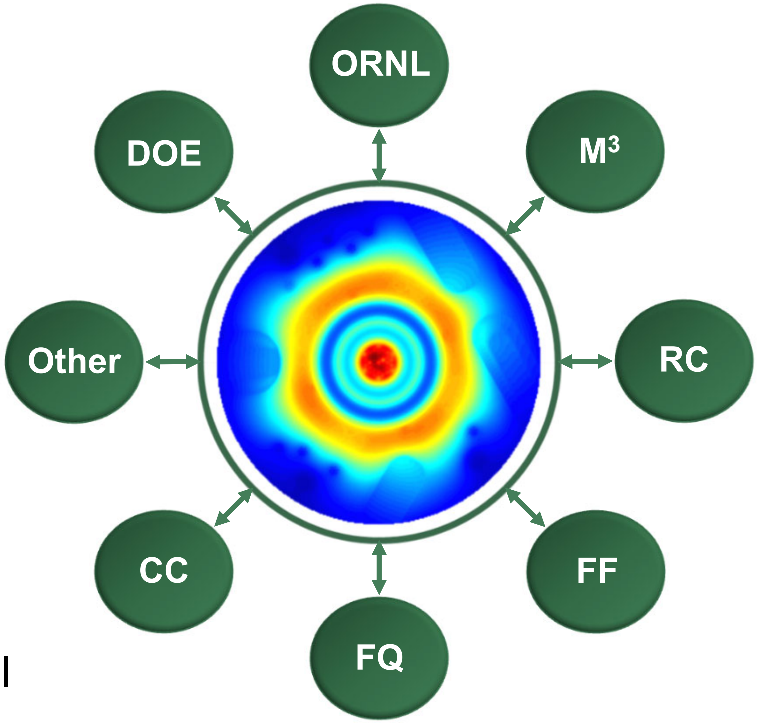
- RC/FQ interface methodology document should be developed to capture definitions, application of margins, meshes, process steps, and information control and account for uncertainties in
  - *fuel properties and correlations,*
  - *fuel manufacturing and inspection (interface with FF),*
  - *reactor performance and safety analyses,*
  - *experiment (fuel and conditions) design,*
  - *experiment conduct (planned vs. as-run), and*
  - *experiment PIE*

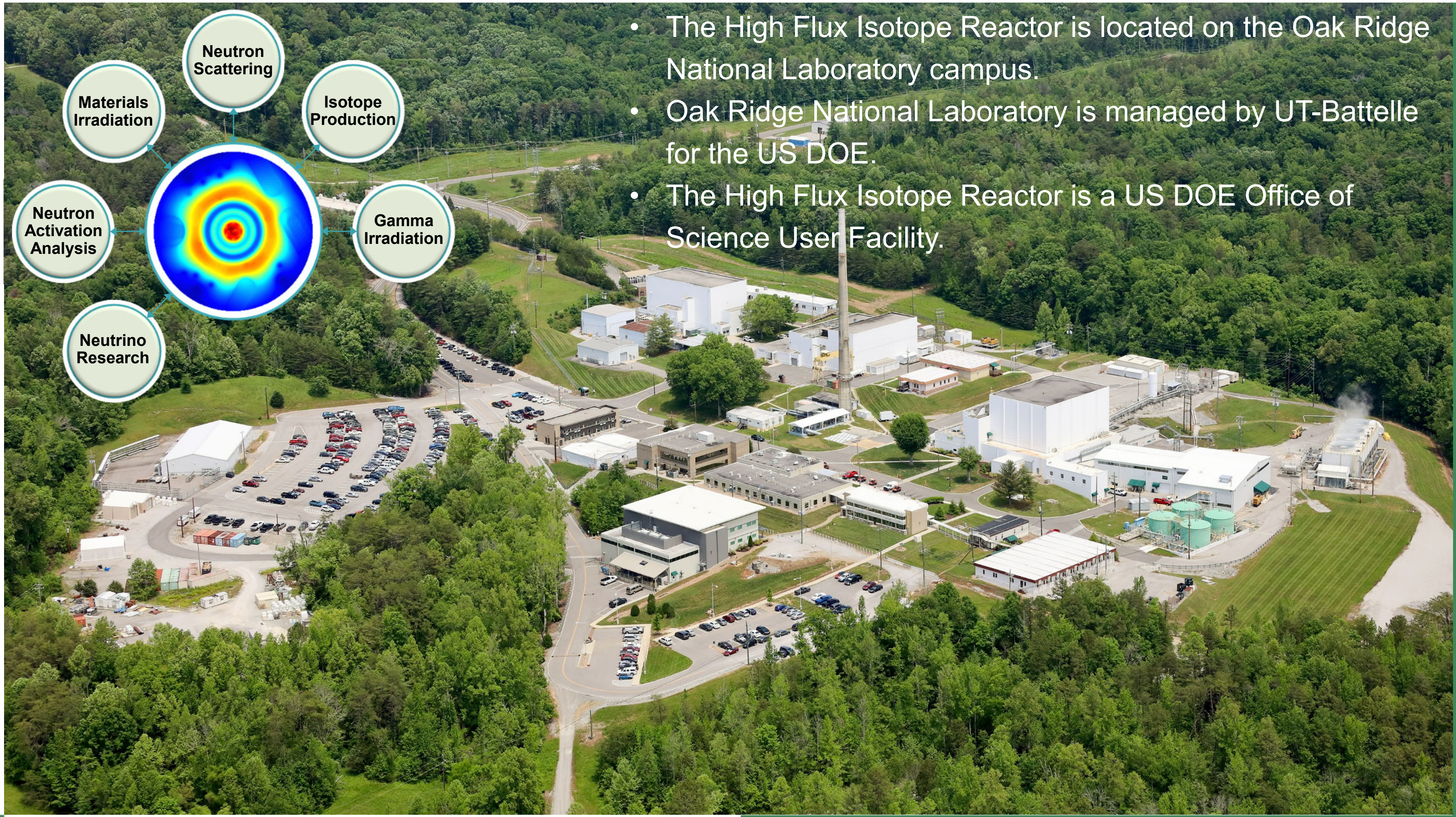
  in a well-defined, integrated, and consistent manner for both down-select and qualification testing for all five USHPRRs to support successful reactor conversions

ORNL, M^3, and Pillars Need to Continue to Work Together

Collaboration and communication are key for successful conversion of HFIR

- Complex fuel fabrication R&D and irradiation testing must be conducted to support down-selection
- Fuel down-selection process must be balanced, multivariate, and quantitative
- Cost of fuel must be understood and managed
- Quality of fuel, fuel qualification report, and SAR inputs must be assured to meet reactor operator and regulator requirements
- Code benchmarking data, fuel fabrication data, material properties data and correlations for LEU fuel types must be provided to support performance and safety analyses
- Program and technical documents need integration and control
- Research reactor operators and sponsors are stakeholders and end users





- The High Flux Isotope Reactor is located on the Oak Ridge National Laboratory campus.
- Oak Ridge National Laboratory is managed by UT-Battelle for the US DOE.
- The High Flux Isotope Reactor is a US DOE Office of Science User Facility.