NATIONAL INSTITUTE OF
STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

TRTR-IGORR– 2023 JOINT RESEARCH REACTOR CONFERENCE

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COLLEGE PARK, MARYLAND

NIST Neutron Source Preconceptual Design

This paper is dedicated to the memory of Robert E. Williams

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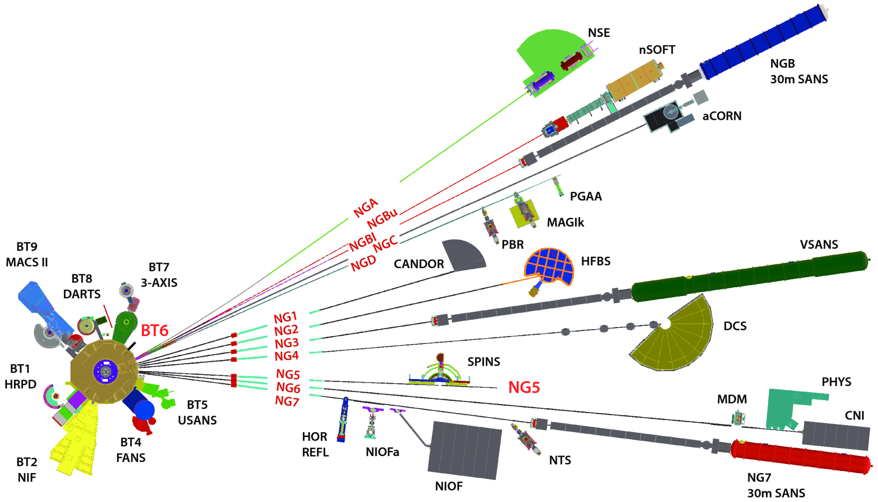
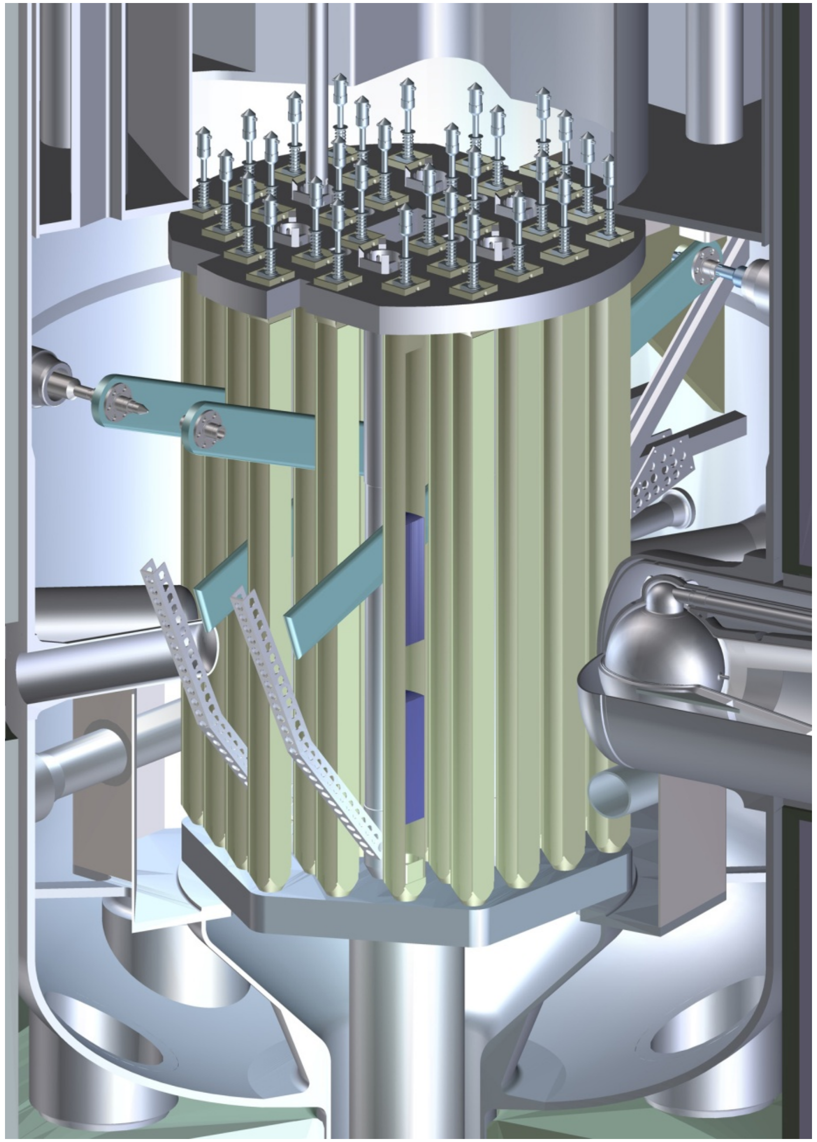
CENTER FOR
NEUTRON RESEARCH

Disclaimer

Introduction: NCNR & NBSR

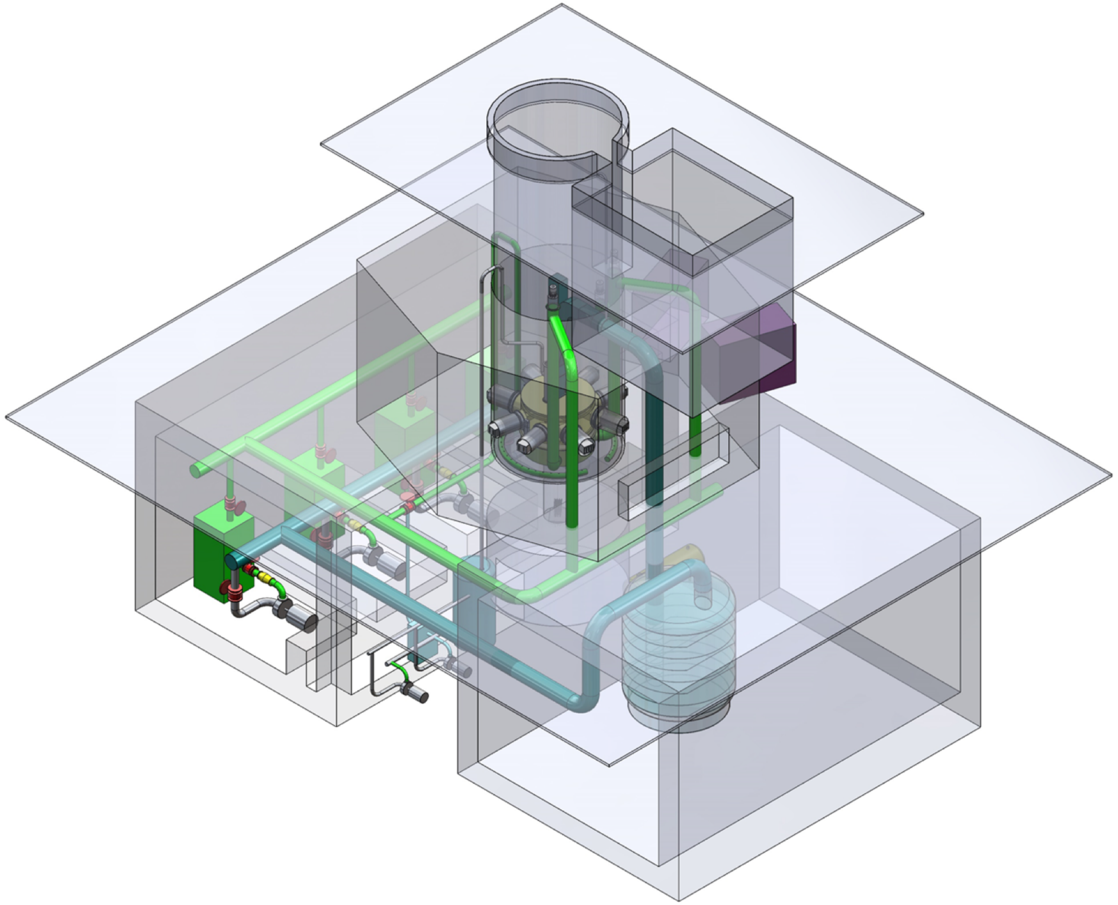
- NCNR is one of the USA primary resources for neutron research
- NBSR history of successful operation since 1967
- NBSR license to expire in 2029
- New NIST neutron source (NNS) is conceptualized
- Neutronics, Thermal Hydraulic, Beam Delivery and Facilities





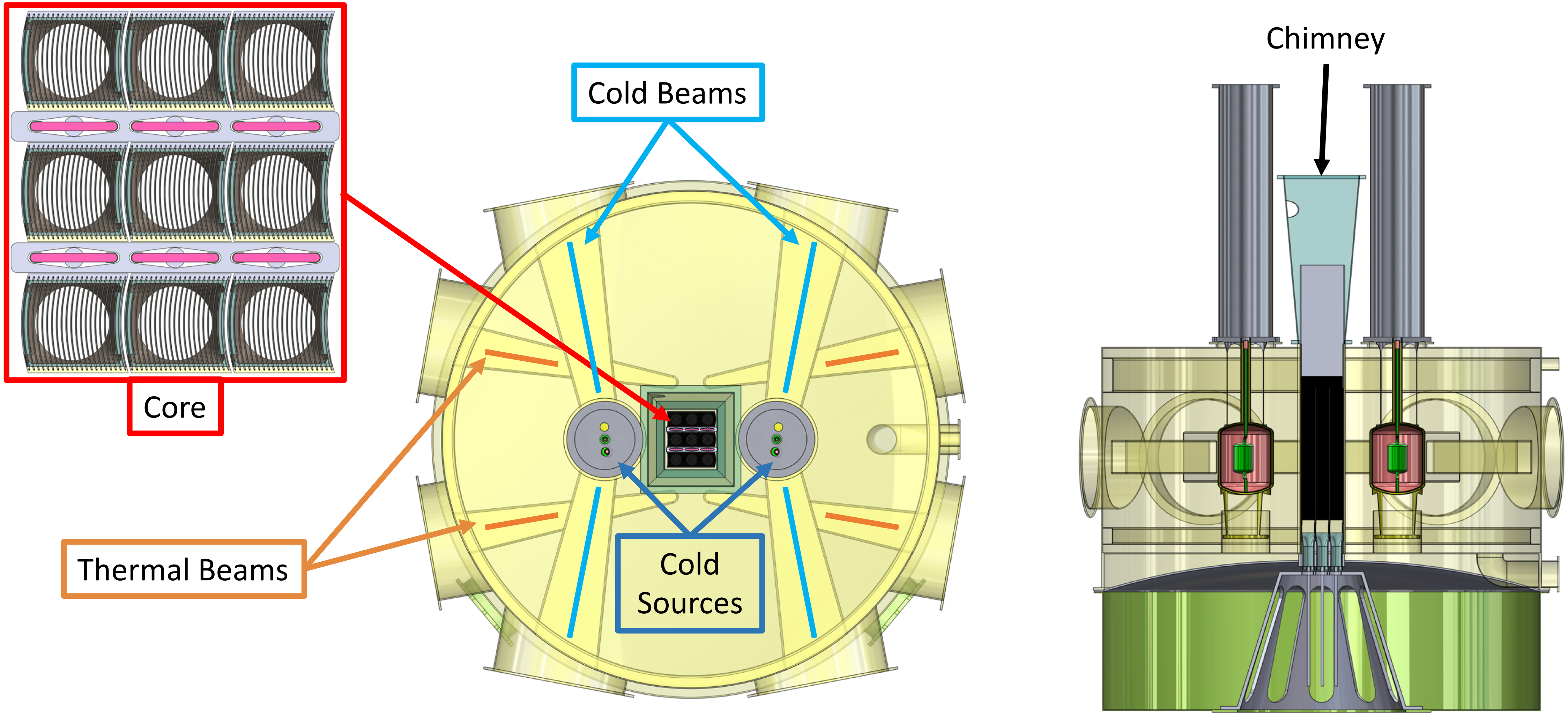
Design of NNS

- Influenced by several reactors designed for neutron science
- Nominal power of 20 MW
- U-10Mo LEU (or U3Si2)
- Light-water-cooled compact reactor core
- Surrounded by heavy-water in the reflector tank
- 2 Cold Neutron Sources
- 8 Thermal Neutron Beams
- 40 days operating cycle



Reactor Pool and Primary Coolant System

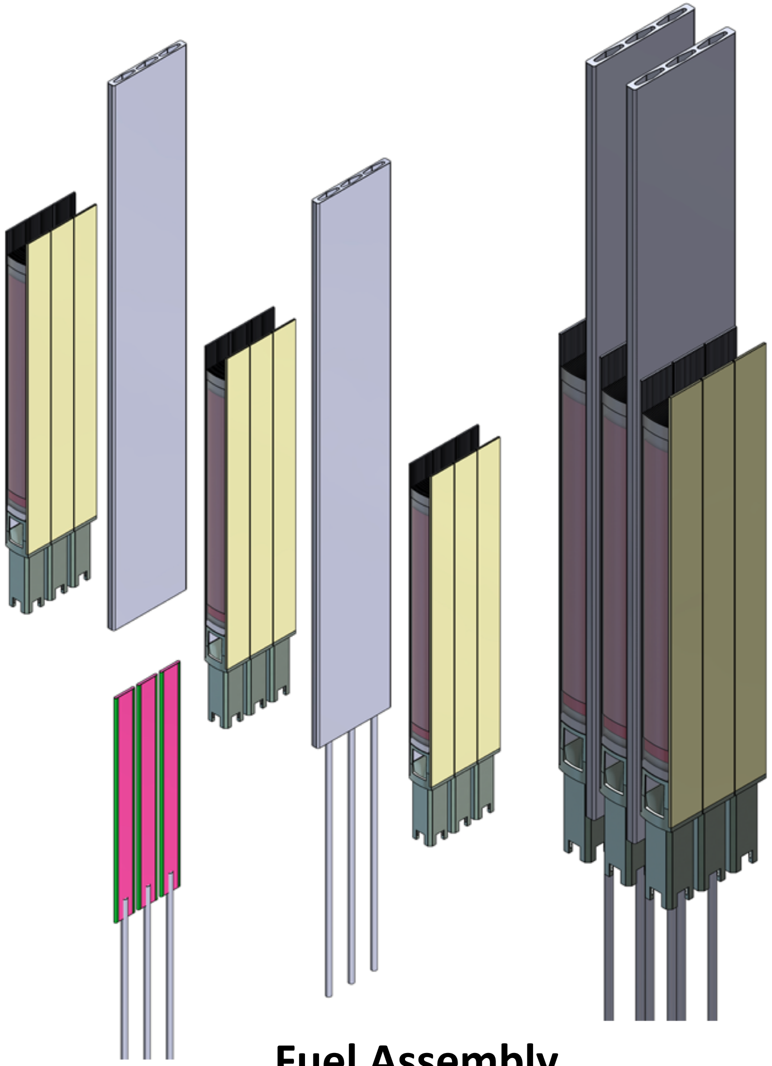
Design of NNS



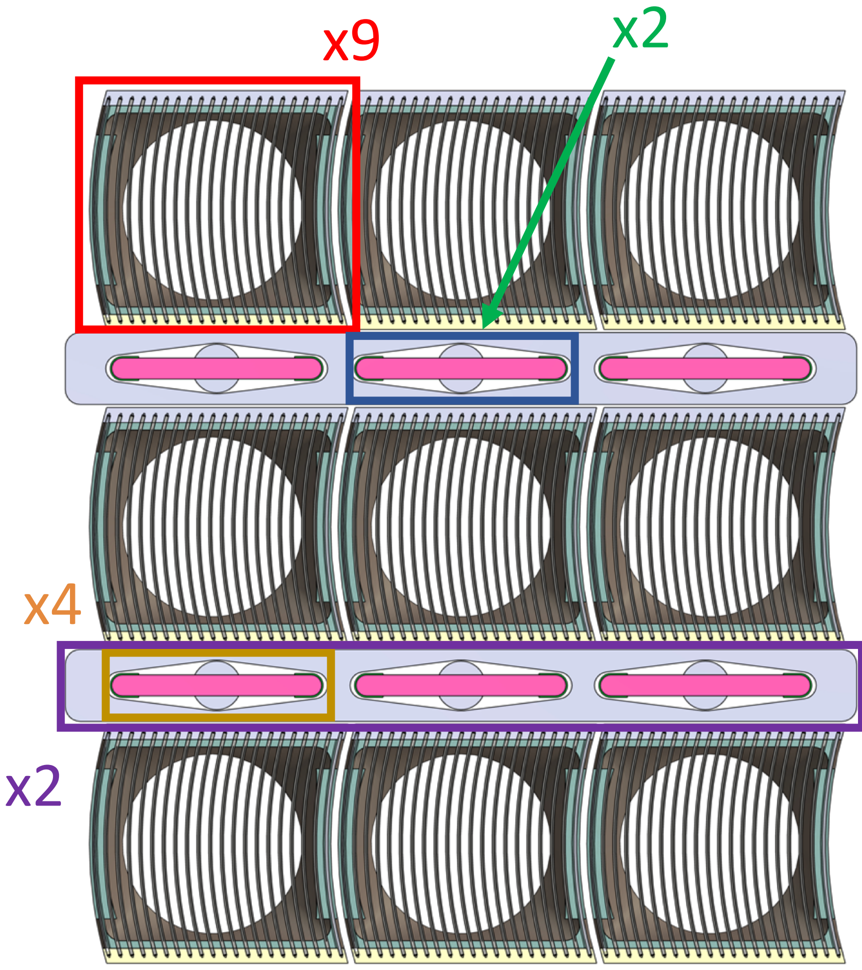
Reflector Tank with the core, cold sources, and beam tubes

Design of NNS

- Nine fuel assemblies (FA) in a 3x3 array
- Each FA contains 21 U-10Mo fuel plates
- 19.75% enriched Y-12 fuel wrapped with ~8 µm thick zirconium foil
- Four control blades and two safety blades placed in the center within two guide boxes
- Core horizontally divided into three rows
- 64 coolant channels at each row
- Optimize fuel cycle length & maintain a negative reactivity feedback

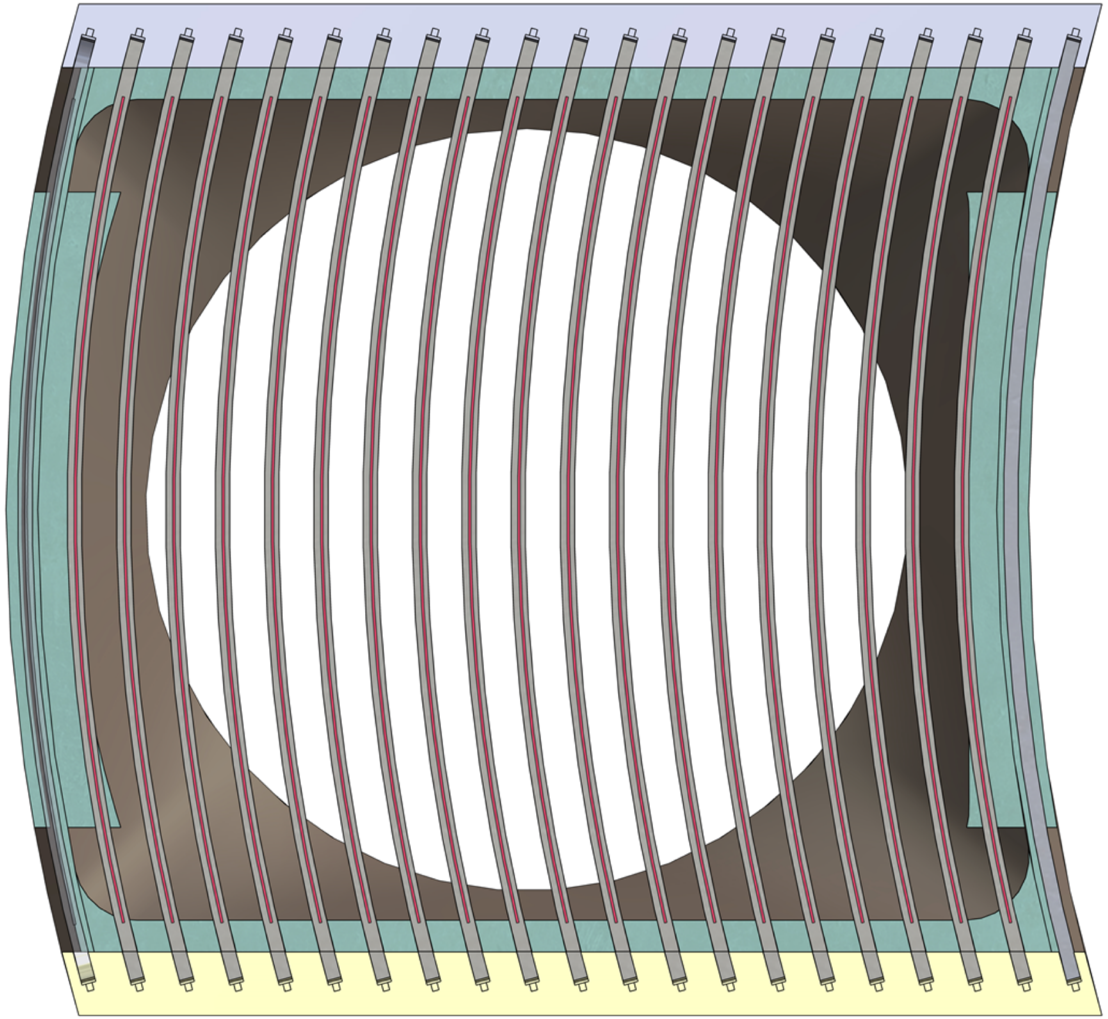


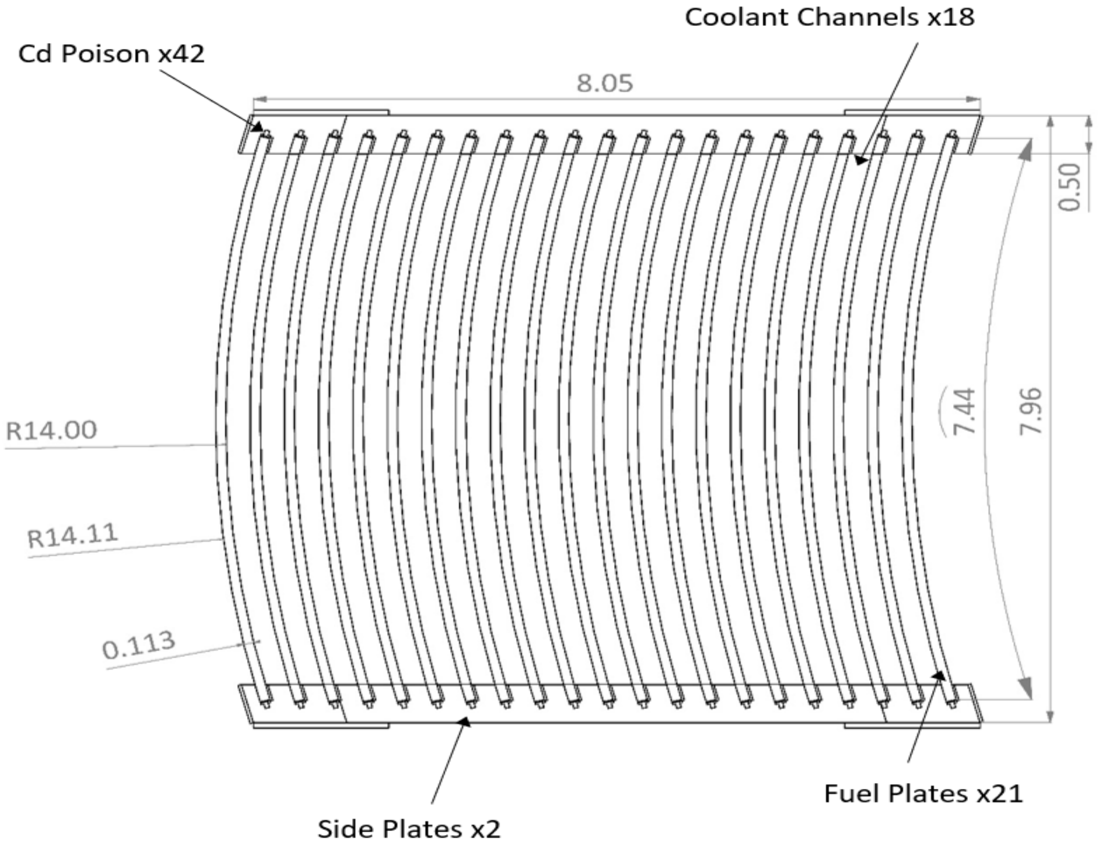
Fuel Assembly



Reactor Core

Design of NNS





Fuel Assembly

Nuclear Design of NNS

- The number of FAs for any core loading is 9
- The reactor has two independent and diverse shutdown systems.
  - Safety Blades
  - Reflector Dump system
- Designed as a high leakage core with a compact structure
- Neutronics analysis is performed via the Monte Carlo N-particle Code (MCNP) & ENDF/B VIII.0
- The thermal treatment of the materials has not been used
- Heavy water reflector tank under investigation, considering size, and/or other options, such as Be
- Burnable poison Cd-rods in fuel assemblies not optimized
- Core size, width/height not optimized for maximum cold source brightness
- Cold source size/locations not optimized for maximum brightness

Assumptions and Simplifications

Category	Assumption	Explanation
Geometric	Flat plates are modeled instead of curved plates.	This assumption is adopted for simplicity and it has been previously found successful in the analysis of the NBSR and other reactors [10]–[12]. Note that the same moderator-to-fuel ratio is maintained even with this assumption.
	Multiple structural components are neglected for simplicity.	The following components are absent from the models as they are considered to have negligible effects on the neutronics model. - Piping - Bottom supports and upper shells for the cold sources - Latches and legs of FAs - Inlet pipe openings in the lower plenum
Materials	All materials are assumed to have homogenous compositions.	This is generally accepted in most neutronics calculations.
	Moderator temperature is assumed to be a constant 293 K.	Although the power is expected to change during operation, the temperature increase is expected to be within 10 K, hence yielding insignificant variations in the cross-sections.
Power	20.2 MW is simulated instead of 20 MW.	To account for non-fission power sources and provide conservative results.

Fuel Cycle States

SU The startup cycle state starts with the 0th day of a cycle. In this state, either the initial core loading compositions

BOC The BOC cycle state covers the first one-quarter of a 40–day cycle of operation.

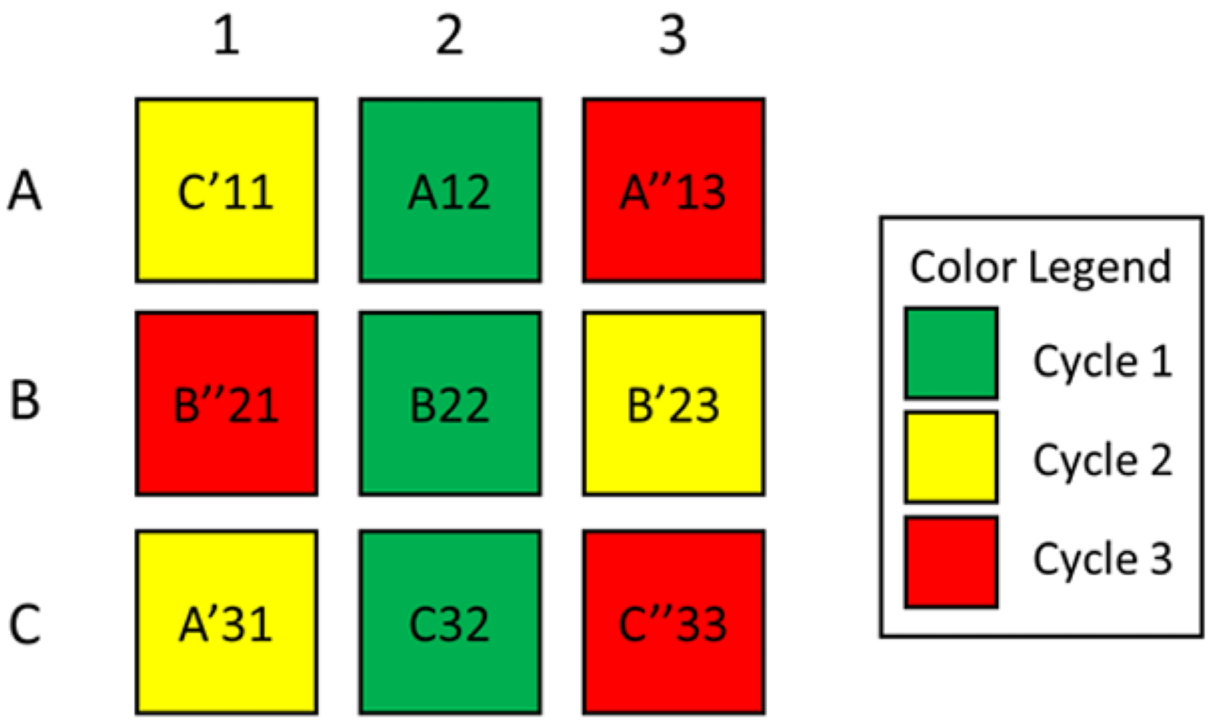
The Q2 cycle state is designed to eliminate possible errors that can arise from the constant location of the control blades while moving from the BOC to the MOC cycle state.

The MOC cycle state covers the third quarter of a 40-days cycle operation starting from the exact middle of the operating cycle.

The cycle state covers the last quarter of a 40–day cycle of operation.

The EOC cycle state is the final part of a cycle that covers 8 days of decaying of short-lived isotopes in the maintenance period of the reactor prior to the next operational cycle.

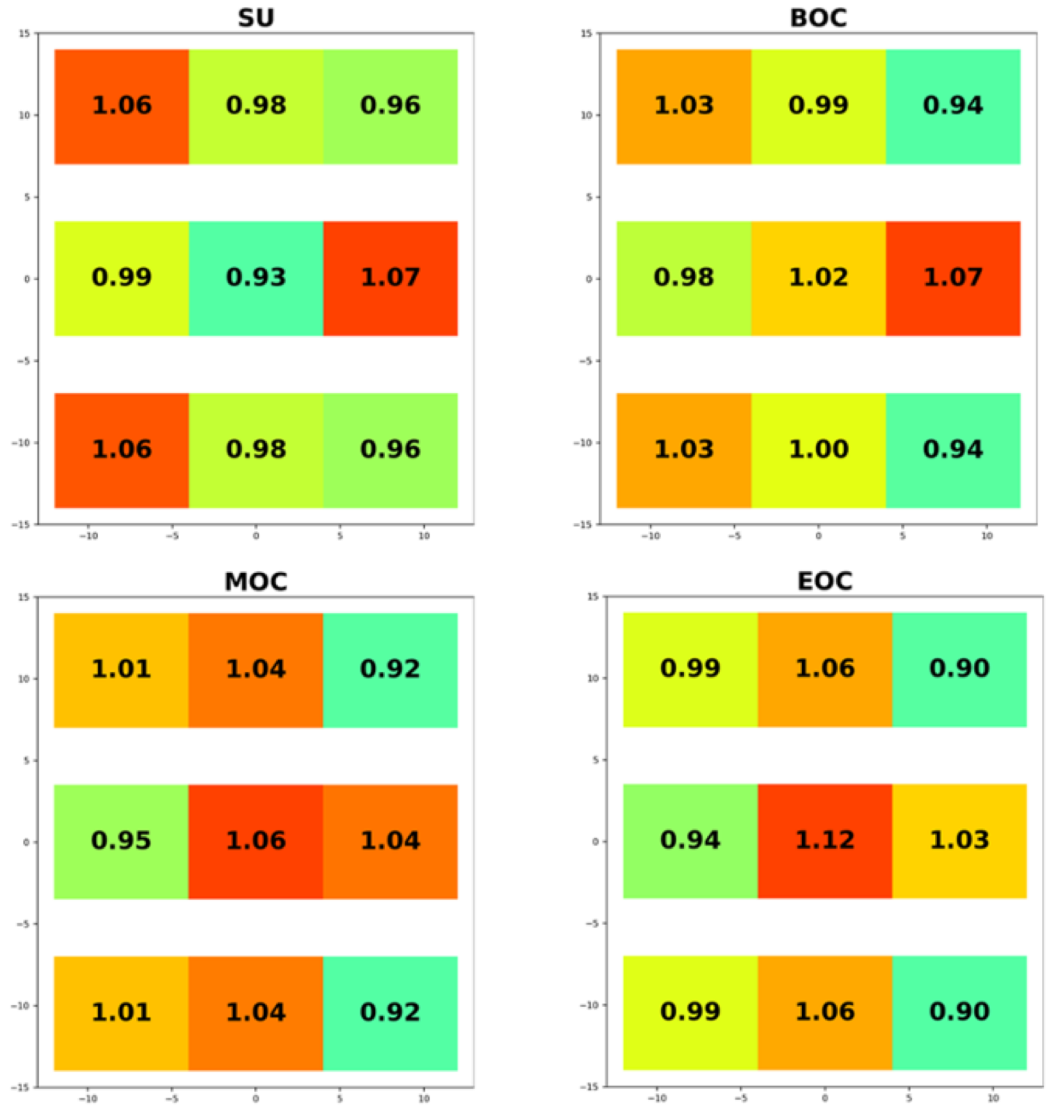
Core Neutronics Analyses – EQ Core



	1	2	3
A	C’11	A12	A’’13
B	B’’21	B22	B’23
C	A’31	C32	C’’33

Color Legend
- 🟩 Cycle 1
- 🟨 Cycle 2
- 🟥 Cycle 3

NNS Current Fuel Management Scheme



SU

1.06	0.98	0.96
0.99	0.93	1.07
1.06	0.98	0.96

BOC

1.03	0.99	0.94
0.98	1.02	1.07
1.03	1.00	0.94

MOC

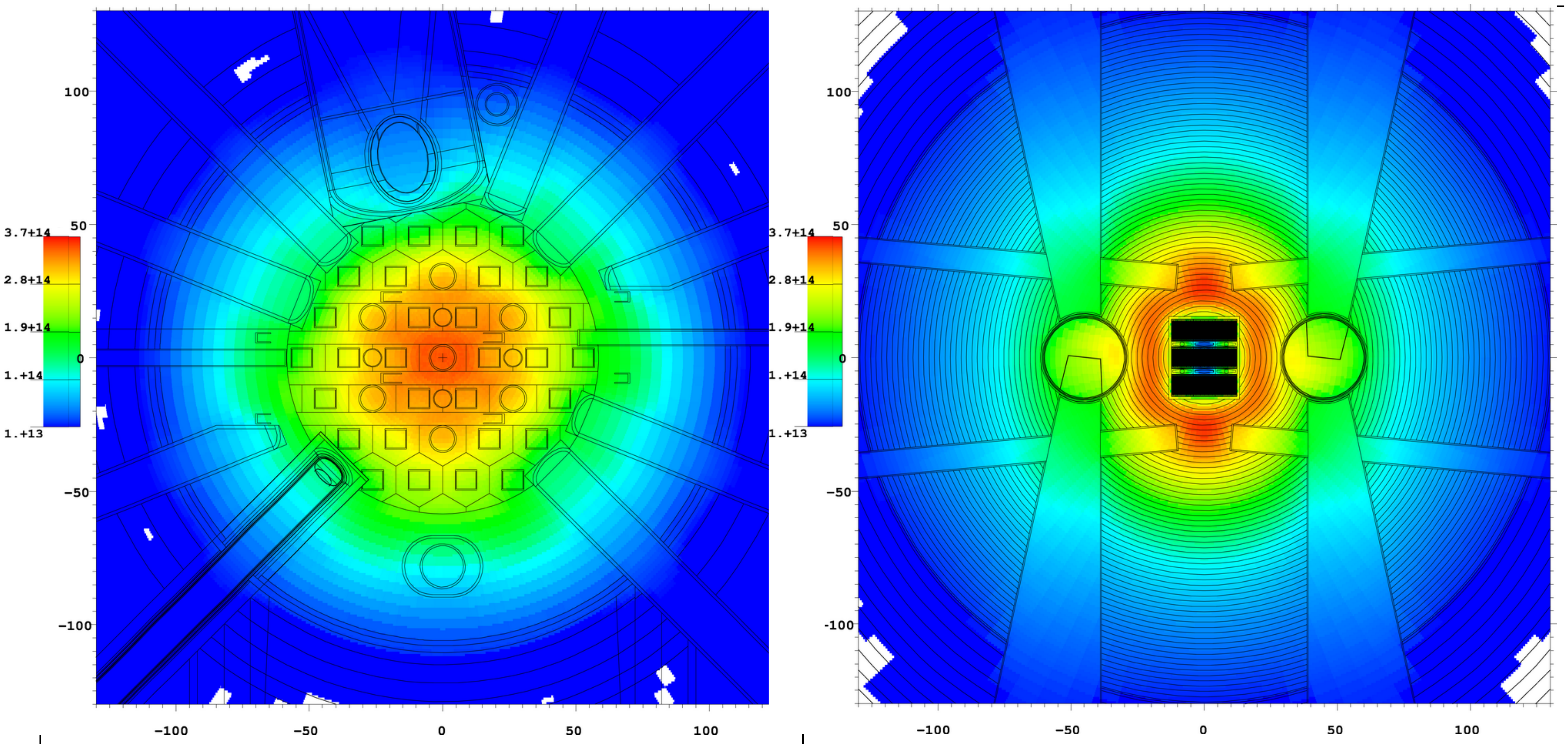
1.01	1.04	0.92
0.95	1.06	1.04
1.01	1.04	0.92

EOC

0.99	1.06	0.90
0.94	1.12	1.03
0.99	1.06	0.90

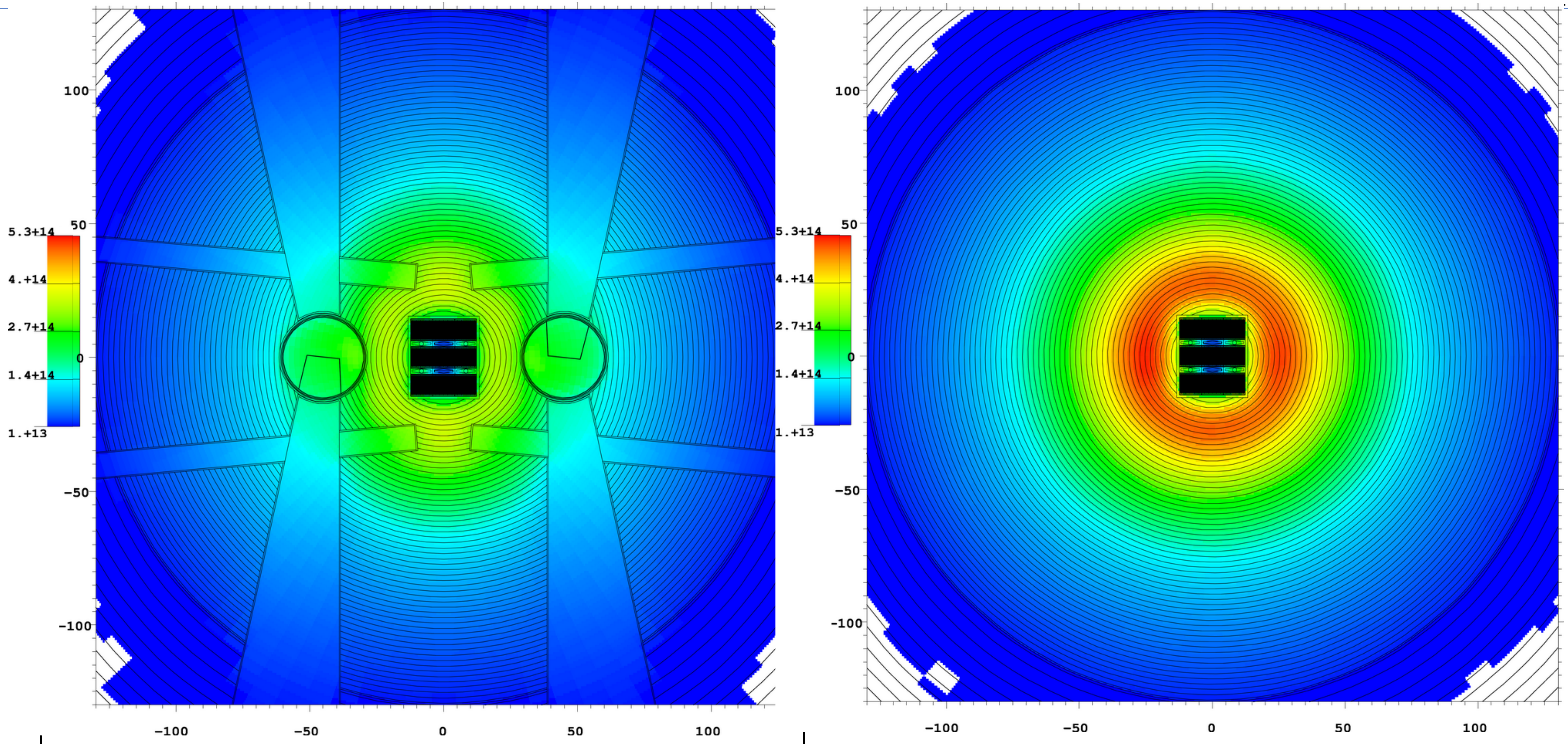
Normalized Power Heatmap of Assemblies in Each Cycle State

Thermal (<0.3eV) neutron flux



NBSR	NNS

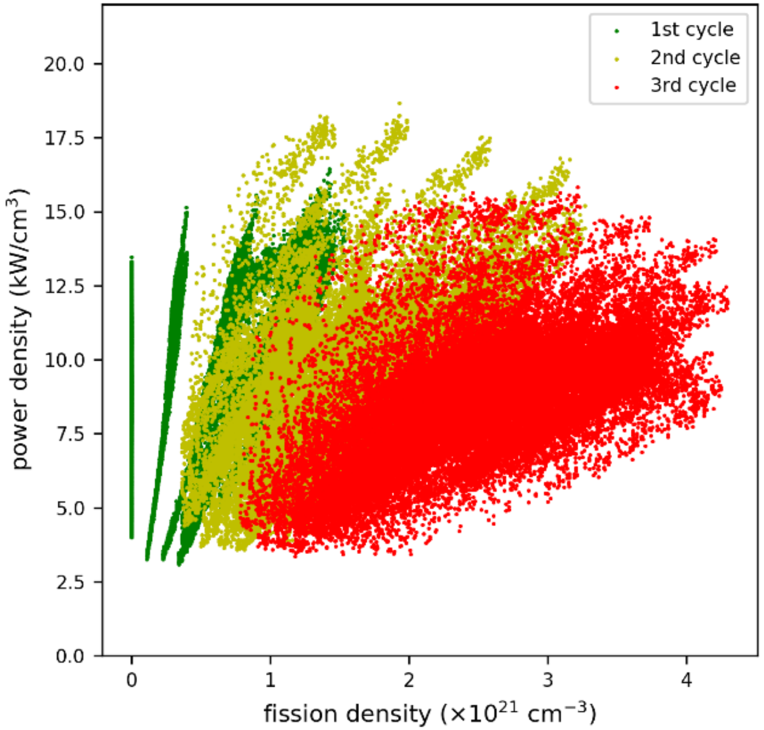
NNS perturbed & unperturbed neutron flux

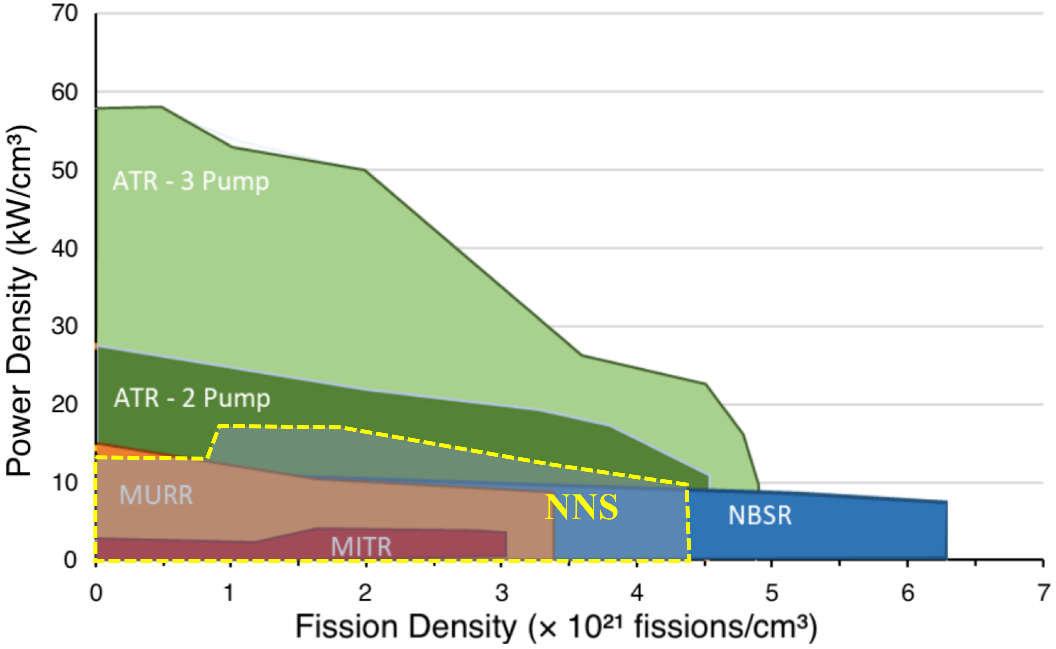


NNS (perturbed)	NNS (unperturbed)

Fission Density Discharge

Elevated power densities for 2nd cycle FAs are observed with values greater than 18 kW/cm^3 and are accompanied with fission densities in the range of 1.5 – 2 × 10^{21} cm^{-3}. The 3rd cycle fuel assemblies have suppressed power densities with elevated fission densities in excess of 3 × 10^{21} cm^{-3}. The maximum fission density is found to be 4.47 × 10^{21} cm^{-3}.

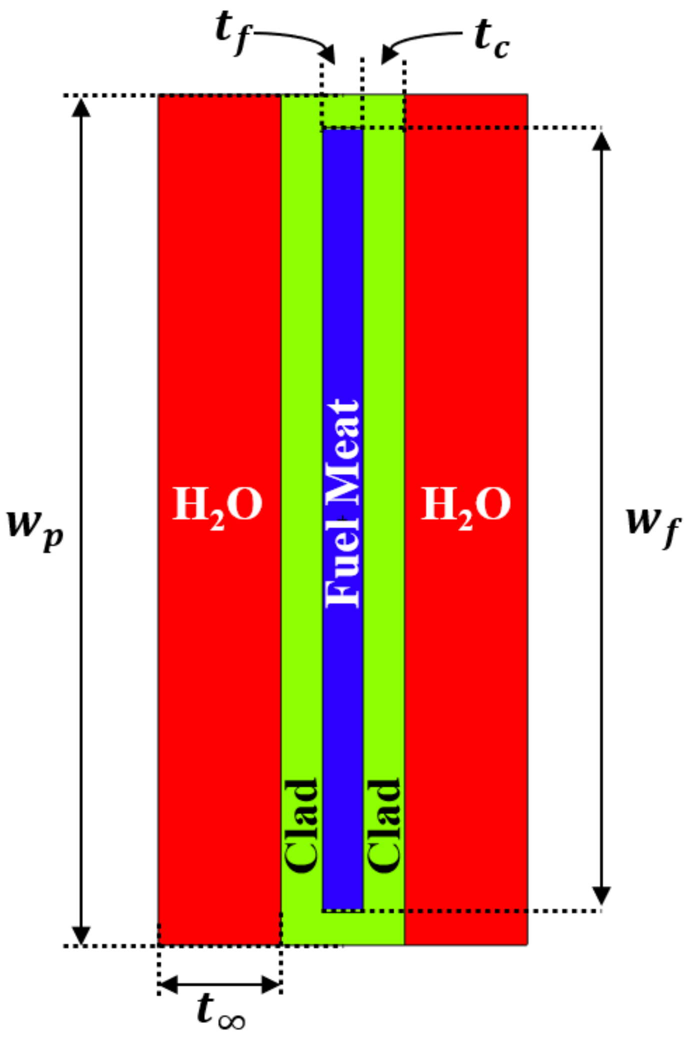




Power and Fission Density Profiles in other USHPRR (modified and reproduced)

Other Fuel U_3Si_2/Al ?

- **Keep unchanged**
  - Width of the fuel meat
  - Width of the fuel plate
  - Thickness of cladding
  - Enrichment of the fuel (19.75%)
- **Safety**
  - NUREG-1313 constraints
  - Criticality Safety
  - Reactor Safety



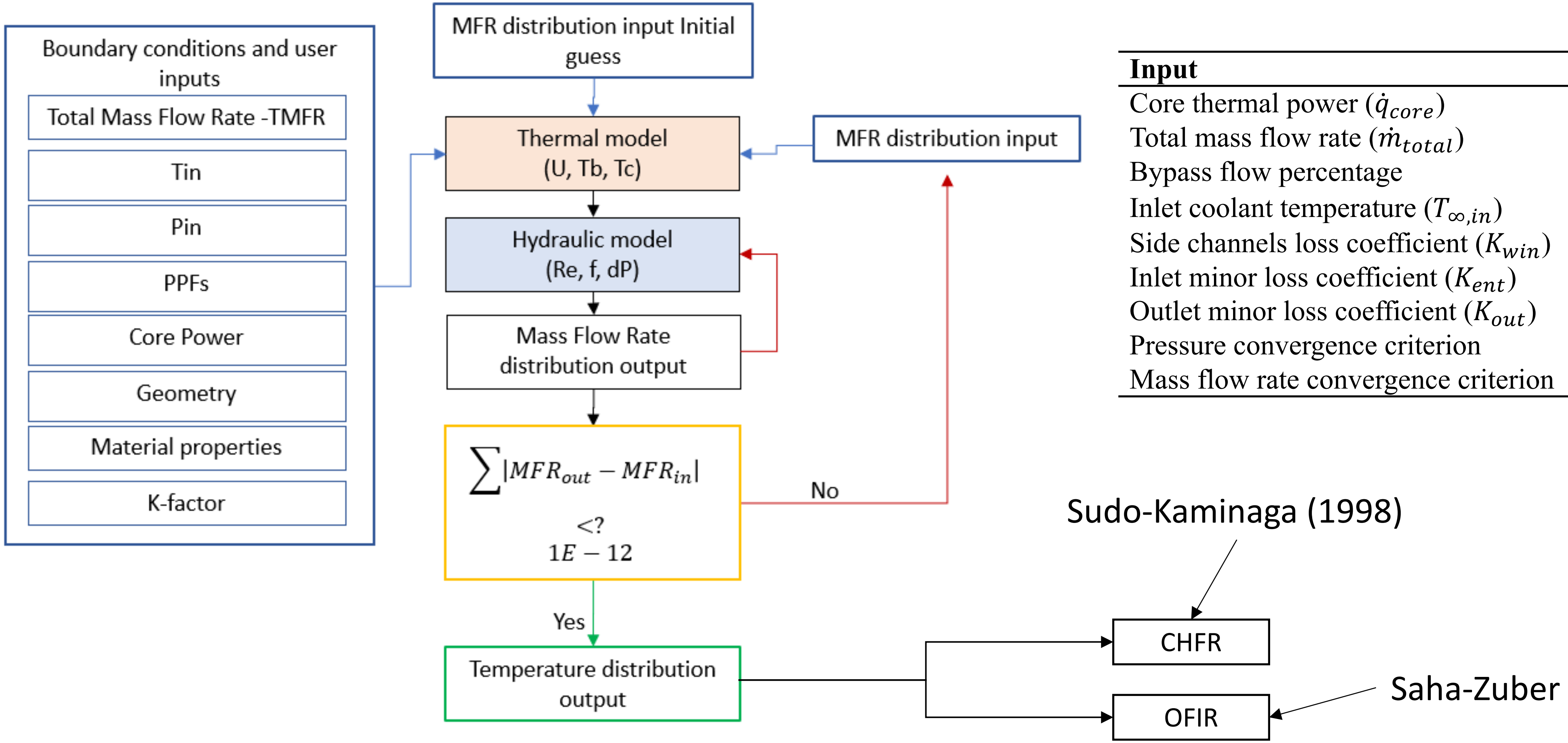
Other Fuel Options

- **Feasibility and optimization study performed 4.8 and 5.2 gU/cm^3 U_3Si_2/Al fuel**
- **Performance compared to the nominal U-10Mo plates**
- **Case 10 contains minimum fuel content with a coolant gap reduction of 14.4%, and +0.61% Δρ reactivity change.**
- **Need to perform more comparisons between the fuel plates, namely**
    - Power and safety margins comparisons
    - Full-core
    - Burnup
    - Reactivity feedback
    - Cycle length analyses

Material	# Fuel Plates	t_f [mm]	t_c [mm]	t_∞ [mm]
U-10Mo (ρ=17.14 g/cm^3)	21	0.250	0.44	1.352
Case 10 U3Si2/Al	19	0.8	0.44	1.2784

Methodology

Simplified Thermal-hydraulics Model



Boundary conditions and user inputs
- Total Mass Flow Rate -TMFR
- Tin
- Pin
- PPFs
- Core Power
- Geometry
- Material properties
- K-factor

MFR distribution input Initial guess

Thermal model (U, Tb, Tc)

MFR distribution input

Hydraulic model (Re, f, dP)

Mass Flow Rate distribution output

$\sum |MFR_{out} - MFR_{in}| \overset{?}{<} 1E-12$

No

Yes

Temperature distribution output

CHFR

OFIR

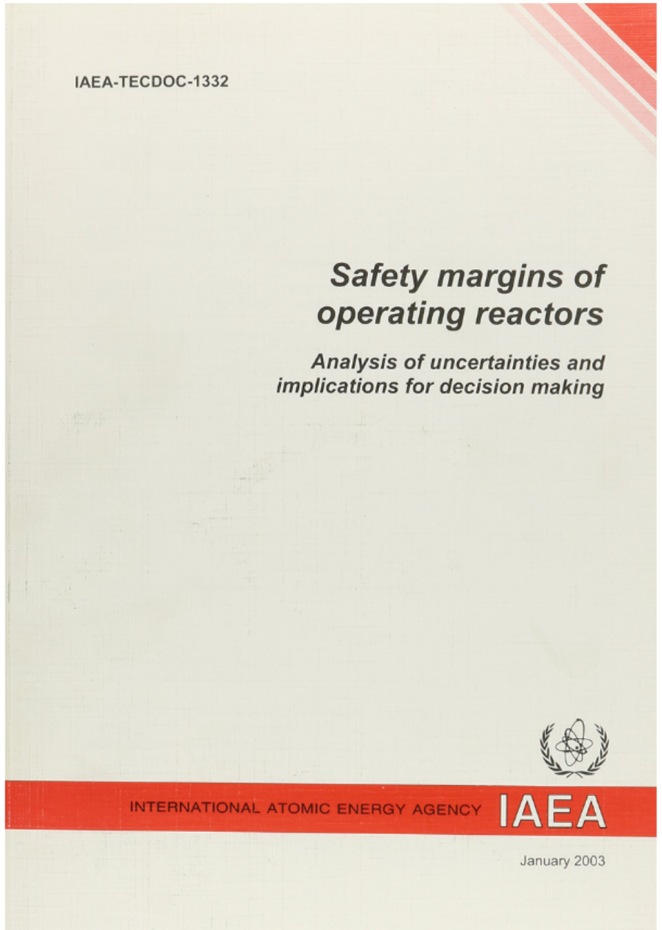
Sudo-Kaminaga (1998)

Saha-Zuber

Input	**Value**
Core thermal power ($\dot{q}_{core}$)	20 MW_{th}
Total mass flow rate ($\dot{m}_{total}$)	540 kg/s
Bypass flow percentage	10% of flow rate
Inlet coolant temperature ($T_{\infty,in}$)	316.5 K
Side channels loss coefficient (K_{win})	0.5
Inlet minor loss coefficient (K_{ent})	0.5
Outlet minor loss coefficient (K_{out})	1
Pressure convergence criterion	10^{-12} bar
Mass flow rate convergence criterion	10^{-12} kg/s

Baroukh, Idan R., et al. "**A Preliminary Thermal-hydraulics Analysis for the NIST Neutron Source**." *Transactions of the American Nuclear Society, v. 126, pp. 1354-1357 (2022).*

Methodology Deterministic vs Stochastic Approaches



IAEA-TECDOC-1332

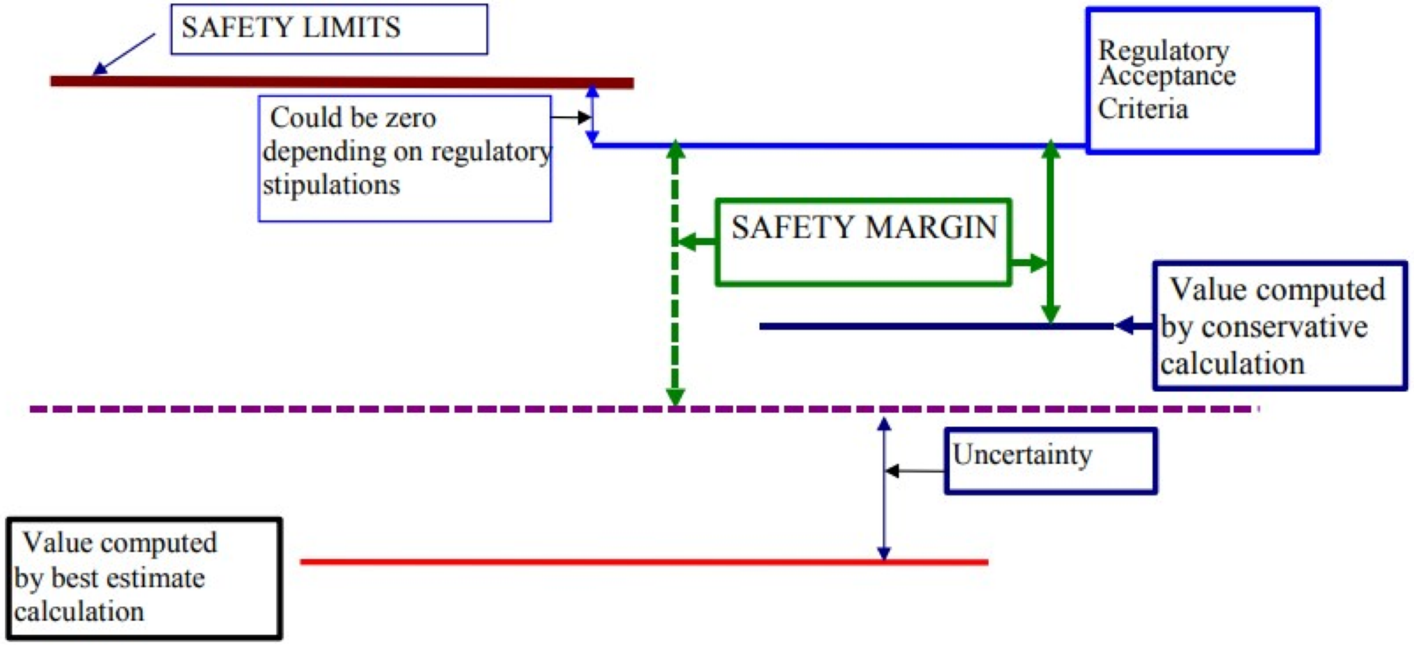
Safety margins of operating reactors

Analysis of uncertainties and implications for decision making

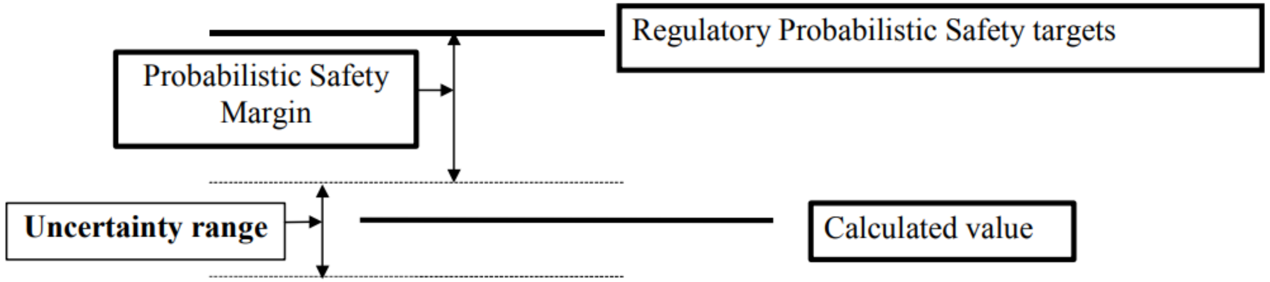
INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

January 2003

Deterministic Approach



Stochastic/Probabilistic Approach

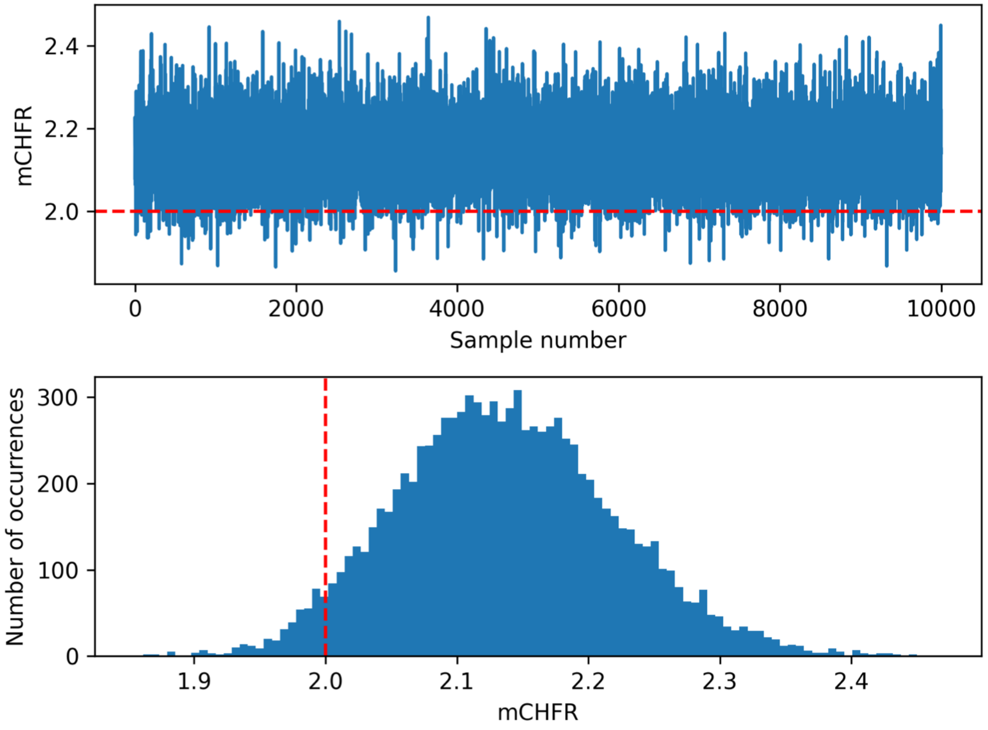


CHFR & OFIR

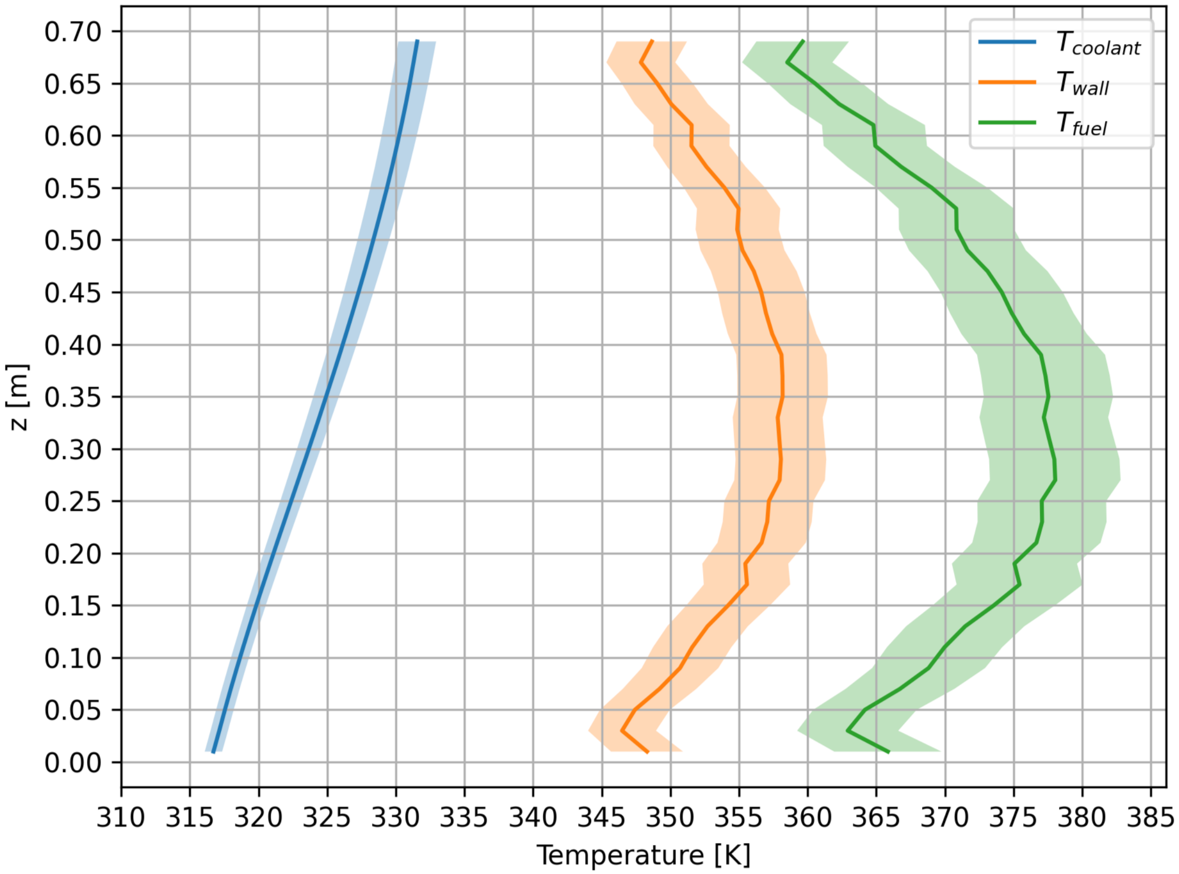
- A custom low-order TH model was successfully used to perform sensitivity analyses on the mCHFR and mOFIR in the current NNS design.
- Deterministic & stochastic approaches were demonstrated, with varying results.
- The deterministic analysis was found to be very conservative for mOFIR, yielding uncertainties well beyond 100%.
    - δ_{mCHFR} of $\pm$14.23%
    - δ_{mOFIR} of $\pm$ 166.39%
- The stochastic analysis showed the following results.
    - δ_{mCHFR} of $\pm$13.1% at 99.7% probability and confidence interval
    - δ_{mOFIR} of $\pm$22.2% at 99.7% probability and confidence interval
- This work communicates the importance of properly selecting an uncertainty analysis method **and bounding constraints** for SAR-related safety analyses.

Core Thermal Hydraulics

- In-house developed thermal-hydraulics solver for the reactor core
- Probability of observing a mCHFR of less than 2.0 is 4.2% for the steady-state operation

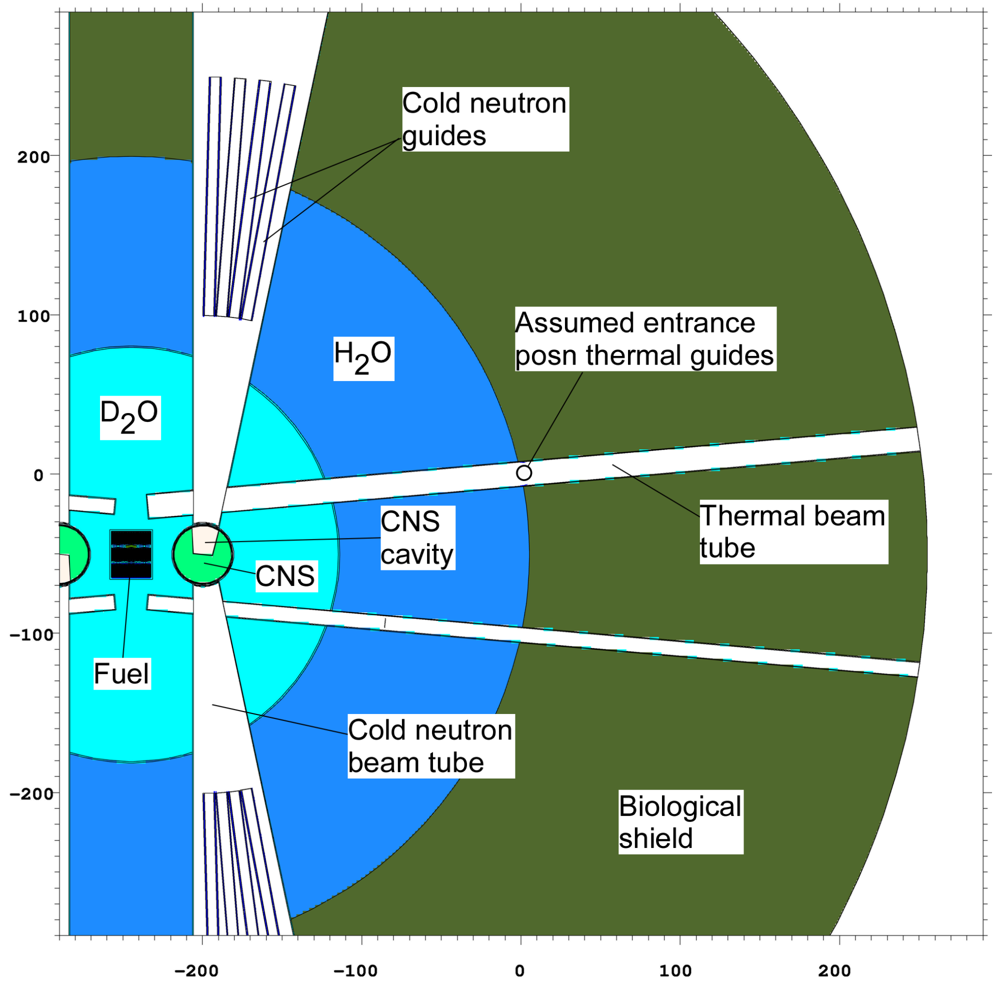


mCHFR distribution at BOC state



Axial distribution of temperature fields at the BOC state

Proposed Cold Neutron Instruments

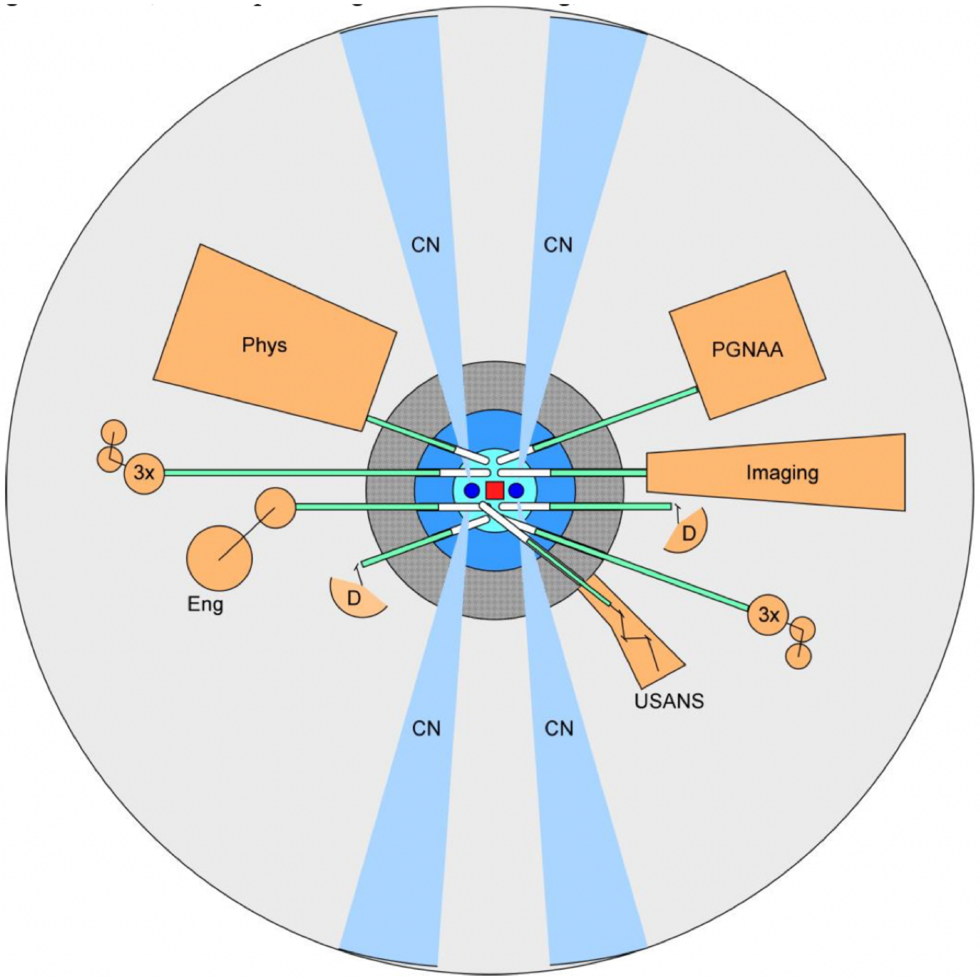


Plan view through the fuel center of the reactor core

Instrument type	Total Number	End position
Small-Angle Neutron Scattering (SANS)	2-3	YES
Reflectometer (CANDOR type)	2	YES
Cold Neutron Imaging (CNI)	2	YES
Cold 3-Axis (CN3X)	2	YES
Backscattering (BS)	2	YES/NO?
Neutron Spin-Echo (NSE) (Mezei-type)	1	YES
Neutron Spin-Echo (NSE) (WASP type)	1	YES
High current physics experimental position (Physics)	1	YES
Prompt Gamma Activation Analysis (PGAA)	1	YES
Neutron Depth Profiling (NDP)	1	YES
Materials Diffractometer (λ > 0.3 nm)?	1?	YES
Interferometer	1?	NO
Monochromatic Physical Measurements Laboratory (PML) positions	2-3?	NO
Miscellaneous monochromatic/ test positions	2-3?	NO
Very Small-Angle Neutron Scattering (vSANS)	1	YES
TOTAL	22-25	16-18

Proposed Cold Neutron Instruments

Proposed Thermal Neutron Instruments



View of Potential Thermal Instruments

Instrument Type	Abbreviation
Prompt Gamma Neutron Activation Analysis	PGNAA
Neutron Microscope	Imaging
High-Resolution powder diffractometer	D
Triple Axis Spectrometer	3X
Ultra-Small Angle Neutron Scattering	USANS
High Throughput Fast Powder Diffractometer	D
White Beam Engineering Diffractometer (with CANDOR-type detector)	ENG
High Current Physics Experimental Position	PHYS

Proposed Thermal Neutron Instruments

Performance Comparison

Cold Source/ config	J_{tot} (all λ) (s^{-1})	J_{tot} ($\lambda \geq 4$Å) (s^{-1})
NBSR LH_2 Unit 2 (all cold guides)	3.0×10^{13} (Ref. [^{i}])	6.3×10^{12} (Ref. [i])
NNS (6 cm × 15 cm) (16 equivalent guide entrances)	2.3×10^{14}	5.8×10^{13}
Gain NNS/NBSR Unit2	7.5	9.2

Table 1. Estimated "useful" ($\mu > 0.99875$) neutron currents entering guide networks for NBSR (LH_2 Unit 2 cold source, guides NG-A to NG-7) versus NNS with 16 equivalent 6 cm × 15 cm guide entrances at 1.5 m from the cold source center.

Cold Source/ config	J_{tot} (all λ) (s^{-1})	J_{tot} ($\lambda \geq 4$Å) (s^{-1})
NBSR LH_2 Unit 2 (all cold guides)	3.0×10^{13} (Ref. [i])	6.3×10^{12} (Ref. [i])
NNS (6 cm × 20 cm) (16 equivalent guide entrances)	2.8×10^{14}	7.0×10^{13}
Gain NNS/NBSR Unit2	9.1	11.1

Table 2. Estimated "useful" ($\mu > 0.99875$) neutron currents entering guide networks for NBSR (LH_2 Unit 2 cold source, guides NG-A to NG-7) versus NNS with 16 equivalent 6 cm × 20 cm guide entrances at 1.5 m from the cold source center.

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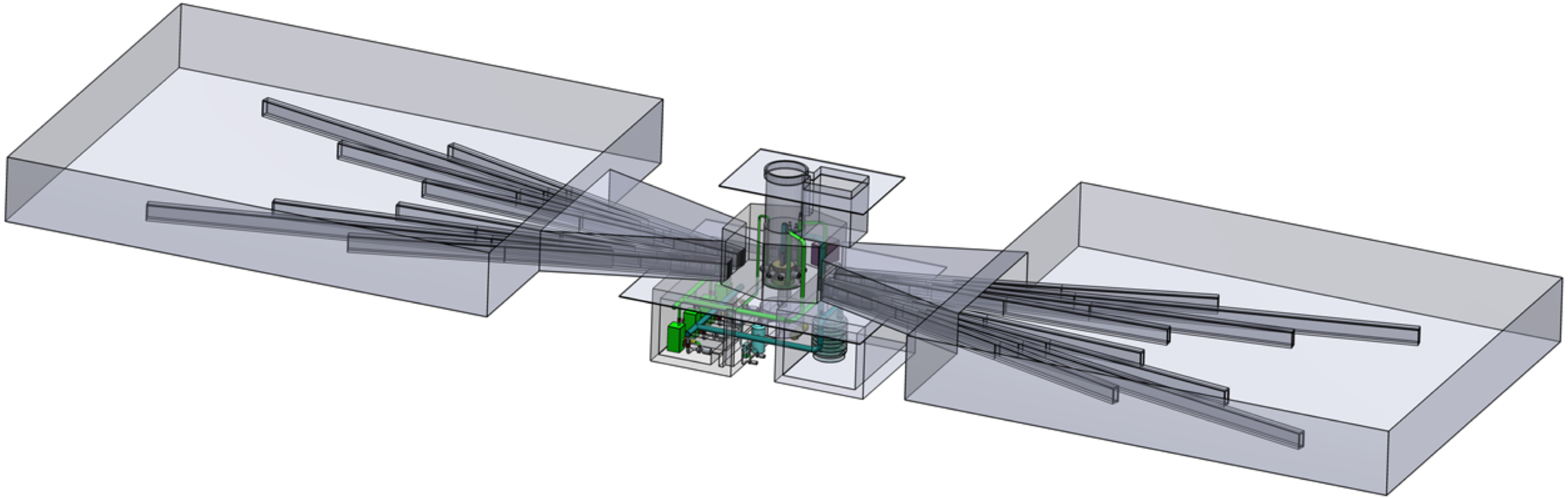
[i] J. C. Cook, "On the requirements for Cold Neutron Sources for the replacement NIST Neutron Source" (Rev. 2 with updated gain factors and Unit2 reference added, Oct 13, 2022), reqs_NNS_cold_source_perf_rev2.pdf.

Performance Comparison

- Peak unperturbed reflector thermal neutron flux
  - NBSR 2×10^{14} $cm^{-2}s^{-1}$
  - NNS 5×10^{14} $cm^{-2}s^{-1}$
- Total cold neutron ($\lambda > 0.4$ nm) current gain at guide entrances **~10 wrt NBSR LH_2 CNS**
- Gain at the instruments may be further enhanced
- Potential for a significant boost in the cold neutron experimental output
- Pool Type Reactor => simple maintenance
- Modular design for long term aging management

Conclusions & Future Work

- CFD verification and validation through experiments
- Hybrid Deterministic and Probabilistic Accident Analysis
- Structural analysis
- Fuel evaluations U3Si2, U3O8 etc.
- Engage with the NRC for licensing requirements



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Questions?

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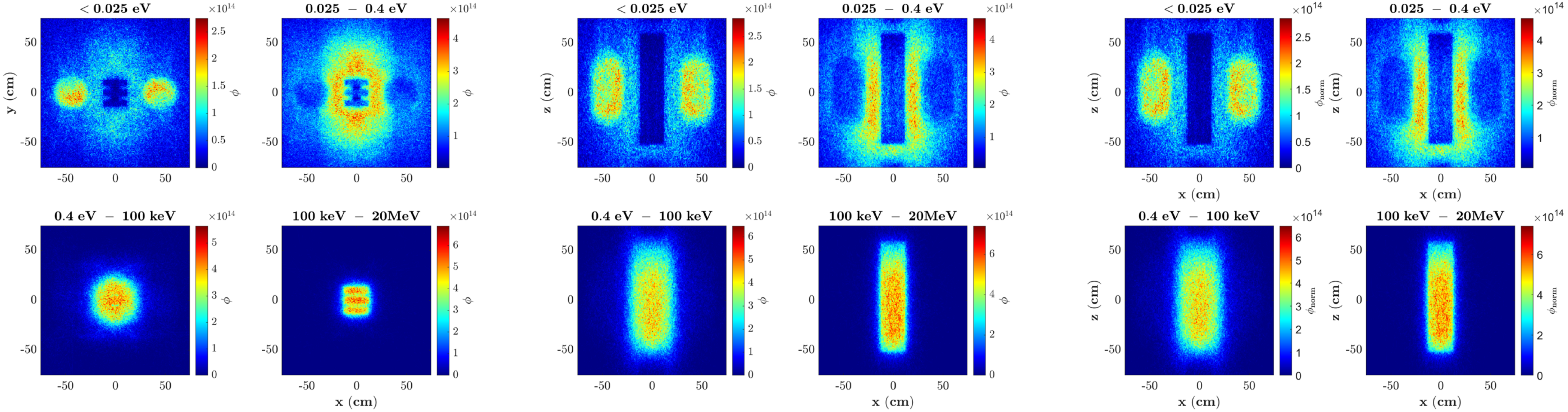
Core Neutron Density Distributions

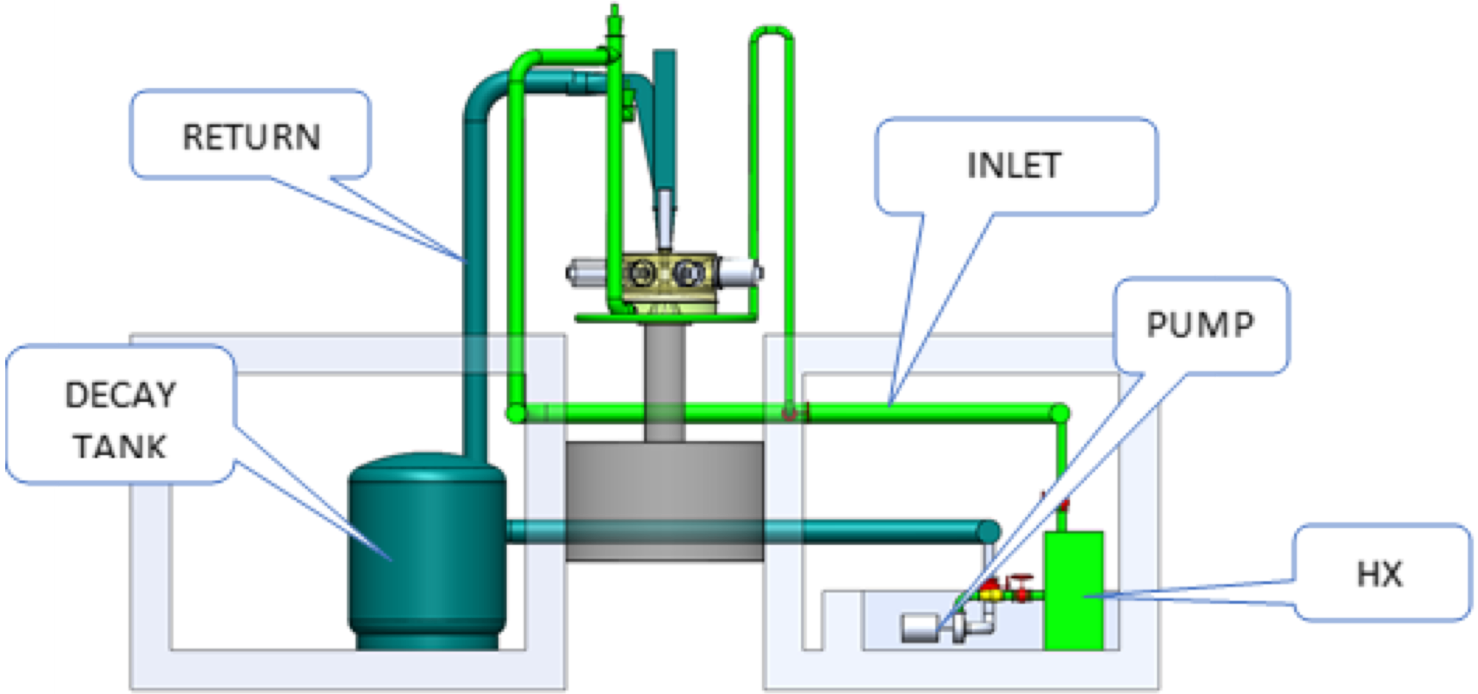
cold and thermal (<0.025 eV), thermal and epi-thermal (0.025 – 0.4 eV)

intermediate neutrons (0.4 eV – 100 keV) and fast neutrons (100 keV – 20 MeV).



The neutron distribution radial (top-view, left image) and (b) axial (side-view) profiles at the SU state

PCS



Elevation view of primary coolant system