Preliminary Safety Analyses on a Conceptual LEU Fueled Research Reactor at NIST

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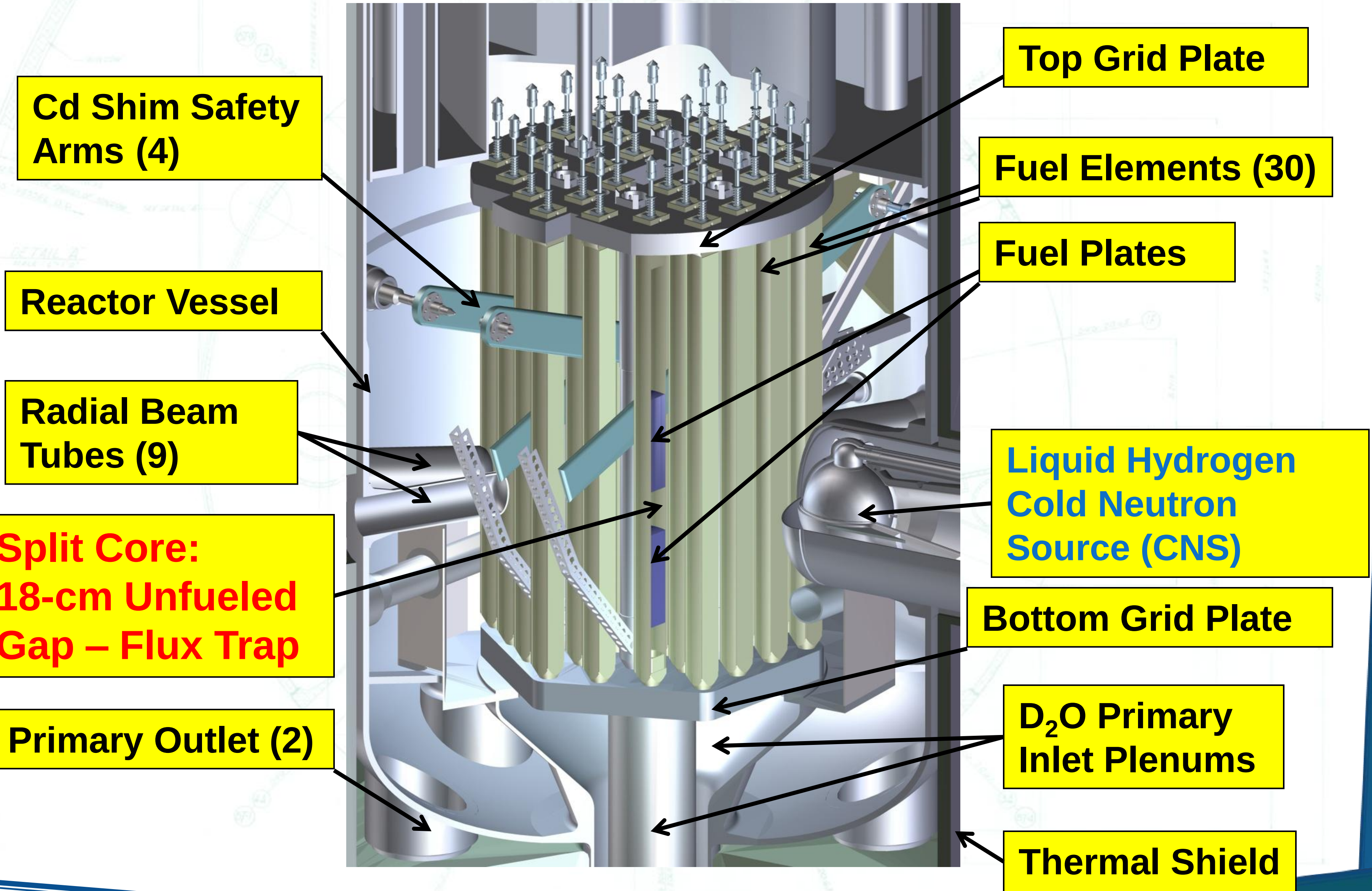
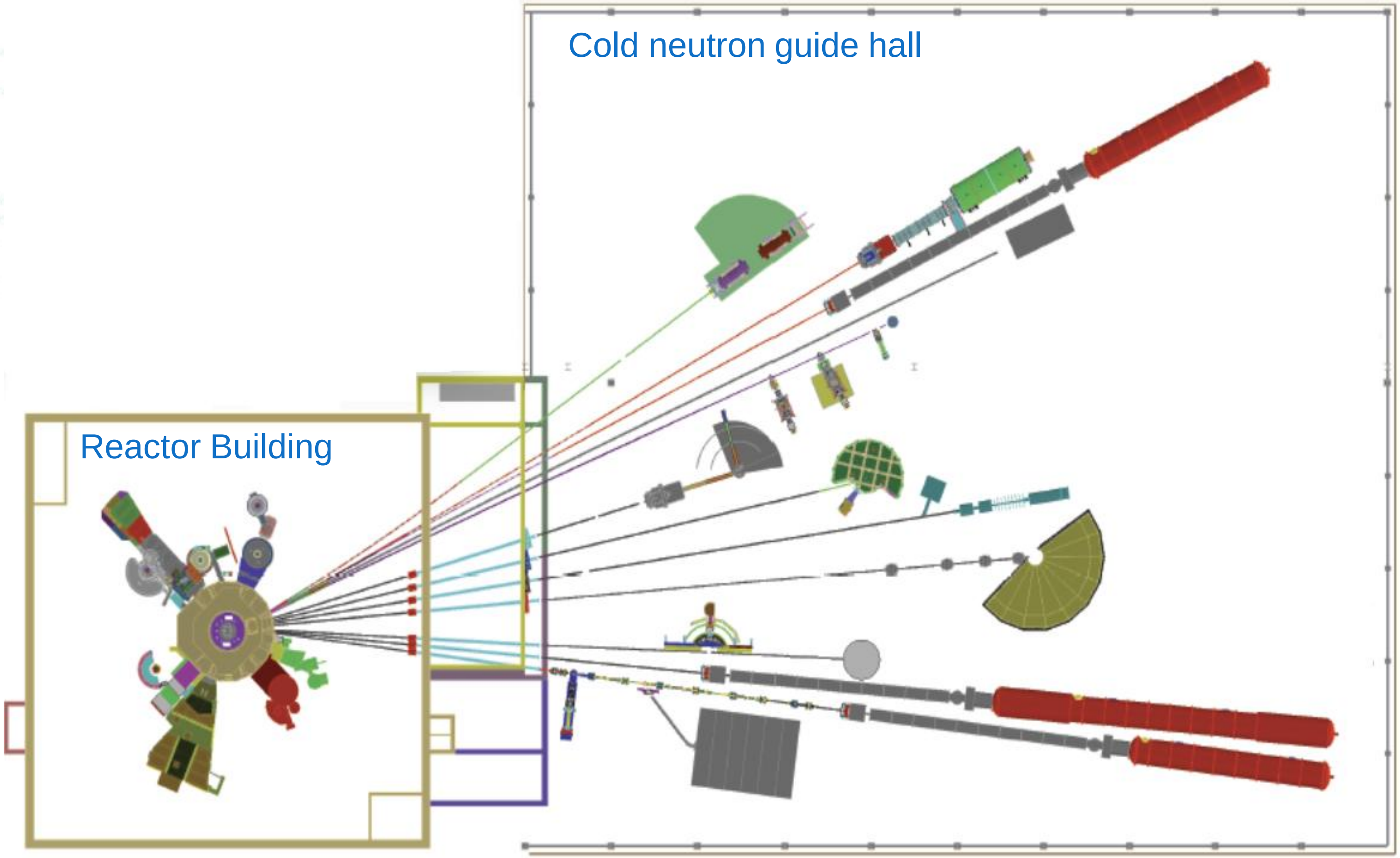
Cut-away View of the Present NIST Reactor (NBSR) Core



Scientific Utilization of the NBSR



NBSR has 28 instruments for various scientific experiments, 21 of them use cold neutrons (as of December 2014).

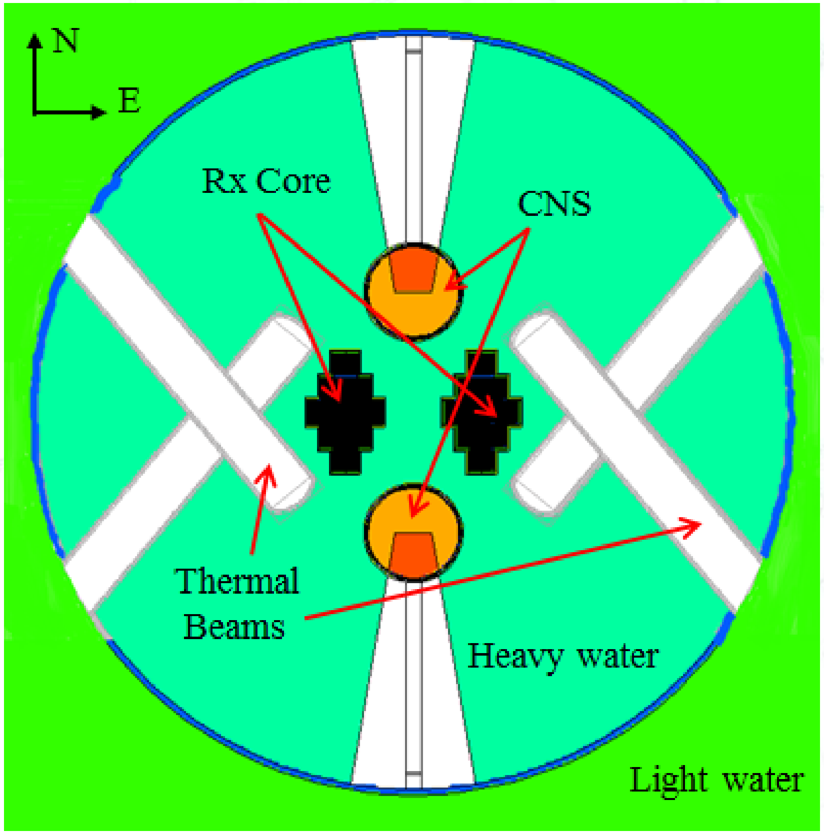
Overview of the Present NBSR

- First critical on Dec. 7th, 1967
- Current operating license will go through 2029
- One additional extension may be achievable
- Most likely reach retirement in 2050s

Challenges for Conversion of NBSR to LEU

- LEU U_3Si_2/Al dispersion fuel is not economical
- LEU U-10Mo monolithic fuel is feasible but not manufactured yet - may be 10 years off
- 30% or more increase on fuel costs
- 10% reduction on neutron performance

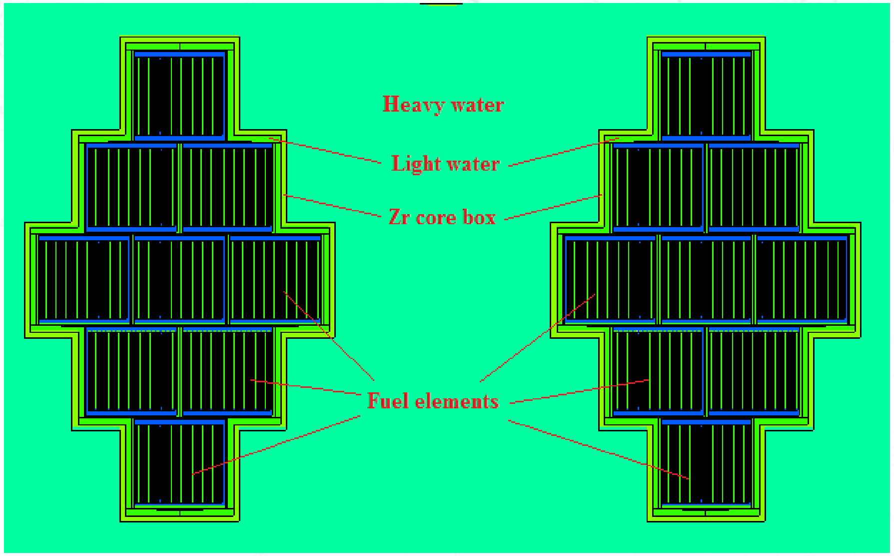
Schematics of the Split-Core Design



Reactor Size (m)	Value
Heavy water tank diameter	2.5
Heavy water tank height	2.5
Light water pool diameter	5.0
Light water pool height	5.0

The mid-plane of the split core reactor. Two CNS are placed in the north and south side of the core, and four thermal beam tubes are located in the east and west side of the core at different elevations.

Horizontally Split Core With 18 Fuel Elements



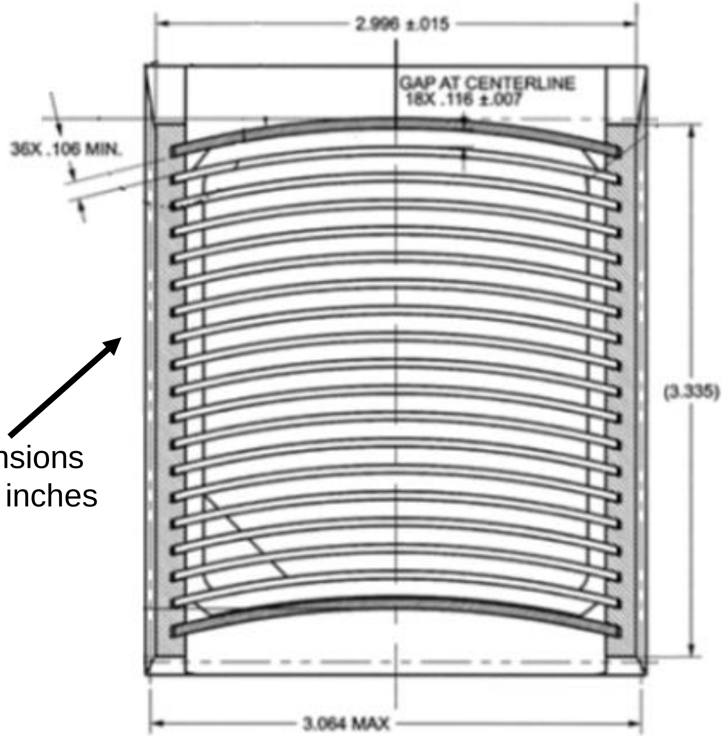
A close view of the horizontally split-core. The core consists of total 18 fuel elements which are evenly distributed into two horizontal split regions.

Core Design Information

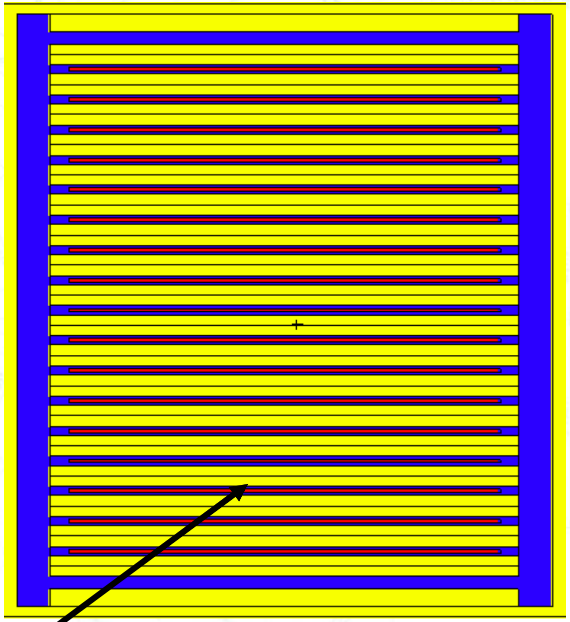
Parameter	Data
Thermal power rate (MW)	20
Fuel cycle length (days)	30
Active fuel height (cm)	60.0
Fuel material	U_3Si_2/Al
U-235 enrichment in the fuel (wt. %)	19.75
Fuel mixture density (g/cc)	6.52
Uranium density (g/cc)	4.8
U-235 mass per fuel element (gram)	391.5
Number of fuel elements in the core	18

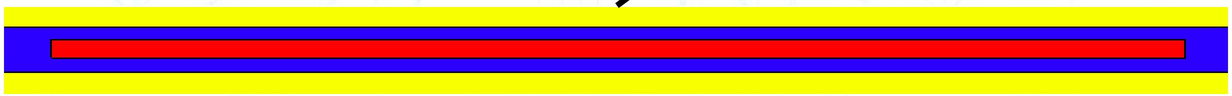
The MTR-type Fuel Plate and Fuel Element

Cross sectional view of the fuel element: 17 fuel plates, 2 end plates and 2 side plates.



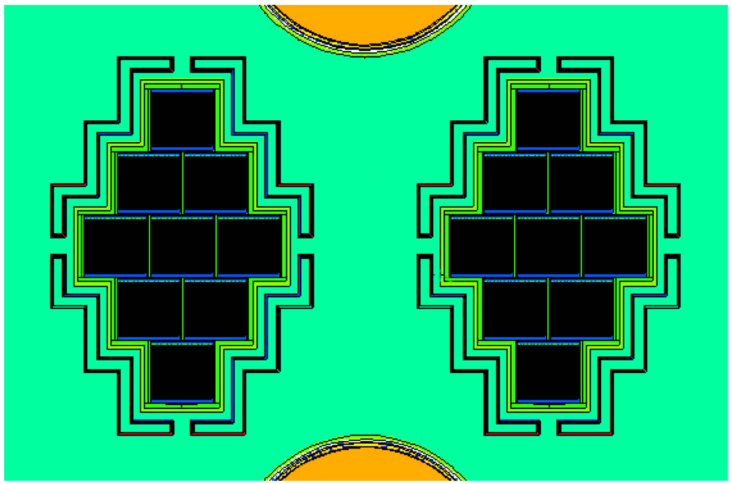
Dimensions are in inches



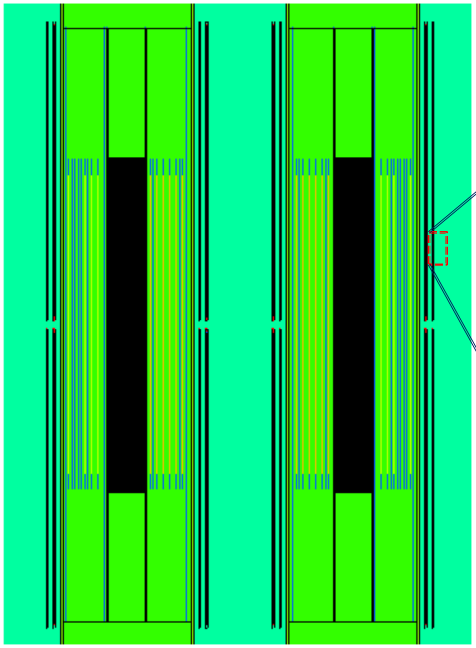


The fuel plate: For the U_3Si_2/Al fuel meat, it is 0.066 cm (26 mil) thick and 6.134 cm wide.

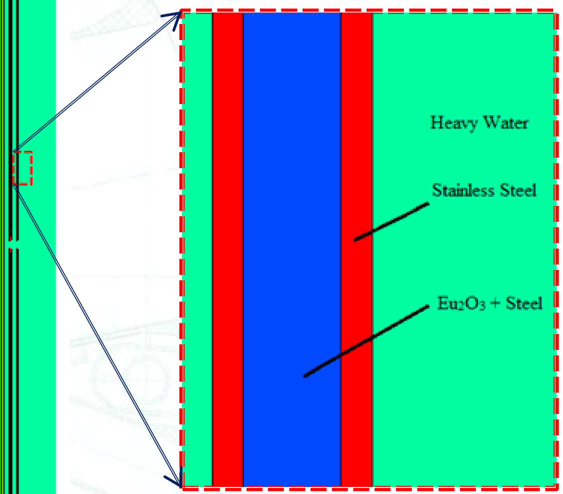
Control Element Design



Top view

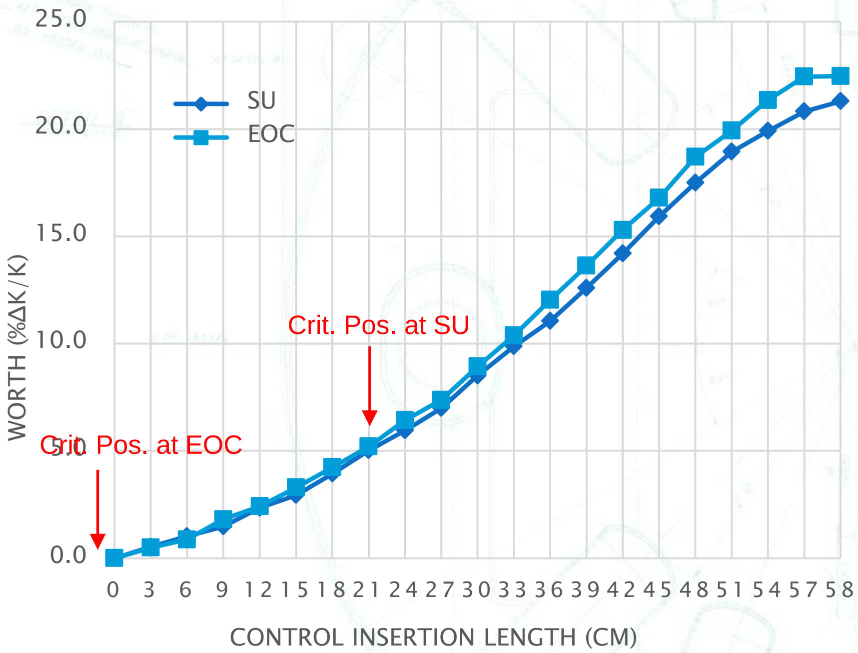


Side view



Control blade

Control Rod Worth Evaluation



Control blades worth curve at SU and EOC

Reactivity (%Δ*k*/*k*) Calculation

	SU	EOC
Maximum excess reactivity (ARO[a])	7.54	1.73
Total control worth (ARI[b])	23.73	25.05
Shutdown reactivity	-16.20	-23.32

[a]All rods out, [b]All rods in.

Critical control rod positions

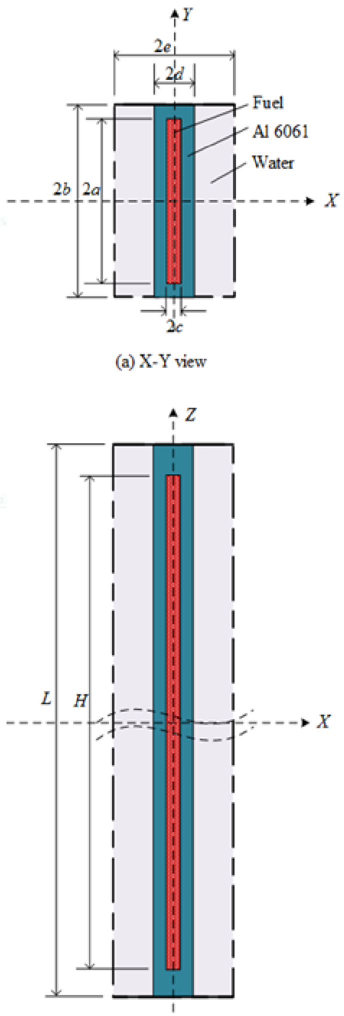
	Position (cm)	k_{eff}
SU	21.42	1.00098
EOC	-7.28[a]	1.00106

[a]Minus value indicates the control rod positions are out of the rage of active fuels (AF).

Safety Analysis Methodology

- MCNP was used to obtain detailed power distribution to locate the hot spots in the core.
- Preliminary safety analyses for the startup (SU) and end of cycle (EOC) core were performed based on single-channel T/H model and point kinetics model (PKM).
- T/H related safety examination was conducted by evaluating minimum critical heat flux (CHF) ratio and minimum onset of flow instability (OFI) ratio using the Sudo-Kaminaga correlations and Saha-Zuber criteria, respectively
- Both the steady-state operational condition and reactivity insertion accident (RIA) transient scenarios for both SU and EOC of the equilibrium core were investigated
- As a matter of expediency, the limitations of MCHFR and MOFIR for the LEU core used are the ones from the NBSR conversion safety analysis report (CSAR).

The Single-Channel T/H Model



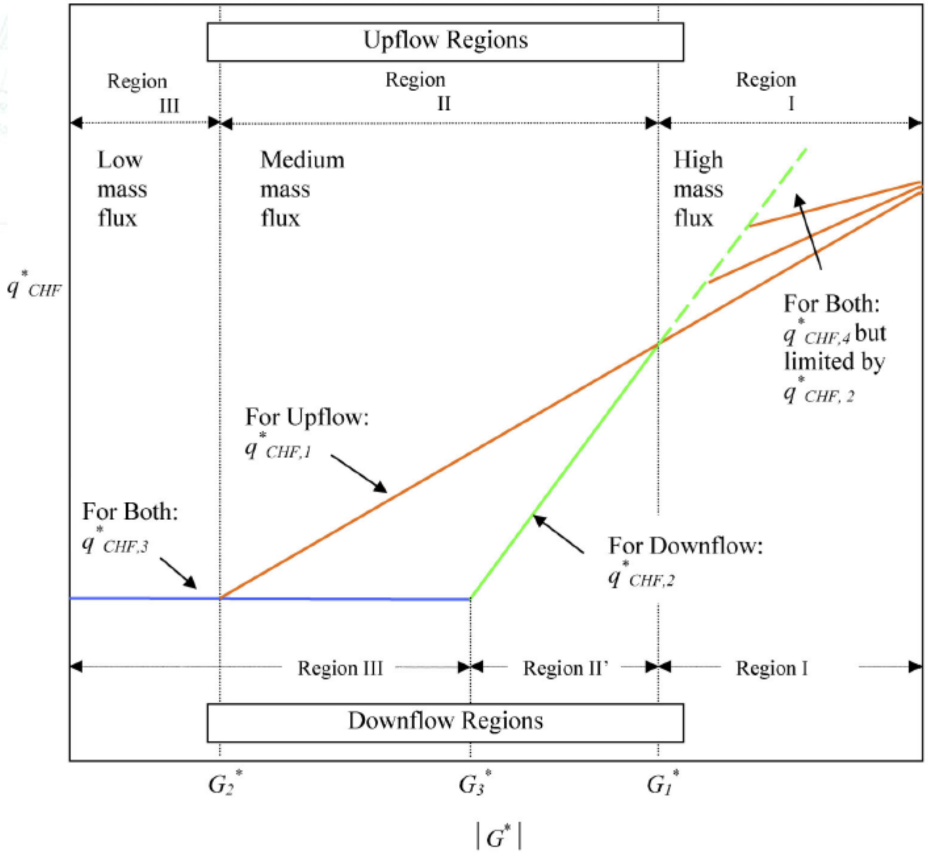
(a) X-Y view

(b) X-Z view

Dimensions	Size (cm)
Half width of the fuel meat (a)	3.067
Half width of the fuel plate (b)	3.3325
Half thickness of the fuel meat (c)	0.033
Half thickness of the fuel plate (d)	0.0635
Half pitch of the fuel plates (e)	0.211
Length of the fuel meat (H)	60
Length of the channel (L)	67.28

T/H Conditions	Value
Outlet pressure (kPa)	135
Inlet temperature (°C)	37
Inlet volumetric flow rate (gpm)	8000
Temperature rise along the channel (°C)	9.54
Flow area of the channel (cm^2)	1.9662
Heated surface area of the channel (cm^2)	736
Wetted perimeter of the channel (cm)	13.63
Hydraulic diameter (cm)	0.58
Press drop along the channel (kPa)	56.04

Critical Heat Flux (CHF)



Sudo-Kaminaga correlation scheme

- The Sudo-Kaminaga correlation[1] is developed specifically for reactors with plate-type fuel and rectangular flow channel.
- S-K correlation takes account of mass flux, inlet and outlet sub-cooling, flow direction, pressure and channel configuration.
- The mass flux boundaries for each region are calculated based on flow fluid properties and flow channel conditions.
- CHF correlations for each region are determined in terms of dimensionless parameters[1].
- The CHFR is evaluated as

$$\mathrm{CHFR} = \frac{q''_{\mathrm{CHF}}}{q''_{\mathrm{Model}}}.$$

[1]. M. Kaminaga, K. Yamamoto, and Y. Sudo,"Improvement of Critical Heat Flux Correlation for Research Reactors Using Plate-Type Fuel," *J. Nucl. Sci. Technol.*, **35**, 12, 943 (1998)

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Onset of Flow Instability (OFI)

- Excursive flow instability, which is indicative of OFI, may occur in channels of reactor with plate-type fuel and cause rapid loss of adequate cooling for the channel.
- The OFI is determined by assuming the onset of net vapor generation is conservative threshold for OFI and the Saha-Zuber criteria[2] are used.
- The heat flux for OFI in S-Z criteria are calculated based the low- and high-mass flow rates determined by the Péclet number.
- The OFIR is evaluated as

$$\mathrm{OFIR} = \frac{q''_{\mathrm{OFI}}}{q''_{\mathrm{Model}}}.$$

[2]. P. Saha and N. Zuber, ''Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling,'' *Proc. 5th Int. Heat Transfer Conf.*, Tokyo, Japan, September 3–7, 1974, Vol. IV, 75 (1974).

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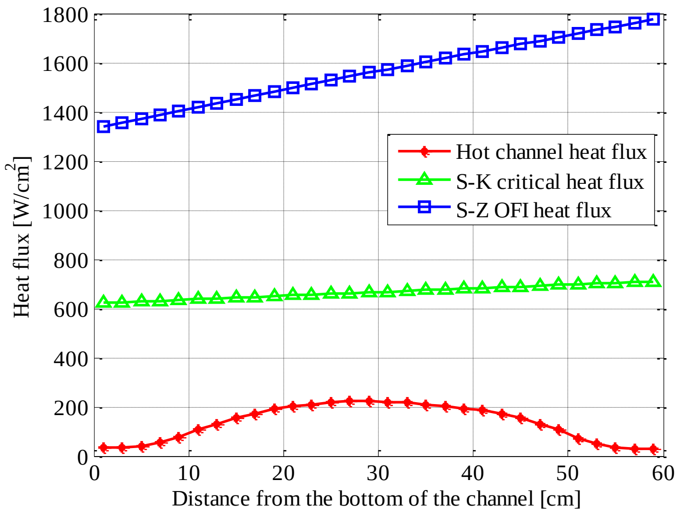
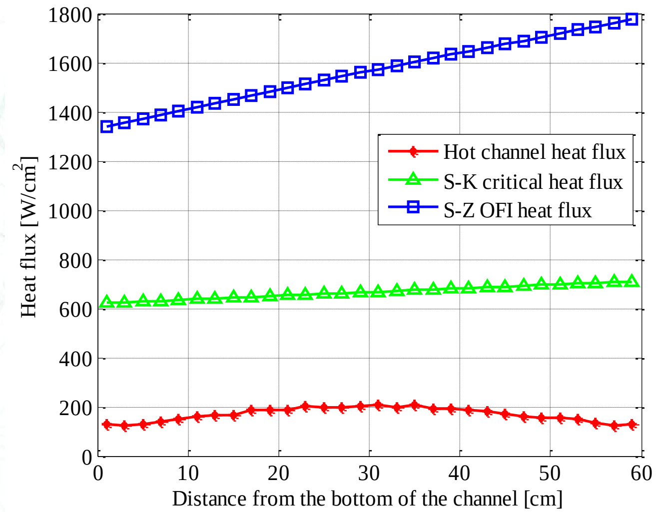
Steady-State Operational Condition





Heat flux along the vertical channel at SU (left) and EOC (right)

CASE	SU	EOC
MCHFR	2.94	3.22
MOFIR	6.85	7.54

Calculated minimum critical heat flux ratio (MCHFR) and minimum heat flux at onset of flow instability (MOFIR) for SU and EOC. The hot channel limits for a LEU core was envisaged as 1.32 for MCHFR and 1.27 for MOFIR.

Kinetics Parameters for the SU and EOC

Kinetics Parameter	SU	EOC
Prompt neutron lifetime - l_p (μs)	97.15	160.69
Prompt neutron generation time[a] - Λ (μs)	97.06 ± 2.22	160.51 ± 3.29
Effective delayed neutron fraction (β_{eff})	0.00837 ± 0.00049	0.00722 ± 0.00042

[a]Note the relationship of prompt neutron lifetime (l_p) and prompt neutron generation time (Λ) is $\Lambda = l_p / k_{eff}$.

- The kinetics parameters were obtained from MCNP calculations based on the adjoint-function weight approach.
- The prompt neutron lifetime is less in SU core mainly due to the decrease of the fission production rate at EOC.
- The effective delayed neutron fraction has some changes from SU to EOC mainly due to the variation of fuel compositions in the fuel, and also due to the neutron spectrum shift at EOC.

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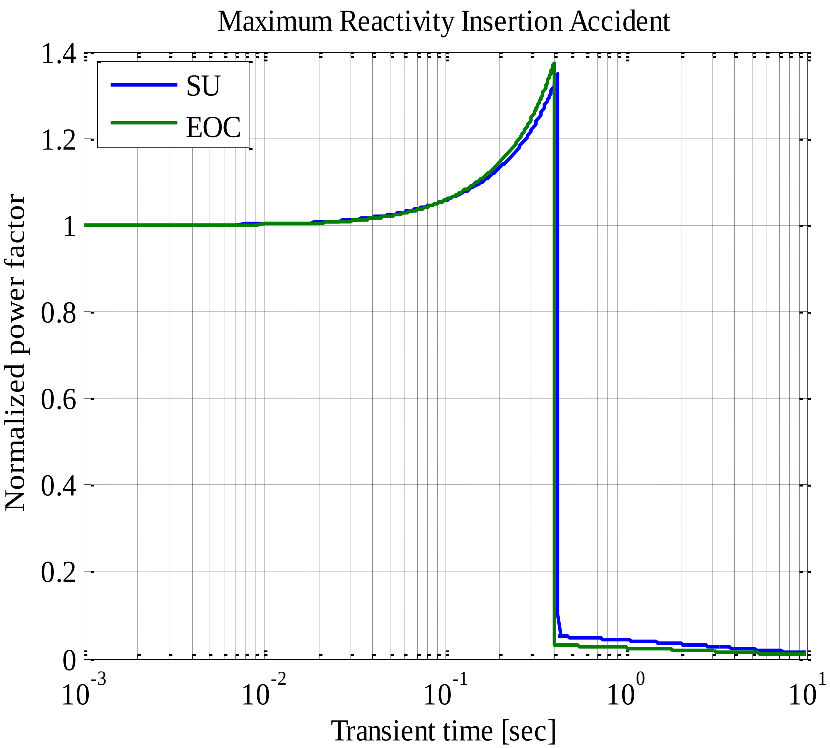
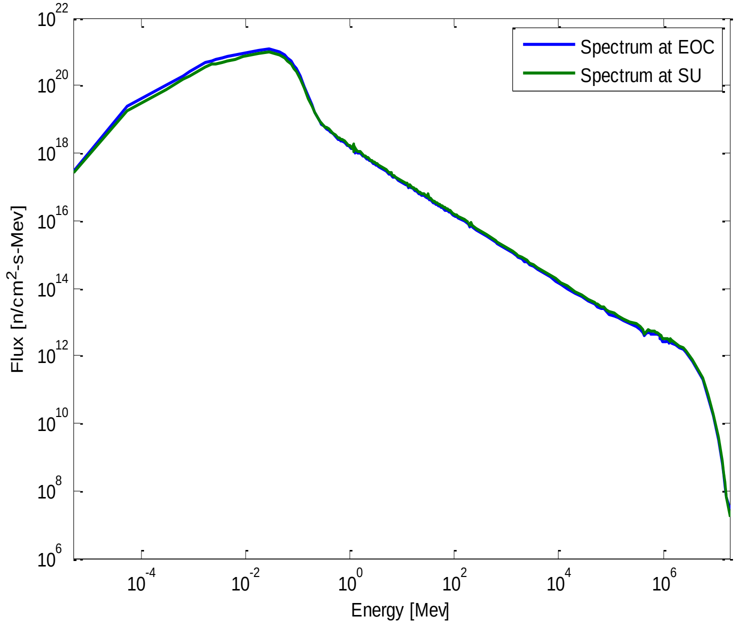
Reactivity Insertion Accident (RIA)



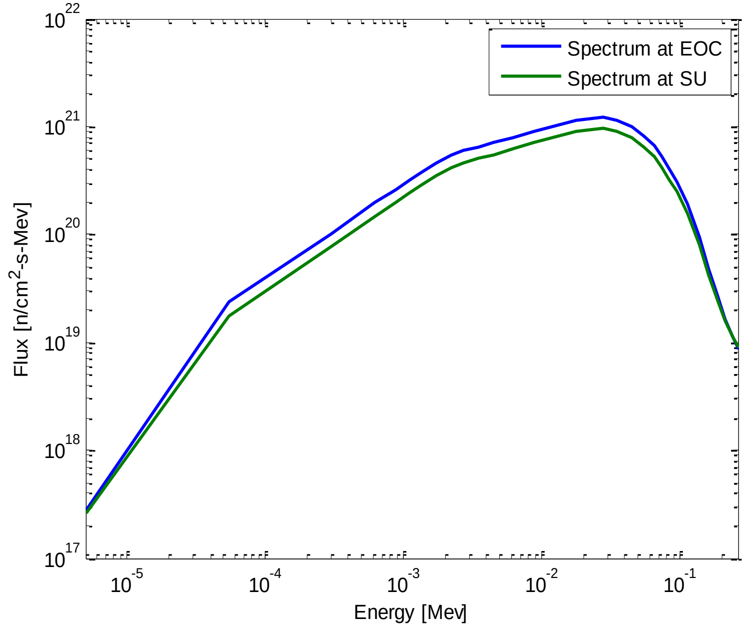
Case	Peak power	Peak time (s)	Trip time (s)
SU	**1.35**	0.421	0.281
EOC	**1.37**	0.399	0.259

- The reactor is initially operating at full power (P=1.0).
- A ramp reactivity insertion starts at t = 0 with assumed insertion rate 500 pcm/sec and stops at t = 0.5 sec.
- The time-step used in entire transient period was ~1 ms.
- The over-power level trip is set to 120% of nominal operating power (P=1.2) in the accident.
- The safety scram is postponed with 140 ms to account for the delay in response of the trip circuits and the finite time for safety rod insertion.
- Upon scram, the control rods are all inserted with the assumption that the initial CR position corresponds to the critical position.

Core Averaged Flux Spectra at SU and EOC



Entire energy range



Thermal energy range

Conclusion and Future Work

- Preliminary safety analyses on NIST's proposed LEU fueled beam reactor were performed using a single-channel T/H model and a point kinetics model.
- The preliminary T/H analysis results indicate reasonably sufficient safety margins were achievable in terms of MCHFR and MOFIR estimated in both steady-state operational and hypothetical design basis transient conditions for the SU and EOC cores.
- Additional accident scenarios including LOF and LOCA will be investigated using more detailed safety analyses methodologies (e.g. multi-channel T/H model) and tools (e.g. ANL-PLTEMP and PARET code).

Thank you!