A Novel Compact Core Design for Beam Tube Research Reactors

Zeyun Wu[1,2], Max Carlson[3], Robert Williams[1], Sean O'Kelly[4], and J. Michael Rowe[1]

[1]NIST Center for Neutron Research, 100 Bureau Drive, Gaithersburg, MD

[2]Department of Materials Science and Engineering, University of Maryland, College Park, MD

[3]Department of Nuclear Engineering and Science, MIT, Cambridge, MA

[4]Andvanced Test Reactor Complex, Idaho National Laboratory, Idaho Falls, ID

ANS Annual Summer Meeting

San Antonio, TX

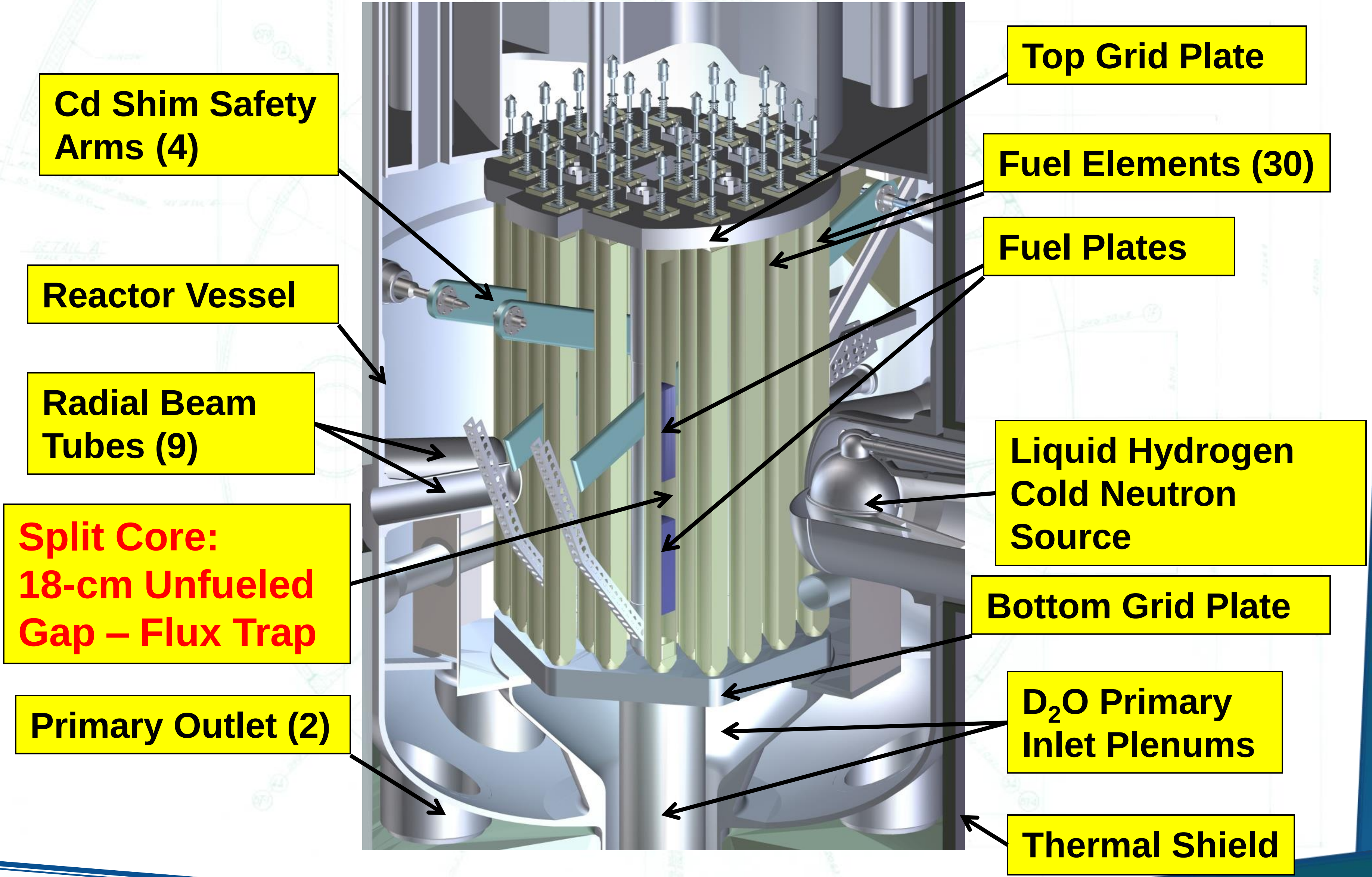
June 10th, 2015

Three Types of Research Reactors

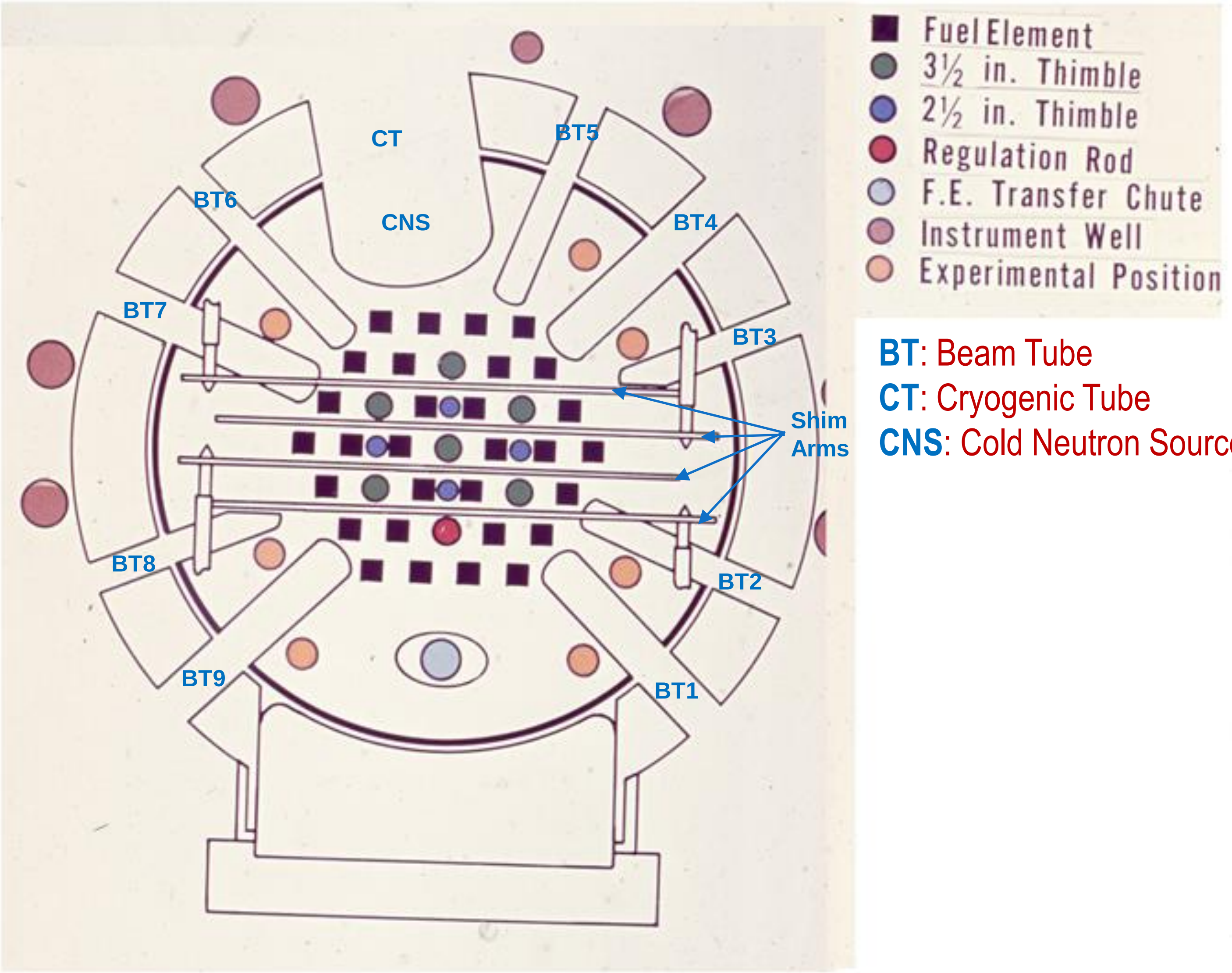
- Material Test Reactors (MTR)
  - Principally aim to investigate radiation damage by mostly fast neutrons in fuels or structure materials
- Isotope Production Reactors
  - Mainly are used to produce radioactive isotopes or sources, and also to dope materials with stable elements via nuclear transmutation with thermal neutrons
- Beam Tube Reactors
  - Primarily provide beams to extract slow (i.e. thermal, cold, or hot) neutrons to enable neutron scattering experiments on samples in many fields of science and research.

Exclusive design considerations will be applied to cater for the needs of the primary utilization!

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



Cross-sectional View of the Mid-plane of the NBSR



BT: Beam Tube
CT: Cryogenic Tube
CNS: Cold Neutron Source

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 workable
- LEU U-10Mo monolithic fuel is feasible but not manufactured yet – may be 10 years off
- 30% more increase on fuel costs
- 10% reduction on neutron performance

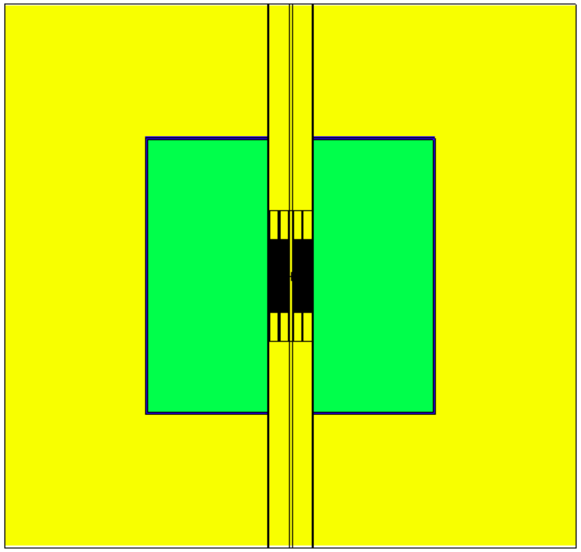
Inverse Flux Trap Principle & *Compact Core* Concept[1]

- The core volume **V** should be made as small as possible for a given constant reactor power **P**
- The compact core should be surrounded with a moderator (reflector) of high quality and large volume to maximize the thermal flux production
- The reactor power **P** should be chosen as high as possible to obtain a high absolute value of the thermal flux

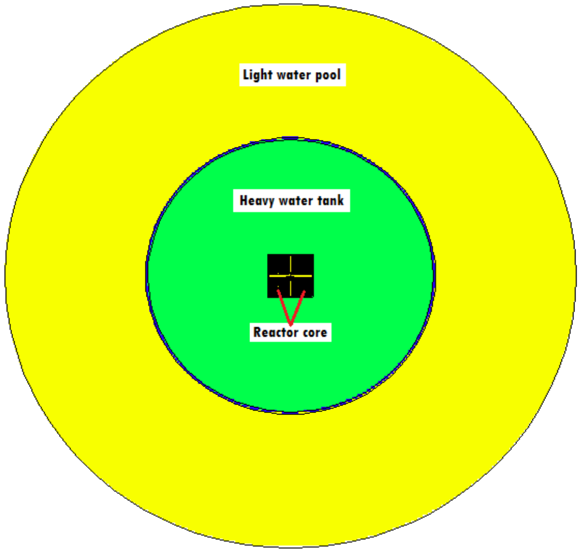
- Some advantages of compact core design
  - High "quality factor" – Φ^{max}_{th} /**P**
  - Large "usable volume" – $\mathbf{V_{eff}}$ in the reflector
  - High spectral purity of the thermal neutron flux Φ_{th}

[1]. K. Boning and P. Von Der Hardt, "Physics and Safety of Advanced Research Reactors," *Nuclear Instruments and Methods in Physics Research* A260 p.239-246 (1987)

Schematics of a Compact Core Configuration



(a) X-Z view



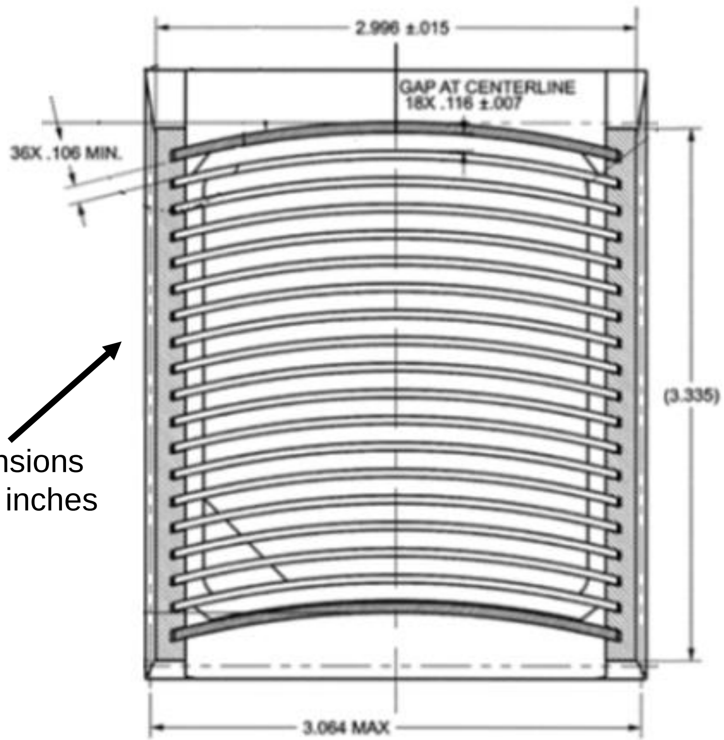
(b) X-Y view

A Schematic view of cutaway side-plane (left) and mid-plane (right) of the reactor.

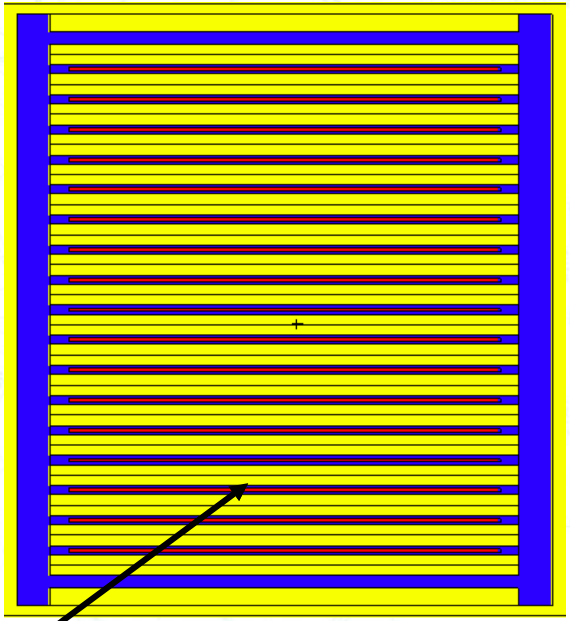
Reactor Size (m)	Value
Heavy water tank diameter	2.5
Heavy water tank height	2.5
Heavy water tank thickness	2.0
Light water pool diameter	5.0
Light water pool height	5.0

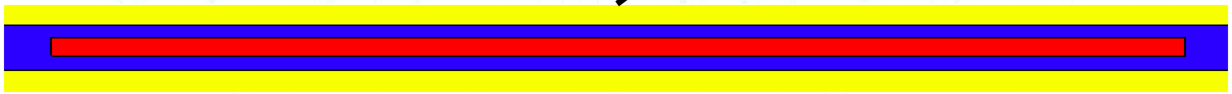
The MTR-type Fuel Plate and Fuel Element

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



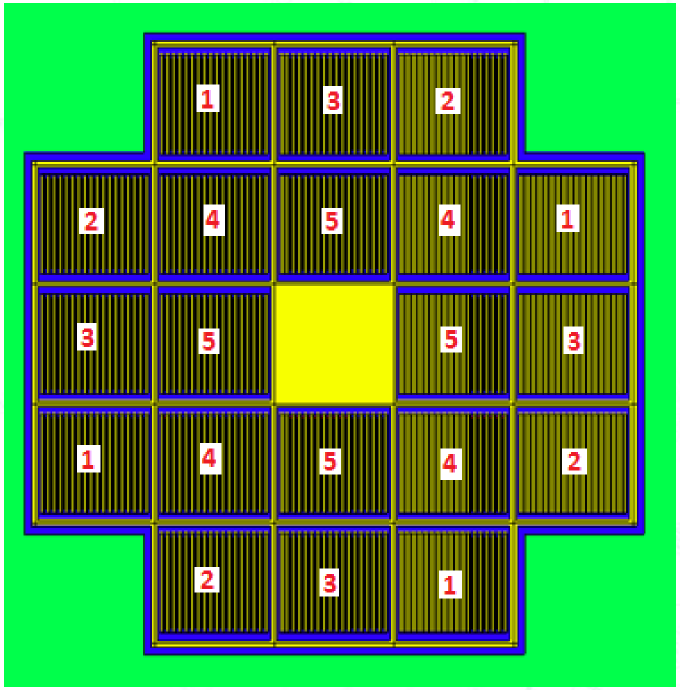
Dimensions are in inches



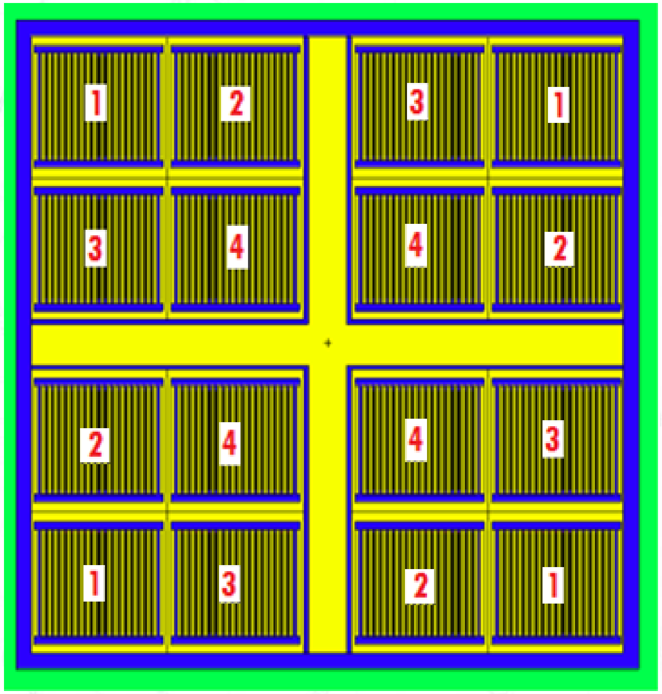


The fuel plate: For the U_3Si_2/Al fuel meat, it is 0.066 cm (26 mil) thick and 6.134 cm wide.

Compact Core Examples:



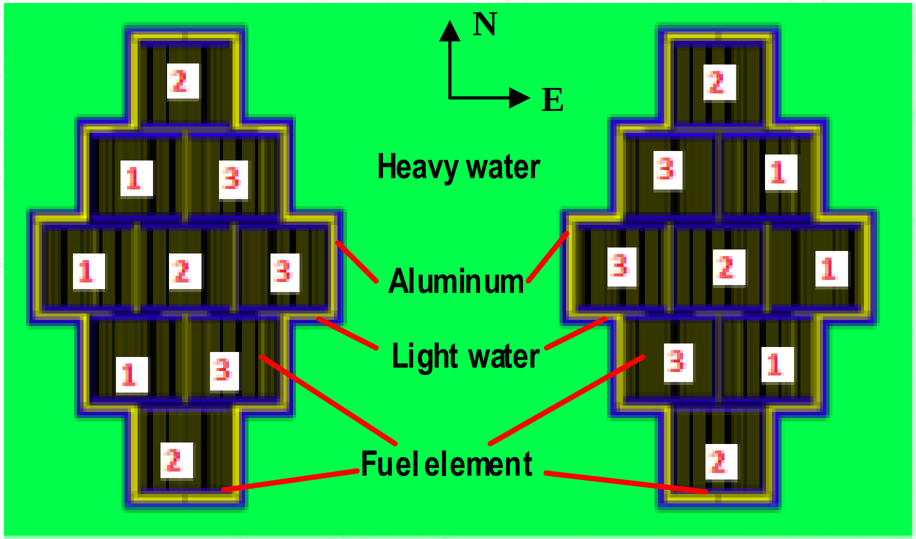
(a) 20 FE Core



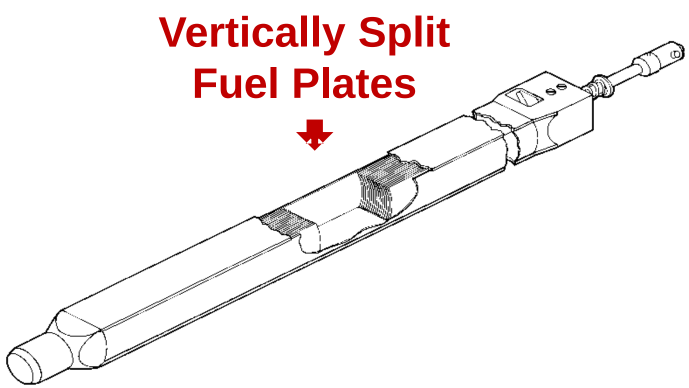
(b) 16 FE Core

The 20 FE core is similar to the CARR (China Advanced Research Reactor) core, and the 16 FE core is similar to the OPAL (Open Pool Australian Light-water Reactor) core.

Horizontally Split Core With 18 Fuel Elements



Schematic view of the core

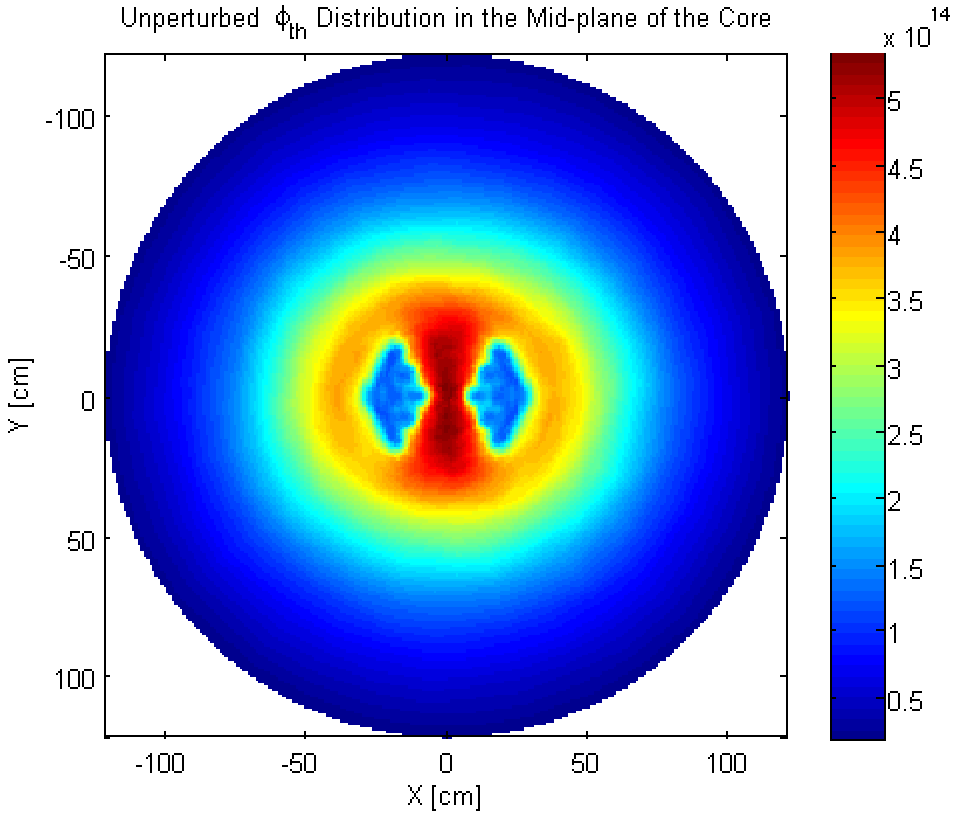


Cut-away view of the NBSR fuel element

Core Design Information

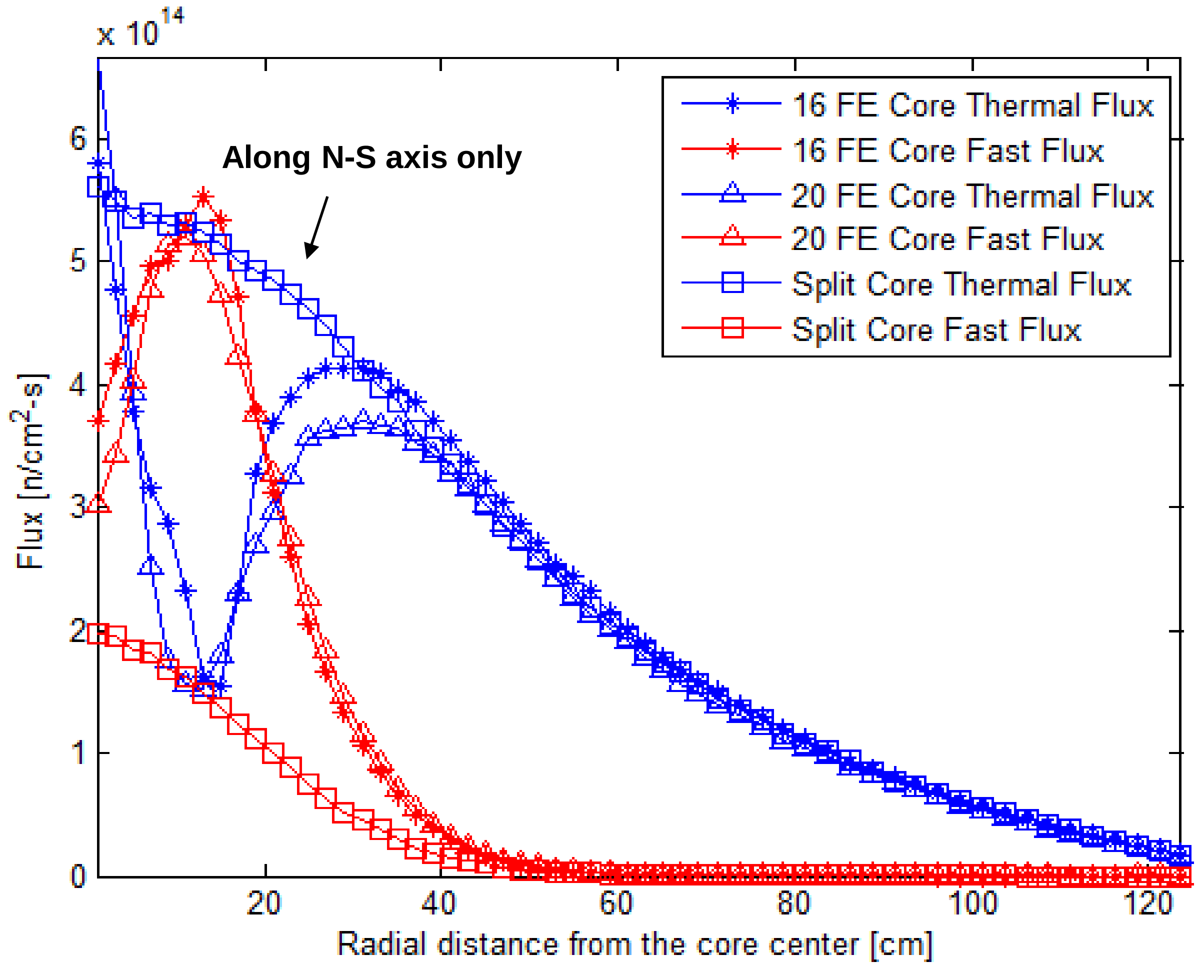
Parameter	Data
Thermal power rate (MW)	20
Fuel cycle length (days)	30
Active fuel height (cm)	60.0
Fuel material	U_3Si_2/Al
U-235 enrichment in the fuel (wt. %)	19.75
Fuel mixture density (g/cc)	6.52
Uranium density (g/cc)	4.8
U-235 mass per fuel element (gram)	391.5
Number of fuel elements in the core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

Planar View of Unperturbed Thermal Flux at EOC of the Equilibrium Core



- Maximum thermal flux occurs in the space between split halves of the core.
- Even outside of core, the thermal flux is 2-3 times existing NBSR beams.

Comparison of Unperturbed Radial Flux at EOC



UNIVERSITY OF MARYLAND

NIST

Figures of Merit of the Three Cores

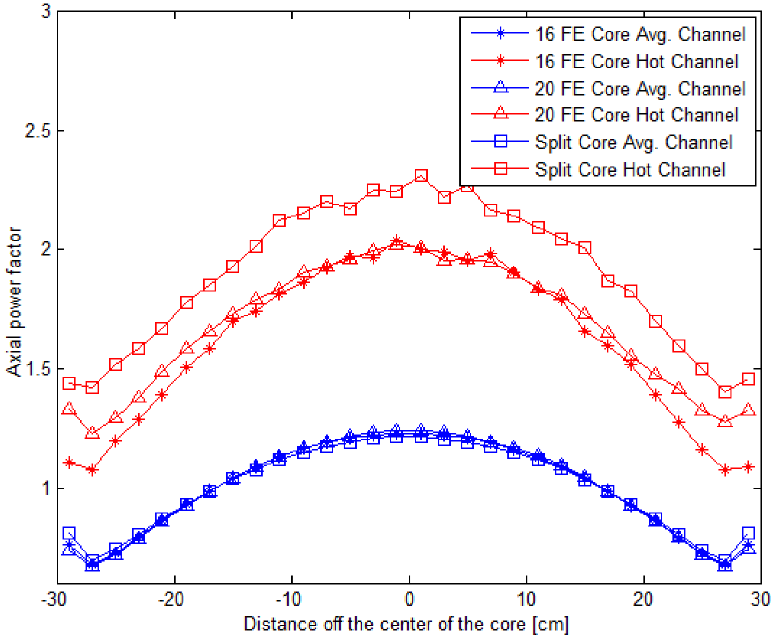
Core Type	16 FE Core	20 FE Core	Split Core
Max. thermal flux in reflector ($\times 10^{14}$ n/cm^2-s)	4.32	3.88	5.62
Quality factor[a] ($\times 10^{13}$ MTF/MW$_{th}$)	2.16	1.94	2.81
Effective volume fraction[b] (%)	27.29	23.20	36.37

[a]Defined as the ratio of maximum thermal flux (MTF) to the total thermal power of the reactor

[b]Defined as the fraction of volume with thermal flux greater than 3×10^{14} n/cm^2-s in the reflector tank

Total Power Peaking Factor (PPF) and Axial Power distribution

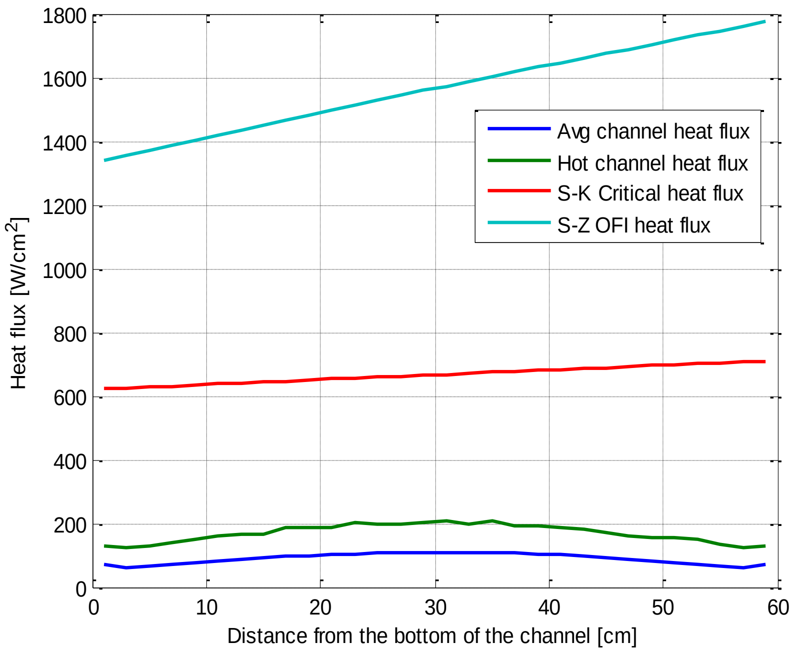
Core Type	16 FE Core	20 FE Core	Split Core
Total PPF	2.14	2.25	2.45
Plate-wise PPF	1.65	1.68	1.91
Fuel Element-wise PPF	1.05	1.14	1.10
Axial PPF	1.23	1.24	1.21



All PPFs stay at an acceptable level based on recent thermal limit condition analyses performed on LEU fueled reactor [**Ref.**].

[Ref.] D. J. DIAMOND, et al. "Conversion Preliminary Safety Analysis Report for the NIST Research Reactor", Brookhaven National Laboratory, Upton, NY, December (2014).

Preliminary Operational T/H Safety Analysis



Heat flux at EOC for the split core

- The critical heat flux (CHF) is estimated using Sudo-Kaminaga correlation[1]
- The heat flux at onset of flow instability (OFI) is determined based on the Saha-Zuber criteria[2]
- The calculated minimum critical heat flux ratio (MCHFR) is **3.22**, and the minimum heat flux ratio at onset of flow instability (MOFIR) is **7.54**
- Both MCHFR and MOFIR have reasonable large safety margins

[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)

[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).

Summary

- A new compact core design for beam tube reactors with a novel fuel element geometry arrangement is proposed.
- Horizontally split core configuration offers higher thermal flux and acquires more accessible spaces in the reflector.
- Results from MCNP calculations verify the superiority of the split core by comparing basic core performance characteristics of the new design to that of the other two cores similar to current existing reactors.
- The design is especially suited to installation of cold neutron sources due to high thermal flux and very low fast flux in the desired locations.

Thank you!