NIST Center for Neutron Research

CHRNS
CENTER FOR HIGH RESOLUTION NEUTRON SCATTERING

Thermal-Hydraulics Feasibility for an Ultra-Compact Nuclear Reactor Core

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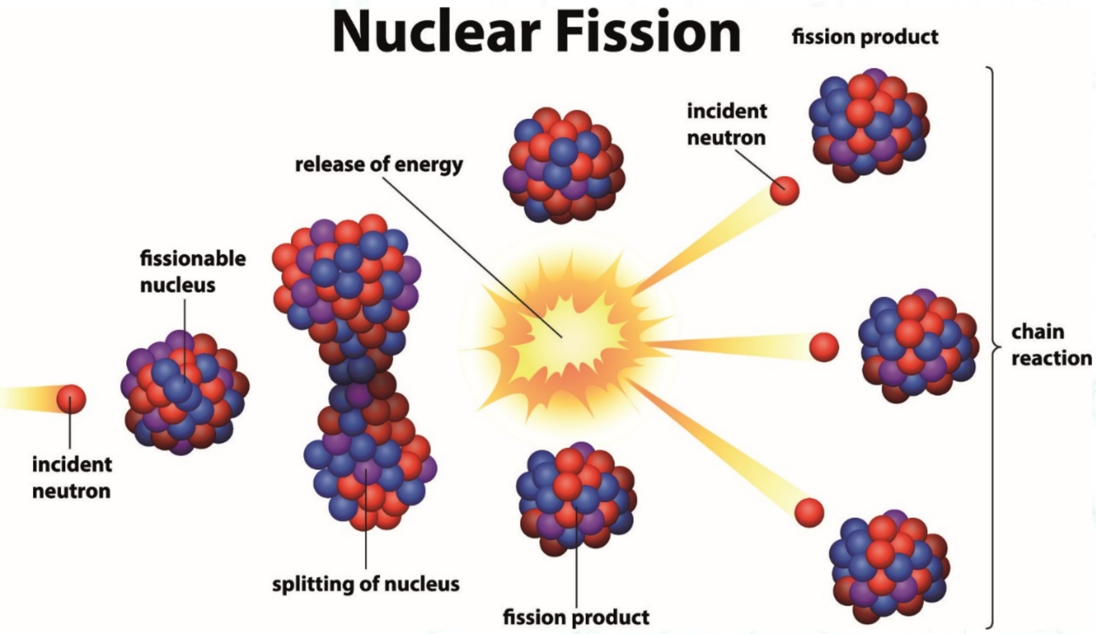
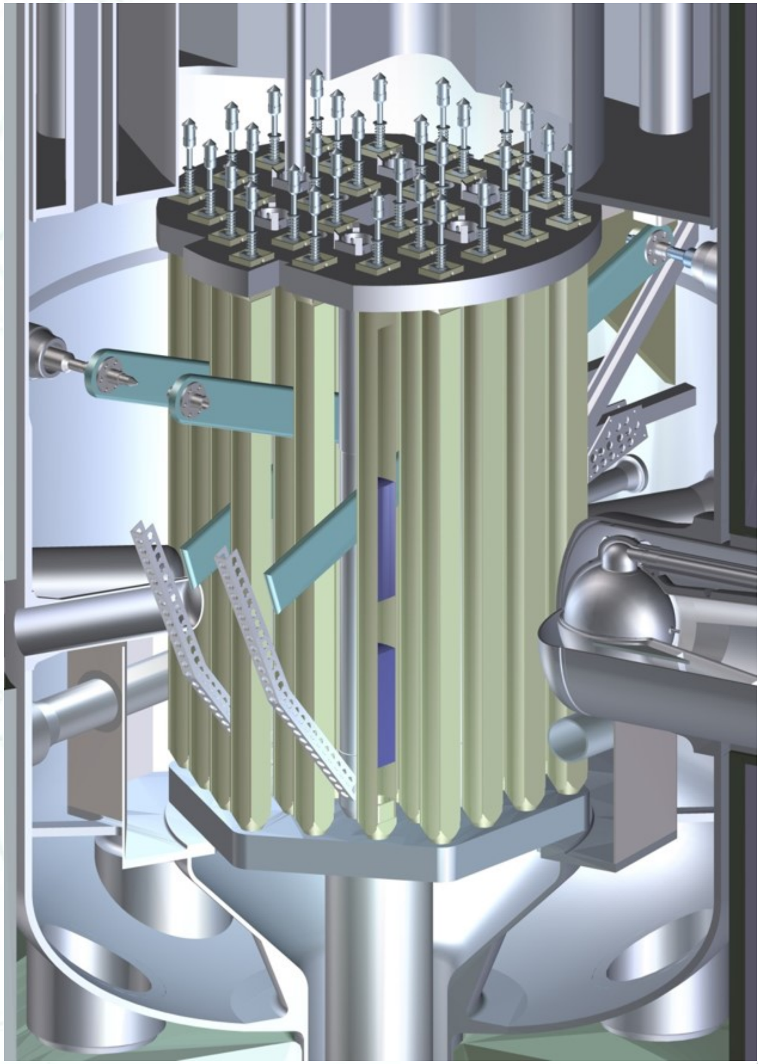
2019 SURF Symposium
6 August 2019
Reactor Operations and Engineering

NBSR

- Operation started in 1967
- Split core



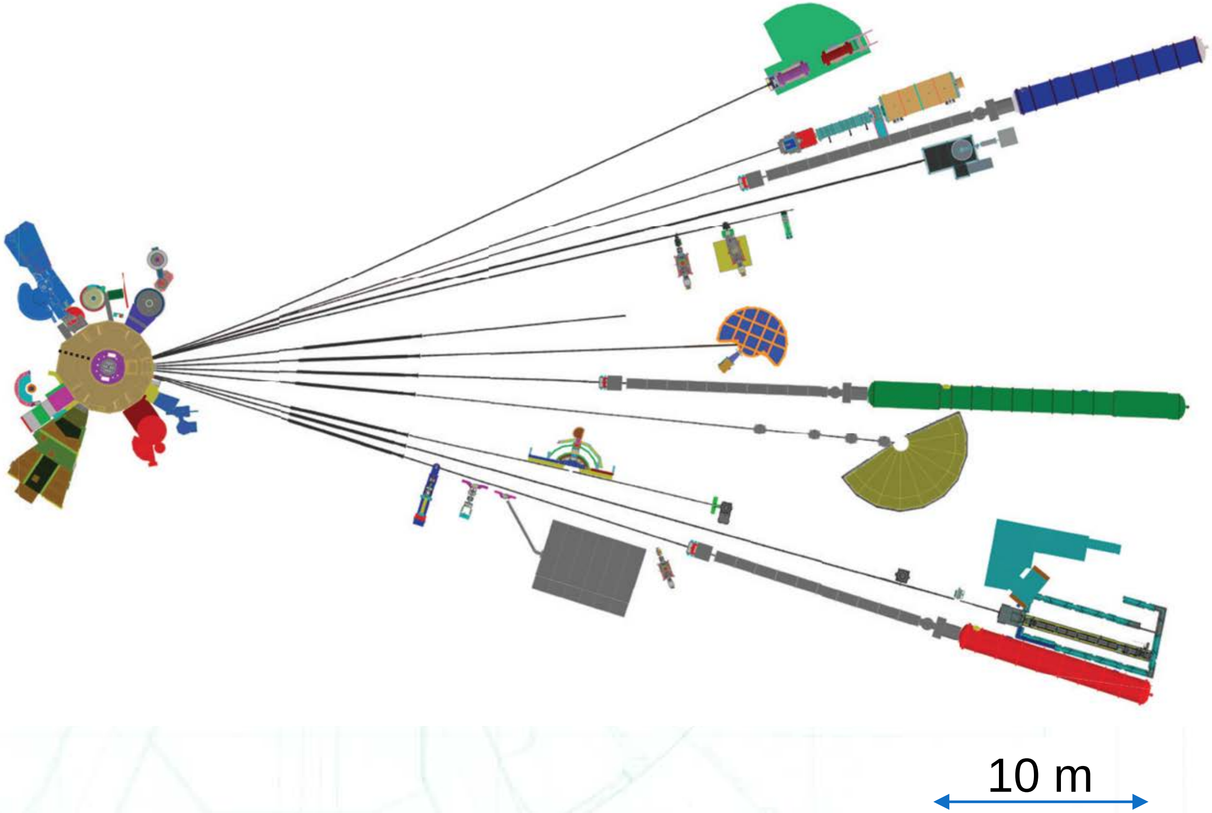
Nuclear Fission



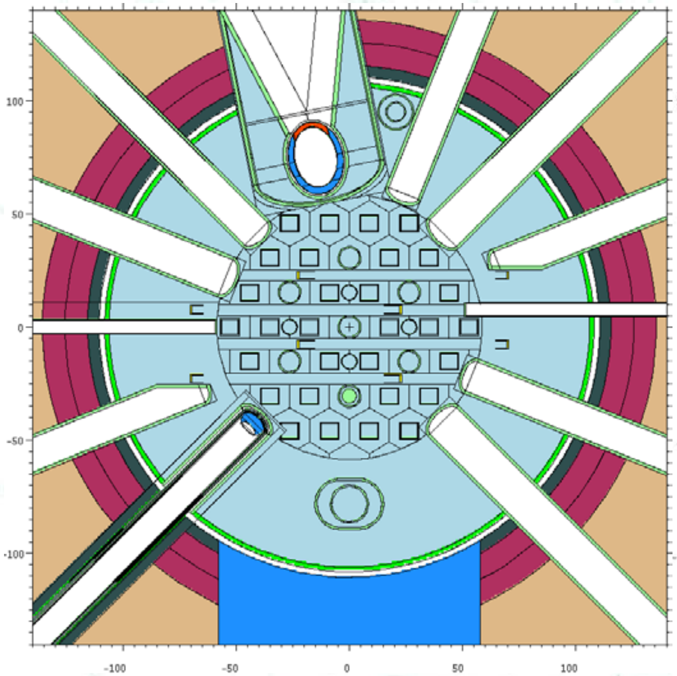
Why Neutron Research?

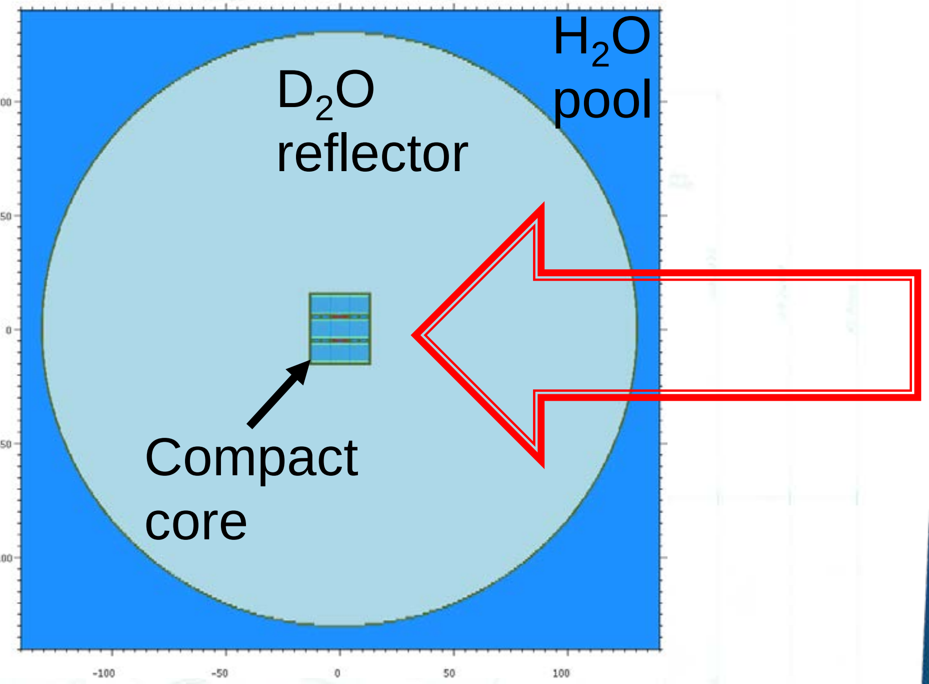
- Wavelengths
- Energies
- Selectivity
- Magnetism
- Neutrality
- Capture

NIST Center for Neutron Research Instruments



Replacement Reactor





NBSR

20 MW
"Loose" core
Closed vessel
HEU (U_3O_8/Al) fuel
30 fuel assemblies

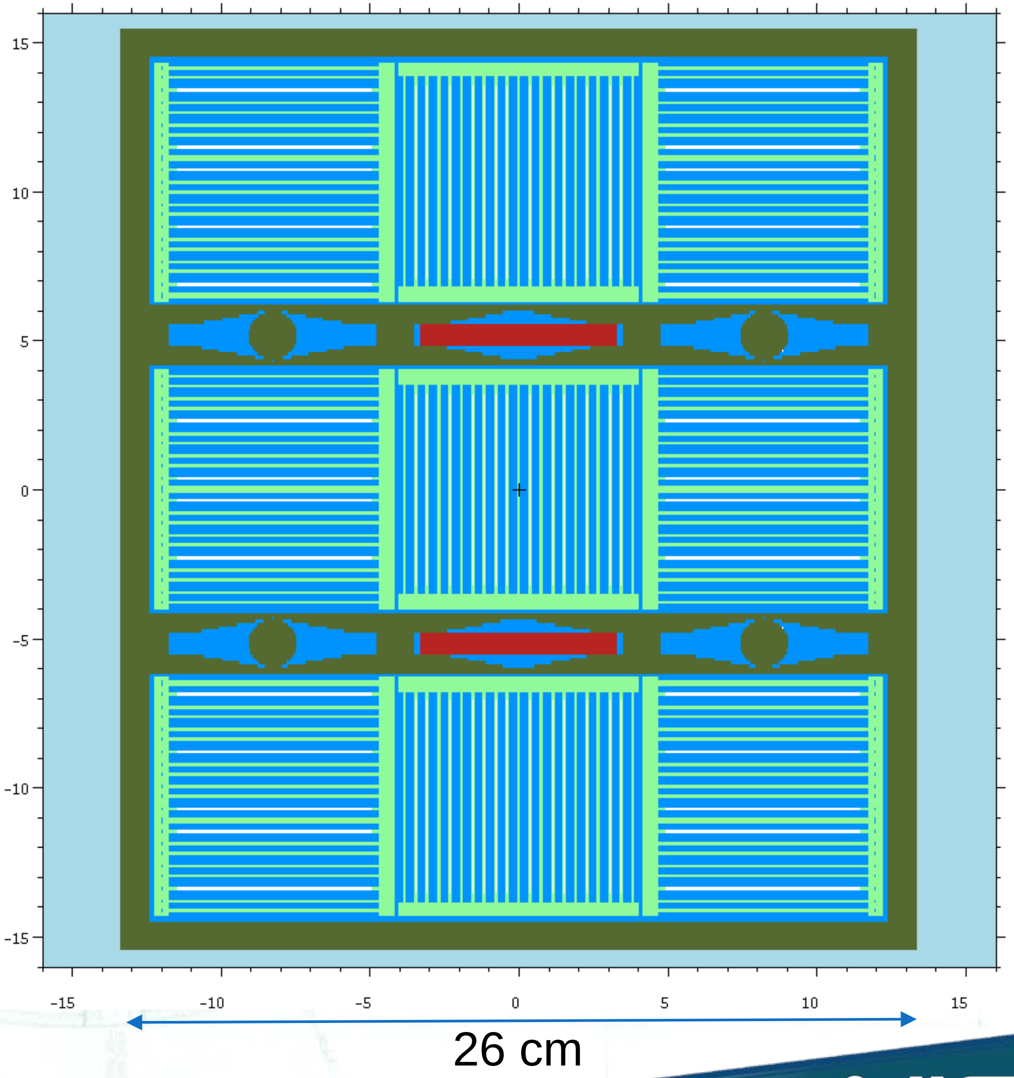
Concept Reactor

20 MW
Compact core
Open pool
LEU (U-10Mo) fuel
9 fuel assemblies

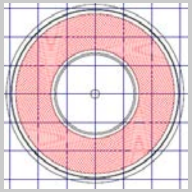
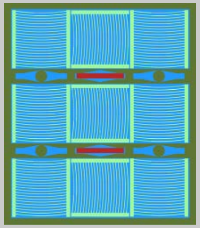
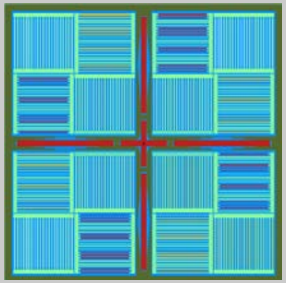
Replacement Reactor Features

- Ultra-compact
  - High Neutron Flux
- Greater accessibility
  - Maintenance

Zircaloy
Aluminum
Light Water
Hafnium
Heavy Water



Motivation for Compact Reactor Core

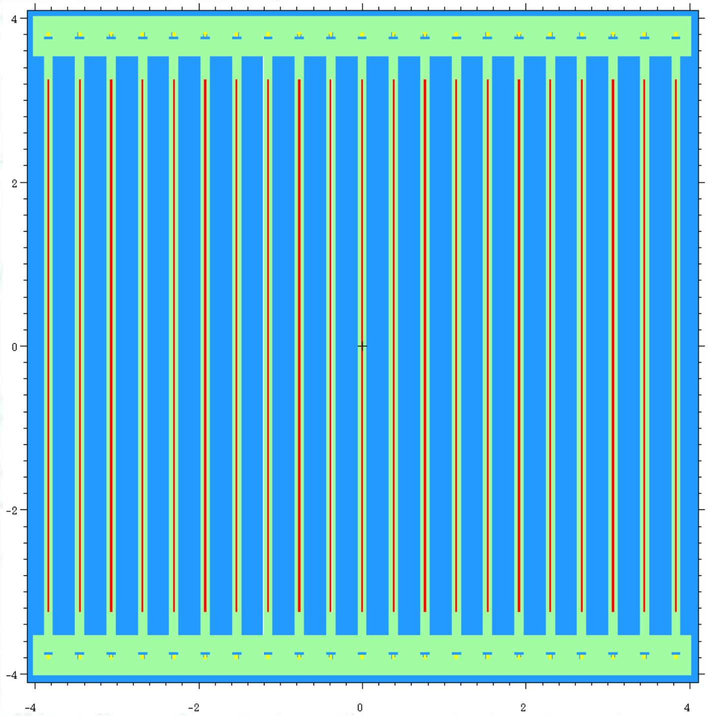
Reactor:	FRM-II	NIST concept	OPAL
Cross-sectional plan view of reactor core			
Power (MW)	20 MW	20 MW	20 MW
Volume	28 L	41 L	69 L
Peak thermal neutron flux in reflector	8×10^{14} $\mathrm{cm^{-2}s^{-1}}$	5.6×10^{14} $\mathrm{cm^{-2}s^{-1}}$	4×10^{14} $\mathrm{cm^{-2}s^{-1}}$

Replacement Reactor Challenges

- Compact core geometries
- Structural robustness
  - Larger forces acting on fuel elements
- Cooling
  - High heat flux per fuel element

Structural Stability

- Miller velocity
- 2/3 of Millers velocity for maximum actual flow
- Miller velocity design limit
  - High flow velocity can cause fuel plates to deform



21 Fuel Plate Cross-Section

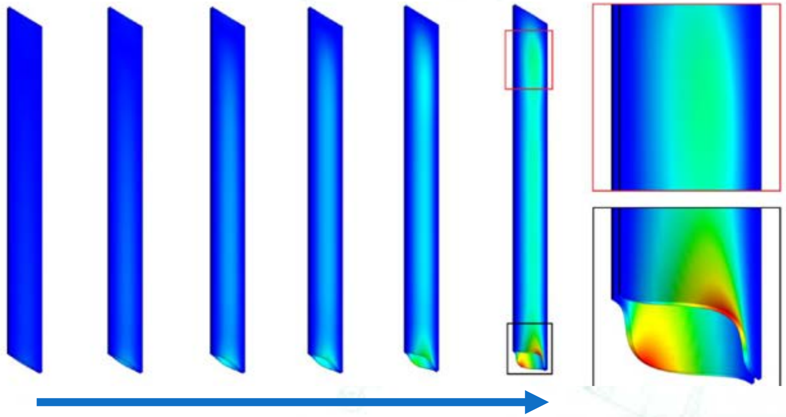


Plate deflection with increasing velocity

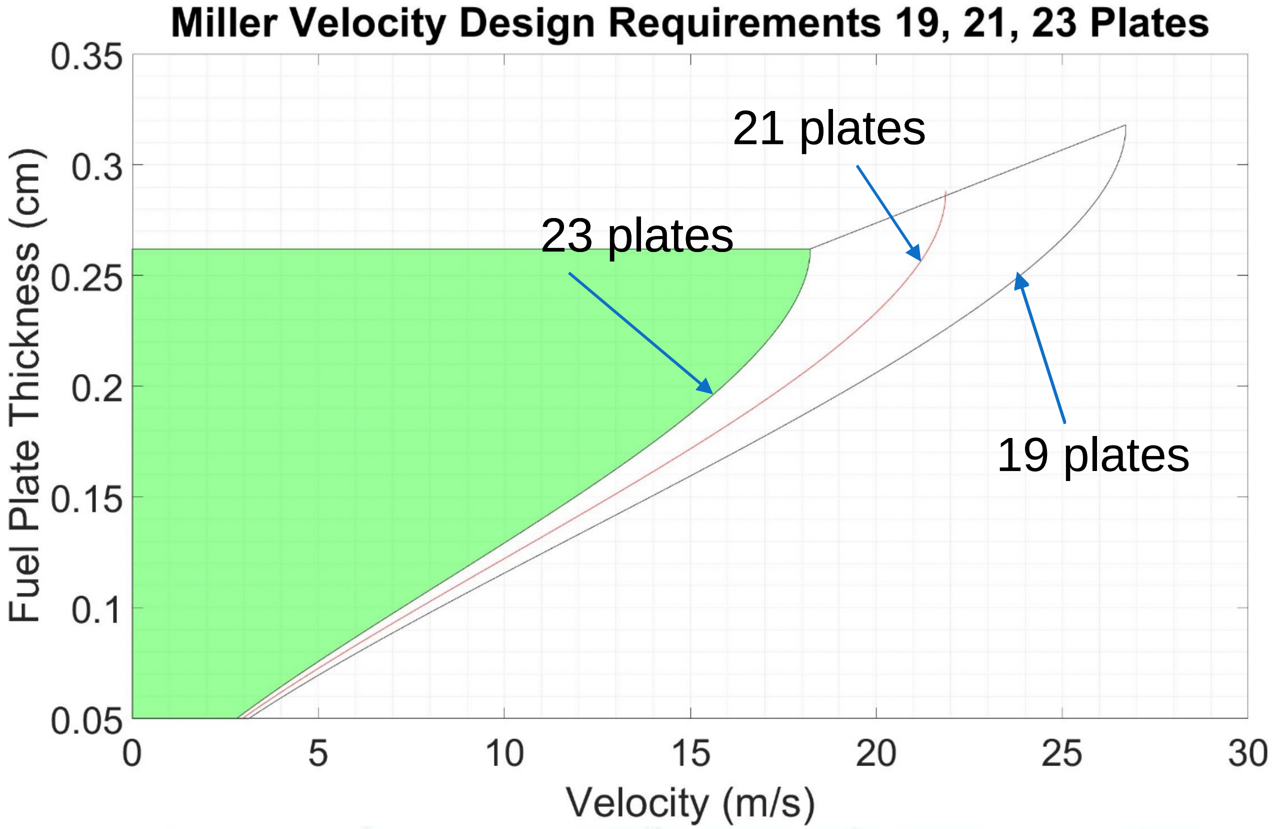
$$v_M = \sqrt{\frac{15Ea^3h}{\rho b^4(1-\upsilon^2)}}$$

E – Youngs Modulus
a – Plate Thickness
h – Channel Width

ρ – Coolant Density
b – Wetted Width
ν – Poisson’s Ratio

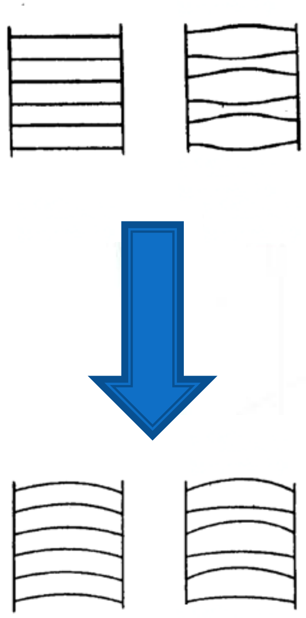
Structural Stability

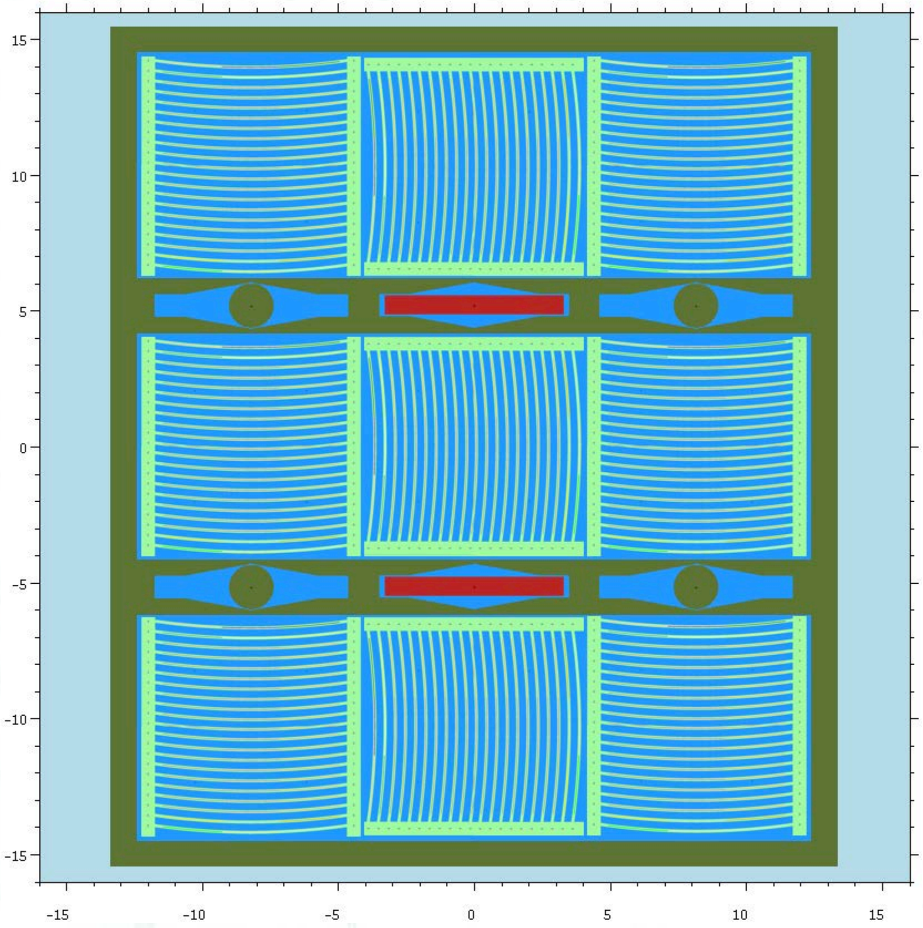
- High coolant flow velocity
- First step for optimized design



Structural Stability

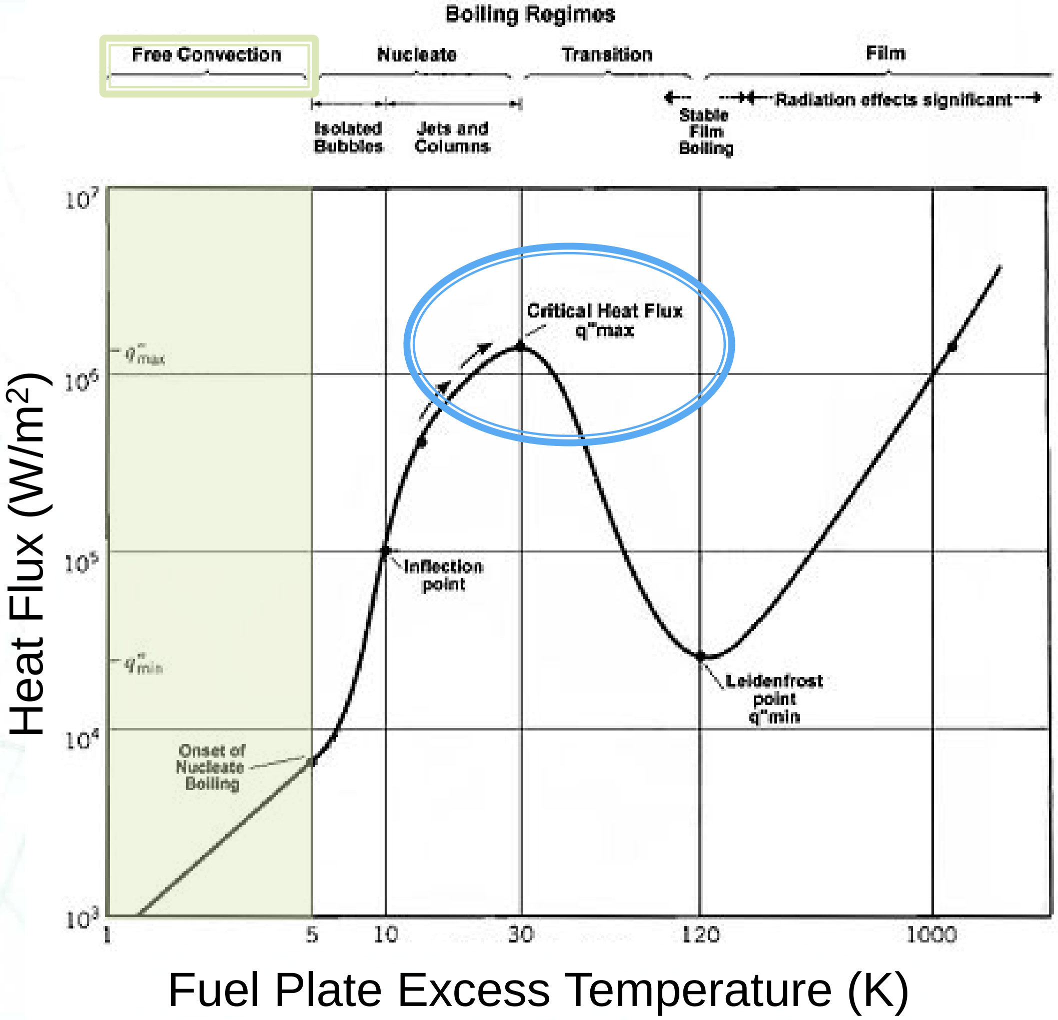
- Curving the fuel plates offers more structural stability





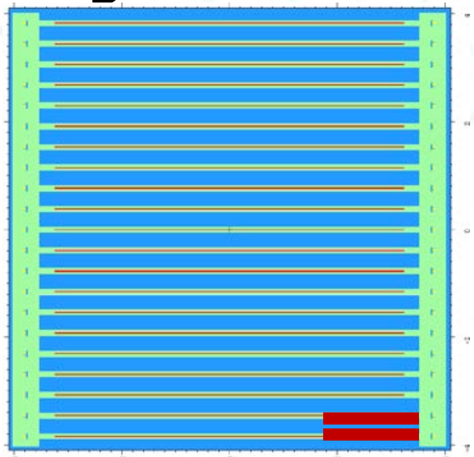
Critical Heat Flux (CHF)

- Failure of the heated surface may occur once the CHF is exceeded
- Design for free convection phase

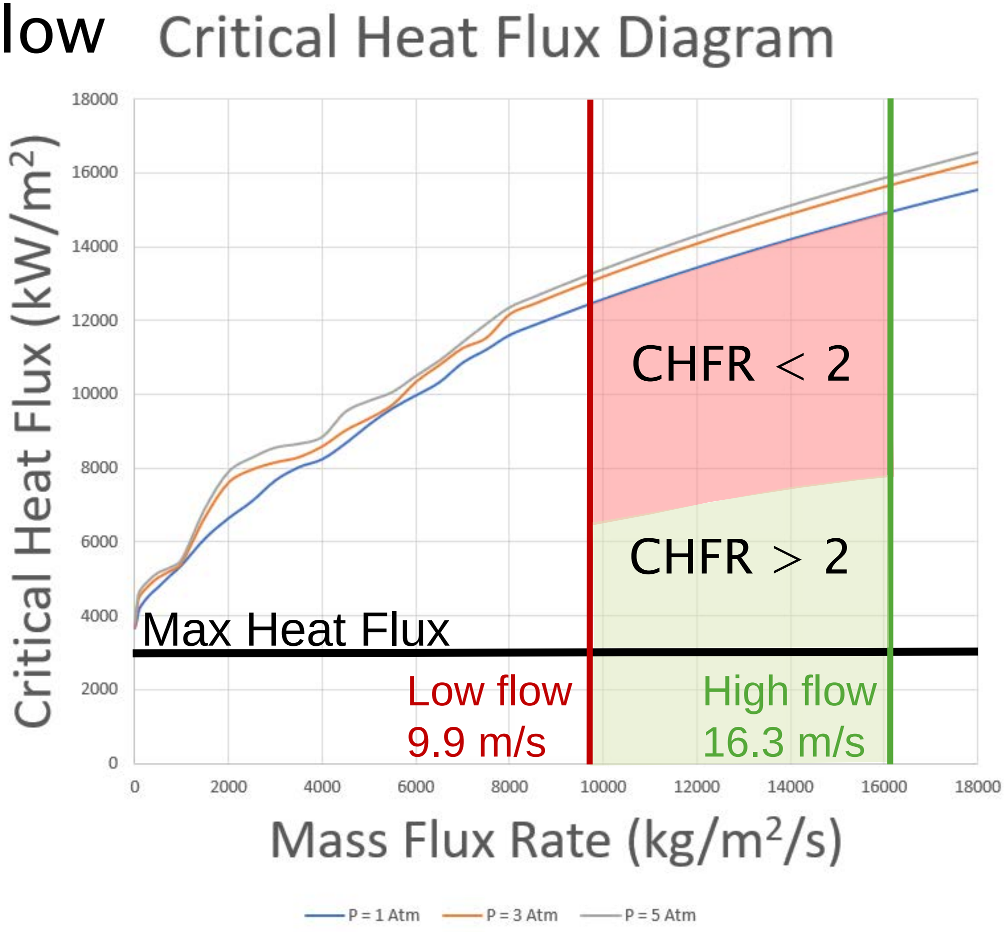


Critical Heat Flux (CHF)

- Low flow and high flow design case



- Average heat flux =1,160 (kW/m²)
- Max heat flux =2,900 (kW/m²)
- CHF Ratio > 2



COMSOL

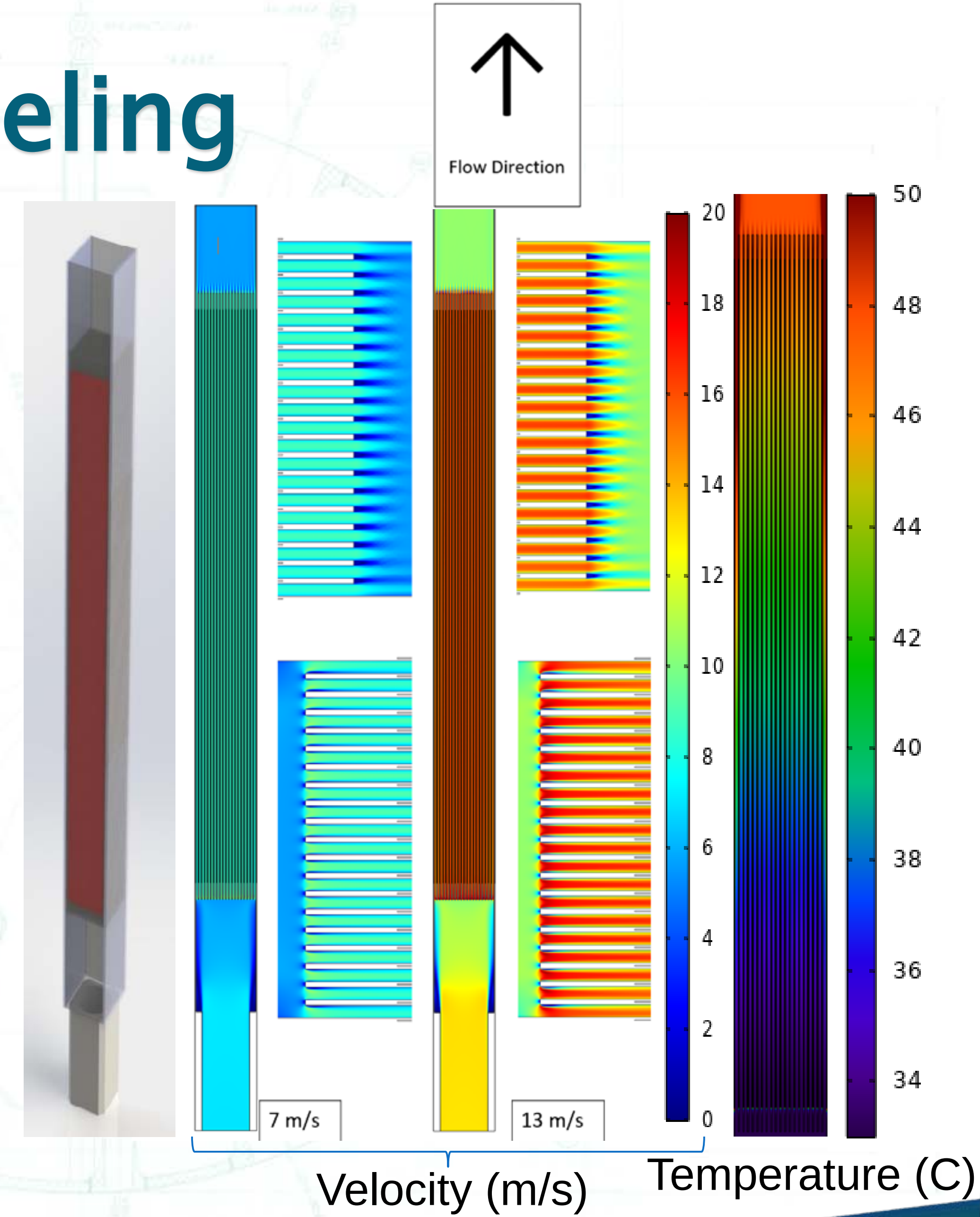
- Multiphysics solver
  - Computational fluid dynamics
  - Heat transfer
  - Nonisothermal flow

- Evaluate
  - Pressure drop
  - Temperature increase
  - Change in flow velocity

COMSOL Modeling

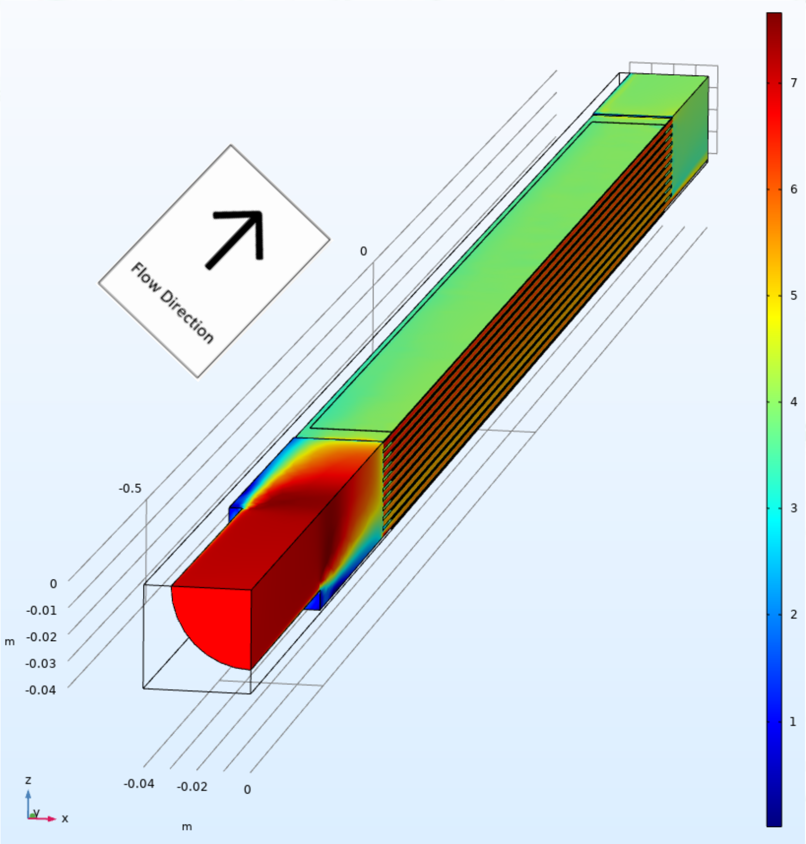
- 2D single element
- Temperature model

Fuel Element Flow Properties			
Inlet Velocity (m/s)	Temperature Increase (degC)	Pressure Drop (Atm)	Channel Flow Velocity (m/s)
7	15.65	0.99	9.2
8	13.70	1.24	10.6
9	12.18	1.50	11.9
10	10.96	1.79	13.2
11	9.96	2.11	14.5
12	9.12	2.45	15.9
13	8.41	2.82	17.2

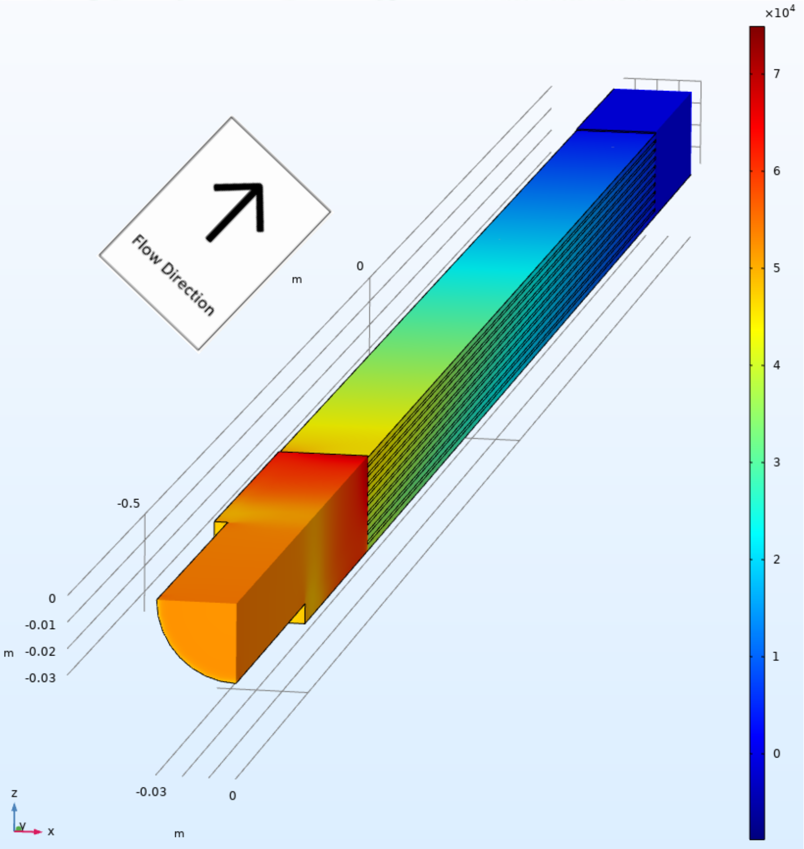


COMSOL Modeling

- 3D single fuel element



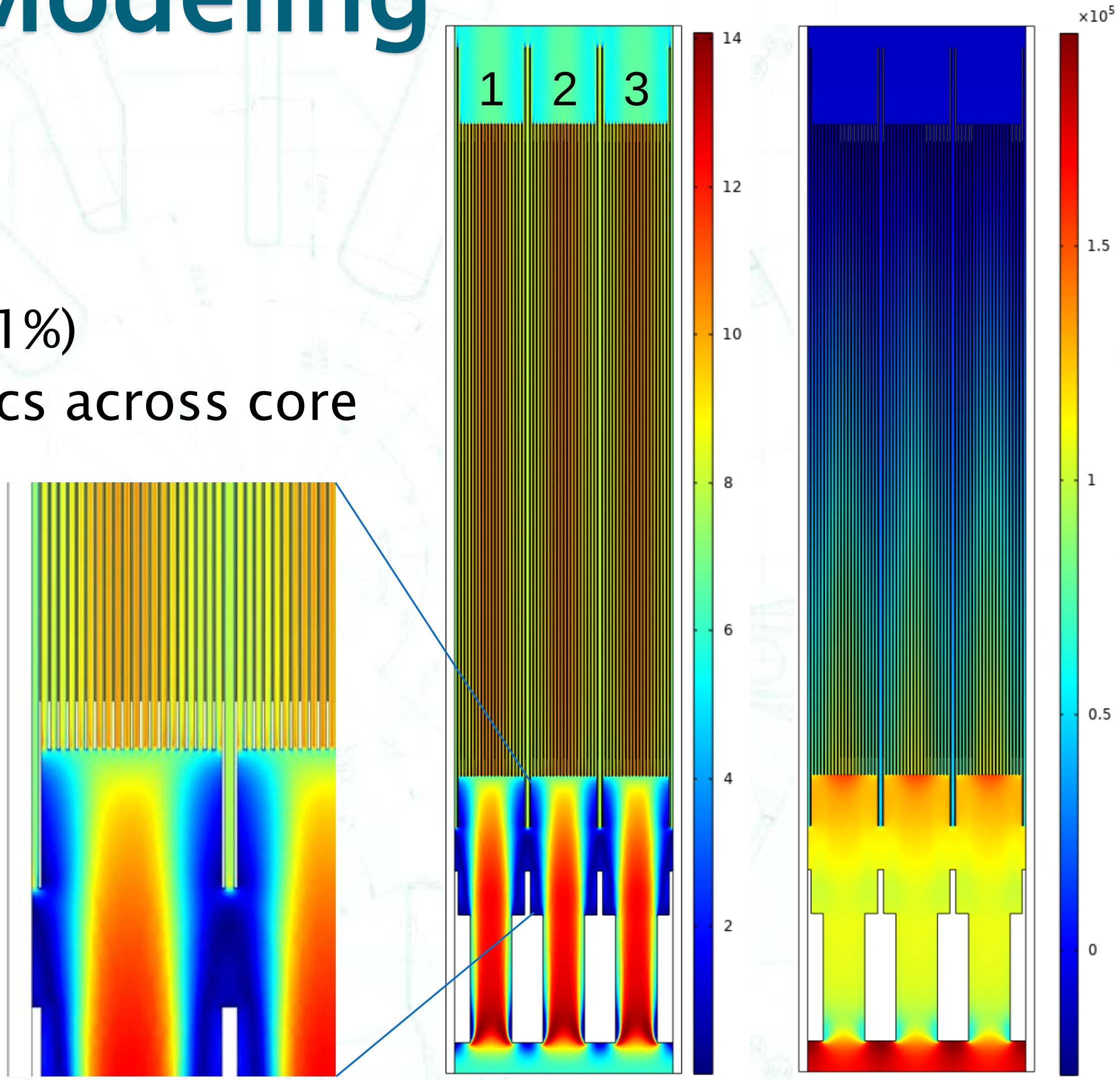
Velocity (m/s)



Pressure (Pa)

COMSOL Modeling

- 2D Core slice
  - Flat fuel plates
  - Bypass flow (7.1%)
  - Thermodynamics across core



Velocity (m/s)

Pressure (Pa)

Conclusion

- COMSOL capabilities can extend to full reactor core
- Structural advantage with curved plates
- Critical heat flux and critical velocity are designed
- Greater neutron flux can be achieved

Future Direction

- Run a full core simulation
- Virtual reactor
- Fluid structure interaction

Acknowledgements

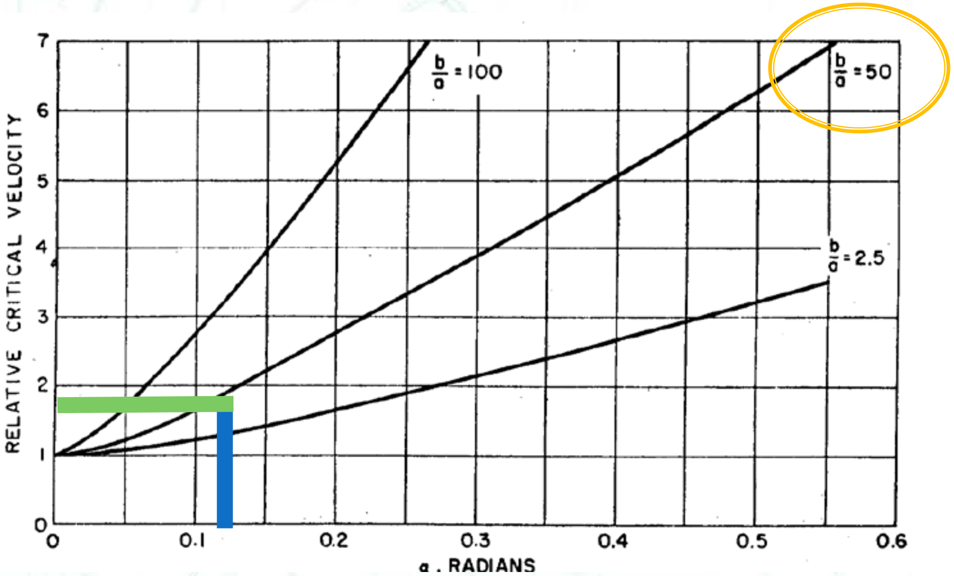
- Danyal Turkoglu
- Daniel Mattes
- Julie Borchers
- Joe Dura
- Reactor Operations and Engineering

Reference

- Mantecón, Javier González. *Evaluation of mechanical stability of nuclear fuel plates under axial flow conditions*. Diss. Universidade de São Paulo, 2019.
- Miller, D.R. *CRITICAL FLOW VELOCITIES FOR COLLAPSE OF REACTOR PARALLEL-PLATE FUEL ASSEMBLIES*. United States: N. p., 1958.
- Groeneveld, D.C. & Shan, Jianqiang & Vasić, A.Z. & Leung, Laurence & Durmayaz, A & Yang, Jun & Cheng, S.C. & Tanase, A. (2007). The 2006 CHF look-up table. Nuclear Engineering and Design. 2007.02.014.

Structural Stability

- Radius of Curvature of 25 cm increases the designed strength
- Factor of 1.7x higher velocity



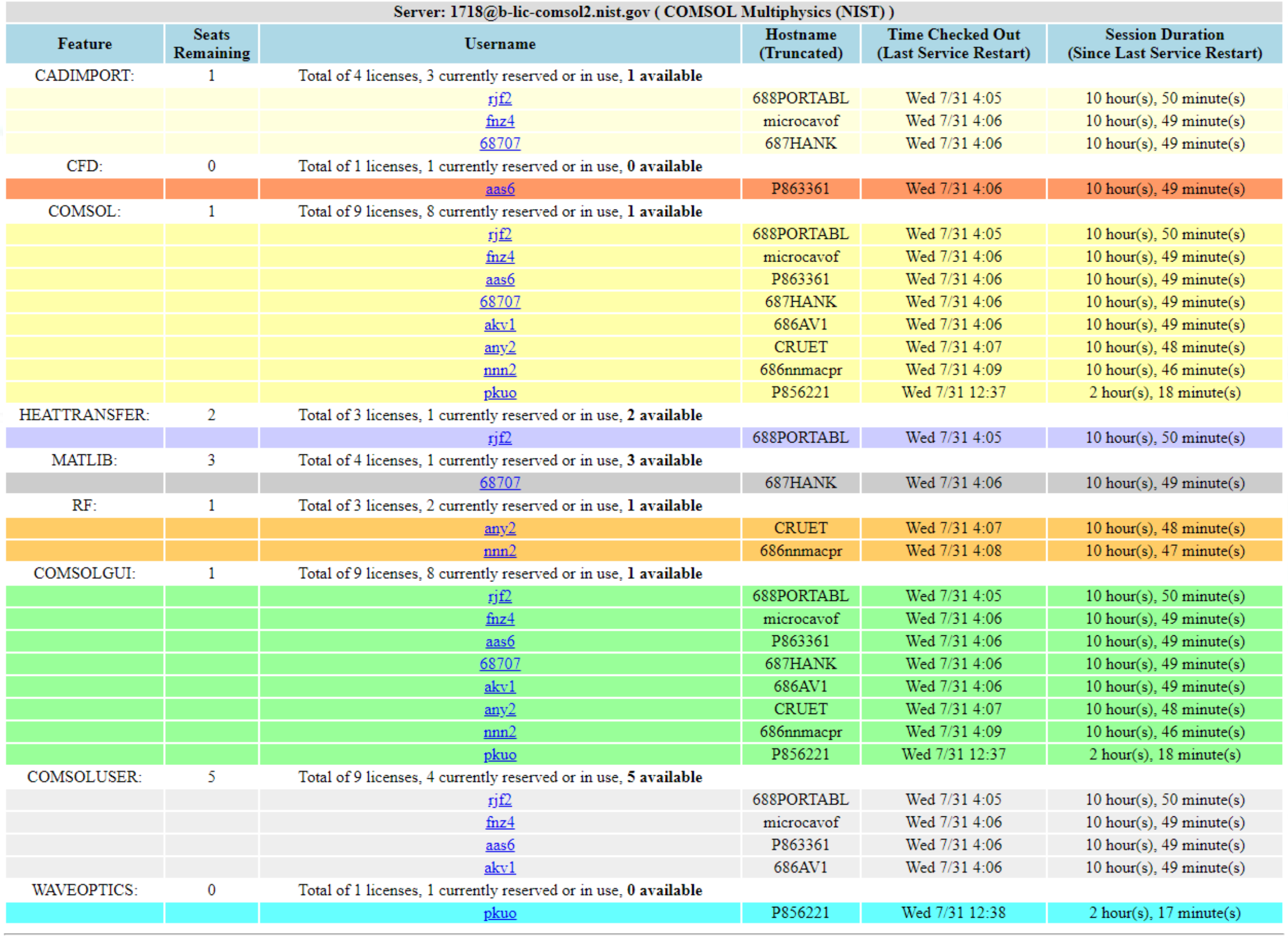
- Alpha = 0.1392

- b/a = 58

- Vrf = 1.7

$$V_{rf} = \left[\frac{48\ \beta_1 \sin^5 \alpha}{45\left(4-3\,\frac{\sin 2\alpha}{\alpha} + 2\cos 2\alpha\right)} \right]^{1/2}$$

Limited COMSOL Availability



Server: 1718@b-lic-comsol2.nist.gov (COMSOL Multiphysics (NIST))

Feature	Seats Remaining	Username	Hostname (Truncated)	Time Checked Out (Last Service Restart)	Session Duration (Since Last Service Restart)
CADIMPORT:	1	Total of 4 licenses, 3 currently reserved or in use, **1 available**			
		rjf2	688PORTABL	Wed 7/31 4:05	10 hour(s), 50 minute(s)
		fnz4	microcavof	Wed 7/31 4:06	10 hour(s), 49 minute(s)
		68707	687HANK	Wed 7/31 4:06	10 hour(s), 49 minute(s)
CFD:	0	Total of 1 licenses, 1 currently reserved or in use, **0 available**			
		aas6	P863361	Wed 7/31 4:06	10 hour(s), 49 minute(s)
COMSOL:	1	Total of 9 licenses, 8 currently reserved or in use, **1 available**			
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		aas6	P863361	Wed 7/31 4:06	10 hour(s), 49 minute(s)
		68707	687HANK	Wed 7/31 4:06	10 hour(s), 49 minute(s)
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		any2	CRUET	Wed 7/31 4:07	10 hour(s), 48 minute(s)
		nnn2	686nnmacpr	Wed 7/31 4:09	10 hour(s), 46 minute(s)
		pkuo	P856221	Wed 7/31 12:37	2 hour(s), 18 minute(s)
HEATTRANSFER:	2	Total of 3 licenses, 1 currently reserved or in use, **2 available**			
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MATLIB:	3	Total of 4 licenses, 1 currently reserved or in use, **3 available**			
		68707	687HANK	Wed 7/31 4:06	10 hour(s), 49 minute(s)
RF:	1	Total of 3 licenses, 2 currently reserved or in use, **1 available**			
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		68707	687HANK	Wed 7/31 4:06	10 hour(s), 49 minute(s)
		akv1	686AV1	Wed 7/31 4:06	10 hour(s), 49 minute(s)
		any2	CRUET	Wed 7/31 4:07	10 hour(s), 48 minute(s)
		nnn2	686nnmacpr	Wed 7/31 4:09	10 hour(s), 46 minute(s)
		pkuo	P856221	Wed 7/31 12:37	2 hour(s), 18 minute(s)
COMSOLUSER:	5	Total of 9 licenses, 4 currently reserved or in use, **5 available**			
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WAVEOPTICS:	0	Total of 1 licenses, 1 currently reserved or in use, **0 available**			
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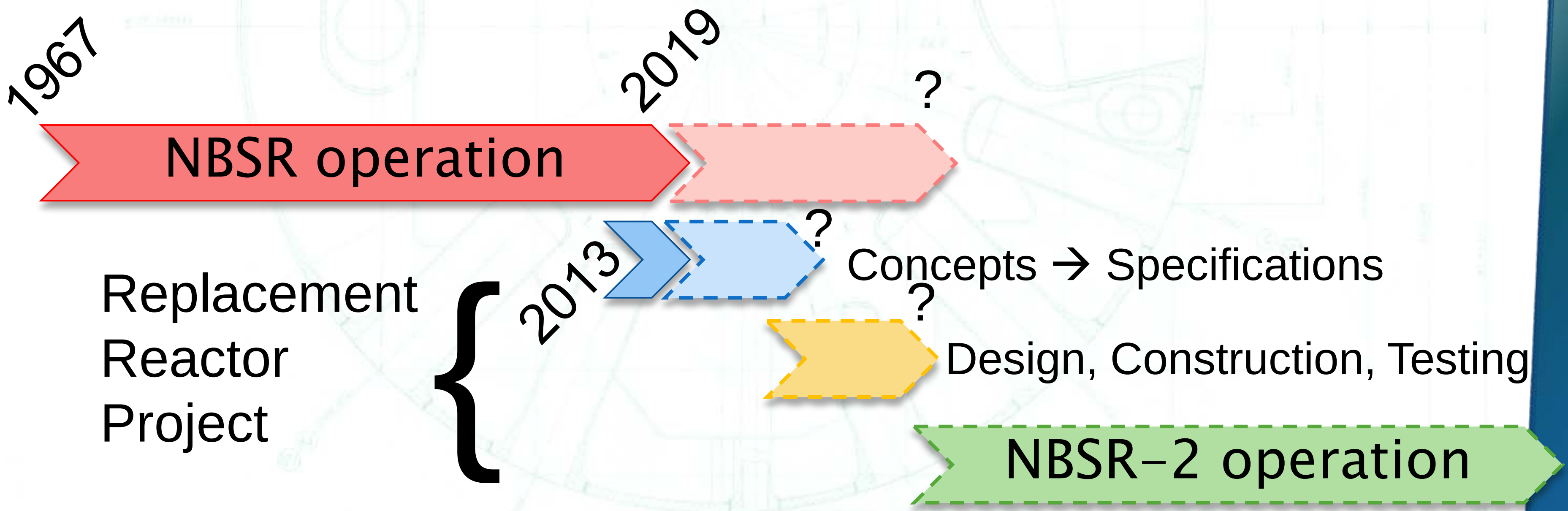
Pathway to a new source

- First began looking into a replacement reactor in 2013
- Several concepts have been investigated in an effort to optimize a reactor design for cold neutron science
- A succession plan that minimizes time between operation of NBSR and the replacement reactor is ideal



1967

2019

?

NBSR operation

Replacement Reactor Project

2013

?

Concepts → Specifications

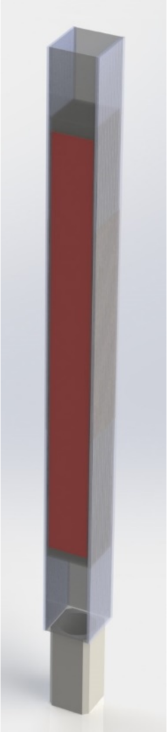
?

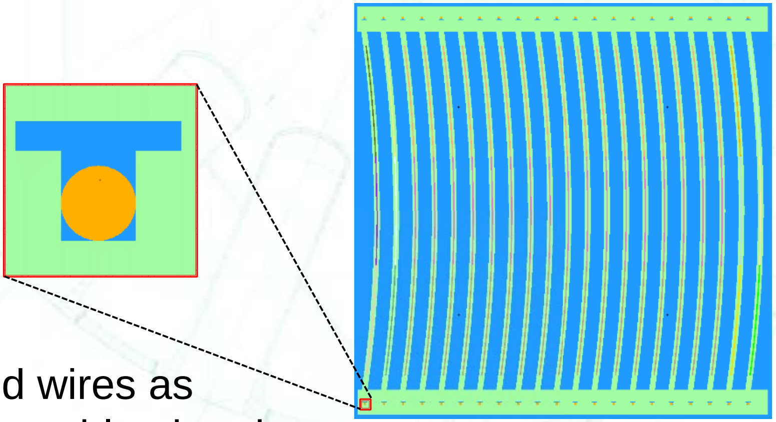
Design, Construction, Testing

NBSR-2 operation

LEU Fuel Assembly Design

	NBSR	Concept Reactor
Foil thickness	0.0216 cm	0.0250 cm
Foil width	6.134 cm	6.5 cm
Foil height	27.94 cm	70 cm
Foils per FA	34 (17×2)	21
U-235 mass per FA	383 g	726 g
Fresh FAs per cycle	4	3
Cycle length	38.5 d	50 d

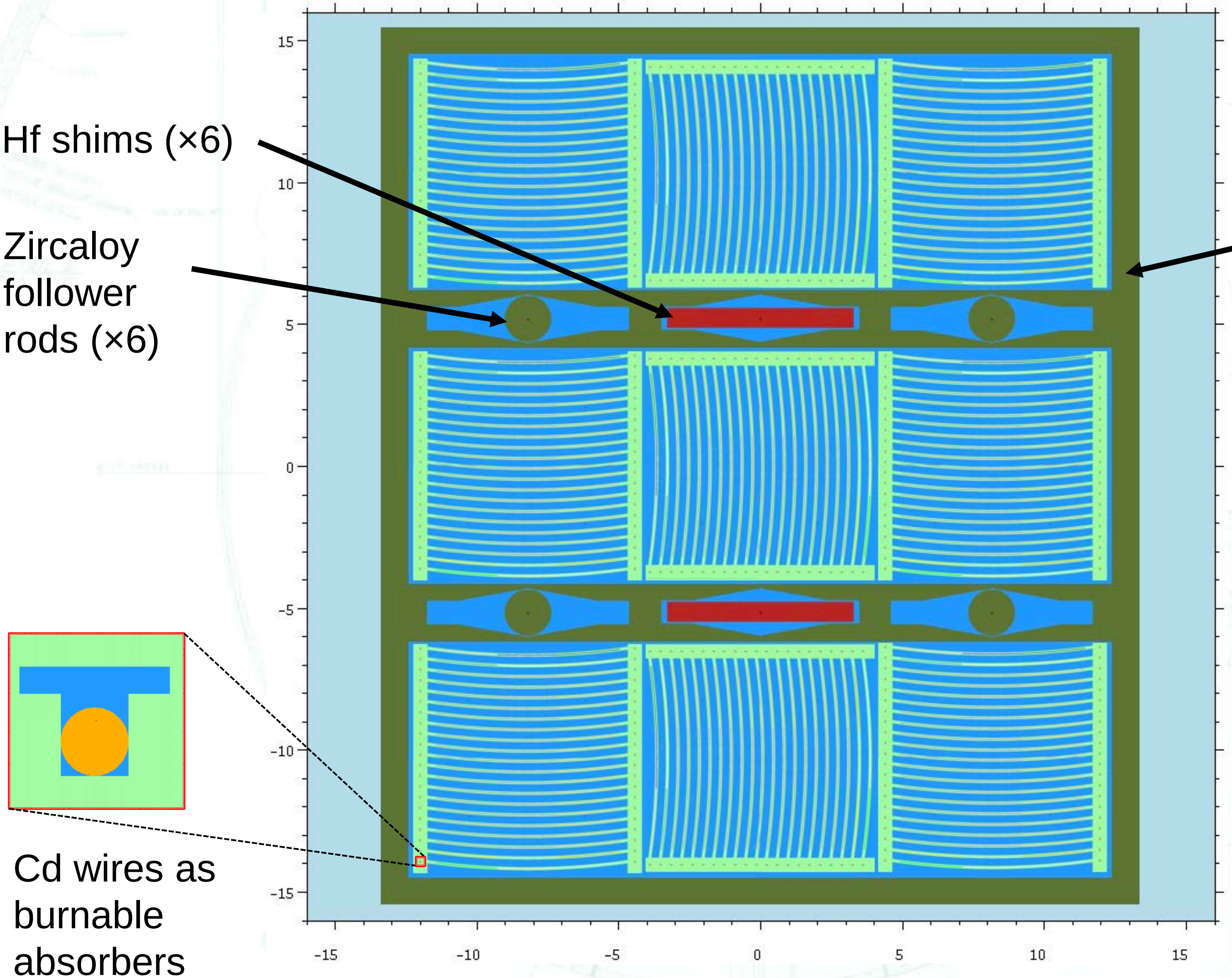




Square profile (8.05 cm × 8.05 cm) allows rotations during refueling

Cd wires as burnable absorbers

Core design



Hf shims (×6)

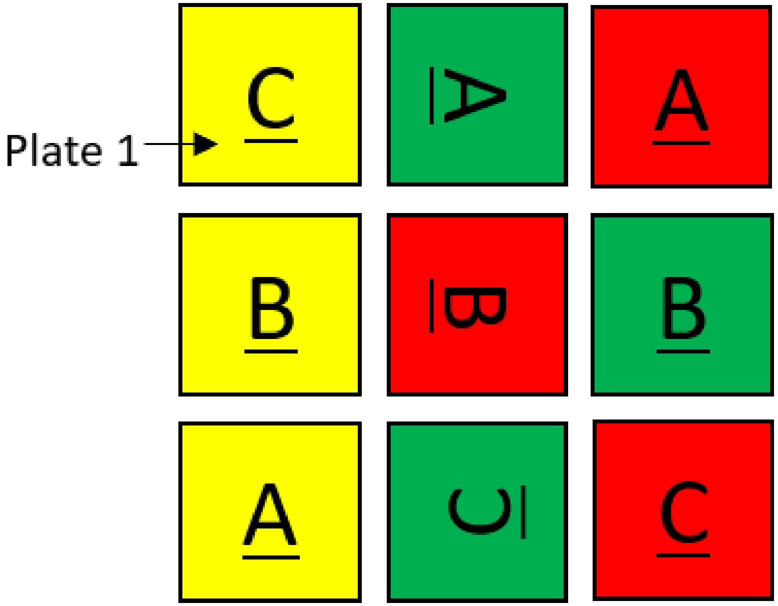
Zircaloy follower rods (×6)

Zircaloy chimney

Cd wires as burnable absorbers

Plan view (*xy*)

Fuel management scheme

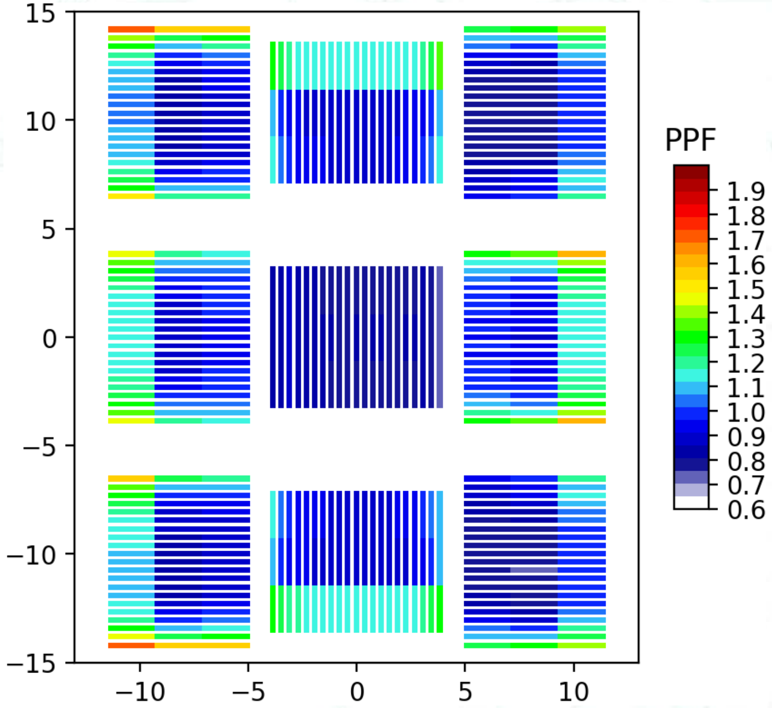


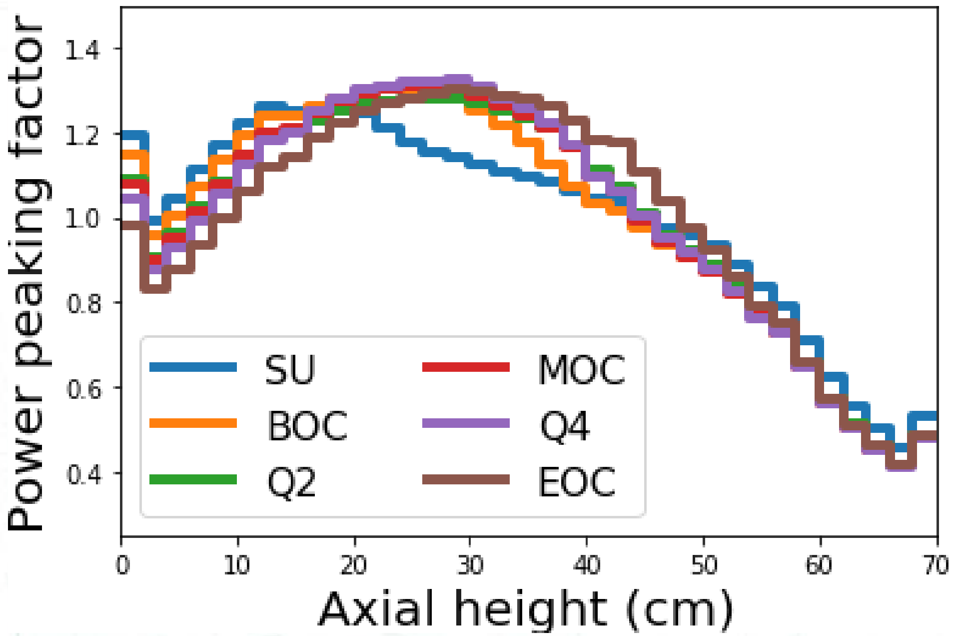
Color legend

- 🟩 Cycle 1
- 🟨 Cycle 2
- 🟥 Cycle 3

- 3 fresh fuel assemblies per cycle for a 50 d cycle

Power distribution

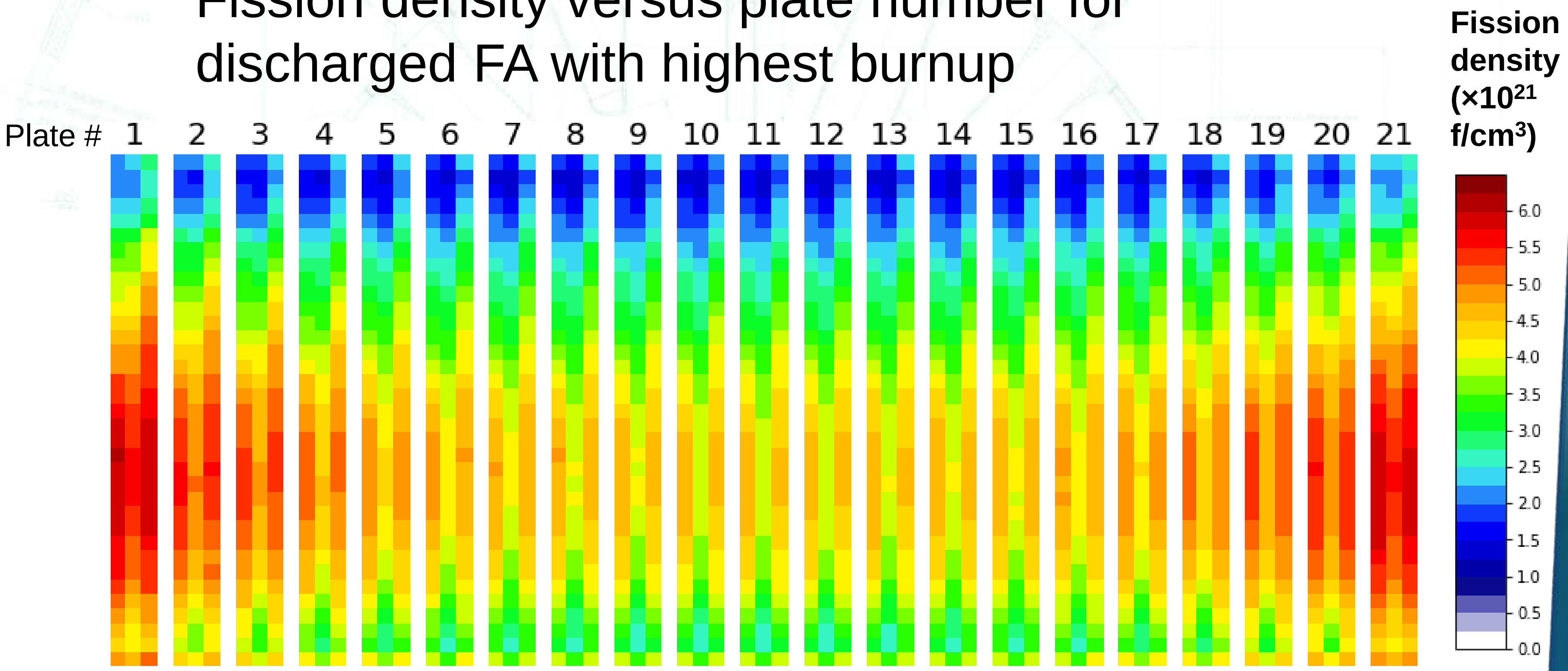

Stripe PPFs at startup


Axial power profiles

- Hot spot power peaking factor: 2.13
  - → Maximum power density: 9.3 kW/cm^3 × 2.13 = 19.8 kW/cm^3
  - → Maximum heat flux: 116 kW/cm^3 × 2.13 = 247 W/cm^2
- Heat flux exceeds NUREG-1313 limit for U_3Si_2 fuel

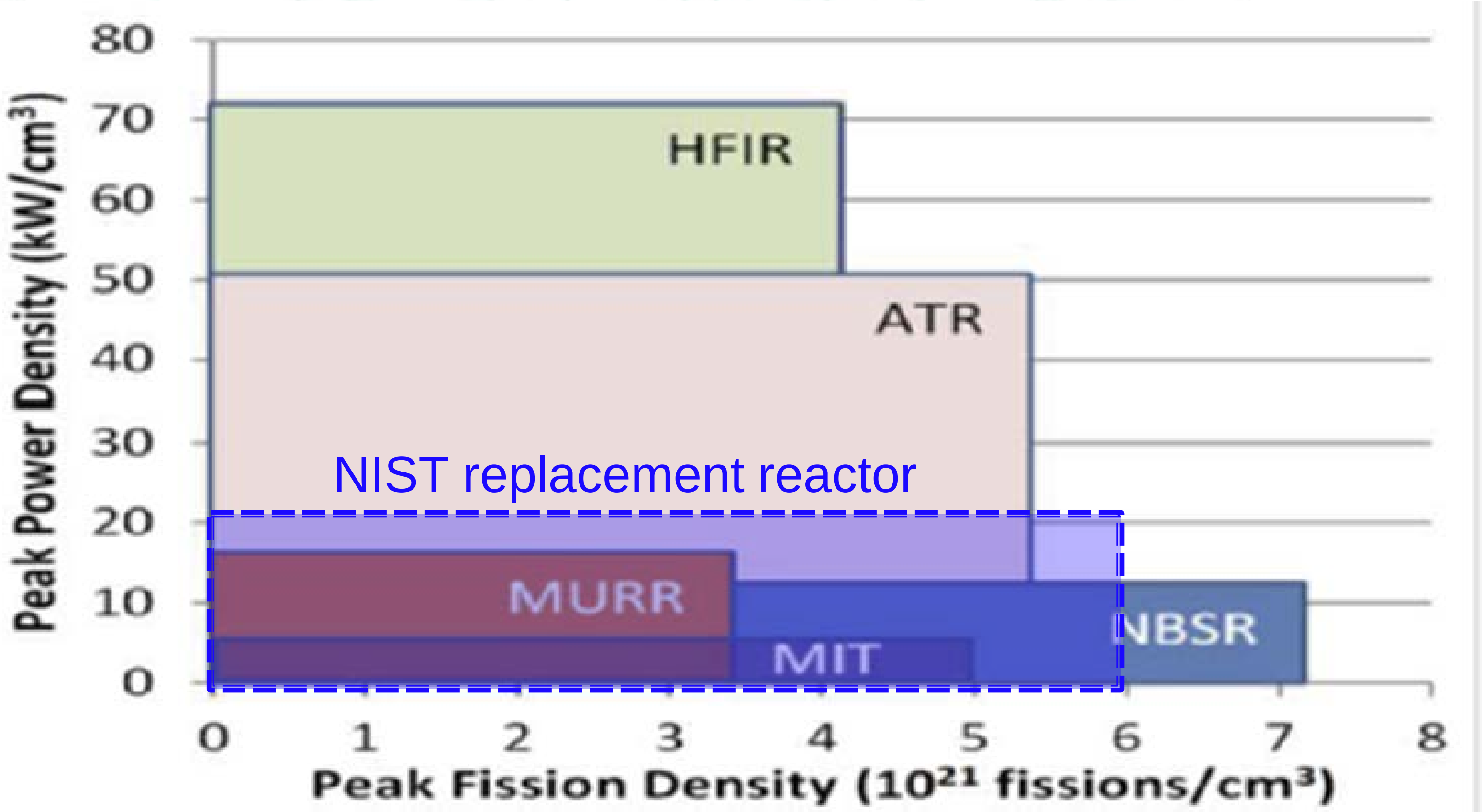
Fission density distribution

Fission density versus plate number for discharged FA with highest burnup



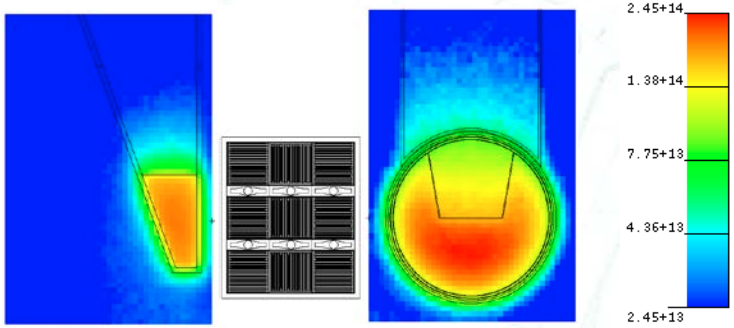
- Potential for high fission densities: 6×10^{21} fissions/cm^3

Peak power density and fission density



Cold neutron source performance

- High unperturbed thermal neutron flux in the reflector: 5.6×10^{14} cm^{-2} s^{-1}
  - More than a factor of 2 greater than NBSR
- Opportunity to optimize cold source designs and locations for neutron science
  - Large gains (>2) in cold source brightness over NBSR are possible



para-LH$_2$ CNS

LD$_2$ CNS

Cold flux

Cold Neutron Source Brightness