Enhanced Safety Analysis Code Suites for the New Reactor Design at NCNR

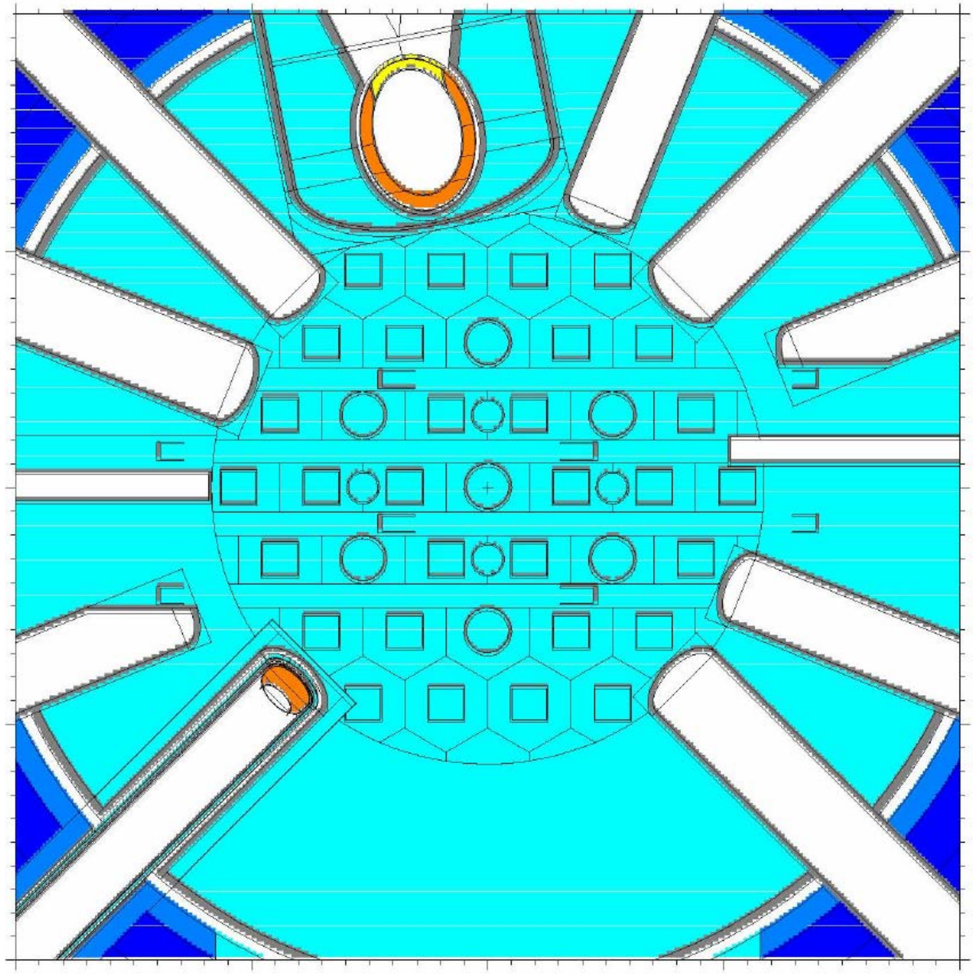
Richard Leos

NIST Center for Neutron Research

Reactor Operations and Engineering Group

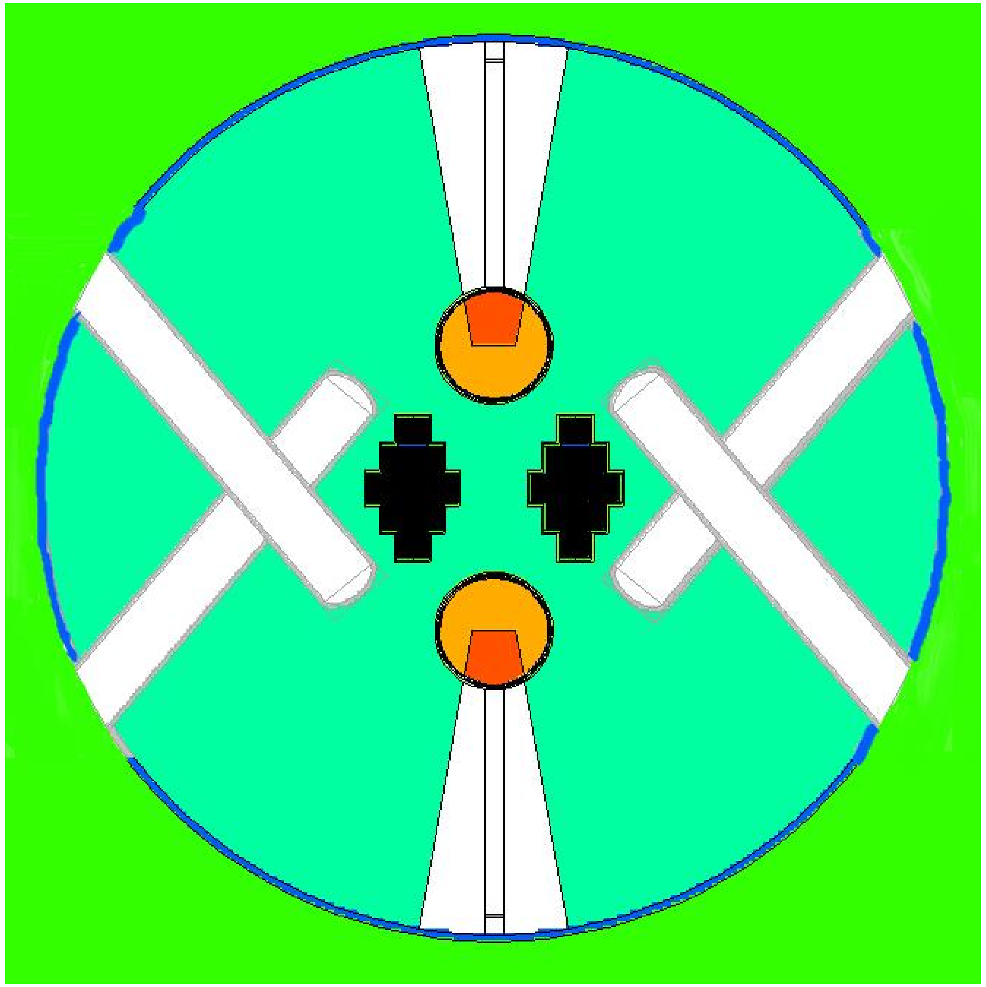
Status of the NBSR

- The lifetime of the National Bureau of Standards Reactor (NBSR) will be coming to an end sometime in the next few decades.
- NBSR Main Characteristics:
  - High-Enrichment Uranium (HEU) fuel: 93 wt%
  - U_3O_8 + Al
  - Vertically Split Fuel Element
  - Full Power: 20 MW
  - D_2O Coolant , Moderator, Reflector



Overview of the New Reactor

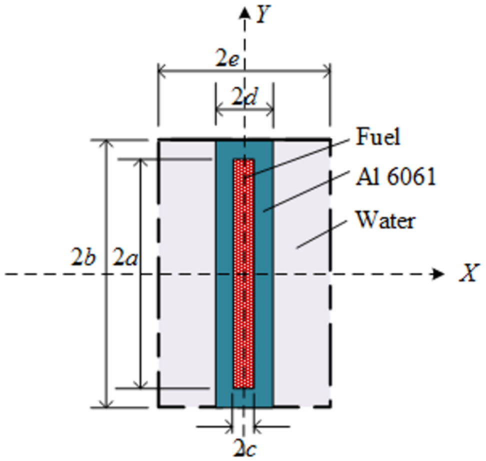
- Reactor Core Characteristics:
  - Low-Enrichment Uranium (LEU) fuel: 19.75 wt%
  - U_3Si_2 + Al
  - <u>Horizontally</u> Split Core
  - **Two** Cold Neutron Sources (CNS)
  - Full Power: 20 MW
  - H_2O Coolant, Moderator
  - D_2O Reflector



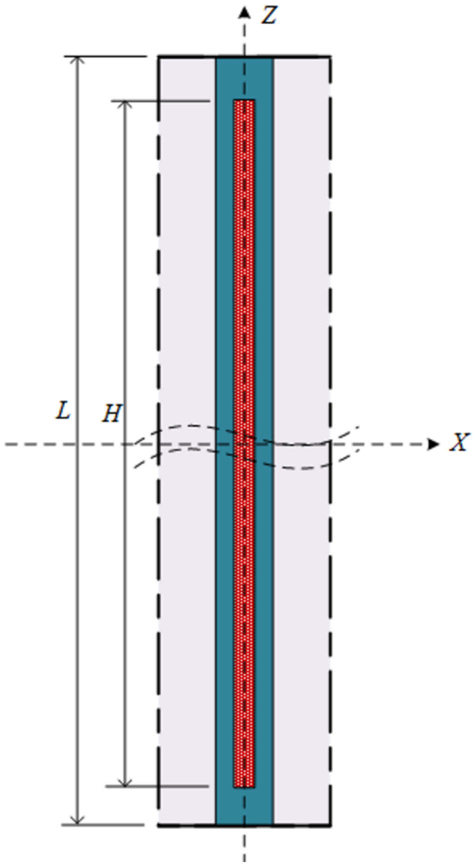
Parameter Changes for New Reactor

Parameters	NBSR	Split Core
Half thickness of fuel meat (c)	0.0254 cm	**0.033 cm**
Length of fuel meat (H)	55.88 cm	**60 cm**
Number of fuel elements	30	**18**

Views of Single Channel



Top View



Side View

Introduction to PARET/ANL Code

- **P**rogram for the **A**nalysis of **RE**actor **T**ransients developed by Argonne National Laboratory (ANL)

- Intended primarily for the safety analysis of test and research reactors that use plate-type (flat) fuel elements

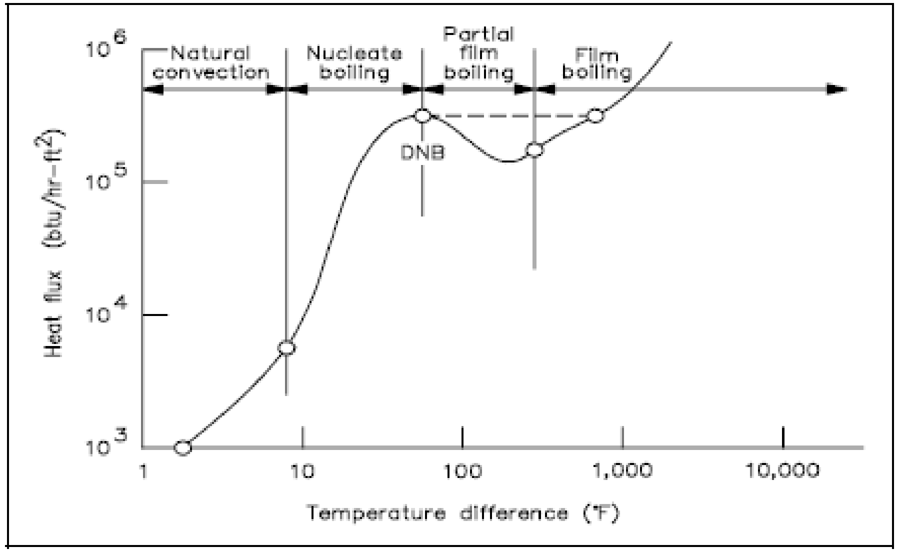
- Based on an evaluation of the coupled thermal, hydrodynamic, and nuclear effects of the core

- Program calculates Critical Heat Flux Ratio (CHFR) using the Mirshak Correlation.

Critical Heat Flux & Onset of Flow Instability

Critical Heat Flux (CHF)

- The thermal limiting condition where a phase change occurs during heating which decreases efficiency of heat transfer causing localized overheating of the heating surface.

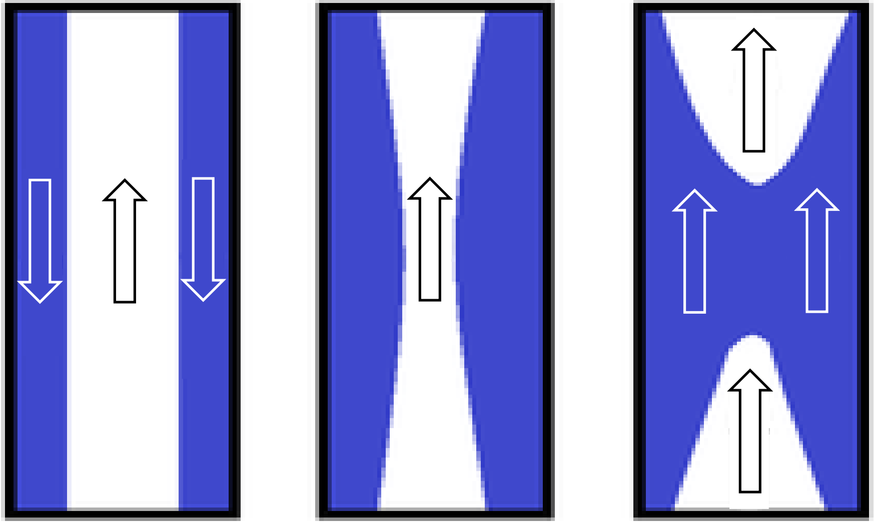


Thermal Limits Criteria

Probability Level	CHFR	OFIR
90%	1.301	1.310
95%	1.391	1.403
99.9%	1.778	1.828

Onset of Flow Instability (OFI)

- Excursive flow instability due to the onset of net vapor generation in the coolant channel.



(A) (B) (C)

Objectives

- Upgrade the critical heat flux ratio (CHFR) calculations for the PARET/ANL output by using the Sudo-Kaminaga correlation
- Determine the safety margins for various transient cases based on the critical heat flux ratio (CHFR) and onset of flow instability ratio (OFIR)

Sudo-Kaminaga Correlation

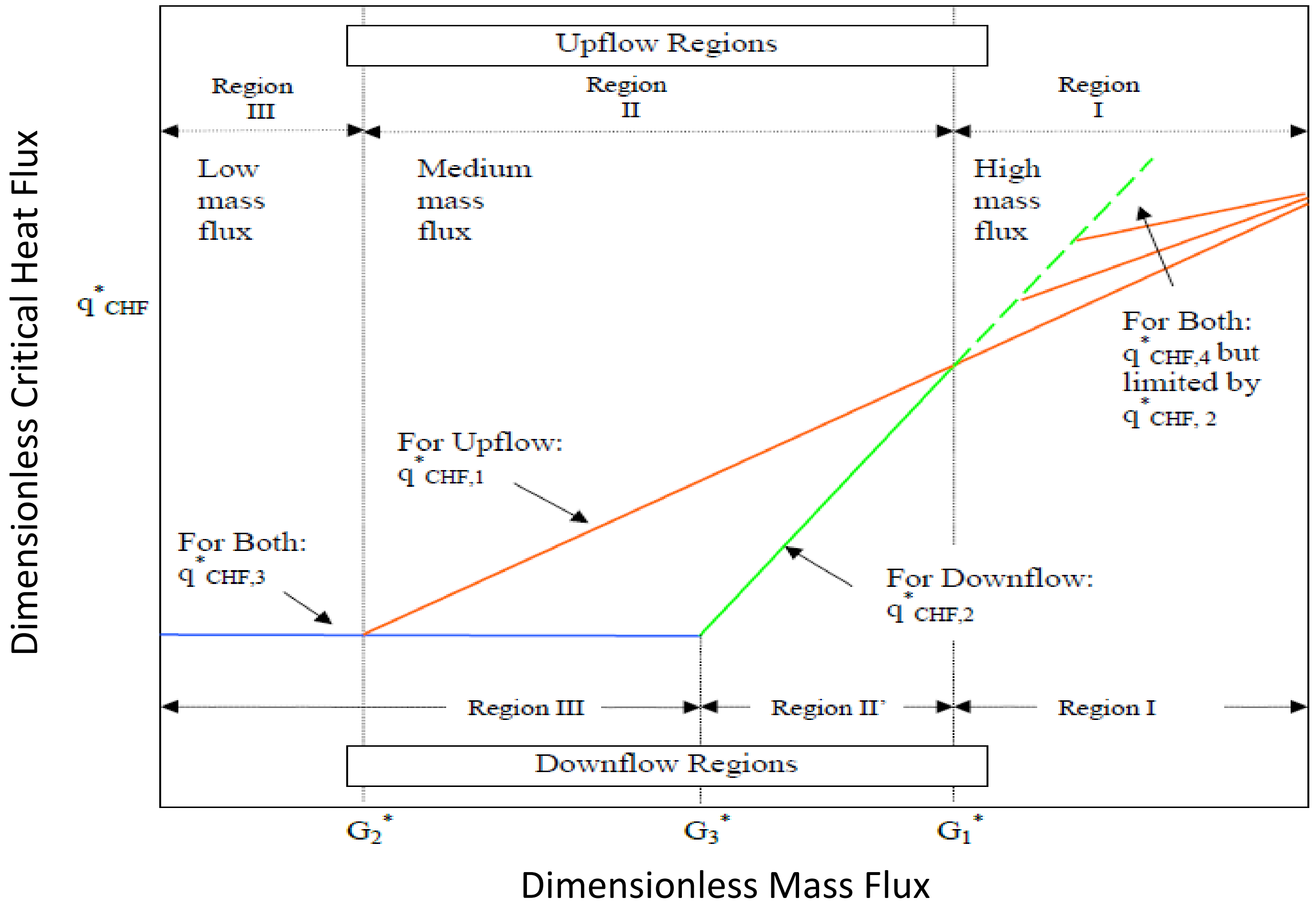
- Used to calculate CHFR for vertical rectangular channels of a research reactor
- Possesses greater geometric similarities to the new reactor
- Considers effects:
  - Pressure
  - Inlet sub-cooling
  - Outlet sub-cooling
  - Channel configuration
  - Mass flux
  - Flow direction

- $q^*_{CHF,1} = 0.005|G^*|^{0.611}$
- $q^*_{CHF,2} = \frac{A}{A_H}|G^*|\Delta T^*_{sub,in}$
- $q^*_{CHF,3} = 0.7\frac{A}{A_H}\frac{\sqrt{\frac{W}{\lambda}}}{\left(1+\left(\frac{\rho_g}{\rho_l}\right)^{\frac{1}{4}}\right)^2}(1.0 + 3.0\Delta T^*_{sub,in})$
- $q^*_{CHF,4} = 0.005|G^*|^{0.611}\left(\frac{5000}{|G^*|}\Delta T^*_{sub,0}\right)$

- $q''_{CHF} = q^*_{CHF}h_{fg}\sqrt{\lambda(\rho_l - \rho_g)\rho_g g}$
- $CHFR = \frac{q''_{CHF}}{q''_{model}}$

Sudo-Kaminaga Correlation (Cont.)

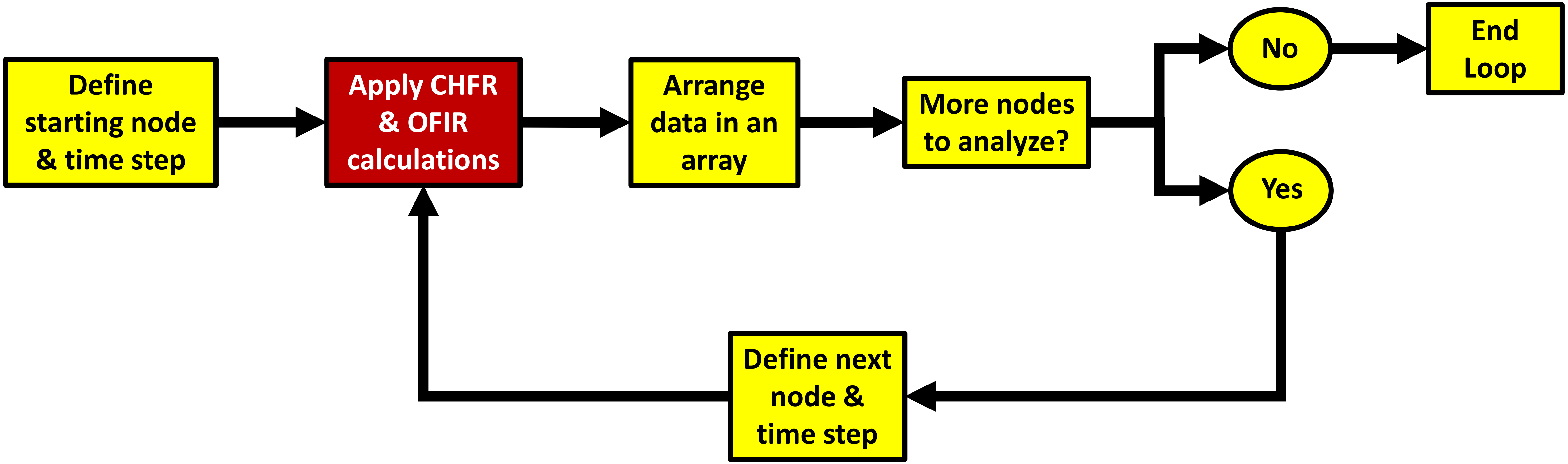
Sudo-Kaminaga Correlation Scheme



OFI Criteria: Saha-Zuber

- Mass flow rate criteria is based on Peclet number: $Pe = \frac{GD_hC_{pf}}{k_f} \leq 70{,}000$
- For low mass flux (Pe ≤ 70,000): $Nu = \frac{q''D_h}{k_f(T_{sat}-T_\lambda)} = 455$
- For high mass flux (Pe > 70,000): $St = \frac{q''}{GC_{pf}(T_{sat}-T_\lambda)} = 0.0065$
- Heat flux for OFI and OFIR: $q''_{OFI} = \begin{cases} 455 * h_{fg} * k_f * (T_{sat} - T_\lambda), & Pe \leq 70{,}000 \\ 0.0065 * G * C_{pf} * (T_{sat} - T_\lambda), & otherwise \end{cases}$
- $OFIR = \frac{q''_{OFI}}{q''_{model}}$

Coding for Calculations



Define starting node & time step

Apply CHFR & OFIR calculations

Arrange data in an array

More nodes to analyze?

No

End Loop

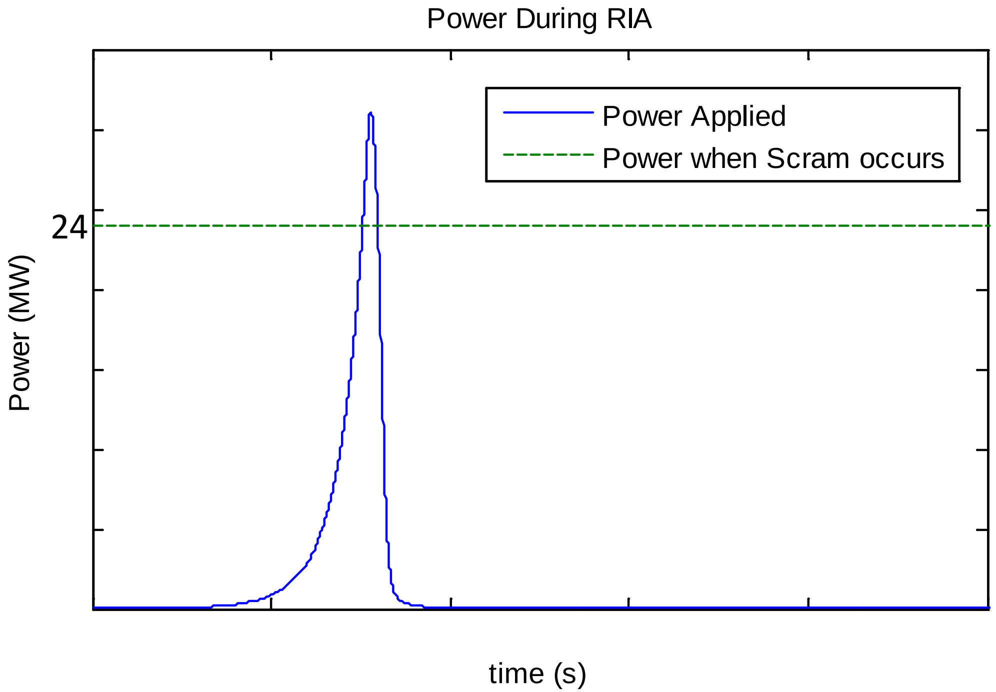
Yes

Define next node & time step

Simulated Transient Cases

Reactivity Insertion Accident (RIA)

- Positive reactivity insertion in the core that may be caused by experiments removed from the core

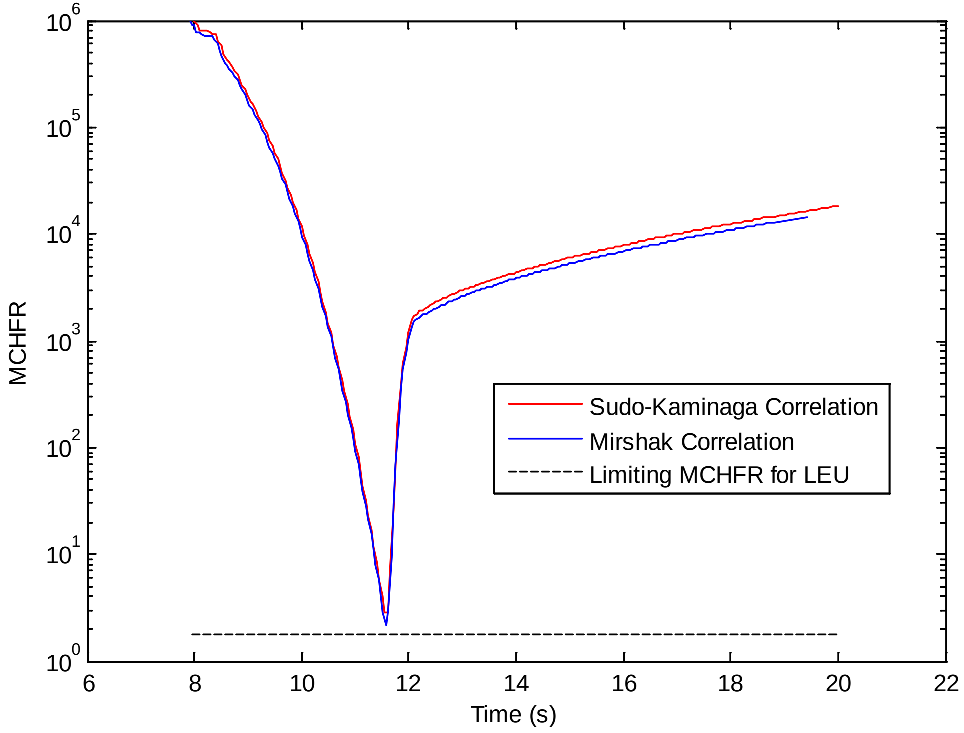


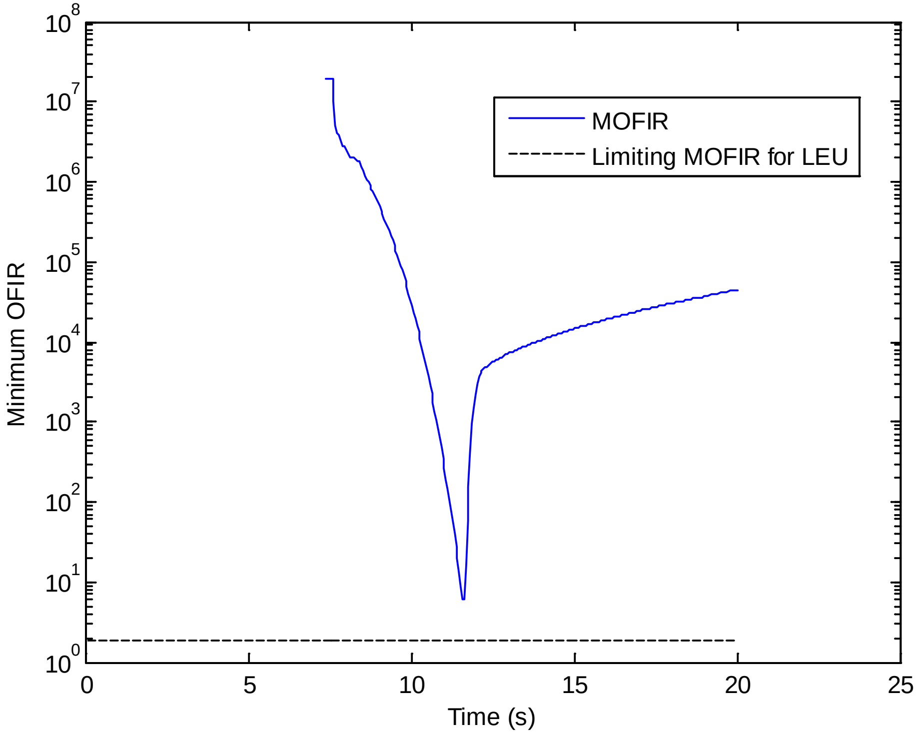
Loss of Flow Accident (LOFA)

- A core heat up due to malfunction of the cooling system even if the reactor power is operating at nominal value
- Parameters
  - Reactor operates at full power (20 MW)
  - Flow decay modeled as exponential decay function
  - Scram occurs when flow decay is reduced by 15%

Case 1: Small Reactivity Insertion Accident

- Initiating Power: 2 W
- Reactivity insertion at slow ramp rate: $0.1/s

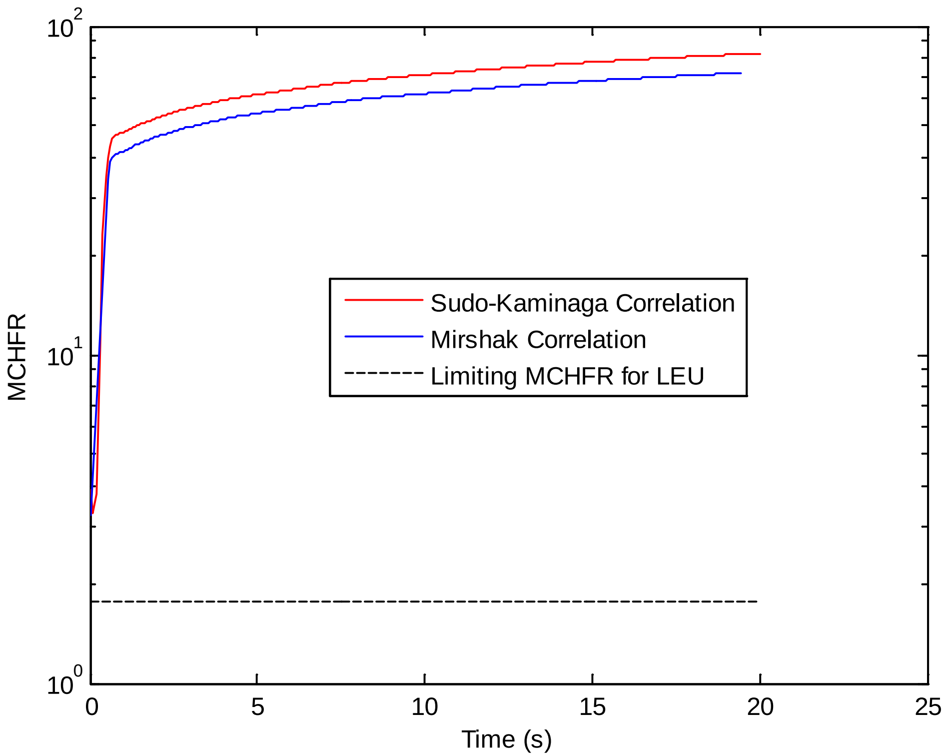

Variation of the Minimum CHFR


Variation of the Minimum OFIR

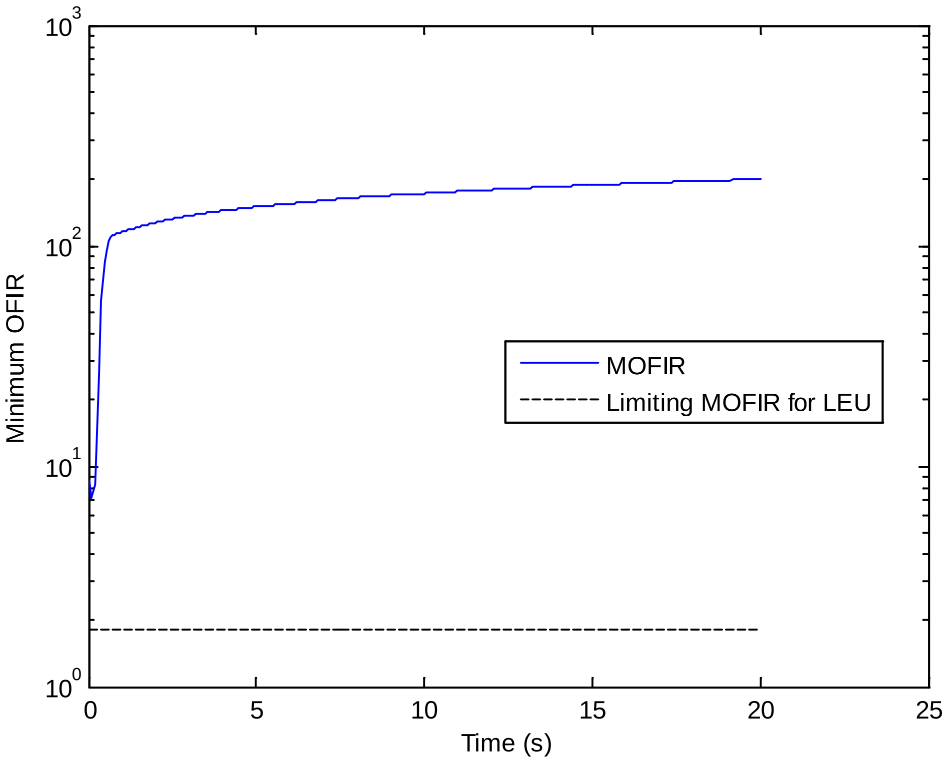
Case 2: Large Reactivity Insertion Accident

- Initiating Power: 20 MW (full power)
- Reactivity insertion: $1.5 in 0.5s

Variation of the Minimum CHFR

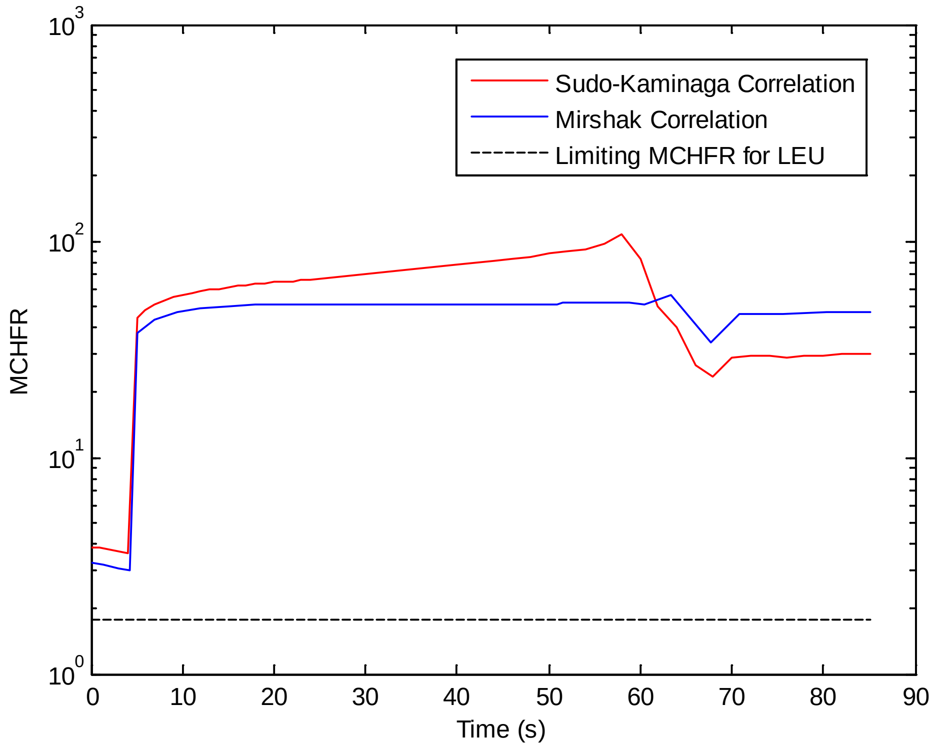


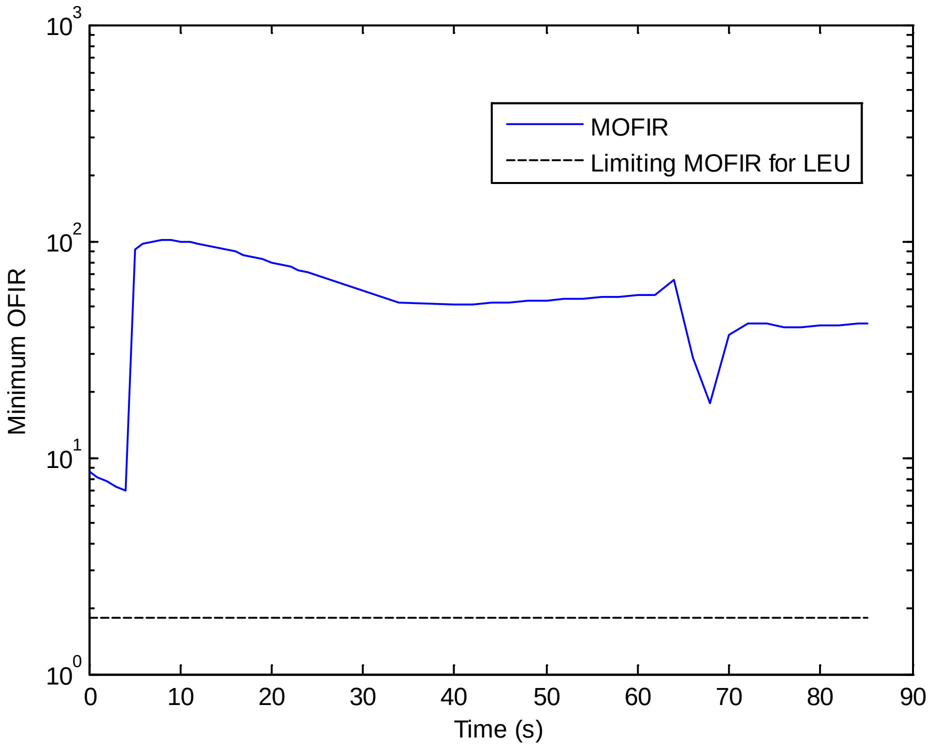
Variation of the Minimum OFIR



Case 3: Slow Loss of Flow Accident

- Decay constant (T): 25 s

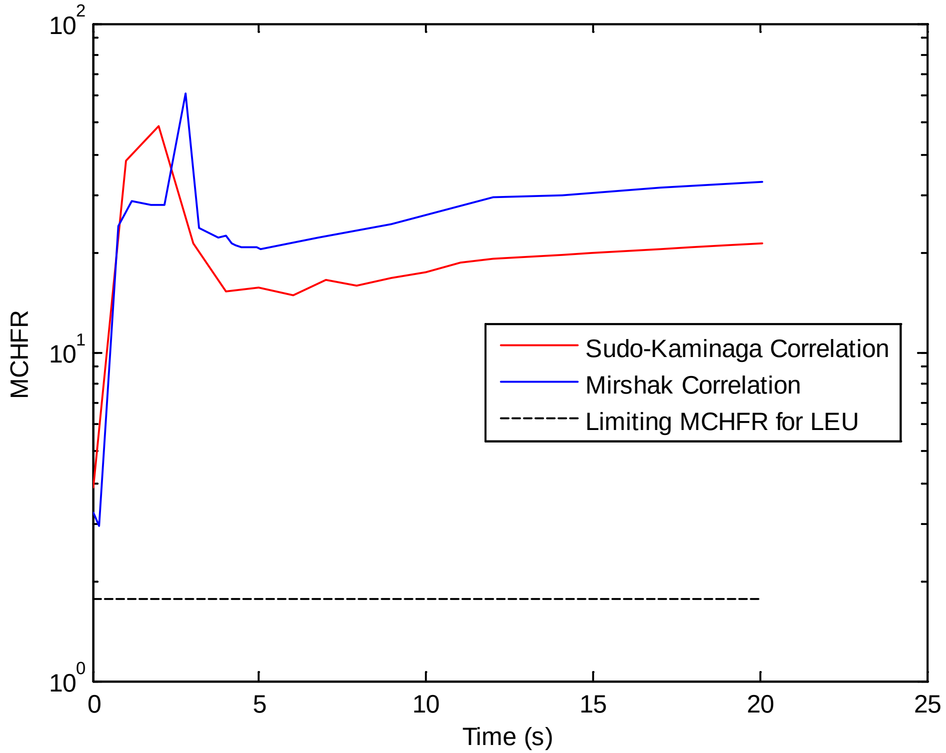

Variation of the Minimum CHFR


Variation of the Minimum OFIR

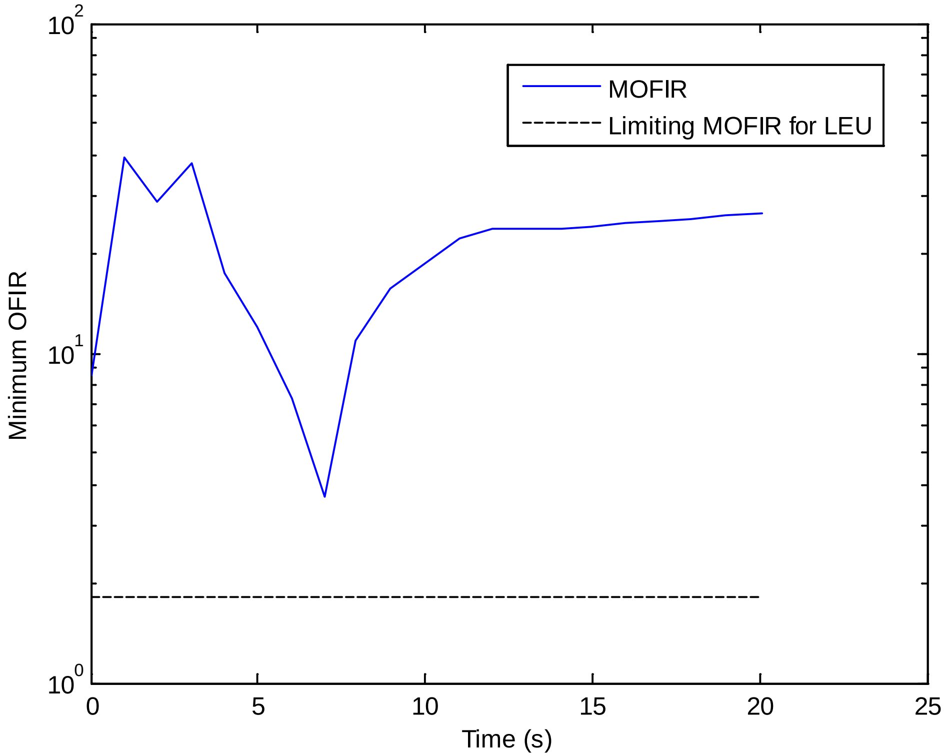
Case 4: Fast Loss of Flow Accident

- Decay constant (T): 1 s

Variation of the Minimum CHFR



Variation of the Minimum OFIR



Summary on All Cases

	Sudo-Kaminaga	Mirshak	
Case #	**MCHFR**	**MCHFR**	**MOFIR**
1	**2.81**	**2.17**	**6.06**
2	**3.29**	**2.50**	**7.18**
3	**3.63**	**2.99**	**6.99**
4	**3.85**	**2.80**	**3.69**

All MCHFR values are above 1.778 (Thermal Limit)

All MOFIR values are above 1.828 (Thermal Limit)

Conclusion

- The results for these cases show that there is at least a 99.9% probability of no fuel damage.
- The new reactor under these parameters can be deemed safe.

Acknowledgements

- Advisors: Dr. Zeyun Wu & Dr. Robert Williams
- SURF Directors: Dr. Julie Borchers and Dr. Joseph Dura