Verification of Thermal-Hydraulics Models for Nuclear Reactors with Plate-Type Fuels

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

NSF CHRNS CENTER FOR HIGH RESOLUTION NEUTRON SCATTERING NIST

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Disclaimer

Certain commercial equipment, instruments, or materials are identified in this study in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

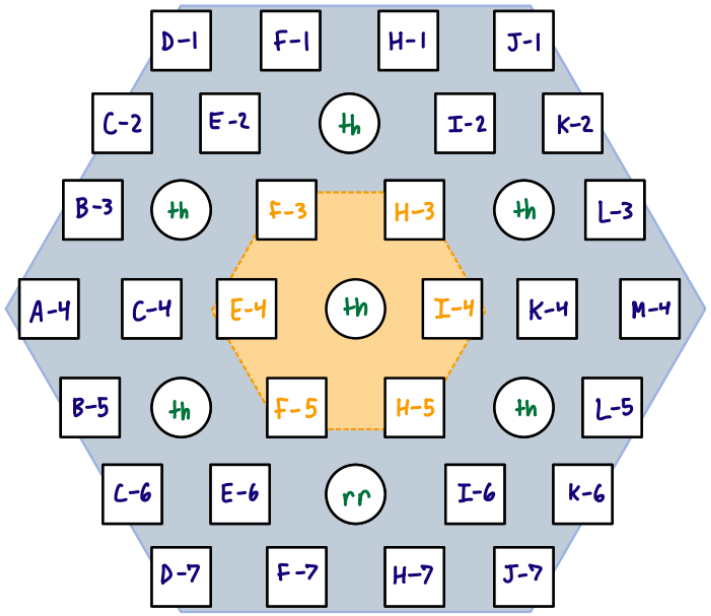
Introduction: About Me

- School: University of Maryland, College Park
  - Rising Junior
- Major: Mechanical Engineering
- Other Interests
  - Minecraft
  - The Legend of Zelda: Breath of The Wild

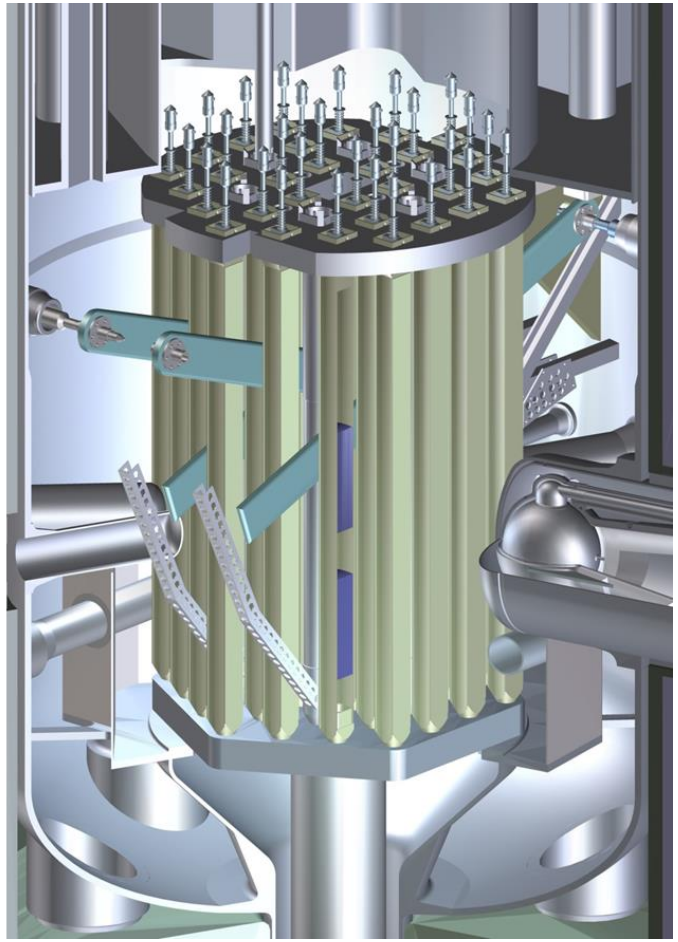
My Survival Minecraft Base

Introduction: NBSR

- National Bureau of Standards Reactor (NBSR)
- 30 Fuel Elements
- D_2O Coolant
  - Deuterium – Hydrogen with Extra Neutron



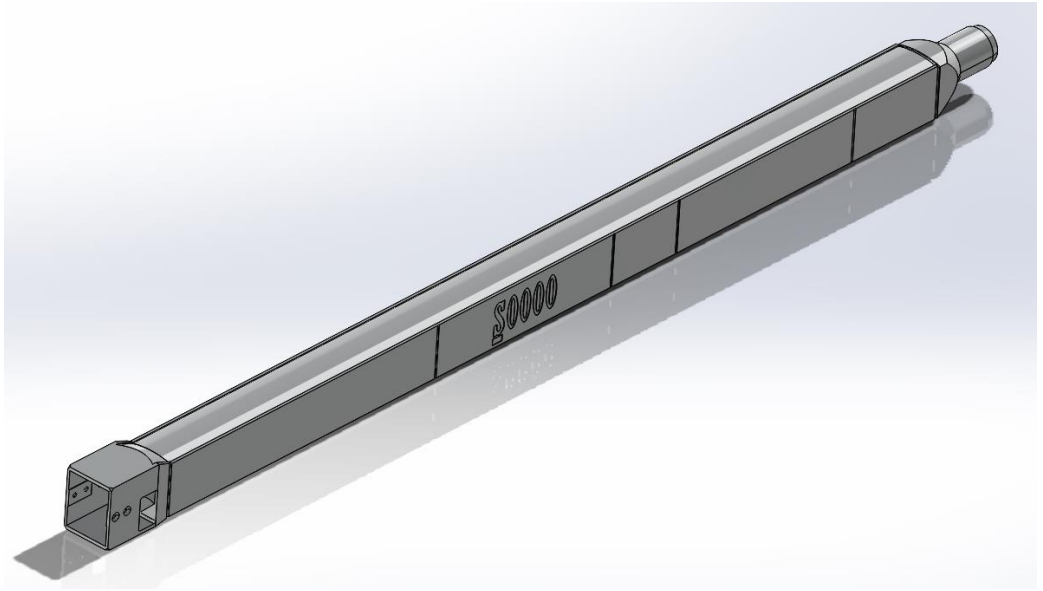
Labeled Top-Down View of Core
Blue – Outer Plenum
Orange – Inner Plenum



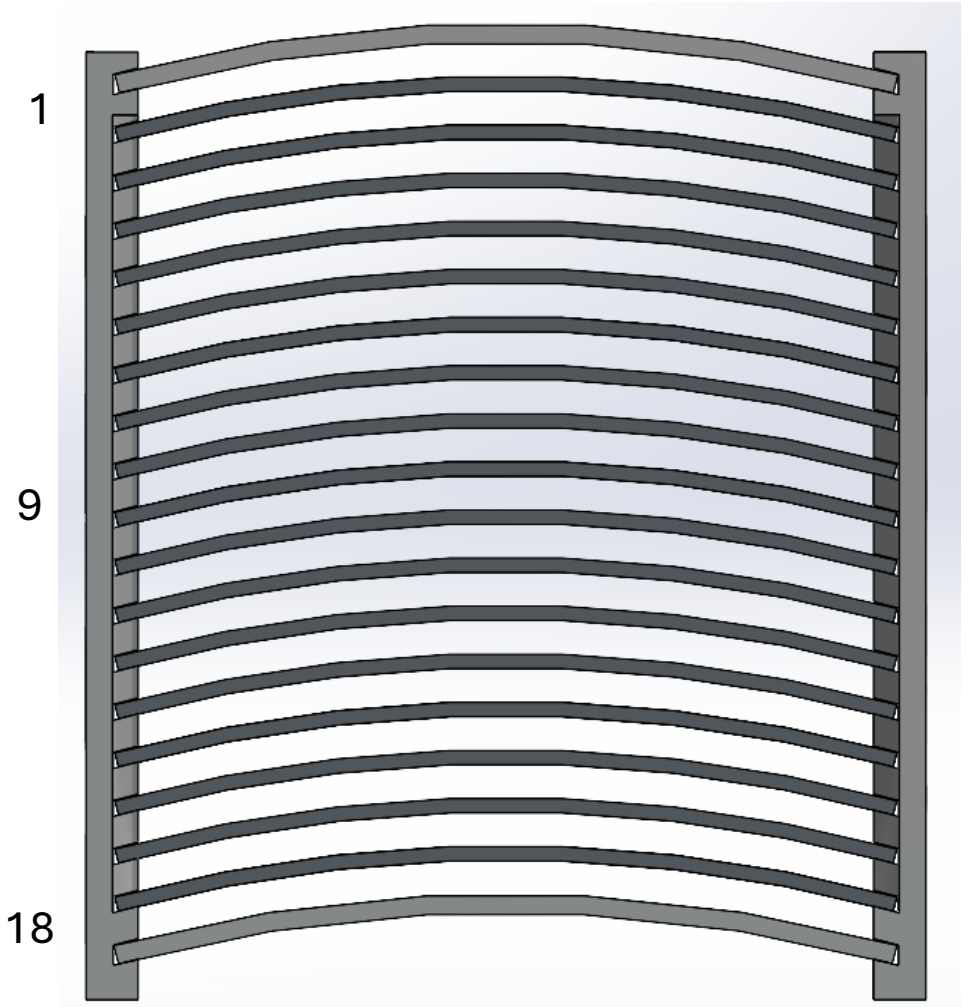
Model of Reactor Core

Subchannels in the NBSR

- Subchannels cool reactor down
  - NBSR has 18 subchannels



Fuel Element in the NBSR



Labeled Subchannels in a Fuel Element

Introduction: PLTEMP

- Created in FORTRAN
- Created by Argonne National Laboratory
- Subchannel Code

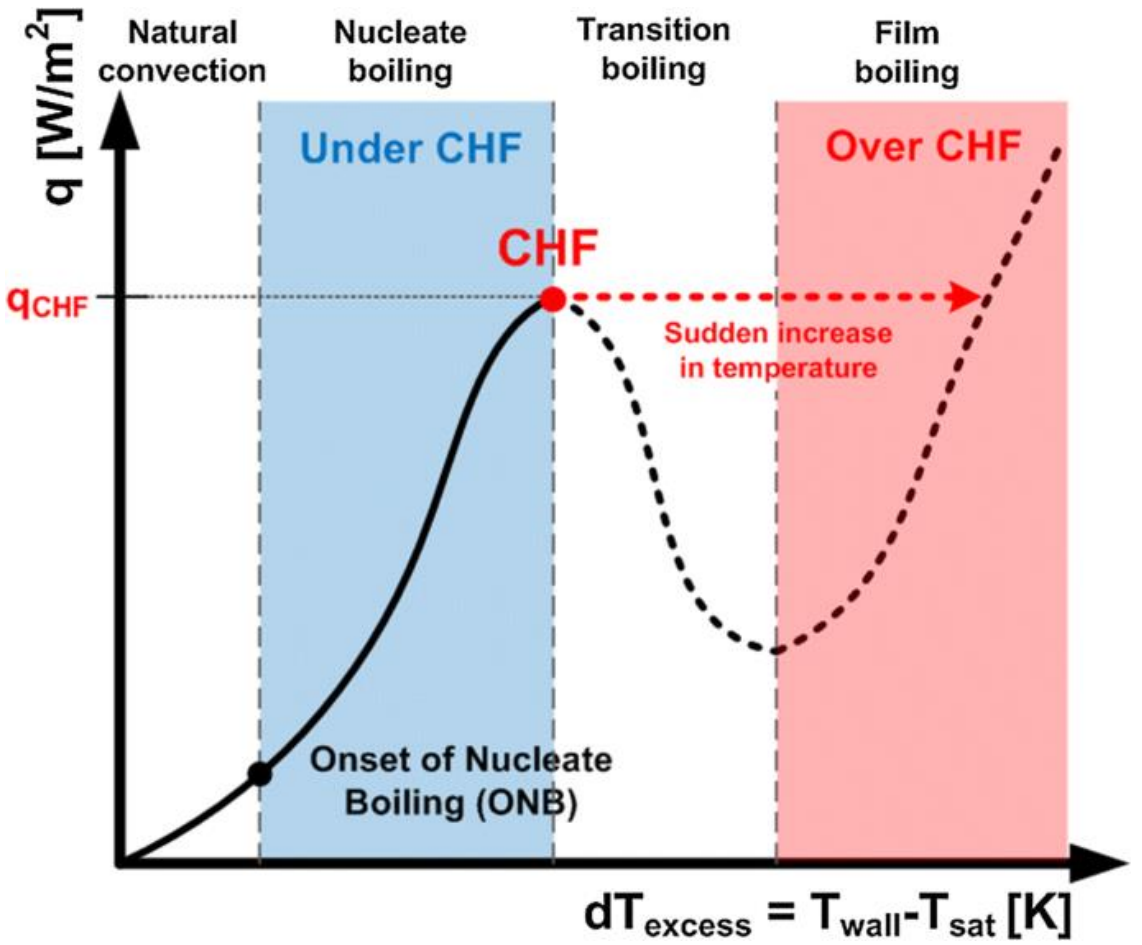
```
!-----------------------  Type I assembly - Inner Plenum, FE  -----------------------
! NELF NF   WFGES         FB          FQ          FH      IBC IBCA     HBC  IBERN
   6   3 2.55200E+01 1.00000E+00 1.00000E+00 1.00000E+00   0   0 0.00000E+00   0 Card 300
!    FBULK       FFILM      FFLUX       FDHTD       FVELC
 1.00000E+00 1.00000E+00 1.00000E+00 1.00000E+00 1.00000E+00                    Card 300A
! IQNODS IQNODF FQL
   1   1 1.00000E+00                                                          Card 301
! IELFHF ICHNHF IPLTHF
   1   1   1                                                                  Card 302
! FZ
 1.00000E+00 1.00000E+00 1.00000E+00 1.00000E+00 1.00000E+00 1.00000E+00      Card 303
!     AF          DF          LZ          ZF       WIDTH       THICK
 3.52380E-03 5.86553E-03 3.81000E-02 0.00000E+00 6.72900E-02 2.95000E-03      Card 304
 3.52380E-03 5.86553E-03 5.58800E-01 0.00000E+00 6.72900E-02 2.95000E-03      Card 304
 3.52380E-03 5.86553E-03 3.81000E-02 0.00000E+00 6.72900E-02 2.95000E-03      Card 304
```

Screenshot of a Portion of the NBSR Input File

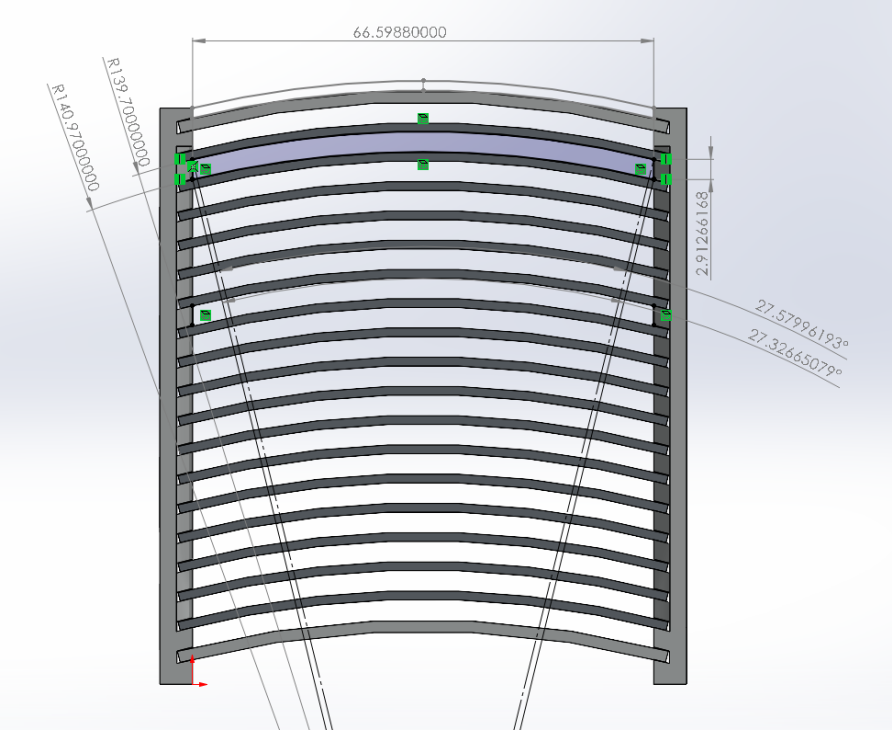
The Critical Heat Flux Ratio (CHFR)

- One of multiple safety margins used for safety analysis
  - Others include OFIR or ONBR
- At critical heat flux, a sudden increase in temperature occurs
- For a reactor to be "safe" – CHFR > 2

$$CHFR = \frac{\text{critical heat flux}}{\text{local heat flux}}$$

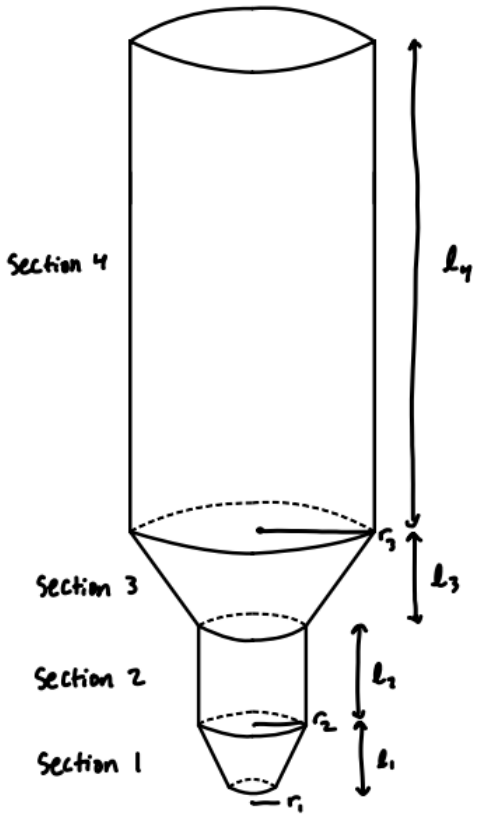


Geometric Properties of the NBSR

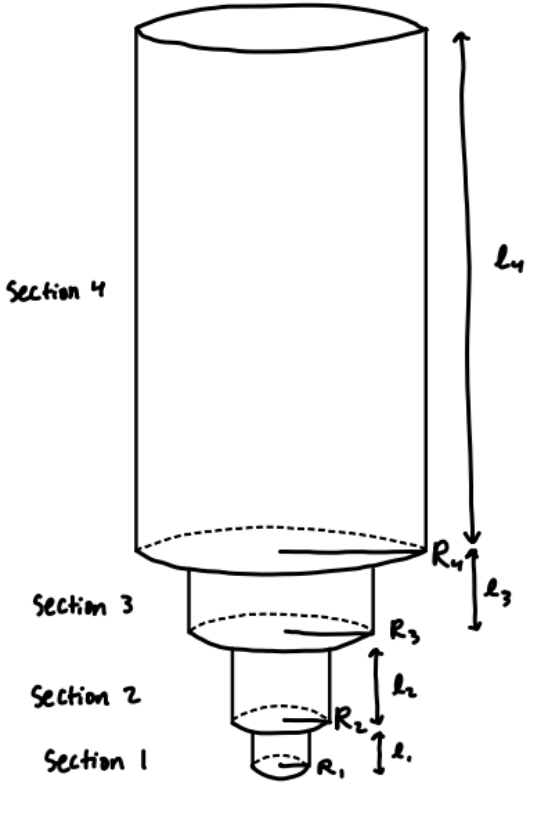


Solidworks Model with Dimensions of Second Coolant Channel

Thimble



Drawing of Thimble (not to scale)



Drawing of Approximated Thimble in PLTEMP (not to scale)

More on NBSR Geometry

(And associated concerns)

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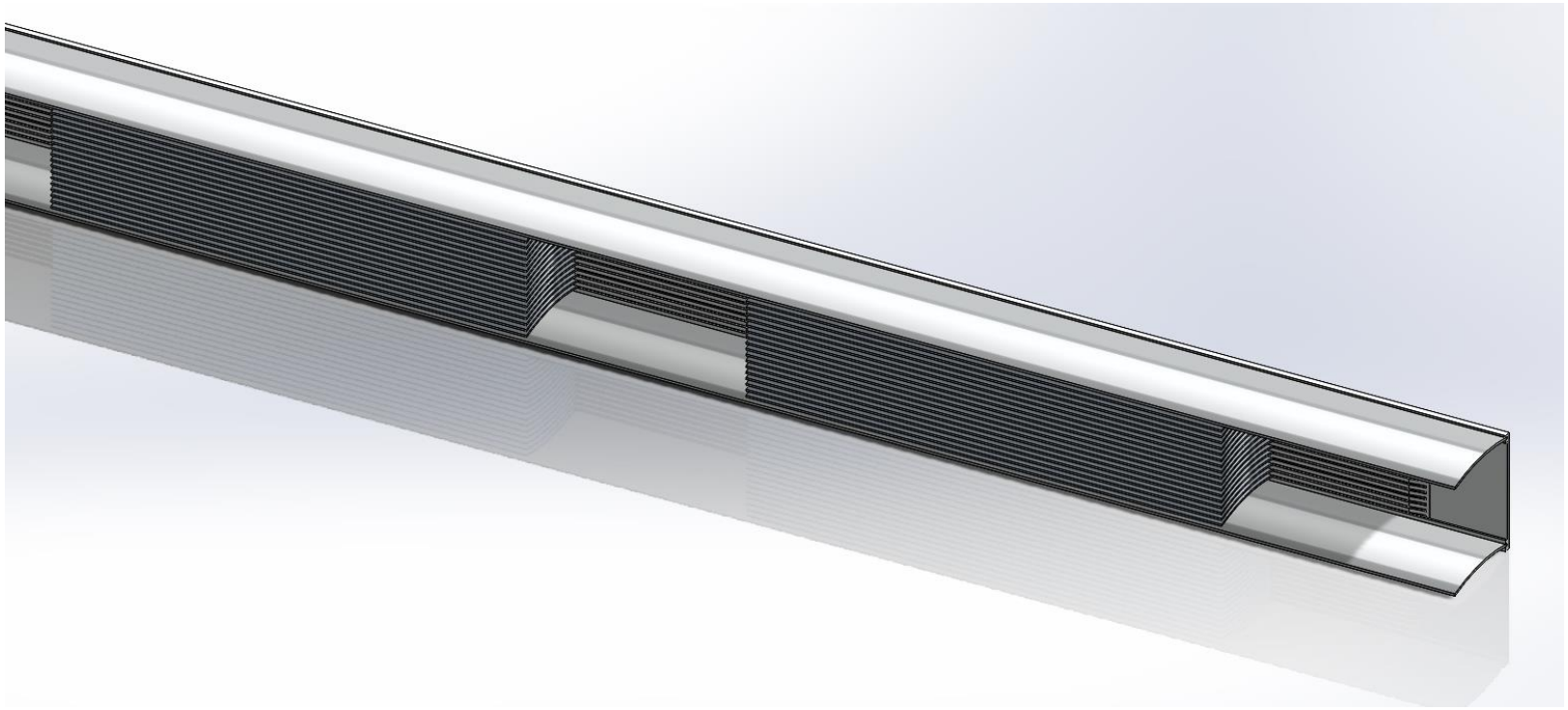
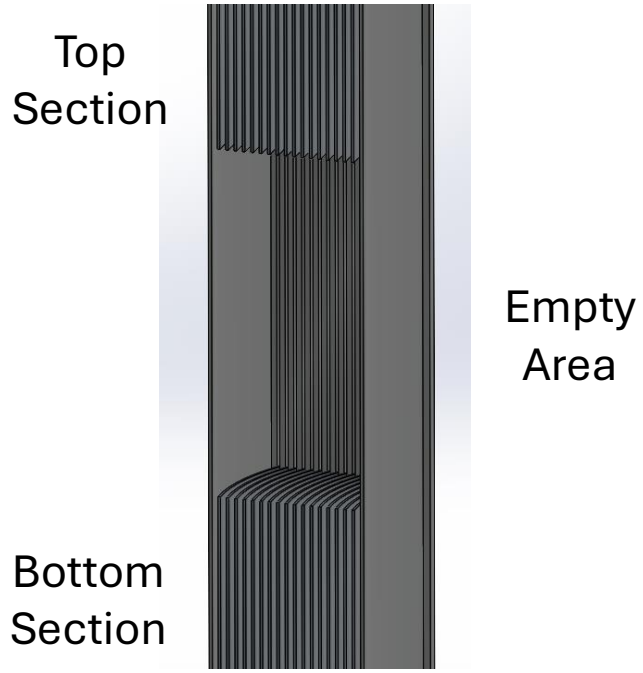
- Split Core Design
  - NBSR has a bottom/top section
  - PLTEMP does not support a split core design



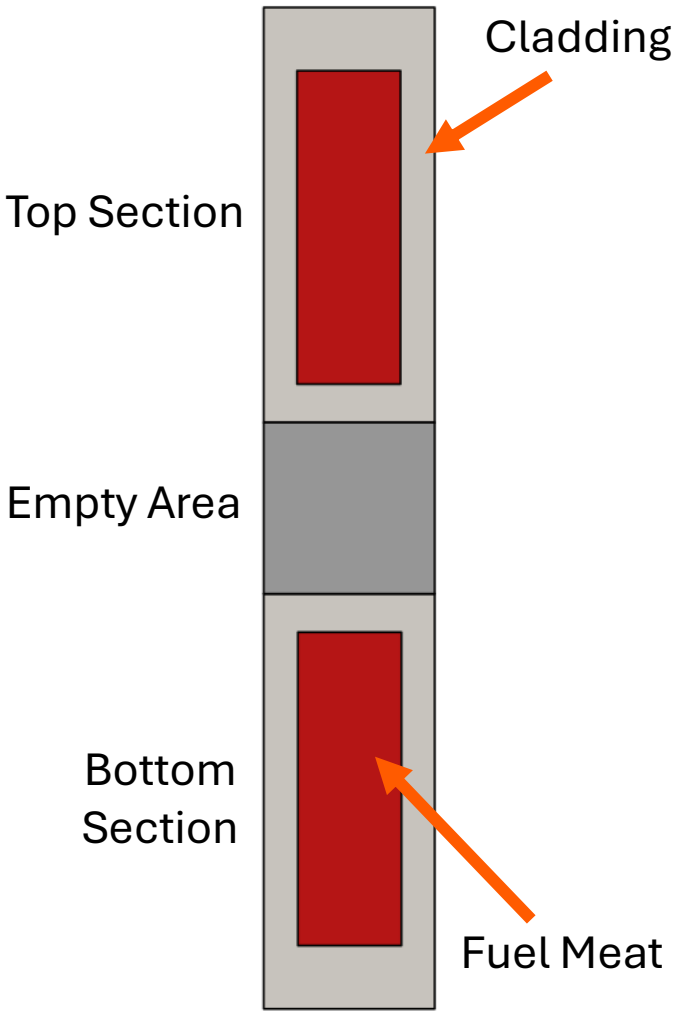
Section View of a Fuel Plate in Solidworks

The Plan

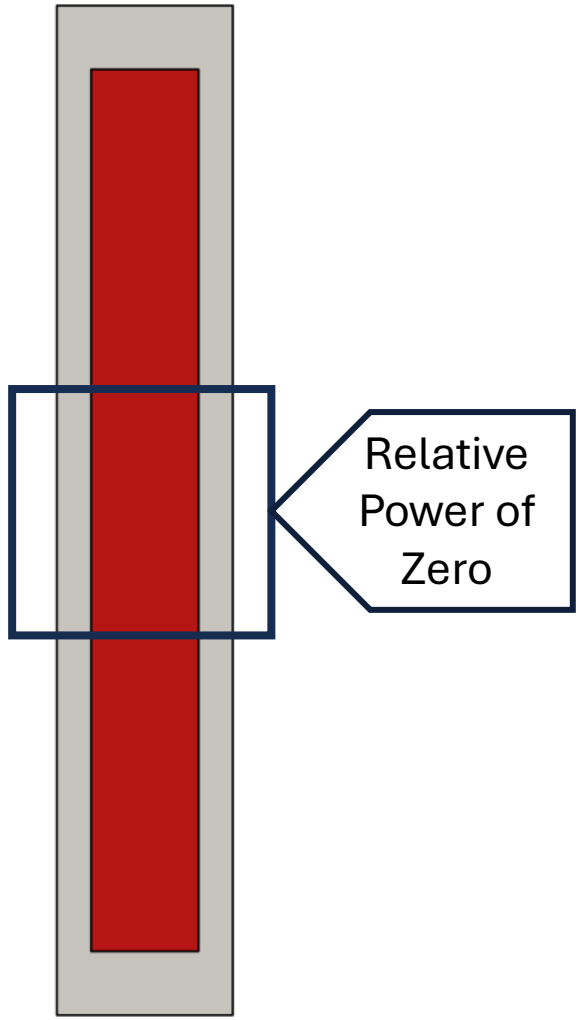
- In unfueled areas, use a relative power of zero to approximate it as an unfueled area



Solidworks Model of Fuel Element in NBSR



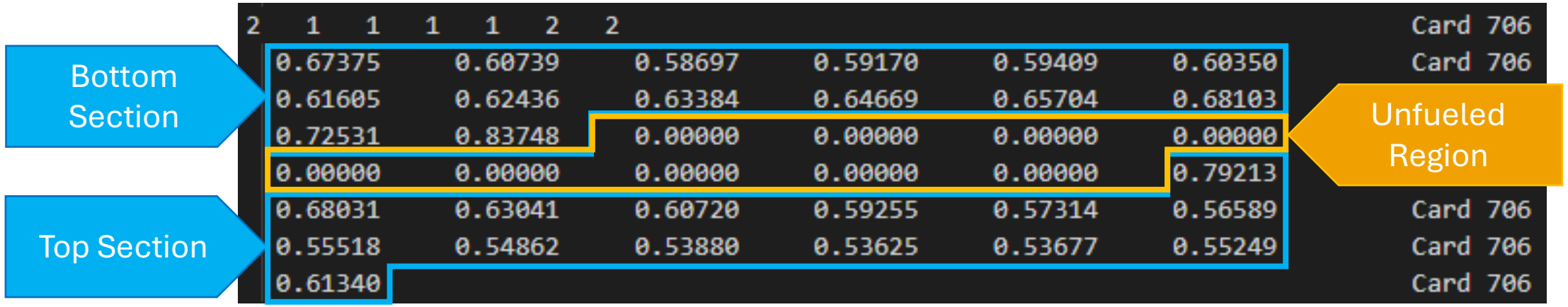
Row of Fuel in the NBSR



Approximated Row of Fuel in PLTEMP(v1)

The Power Profile

- Power profile – representation of power distribution in reactor
- The plan: in unfueled areas, use a relative power of zero to approximate it as an unfueled area



Screenshot of a Portion of the Power Profile

Why the Plan Didn't Work

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- This is not supposed to happen

```
WARNING: Routine OFIRATIO failed to converge to the desired accuracy after 3000 iterations, with a guess OFIR =  9.3612E
+00, actual HEAT FLUX =  5.7136E+02
         HEAT FLUX diff. achieved =  5.3755E+03, guess HEAT FLUX =  5.3755E+03 compared to HEAT FLUX from correlation =
 0.0000E+00

WARNING: Routine OFIRATIO failed to converge to the desired accuracy after 3000 iterations, with a guess OFIR =  9.9929E
+00, actual HEAT FLUX =  1.0708E+02
         HEAT FLUX diff. achieved =  1.0754E+03, guess HEAT FLUX =  1.0754E+03 compared to HEAT FLUX from correlation =
 0.0000E+00

WARNING: Routine OFIRATIO failed to converge to the desired accuracy after 3000 iterations, with a guess OFIR =  9.4954E
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WARNING: Routine OFIRATIO failed to converge to the desired accuracy after 3000 iterations, with a guess OFIR =  9.3453E
+00, actual HEAT FLUX =  1.0785E+02
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 0.0000E+00
```
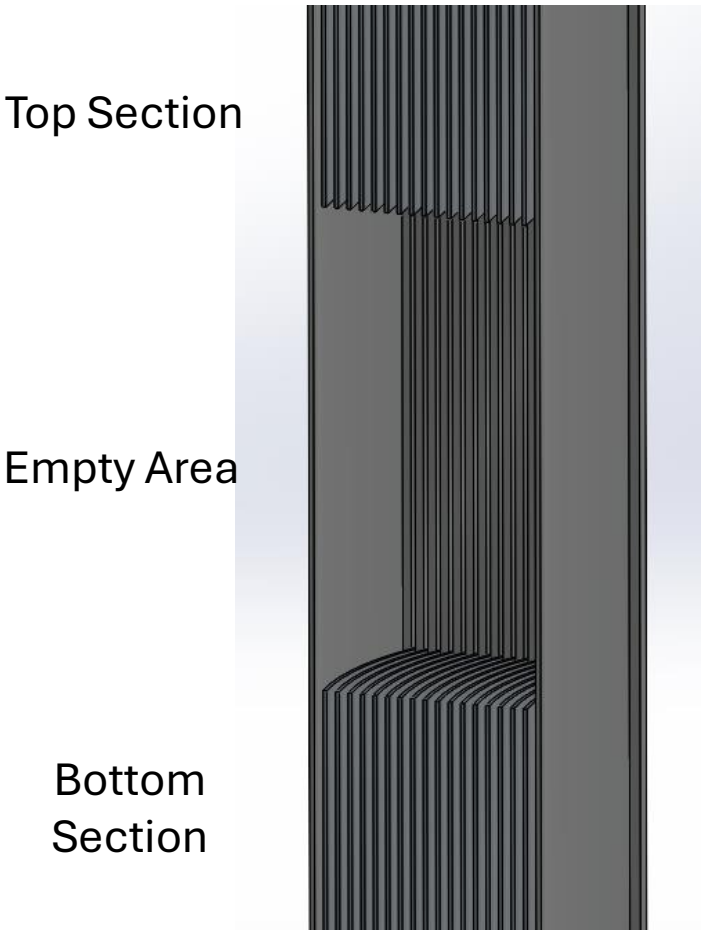
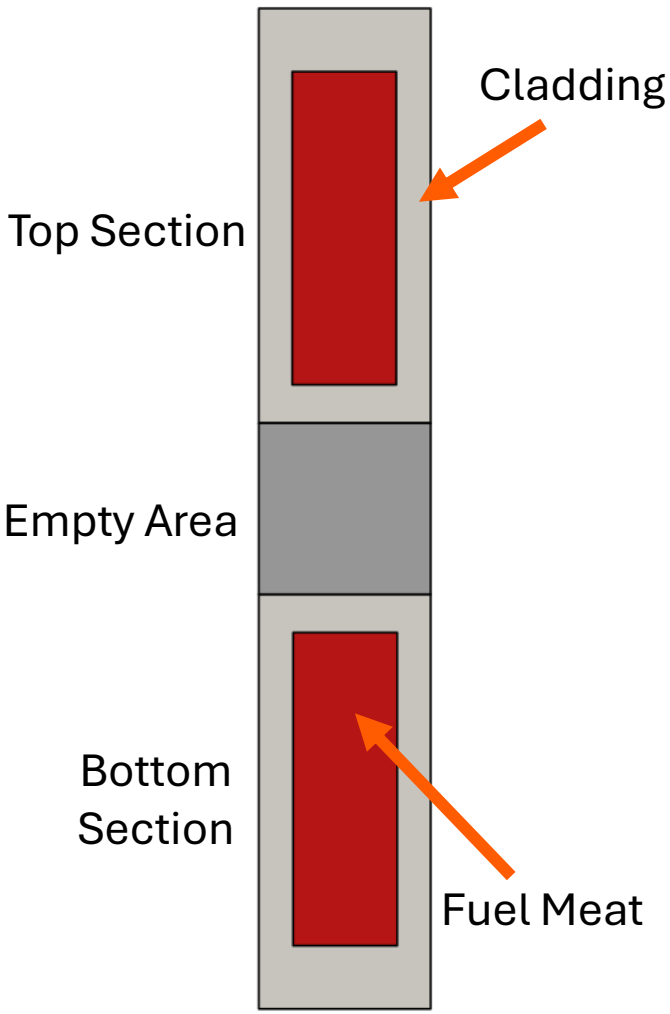

Revisiting the Plan

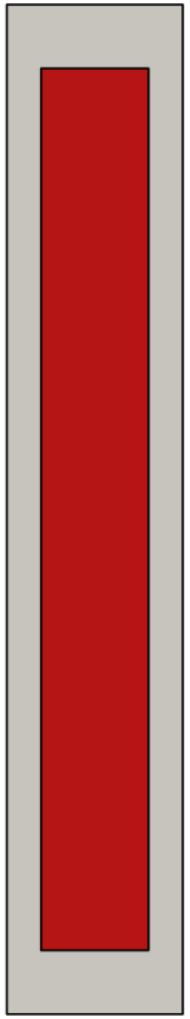
(And creating the current model)



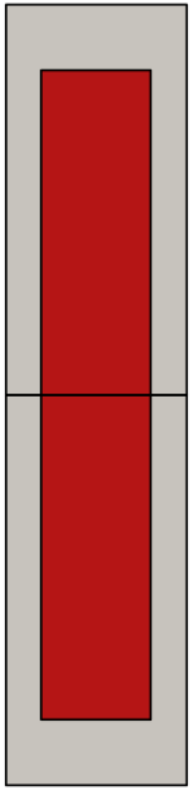
Solidworks Model of Fuel Element in NBSR



Row of Fuel in the NBSR



Approximated Row of Fuel in PLTEMP(v1)



Approximated Row of Fuel in PLTEMP(v2)

Results

- Assumption: power is not generated equally throughout the reactor (power analysis done elsewhere)

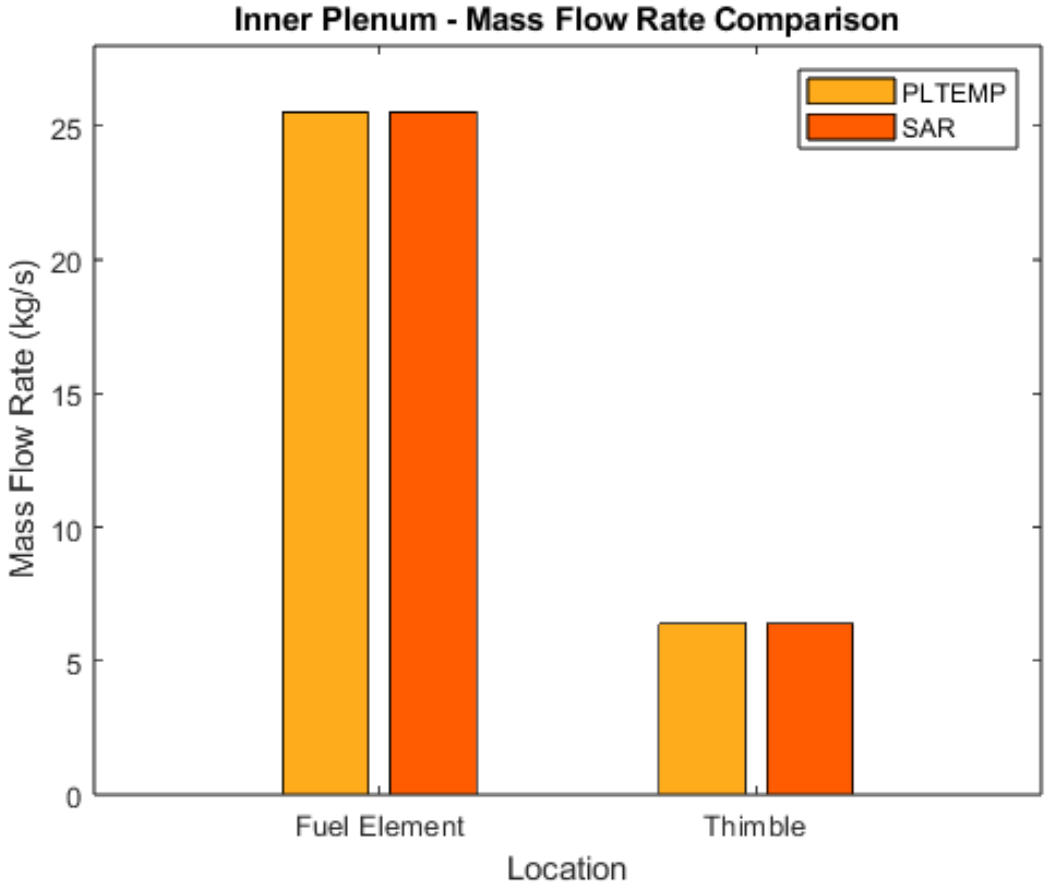
LOCATION OF LIMITING SAFETY MARGINS & TEMPERATURES IN THE REACTOR WITH LATERAL CONDUCTION (OVER ALL ASSEMBLIES, PLATES & STRIPES), WITH ALL 6 HOT CHANNEL FACTORS SPECIFIED BY THE USER

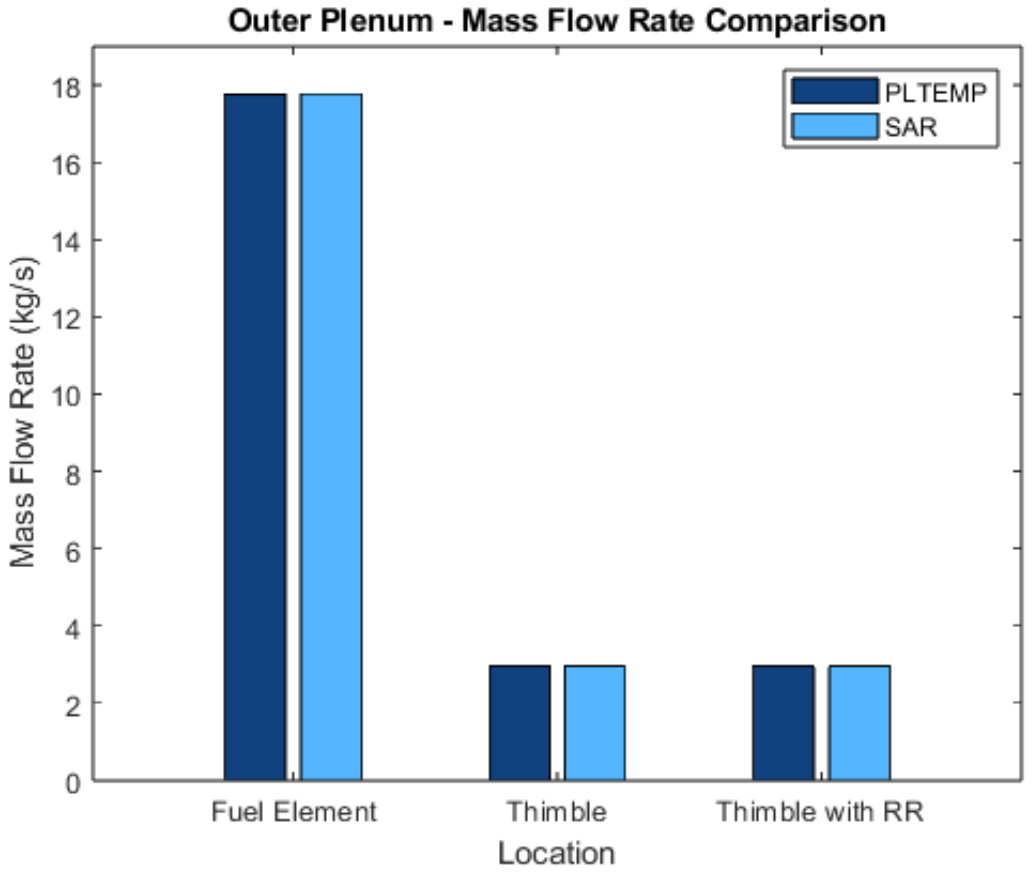
		<--------- L O C A T I O N ---------->				
		Plate Channel	Lateral Mesh	Axial Mesh	Assembly Number	Fuel Type
Max coolant temperature (C):	54.615	5	4	29	1	2
Max cladding surface temperature (C)	93.157	8	4	14	14	2
Max fuel temperature (C)	96.613	8	4	14	14	2
Max heat flux (MW/m^2)	0.971	8	4	14	24	2
Minimum ONBR	1.930	8	4	14	24	2
Minimum OFIR in channel	4.147	10	4	28	1	2
Minimum CHFR	4.136	8	4	14	14	2

PLTEMP Summary of Limiting Safety Margins & Temperatures

Results – Mass Flow Rate

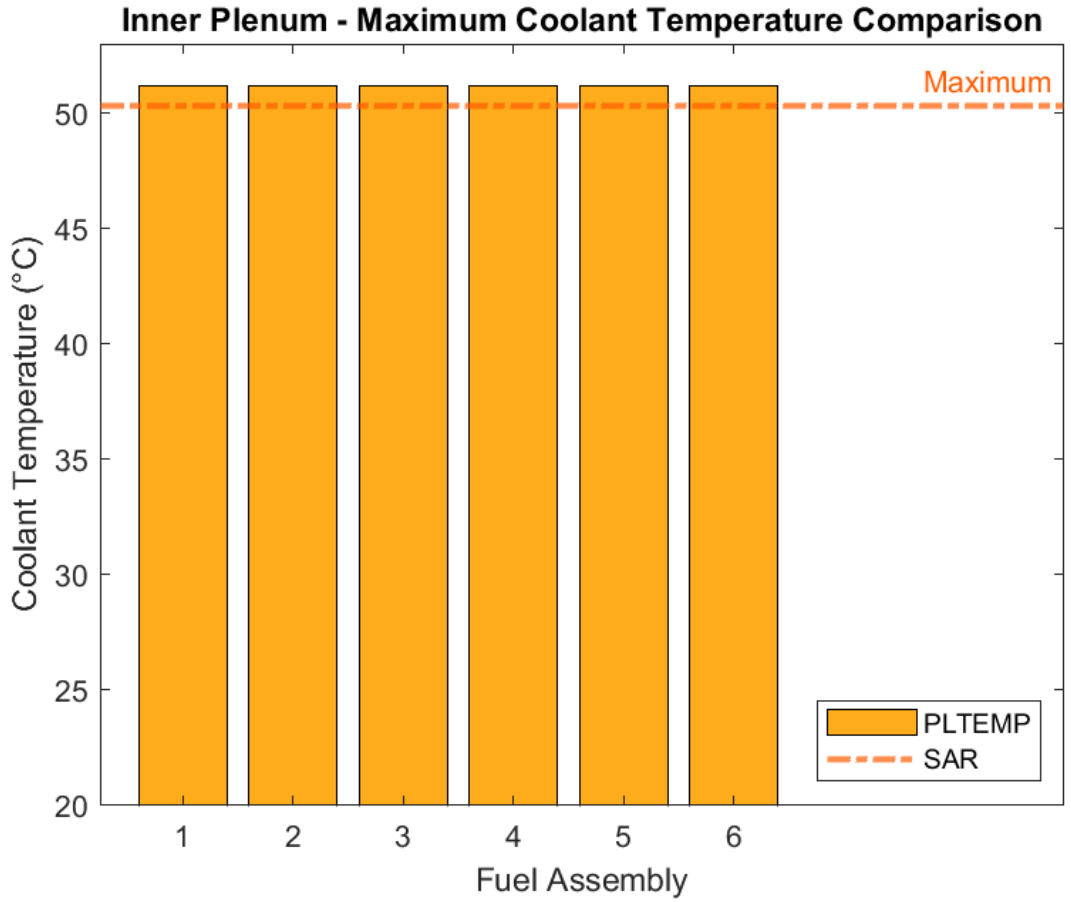
- Mass Flow Rate – rate at which coolant flows through a fuel assembly

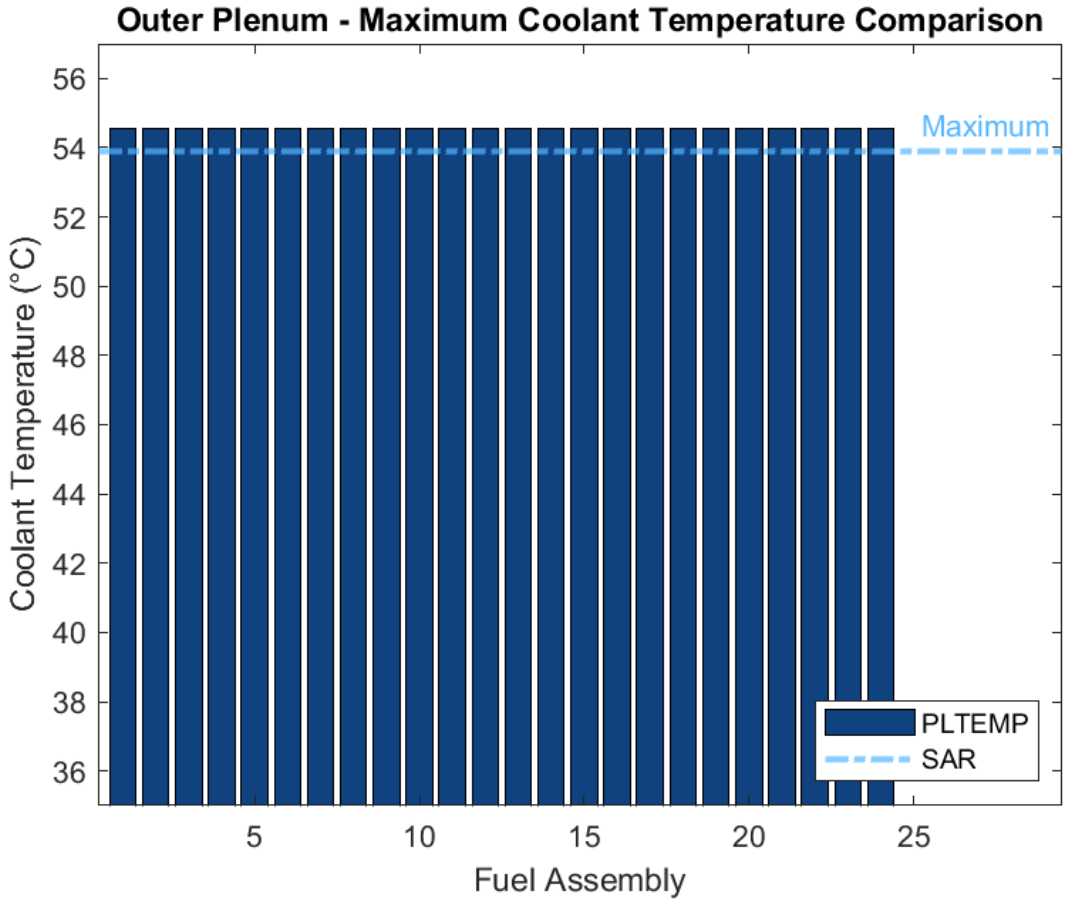




Results – Coolant Temperature

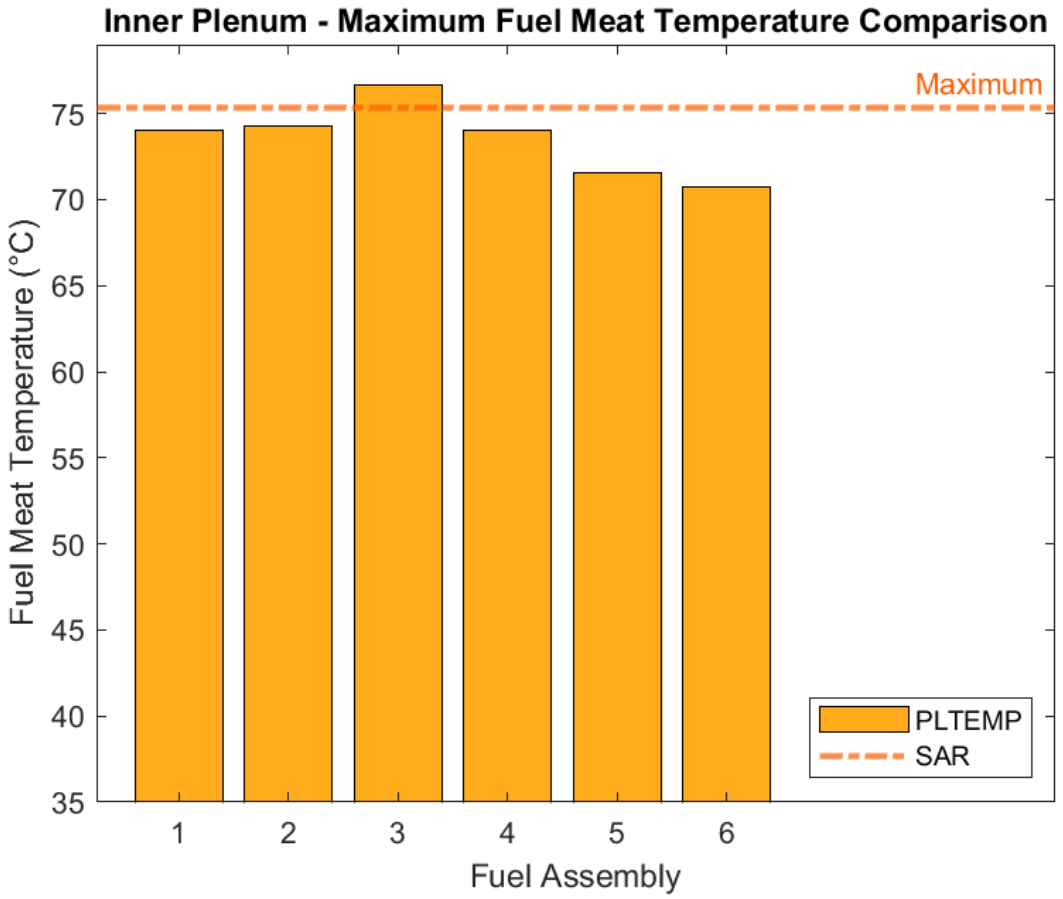
- Coolant Temperature – temperature of heavy water in reactor

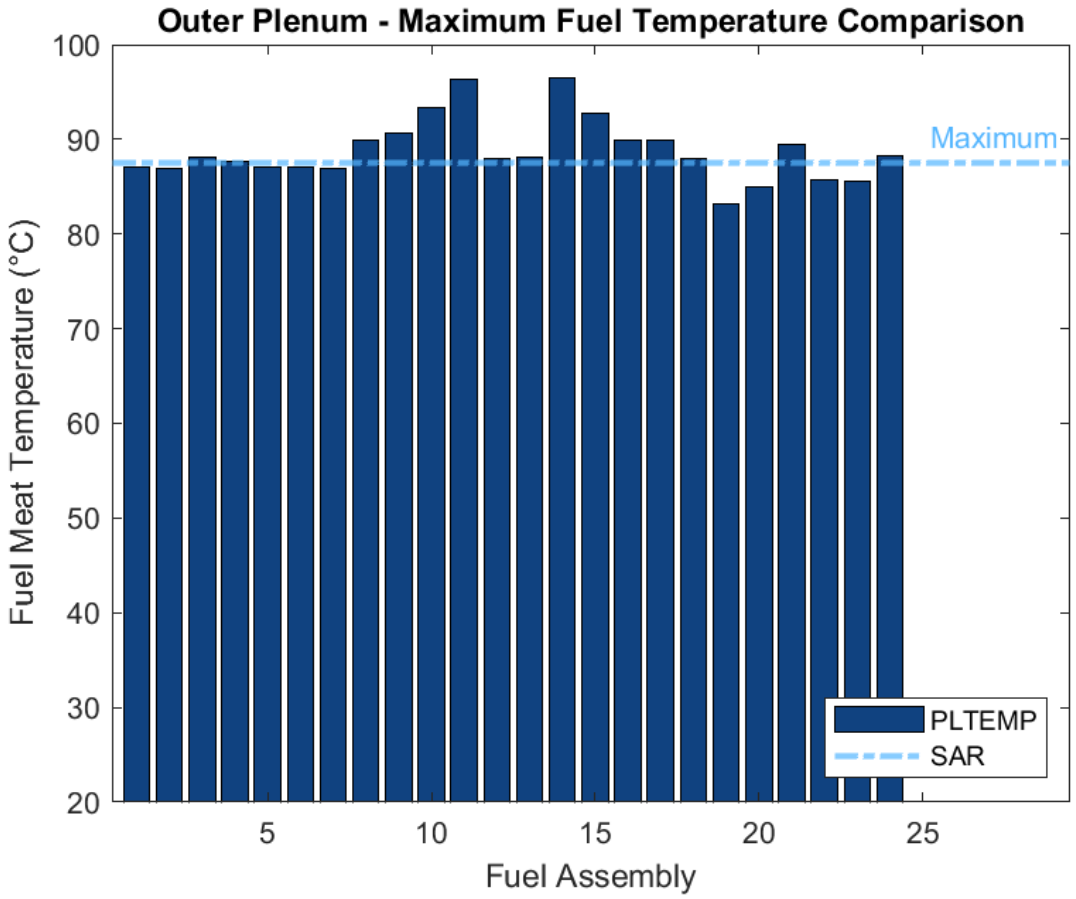




Results – Fuel Meat Temperature

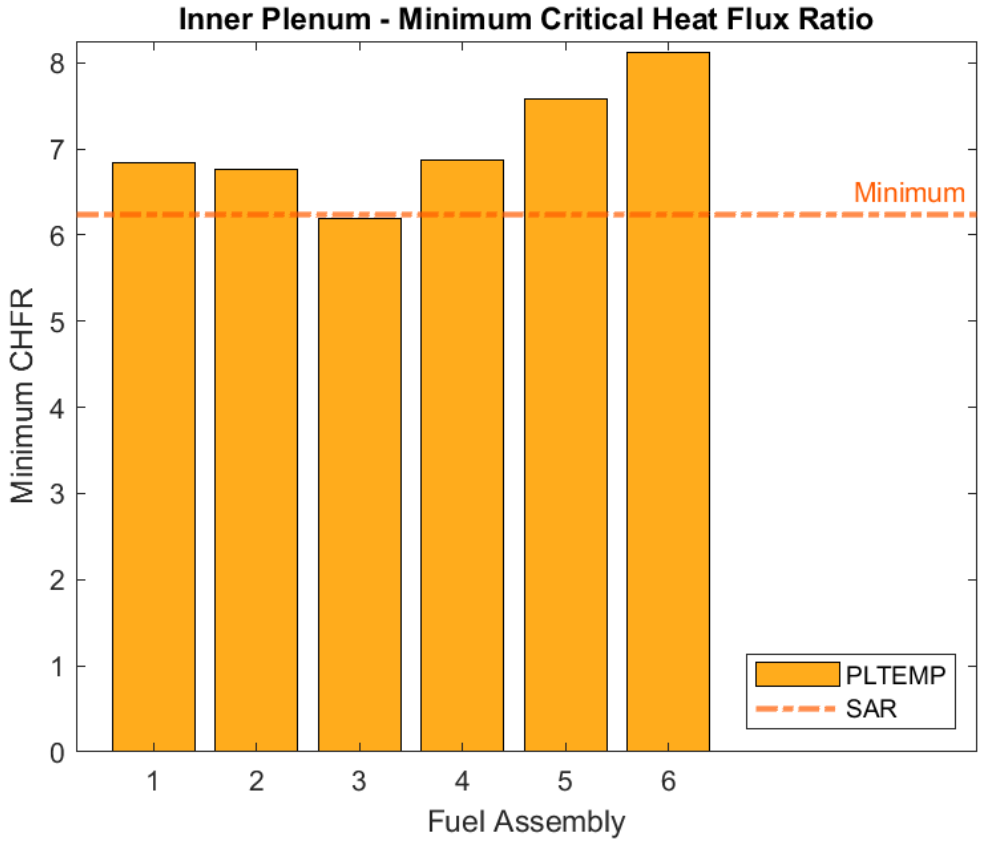
- Fuel Meat Temperature – Temperature of the fuel meat (inner component of fuel plates)

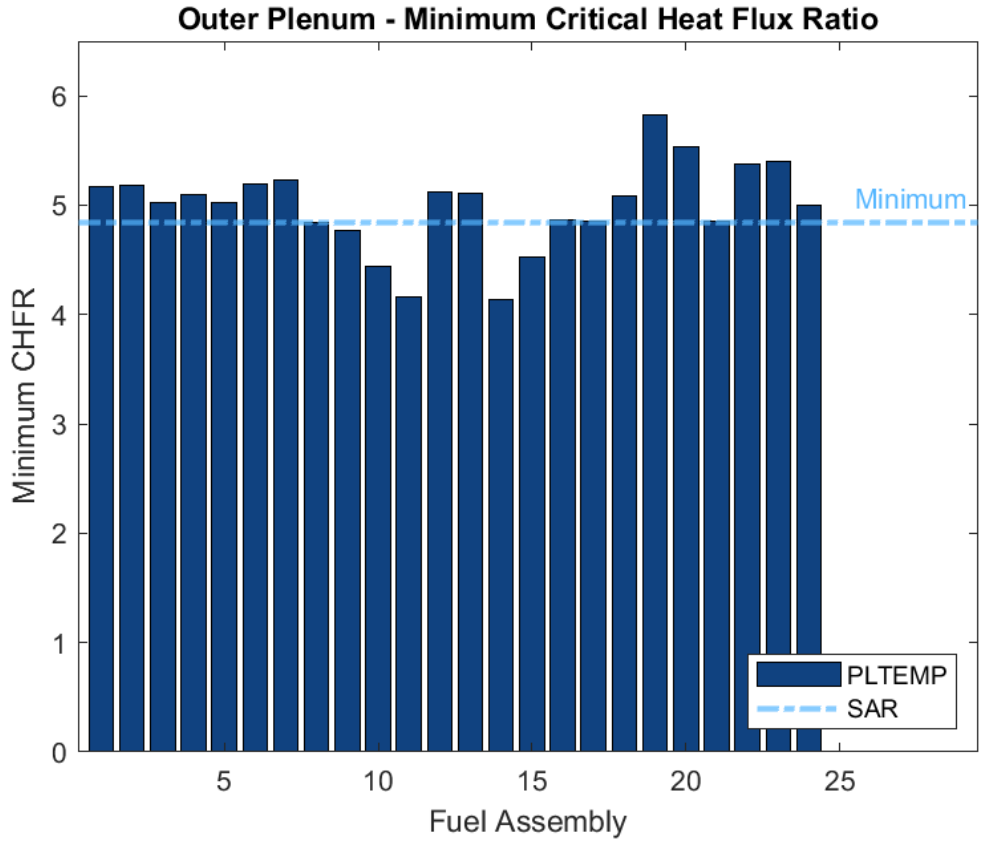




Results – Critical Heat Flux Ratio

- Critical Heat Flux Ratio – ratio of critical heat flux to local heat flux
- To be considered “safe” – CHFR > 2





Future Projects

- Improving the Current Model
  - Experiment with Modeling Top/Bottom Sections Separately
  - Adjusting Correlations Used
  - Complete Verification and Validation Process
- Creating New Models with Different Programs
  - Pronghorn
  - COBRA-TF

Acknowledgements

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- SURF Directors: Cara O'Malley, Julie Borchers, Leland Harriger, Susana Teixeira
- NCNR/SURF Peers (shoutout to The Cove)
- Programs: PLTEMP, Solidworks, Matlab, Excel, Notability

References

L. Cheng, et. al. *Safety Analysis Report (SAR) for License Renewal for the National Institute of Standards and Technology Reactor – NBSR: NBSR 14 Appendix A.*, U.S. Department of Commerce, April 2004. Accessed August 2024.

M. Kalimullah, et. al. *A User's Guide to PLTEMP/ANL Code*, ver. 4.3, Argonne National Laboratory, March 2021. Accessed August 2024.

Park, JY., Peng, L. & Choi, JW. "Critical heat flux limiting the effective cooling performance of two-phase cooling with an interlayer microchannel." *Microsyst Technol* **25**, 2831–2840 (2019). https://doi.org/10.1007/s00542-018-4270-y. Accessed August 2024.

Safety Analysis Report for the National Institute of Standards and Technology Reactor – NBSR, vol. 14, U.S. Department of Commerce, 2004. Accessed August 2024.

Questions??