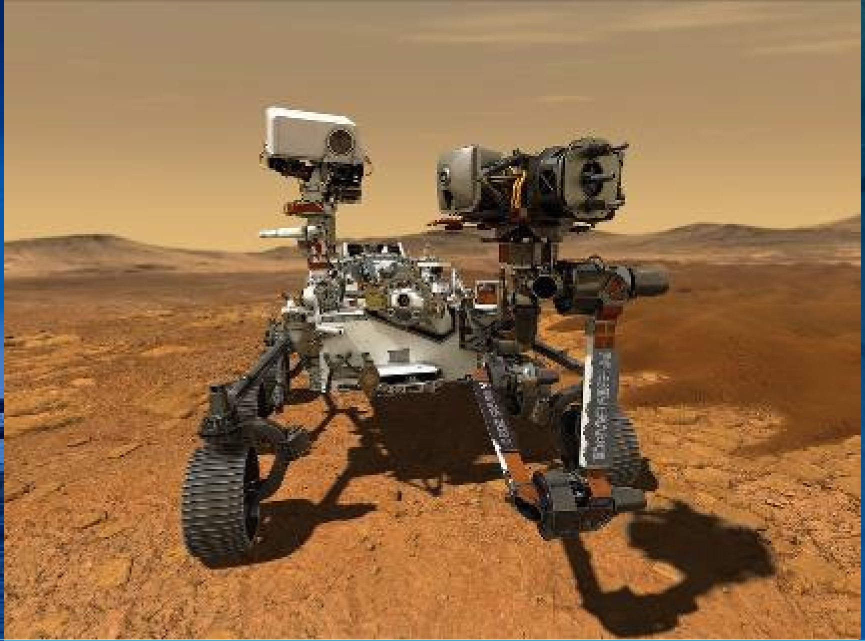


Sebastian Schunert

REACTOR PHYSICS METHODS AND ANALYSIS

Modeling Advanced Reactors with MOOSE

INL/MIS-21-64710

North Carolina State University

September 7th, 2021

Idaho National Laboratory

Credits

- **Many people have worked on portions of the research presented here**
  - Vincent Laboure, Javier Ortensi, Paolo Balestra, Yaqi Wang, Zach Prince, Chang-Ho Lee, Hansol Park, Yeon Sang Jung, Mark DeHart, Abdalla Abou Jaoude, Tian Jin, Ching-Sheng Lin, Logan Harbour, Guillaume Giudicelli, Ramiro Freile, Mauricio Tano, Sterling Harper
  - INL, ANL, TAMU, TerraPower
- **Funding agencies**
  - INL laboratory directed research and development (LDRD), NEAMS, ART, NRC, NASA, NRIC/Virtual test bed

National Laboratories

Idaho National Laboratory
Idaho Falls, Idaho

Pacific Northwest National Laboratory
Richland, Washington

National Renewable Energy Laboratory
Golden, Colorado

Argonne National Laboratory
Argonne, Illinois

Fermi National Accelerator Laboratory
Batavia, Illinois

Ames Laboratory
Ames, Iowa

National Energy Technology Laboratory
Morgantown, West Virginia
Pittsburgh, Pennsylvania

Brookhaven National Laboratory
Upton, New York

SLAC National Accelerator Laboratory
Menlo Park, California

Lawrence Berkeley National Laboratory
Berkeley, California

Lawrence Livermore National Laboratory
Livermore, California

Princeton Plasma Physics Laboratory
Princeton, New Jersey

Thomas Jefferson National Accelerator Facility
Newport News, Virginia

Savannah River National Laboratory
Aiken, South Carolina

Sandia National Laboratory
Livermore, California
Albuquerque, New Mexico

Los Alamos National Laboratory
Los Alamos, New Mexico

Oak Ridge National Laboratory
Oak Ridge, Tennessee

Addressing the world’s most challenging problems

Nuclear S&T

- Nuclear fuels and materials
- Nuclear systems design and analysis
- Fuel cycle science and technology
- Nuclear safety and regulatory research
- Advanced Scientific Computing

Advanced Test Reactor Complex

- Steady-state neutron irradiation of materials and fuels
  - Naval Nuclear Propulsion Program
  - Industry
  - National laboratories and universities

Materials & Fuels Complex

- Transient testing
- Analytical laboratories
- Post-irradiation examination
- Advanced characterization
- Fuel fabrication
- Space nuclear power and isotope technologies

Energy & Environment S&T

- Advanced transportation
- Environmental sustainability
- Clean energy
- Advanced manufacturing
- Biomass

National & Homeland Security S&T

- Critical infrastructure protection and resiliency
- Nuclear nonproliferation
- Physical defense systems

The East Idaho Lifestyle

- Enjoy unparalleled access to the region’s world-class skiing, hiking, camping, climbing, mountain biking, hunting, fishing, and much more
- Live close to some of the country’s greatest natural wonders: Yellowstone National Park, Grand Teton National Park, Craters of the Moon National Monument, Jackson Hole, and more

NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

The Reactor Multiphysics Team (RMT)

- Primary development of the Griffin (neutronics) and Pronghorn (coarse mesh TH) codes within the NEAMS program
- Partnering with companies on GAIN vouchers and Advanced Reactor Demonstration Project (ARDP) awards
- Advises the US NRC on tools for analysis of advanced reactors
- Funded by NRC, NEAMS, NASA, NRIC, ART
- Scope runs the gamut from algorithm development, implementation, to reactor analysis
- Reactors we worked on: PBRs, FHRs, MSRs, NTPs, prismatic VHTRs, micro-Rx

NRIC

RADIANT

NASA

X energy

BWXT
BWX Technologies, Inc.

REACTOR PHYSICS METHODS AND ANALYSIS (C110)

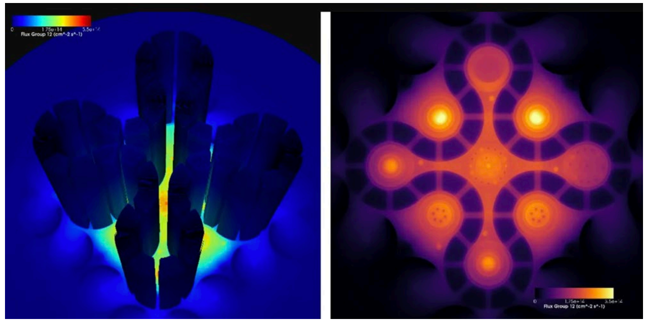
To develop and apply modern tools and techniques to fully characterize current and advanced nuclear reactor design and systems in support of testing, licensing, and deployment wherever energy is needed.

Integrated energy systems

Modeling autonomous fission batteries

Technology maturation with Marvel

Next generation advanced reactor codes

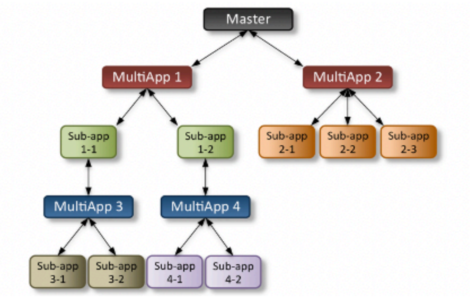


- **C110 is hiring!**
  - Nuclear engineer with a multiphysics background
  - Nuclear engineer with a neutronics background
  - Ask for the links!

MOOSE

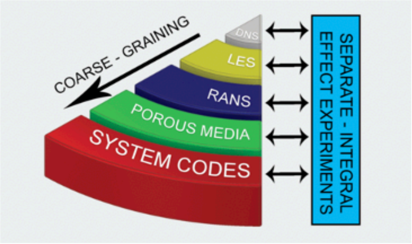
Flexible

- 1D, 2D, 3D, RZ
- Variety of physics modules
- Multi-scale in time & space via MultiApp
- Extendible



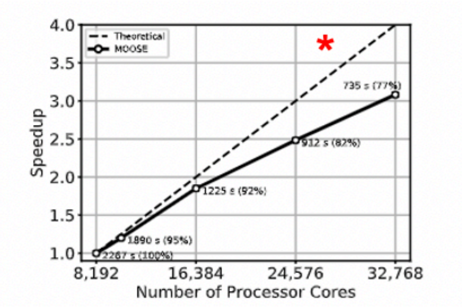
Tunable fidelity

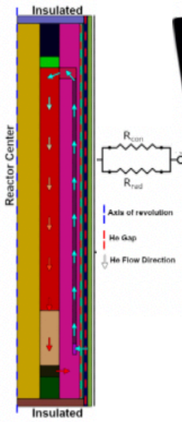
- 1D/0D lumped models
- Intermediate fidelity homogenized models
- High-fidelity "explicit" geometry



Scalable

- MOOSE supports hybrid parallelism
- Scales well on workstation & HPC
- 2D/RZ models execute in minutes
- High-fidelity 3D models execute on HPC



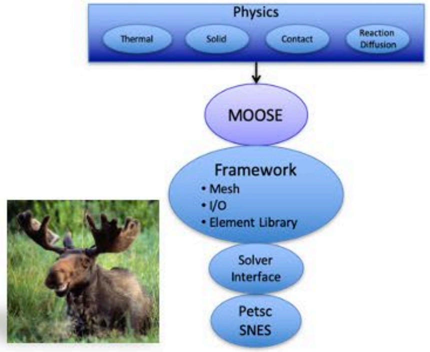


2 minutes

*Picture courtesy MOOSE, Software X

The MOOSE Herd

MOOSE
HPC Framework



Physics
- Thermal
- Solid
- Contact
- Reaction Diffusion

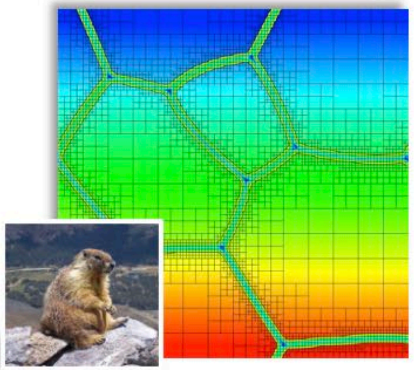
MOOSE

Framework
- Mesh
- I/O
- Element Library

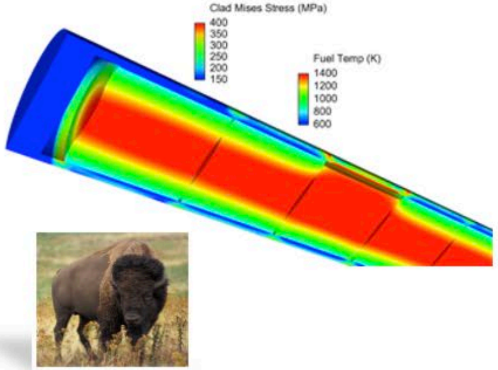
Solver Interface

Petsc SNES

Marmot
Mesoscale Materials

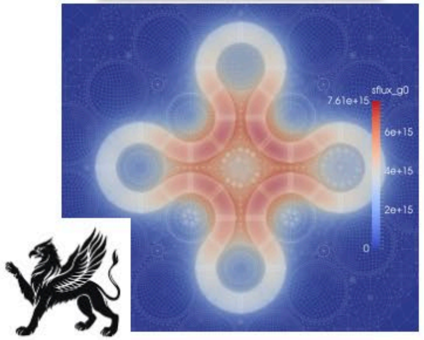


Bison
Nuclear Fuel Performance

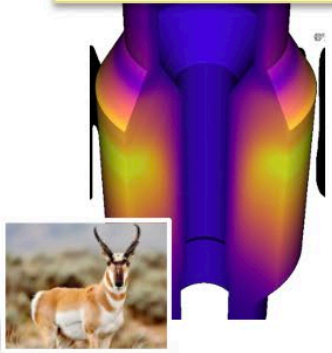


Grizzly
Structural Mechanics for Component Aging

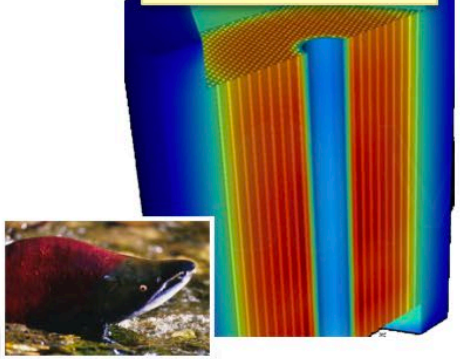
Griffin
Radiation Transport



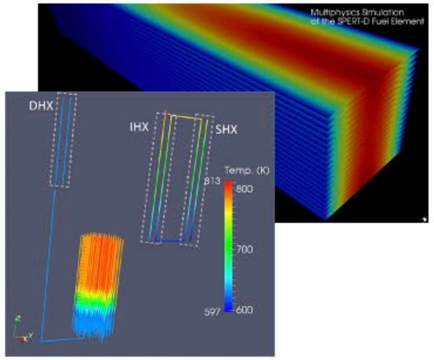
Pronghorn
Engineering Scale Flow



Sockeye
Heat pipe Simulation



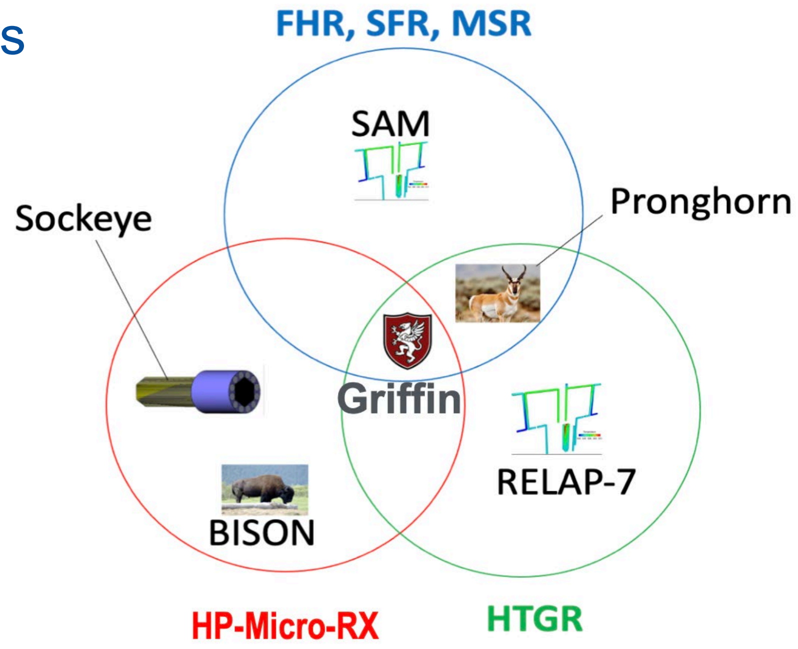
SAM and RELAP-7
Multiscale Multiphysics Systems Analysis



What is Griffin and Why is it important?

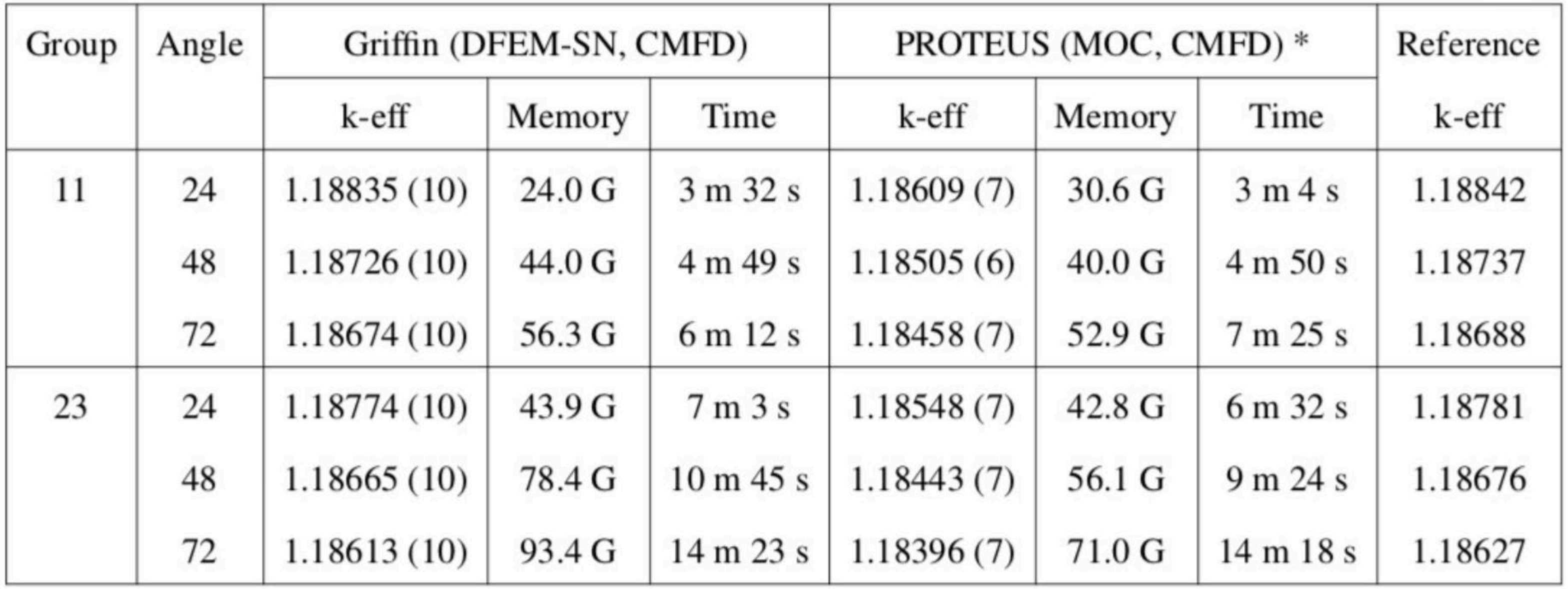
Griffin is a generalized tool for reactor physics for non-LWR reactors

- **Multiphysics-oriented**
  - Provides native coupling to all MOOSE-based tools
  - Takes advantage from common investment in framework
- **Flexible and Extendable**
  - Regular and unstructured geometries
  - Various types of calculations (variable fidelity)
  - Easy addition of functionality
- **Robust**
  - Consistent with NQA-1 process
  - Strict software development cycle
- NRC's designated non-LWR neutronics code
- 50/50 partnership between INL and ANL

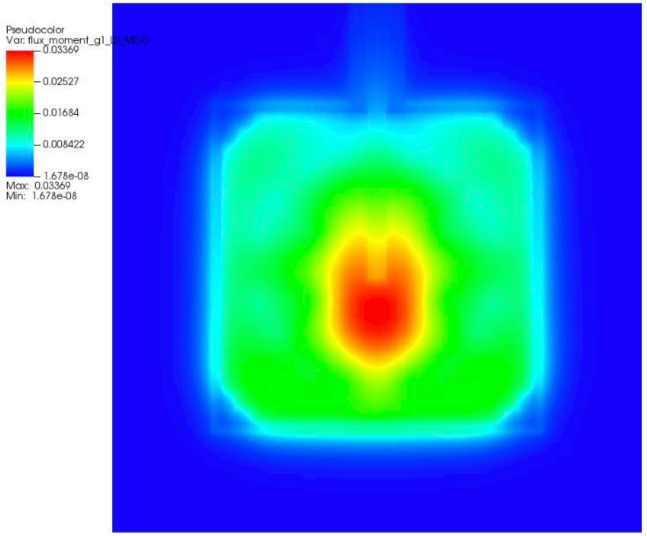


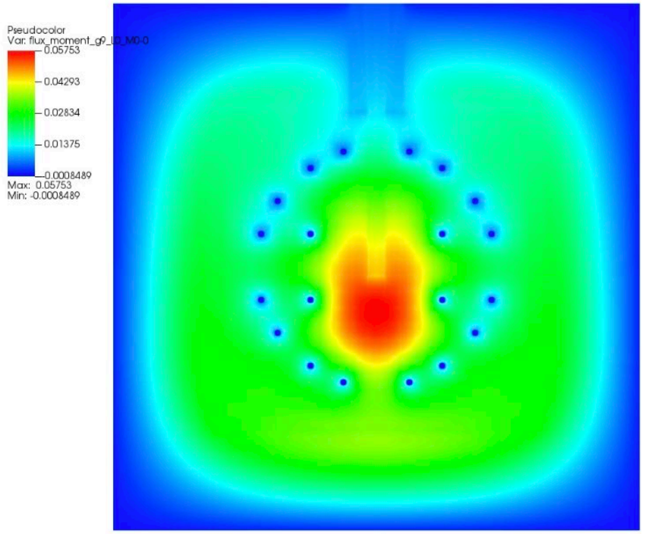
Griffin Transport Solver Improvement

- Fiscal year 2021 has seen a tremendous improvement of Griffin’s discontinuous FEM S_N solver
- Comparison against PROTEUS MOC for TREAT benchmark
- Next fiscal year variational nodal method and diffusion solver will be improved



Group	Angle	Griffin (DFEM-SN, CMFD)			PROTEUS (MOC, CMFD) *			Reference
		k-eff	Memory	Time	k-eff	Memory	Time	k-eff
11	24	1.18835 (10)	24.0 G	3 m 32 s	1.18609 (7)	30.6 G	3 m 4 s	1.18842
	48	1.18726 (10)	44.0 G	4 m 49 s	1.18505 (6)	40.0 G	4 m 50 s	1.18737
	72	1.18674 (10)	56.3 G	6 m 12 s	1.18458 (7)	52.9 G	7 m 25 s	1.18688
23	24	1.18774 (10)	43.9 G	7 m 3 s	1.18548 (7)	42.8 G	6 m 32 s	1.18781
	48	1.18665 (10)	78.4 G	10 m 45 s	1.18443 (7)	56.1 G	9 m 24 s	1.18676
	72	1.18613 (10)	93.4 G	14 m 23 s	1.18396 (7)	71.0 G	14 m 18 s	1.18627

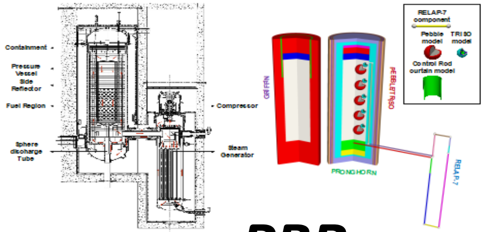




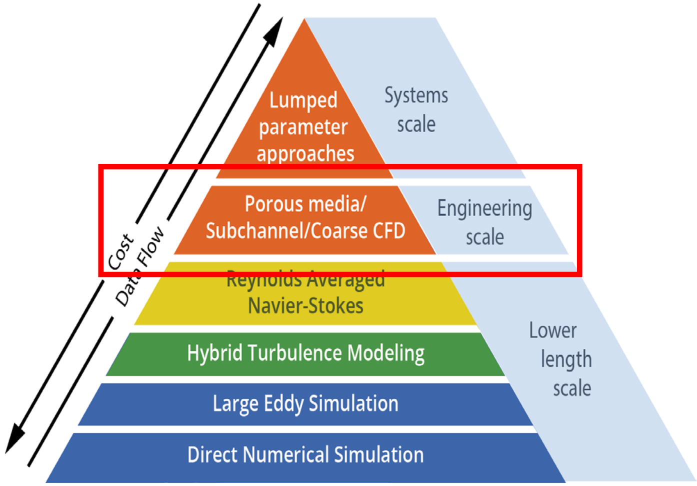
What is Pronghorn and Why is it important

What is Pronghorn? A coarse-mesh thermal-hydraulic core simulator for advanced reactors

Modeling engineering-scale phenomena relevant to advanced nuclear reactor concepts without complete resolution of geometry and material heterogeneity.



PBRs

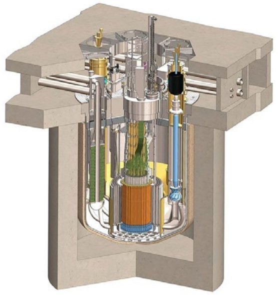


Pronghorn

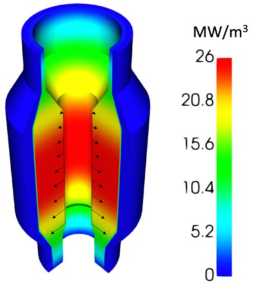
Coarse mesh TH core simulator

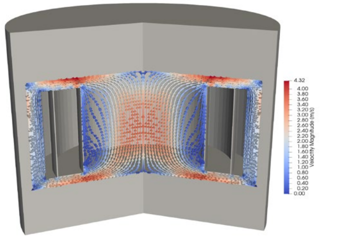
- Subchannel
- Porous Medium
- MOOSE Navier Stokes
- THM

FHRs



LMFR





MSRs

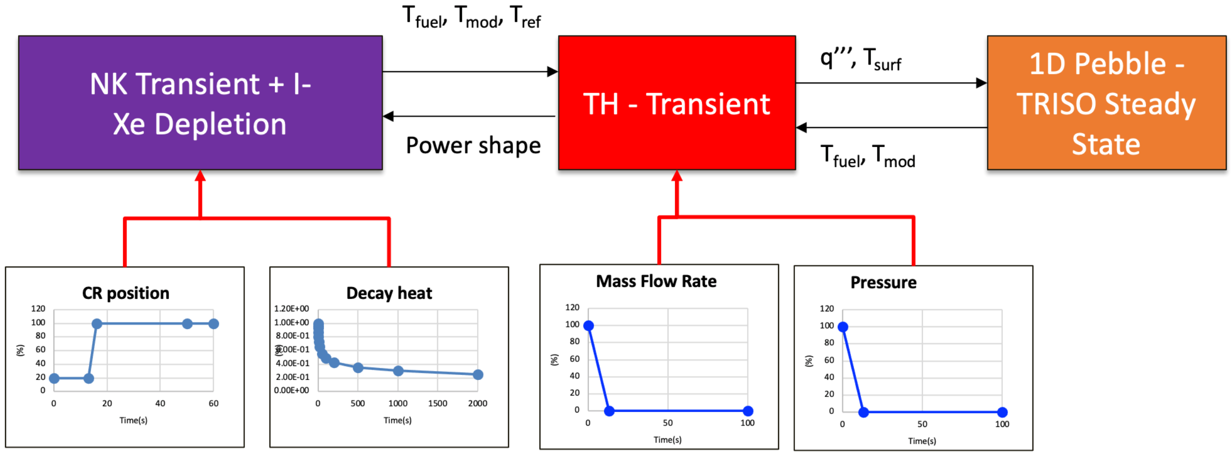
***Importance** of Pronghorn: Model multi-dimensional flow problems during long transients (50 h) in minutes on a laptop*

Pebble Bed Reactors

Safety related transients with Pronghorn

Event Sequence:

1. 0 - 13s:
    1. A linear reduction in reactor inlet coolant mass flow from 192.7 kg/s) to 0kg/s.
    2. Reduction in reactor helium outlet pressure from nominal (90 bar) to 60 bar over 13 seconds.
2. 13-16s: All control rods are fully inserted over 3 seconds (SCRAM)
3. 16 –180,000s: no change in input parameters (50h)



T_{fuel}, T_{mod}, T_{ref}

NK Transient + I-Xe Depletion

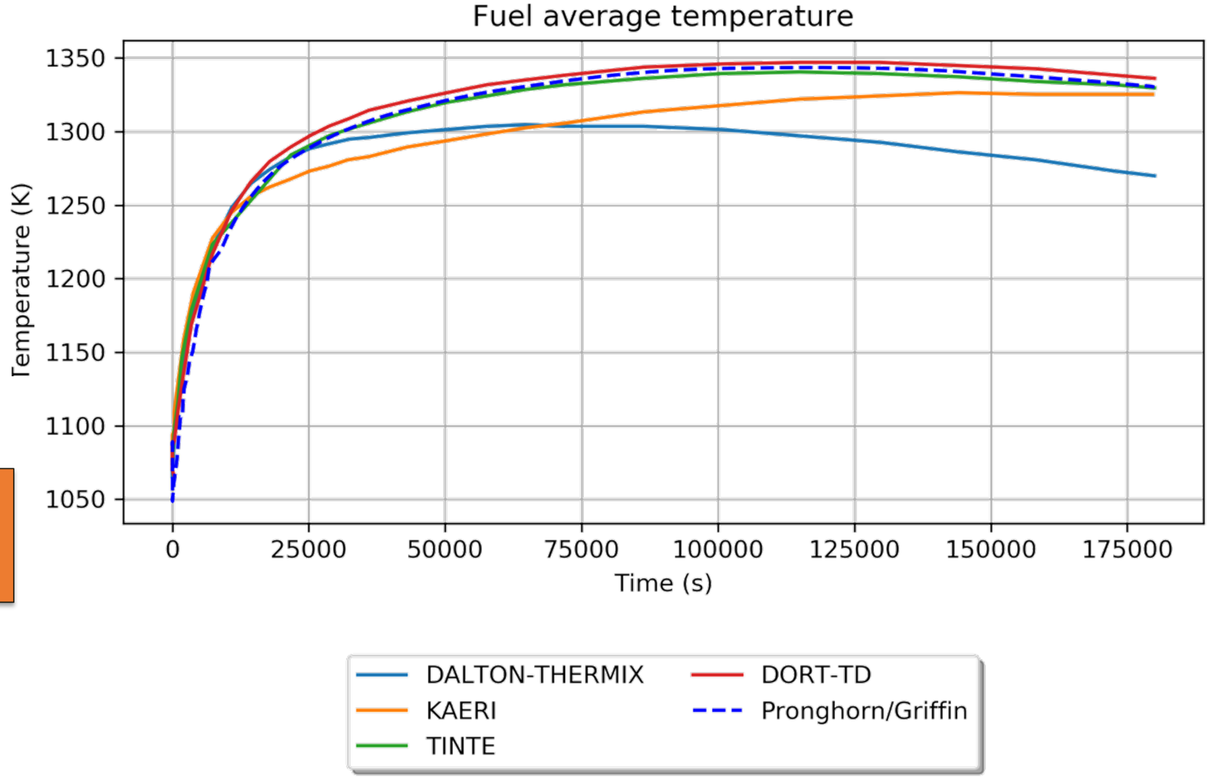
Power shape

TH - Transient

q''', T_{surf}

T_{fuel}, T_{mod}

1D Pebble - TRISO Steady State



1. **Neutron Kinetics + Xe/I tracking**
2. **Thermal-hydraulics**
3. **Pebble/TRISO temperature model**

Coupled Steady ~ 6 min
Transient ~20-22 min

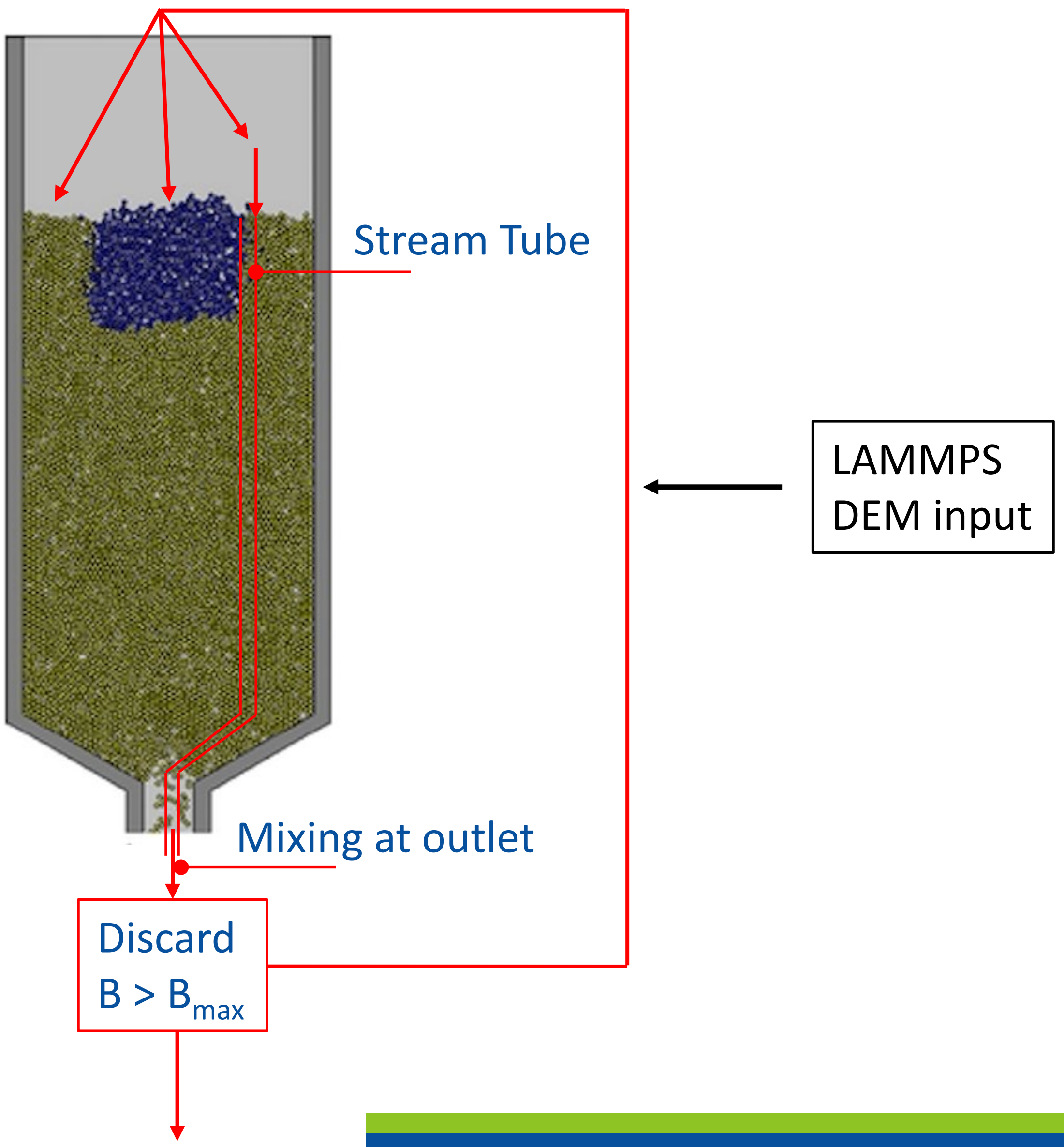
Pebble Depletion

Problem Statement

- Pebbles are irradiated WHILE moving through core
- Pebbles are recirculated multiple times and discarded if burnup threshold is exceeded
- Coupled advection & depletion problem w/ special periodic BCs

Streamline approach

- "Eulerian" control volume approach
- Balance of isotopes & pebbles of "burnup group" in each element
- At outlet, discard pebbles in "burnup group" > burnup limit



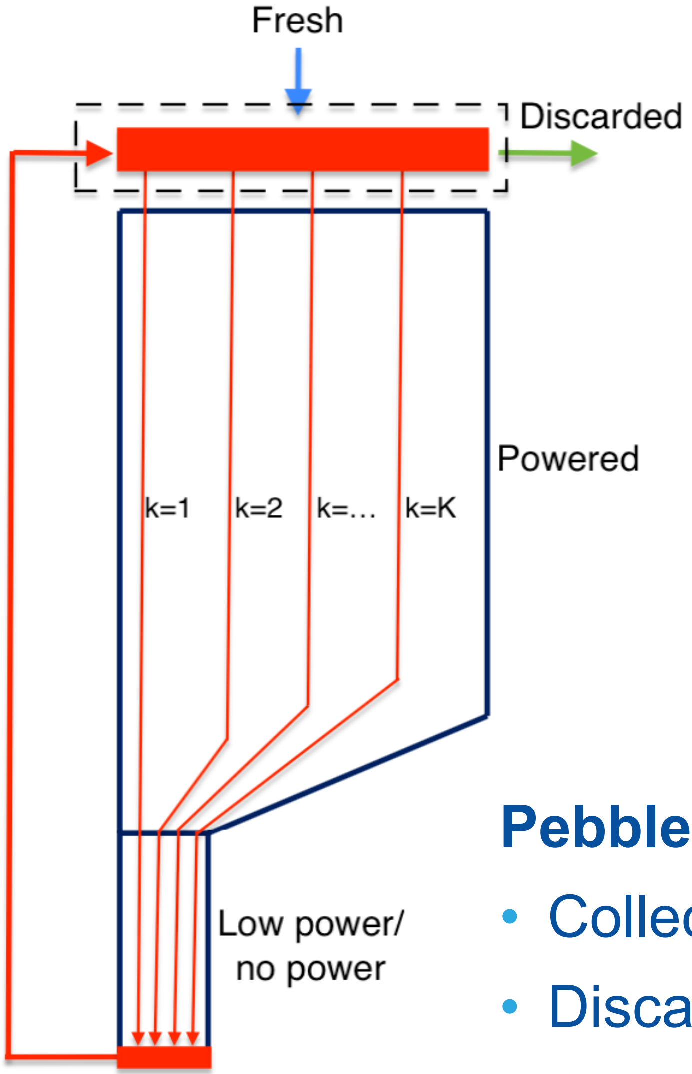
Stream Tube

Mixing at outlet

Discard
$B > B_{max}$

LAMMPS
DEM input

Equilibrium Core Calculations

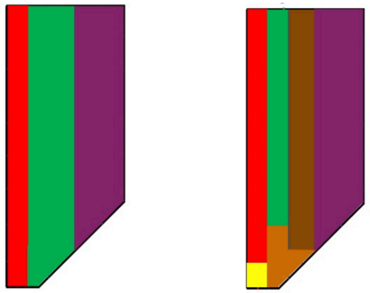


Eulerian Streamline Pebble Depletion

- Coupled advection & depletion problem w/ special periodic BCs solved on a 1D streamline
- Detailed balances (by finite volume) in space & burnup
- Pebbles discarded at outlet if burnup > limit

Mapping Neutronics/TH to streamlines

- 3D core distributions are mapped to 1D streamlines
- Fraction of multi-D element is assigned to the streamlines using fractional volume matrix



Strategies for the fractional volume matrix

Strategy 1: nearest streamline

Strategy 2: equidistance to streamlines

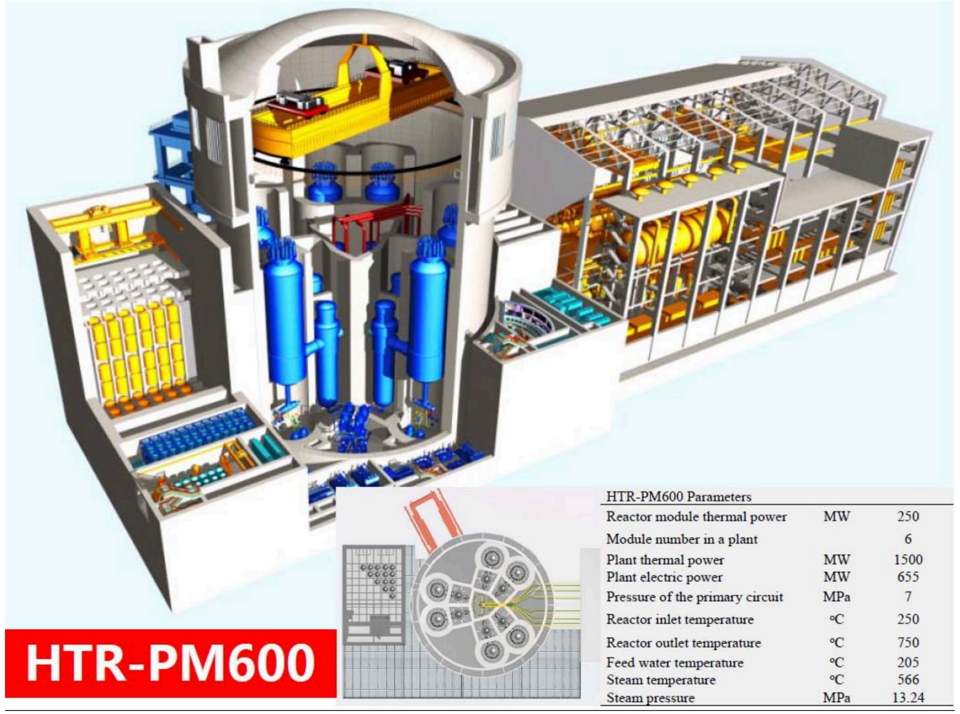
Pebble handling system

- Collects outflow of pebbles and isotopes from streamlines
- Discards the portion with burnups exceeding limit
- Compute fresh pebble stream

What is HTR-PM?

- 200MWe reactor demonstration plant built in China
- Design is based on German HTR-MODUL
- “The No.1 reactor achieved first criticality at 9.35am on 12 September, China Huaneng announced. It noted this milestone was reached 23 days after the start of fuel loading.” [2]
- **Why is this relevant for us?** X-energy plans to build a pebble bed reactor under the Advanced Reactor Demonstration Program in the US

6 reactor concept “HTR-PM600” [1]



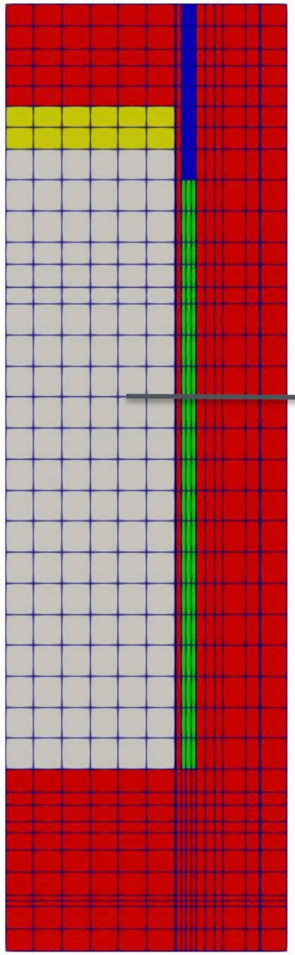
HTR-PM600 Parameters

Reactor module thermal power	MW	250
Module number in a plant		6
Plant thermal power	MW	1500
Plant electric power	MW	655
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	°C	250
Reactor outlet temperature	°C	750
Feed water temperature	°C	205
Steam temperature	°C	566
Steam pressure	MPa	13.24

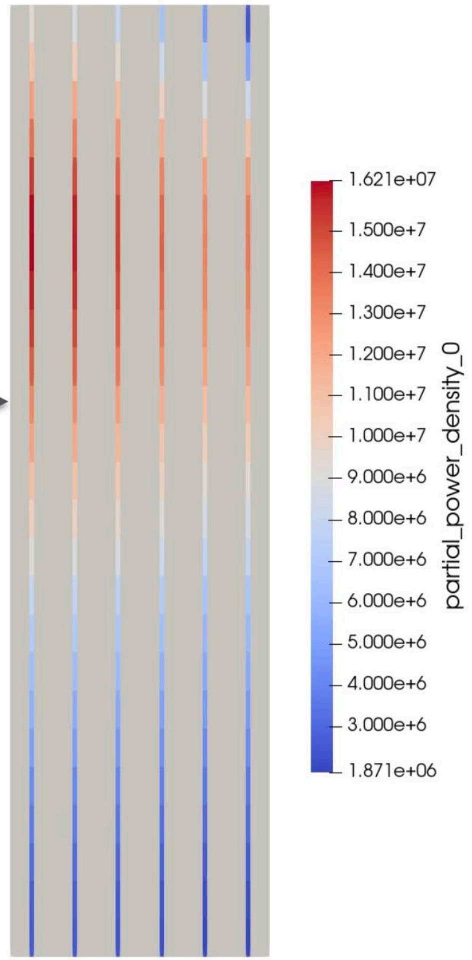
[1] Panel on Innovations and Advances in Nuclear Technologies “The Status of HTR-PM, a 200MWe High Temperature Gas-cooled Reactor demonstration plant constructed in China”
[2] https://www.world-nuclear-news.org/Articles/Chinas-HTR-PM-reactor-achieves-first-criticality

HTR-PM Model

Parameter	Value/Description
Dimensions	Pebble bed is 1.5m radius and 11m height
Geometry	RZ geometry, 6 radial and 21 axial core regions
Pebble types	1 pebble type with 7g IHM/pebble
Number of passes	15
Number of streamlines	6 (equally spaced)
Number of burnup groups	10 (from 0-100 at 10 GWd/MT intervals)
Residence time	70.5 days
Discharge burnup	90 GWd/MT
Neutron libraries	4, 9, 26 (DRAGON microscopic XS) ENDFB/VIII.r0 Transport XS in void regions from Serpent CMM 294 isotopes Tabulation - Burnup, Tfuel, Tmod
MP coupling	Picard iteration MainApp – Griffin SubApp1 – 1D Streamline SubApp2 – 2D Pronghorn (CFEM) SubApp3 – 1D Pebble/TRISO for each pebble type

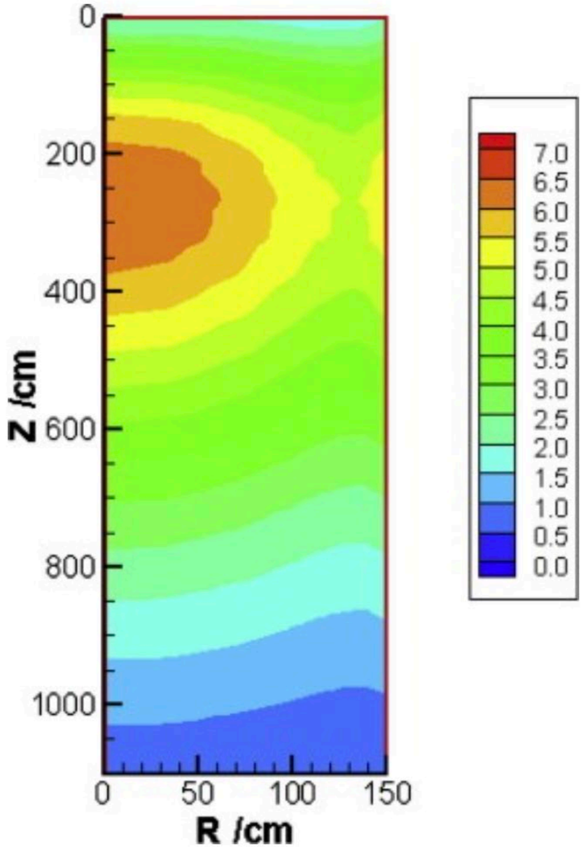


Griffin computational mesh

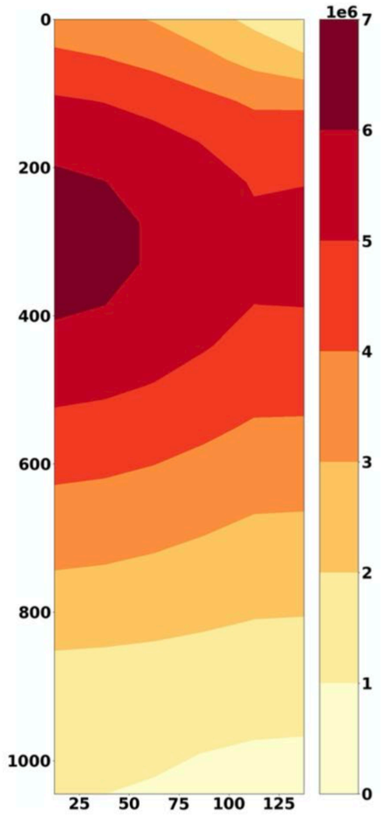


Griffin streamline overlay

Comparison to published results (VSOP)



V.S.O.P.



Griffin

Y. Zheng, L. Shi, Y. Dong
Annals of Nuclear Energy, Vol. 36 (6), June 2009

k_{eff}
- Griffin 1.00061
- V.S.O.P. 1.0000 (assumed)

Maximum power density
- Griffin 6.58 MW/m^3
- V.S.O.P. 6.57 MW/m^3

Power peaking
- Griffin 1.88
- V.S.O.P 2.04
- ART program will be working on verification of the Griffin equilibrium core solutions for a number of problems
- Serpent full core equivalent model

Molten Salt Reactors

Molten Salt Reactors

Molten Salt Reactors are one technology selected for an Advanced Reactor Demonstration Project Award. Southern Company's MCRE will be built at INL.

- MSRs will be a reality at INL
  - National Reactor Innovation Center (NRIC)
  - Southern Company/TerraPower's reactor experiment
  - NS&T's fission battery initiative

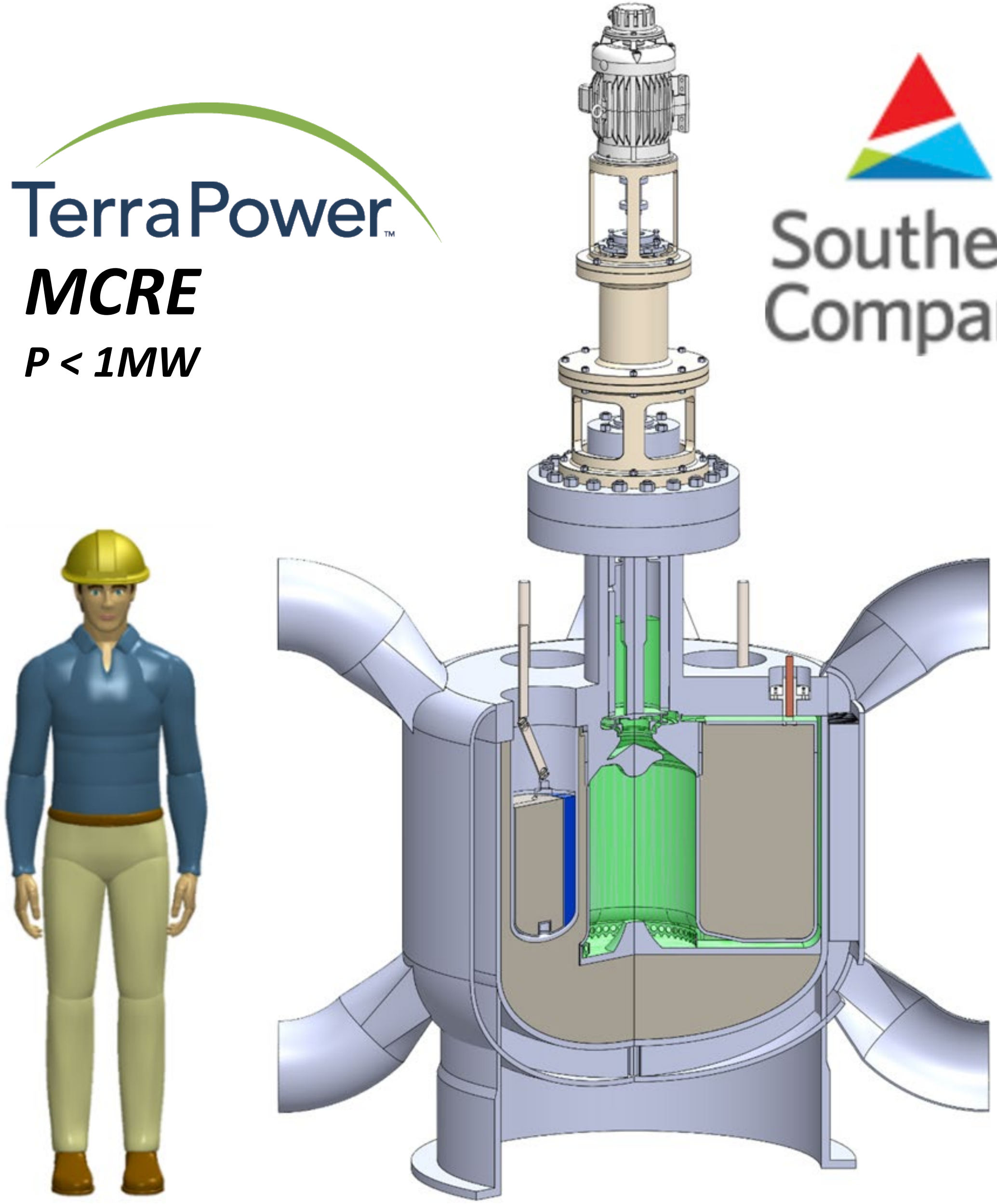
- Molten Chloride Reactor Experiment (MCRE) is unique validation opportunity
- Licensing basis for reactor transients
- Southern Company targets mid-20s

TerraPower

MCRE

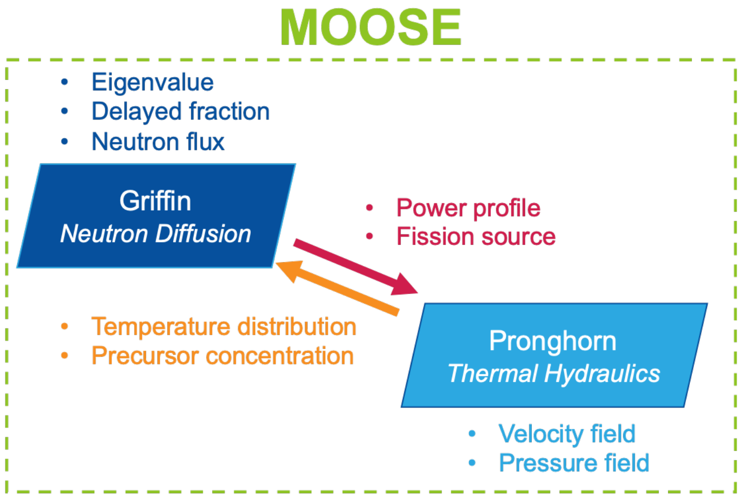
$P < 1MW$

Southern Company



Molten Salt Reactors

- Griffin/Pronghorn are capable of delayed precursor drift tracking
- Molten Salt Fast Reactor (SAMOFAR) 3000 MWth
- Radially-symmetric model
- Porous media approach for pump & heat exchanger
- Steady-state & ULOF (instant reduction of pump head to 0)
- Sensitivity analysis of max. temperature & power-to-flow ratio



MOOSE

- Eigenvalue
- Delayed fraction
- Neutron flux

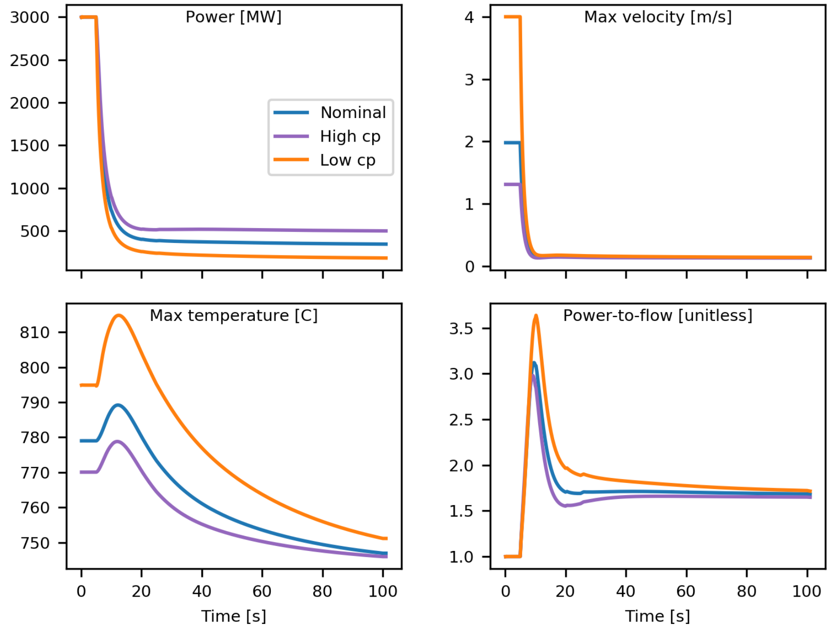
Griffin
Neutron Diffusion

- Power profile
- Fission source

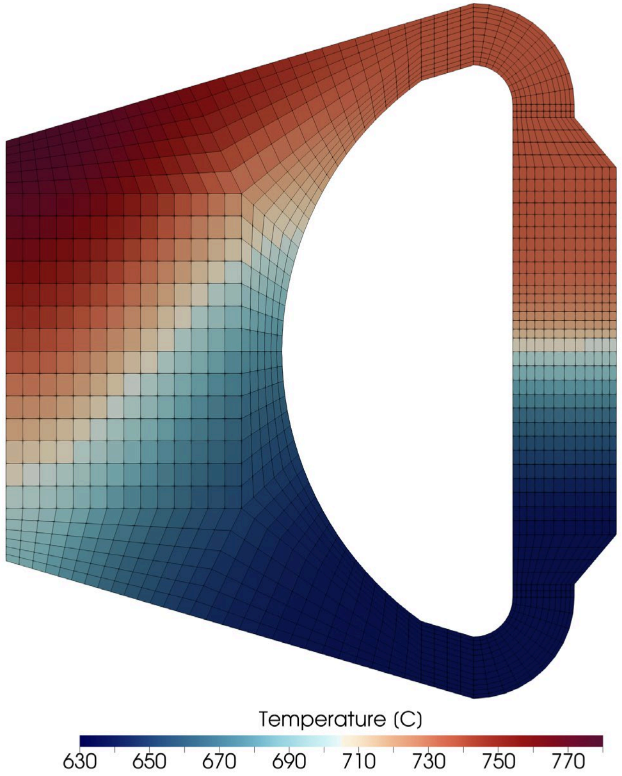
- Temperature distribution
- Precursor concentration

Pronghorn
Thermal Hydraulics

- Velocity field
- Pressure field

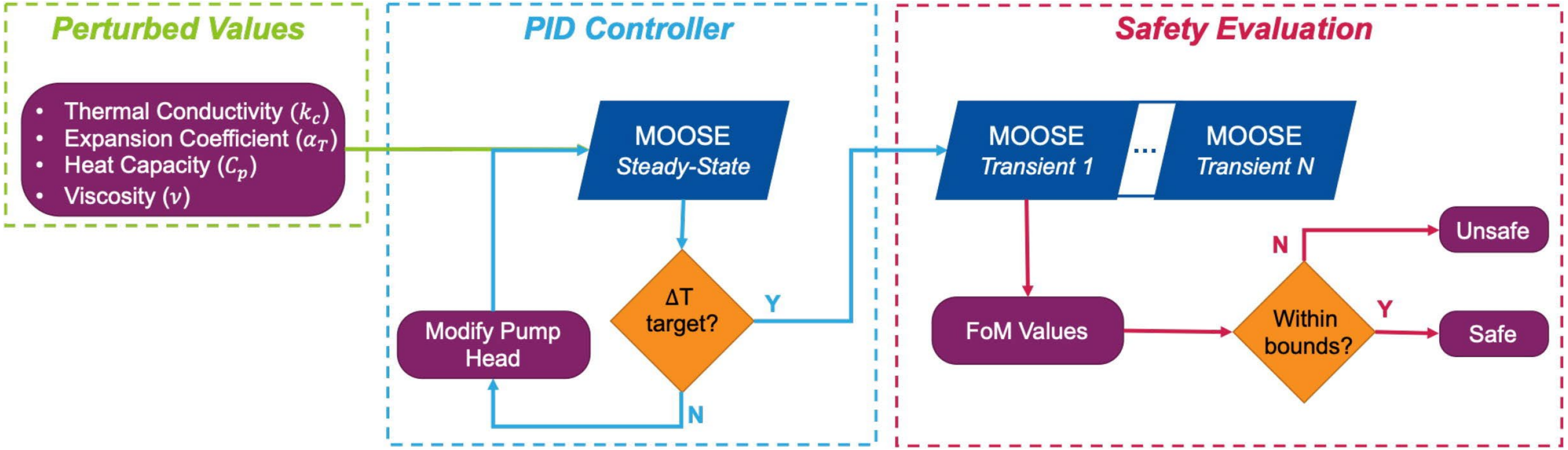


Steady-state temperature distribution



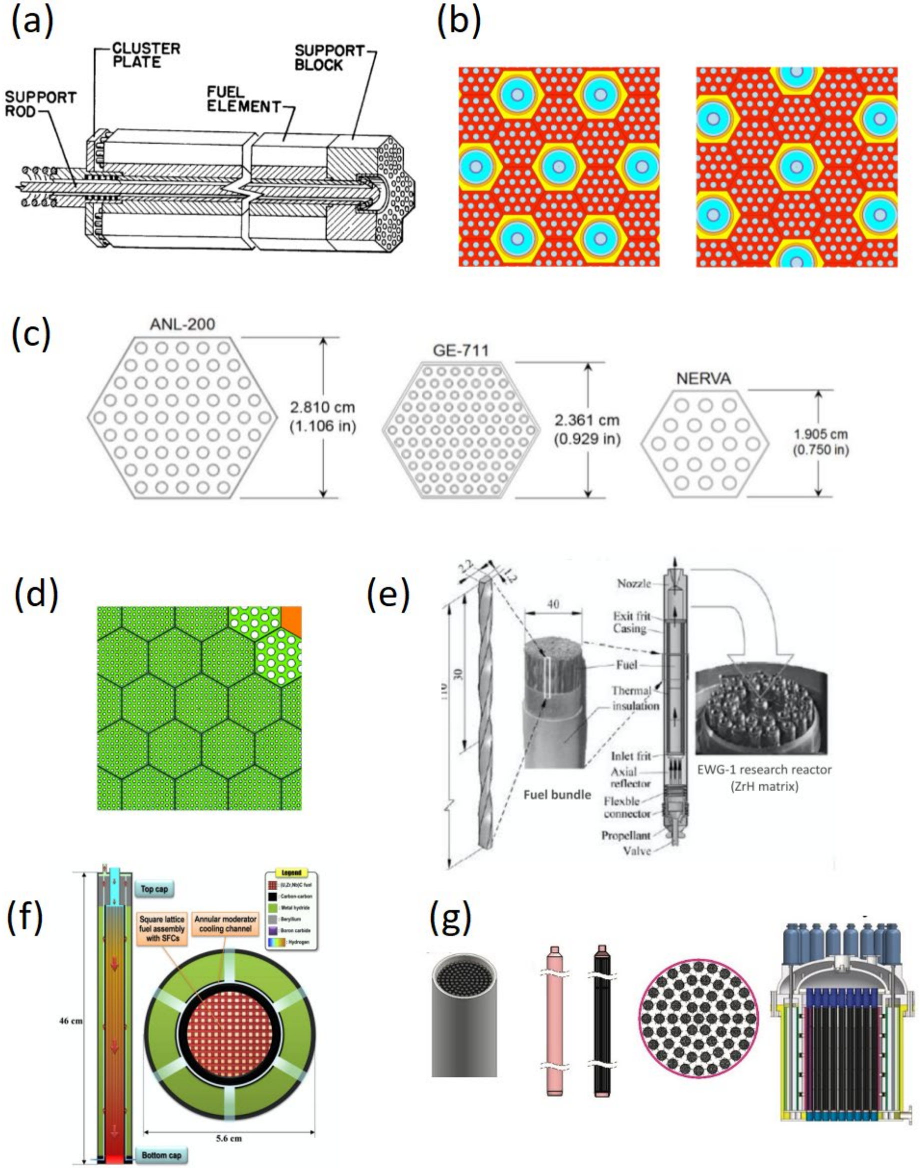
Augmented Monitoring & Inspection Workflow (M&I)

- M&I proposes to operate MSRs without conducting extensive irradiations in prototypic conditions to receive initial fuel qualification (Flanagan)
- If salt properties deteriorate beyond a certain point, reactor must shut-down
- What are unsafe conditions, though?
- We propose to use MOOSE based modeling and simulation to map material properties to safety quantities of interest for all transients of interest.



Nuclear Thermal Propulsion (NTP)

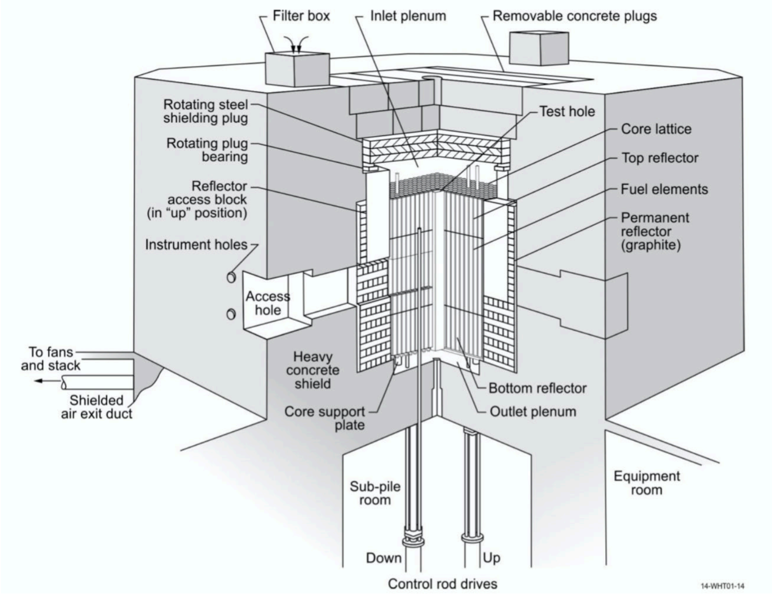
Nuclear Thermal Propulsion



1. SIRIUS experimental campaign
2. NASA “reference” plant model

SIRIUS experiment series

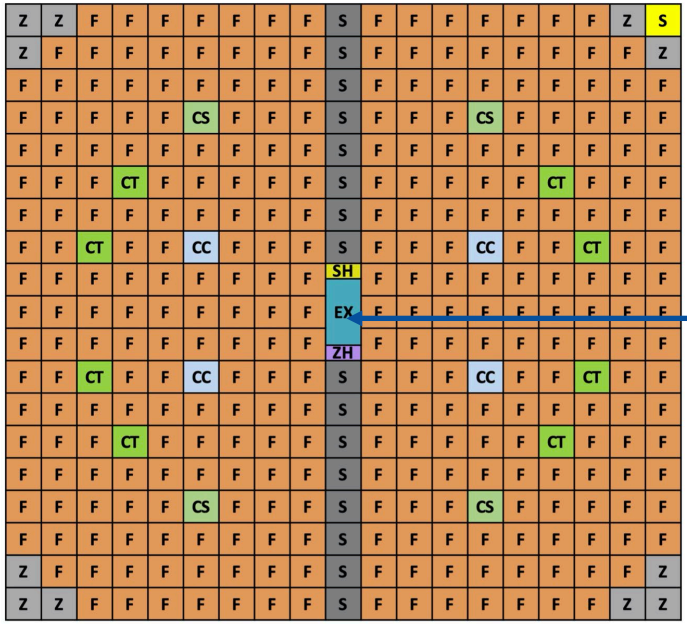
- Experimental campaign for transient testing of new Nuclear Thermal Propulsion Fuel: UN-CERMET & UN-CERCER
- Experiments are performed in TREAT
- Challenges of NTP fuel:
  - Very hot: 2600-2850 K
  - Fast heat rates: 100 K/s
- SIRIUS series progresses in complexity:
  - SIRIUS-1: UN-CERMET specimen fabricated at INL
  - SIRIUS-2: like SIRIUS-1 but NASA fabricated fuel
  - SIRIUS-3: stack of fuel but not cooled
  - SIRIUS-4: first hydrogen-cooled experiment
- CAL experiment is a pre-run at low power to calibrate instrumentation and transient parameters



Multiphysics Simulations of SIRIUS-CAL

- Calibration experiment for SIRIUS-1

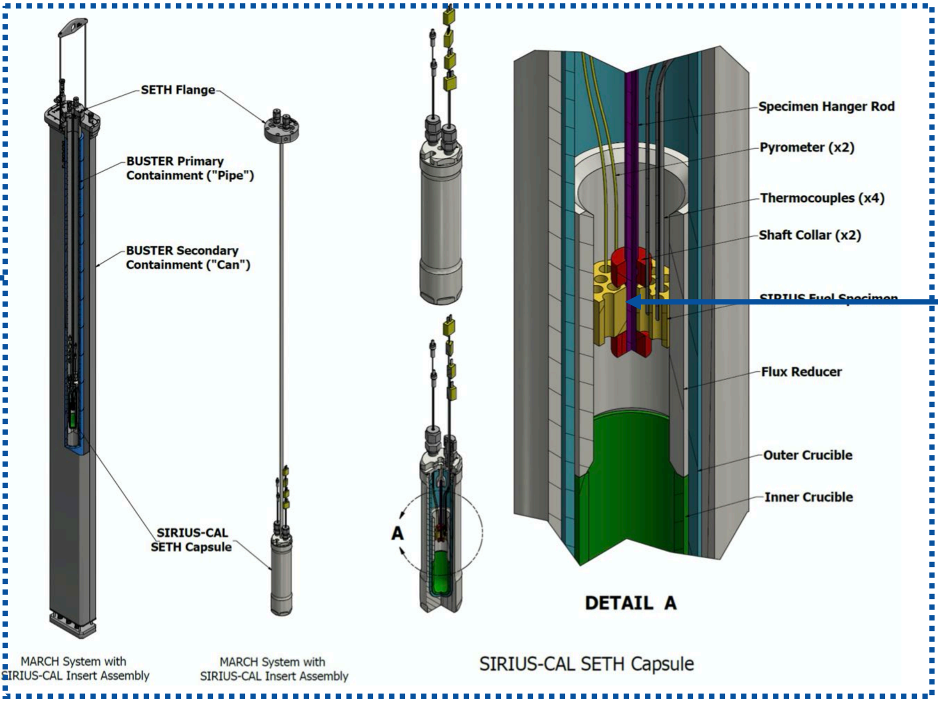
TREAT core configuration



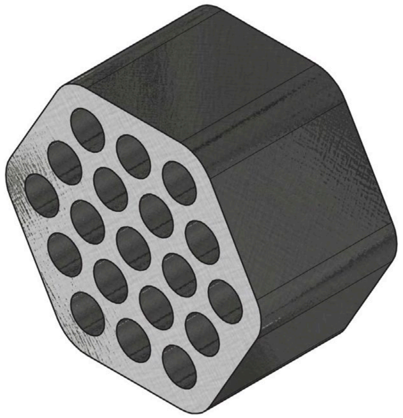
Z	Z	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	Z	S
Z	F	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	F	Z
F	F	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	F	F
F	F	F	F	F	CS	F	F	F	S	F	F	F	CS	F	F	F	F	F
F	F	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	F	F
F	F	F	CT	F	F	F	F	F	S	F	F	F	F	F	CT	F	F	F
F	F	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	F	F
F	F	CT	F	F	CC	F	F	F	S	F	F	F	CC	F	F	CT	F	F
F	F	F	F	F	F	F	F	F	SH	F	F	F	F	F	F	F	F	F
F	F	F	F	F	F	F	F	F	EX	F	F	F	F	F	F	F	F	F
F	F	F	F	F	F	F	F	F	ZH	F	F	F	F	F	F	F	F	F
F	F	CT	F	F	CC	F	F	F	S	F	F	F	CC	F	F	CT	F	F
F	F	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	F	F
F	F	F	CT	F	F	F	F	F	S	F	F	F	F	F	CT	F	F	F
F	F	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	F	F
F	F	F	F	F	CS	F	F	F	S	F	F	F	CS	F	F	F	F	F
F	F	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	F	F
Z	F	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	F	Z
Z	Z	F	F	F	F	F	F	F	S	F	F	F	F	F	F	F	Z	Z

F	Fuel element
CT	Fuel element containing transient control rod
CS	Fuel element containing safety control rod
CC	Fuel element containing compenstation control rod
S	Non-fueled source element
Z	Zirc-clad non-fueled graphite element
S	Zirc-clad slotted graphite block
EX	Experiment region
SH	Half-width zirc-clad slotted element
ZH	Half-width zirc-clad non-fueled graphite element

Experiment vehicle and sample holder



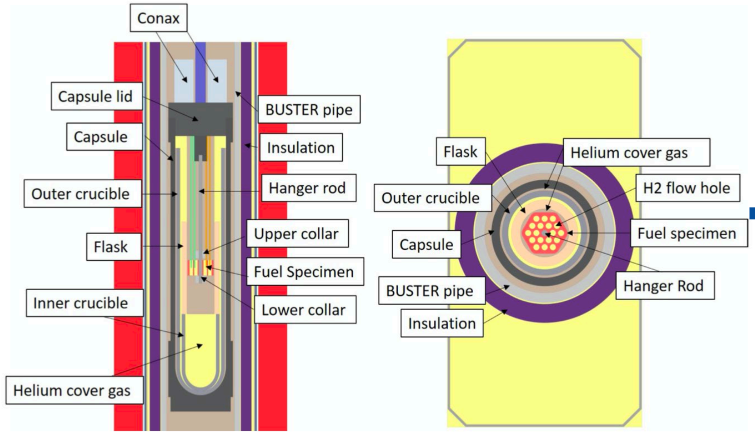
Sample (size of a quarter)



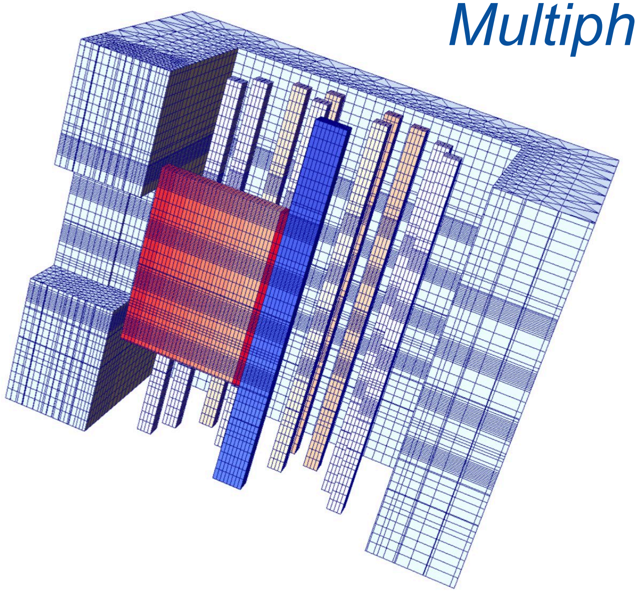
Multiphysics Model of SIRIUS-CAL

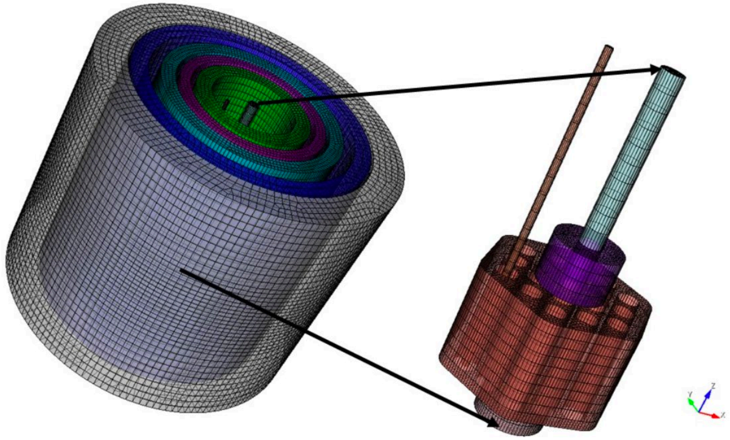
- Multiphysics model uses 2-step process: Serpent cross section, Griffin diffusion with SPH equivalence
- Transient is a coupled Griffin neutronics + thermal model

*Serpent **steady-state** for XS*



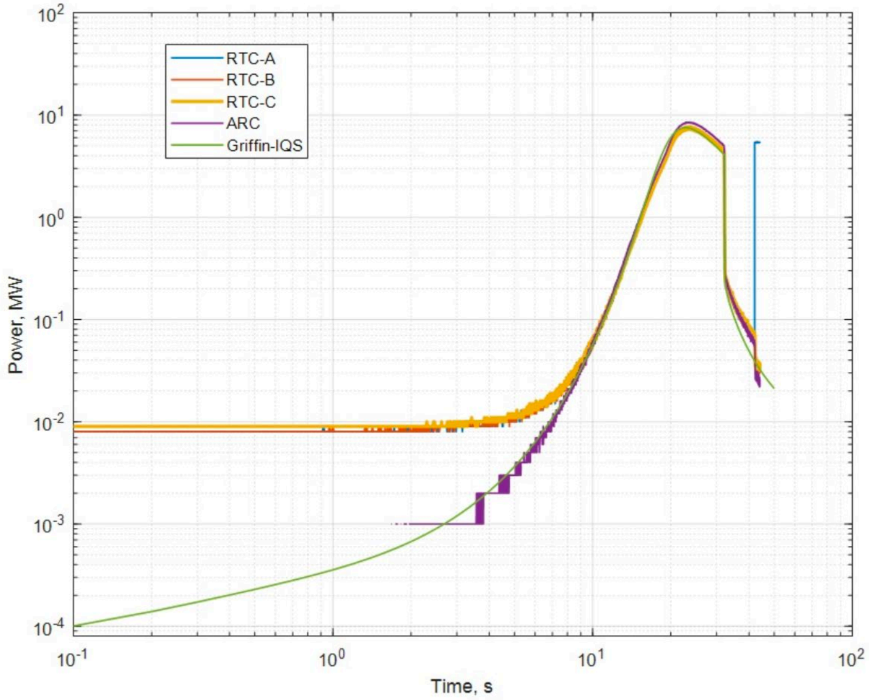
Griffin (Diffusion + SPH)
*Multiphysics **transient***


Neutronics


Thermal

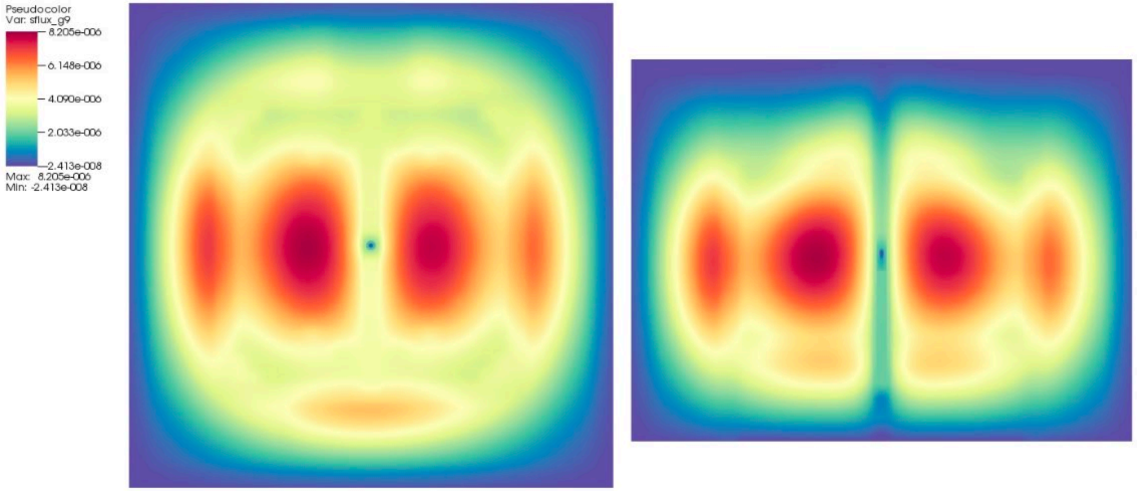
SIRIUS-CAL Multiphysics Results

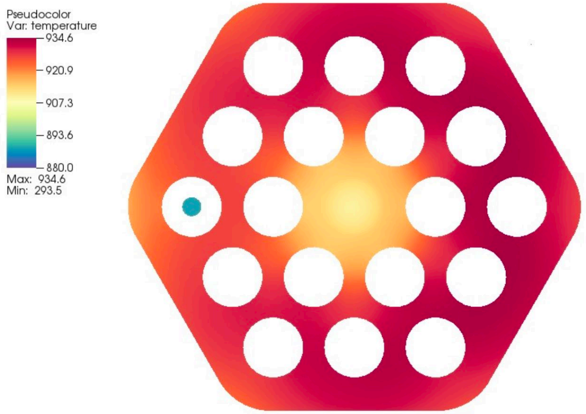
- SIRIUS-CAL reactivity insertion is 0.55% dk/k
- We currently adjust control rod motion to match TREAT initial period – ongoing work to be fully predictive for TREAT transients
- Goal is validation for SIRIUS-CAL



Measured and simulated power traces

Thermal fluxes in steady-state



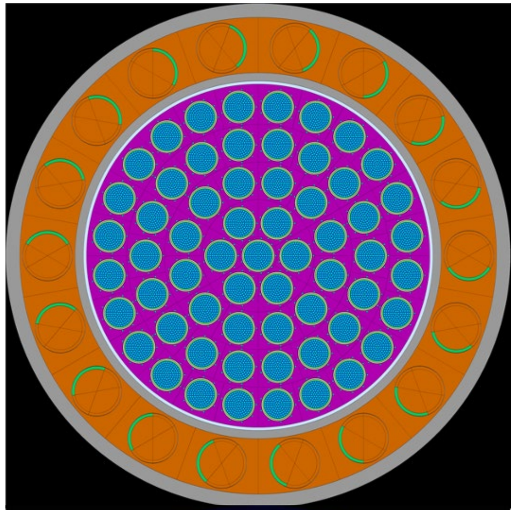


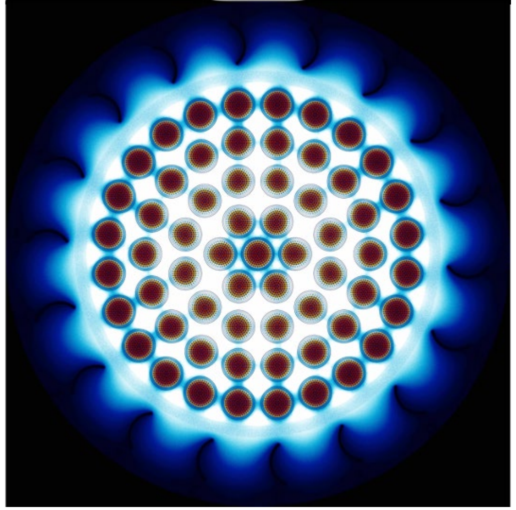
Temperature distribution in the specimen

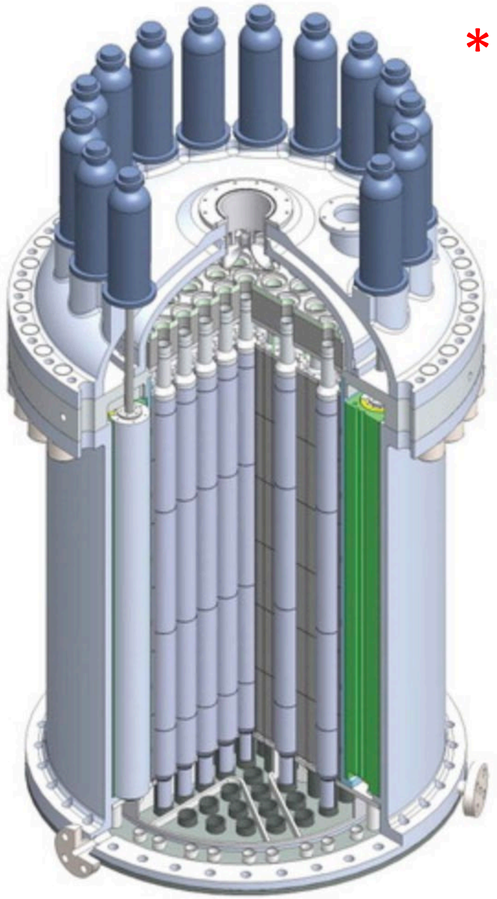
Full-Core Model Overview

- 61 Fuel Elements in 5 rings
- 18 Control Drums in Be reflector to adjust reactivity/power
- For this presentation, all the drums are simultaneously rotated with the same rotation angle
- Griffin allows independent rotation (e.g., for a simulated reactivity insertion accident)

New CERMET/CERCER NASA/BWXT NTP concept







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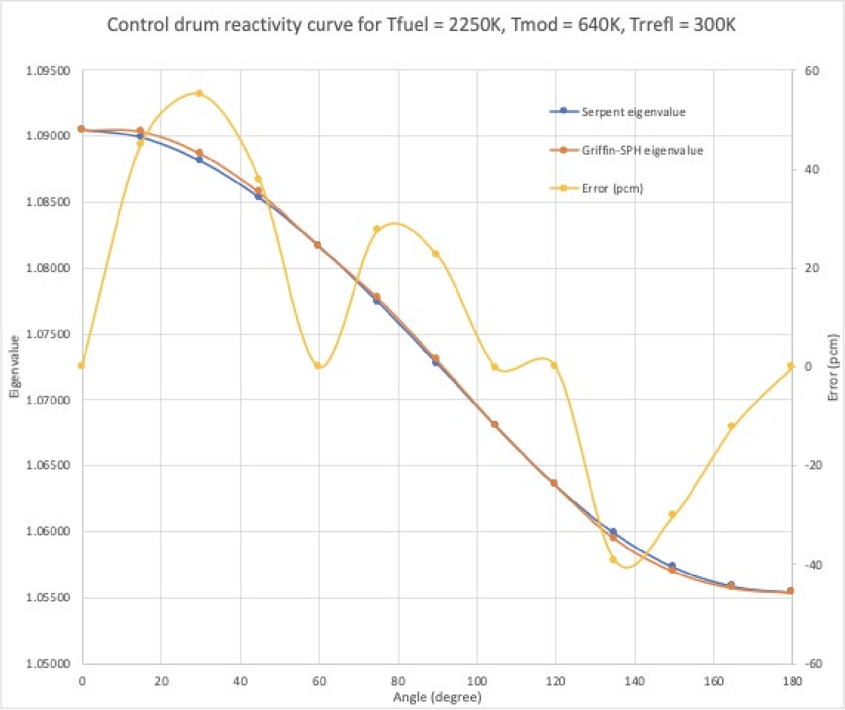
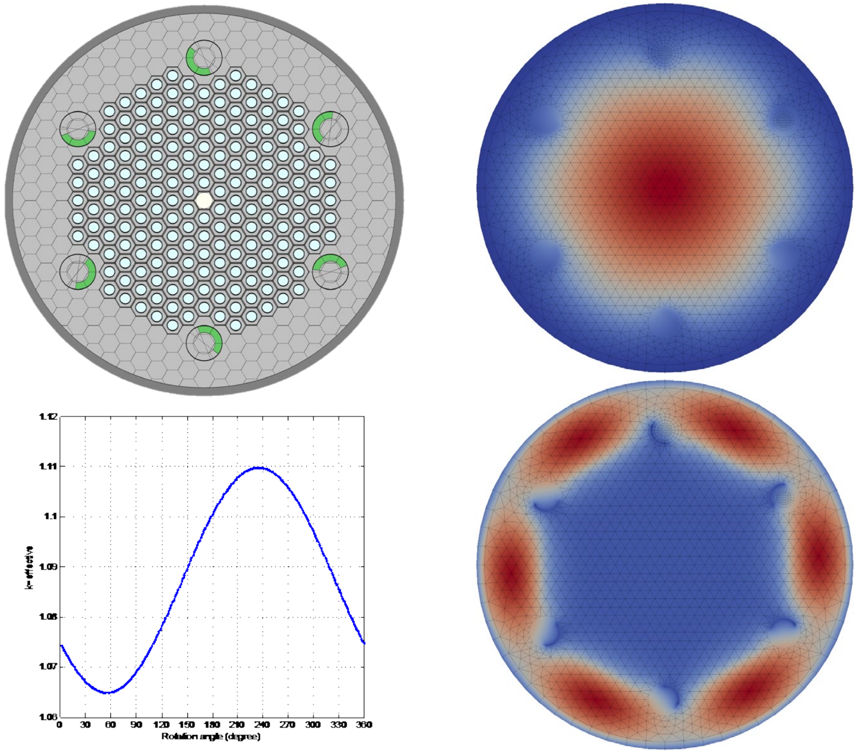
* Picture courtesy: Space Nuclear Propulsion Fuel and Moderator Development Plan Conceptual Testing Reference Design, J. Gustafson, NT 207.

Control Drum Worth with Griffin Cusping & SPH

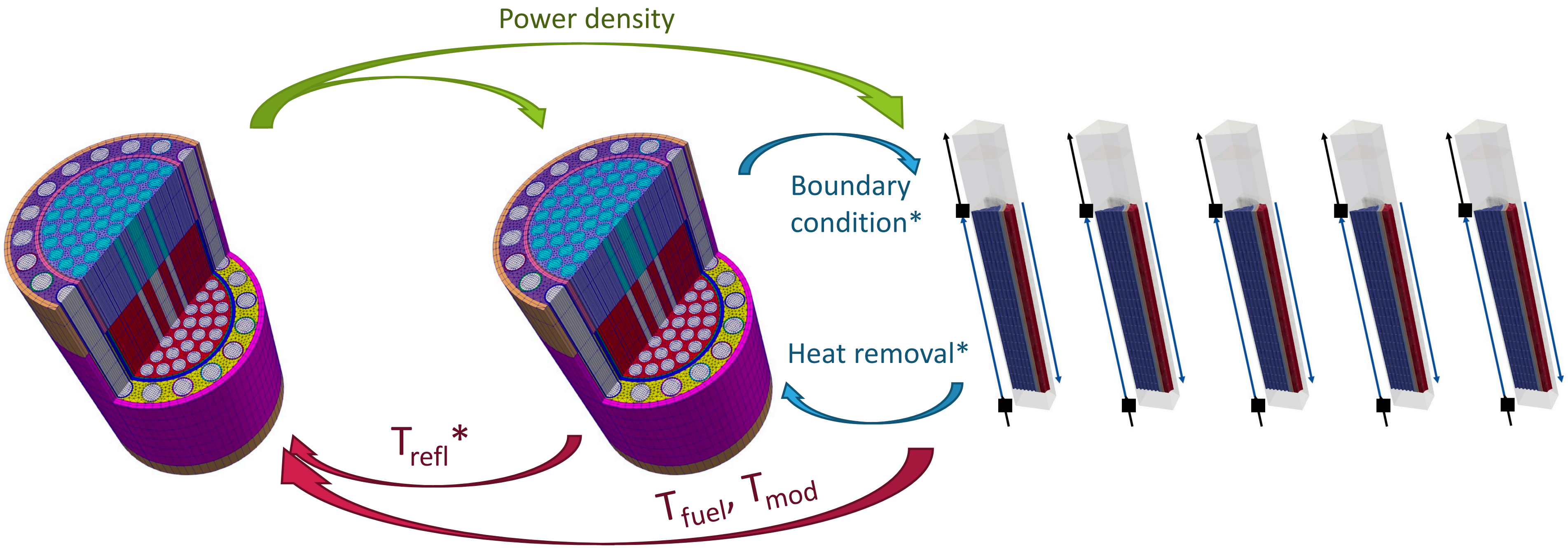
- At state points (0, 60, 120, 180), eigenvalue and power profile exactly reproduced
- Between state points, cusping treatment from Griffin is utilized
- Bias between -40 and +60 pcm
- Single eigenvalue calculation in a few minutes



Control drum treatment



Example – Coupled NTP Full-Core Model



Full-core Neutronics:
primary app

Full-core Heat Conduction:
sub-app 1

5 Fuel Element Heat Conduction: sub-app 2
5 TH channels: sub-app 3

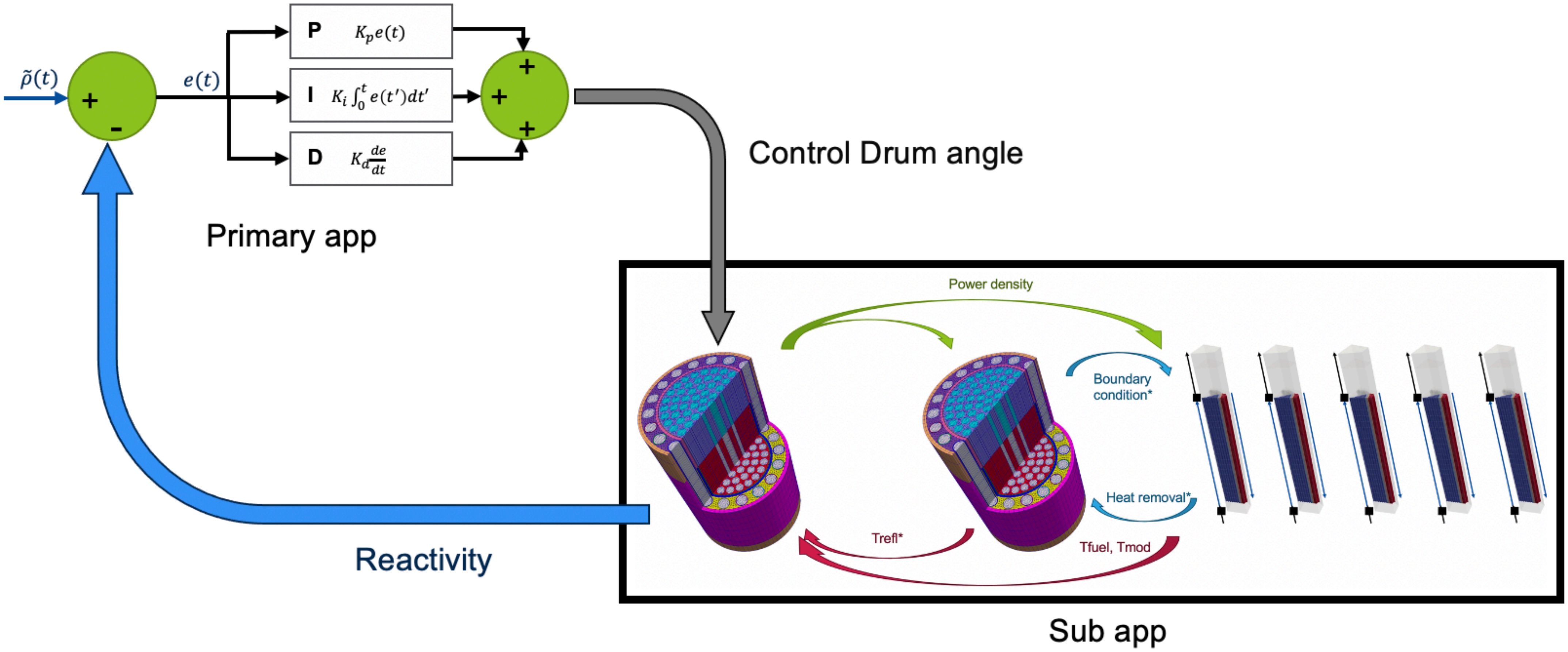
**not in current model*

Start-up Transient Assumptions

- *Goal: go from low power to full power in a few minutes*

- Currently, we assume 100% H2 flow rate established at the beginning of the transient
- Assume initial temperature:
  - Tfuel = 500 K
  - Tmod = 270 K
  - Trrefl = 300 K
- Initial power: 610 kW (10 kW/fuel element)
- Initial CD angle $\theta_i = 120°$
- Final CD angle $\theta_f = 60°$
- Drum rotation determined by PID controller

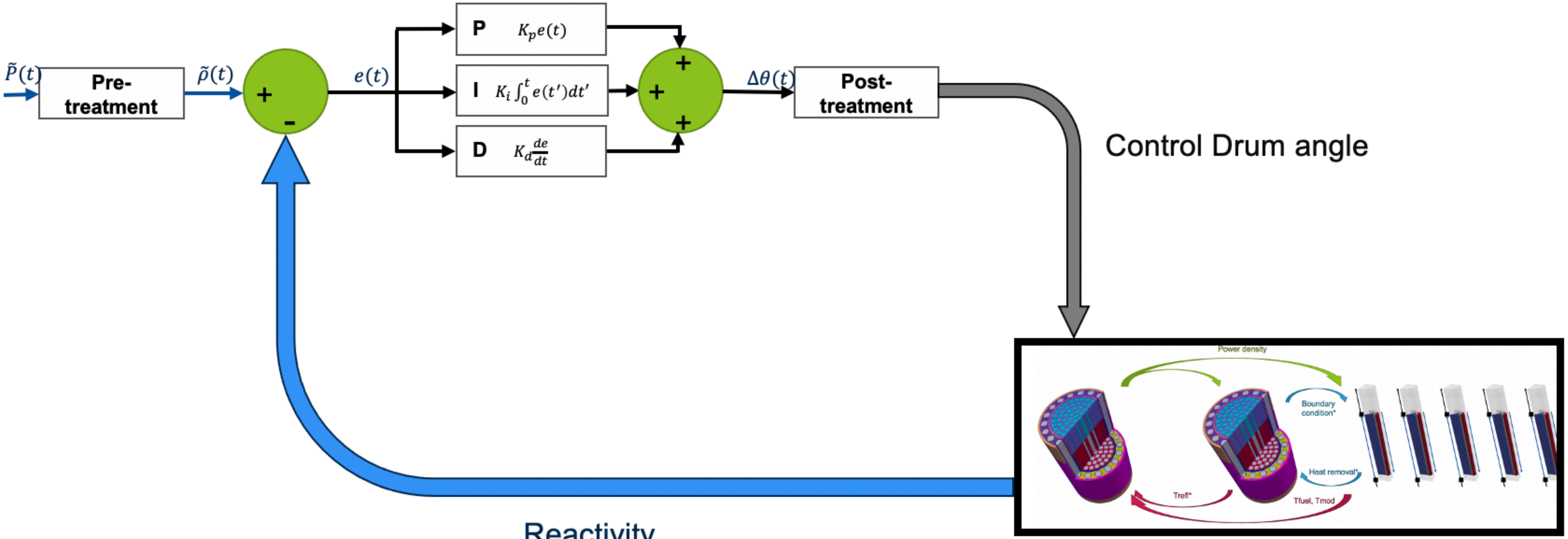
PID Control of Drums



- For now, ignores any limitation on drum rotation (speed, etc.)

PID Control of Drums (2)

- If desired, could input a power setpoint
- Truncation to make sure the CD angle stay within $[\theta_f, \theta_i]$



$\tilde{P}(t)$

Pre-treatment

$\tilde{p}(t)$

+

-

$e(t)$

P $K_p e(t)$

I $K_i \int_0^t e(t')dt'$

D $K_d \frac{de}{dt}$

+

+

+

$\Delta\theta(t)$

Post-treatment

Control Drum angle

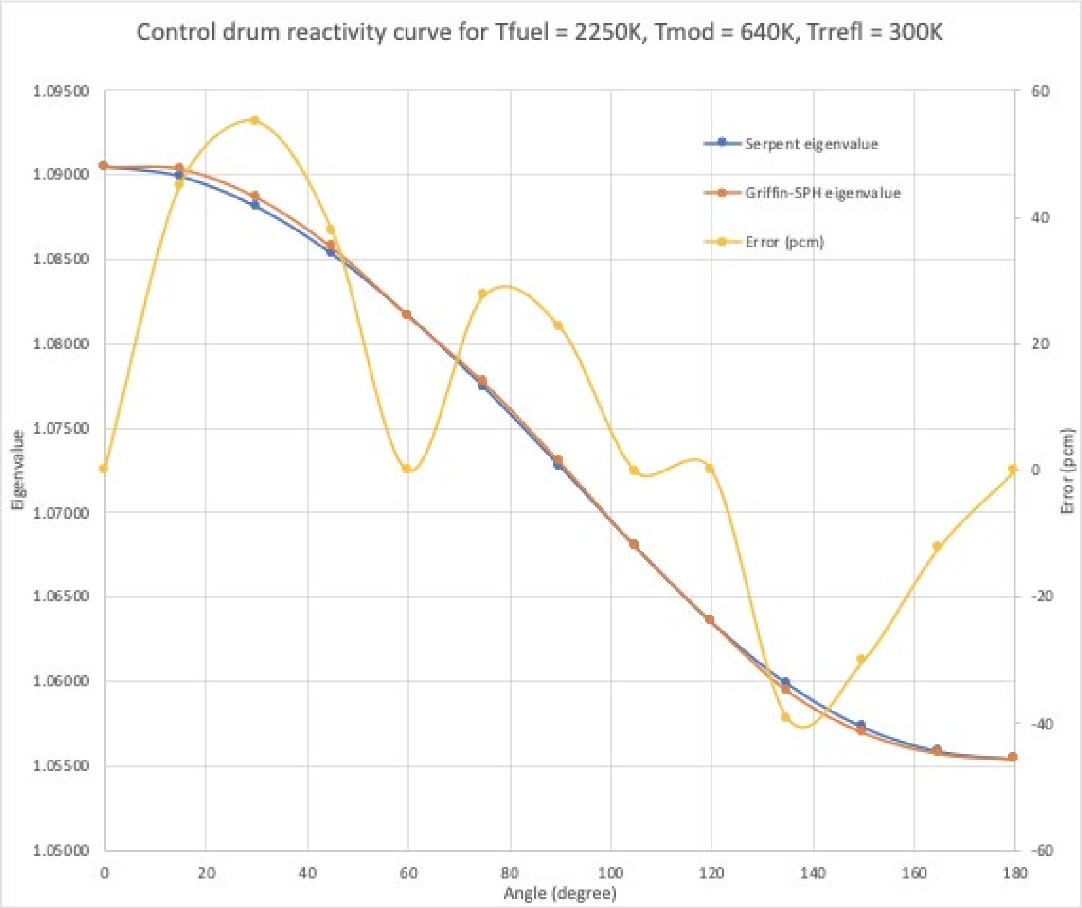
Reactivity

PID: Remarks

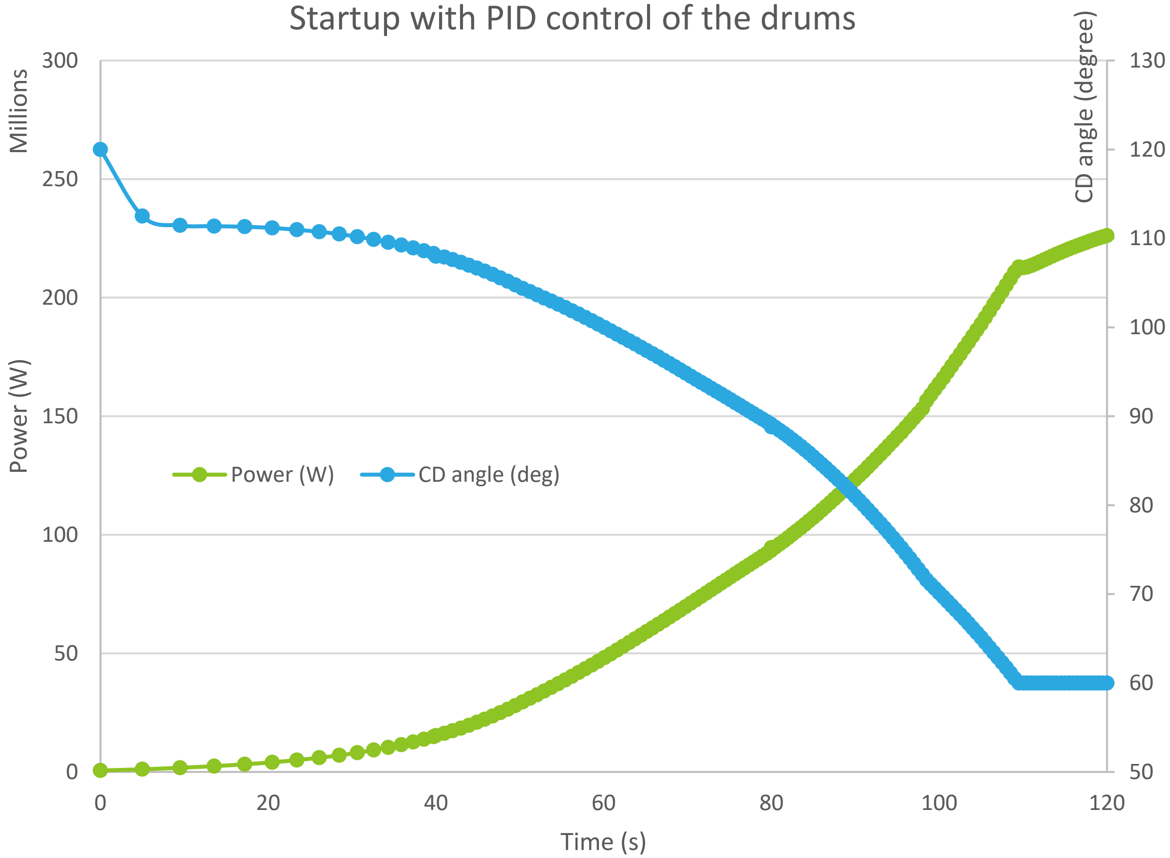
- If only proportional term is included in PID:

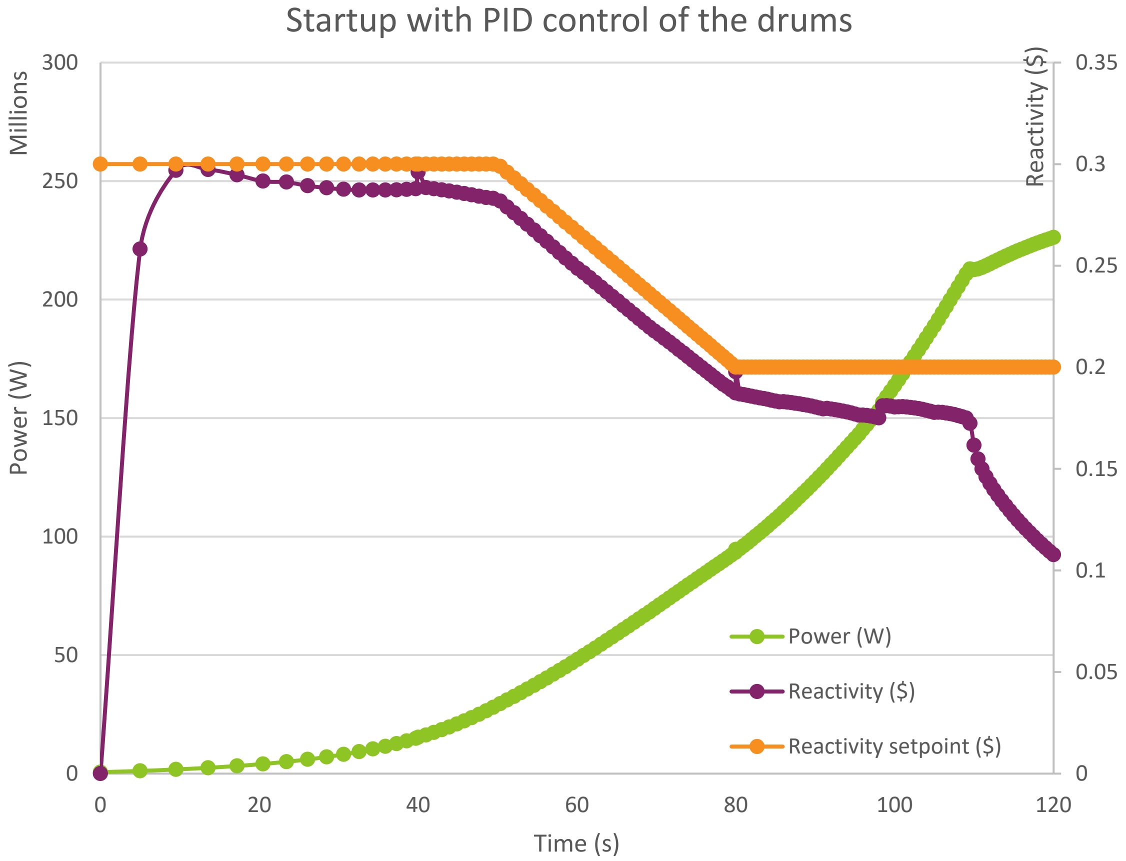
$$K_p = \frac{\Delta\theta}{\Delta\rho}$$

- For the CD angle between $60°$ to $120°$, CD worth ~ 25-30 pcm/° or 24-30 °/$
- $K_p = 25$ °/$ should be reasonable
- Direct correlation between reactivity and CD angle: this is why we choose to rotate drums based on reactivity and not power (time delay between reactivity and power)



Start-up Transient with PID: $K_p = 25, K_i = K_d = 0$





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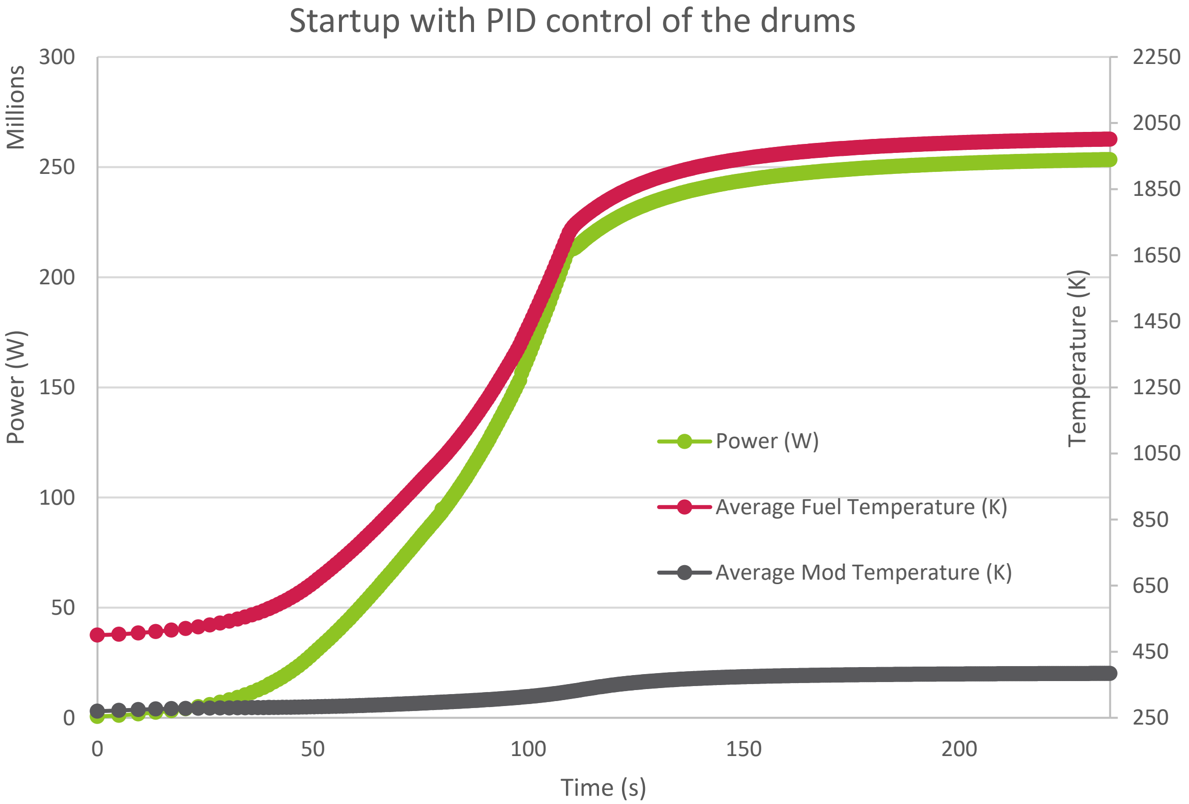
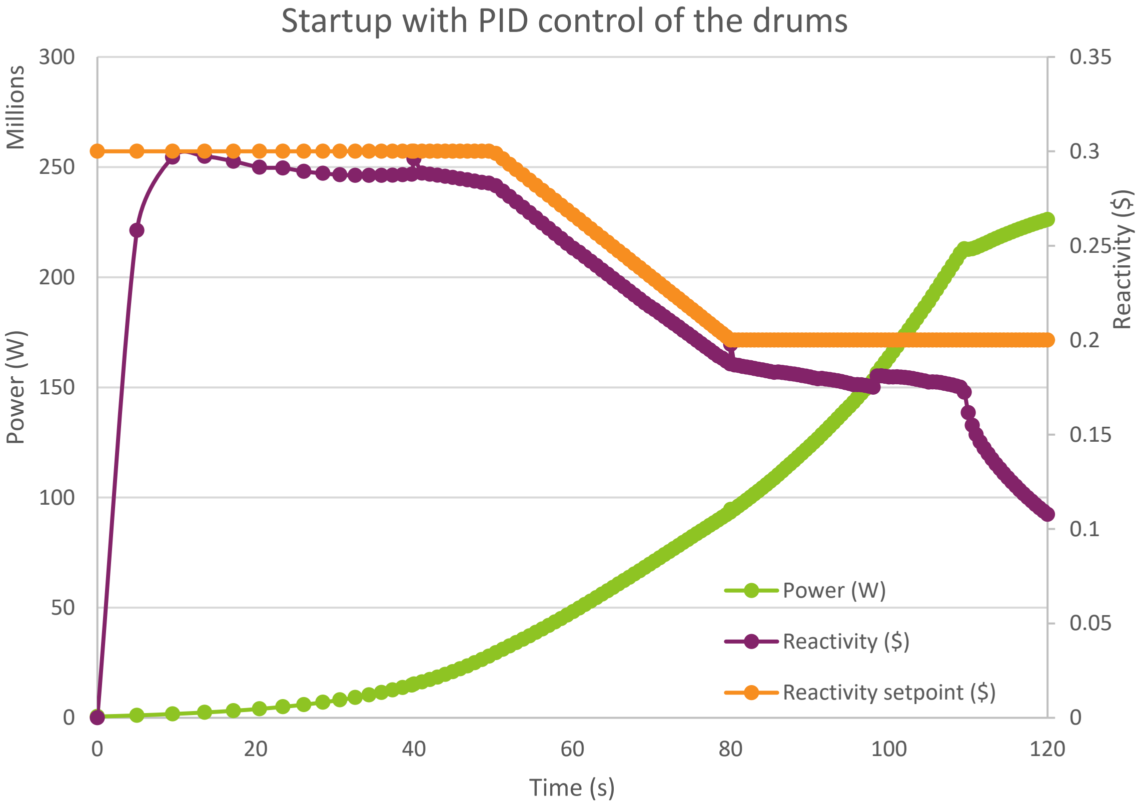
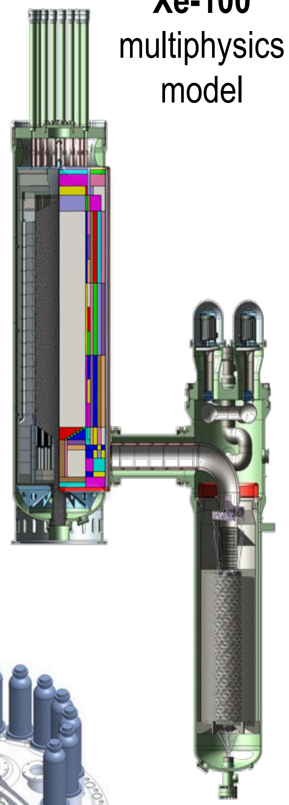
Start-up Transient with PID: $K_p = 25, K_i = K_d = 0$



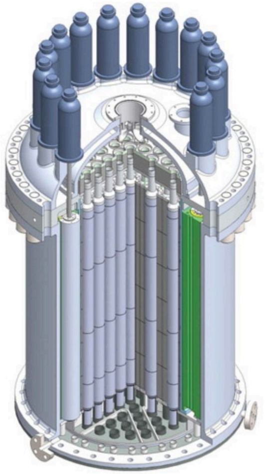


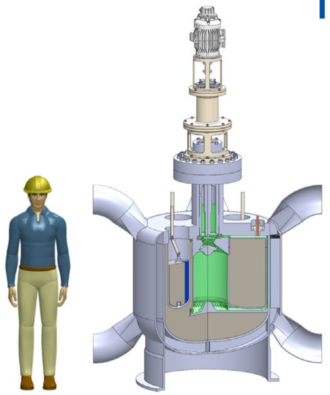
Summary

- INL is the nation's premier nuclear science and technology laboratory
- The reactor multiphysics team works at the forefront of solving some of the most challenging M&S problems for advanced reactors
- Our work relates directly to the nation’s energy future via ARDPs, private/public partnerships, & reactor demonstrations
- I presented only 3 examples of many contributions to the nation’s energy future:
  - Pebble bed reactors
  - Molten salt reactors
  - Nuclear thermal propulsion systems



Xe-100 multiphysics model





Idaho National Laboratory