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MOOSE NTP modeling: current status, needs and challenges

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Changing the World's Energy Future

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Idaho National Laboratory

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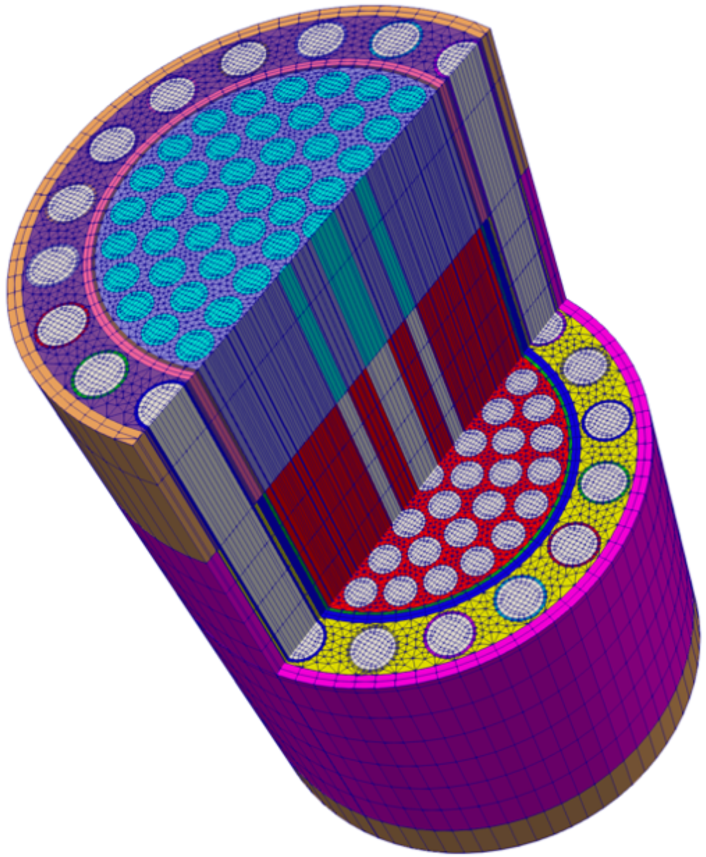
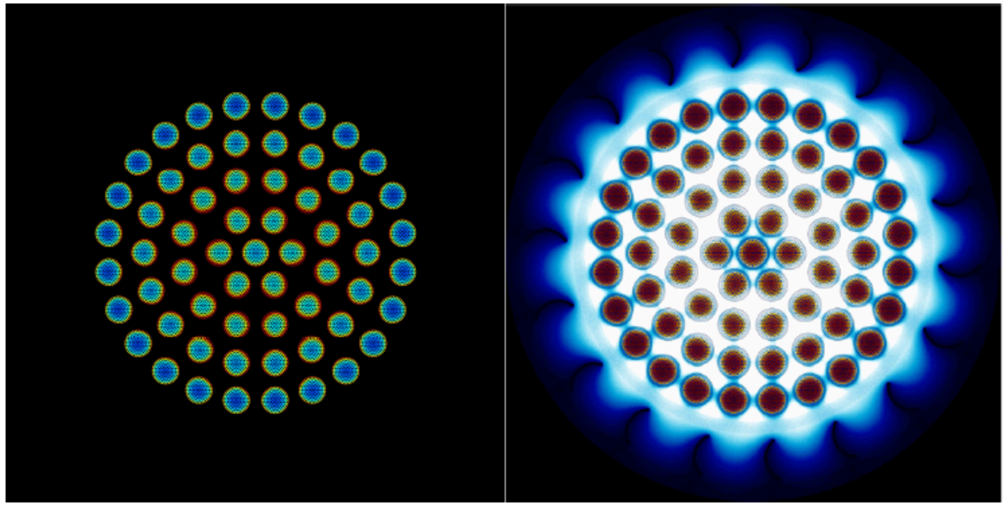
MOOSE NTP modeling: current status, needs and challenges

Idaho National Laboratory

Outline

- Model Description
- Startup/Shutdown Results
- Recent Improvements
- Needs & Challenges





(a) Power density distribution. (b) Fission rate and thermal flux.

Default source throughout presentation: V. Labouré, S. Schunert, S. Terlizzi, Z. Prince, J. Ortensi, C-S Lin, L. Charlot, and M. DeHart, "Automated Power-following Control for Nuclear Thermal Propulsion Startup and Shutdown Using MOOSE-based Applications", under revision in Progress in Nuclear Energy

Model Description

Control of NTPs

- Turbine controls pump (i.e. mass flow rate)
- Turbine power (and, in turn, mass flow rate and thrust) controlled via BCV, following a **chamber pressure (Pc) signal**
- Reactivity (and, in turn, the specific impulse) controlled via control drums (CD) and SSCV (adjusts moderation) following a **chamber temperature (Tc) signal**
- In practice, complicated by the fact that more flow means more moderation and more cooling so mass flow rate and temperature not independent

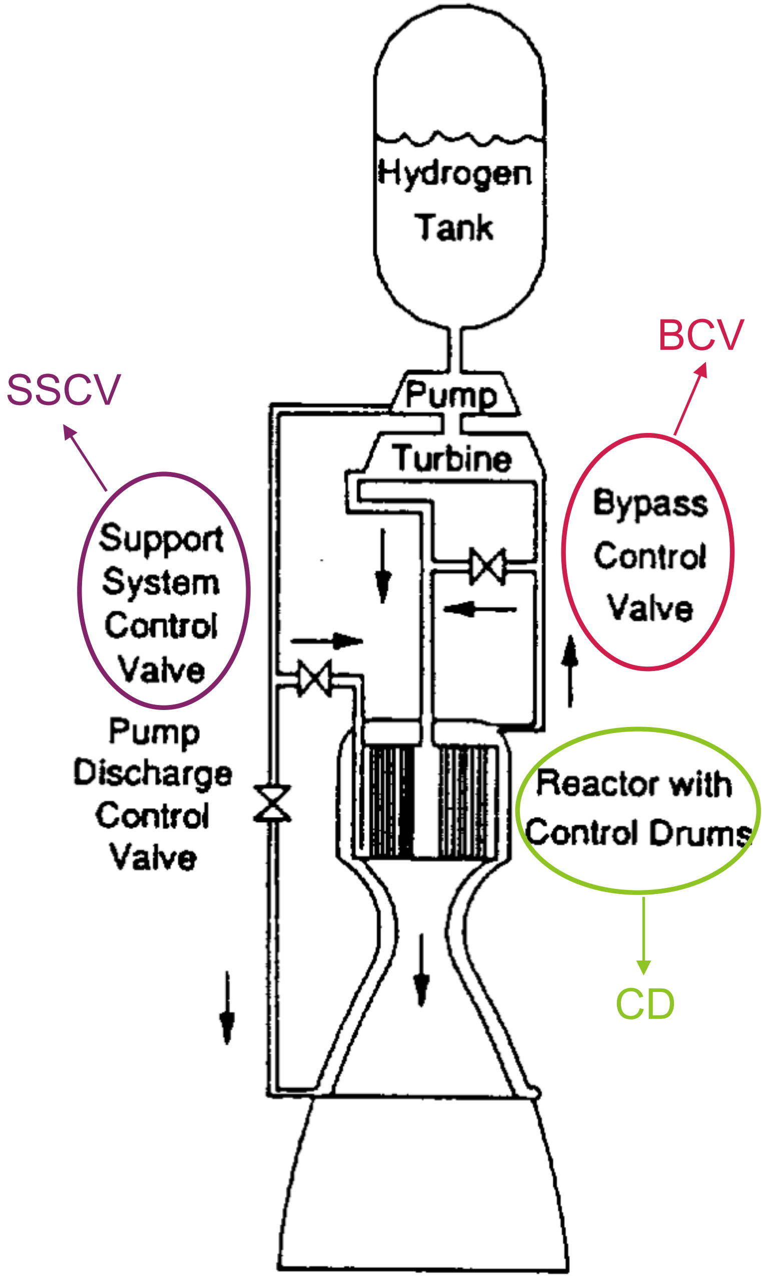
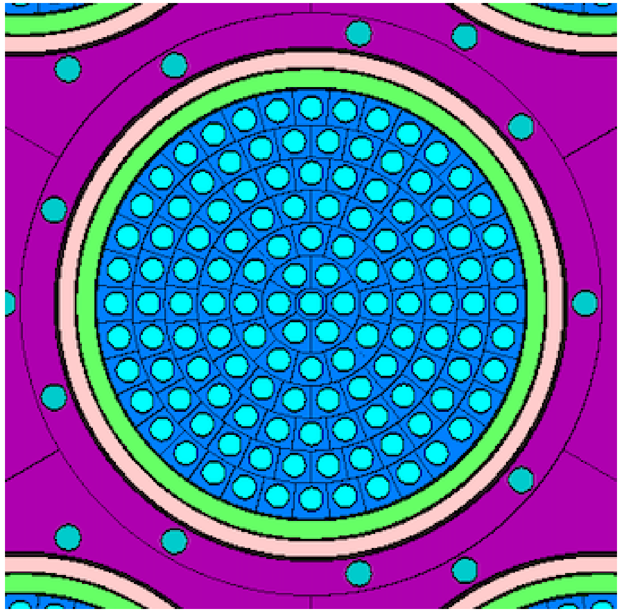


FIGURE 11. Nuclear Thermal Rocket Engine Flow Schematic.

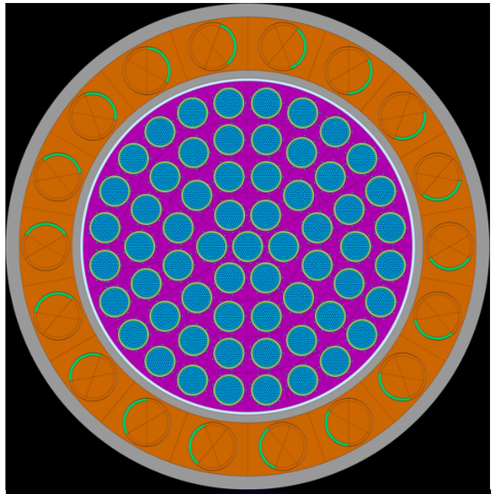
Source: Carl E Lorenzo and Jeffrey L. Musgrave, “Overview of Rocket Engine Control”, NASA Technical Memorandum 105318 (1992)

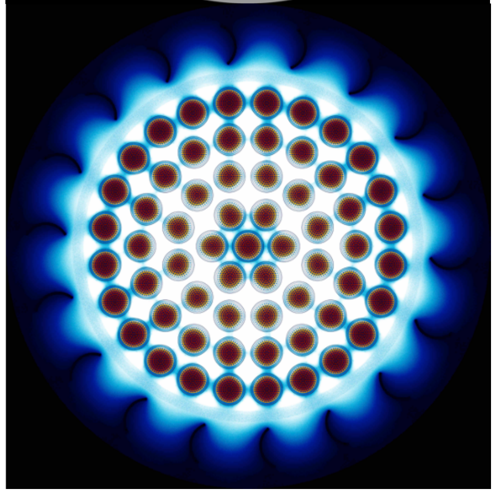
NTP Design Overview

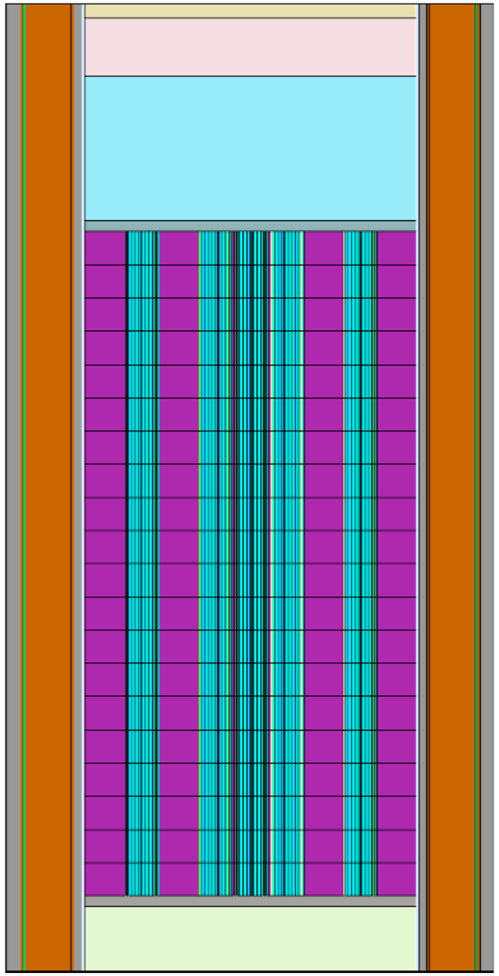
Fuel Element



Full-core



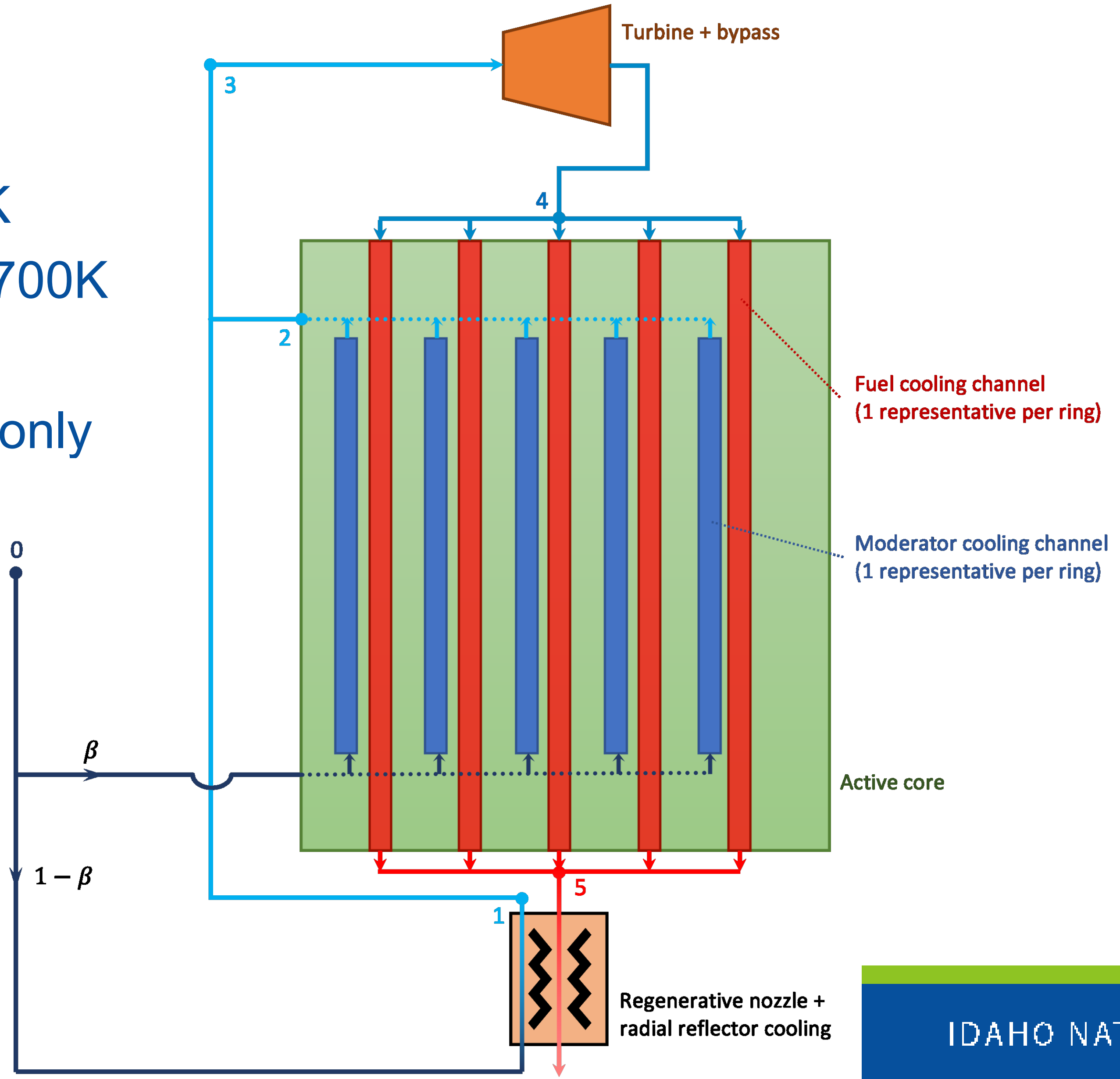




- Design not (yet) meant to be final
- Proof of concept of the MOOSE-based tools
- Currently CERMET model (will be changed to CERCER this FY)

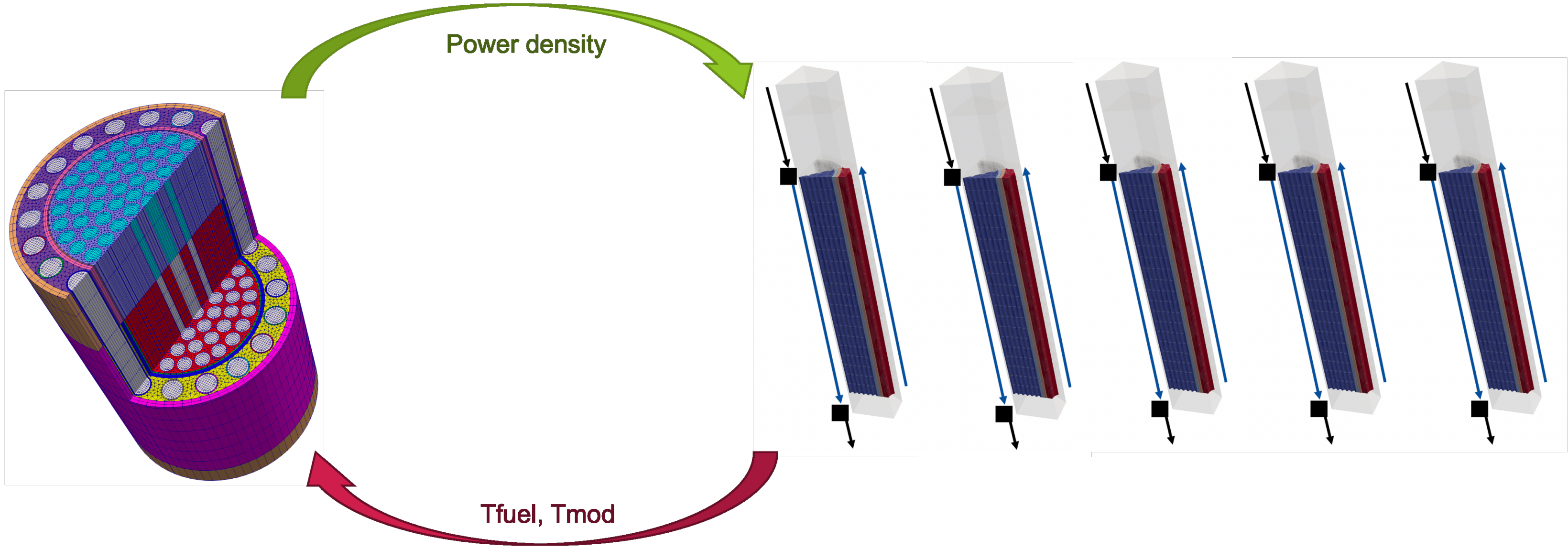
Sketch of the NTP System Considered

- Hydrogen propellant
- Inlet temperature ~ 50K
- Outlet temperature ~ 2700K
- Total power ~ 315 MW
- Control through drums only



Summary of the Base Sabertooth Model

- Full-core SPH diffusion with control drum (CD) cusping treatment
- For each ring of assembly: 1 representative thermal model + fuel cooling channel + moderator cooling channel
- Currently neglects intra-assembly heat transfer
- Boundary condition based system model
- Controllers actuating CD rotation



Full-core Neutronics:
sub app 1

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

Startup/Shutdown Results

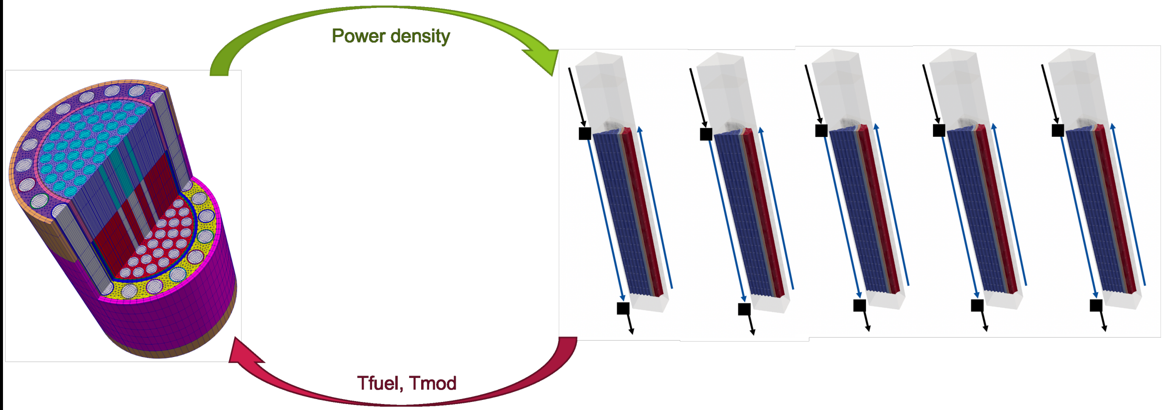
Control of Drums

Desired power

Power-Following Controller

Primary app

Control Drum angle



Full-core Neutronics: sub app 1

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

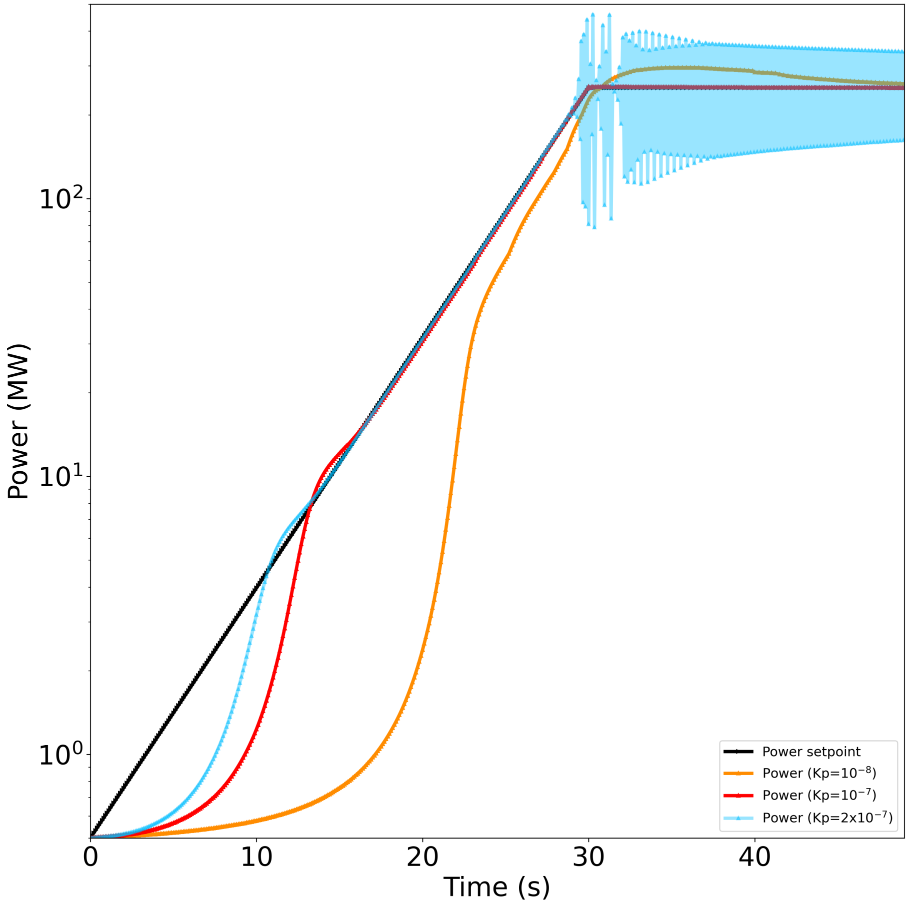
Sub app

Power + reactor data

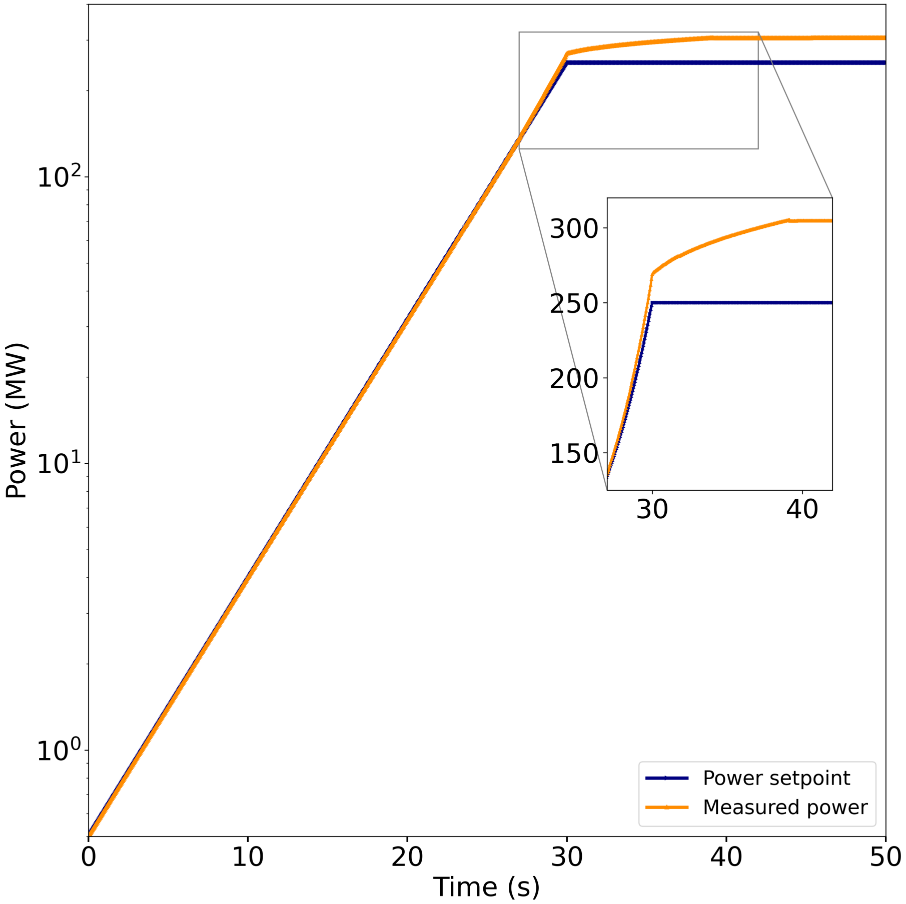
- Initially tested control strategies using a power signal
- Latest work investigating temperature signal

Power- vs Reactivity-Driven PID Control

- Control via a power signal has a slow initial response
- Can become unstable if made too reactive
- On the other hand, a reactivity signal has an immediate effect on power
- But does not stabilize to the desired power

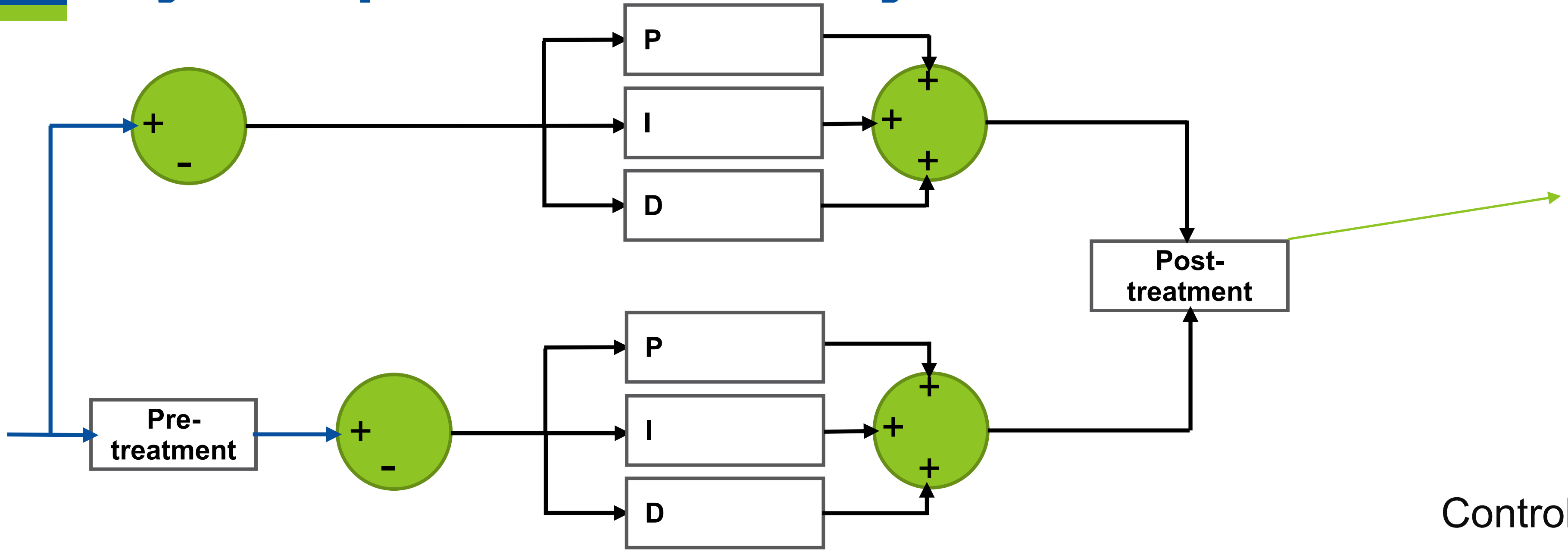


Using a power signal for different values of the proportional gain



Using a reactivity signal for different values of the proportional gain

Hybrid power-reactivity-driven PID Control



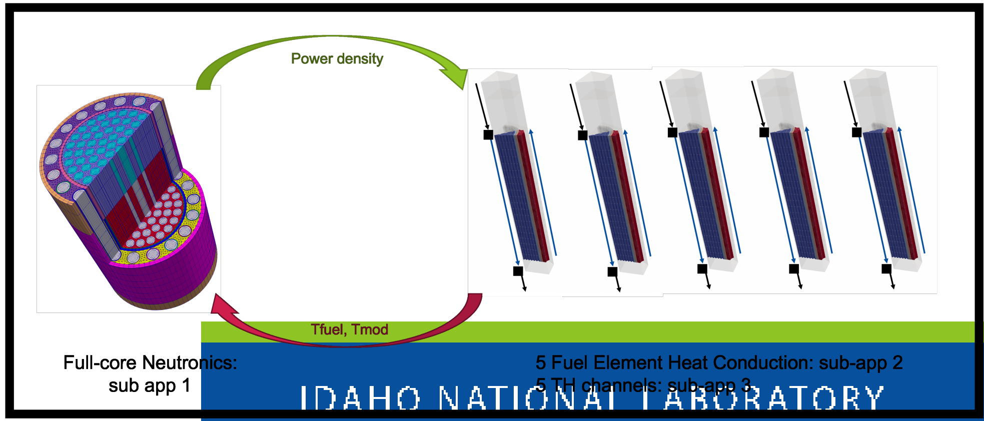
$$\Delta\theta = \xi\Delta\theta_{\mathcal{P}}(t) + (1-\xi)\Delta\theta_{\rho}(t)$$

$$\xi \equiv \frac{\ln\left(\frac{\mathcal{P}}{\mathcal{P}_i}\right)}{\ln\left(\frac{\mathcal{P}_f}{\mathcal{P}_i}\right)}$$

Control Drum angle

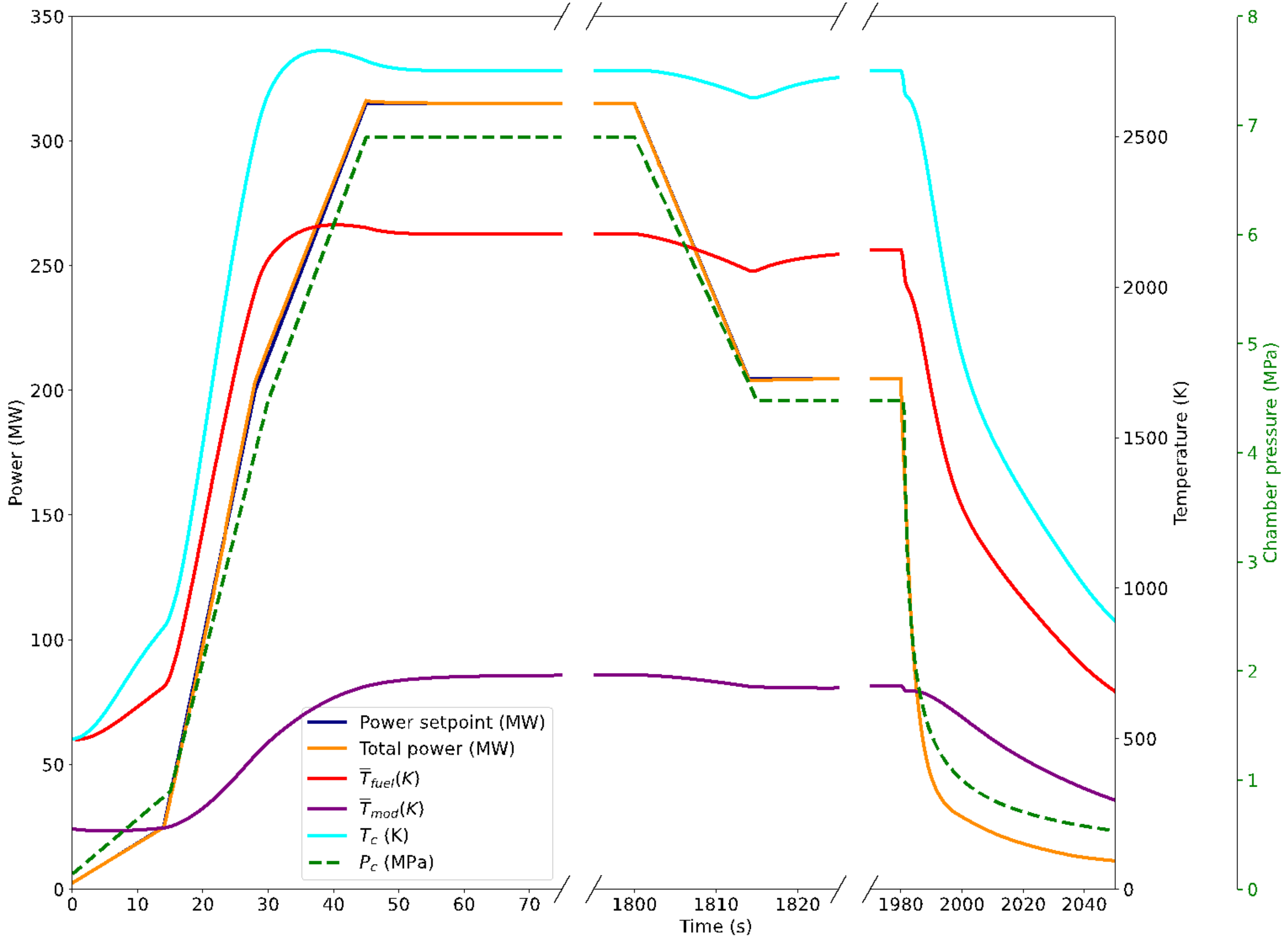
Reactivity (+ kinetics data)

Power



Startup/Shutdown Results

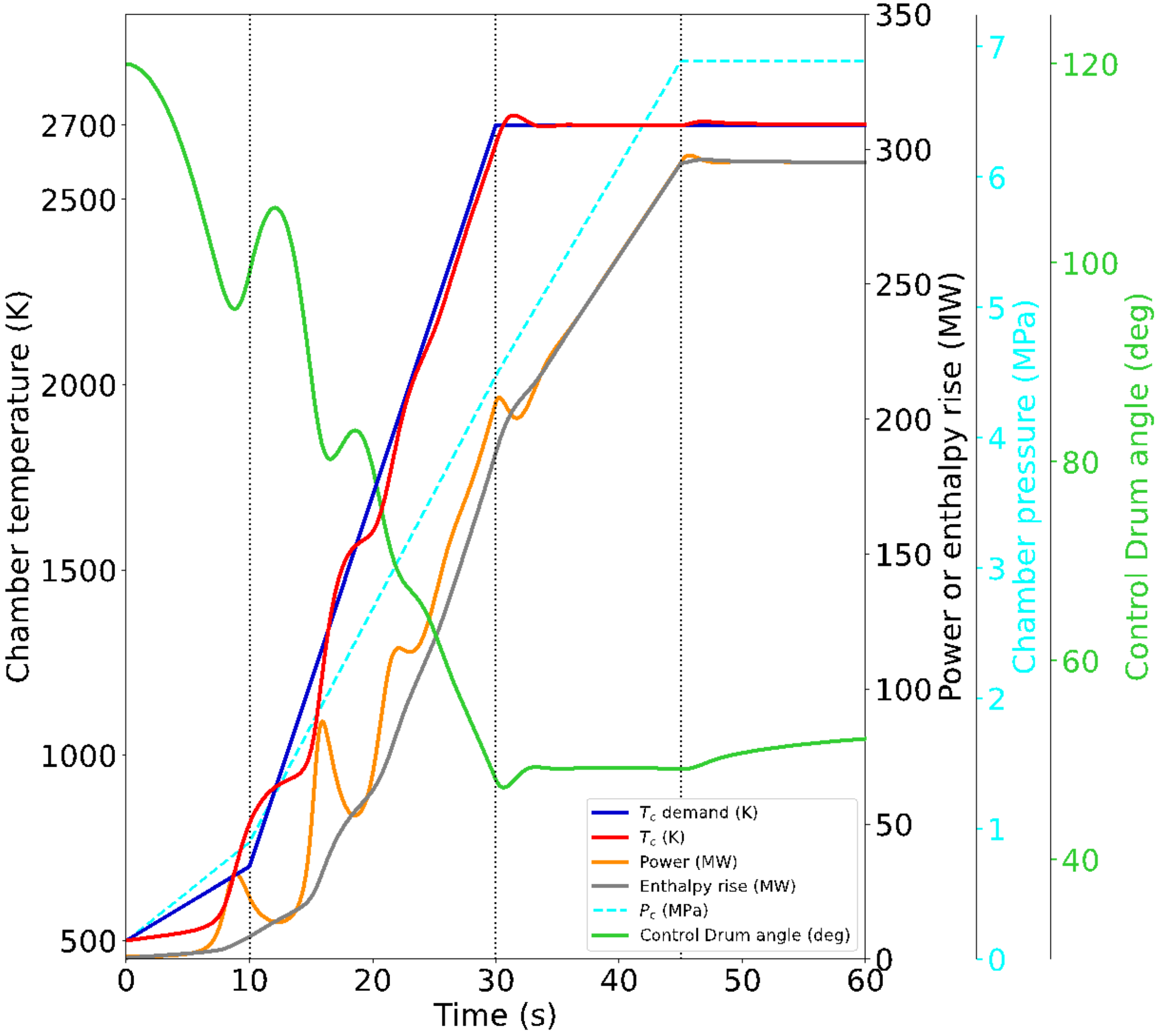
- Pressure/mass flow rate as BC
- Decay heat model accounting for burn time and throttling
- Pre-defined power setpoint
- Good controller response
- Temperature overshoot (~3%) and not constant during throttling because not using a temperature demand
- Investigating temperature-controlled systems
- Planning to enhance model to include BCV and SSCV control



Recent Improvements

Temperature Proportional Controller

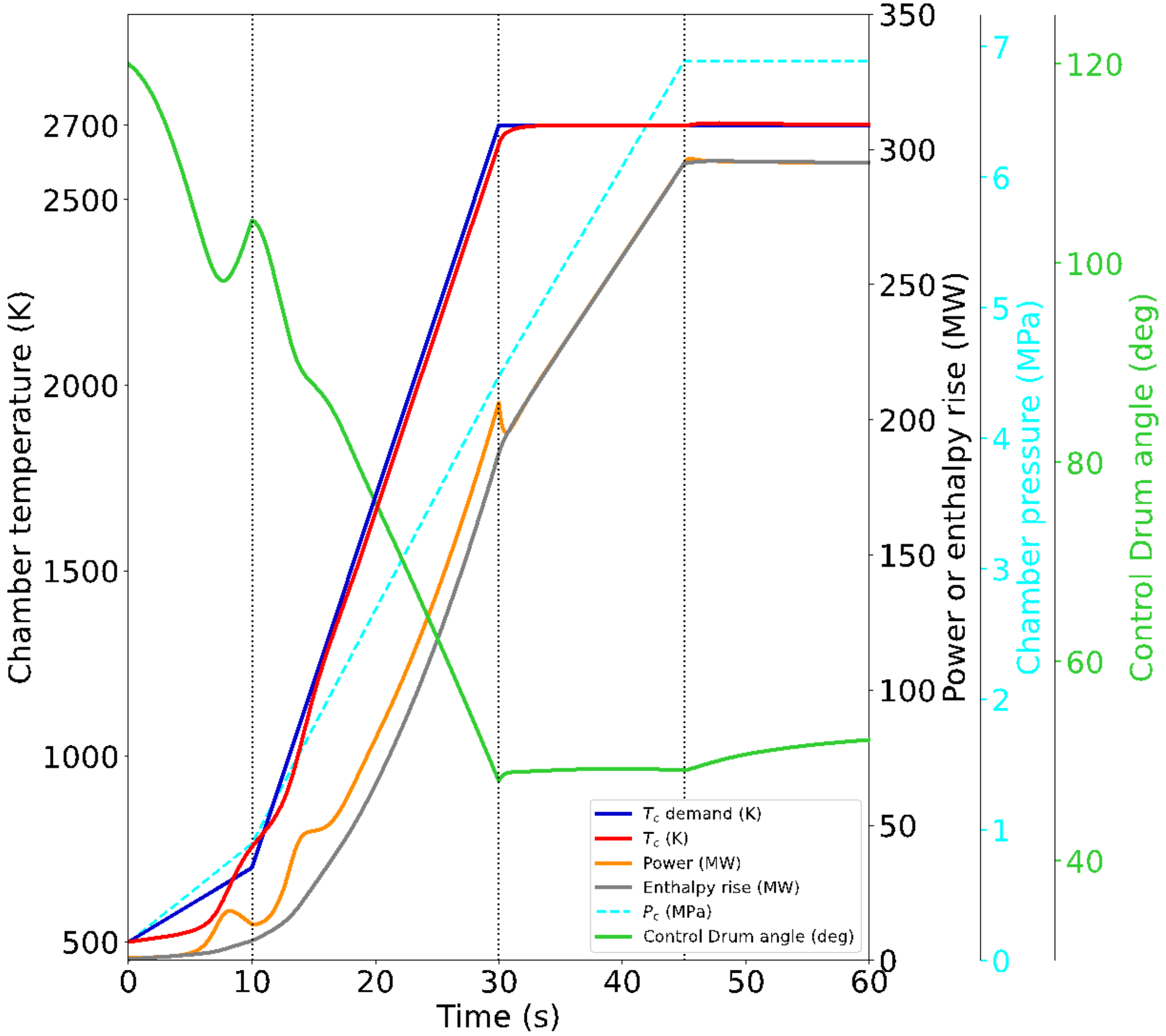
- Simplified point kinetics model coupled with single fuel element and cooling channel
- Pc and mass flow rate prescribed as boundary condition
- Tc directly used as a signal
- Oscillatory behavior due to delay between drum rotation and chamber temperature rise
- Initial response quite slow



Source: V. Labouré, S. Terlizzi and S. Schunert, "Hybrid Temperature-Reactivity PID Controllers for Nuclear Thermal Propulsion Startup", submitted to NETS 2023 conference.

Temperature Proportional-Derivative Controller

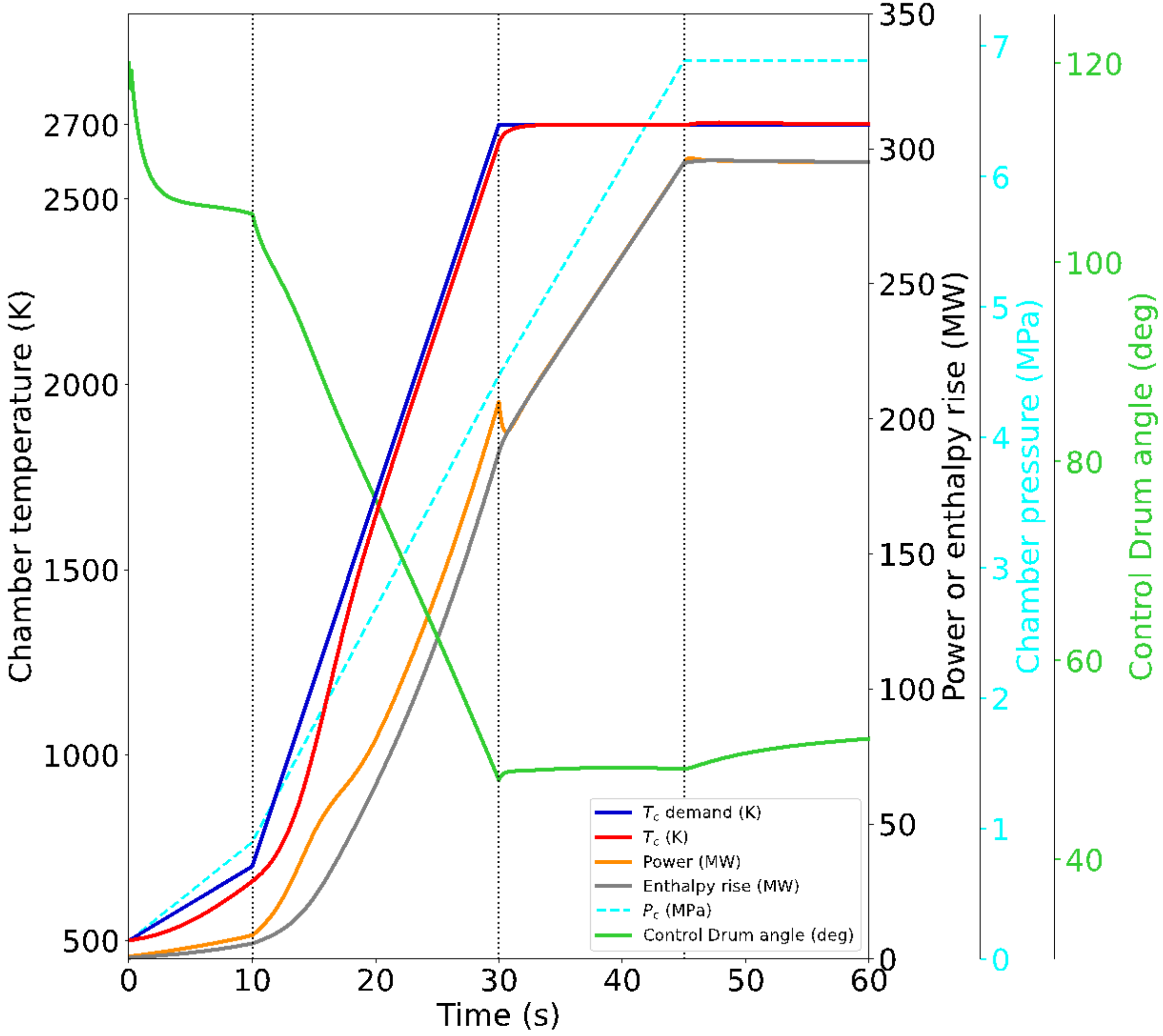
- Simplified point kinetics model coupled with single fuel element and cooling channel
- Pc and mass flow rate prescribed as boundary condition
- Tc directly used as a signal
- Derivative term (i.e., anticipation) included
- Much smoother behavior
- But initial response still slow/oscillatory



Source: V. Labouré, S. Terlizzi and S. Schunert, "Hybrid Temperature-Reactivity PID Controllers for Nuclear Thermal Propulsion Startup", submitted to NETS 2023 conference.

Hybrid Temperature-Reactivity Controller

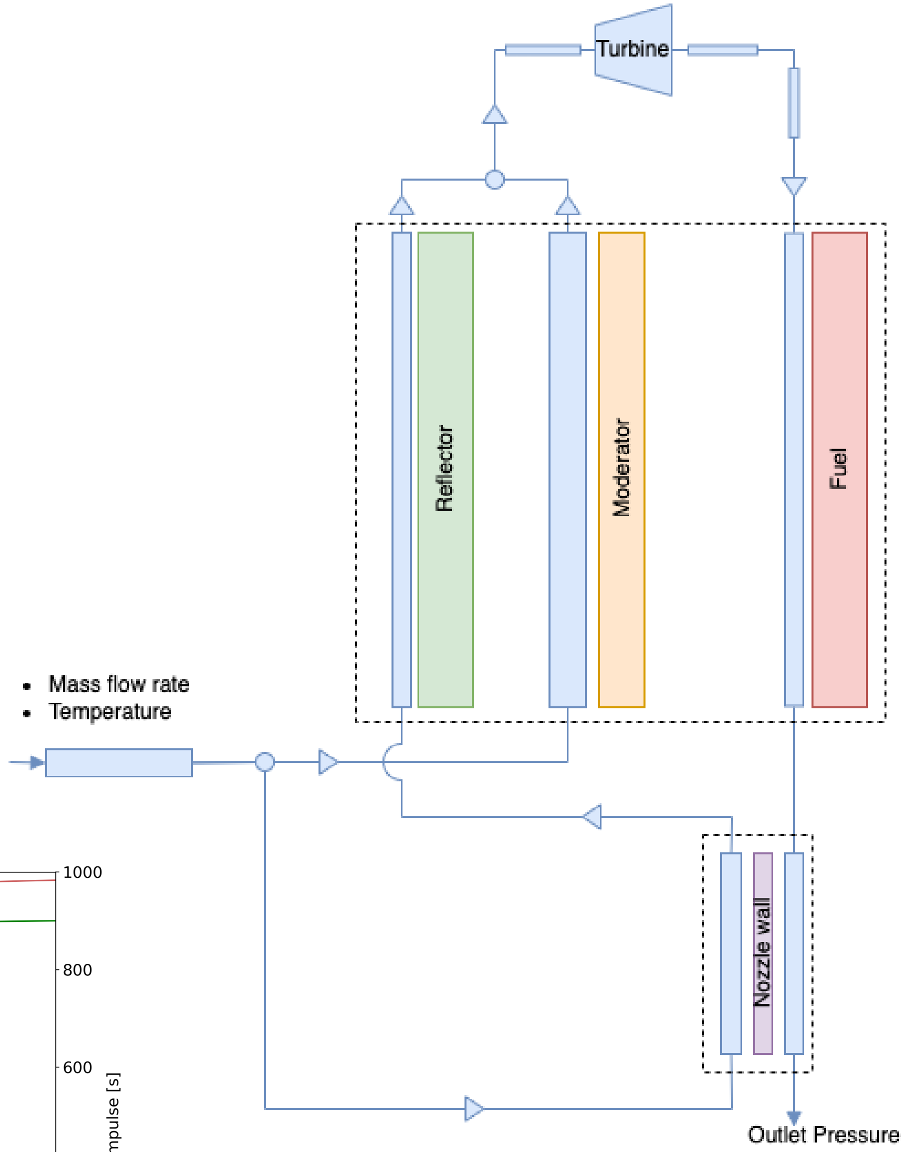
- Adding an initial reactivity signal (derived from Tc), initial delay/oscillations are reduced
- But initial delay not eliminated, partly because of delay between power generation and chamber temperature rise
- Derivative controller may not be practical in real system (due to noise)
- One alternative is to use time-dependent gains but how to tune them on a real system (especially near full power)?

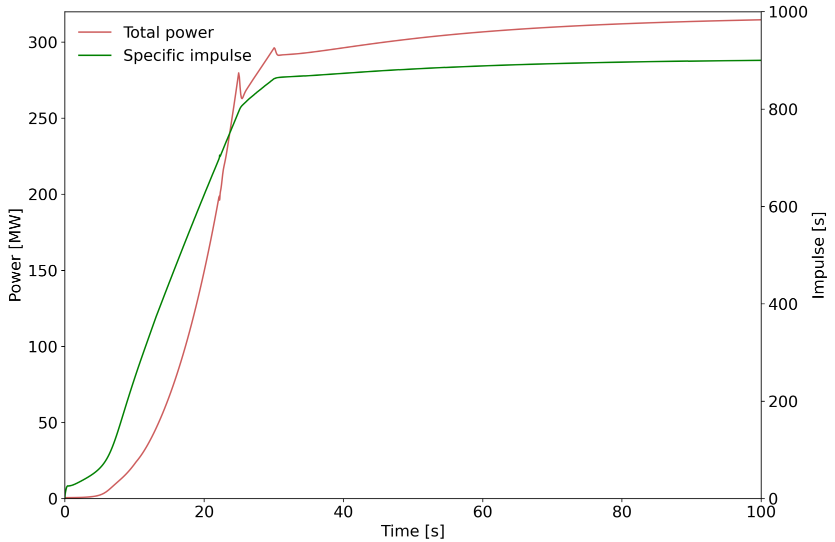


Source: V. Labouré, S. Terlizzi and S. Schunert, "Hybrid Temperature-Reactivity PID Controllers for Nuclear Thermal Propulsion Startup", submitted to NETS 2023 conference.

System Model

- Point kinetics neutronics model
- Better hydrogen properties (but still to be improved)
- Most components modeled (except nozzle and pump)





Source: L. Charlot, S. Schunert, V. Labouré and M. DeHart, " Modeling Nuclear Thermal Propulsion Reactor Expander Cycle Startup Transients ", submitted to NETS 2023 conference.

Needs & Challenges

System Model and Hydrogen Properties

- Needs:
  - Better H2 properties *[ongoing, can this be obtained?]*
  - Model nozzle *[preliminary testing ongoing]*
  - Add BCV to be able to follow a pressure demand
  - Incorporate into full-core multiphysics model

- Challenges:
  - Solver stability seems degraded

Chamber Pressure and Temperature Following Control

- Needs:
  - Temperature-following controller *[ongoing]*
  - Incorporate into full-core multiphysics model *[planned this FY]*
  - Account for any limitation on drum rotation (speed, instrumentation delay, etc.) *[shouldn't be very difficult but could add instability]*
  - Pressure-following controller to actuate BCV

- Challenges:
  - Temperature delay seems difficult to overcome (unless varying gains are used for controllers)
  - How to determine varying gains on a real system?

Cross-Section (XS) Generation

- Needs:
  - Account for axial shape change (temperature, H2 density) during transient *[planned for this FY]*
  - Model SSCV via cross-sections (H2 density) *[planned for this FY]*
  - libraries for ZrHx *[can this be obtained?]*

- Challenges:
  - Currently relying on:
    - correlations to determine H2 density and some component temperatures
    - average axial shapes that are assumed fixed
  - Number of tabulation points quickly becomes intractable
  - (Linear) XS interpolation cost grows as 2^n (n = number of tabulation variables)

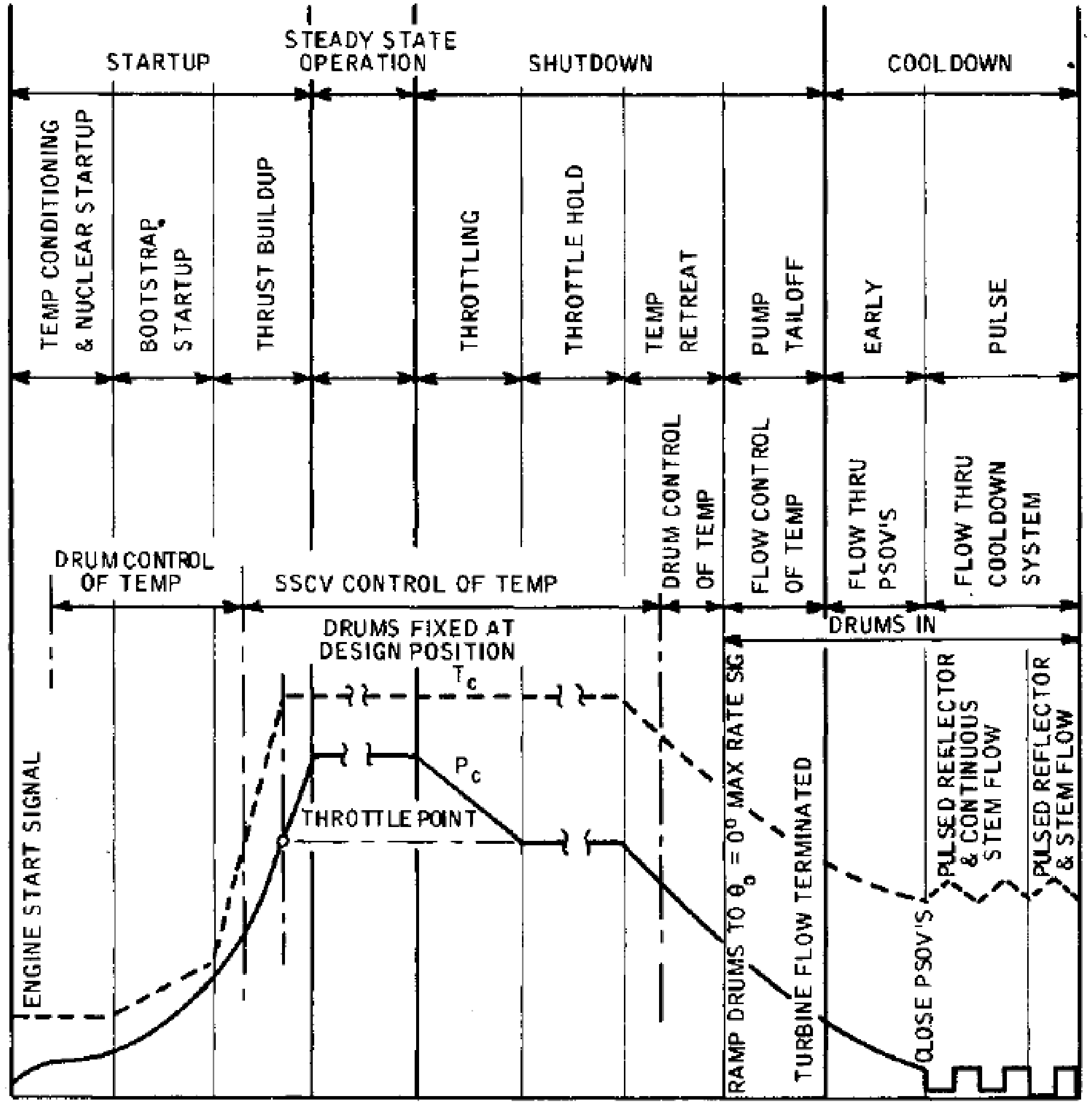
Conclusion

- Full-core multiphysics model with spatially detailed neutron flux and temperature profiles
- Power-following controllers successfully deployed
- Temperature-following controllers proposed to limit delay and oscillatory behavior

- Ongoing/Future work includes:
  - Update model (from CERMET to CERCER)
  - Better system model, including accurate fluid properties
  - Follow temperature and pressure signals
  - Control including BCV and SSCV (requires new XS)
  - Account for any limitation on drum rotation (speed, instrumentation delay, etc.)

Backup Slides

NERVA Engine Operational Phases



- Complicated start-up/shutdown phases
- Complicated control system (drum and valves)
- Chamber pressure ~ mass flow rate
- Chamber temperature * mass flow rate ~ power

- Conditioning: cool pump, pre-heat core, achieve criticality, ~ 5 minutes
- Bootstrap/thrust build-up: ~30s
- Steady-state: 30-60 minutes
- Throttle hold: ~65% thrust for 1-3 min
- Cooldown: remove decay heat with pulses

Source: Altseimer, J.H., Mader, G.F., Stewart, J.J., 1971. Operating characteristics and requirements for the NERVA flight engine. Journal of Spacecraft and Rockets 8, 766–773.

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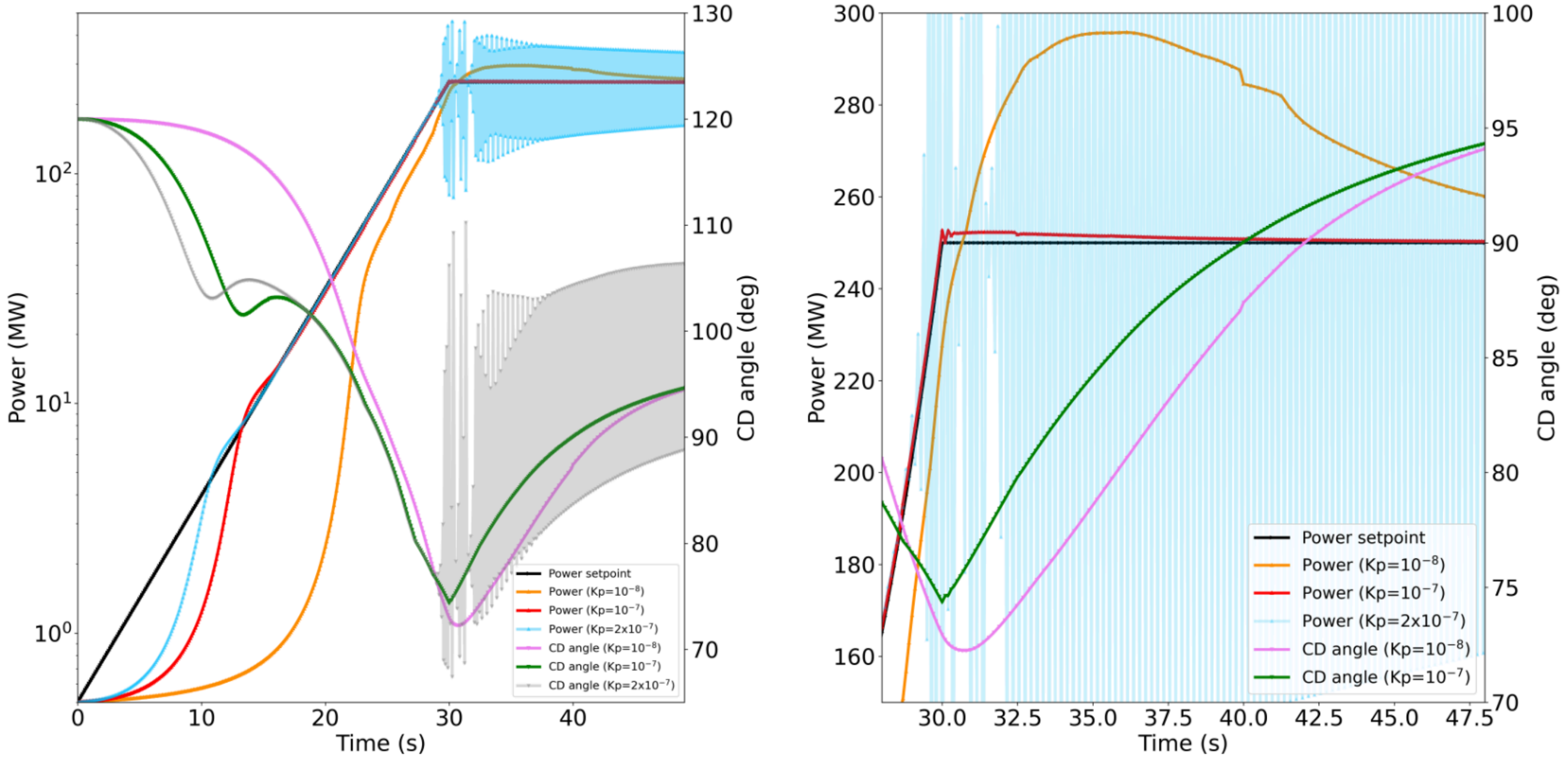
Power-driven PID Control

- To get good initial agreement, need to increase
- But becomes unstable after a while
- won't help because delayed effect
- typically decreases stability



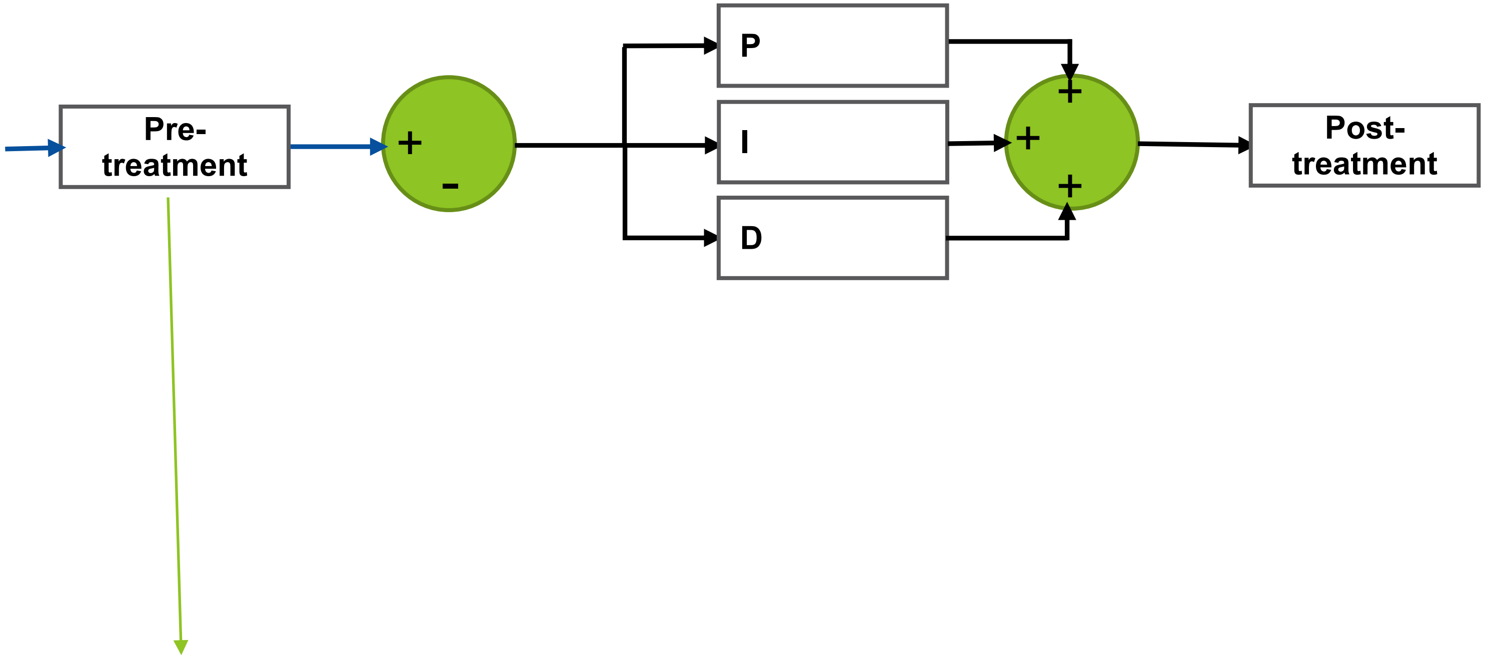
(a) Global behavior.

(b) Between 28 and 48 s.

Figure 12: Evolution of the power and CD angles for various values of K_p (in deg/W) for the power-driven PID controller when applied to the exponential ramp-up benchmark.

Reactivity-driven PID Control

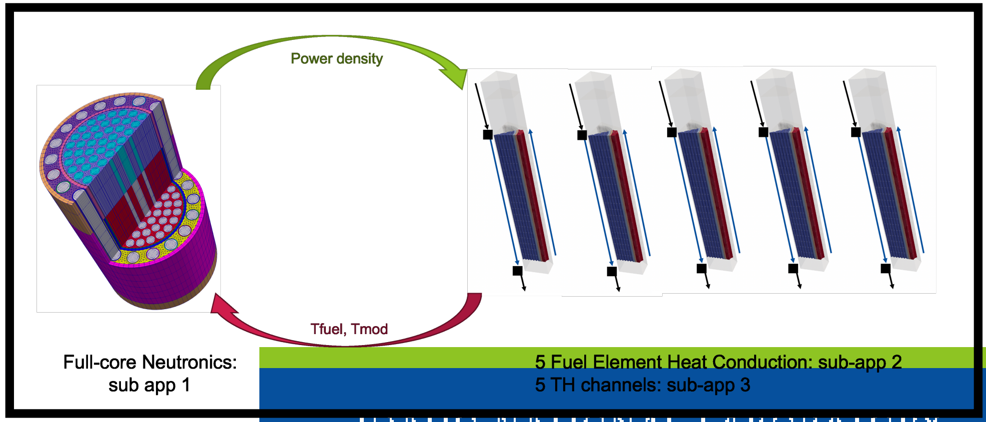
- Other approach: control reactivity (since no time delay between and)
- Can easily determine a good (based on CD differential worth)



Control Drum angle

$$\rho_d = \frac{\Lambda}{\mathcal{P}_d \beta_{eff}} \left(\frac{d\mathcal{P}_d}{dt} - \sum_i \lambda_i C_i \right) + 1$$

Reactivity (+ kinetics data)



Reactivity-driven PID Control

- Great initial behavior
- But no good way to stabilize to the desired power
- Probably because inaccurate kinetics data

$$\rho_d = \frac{\Lambda}{\mathcal{P}_d \beta_{\text{eff}}} \left(\frac{\mathrm{d}\mathcal{P}_d}{\mathrm{d}t} - \sum_i \lambda_i C_i \right) + 1$$

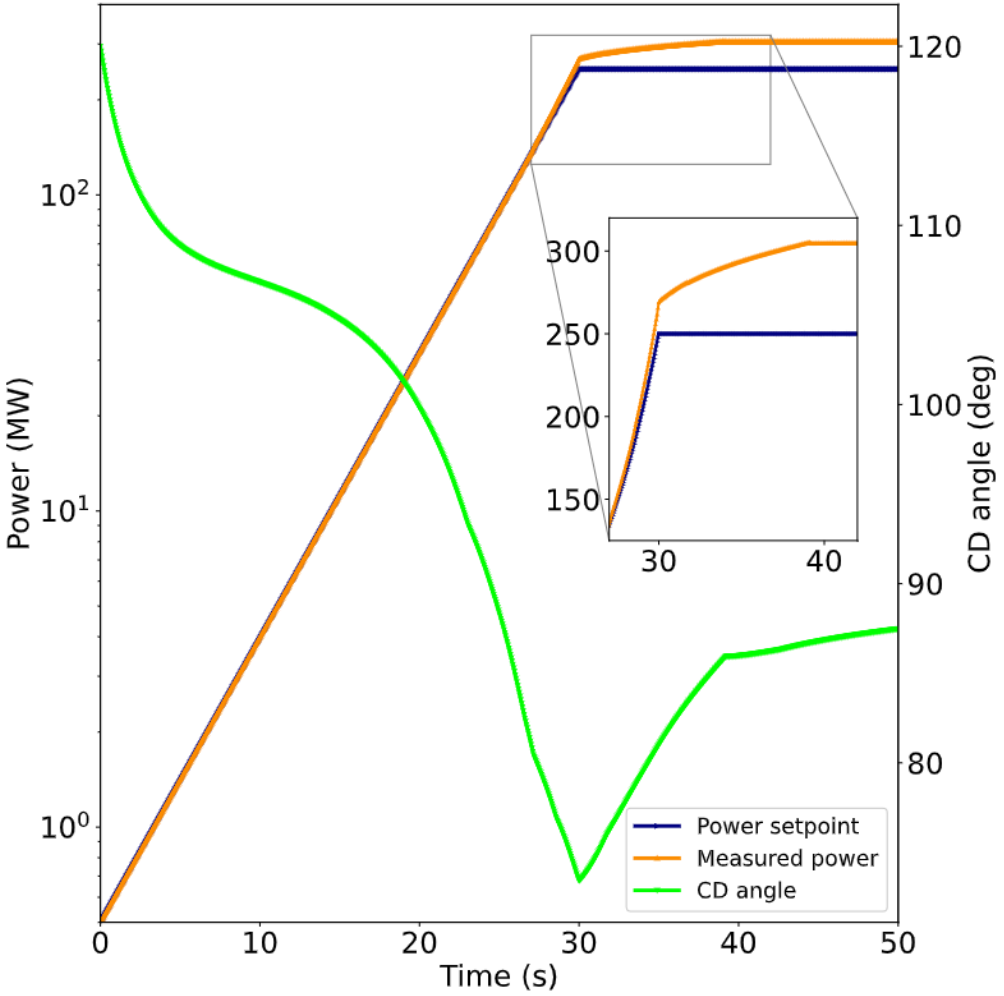


Figure 14: Evolution of the power and CD angle for the reactivity-driven PID controller when applied to the exponential ramp-up benchmark.

LABORATORY

Hybrid power-reactivity-driven PID Control

- Great initial behavior
- Little overshoot
- Robust (seamlessly handles sudden changes in reactivity feedback)
- Reactive controller (not predictive)

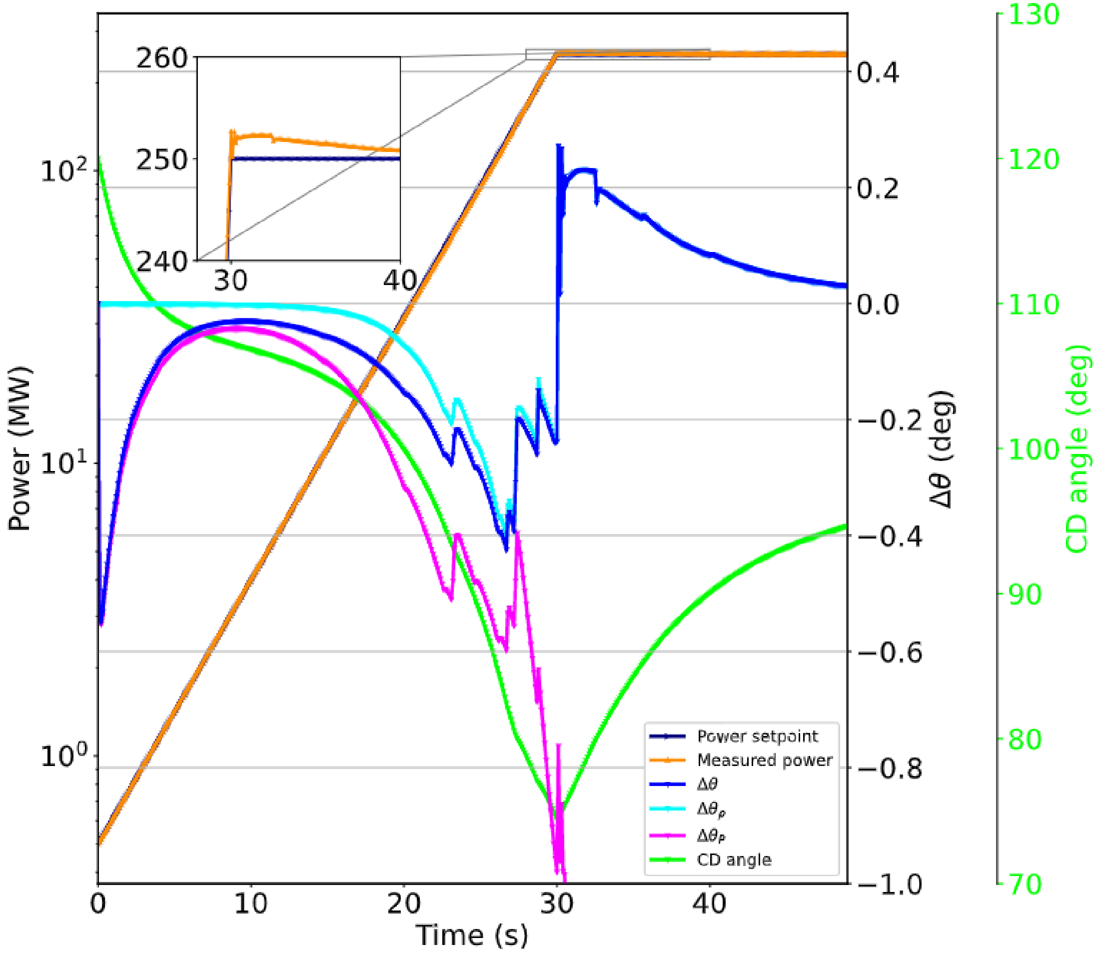


Figure 17: Evolution of the measured and demanded powers, as well as the CD signal and CD angle for the hybrid PID controller when applied to the exponential ramp-up benchmark.

RATORY

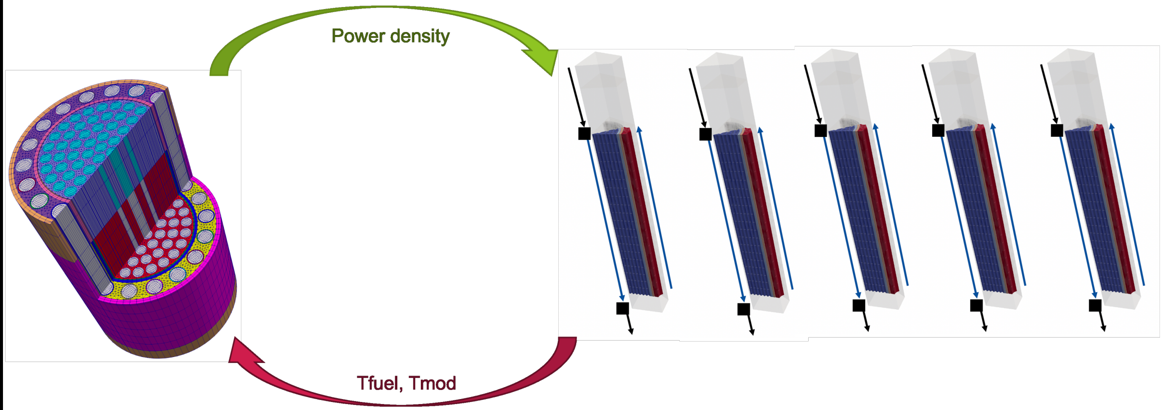
Period-Generated Control

Desired power

Period-generated Controller

Primary app

Control Drum angle



Full-core Neutronics: sub app 1

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

Sub app

Power + reactor data

- Predictive controller
- Anticipates reactivity feedback + kinetics

Period-generated Control of Drums

- Great initial behavior
- Little overshoot
- Requires PKE data, including:

$$\lambda_e' = \frac{\sum_{i=1}^{I} \lambda_i^2 C_i}{\sum_{i=1}^{I} \lambda_i C_i}$$

DNP concentrations

$$\rho_u(t) = \frac{\partial \rho}{\partial u}\frac{\partial u}{\partial t}$$

Rate of change (e.g., Tfuel, Tmod, CD angle)

Reactivity coefficients

- Depends on feedback model but small changes does not significantly degrade performance

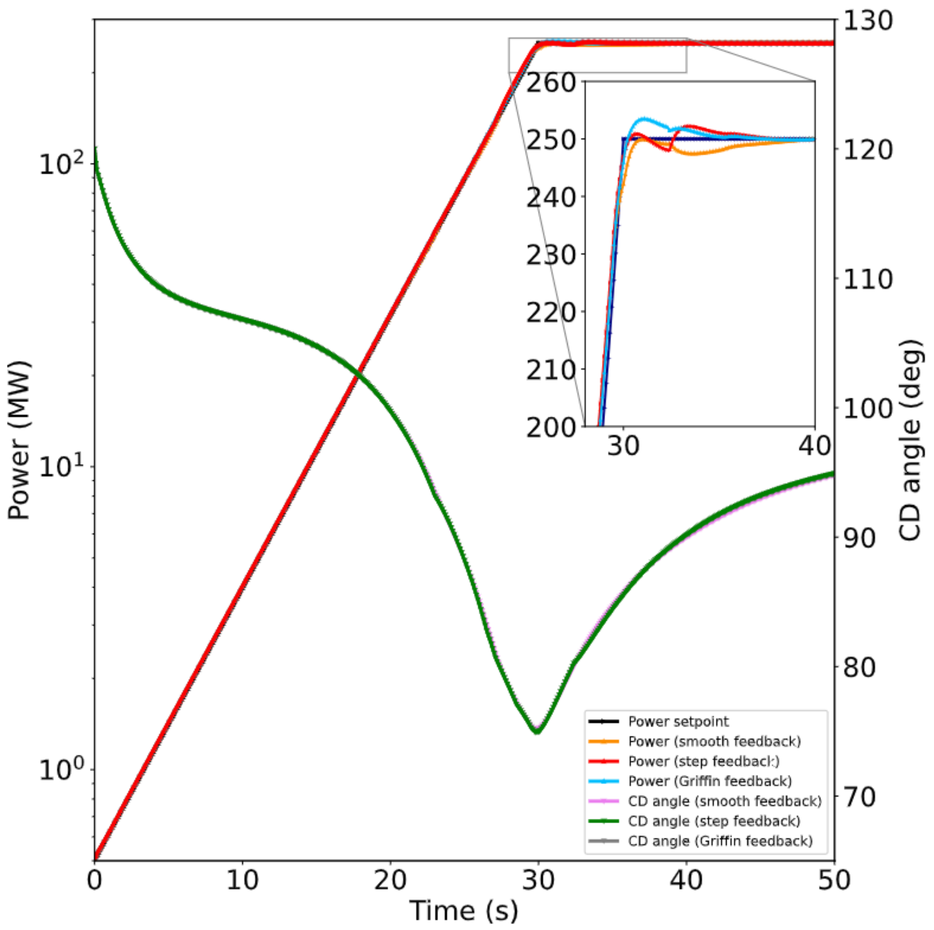


Figure 20: Evolution of the measured/demanded powers and the CD angle for the PGC under various moderator temperature feedback approximations applied to the exponential ramp-up benchmark.

Comparison of Controllers

Table 3
Summary of the strengths and weaknesses of the various control strategies considered in this work. Green and red are used to indicate an advantage or disadvantage, respectively.

Case	Power overshoot	Accurate initial response?	Need coefficient tuning?	Need kinetics data?	Need feedback coefficients?	Need temperature and CD angle change rate?
Power-driven PID	1.1%	No	Yes	No	No	No
Reactivity-driven PID	22.4%	Yes	Yes	Yes	No	No
Hybrid PID	1.1%	Yes	Yes	Yes	No	No
Period-generated	0-1.4%	Yes	No	Yes	Yes	Yes

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How do we experimentally compute the DNP concentrations?

1. Estimate the non-fission neutron source S

2. Obtain from Measurement or Simulation

3. Measure N(t) using neutron detector

[illegible]

[illegible]

Source: M. Jaradat, TREAT Transient Analysis, C110 presentation, October 2022.

- I initially thought we would need a numerical model to compute
- But can be done experimentally
- Thus, kinetics data should be doable with a real system
- However, rate of change (e.g. Tfuel) needed by period-generated controller would likely require a numerical model