INL/CON-23-72457-Revision-0

Hybrid Temperature-Reactivity PID Controllers for Nuclear Thermal Propulsion Startup

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Changing the World's Energy Future

Vincent M Laboure, Stefano Terlizzi, Sebastian Schunert

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Vincent Labouré, Stefano Terlizzi, Sebastian Schunert

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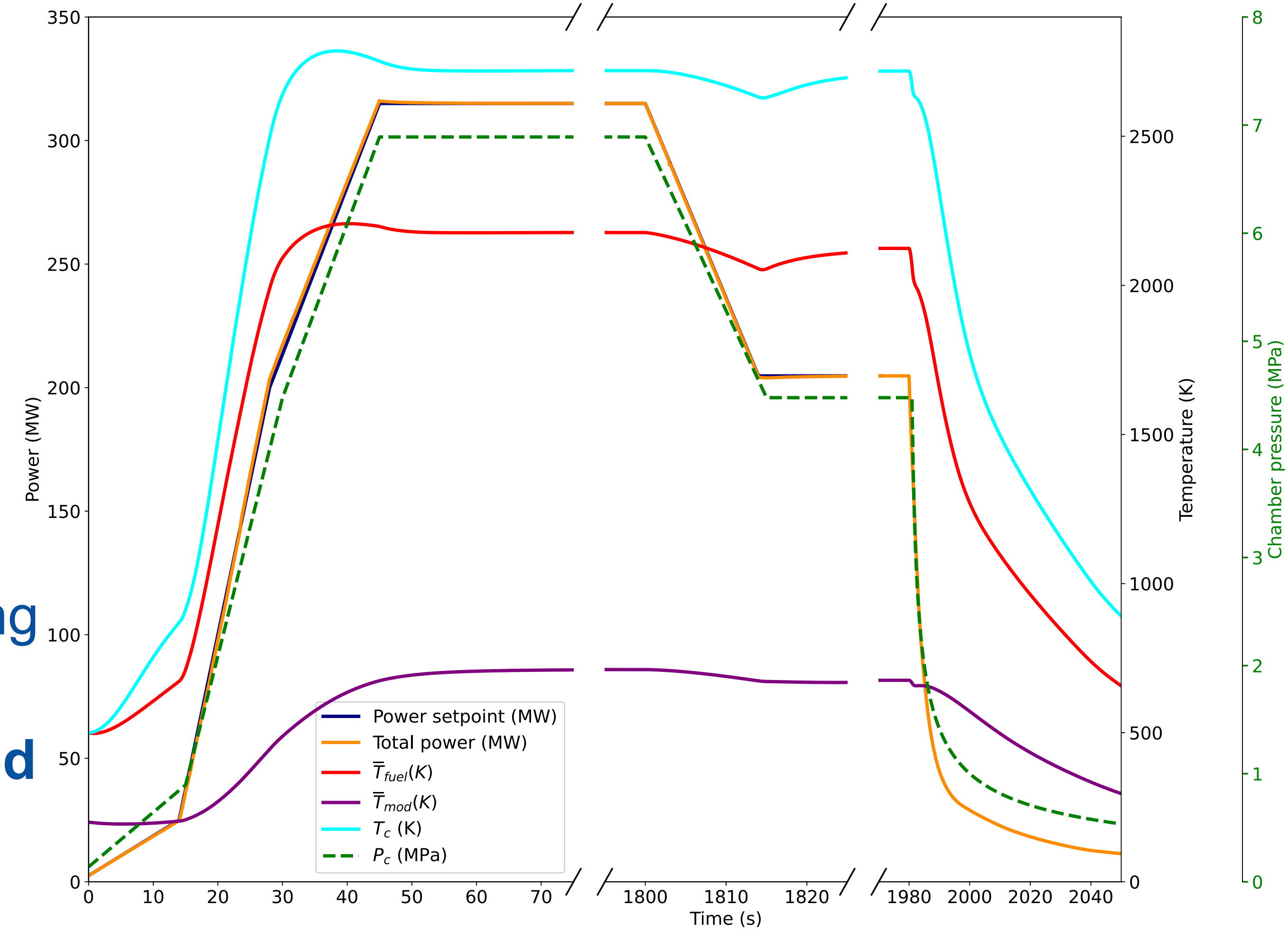
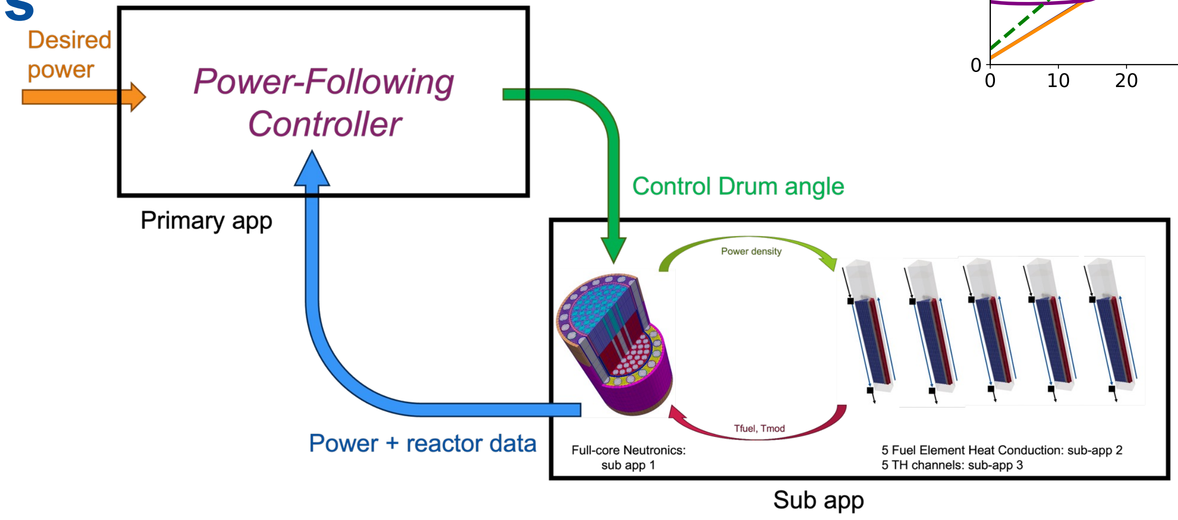
Outline

- Motivation
- Simplified Model
- Temperature/Reactivity Control
- Future Work

Motivation

- Pressure/mass flow rate as BC
- Pre-defined power setpoint
- Good controller response
- Temperature overshoot (~3%) and not constant during throttling because not using a temperature demand
- **Goal: investigate temperature-controlled systems**





Source: 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", accepted by Progress in Nuclear Energy in April 2023.

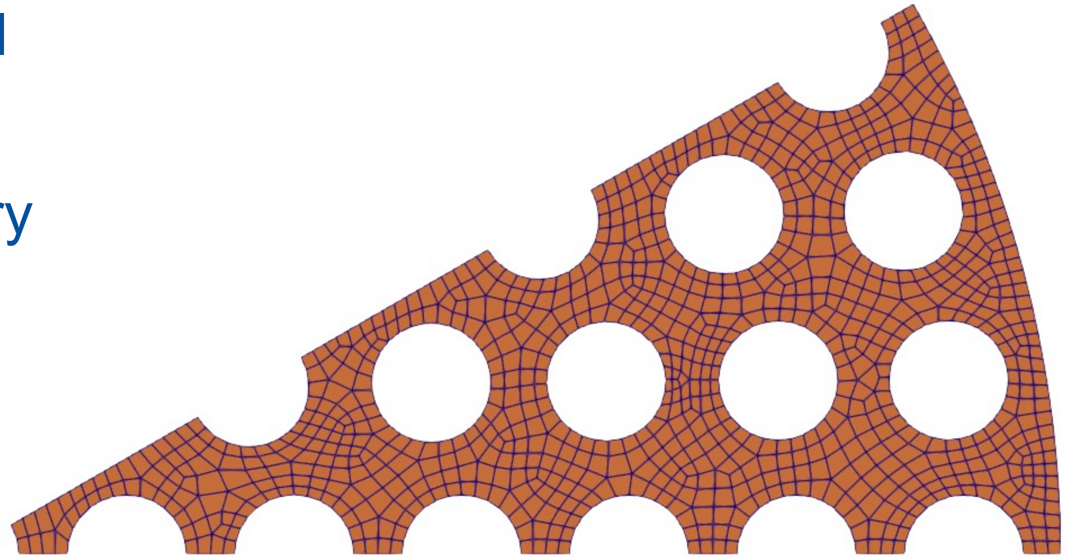
Multiphysics Model

- Simplified PKE model with fixed reactivity coefficients and prototypical kinetics parameters
- Single 3-D representative fuel element with heat conduction and convection at cooling channel boundary
- Single 1-D representative fuel cooling channel
- Chamber temperature (T_c) used for control
- Chamber pressure (P_c) prescribed as boundary condition and mass flow rate given by:

$$\dot{m}(t) = \frac{\dot{m}_{nom}\sqrt{T_{c,nom}}}{P_{c,nom}} \frac{P_c(t)}{\sqrt{T_c(t)}}$$

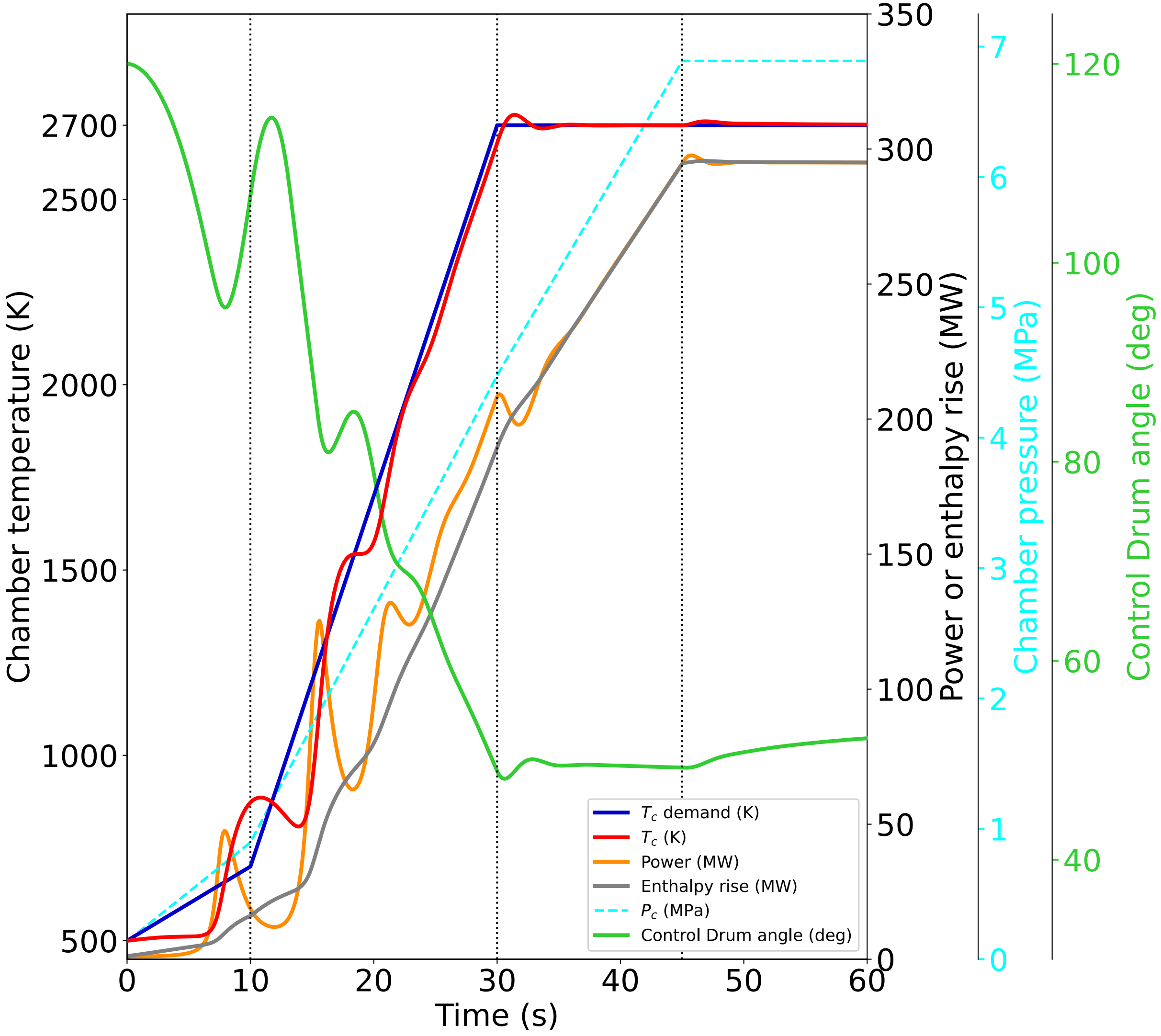
TABLE I. Kinetics parameters used in the neutronics model. λ_i and β_i are the delayed neutron decay constants and fractions, respectively. Λ is the mean generation time.

Delayed Group	λ_i (s^{-1})	β_i (pcm)	Λ (s)
1	1.3346×10^{-2}	24.6	1.33×10^{-5}
2	3.2667×10^{-2}	128.6	
3	1.2094×10^{-1}	124.3	
4	3.0444×10^{-1}	282.0	
5	8.5639×10^{-1}	121.7	
6	2.8764×10^{0}	50.8	
Sum		732.1	



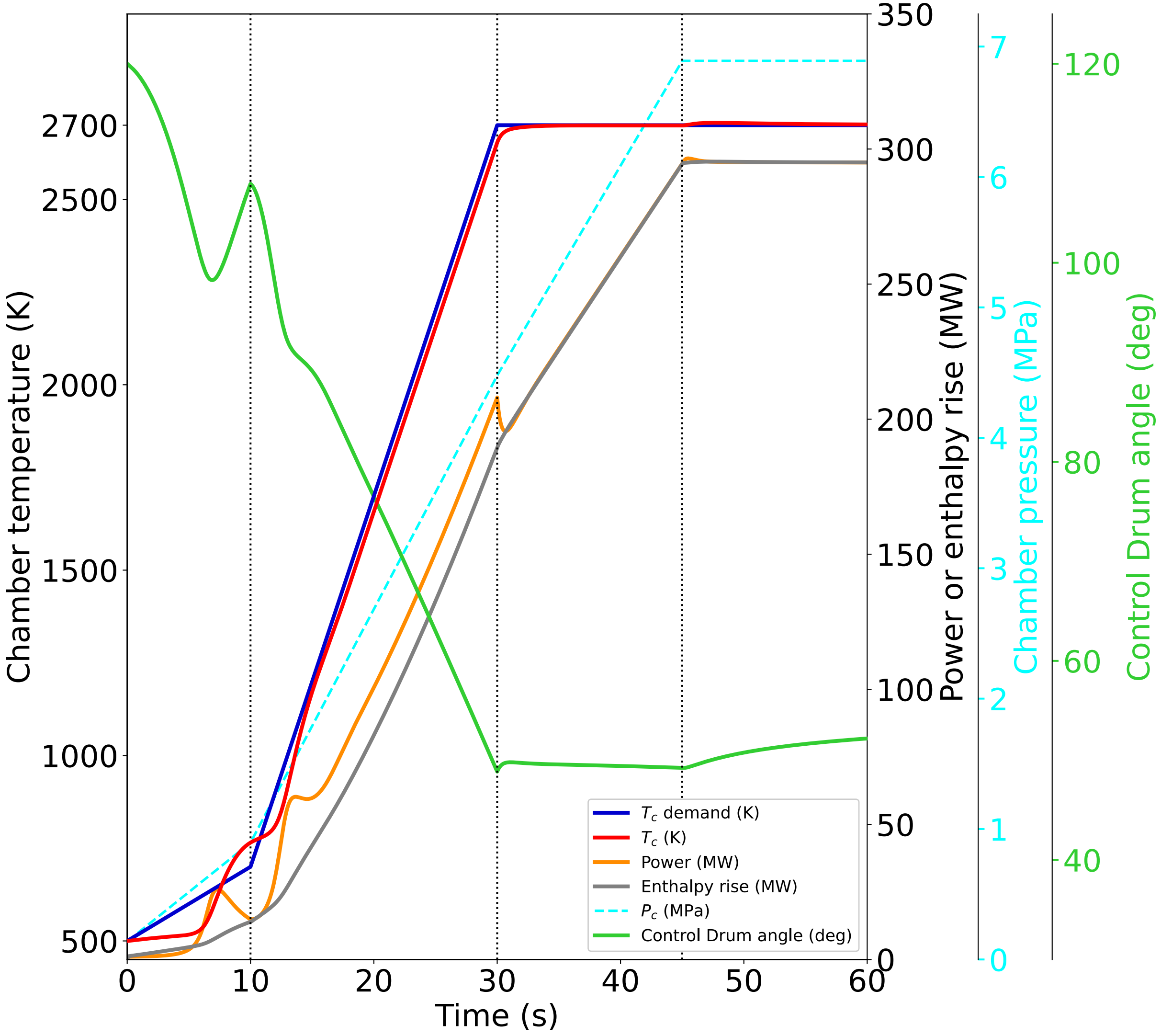
Temperature Proportional Controller

- Drums controlled by directly comparing the predicted and desired chamber temperatures
- Oscillatory behavior due to delay between drum rotation and chamber temperature rise
- Initial response quite slow
- Temperature overshoot



Temperature Proportional-Derivative Controller

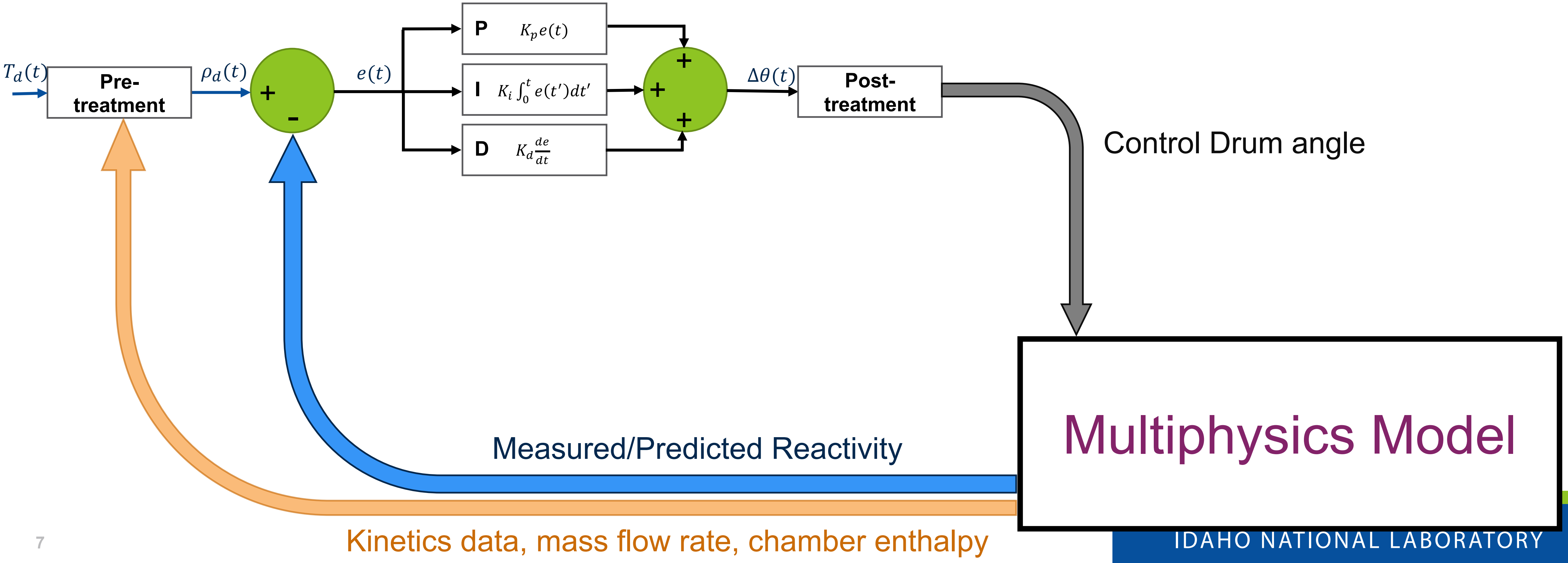
- Derivative term (i.e., anticipation) included
- Much smoother behavior
- Initial response still slow/oscillatory
- But overall behavior much better
- Caveat: derivative component would require noise filtering



Reactivity Controller

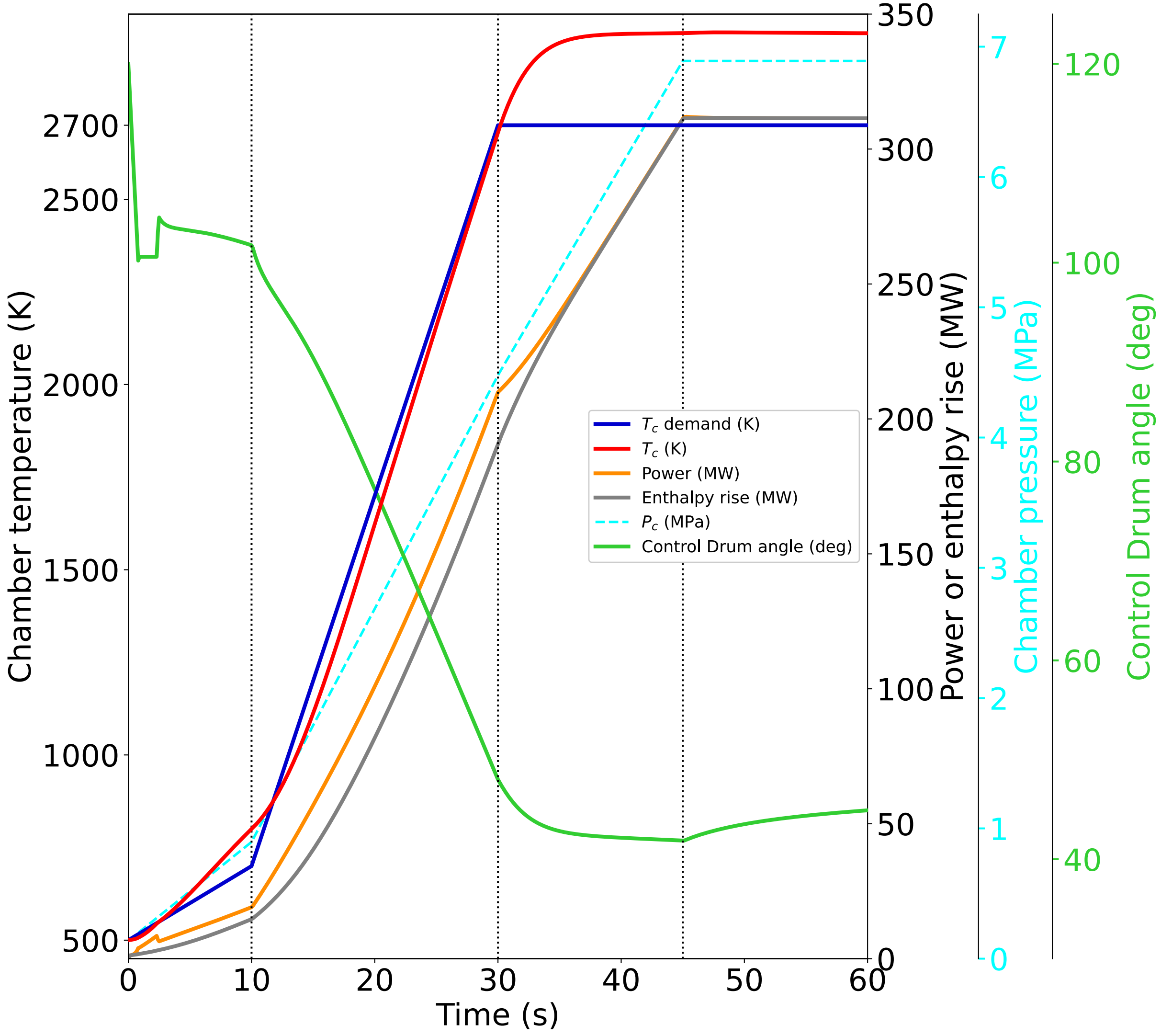
$$\begin{cases} \mathcal{P}_d \approx \dot{m}(H_{out}(T_d) - H_{tank}) \\ \rho_d = \dfrac{\Lambda}{\mathcal{P}_d\,\beta_{eff}}\left(\dfrac{d\mathcal{P}_d}{dt} - \sum_i \lambda_i C_i\right) + 1 \end{cases}$$

- Pre-treatment to convert temperature demand to reactivity demand
- Post-treatment to make sure the CDs do not exceed a certain speed (25 deg/s) and reactor period stays above 2.5 s



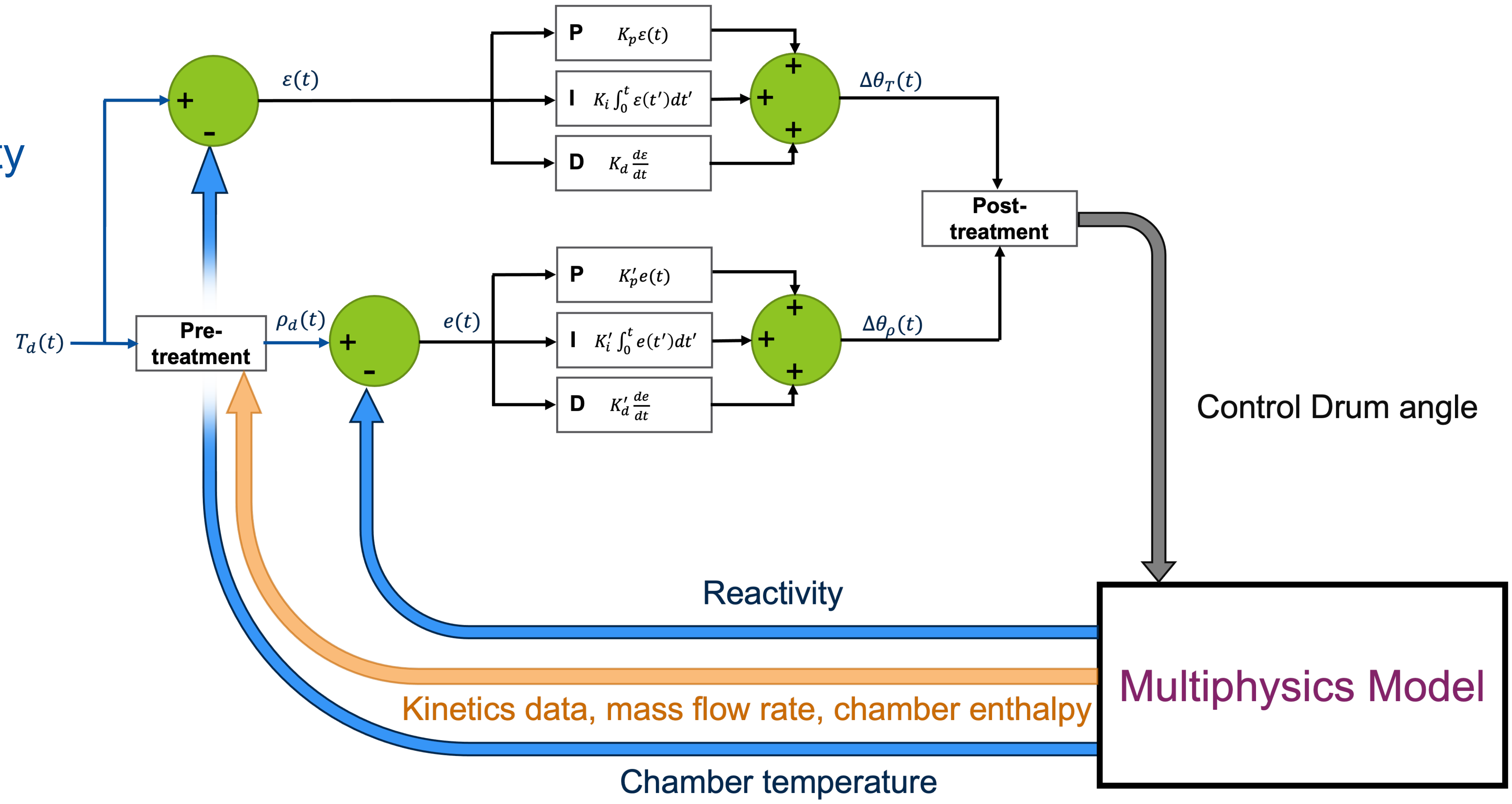
Reactivity Proportional Controller

- Faster initial response
- Initially, CD speed limited and set to 0 when the period goes lower than 2.5 s
- But T_C does not stabilize to the desired temperature because of inexact conversion $T_d \rightarrow \rho_d$



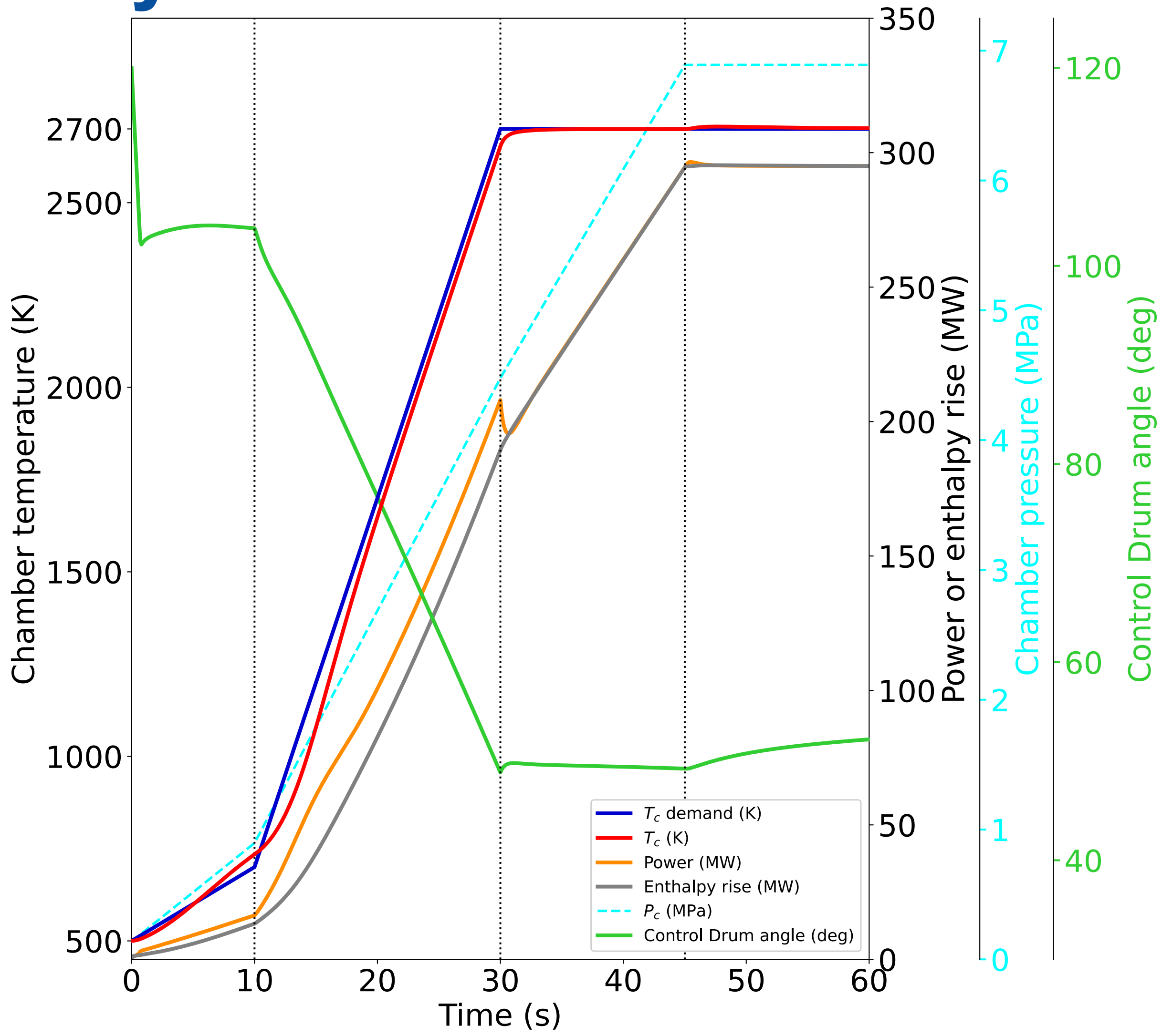
Hybrid Controller

- Use the reactivity component at early times
- Use the temperature component at later times



Hybrid Temperature-Reactivity Controller

- Initial delay/oscillations are reduced
- 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)?



Conclusions

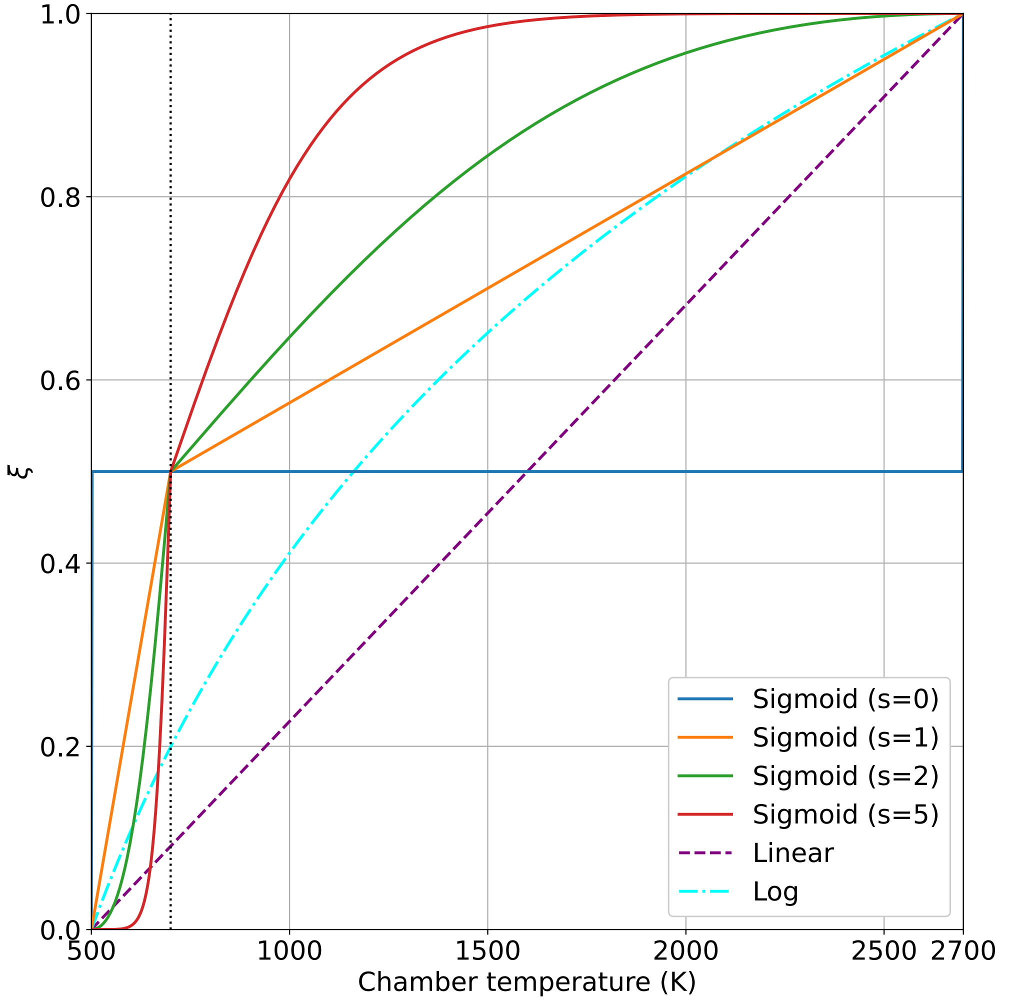
- New controller proposed to limit delayed and oscillatory behavior
- But derivative term could be difficult to use in practice (noisy signal)
- Temperature delay difficult to fully overcome (unless varying gains are used for controllers)
- But difficult to determine varying gains on a real system unless it can be tested at nominal conditions
- Need to make the model more complex to further test limitations (e.g., moderator capacitance could prevent from reaching nominal temperatures within 30 s, etc.)
- Future work:
  - Incorporate into full-core multiphysics model
  - Account for instrumentation delay
  - Pressure-following controller to actuate the bypass control valve

Backup Slides

Temperature-Reactivity Weighting

- Many ways of weighting:
  - Linear
  - Logarithmic
  - Sigmoid

$$\theta(t_{n+1}) = \theta_i + \sum_{k=1}^{n} \Delta\theta(t_k) = \theta_i + \sum_{k=1}^{n} \left(\xi \Delta\theta_T(t_k) + (1-\xi)\Delta\theta_\rho(t_k)\right), \quad (5)$$



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

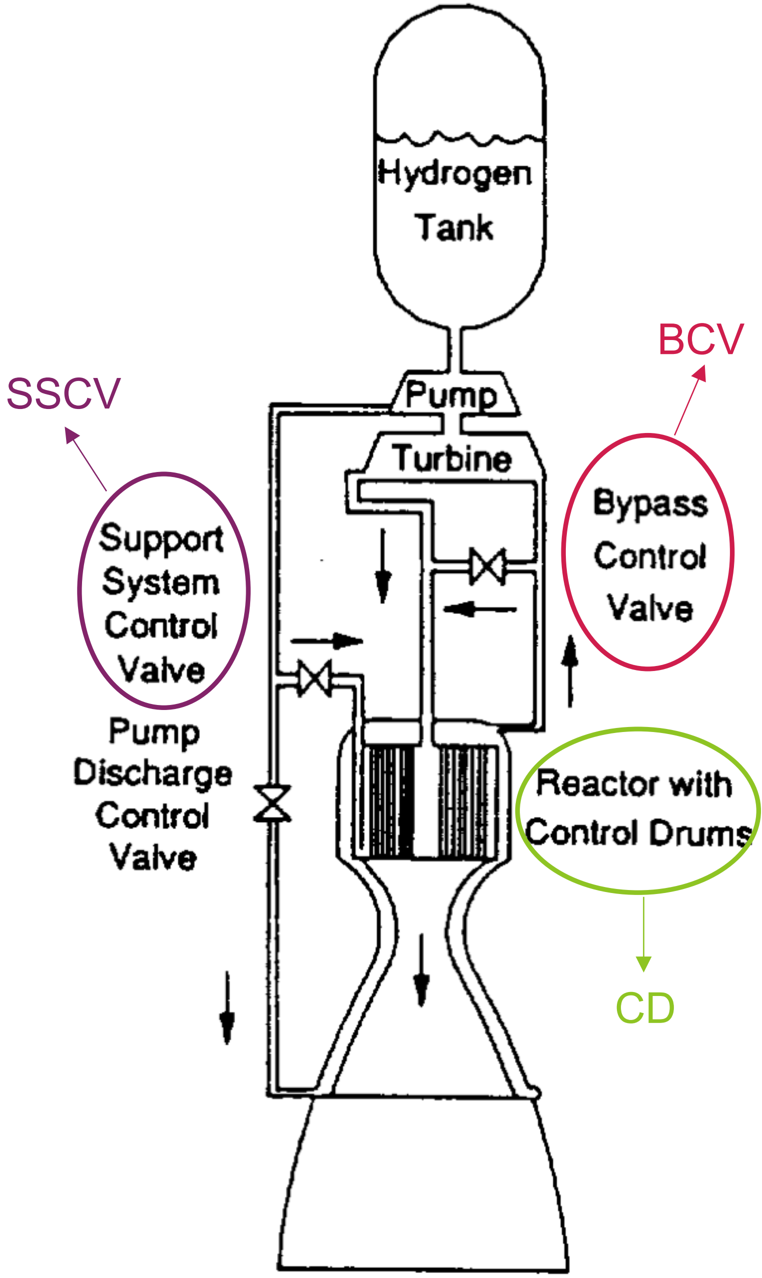
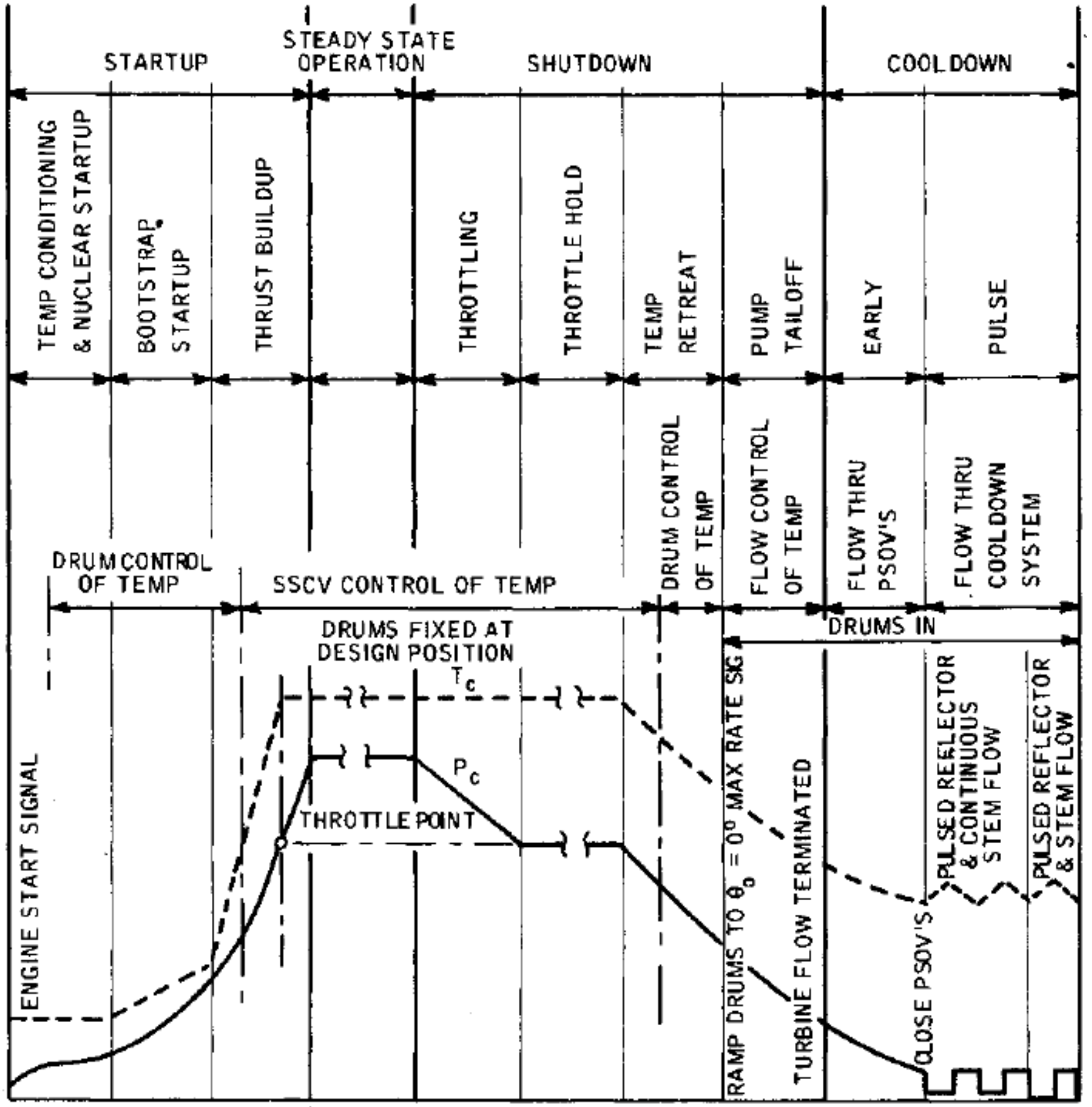


FIGURE 11. Nuclear Thermal Rocket Engine Flow Schematic.

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

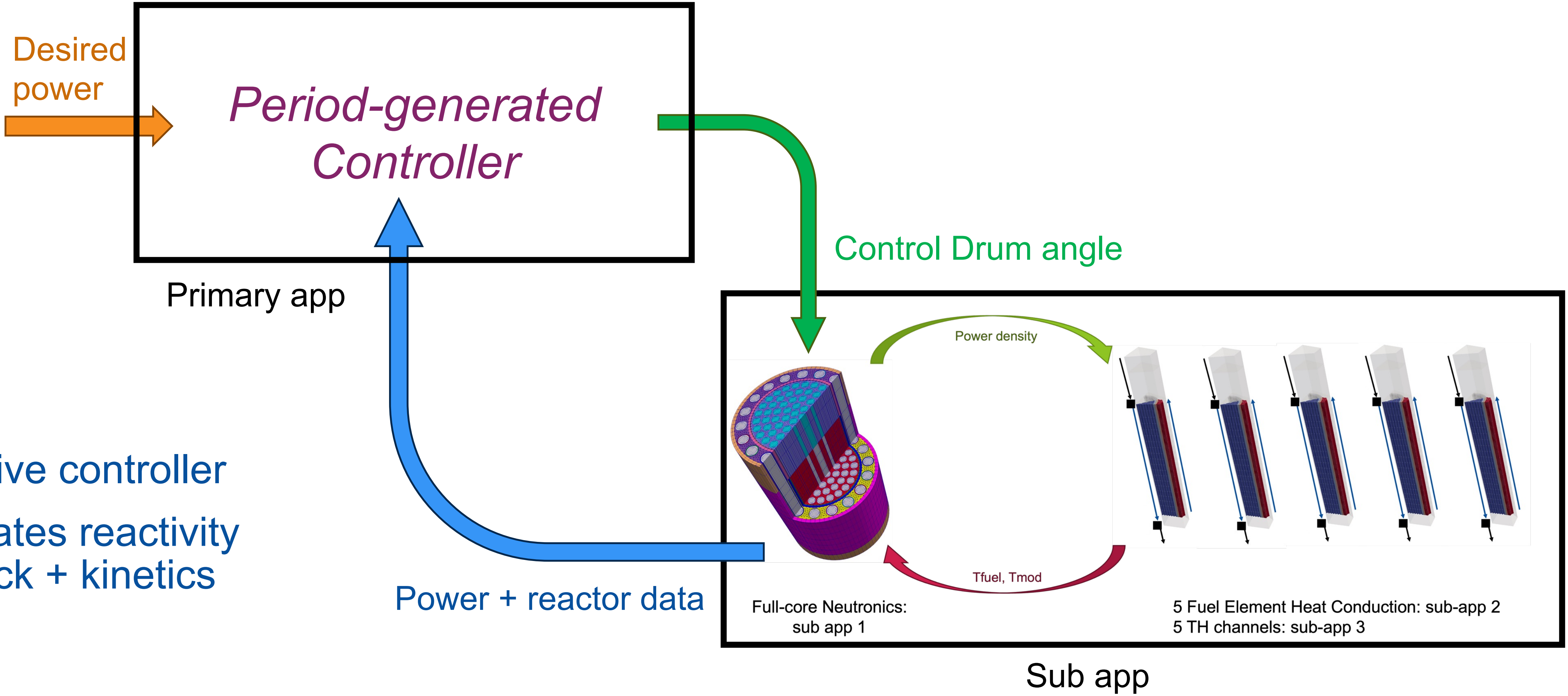
NERVA Engine Operational Phases



- Complicated start-up/shutdown phases
- Complicated control system (drum and valves)
- Chamber pressure ~ mass flow rate * sqrt(Tc)
- 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, e.g., 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.

Period-Generated Control



- 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

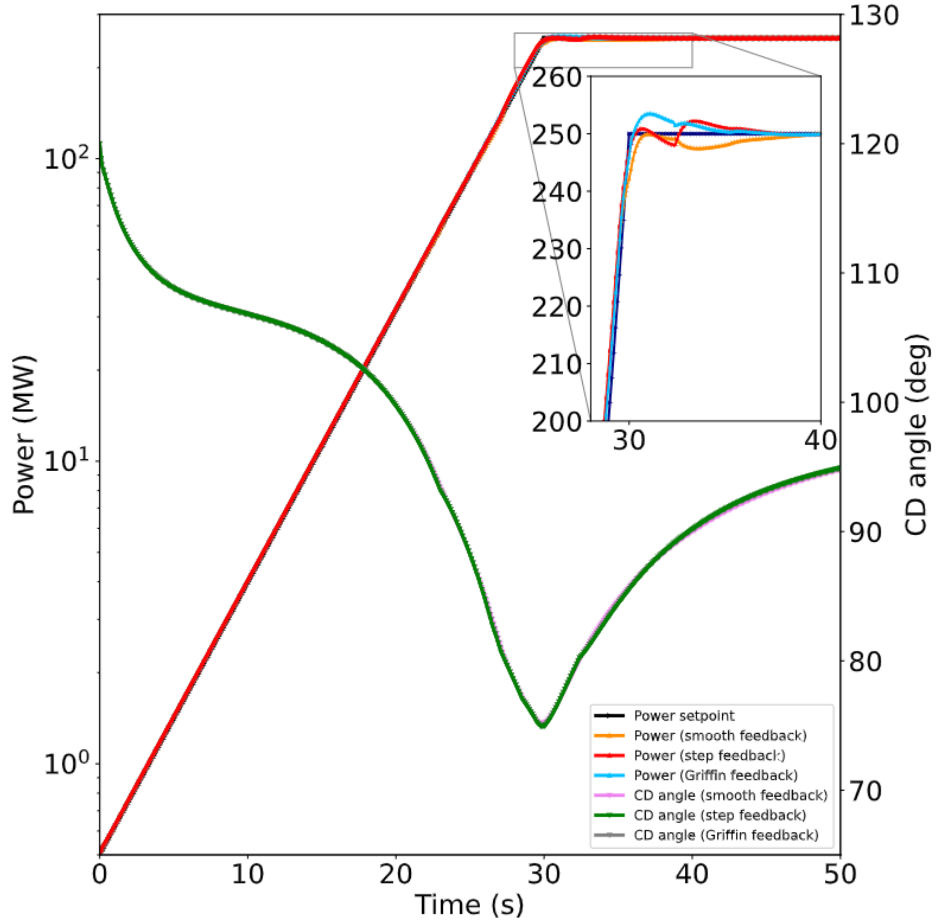


Figure 20: Evolution of the measured/demanded powers and the CD angle for the PGC under various moderator temperature feedback approximations applied to the exponential ramp-up benchmark.

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

How do we experimentally compute the DNP concentrations?

1. Estimate the non-fission neutron source S

2. Obtain β_{eff}, Λ from Measurement or Simulation

3. Measure N(t) using neutron detector

4. $C_k(t+\Delta) = C_k(t) + \frac{\beta_k}{\Lambda}\int_t^{t+\Delta} N(t)dt - \lambda_k \int_t^{t+\Delta} C_k(t)dt$

5. $\frac{\rho(t+\Delta)}{\beta_{eff}} = 1 + \frac{\Lambda}{\beta_{eff}} \frac{1}{N(t+\Delta)}\left[\frac{N(t+\Delta)-N(t)}{\Delta} - \sum_{k=1}^{K} \lambda_k C_k(t+\Delta) - S\right]$

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

- I initially thought we would need a numerical model to compute C_i
- 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