

PARCS Applications – 3D Reactor Dynamics for Safety Analysis

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Outline

- Introduction to safety analysis – why are we doing this?
- PARCS features that are necessary/useful for running transient simulations
- Exercises
 - Uncontrolled bank withdrawal
 - Control rod ejection accident
- Summarize

Introduction to safety analysis

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Safety basis of transient simulations

- Reactor licensees must demonstrate that their reactor remains in a “safe” condition during normal and off-normal operation
 - For anticipated operational occurrences (A^{OO}s): no fuel failure
 - For postulated accidents (P^As): core remains intact and coolable
- Traditionally, they evaluate a large suite of possible transient scenarios to show that, for each one, the event-specific acceptance criteria are met – so-called “Chapter 15” or “design basis” safety analysis
- NRC Standard Review Plan (SRP) for LWRs, Chapter 15, spells out the NRC staff's expectation for which events are analyzed and what their allowable consequences are

Approaches to safety analysis

- Most (all?) utilities do not want to pay for cycle-specific safety analysis – they use a “**bounding envelope**” approach
 - Conservative evaluation models with bounding assumptions
 - Create margin for future reloads such that they don't have to repeat transient simulations with every core design
 - Envelope is codified within the plant's technical specifications (**TSs**)
 - Major changes in systems or operations typically require re-analysis (e.g., uprates) – create a new envelope
- Yesterday's static analyses were examples of how a reload would be shown to be within the safety envelope
 - E.g., if a reload's highest ejected rod worth (**ERW**) (+ additional safety margin) < value used in safety analysis, design is acceptable with respect to ERW

Role of reactor dynamics in safety analysis

- If we perturb the plant's reactor system, the core is going to respond by changing its power level and/or flux shape
- To the extent possible, licensees want to use simple, conservative models to define safety envelope – leads to heavy use of point kinetics
 - Easily biased – can add margin to parameters cleanly
 - Many events are fairly uniform – spatial kinetics is overkill
 - Combined with conservative hot channel models, can create easily defensible evaluations of core performance during AOOs/PAs
 - For most events, there is plenty of margin – don't need anything sophisticated
- However, core simulators like PARCS are very useful for safety analysis
 - As we saw yesterday, PARCS can be used to generate feedback coefficients, trip worth, etc., which can be used in more simplified models
 - Some events are very local – need spatial kinetics for an accurate evaluation

The magical world of reactivity transients

- There are several events which do require spatial kinetics for accurate evaluation
- SRP 15.1.5 – main steamline break (PA)
 - Major break on secondary side creates an asymmetrical primary side cooldown and concordant reactivity insertion
 - Combined with an inconveniently located stuck rod, can lead to return-to-power and DNBR/centerline melt fuel failures
 - We will not cover this any further here
- We are going to stay in SRP 15.4 – Reactivity initiated events
 - We can evaluate most of these without needing a systems analysis code
 - They are typically shorter-term transients, which means we can run several cases

SRP Section 15.4

- 15.4.1: Uncontrolled Control Rod Assembly Withdrawal from a Subcritical or Low Power Startup Condition
- 15.4.2: Uncontrolled Control Rod Assembly Withdrawal at Power
- 15.4.3: Control Rod Misoperation (System Malfunction or Operator Error)
- 15.4.4-15.4.5: Startup of an Inactive Loop or Recirculation Loop at an Incorrect Temperature, and Flow Controller Malfunction Causing an Increase in BWR Core Flow Rate
- 15.4.6: Inadvertent Decrease in Boron Concentration in the Reactor Coolant System (PWR)
- 15.4.7: Inadvertent Loading and Operation of a Fuel Assembly in an Improper Position
- 15.4.8: Spectrum of Rod Ejection Accidents (PWR)
- 15.4.9: Spectrum of Rod Drop Accidents (BWR)

Before we begin...

- Standalone PARCS is an excellent tool for solving LWR core physics problems **under close-to-normal conditions**
- **HOWEVER**: it is limited in thermal-hydraulics and fuel performance, both of which are also important for transient simulations
 - No way to feed secondary side effects back into inlet temperature
 - Transient stand-alone PARCS lacks a robust multiphase flow solver or critical heat flux
 - Very limited capability to represent fuel performance
- **THEREFORE**: if you want to do “real” simulations of Chapter 15 accidents:
 - You *could* use PARCS as the first step of a **conservative evaluation** model to calculate power response, then provide that as a boundary condition to a systems or subchannel code
 - NRC uses PARCS coupled with our flagship TH systems code TRACE, which is designed as a general-purpose solver for any design basis LWR transient
 - We have efforts underway to further improve our capabilities by coupling our fuel performance code FAST into TRACE/PARCS

Modeling transients in PARCS

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General methodology

- Run a static model based on statepoint you want to start the transient from first
 - Calculate critical boron concentration (CBC)
 - Generate *restart* file the transient input model can read in (parcs_rst)
 - Relatively recent feature for standalone PARCS (as of v3.3.5)



- Copy static model into a new input file for the transient
 - Change **CNTL** block
 - Change **GEOM** block to split out WRSO (and for REA, add ejected rod), and add PPR input, if required
 - Remove **INP_HST** and **INP_OPT** cards from **DEPL** block
 - Add **TRAN** block

CNTL block changes

- Change some existing blocks
 - `XE_SM` – allow time-dependent xenon and samarium during transient
 - `BANK_POS` – add new banks for stuck rod and/or ejected rod – put them at same initial position as mother bank
 - `SEARCH` – switch to keff search
 - If PPR is desired, make change to `PLOT_OPT` and add `PIN_POWER`
- Add some new blocks
 - Add `RESTART` card – include restart file generated by static initialization
 - Add `DECAY_HEAT` card
 - In steady-state/depletion, don't discriminate between heat generated through fission vs. fission product decay
 - In transient, the distinction becomes very important
 - Add `KIN_OPTS` card – turn on several useful edits for interpreting transient simulation

CNTL changes

Add transient Xe/Sm options

Add bank for stuck rod

Switch search to keff

Add transient card

Activate read from restart file, give file name and set to read from last step in restart file

Turn on decay heat

Turn on kinetics options

```
!*****
CNTL
...core_type...PWR
!
...int_th...T...-1...! Use ME solver
!
...xe_sm...1...1...2...2
!
...core_power...50.0
!...BankA...BankB...BankC...BankD...BankS StkS1
...bank_pos...231.0 231.0 180.0 55.0 231.0 231.0
!
...search...keff
!
...transient...T
...restart...T... 'exercisel_050_static.parcs_rst'...-1
...decay_heat...T
!-----
...depletion...T...5.0e-5...T
!...TREE,nset,adf,xes,ene,j1f,chi, chd,vel,det,yld,cdf,gff,bet,lam,dht
...TREE_XS...T...14...T...T...F...F...T...F...T...T...T...T...F
!...pow.flux.th.prec...xesm.pin
...PLOT_OPTS...0...0...0...0...0...2
!...iter_output.cpu_timer.write_linsys.range_warn
...run_opts...F...T...F...F...F
!...calc_adjoint.rho_split...pk_vals...calc_harmon
...kin_opts...T...T...T...F...
...PIN_POWER...T
...XS_EXTRAP...1.0...1.0
!*****
```

GEOM block changes

- If you want to **split out** a stuck and/or ejected rod into their own banks:
 - Append new bank types to the **CRB_TYPE** list
 - Modify **BANK_CONF** to locate them
 - Locations are informed by static analysis we performed yesterday
- If you want to use **PPR**:
 - Add **PINCAL_LOC** card with 1s in the locations you want PPR performed – you don't have to use full-core PPR
 - For transients, typically look at static maps to determine:
 - High-power assemblies
 - Assemblies with moving/stuck control rods and their face-neighbors
 - This can help reduce computation time

Adding a TRAN block

- **TRAN** is where we're going to add all the controls that drive the transient
 - Timestep control (PARCS standalone does not have adaptive time stepping) (**TIME_STEP**)
 - Move control rods (**MOVE_BANK**)
 - Change boron concentration (**CHANGE_PPM**)
 - Define stuck control rods (**LIMIT_CR**)
 - Define reactor trip characteristics (**SCRAM_CR** and **TRIP_CR**)
- **TRAN** follows the **DEPL** block
- Pro tip – RTFM

TRAN block

```
!*****
TRAN
.....time_step...4
.....0.05...0.001
.....0.2...0.005
.....1.0...0.01
.....5.0...0.05
.....move_bank...7...2...0
.....0.0...0.0
.....0.1...231.0
.....scram_cr...T...0.3...2.1
.....trip_cr...0...114.0
.....limit_cr...5*0.0...2*231.0
!*****
```

Time stepping information – Give number of time-timestep pairs first

Move rod bank – Give which bank to move, then number of time-position pairs
First time position should be same as bank_pos input

Characteristics of the reactor trip – switch it on, set delay between signal and start of trip, set time it takes for rods to fully insert

Trip signal – first entry is TRACE TRIP ID (not used in standalone), second entry is power at which to send trip signal

This is how you set maximum insertion depth of a rod bank following reactor trip – it's how you stick rods
Input looks like bank_pos

Exercise 8: Uncontrolled control rod assembly withdrawal at power

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Event description

- PWR control rods are arranged in banks/groups
- For this event, it is postulated that the **highest-worth group** is ramped out
 - Control rod removal leads to reactivity insertion, leading to power increase and power shape distortion
 - Inherent feedback limits excursion; reactor protection system will trip reactor if power gets too high
 - Range of initial power levels, times-in-life and ramp rates must be considered
 - SRP 15.4.2 considers this an AOO – no fuel failure criterion
- For this exercise, we will focus on relative importance of Doppler vs. coolant feedback at BOC vs. EOC for a single initial power condition

Plan of attack

- Start with base model at **BOC, 50% power**, equilibrium xenon and read-in samarium, rods at rod insertion limits (RILs)– initialize off the depletion at RILs history case
- Run static case to initialize, then read that into 30-second transient case
- Pull D-bank from RIL to all-out within the first 15 seconds
- Repeat for an EOC case with reading in xenon/samarium from depletion
- Look at outputs of interest
 - **Core power level**
 - **FdH** – would feed into the critical heat flux model in a subchannel analysis code
 - **Max fuel temperature**
 - **Reactivity split** – control rod vs. power shape redistribution vs. Doppler vs. coolant reactivity vs. time throughout transient

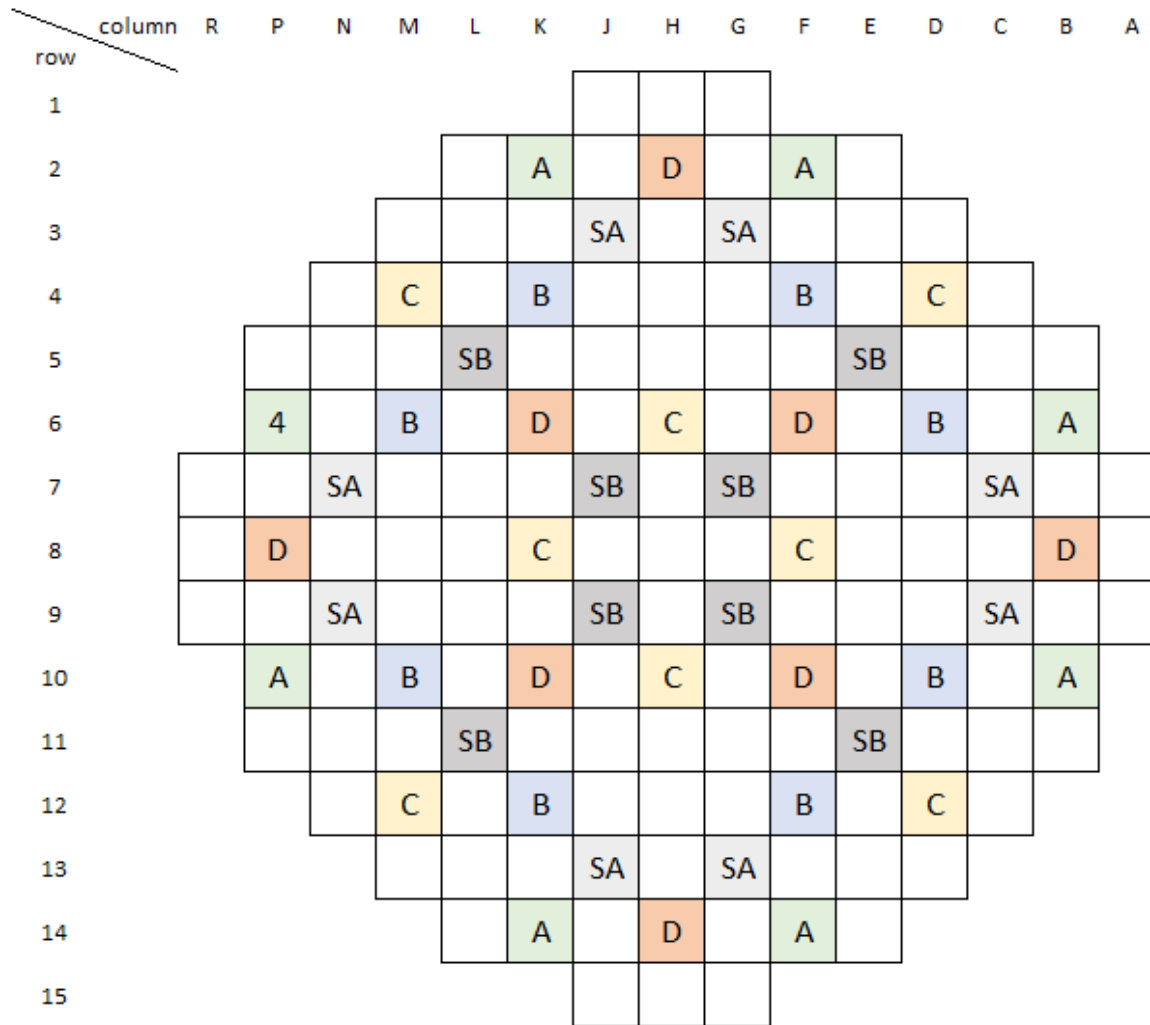
Exercise 8: Input modifications for BOC case

- Open `exercise8.parcs_inp`
- Set up static case (`exercise8_BOC_static`)
 - Modify case name
 - Set Xe/Sm options to equilibrium/read in
 - Add stuck rod from Shutdown A bank (NNE octant)
 - Start at 50% power, set banks to their 50% power RILs (Bank D @ 74 steps, Bank C @ 202 steps)
 - Read in first step of ARO depletion history file – make sure to read in Sm
- Set up transient case (`exercise8_BOC_tran`)
 - Modify case name (again)
 - Change `CNTL` as needed, add `PPR` to Bank D assemblies in NNE octant and their N/E/S/W neighbors
 - Set transient to 30 second length with prescribed timesteps, withdraw Bank D from 0 to 15 seconds

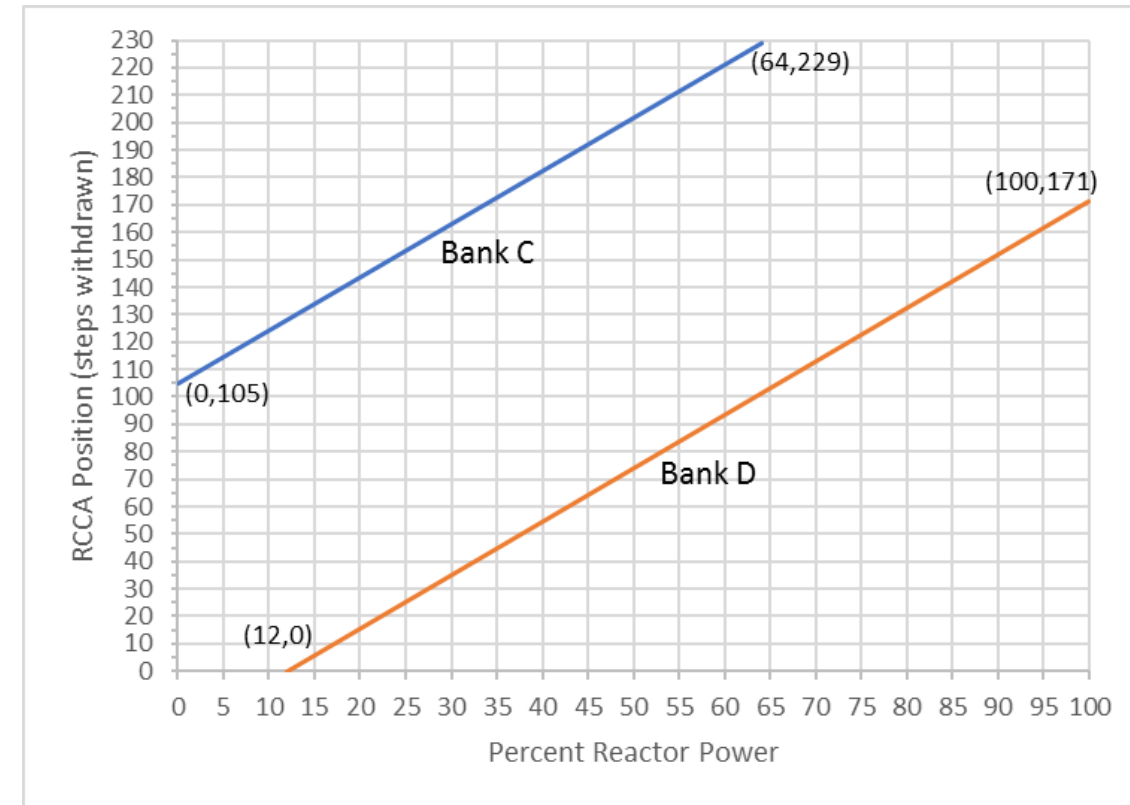
Exercise 8: Input modifications for EOC case

- Set up EOC, read-in xenon/samarium case as well (`exercise8_EOC_static`, `exercise8_EOC_static`)
- Execute inputs
- Execute `plot_exercise8.bat`
 - Runs a Python script that will generate plots of interest

Control rod layout

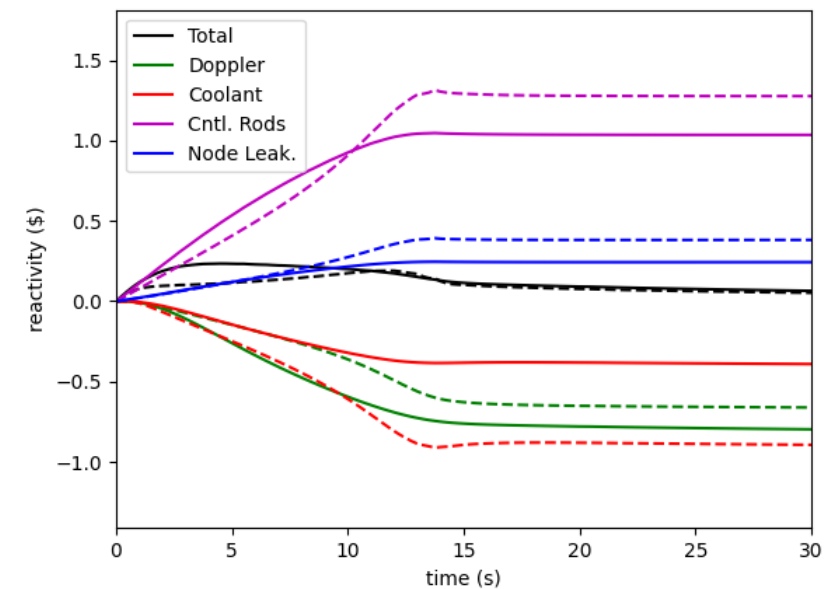
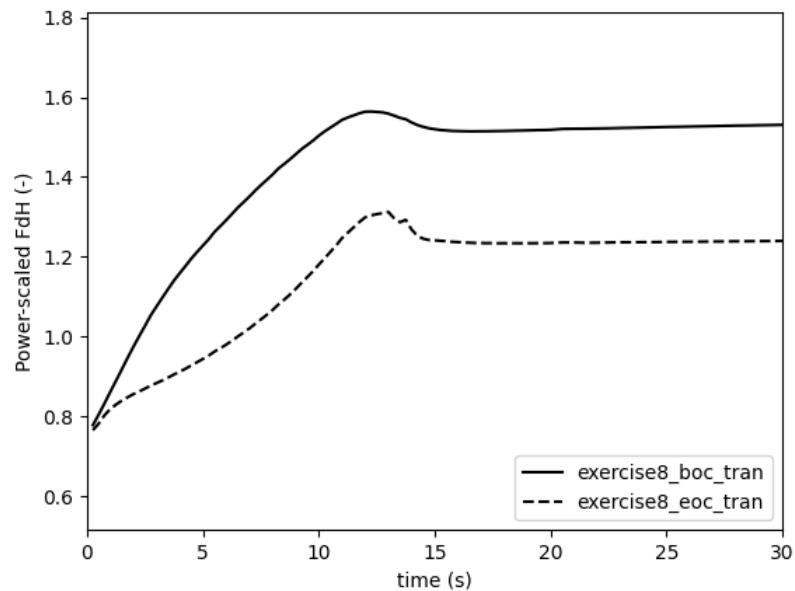
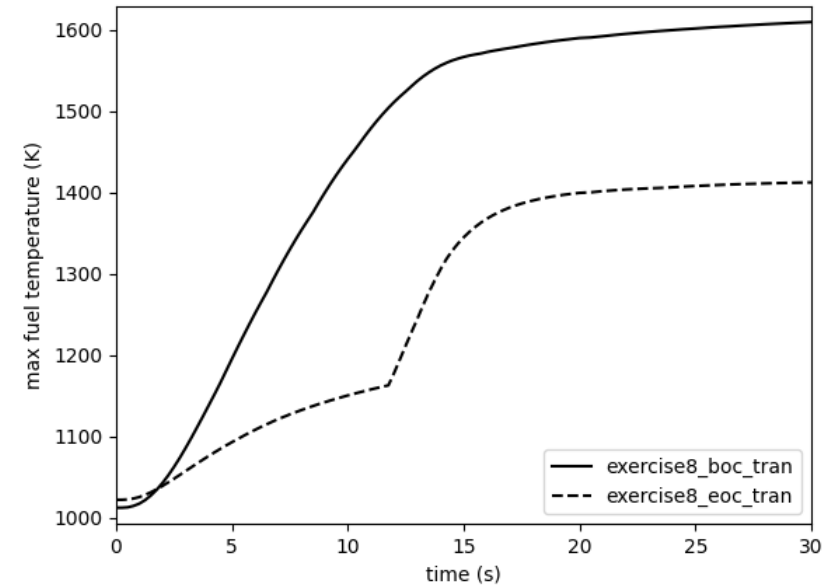
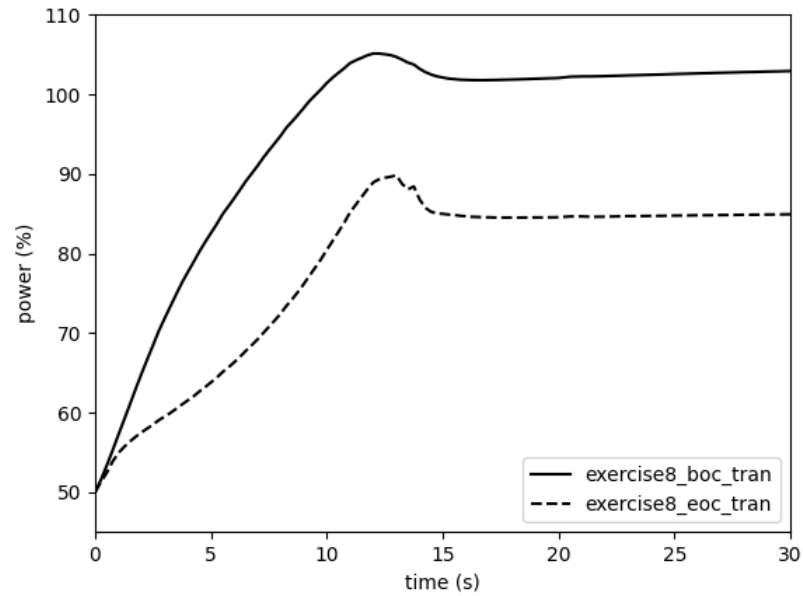


Control Rod Locations



Rod Insertion Limits (RILs)

Exercise 8: Results



Exercise 8 conclusions

- Clearly, system **boron concentration** and β have a strong influence over the details of the transient response
- In this case, for both BOC and EOC, the **inherent feedback** was strong enough to limit the power increase over the timescales of the rod withdrawal
 - At BOC – **less negative MTC**, and so Doppler provides most inherent feedback
 - At EOC – **more negative MTC**, so coolant reactivity provides most inherent feedback
- In both cases, system equilibrates at **new power level well below high-power setpoint**

Exercise 9: Spectrum of rod ejection accidents (PWR)



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Event description

- Failure of control rod drive mechanism (CRDM) housing could cause a control rod to pop out the top of a PWR
- Would cause rapid, localized reactivity insertion that could create severe challenges to core coolability
 - Considered a postulated accident
 - As title suggests, a spectrum of initial conditions must be considered
- Fuel acceptance criteria in Regulatory Guide (RG 1.236)
 - Prompt enthalpy rise
 - Fuel centerline melt
 - Function of pre-transient statepoint of fuel (particularly local cladding hydrogen concentration)

Plan of attack

- Based on our static analysis yesterday, we found large reactivity worths of Bank D rods from RILs at EOC
- We are going to compare simulations with those rods using the ARO vs. RIL depletion history files
- This will give us a sense of how much the difference in worth translates to peak power/peaking differences
- What we will not do is explicitly evaluate against RG 1.236 criteria
 - Requires the use of transient fuel performance tool

Exercise 9: Input modifications

- Copy `exercise9.parcs_inp` into `exercise9_aro_static.parcs_inp`
 - Split out stuck rod and ejected rod into their own banks
 - Run CBC search at EOC HZP RIL conditions using ARO history file
- Then copy that into `exercise9_aro_tran.parcs_inp`
 - Make transient modifications
 - Based on static analysis, activate PPR in assembly with and face-adjacent to ejected rod (H-1, J-2, H-2, G-2, H-3)
- Repeat both steps for RIL depletion case

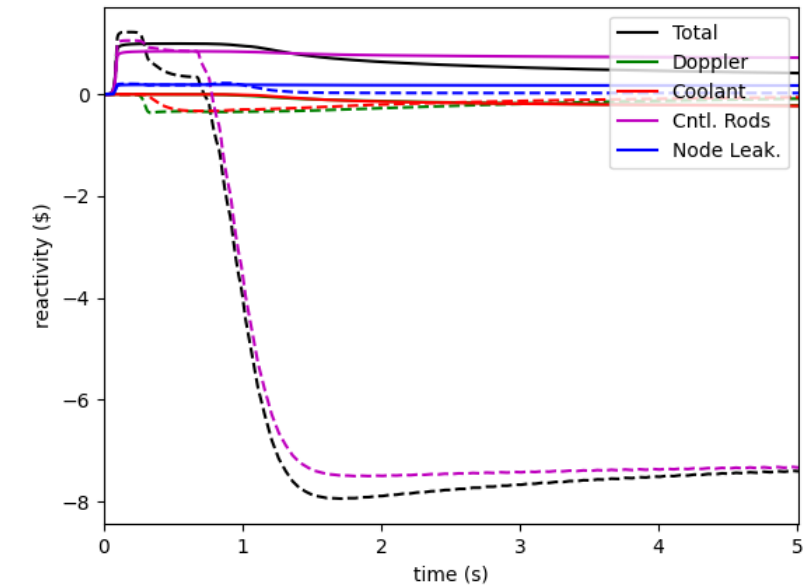
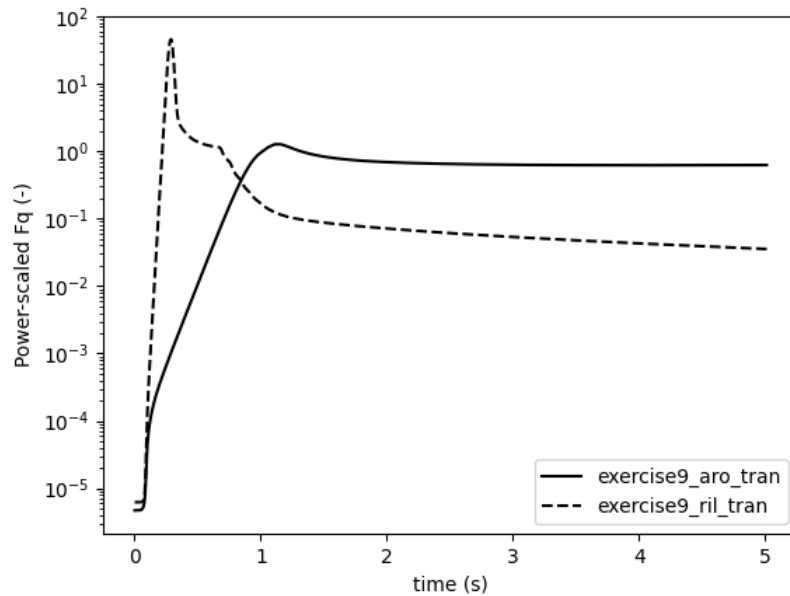
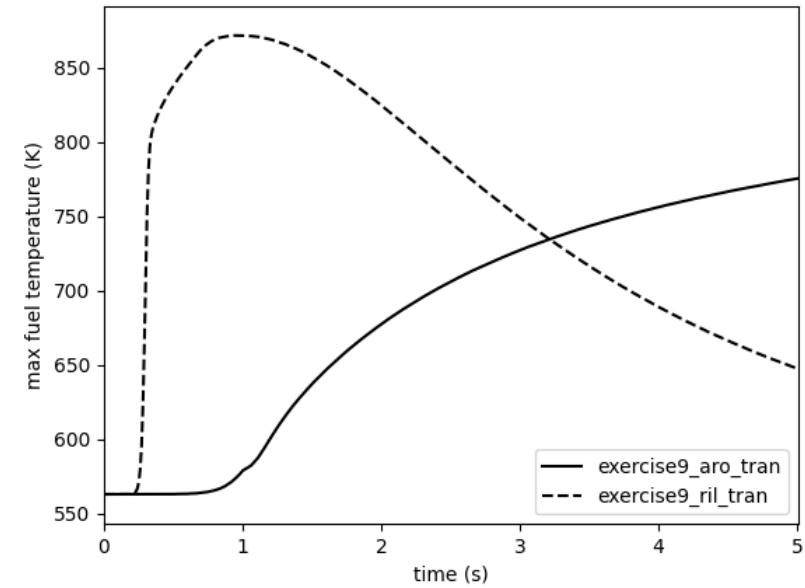
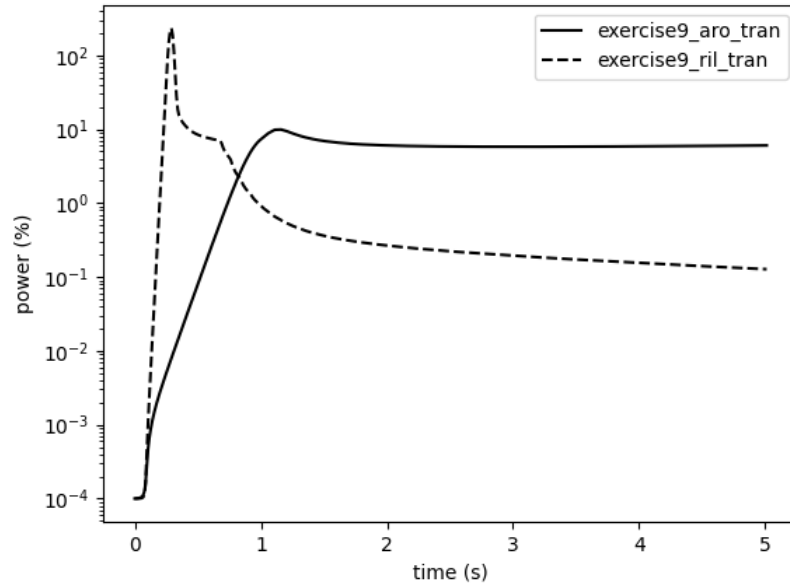
Exercise 9: TRAN block

- We are going to eject our Bank D rod within the first 0.1 s of the transient
 - Need very fine timesteps early to keep solution stable

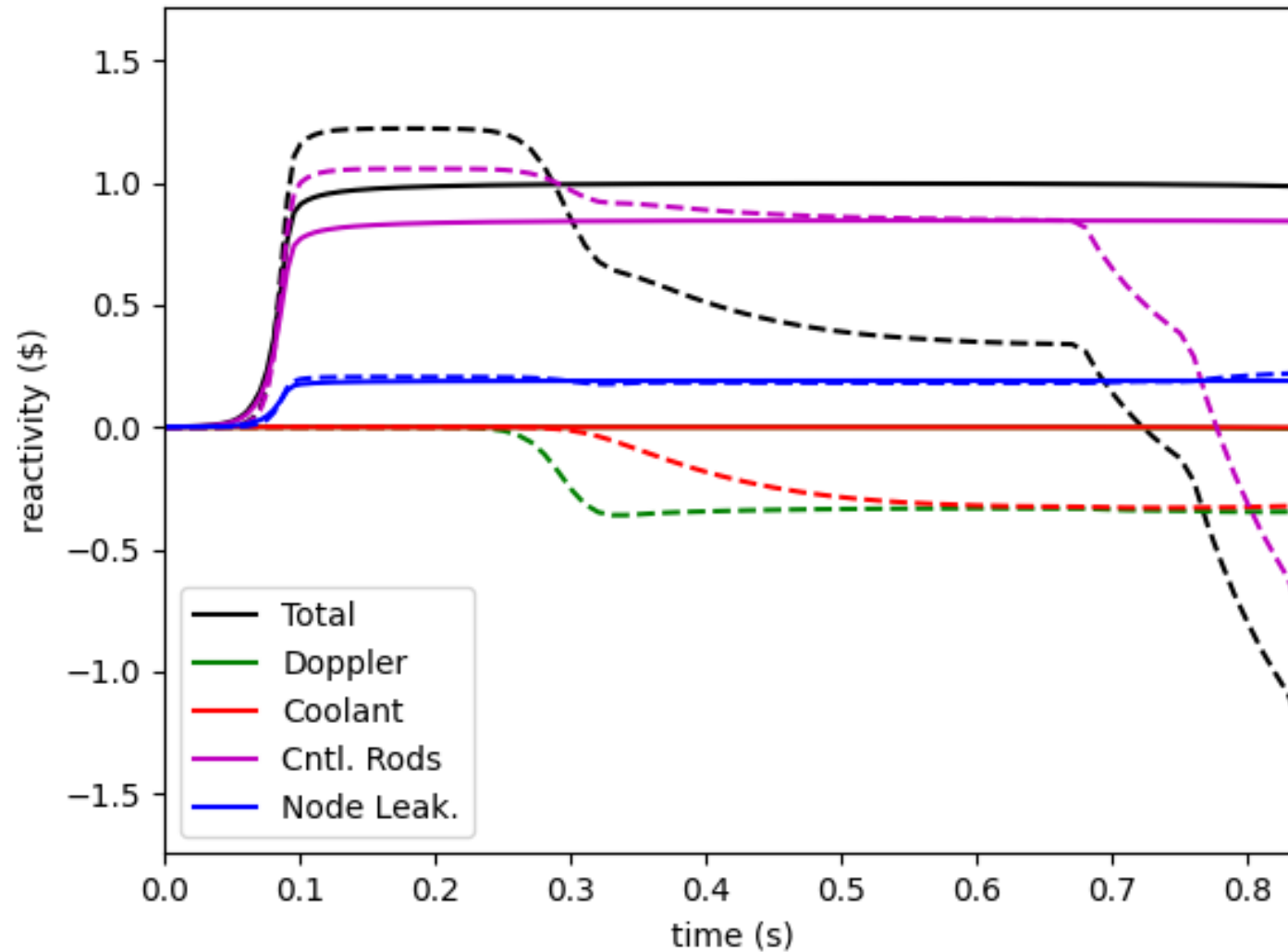
Time interval (s)	Time step size (s)
0.0 – 0.05	0.001
0.05 – 0.2	0.005
0.2 – 1.0	0.01
1.0 – 5.0	0.05

- We will also include some reactor trip information
 - Trip setpoint should be 114% power
 - Delay of 0.3 s between trip signal and start of rod insertion
 - Trip insertion time of 2.1 s
 - Don't forget to stick both stuck rod and ejected rod

Exercise 9: Results



Exercise 3: Zoom in on reactivity



Exercise 3 conclusions

- Additional 0.23\$ of static worth for ARO vs. rodged depletion changes transient from sub-prompt to prompt critical excursion
 - Also significantly narrows power pulse
 - Integrate the power transient to determine energy deposition
 - Peak local power > 14x HFP core average power
- Transient reactivity split allows us to see contributors to static worth
 - For rodged depletion case, static worth was ~1.25\$
 - Removal of absorption is ~1.06\$
 - Flux shape redistribution is ~0.21\$
- Prompt-critical REAs are primarily mitigated by inherent feedback – too fast for reactor protection system

Transients conclusions

- Transients are a key piece of reactor safety determinations
- PARCS is designed to handle full spectrum of design basis reactivity-driven transients
 - For longer-running (>10 s) or more severe transients, should be used in concert with more detailed thermal-hydraulics and fuel performance tools
- We covered three examples in this session
 - Bank withdrawal
 - Boron dilution/boration
 - Rod ejection
- If you want to run PARCS to help in your work, **please reach out**

Thank you for your attention!

