Overview of the Kilopower System Development and Testing at the Nevada National Security Site

Max Chaiken
Kilopower Project
NASA GRC

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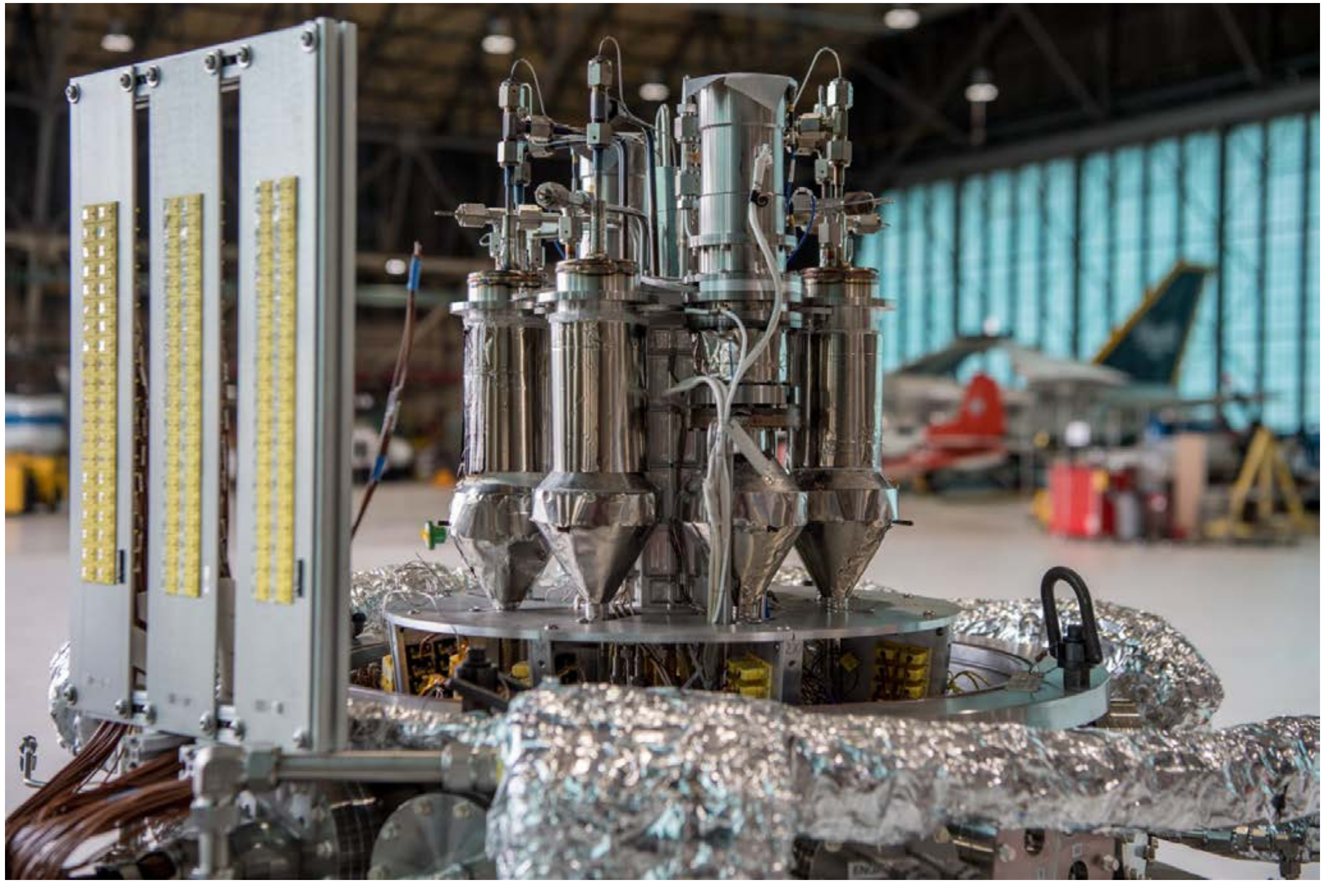
Introduction



- Kilopower
  - Space fission power source
  - Fast spectrum nuclear reactor
  - Surface or space power
- KRUSTY
  - Ground nuclear hardware test
  - 3 1/2 year development
  - Concluded with successful nuclear test in March 2018
- Future
  - Finish hardware development
  - Define system and programmatic requirements
  - Get into space!

Outline

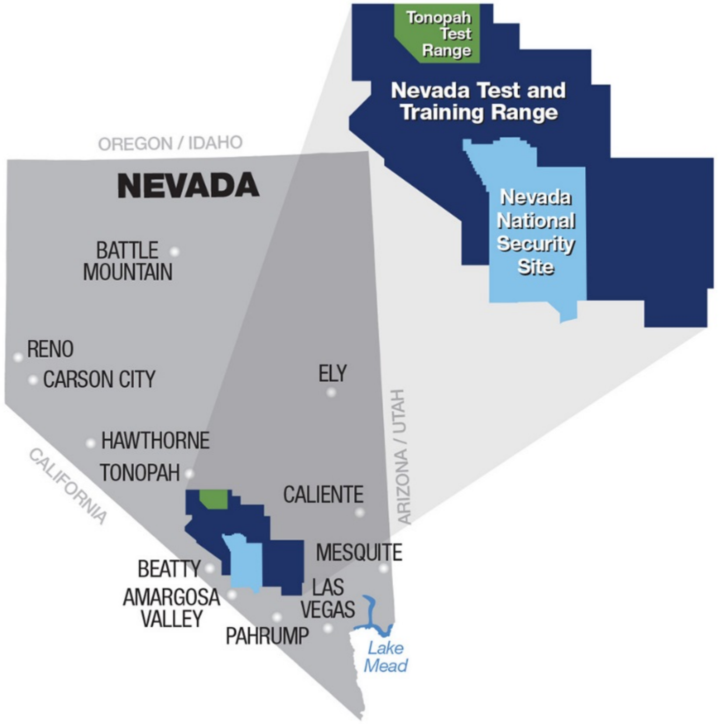
- Kilopower Description
- KRUSTY Description
- Nuclear Reactor Dynamics
- Test results discussion
- Next steps

Kilopower System Overview

- **Fast spectrum nuclear reactor**
  - Uranium/Molybdenum high temperature metal core
  - Beryllium Oxide (BeO) radial and axial neutron reflectors
  - Boron Carbide (B_4C) control rod
- **Heat pipe thermal transfer**
  - Haynes 230 alloy pipes
  - Sodium working fluid
  - ~800 ºC temperature
- **Radiation shield**
  - Lithium Hydride (LiH) neutron shielding
  - Tungsten or Depleted Uranium gamma shielding
- **Stirling engine thermal power conversion**
  - Radioisotope Power Systems heritage
  - High efficiency 30-40%
- **Heat rejection radiators**
  - Titanium-water heat pipes
  - ~100 ºC temperature

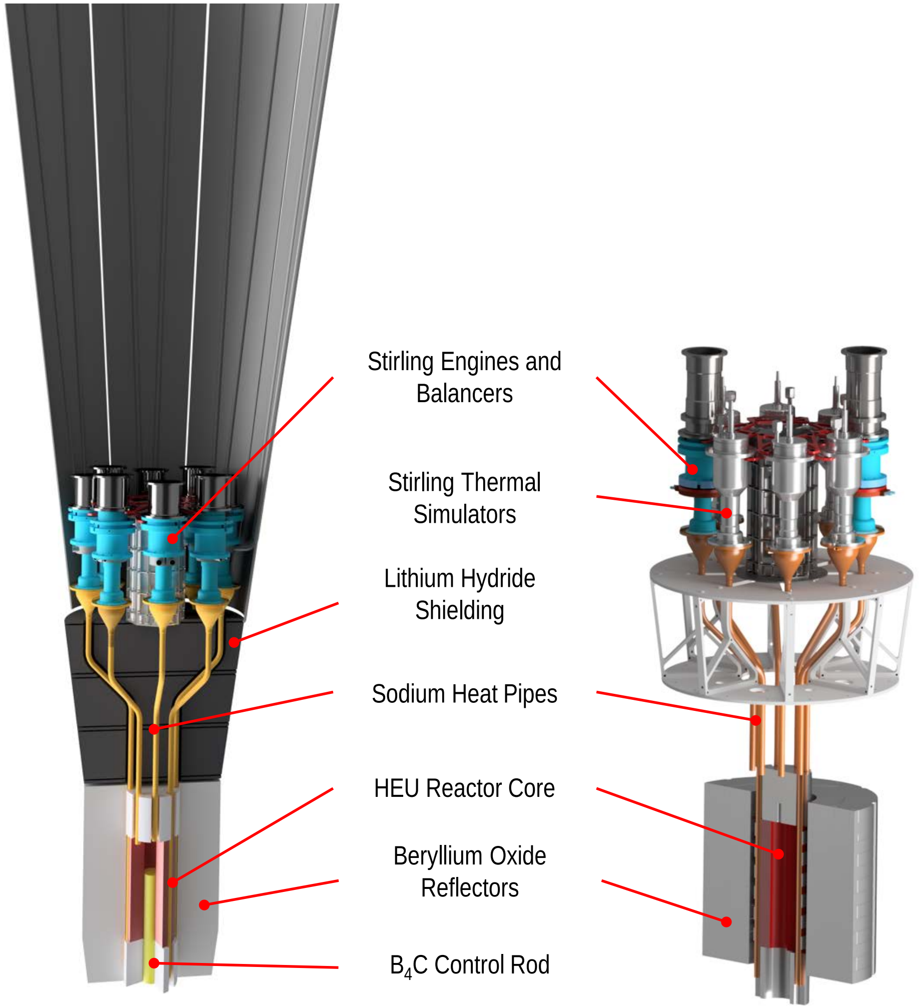
Kilopower Reactor Using Stirling TechnologY

- Collaboration between NASA and DoE
  - GRC, MSFC
  - LANL, Y12, NNSS
- Test performed at the Nevada National Security Site
  - In the Device Assembly Facility (DAF)
  - Using existing criticality control hardware (COMET test stand)
- Maintained budget and schedule
  - 3 1/2 year development
  - $20M price tag split in a cost share with DoE
- First space nuclear hardware test in >50 years
  - SNAP-10A: Flown 1965
  - SP-100: Designed 1983-1995, no nuclear testing
  - Prometheus: Designed 2003-2005, no nuclear testing
- First new fission reactor design fully tested in 40 Years



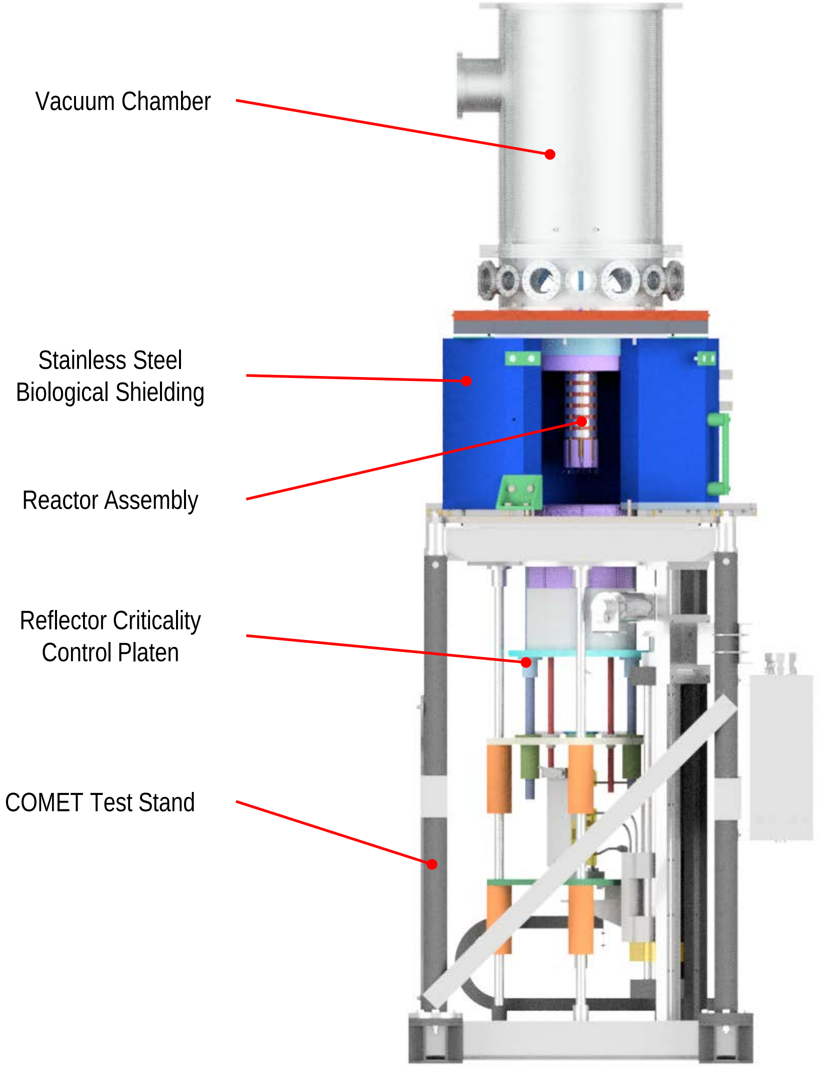
KRUSTY System Components

- The KRUSTY test was designed to represent as many significant flight subsystems as possible
- Flight prototypic
  - *Core*
  - Reflector
  - Heat pipe material and fluid
  - Stirling engine heat conversion
- Missing
  - Startup using Boron Carbide control rod
  - Radiation shielding
  - Microgravity heat pipe operation
  - Only 2 engines, 6 simulators
  - Engines do not have optimized power level or thermal interfaces
  - Heat rejection radiators

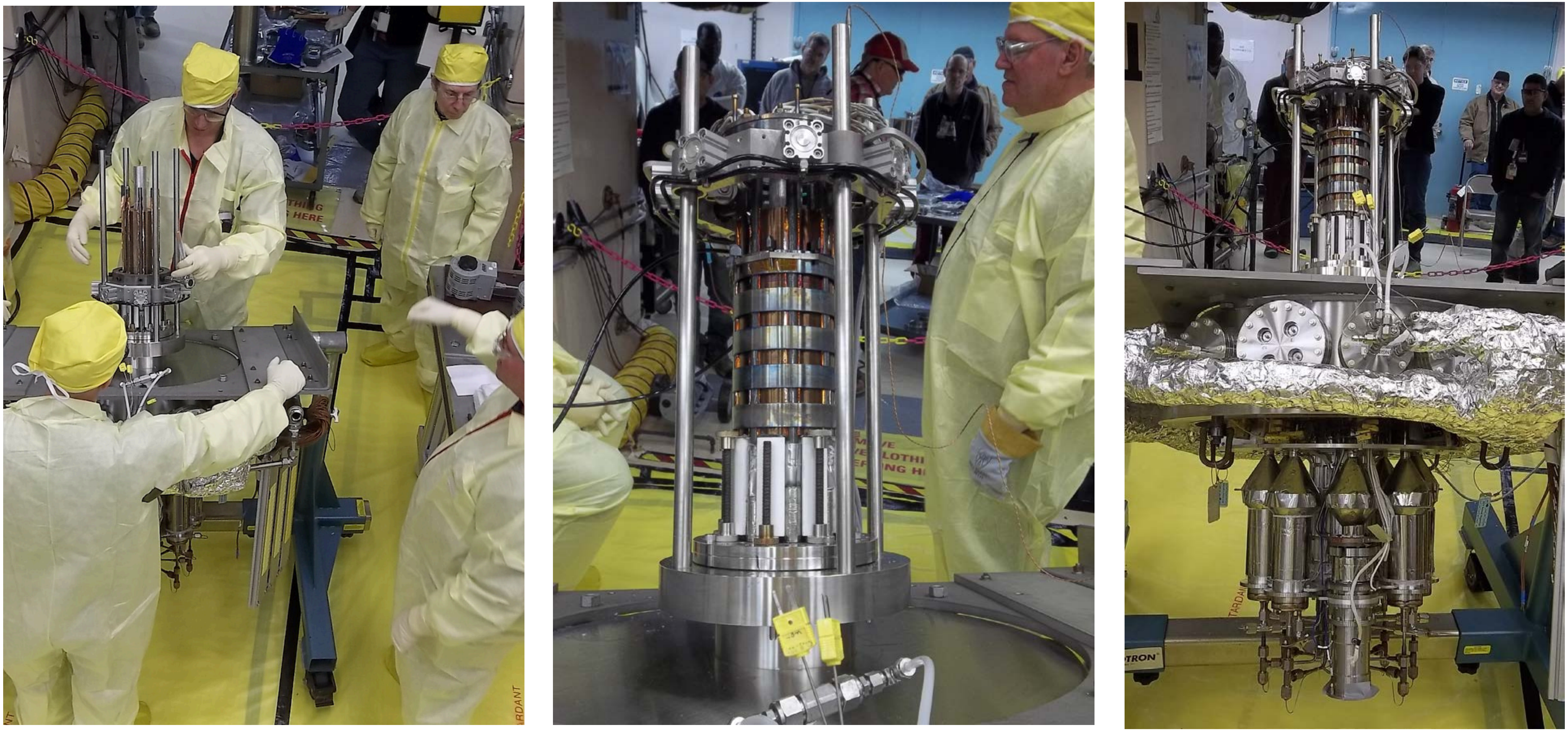


KRUSTY Test Components and Instrumentation

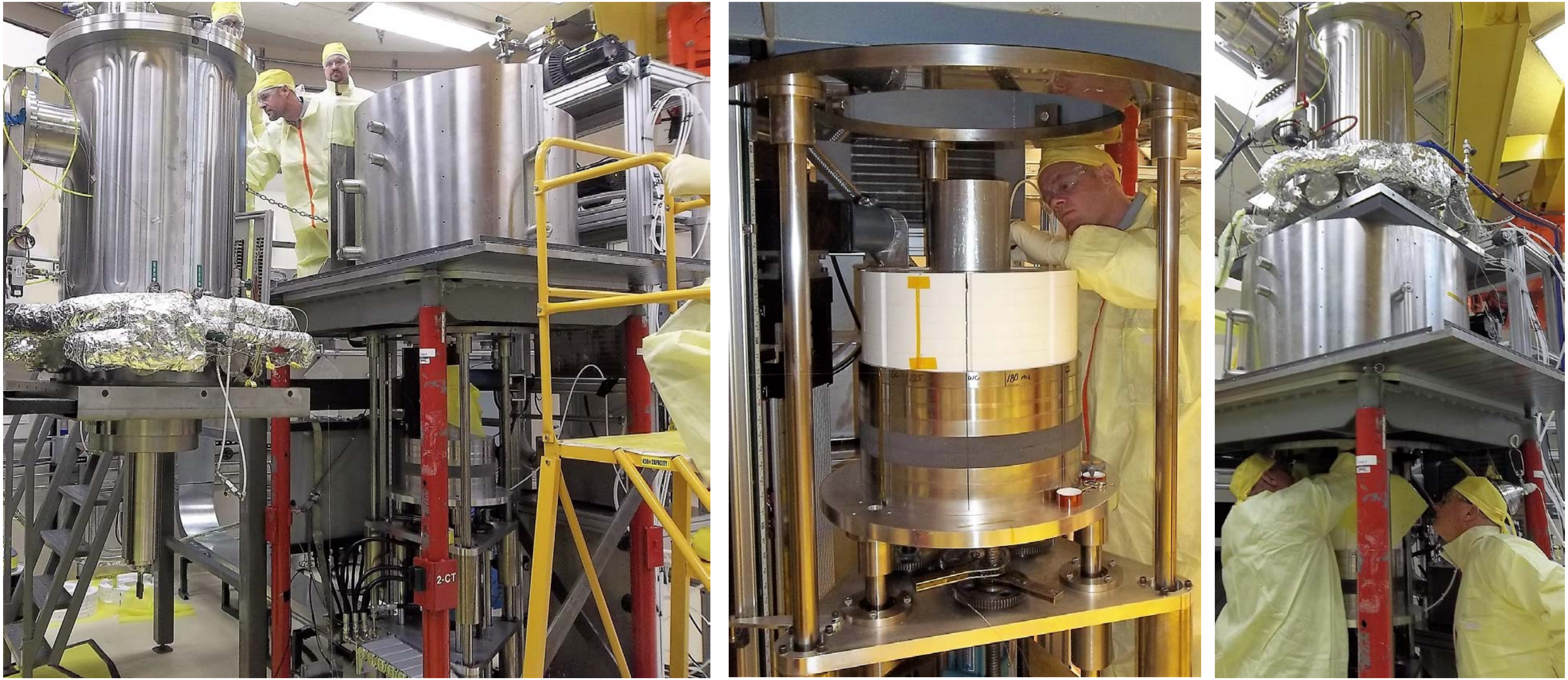
- Thermocouples
  - Core, Heat Pipe, Engine, Gas temperatures
  - Over 140 in total
- Engine Parameters
  - Voltage
  - Current
  - Power
  - Piston Amplitude
- Vacuum Chamber Pressure
- Gas Flow
- Neutron Counters
- COMET Platen Position



Reactor Assembly



Experiment Assembly

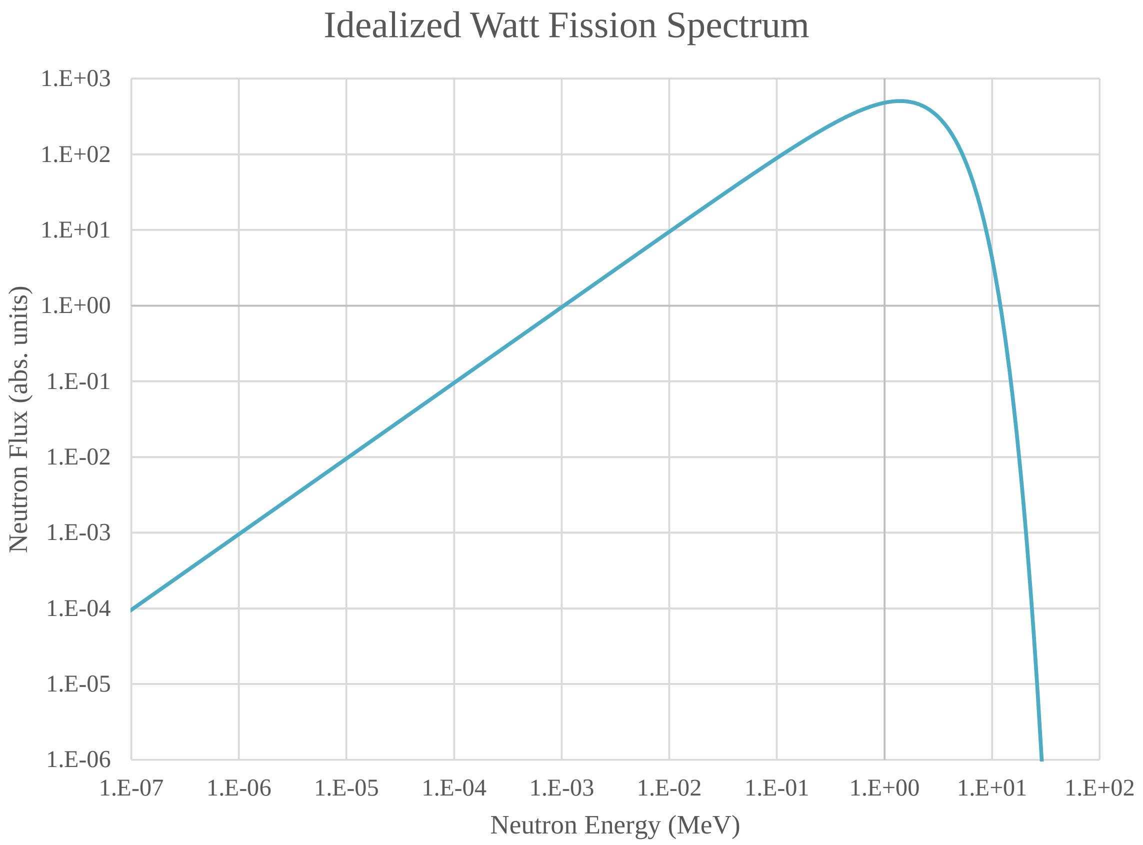


Control Room

The Nuclear Physics of Kilopower and KRUSTY

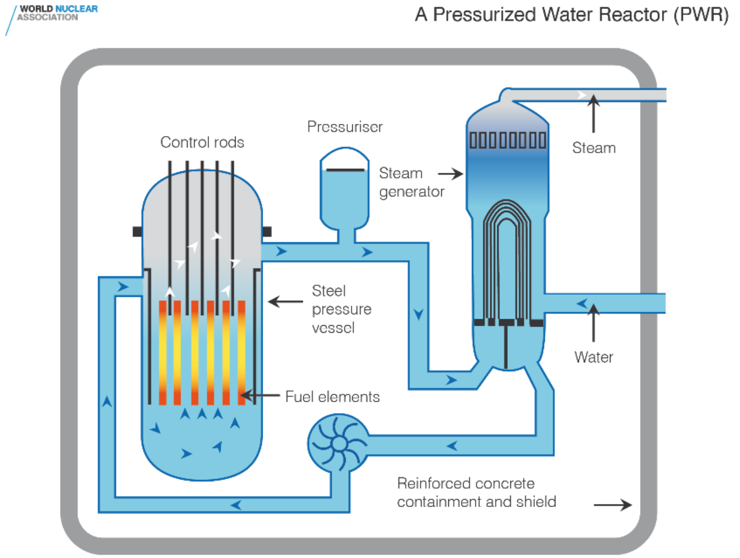
Fast vs. Thermal reactors

- Reactors grouped into two broad types based on the neutron energy spectrum during operation
- Fission neutrons born at energies following the Watt spectrum
- Fast reactors operate closer to the Watt spectrum
- Thermal reactors operate with "thermalized" or slow neutrons, achieved through moderation (i.e. scattering from high to low energies)

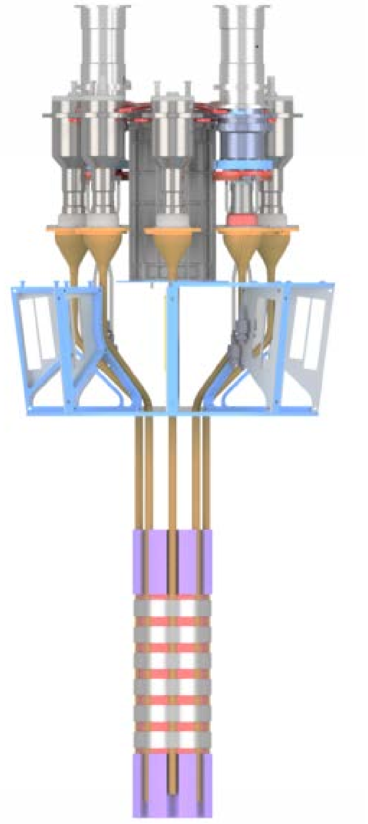


Fast vs. Thermal reactors

- Thermal reactors
  - Needs a moderator to thermalize neutrons (e.g. water, graphite, beryllium)
  - Moderator introduces potential positive reactivity feedbacks
- Fast reactors
  - No moderator
  - Can be smaller and simpler (in theory)
  - Needs higher enrichments due to smaller fission cross-sections
  - Allows for high degree of passive control and load following

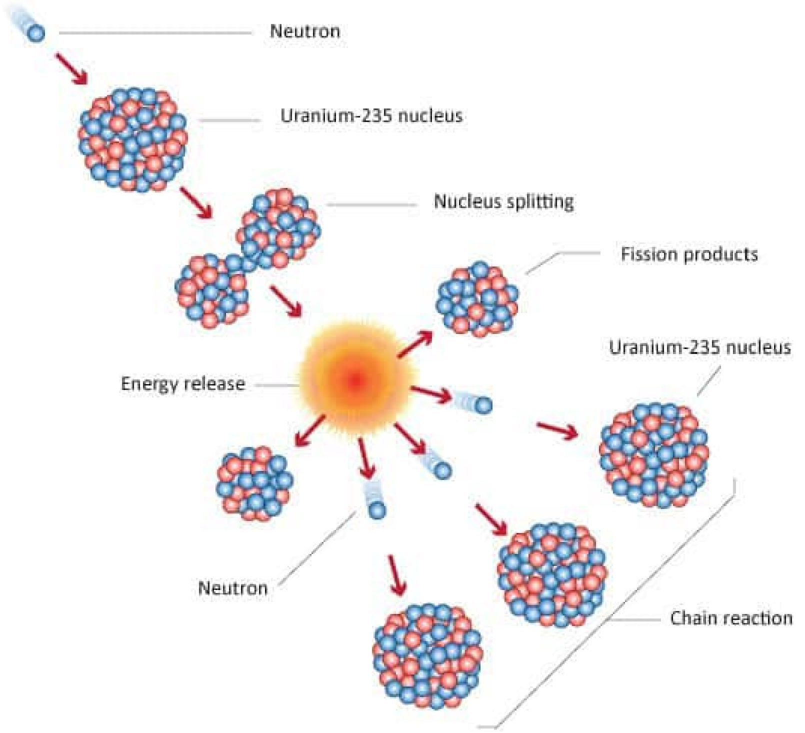


http://www.world-nuclear.org/gallery/reactor-diagrams/pressurized-water-reactor.aspx



Nuclear chain reaction

- Effective neutron multiplication factor, k_{eff}, determines operation of a nuclear chain reaction
  - Ratio of number next generation neutrons over current generation
  - $k_{eff} < 1$ – Subcritical, diminishing chain reaction, decreasing power
  - $k_{eff} = 1$ – Critical, sustaining chain reaction, maintaining power
  - $k_{eff} > 1$ – Supercritical, expanding chain reaction, increasing power
- k_{eff} is effected by what happens to neutrons in the reactor environment
- Calculated with probabilities, but governed by the law of large numbers



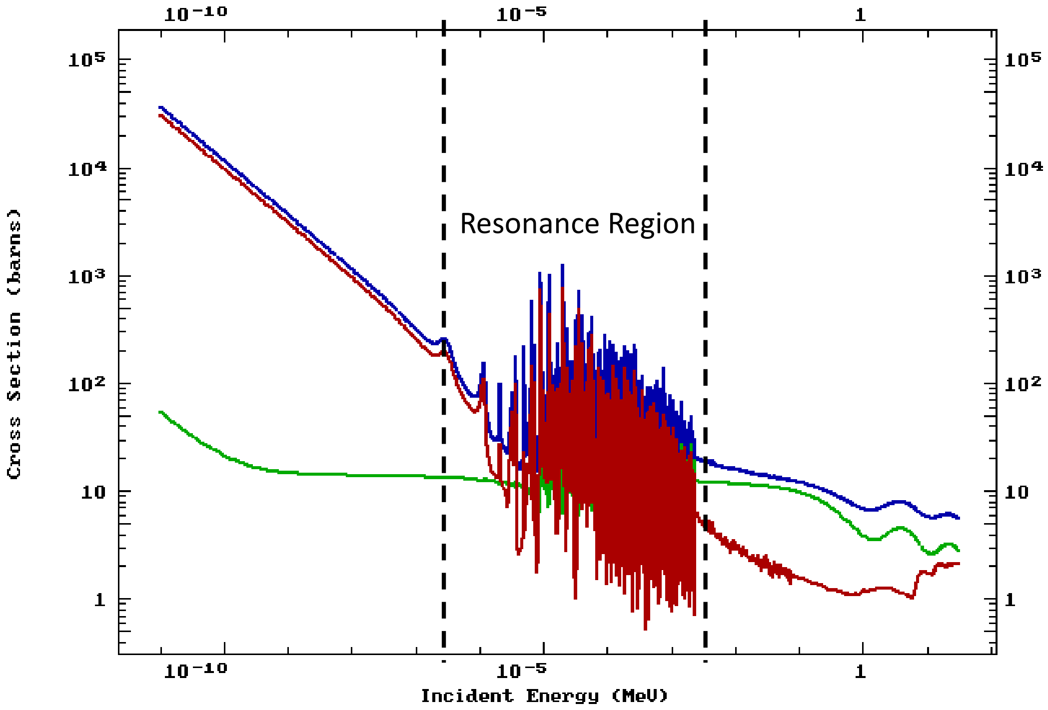
https://www.nuclear-power.net/nuclear-power/reactor-physics/nuclear-fission-chain-reaction/

Neutron inventory

- Neutrons are born through fission reactions
  - $U^{235} + neutron \rightarrow fission\ fragments + 2.4\ neutrons\ (average) + 192.9\ MeV$
  - $Pu^{239} + neutron \rightarrow fission\ fragments + 2.9\ neutrons\ (average) + 198.5\ MeV$
- Three main events can happen to a neutron once it is born
  - Absorbed by fuel leading to fission
  - Absorbed by material leading to transmutation
  - Scattered outside reactor
- Fate of neutrons determined by interaction cross-sections with materials in the reactor

Nuclear interaction cross-sections

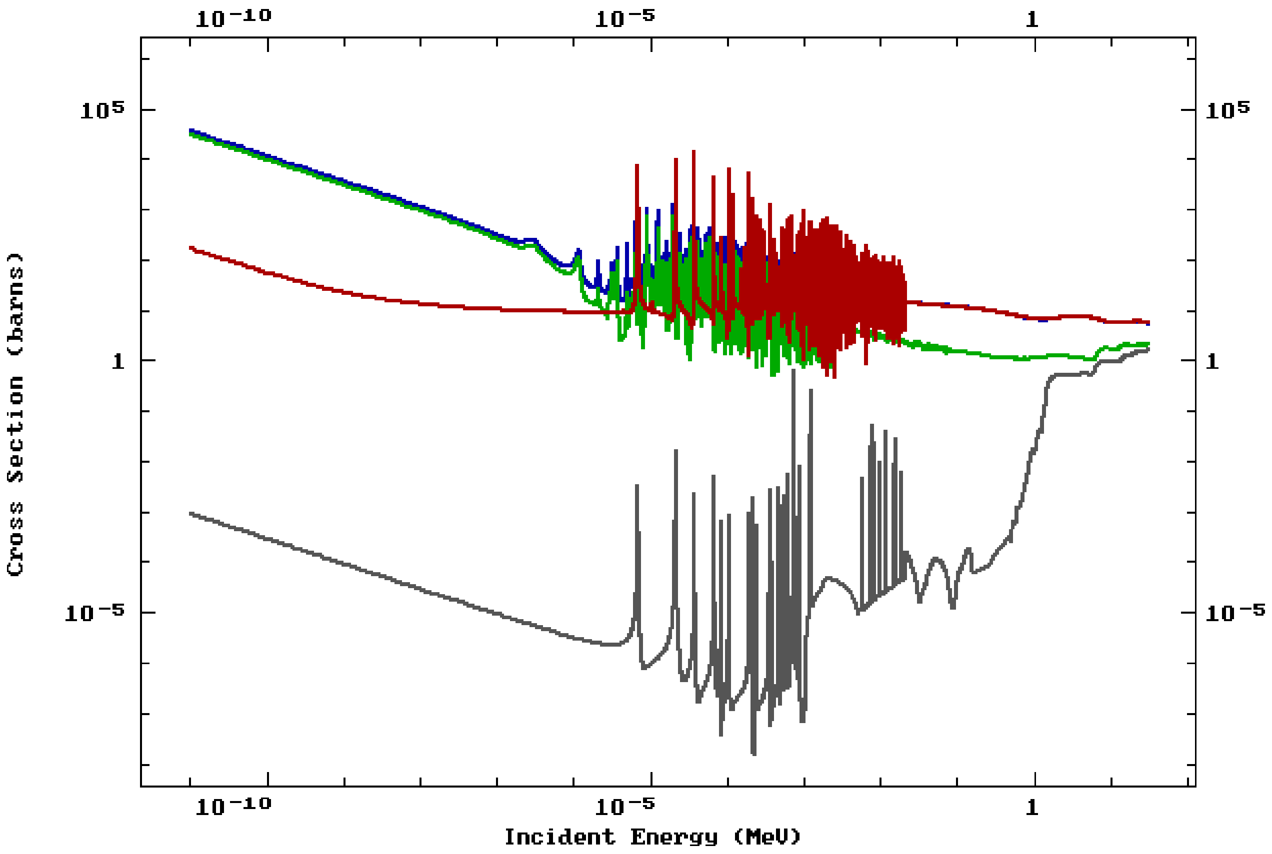
- Determine the likelihood of a nuclear interaction
- Microscopic cross-section, σ
  - Isotope specific
  - Vary based on relative neutron energy
  - Resonance regions
  - Units of area (1 barn = $1\text{x}10^{-24}$ cm^2)
- Macroscopic cross-section, Σ
  - Product of σ and atomic density ($\#/\text{cm}^3$)
  - Determine physical response of actual system
  - Units of inverse length (cm^{-1})
- Total cross-section comprised of a summation of various categories
  - Capture, σ_c
    - Absorption, σ_a
    - Fission, σ_f
  - Scatter, σ_s



ENDF U-235 Microscope cross-sections

Total, Elastic Scattering, Fission

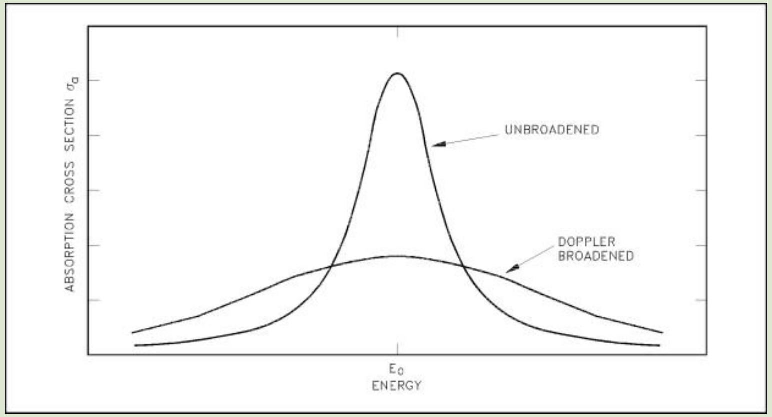
Comparison: U-235 to U-238



ENDF U-235 Microscope cross-sections
Total, Fission

ENDF U-238 Microscope cross-sections
Total, Fission

Cross-section temperature feedback

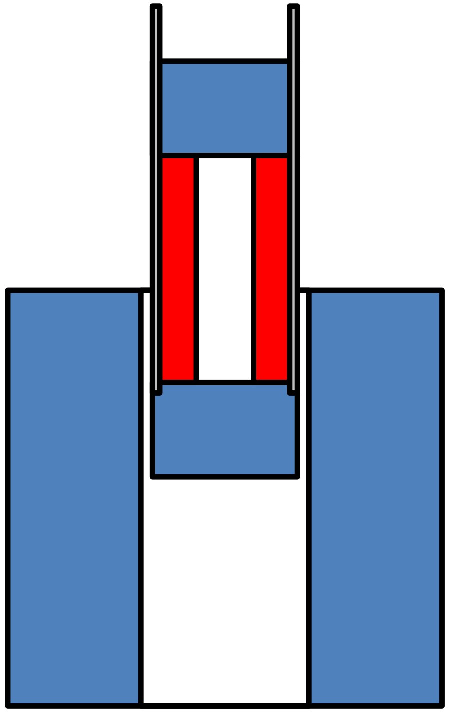
Microscopic Feedback	Macroscopic Feedback
<u>Doppler broadening</u> Increase in temperature widens the range of relative energies for each resonance peak Overall effect is to increase resonance likelihood  https://www.nuclear-power.net/glossary/doppler-broadening/	<u>Thermal Expansion</u> Expansion reduces mass density, and therefore atomic density Macroscopic cross-section is reduced Most noticeable in fuel, but affects other reactor components as well (e.g. BeO reflector) Can be positive or negative

Reactor Control

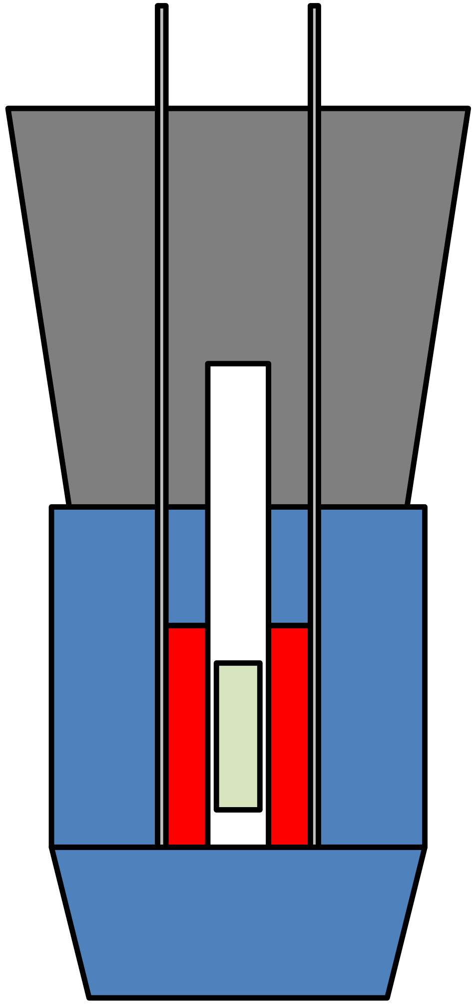
- Active control
    - Control rods
    - Startup, shutdown
    - Small adjustments over lifetime operation
- Passive control
    - Thermal feedback
    - Can be positive or negative
    - Integral to load following behavior
- Prompt vs. Delayed neutrons
    - Prompt neutrons are born during fission interaction, with a timeframe of ~10^{-14} seconds
    - Delayed neutrons are born during the radioactive decay of fission products, with a timeframe of ms to seconds
    - This difference in neutron production timeframes has extremely significant effects on nuclear reaction control
- Reactor control hinges on *delayed neutron fraction,* β
    - β is highly dependent on what fissile isotopes are present
    - Typical value of β for U-235 is around 0.0064 or 0.64% of the neutron inventory

Kilopower vs KRUSTY active controls

Reflector: Scatters leaked neutrons back into core



KRUSTY Test Active Reactivity Control
Reflector raised on NNSS criticality-rated platen



Control rod: absorbs neutrons until it is removed

Kilopower Flight Active Reactivity Control
Control rod removed by motor drive

Reactivity

- Relative change in k_{eff} from a critical state, defined as $\rho = \frac{k_{eff}-1}{k_{eff}}$
- Reactivity is a result of
  - Materials
  - Geometry
  - Feedback
- $\rho = 0$ for a critical reactor
- Widely used units are “dollars” and “cents”
  - $\frac{\rho}{\beta} = \$$
  - $\rho = \beta = $ \$1 of reactivity
  - Intuitive response of reactor power to reactivity insertions
- At \$1 of positive reactivity prompt neutrons alone are sufficient to increase the neutron population, leading to power increases on extremely quick time scales (~10 μs, or the mean neutron lifetime)

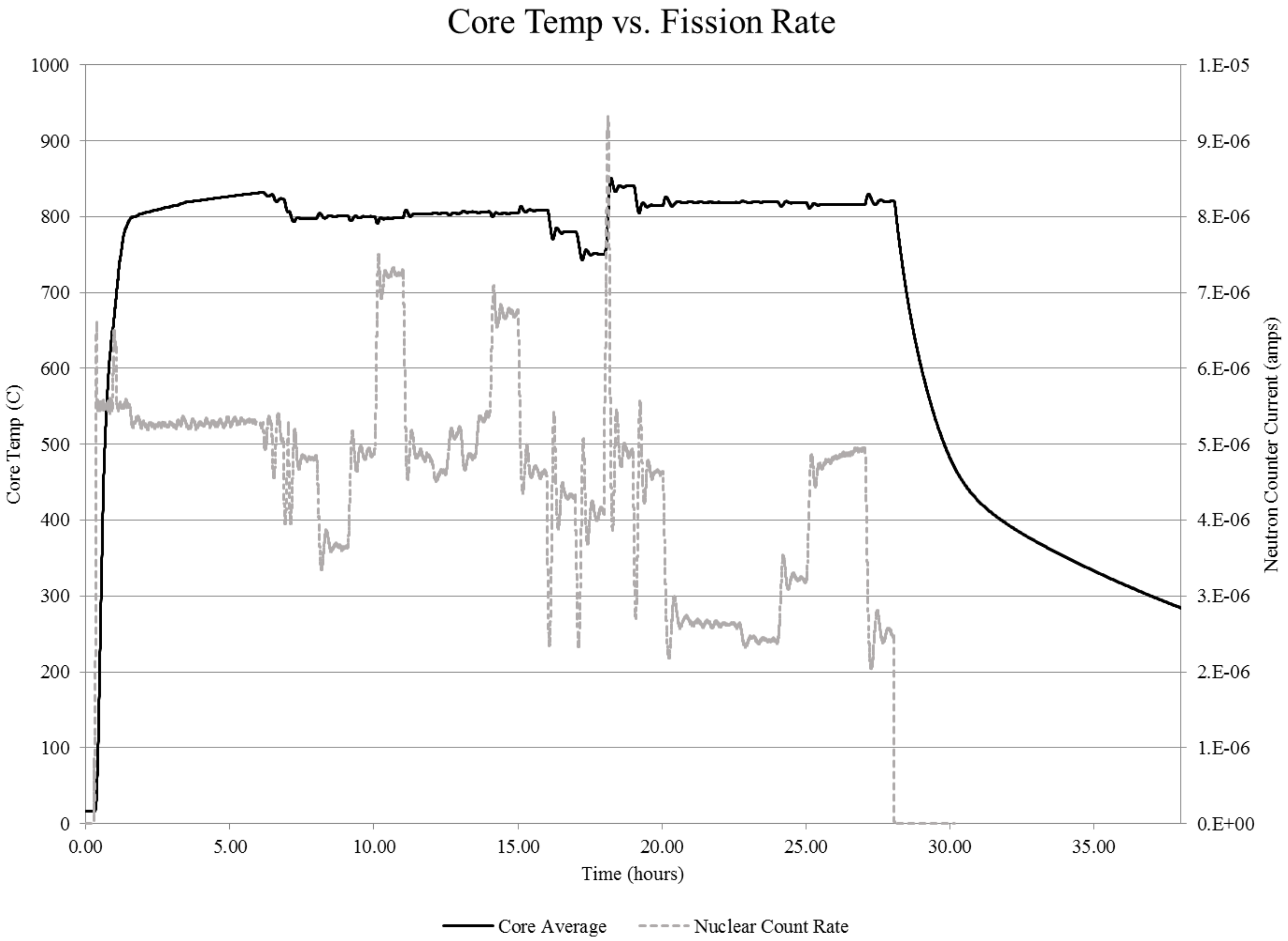
Nuclear Reactor Dynamics Summary

- Power dynamics set by neutron multiplication
- Neutron multiplication set by nuclear interactions, which depend on:
  - Material cross-sections (reactor design)
  - Geometry (active control)
  - Temperature (passive feedback)
- Change in neutron multiplication is represented as reactivity
  - <\$0: subcritical, decreasing power
  - \$0: critical, steady state power
  - \$0 - \$1: delayed supercritical, controlled increase in power
  - >\$1: prompt supercritical, generally means a bad day for someone
- Reactivity added or subtracted either actively (control rod) or passively (feedback)
- Power not proportional to temperature, only to fission rate

Overview of KRUSTY Test Results

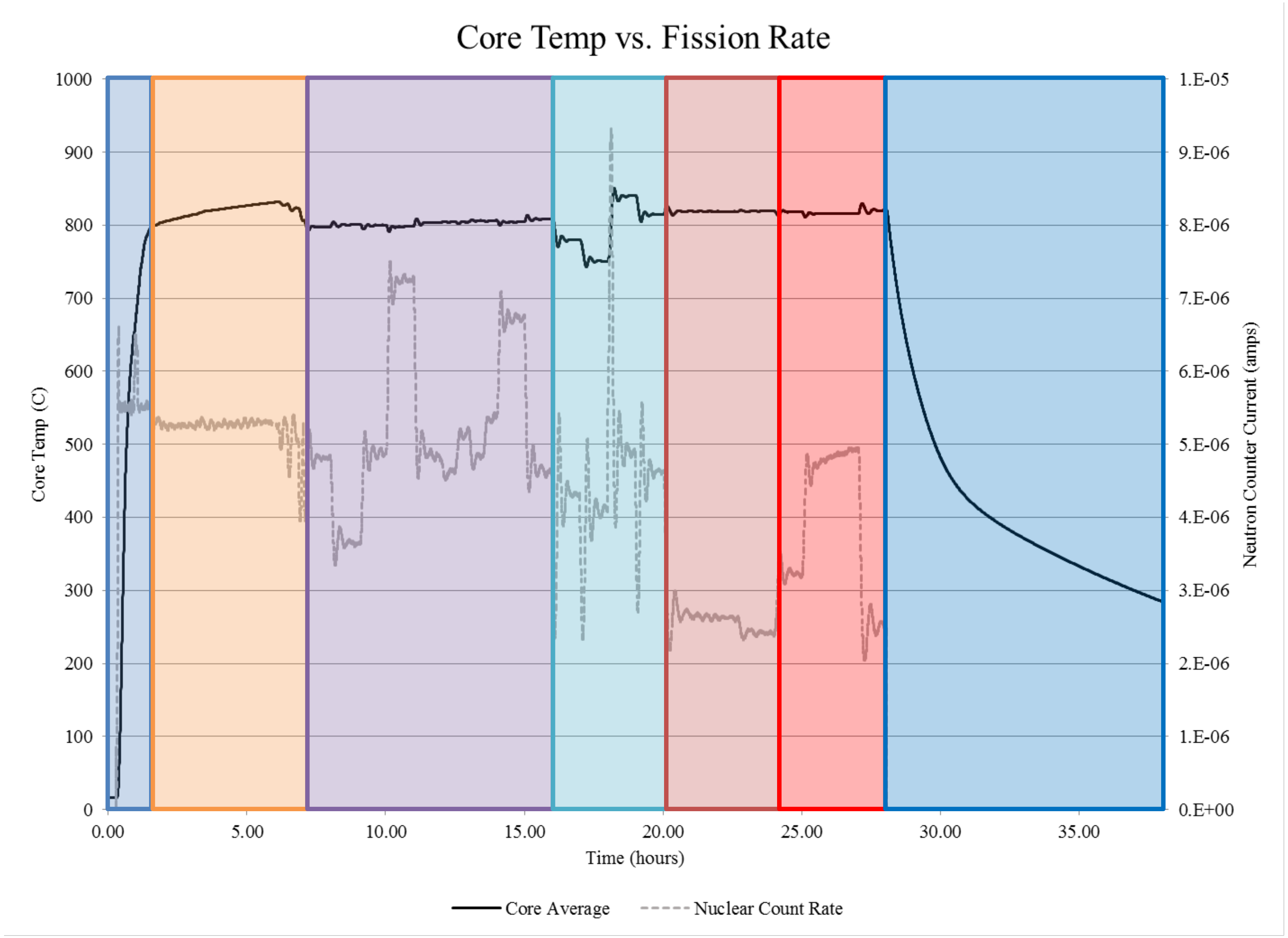
Full Test

- Operated for ~28 hours
- Nominal steady state
- Off-nominal responses
- Fission rate measured by neutron counters positioned around the experiment
- Fission rate does not provide a 1-to-1 correlation with nuclear power produced



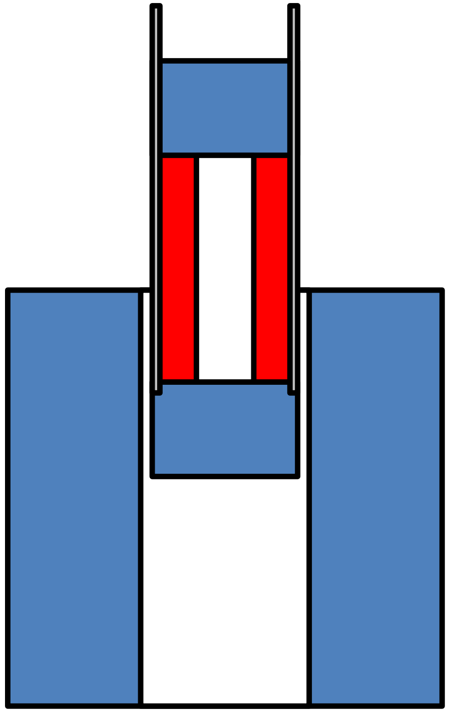
Full Test

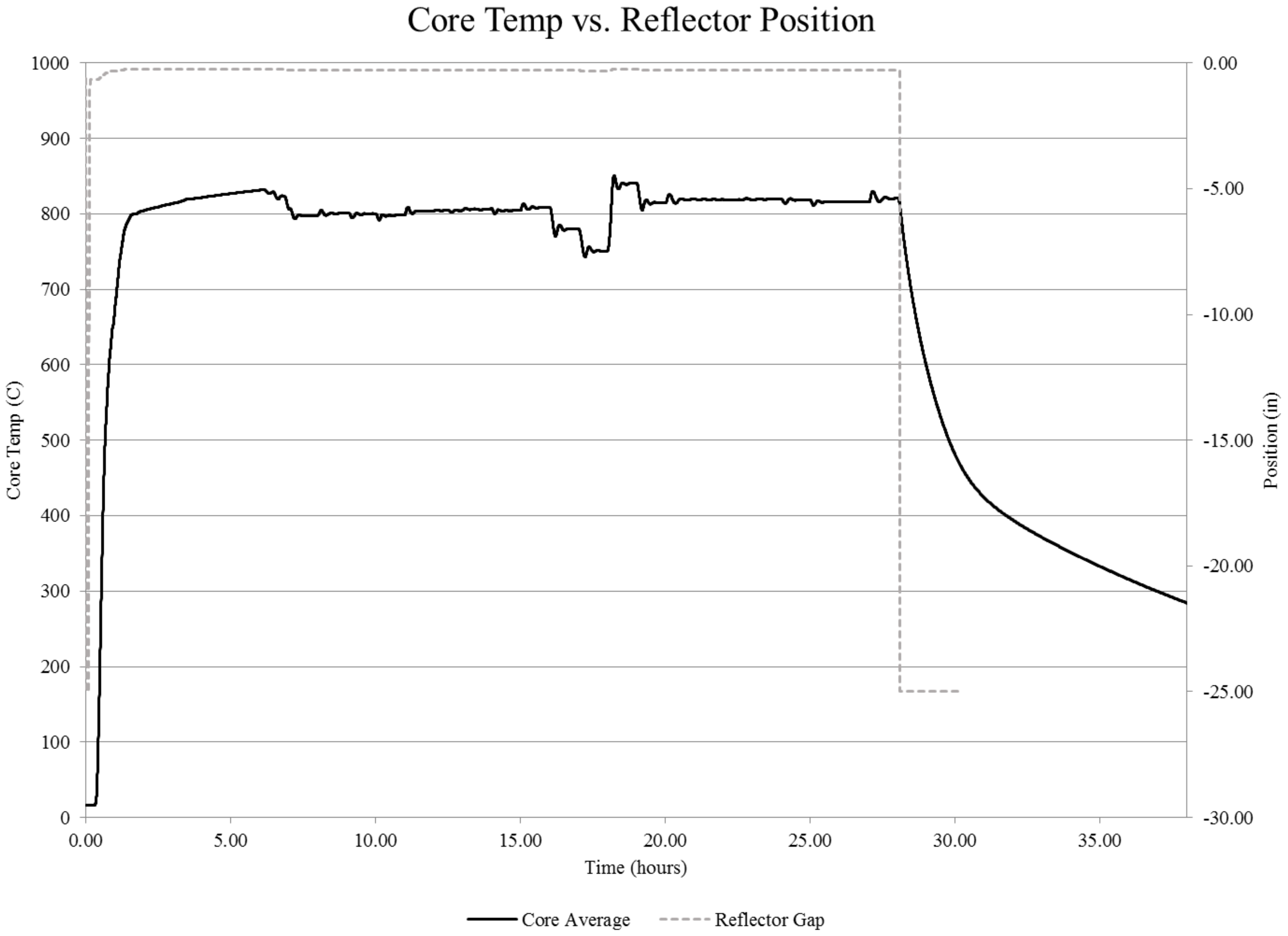
- Startup
- Break-in
- Power Transients
- Nuclear Transients
- Loss of Coolant Test
- Engine Restart
- SCRAM and Cooldown



Active Control

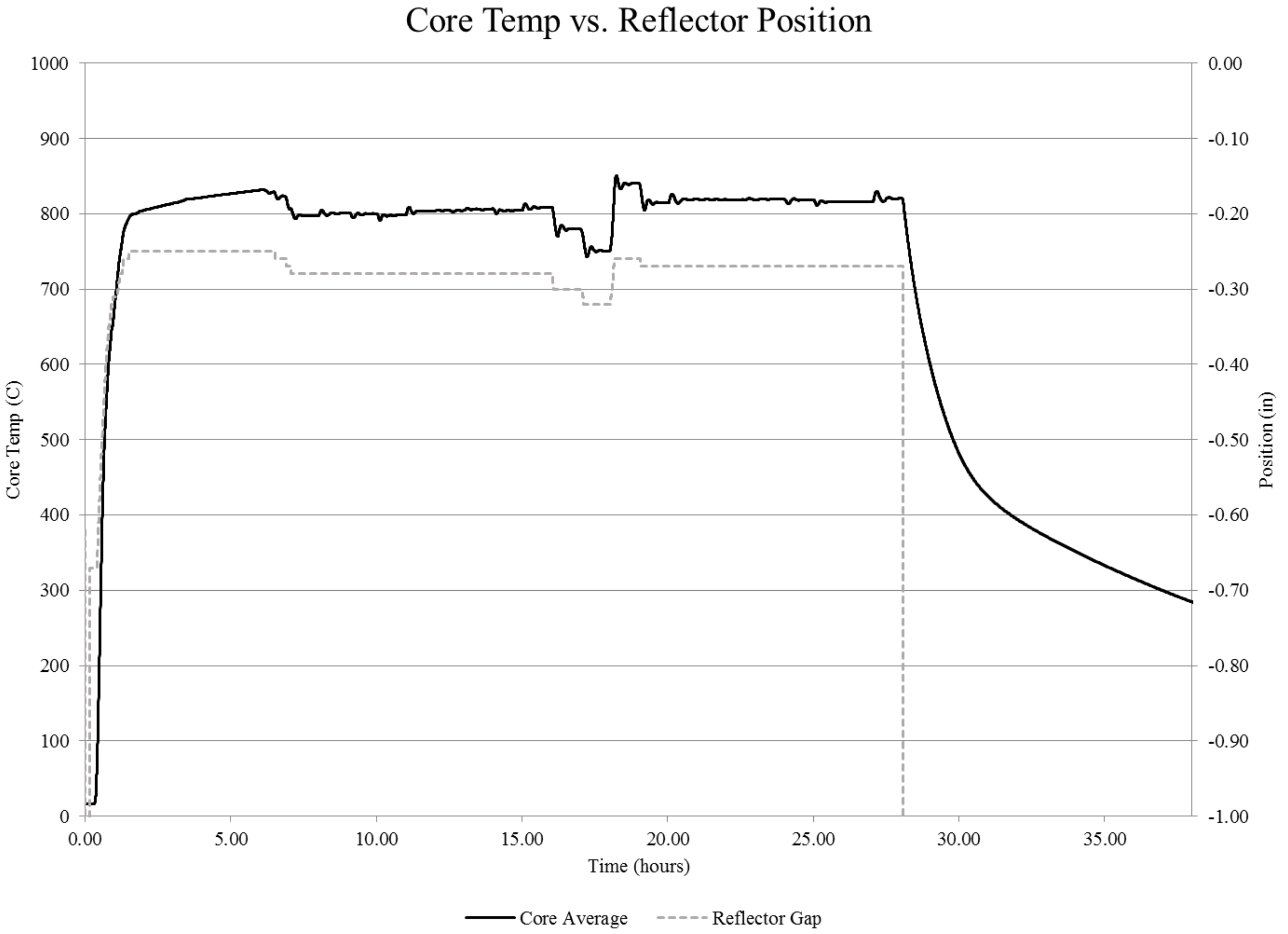
- Reactivity inserted by raising the reflector platen
- Hard to see any change on this scale





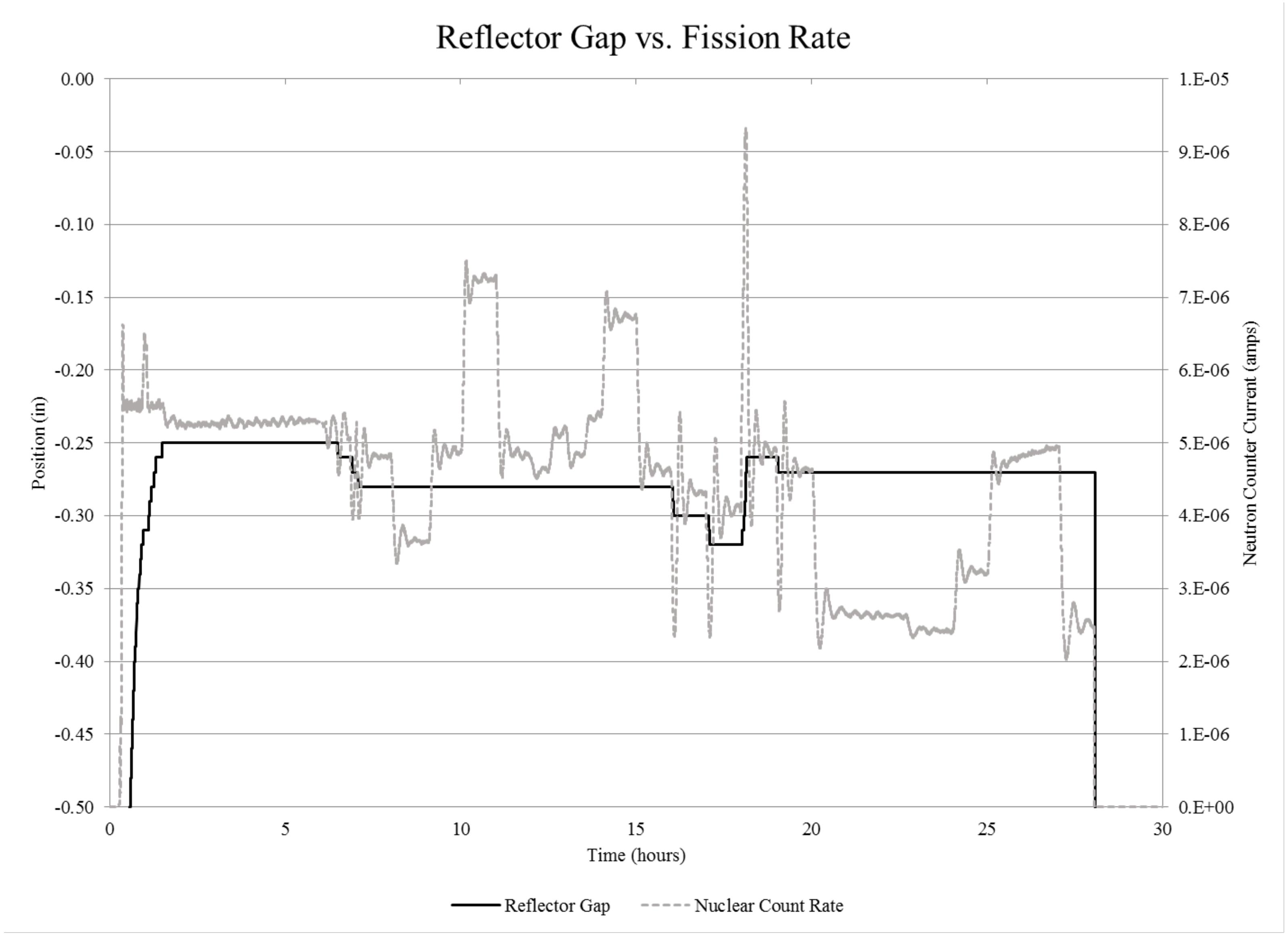
Active Control

- Control on a scale of mils
- Small changes in geometry can lead to large changes in reactivity
- Large reactivity worth of the KRUSTY reflector control scheme responsible for these small control movements
- B_4C rod in flight system will control over larger movement scales



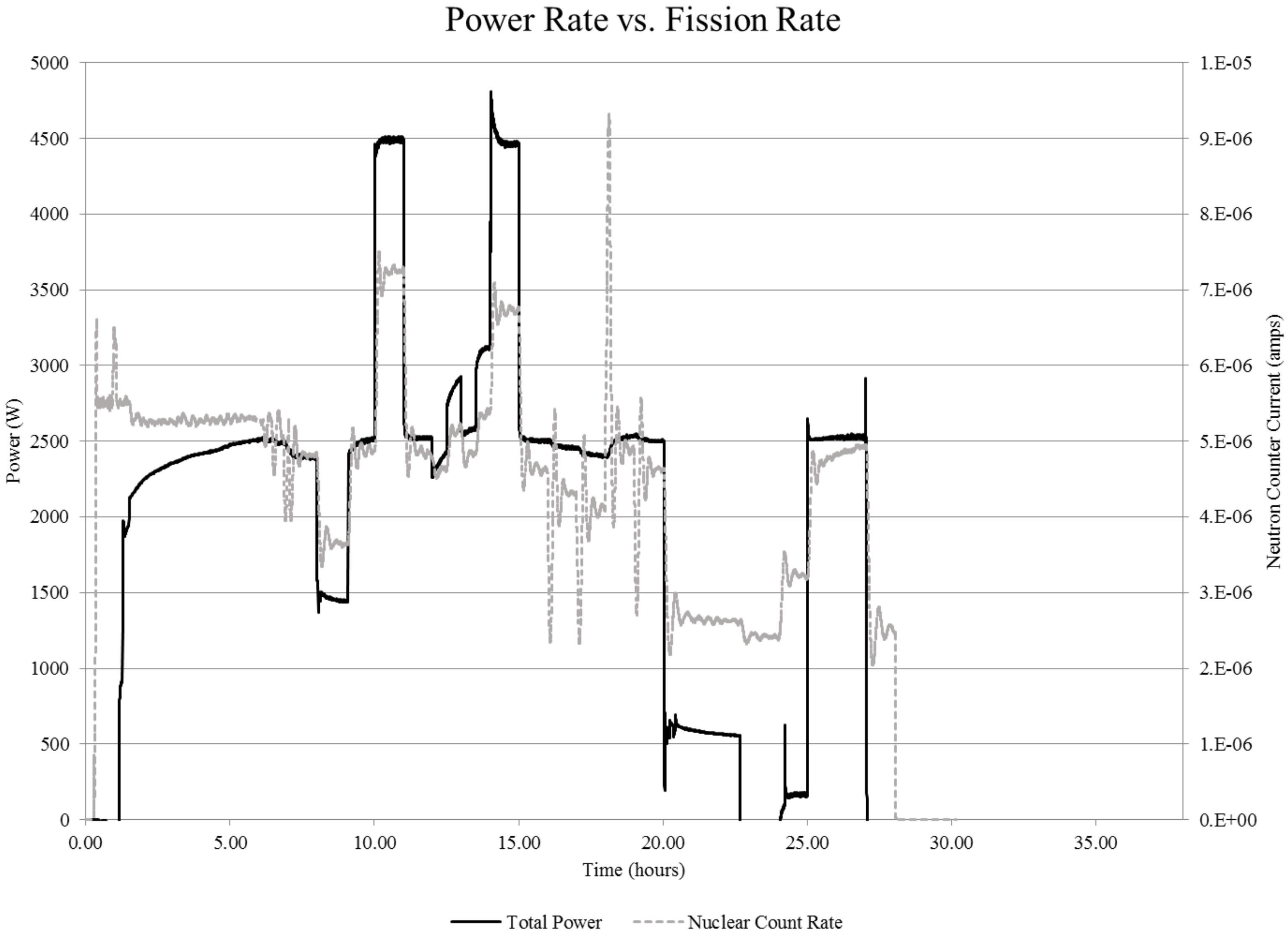
Multiple effects on reactivity

- Fission rate changes even without change in reflector position
- Shows the significance of passive reactivity feedback



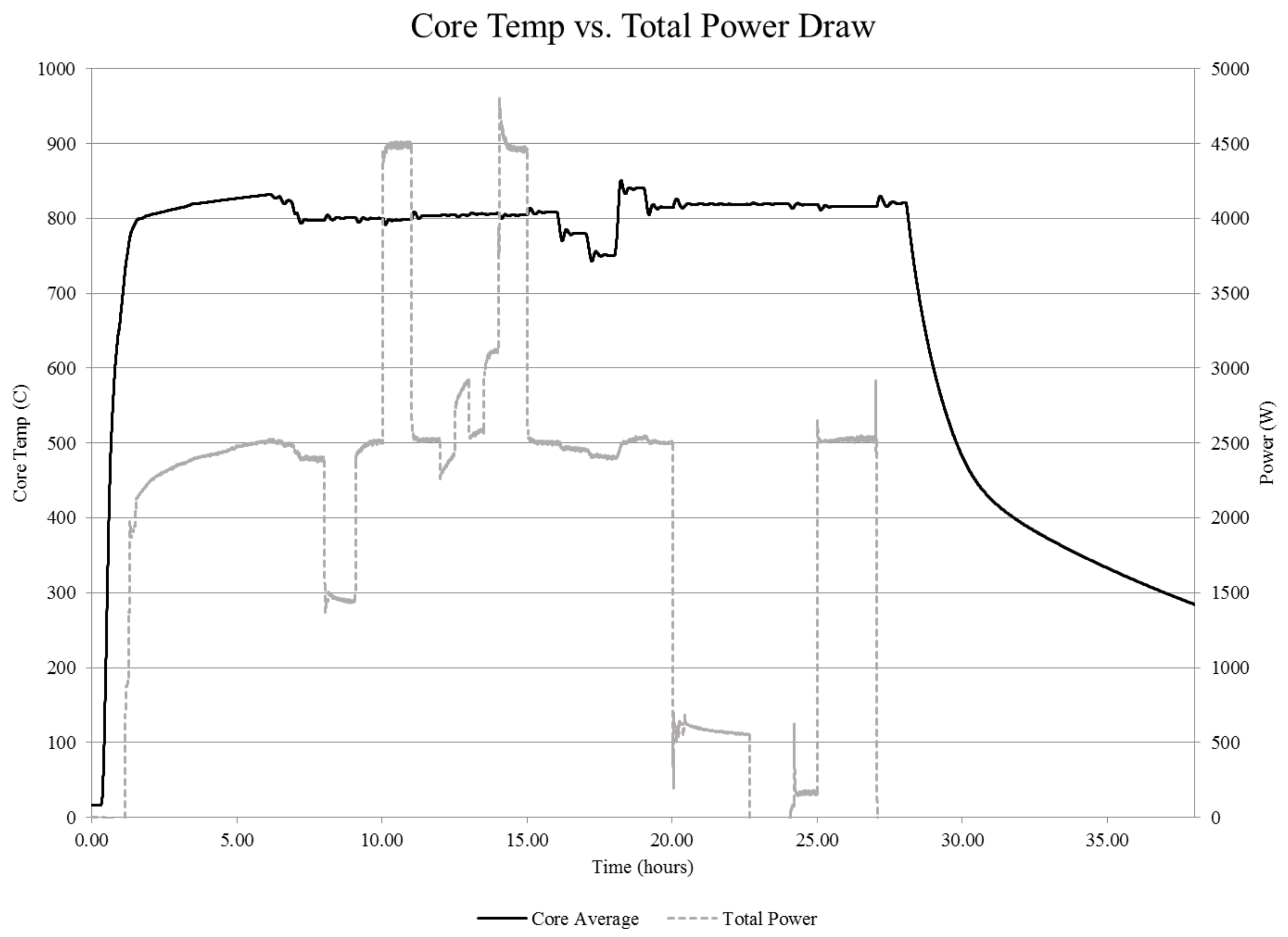
Load following

- Fission rate follows power
- Power does not necessarily follow fission rate



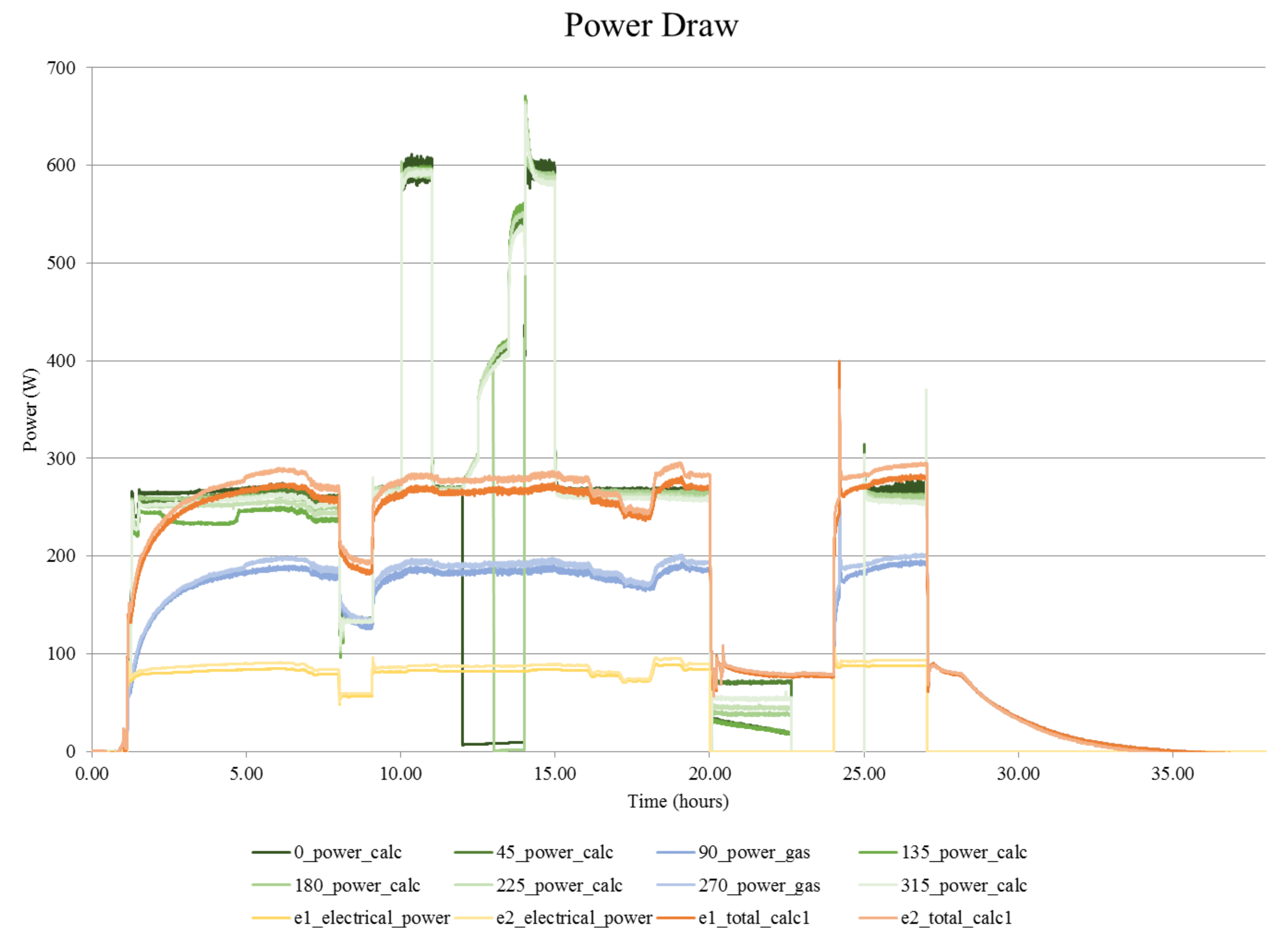
Constant Temperature variable power source

- Core temperature does not significantly change during power transients
- Power does not significantly have to change when core temperature changes



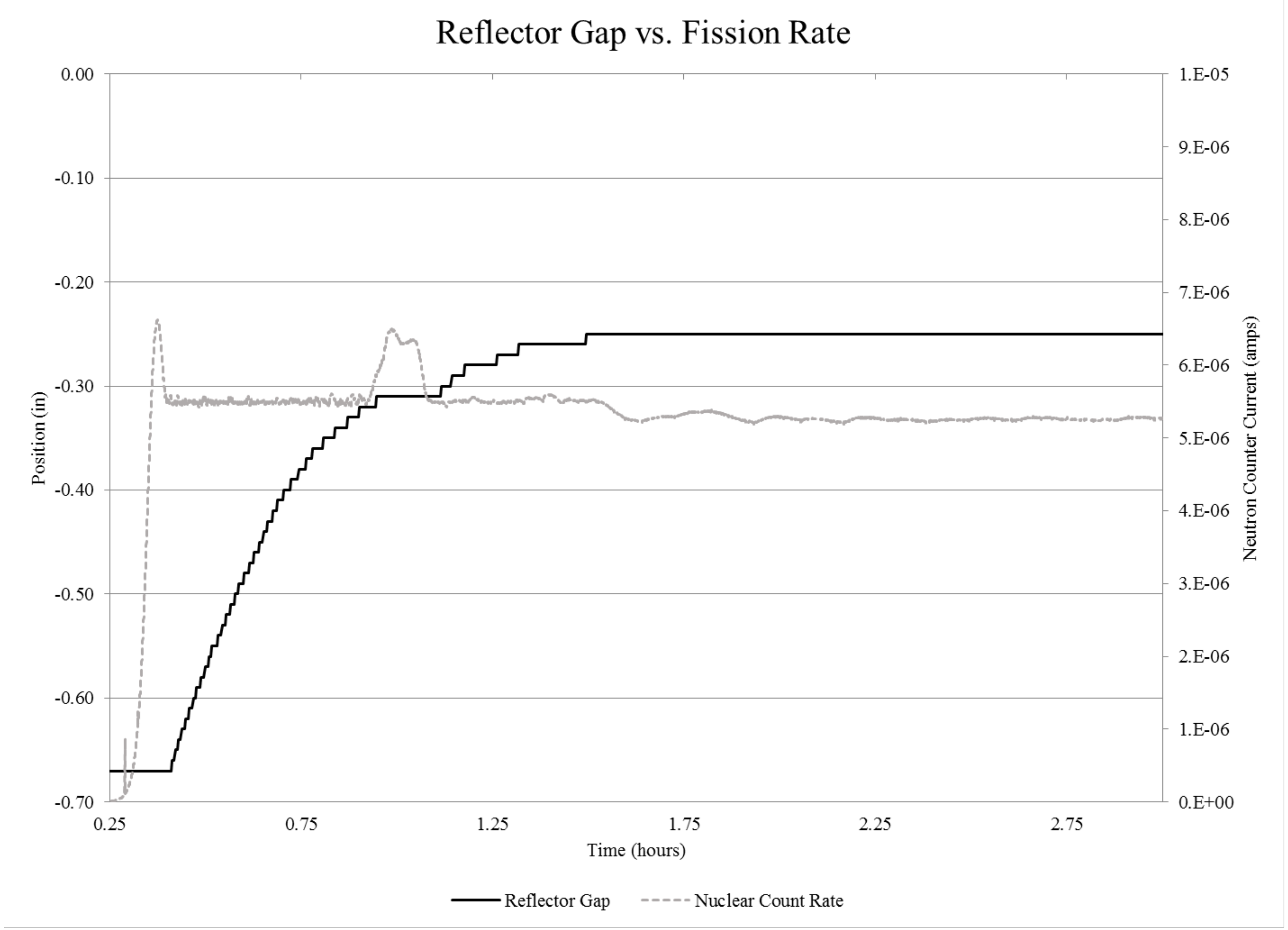
Components of power draw

- Two Advanced Stirling Engines (ASCs) producing electrical power
- Six Stirling Simulators approximating the missing engines
- N_2 gas for thermal power removal from engines and simulators



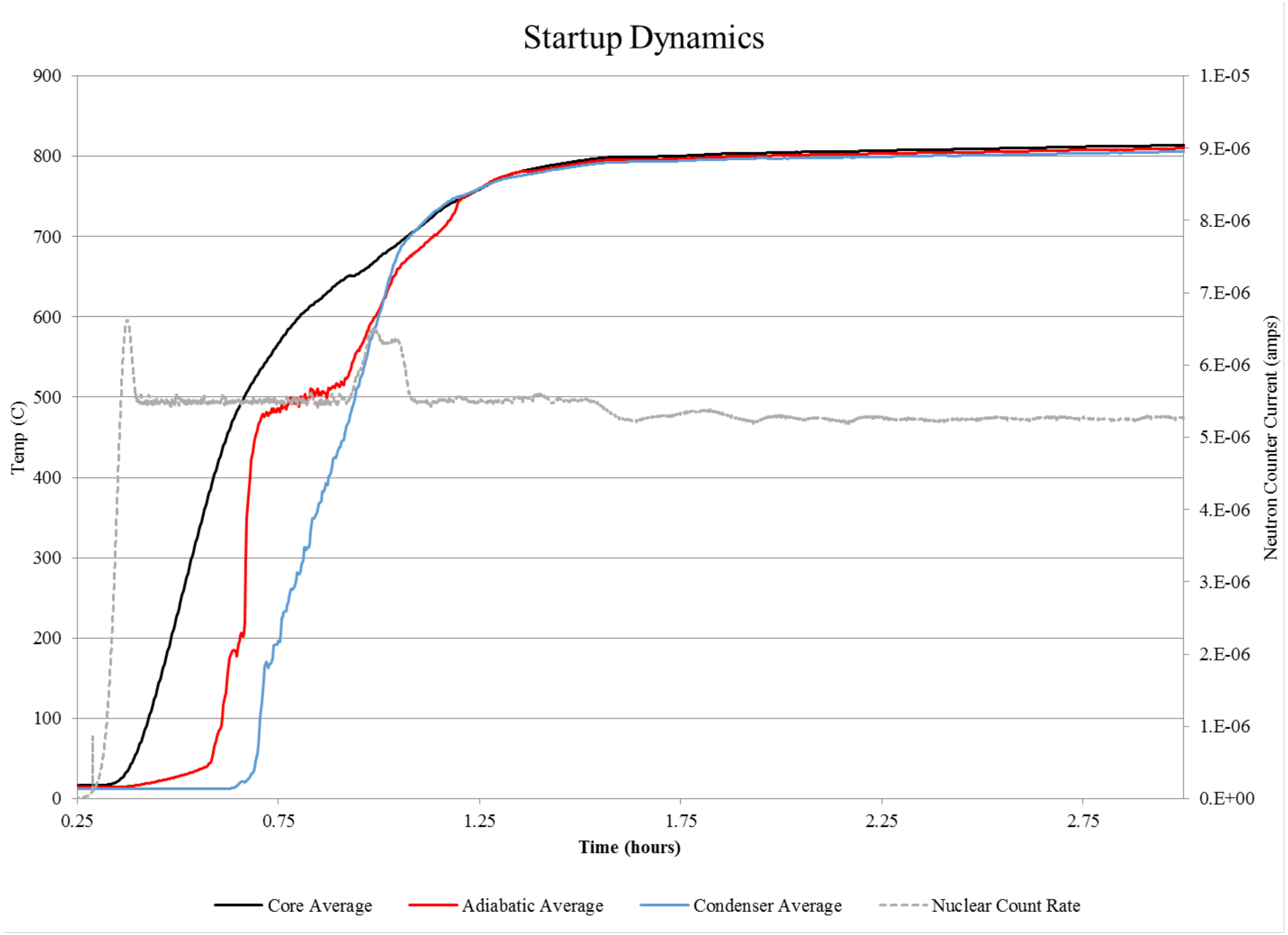
Startup

- Supercritical increase in power
- Reactivity feedback turns power over
- Active control used to maintain constant power during heat-up
- Short transient visible around one hour, what is it?



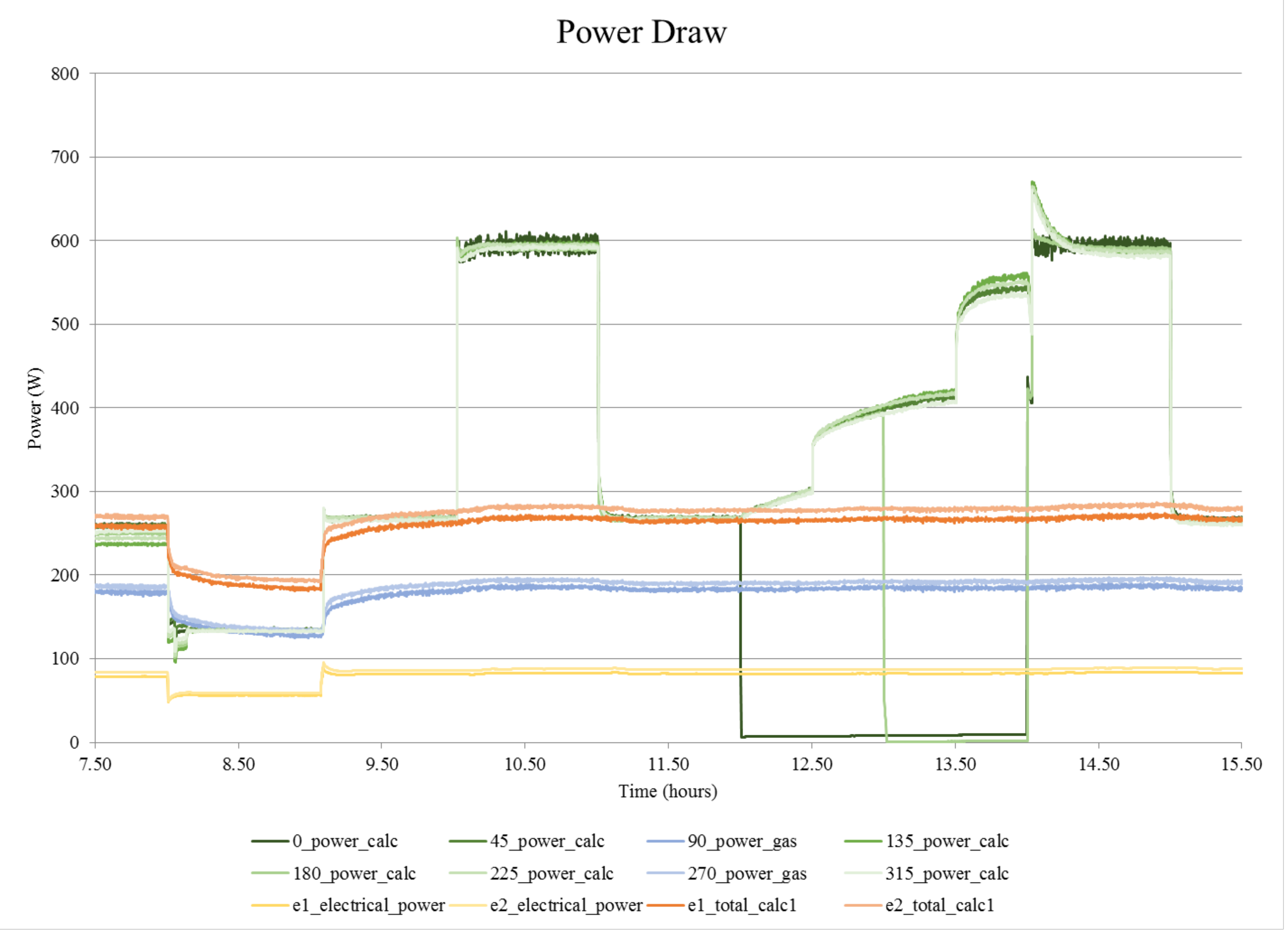
Startup

- Reactor power transient caused by heat pipe dynamics
- Heat pipes reach a more efficient heat transfer temperature and cool the core, causing a reactivity feedback



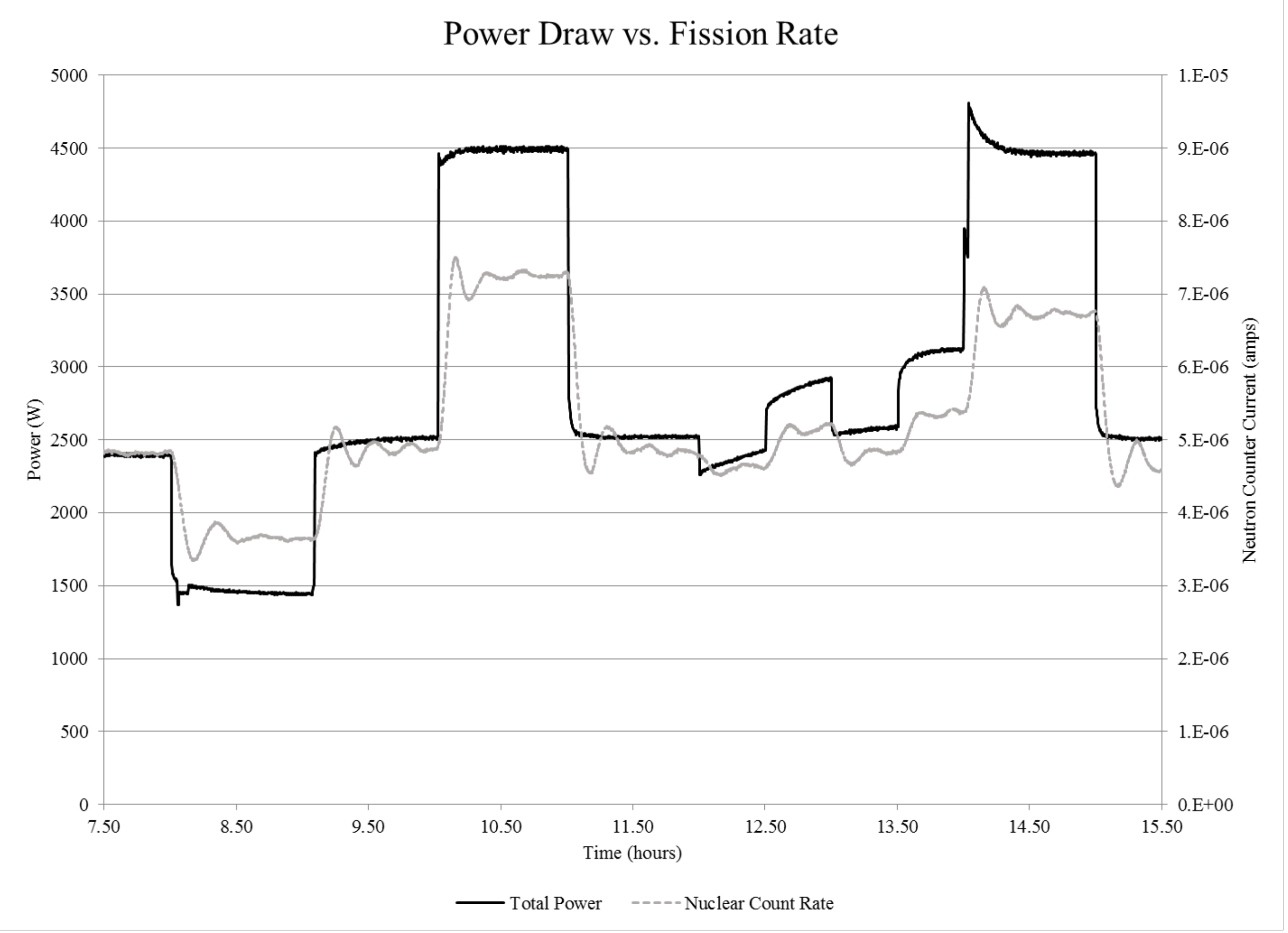
Power transients – passive control

- Decreased engine power
- Increased simulator power
- Shut off simulator at radial position 0
- Shut off simulator at radial position 180
- Simulates heat pipe or engine failure



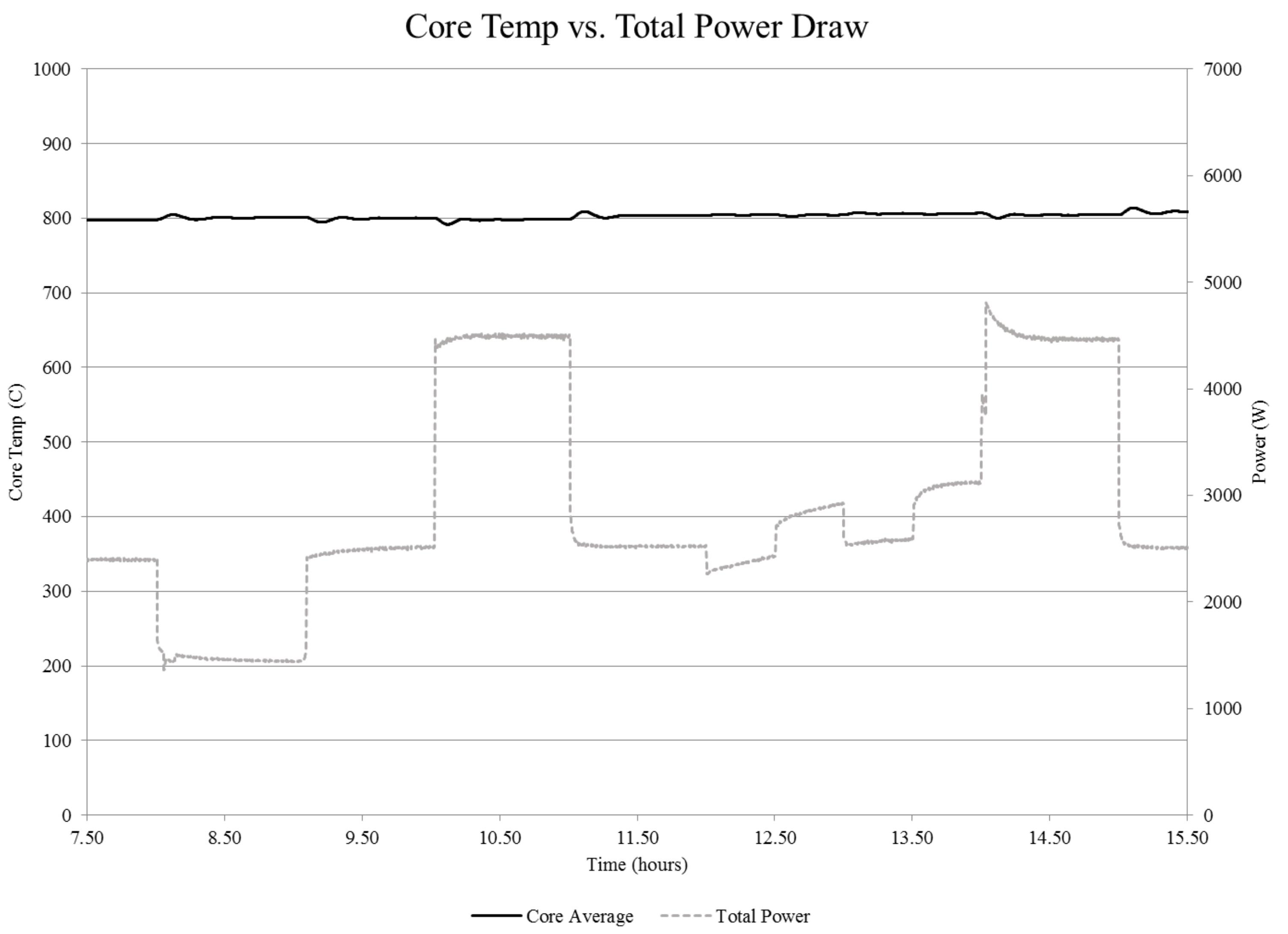
Power transients – passive control

- Fission rate load follows exceptionally well
- Small damping oscillations as reactivity feedback effects work themselves out
- However…



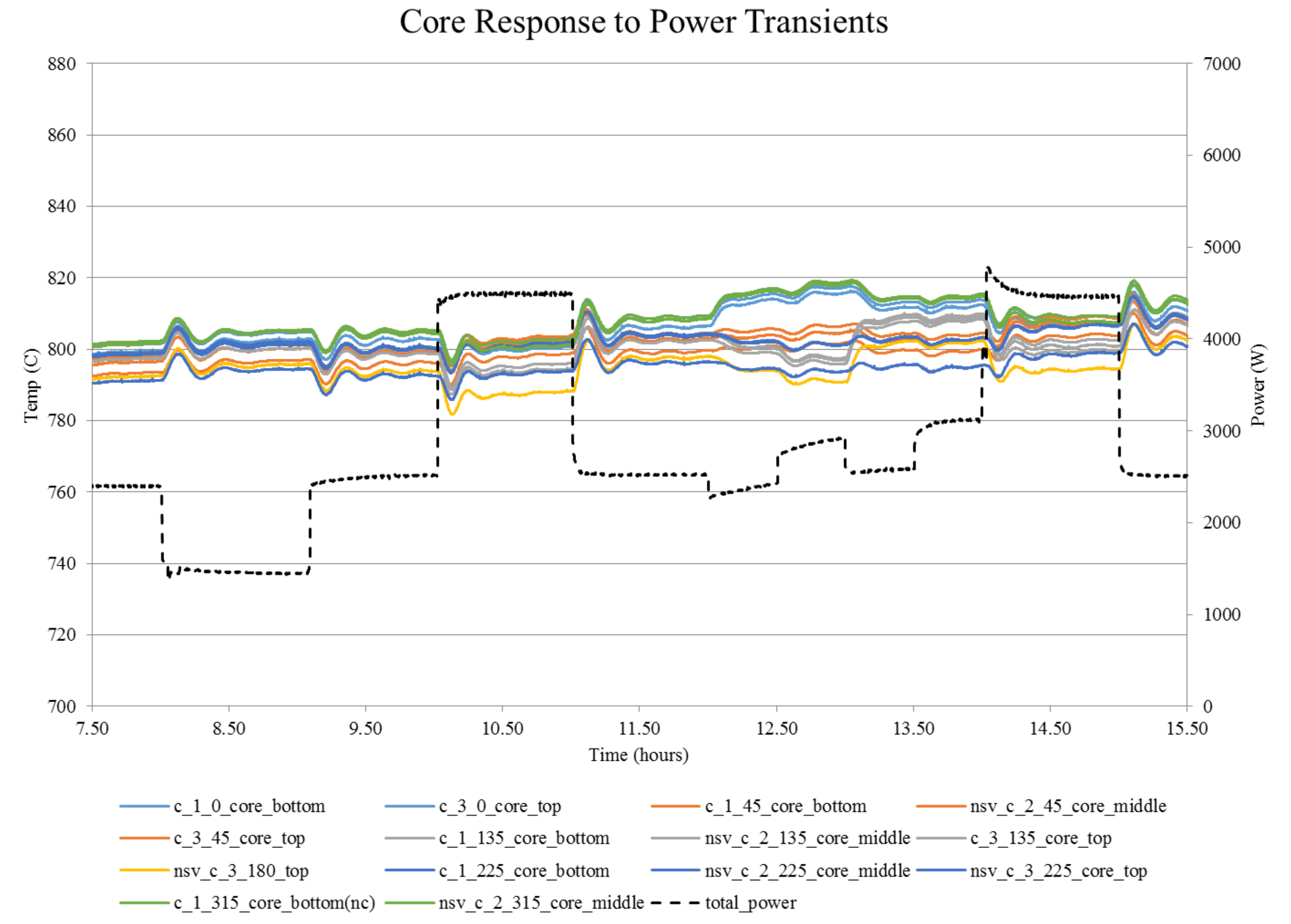
Power transients – passive control

- Core temperature remains almost unperturbed during power transients
- Small oscillations quickly dampen back to steady state operation



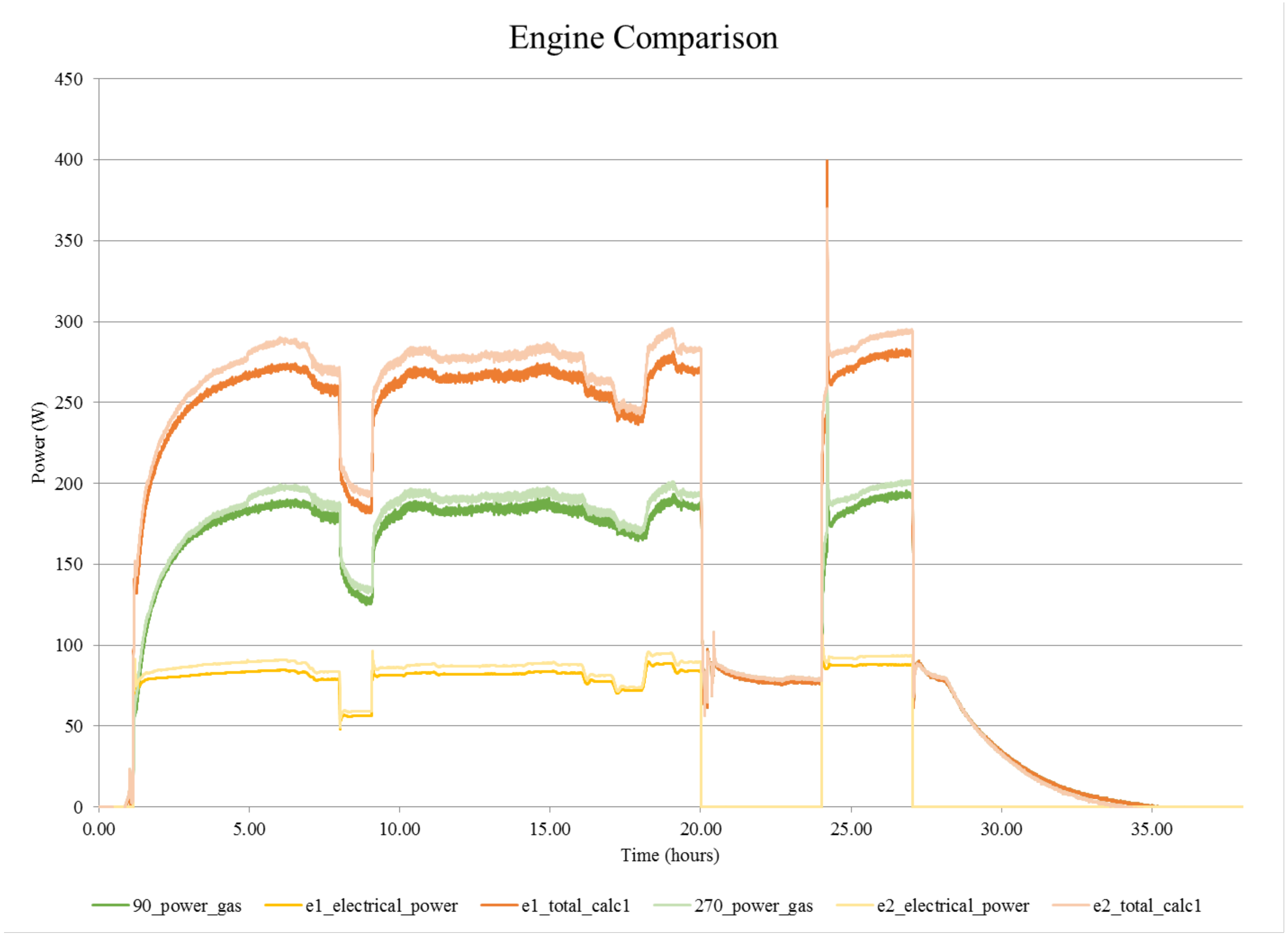
Power transients – passive control

- Radial temperature distribution does change
- 0 and 315 position temps increase when simulator 0 shuts off
- Other temps decrease, average temp remains unchanged
- 135 and 180 position temps increase when simulator 180 shuts off



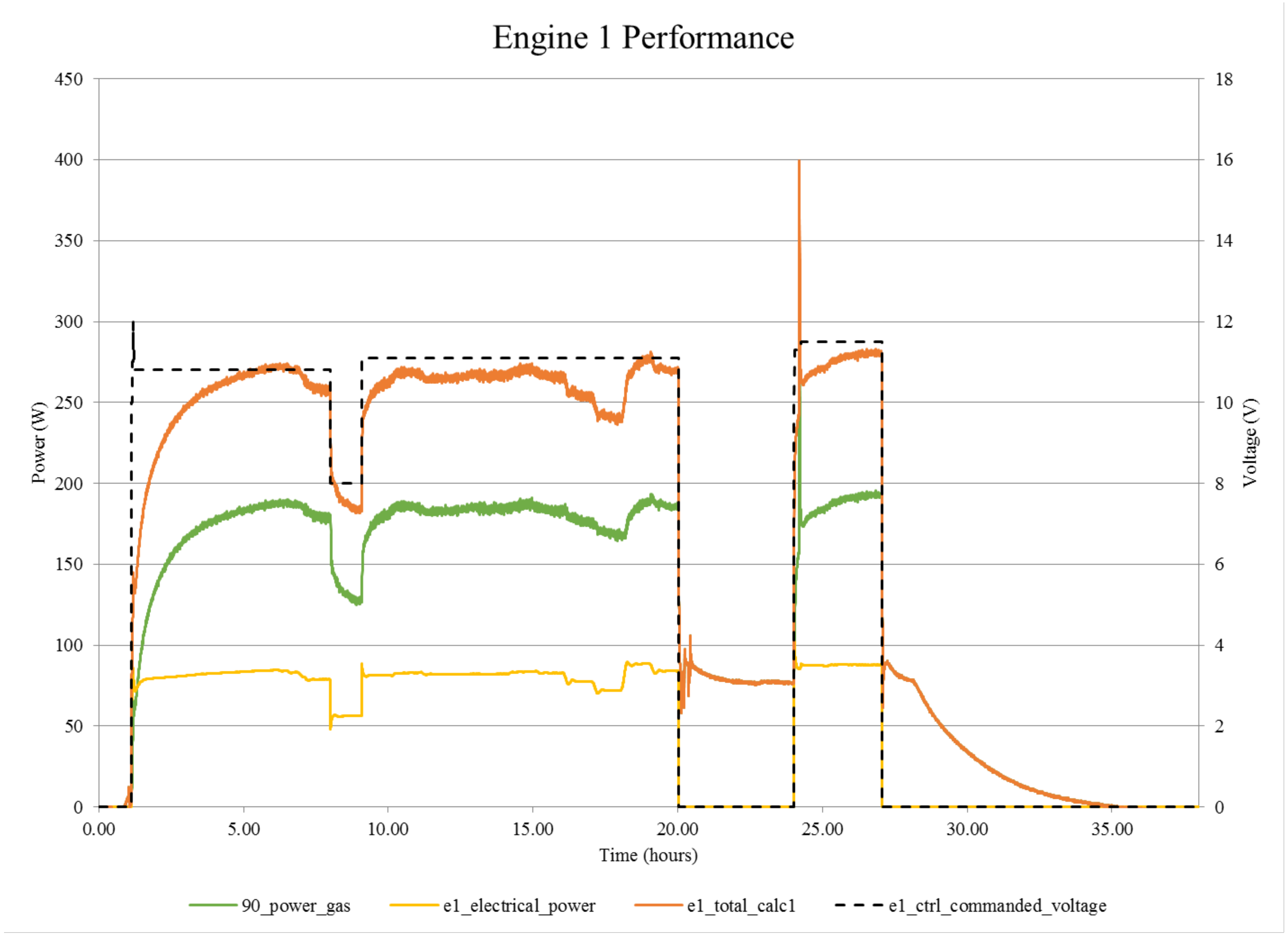
Engine results

- Two ASC engines
- Output of ~80-85 W each
- Thermal power removed by N_2 gas rather than radiators



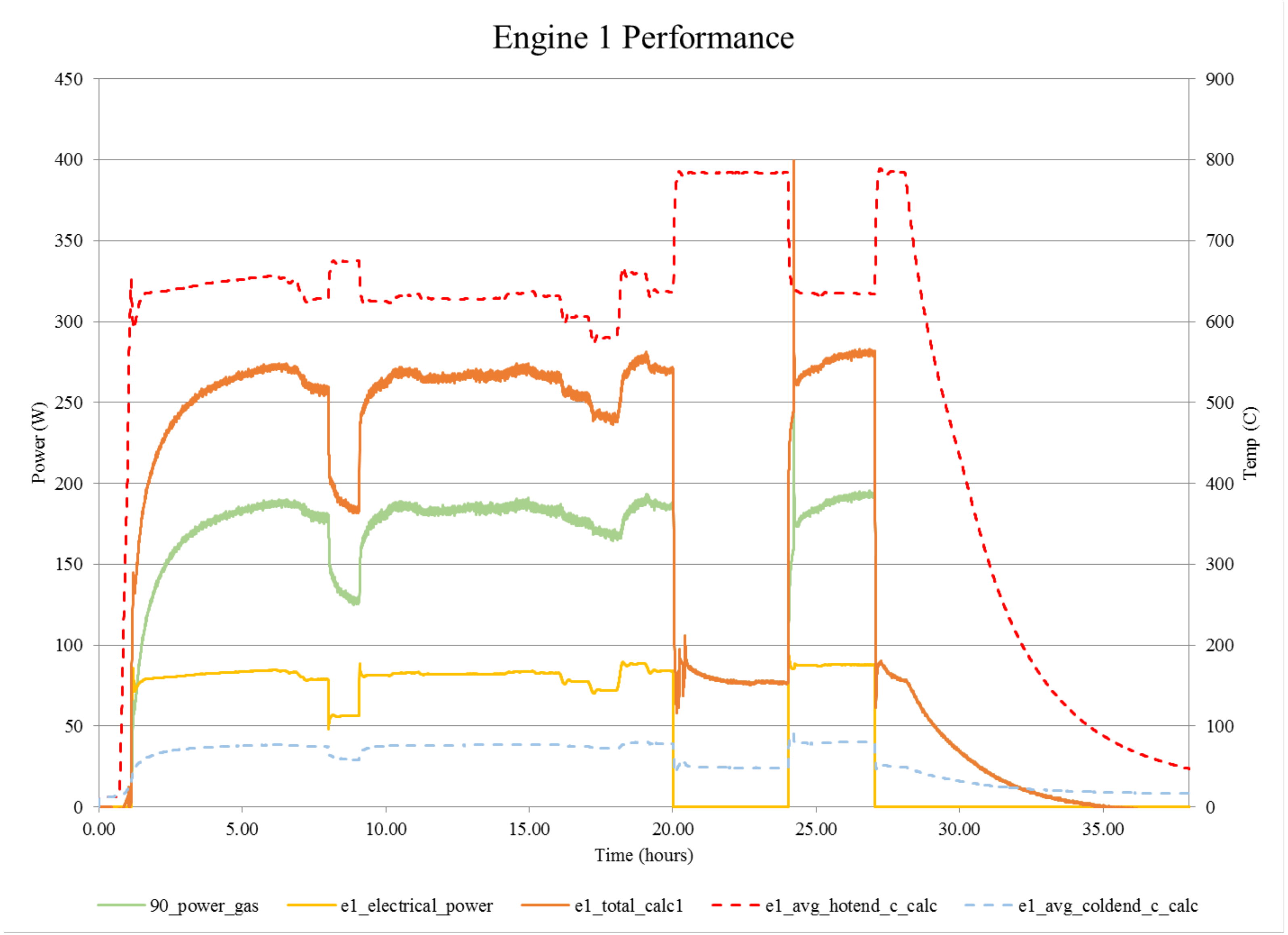
Engine results

- Engines controlled by setting the alternator voltage
- Power can still change without change in commanded voltage



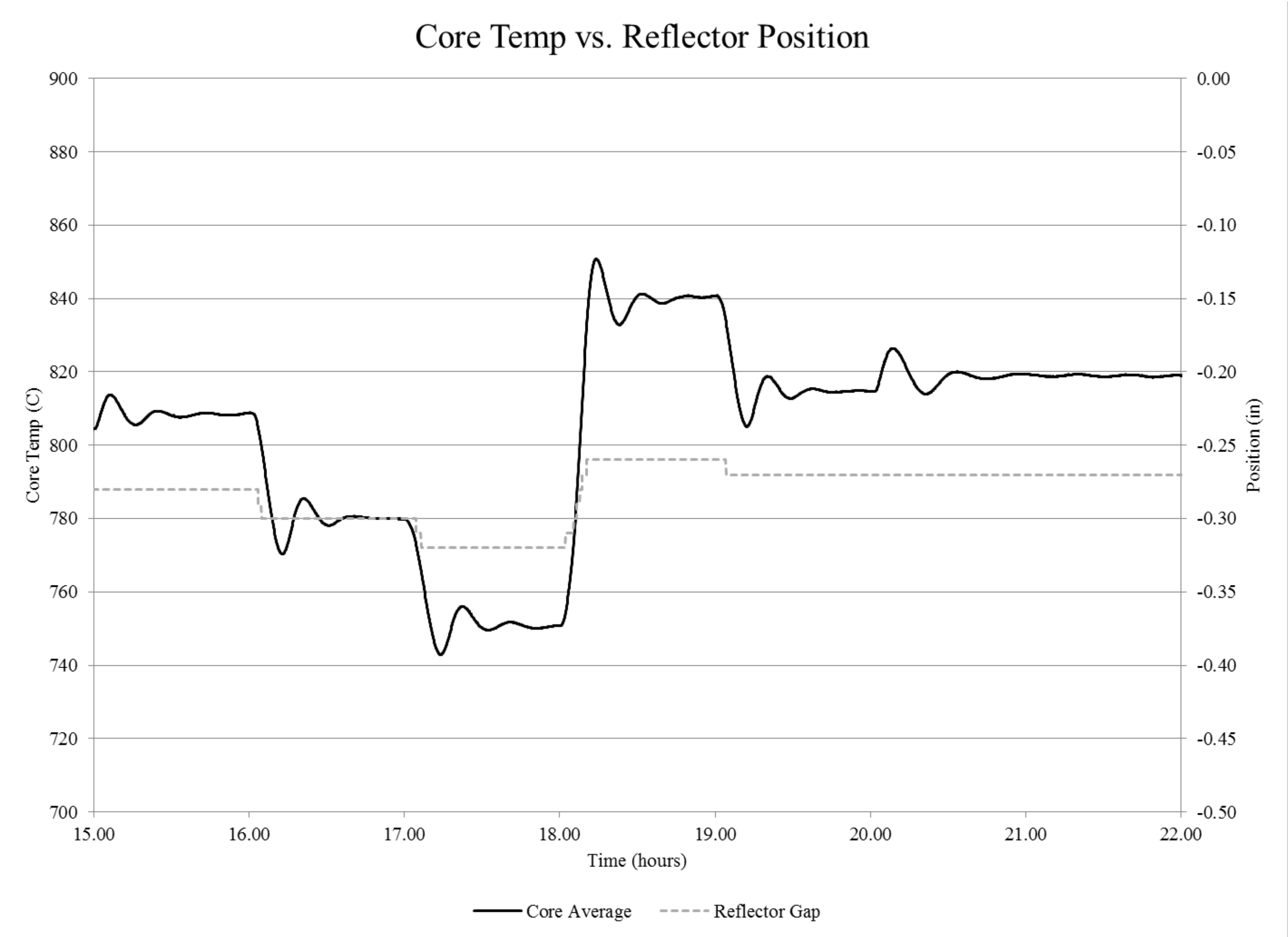
Engine results

- Temperature of the engine heat acceptor also changes power
- Heat rejection temperature of the engine also plays a part, and effects the selection of radiator components



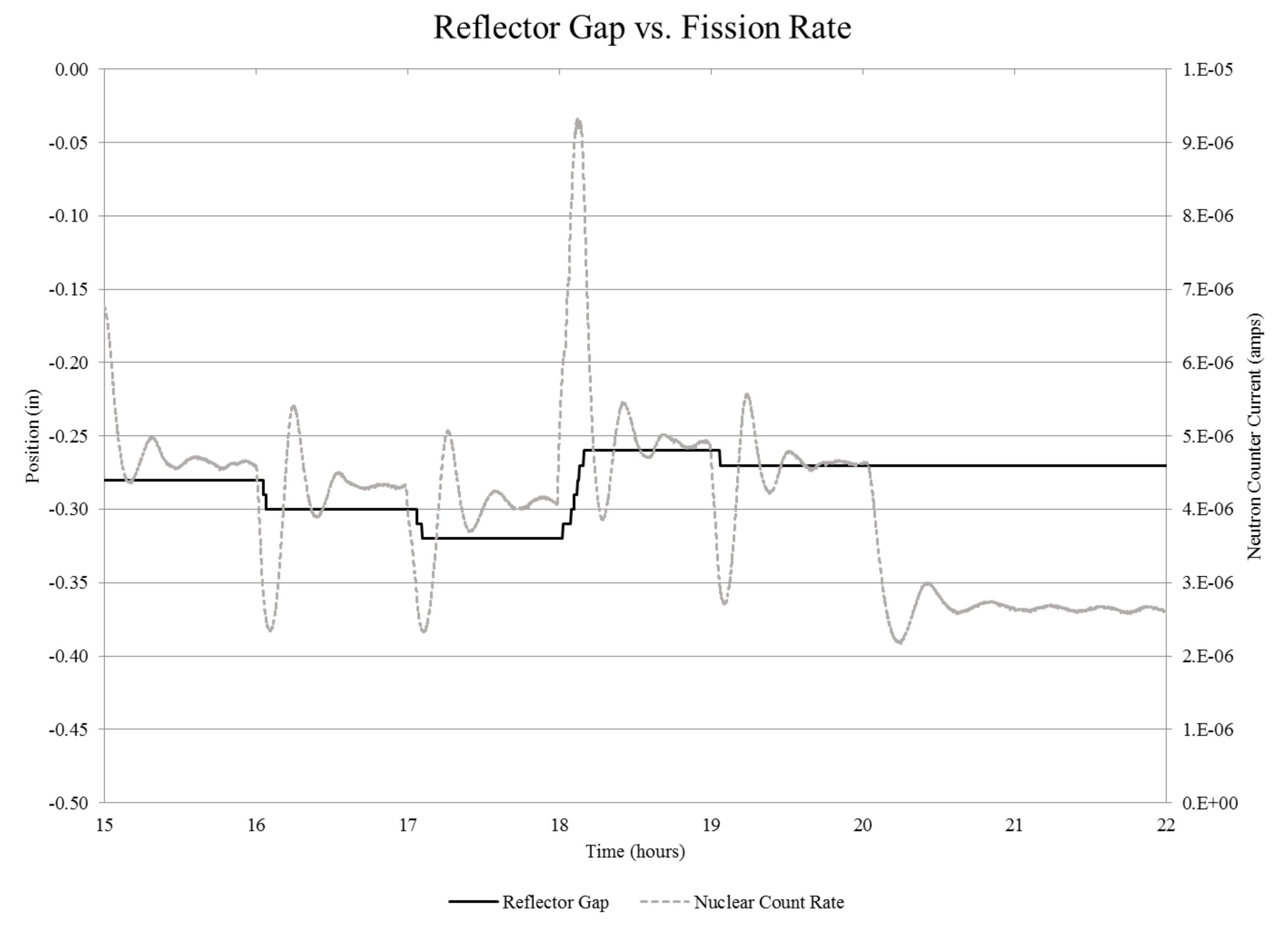
Nuclear transients – active control

- Raise and lower reflector platen to perform active control transients
- Core temperature changes proportionally to change in reactivity control



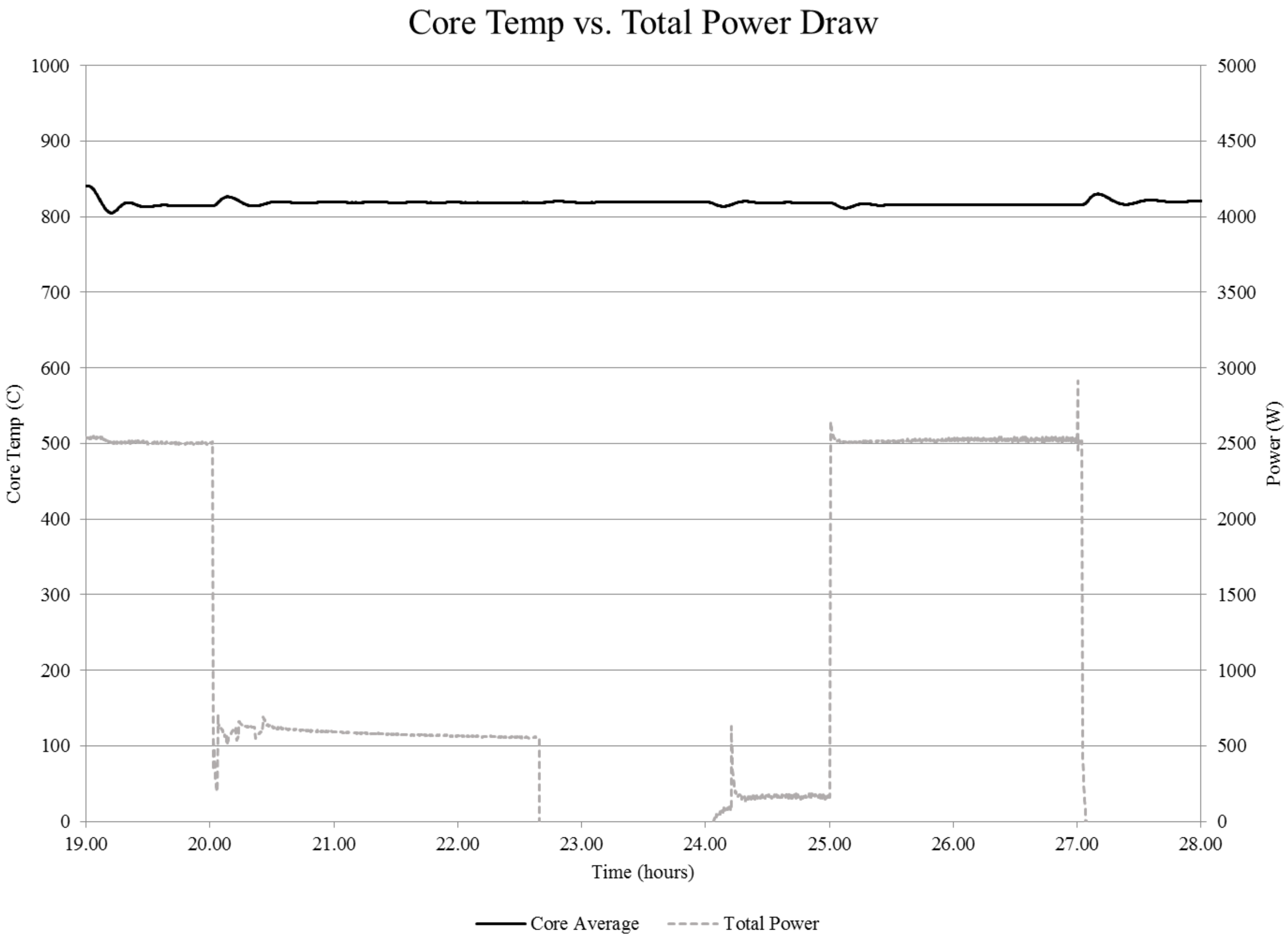
Nuclear transients – active control

- Nuclear power changes slightly due to lack of fine control on stirling engine power
- Less steady state change than during power transients
- Higher oscillations than during power transients due to higher changes in core temperature



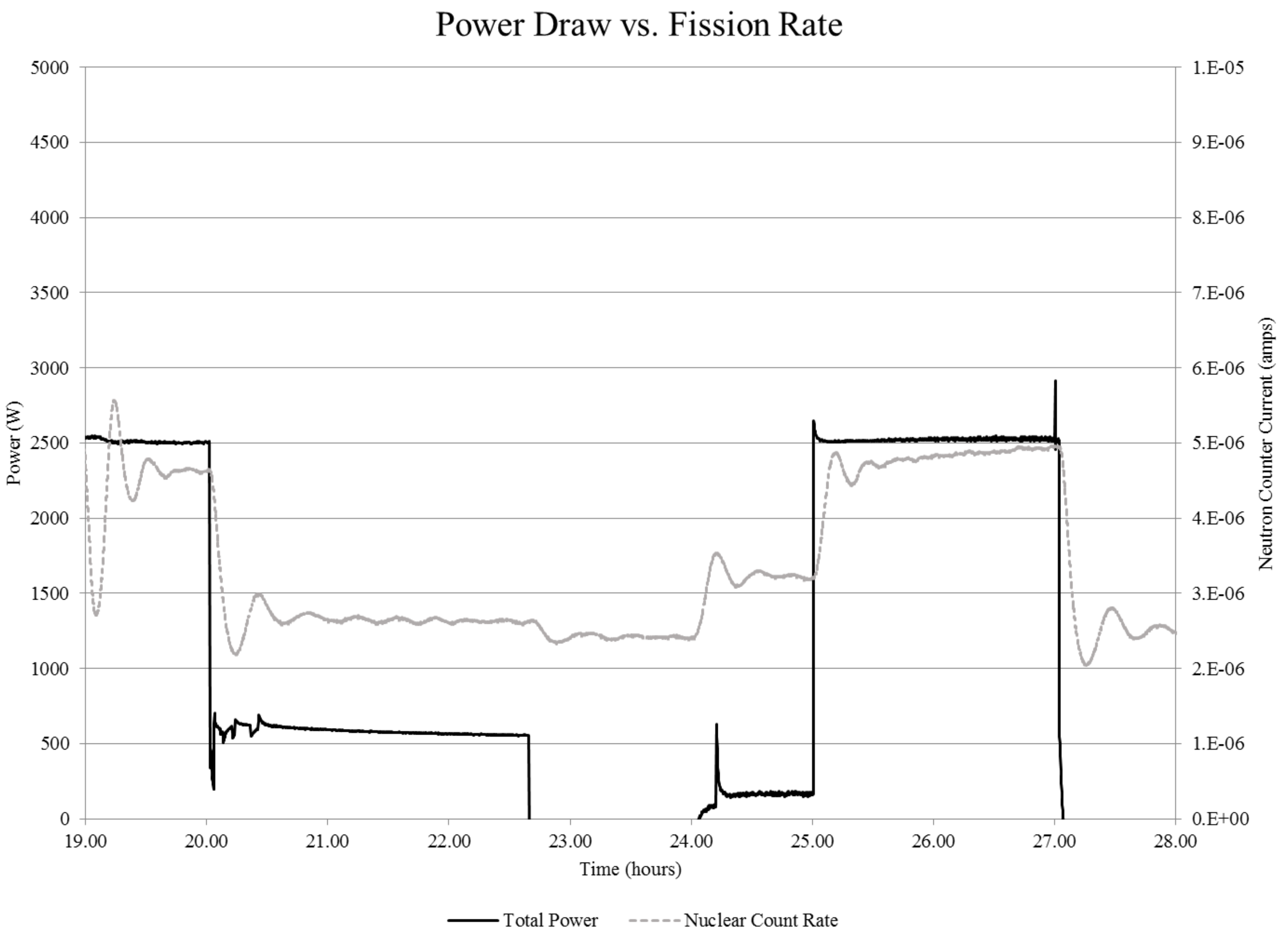
Loss of Coolant

- Loss of coolant simulated by turning off engines and gas flow to simulators
- Core temp is not significantly effected, highlighting the robustness of the passive control



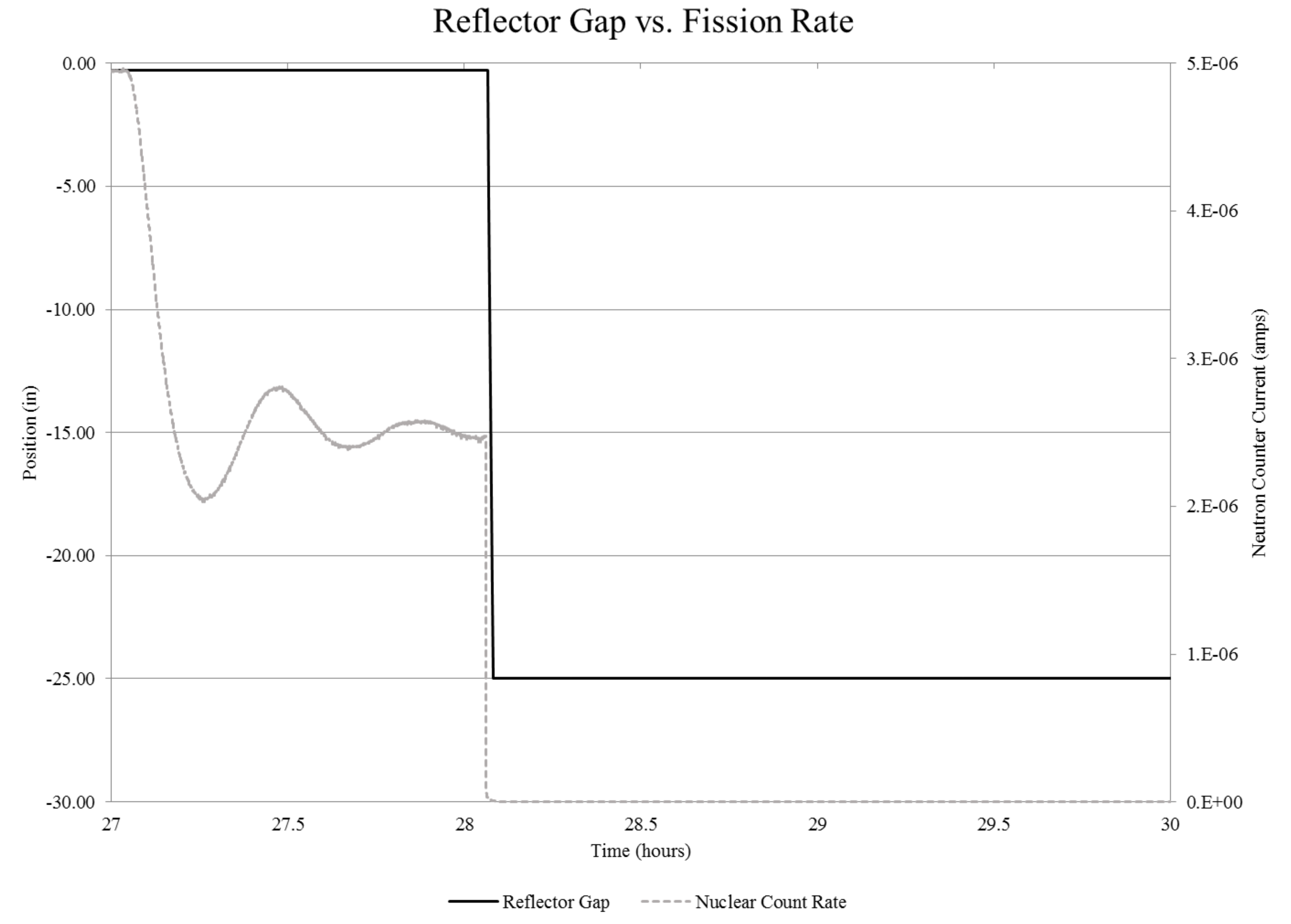
Loss of Coolant

- Fission rate again load follows
- Power drops by factor of ~5
- Fission rate drops by factor of ~2
- Points to significant thermal losses in test setup



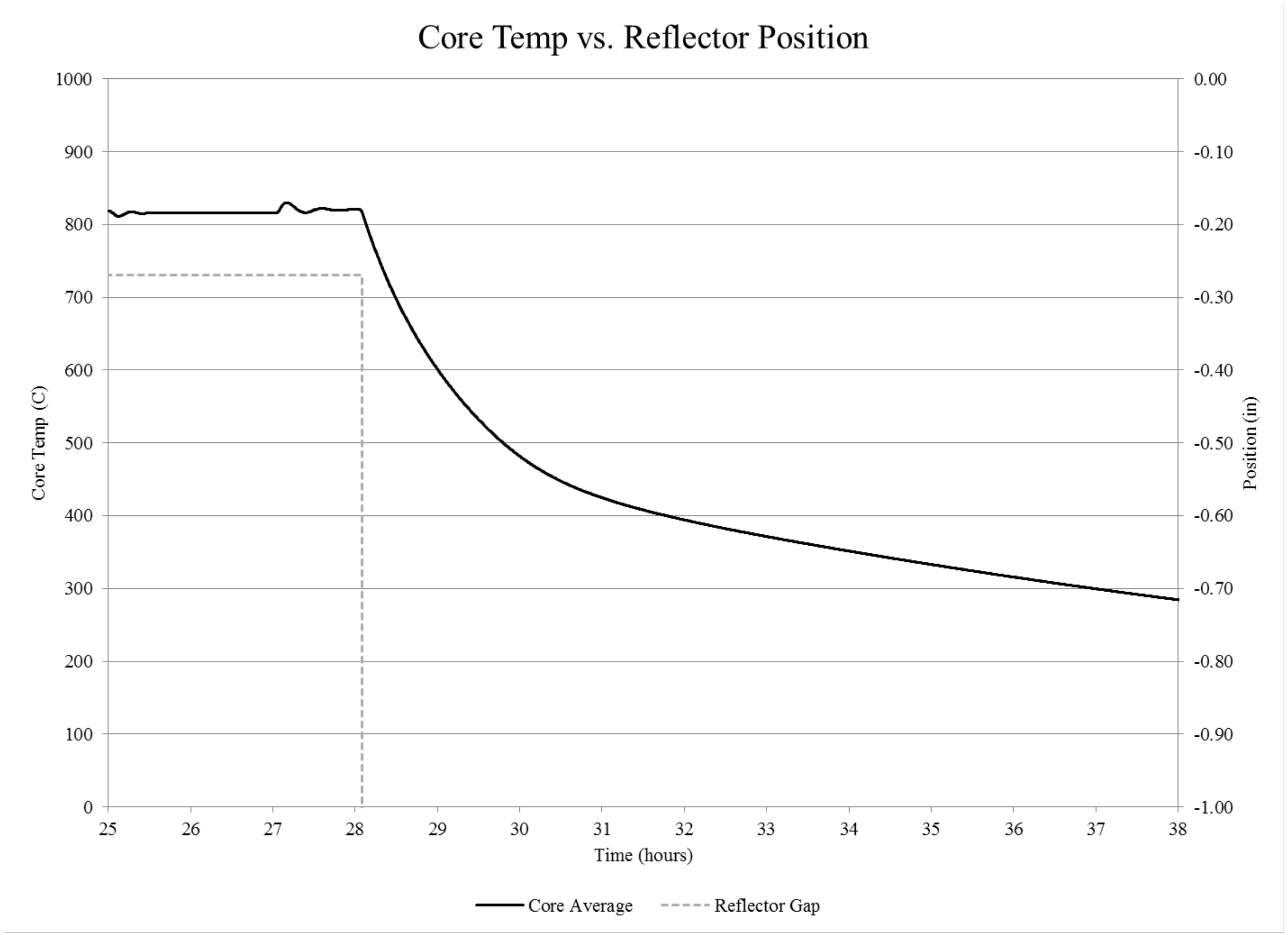
Shutdown

- Reactor power drops quickly once reflector is dropped
- Unlike commercial reactors, fission product decay power is not an issue for low power reactors



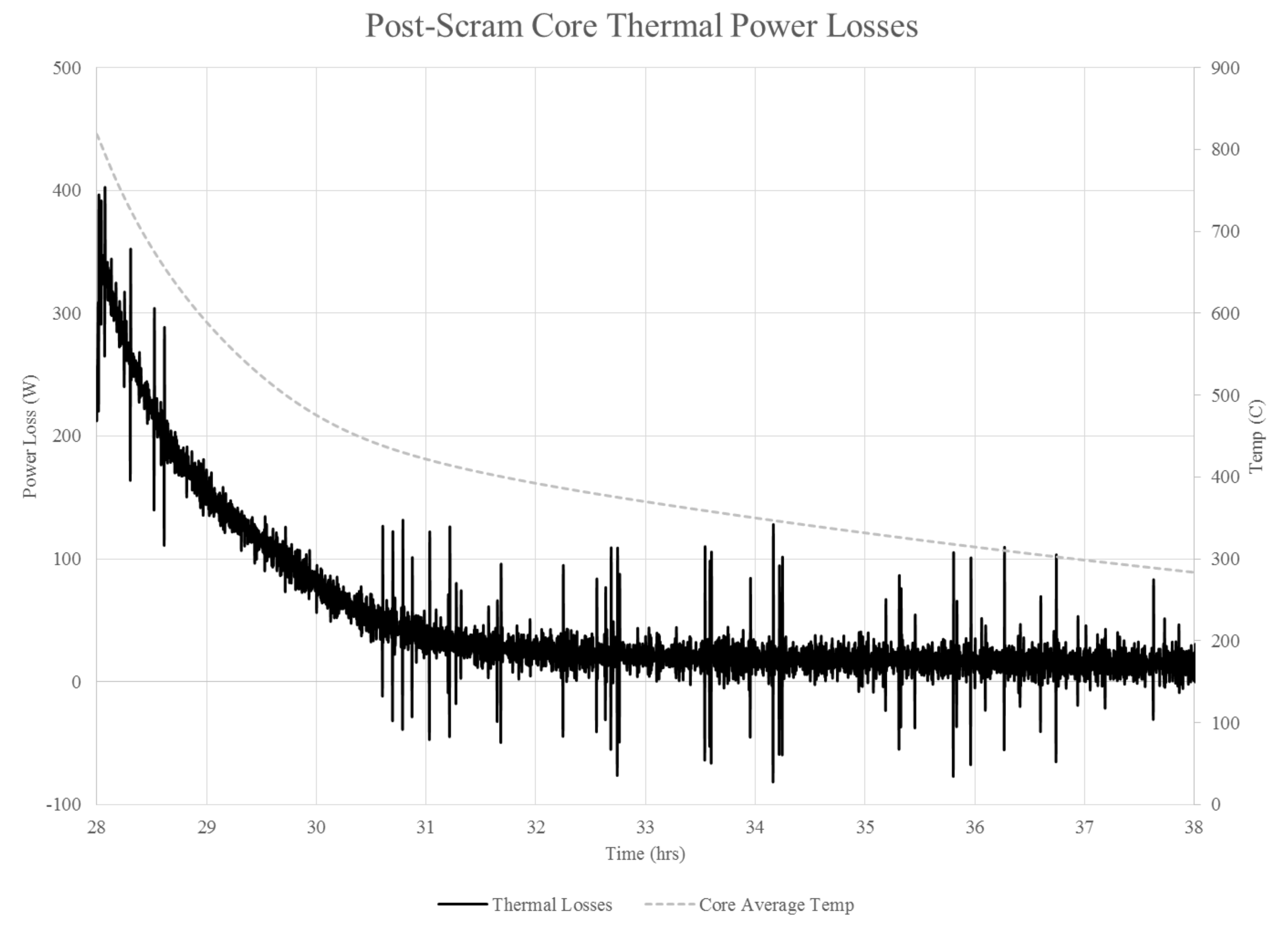
Shutdown

- Core temperature drops slowly due to vacuum environment
- Offers a look into thermal losses at temperature during the test



Thermal Losses

- Core alone appears to be losing ~350 W at operating temperature
- Also losses from heat pipes, simulators, engines, structures
- Need to revisit a complete thermal model of the KRUSTY test set up



Performance Summary

Event Scenario	Performance Metric	KRUSTY Experiment	Performance Status
Reactor Startup	< 3 hours to 800 deg. C	1.5 hours to 800 deg. C	Exceeds
Steady State Performance	4 kWt at 800 deg. C	> 4 kWt at 800 deg. C	Exceeds
Total Loss of Coolant	< 50 deg. C transient	< 15 deg. C transient	Exceeds
Maximum Coolant	< 50 deg. C transient	< 10 deg. C transient	Exceeds
Convertor Efficiency	> 25 %	> 35 %	Exceeds
Convertor Operation	Start, Stop, Hold, Restart	Start, Stop, Hold, Restart	Meets
System Electric Power Turn Down Ratio	> 2:1 (half power)	> 16:1	Exceeds

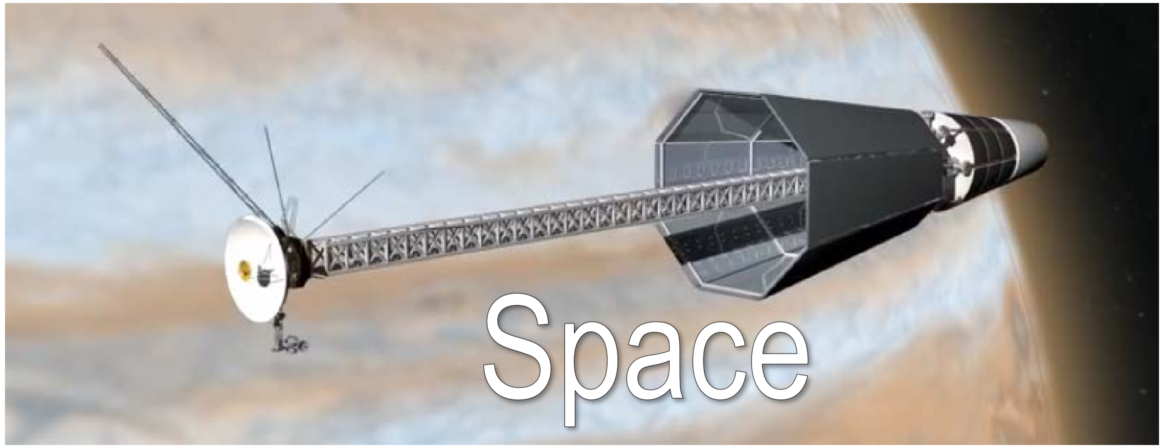
KRUSTY Conclusions

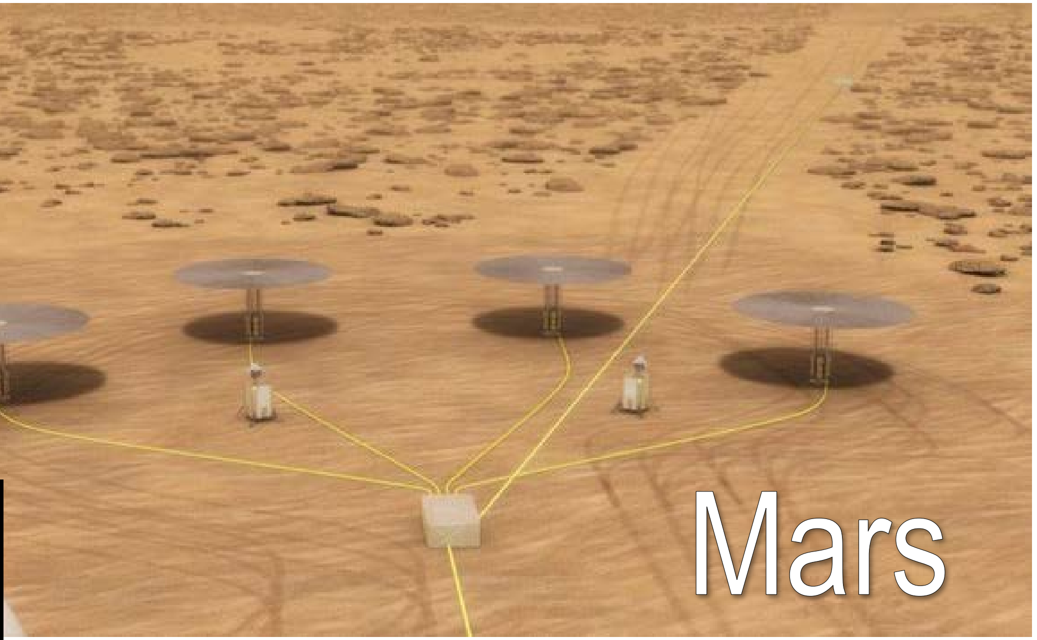
- Metal core fast reactor provides simplest solution for a low mass passively controlled space nuclear reactor
- Kilopower system has excellent load following and fault tolerance capabilities
- DoE now has the procedure and test data to safely make baseline Kilopower reactor cores, significantly lowering risk for future development
- Small teams with achievable, step-by-step milestones can succeed even in nuclear development programs, a field notoriously susceptible to cancellations

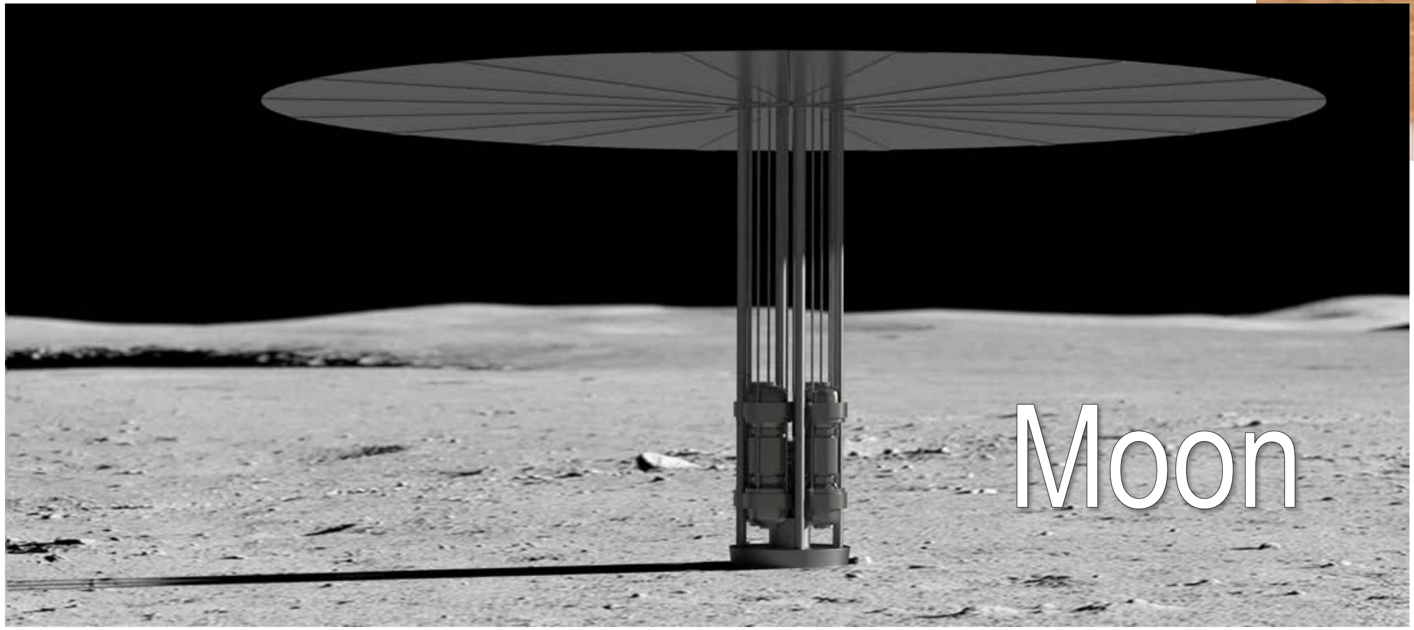
Kilopower Next Steps

- Hardware development
  - Radiation shield trades (B_4C vs. BeO vs. LiH)
  - Redesign heat pipes for microgravity environment (add an internal wick)
  - Develop appropriately sized Stirling engines and controllers (highest risk)
- System-level studies
  - Life test as much as possible
  - Fission radiation environment vs. space radiation effects on electronics
  - Optimize mass
- Mission/programmatic studies
  - Launch safety/security
  - Missions enabled by fission power
  - Multi-mission architecture vs. specific mission designs

The Future of Kilopower







Questions?