Comparison of High Temperature KRUSTY Operation with Dynamic Simulations (IER-476)

Robert Kimpland and Rene Sanchez

NCSP Technical Program Review
Amarillo, TX
March 25-29, 2019

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Overview

- The main objective of the KRUSTY experiment is to evaluate the operational performance of a compact reactor that closely resembles the flight unit NASA will use for deep space exploration missions.
- Test the dynamic behavior of the reactor (transients).
- Verify the integrity of the fuel

Warm Criticals and the High Temperature Run (28-hr run)

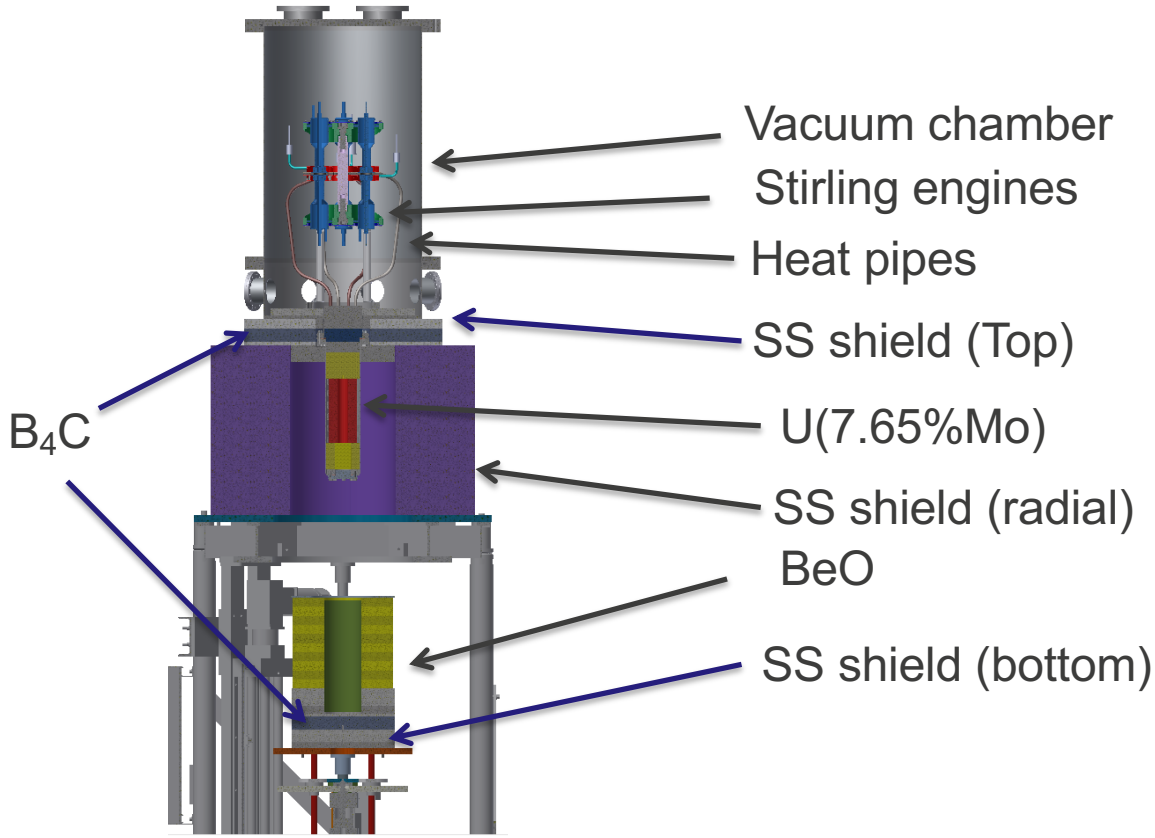
Warm Criticals (Phase 3)

- 15 cent free run
- 30 cent run
- 60 cent run

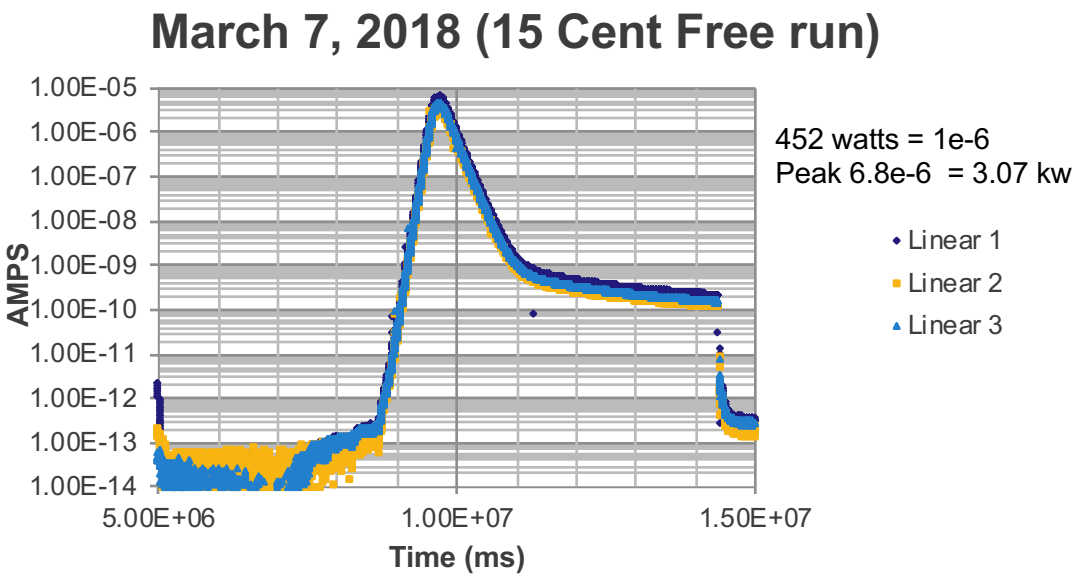
High Temperature run (Phase 4)

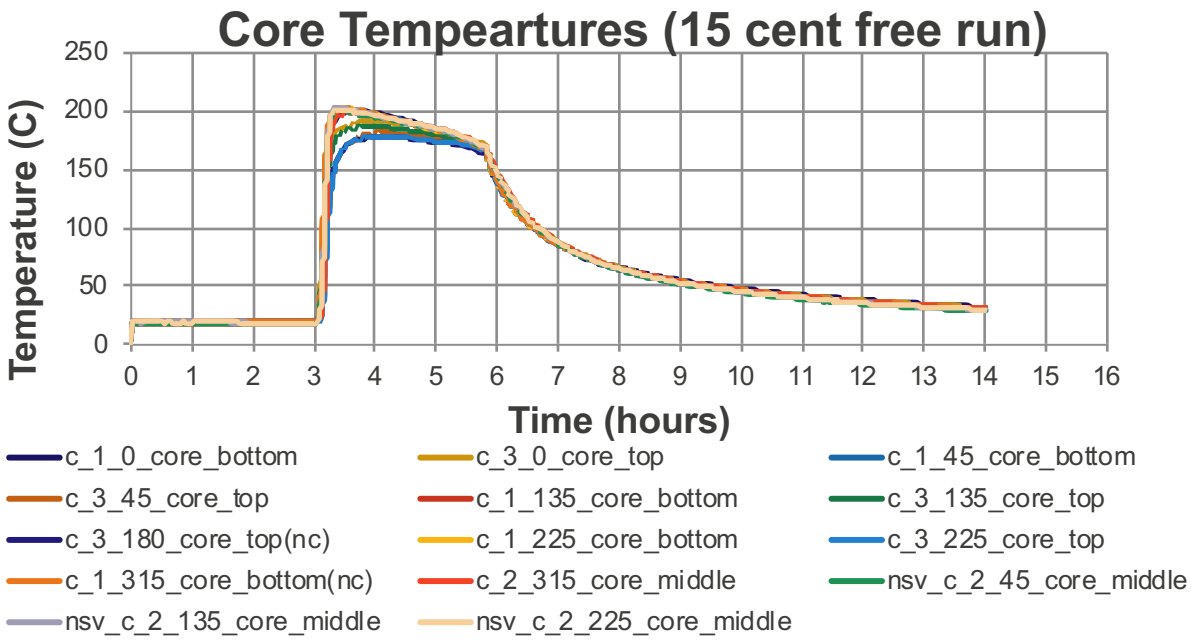
- Operating Reactor at high temperature (800°C) for 28-hr and performing some transients while operating at full power.

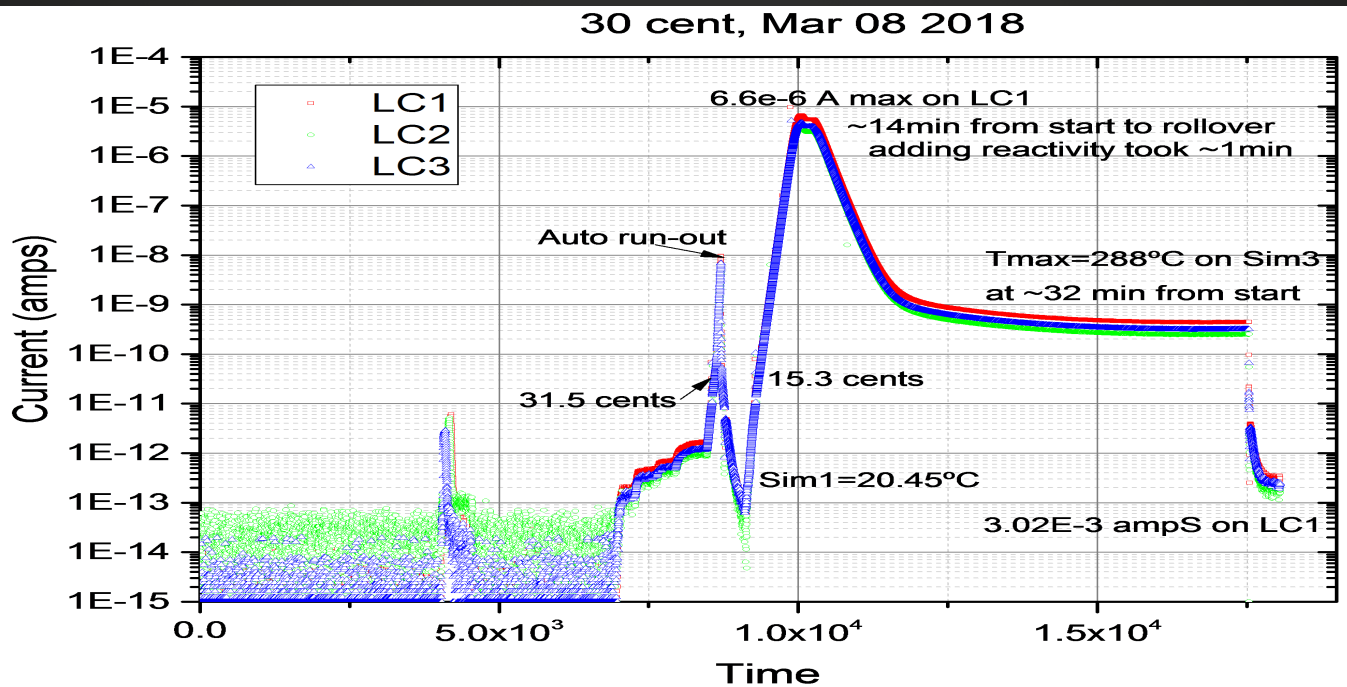
KRUSTY

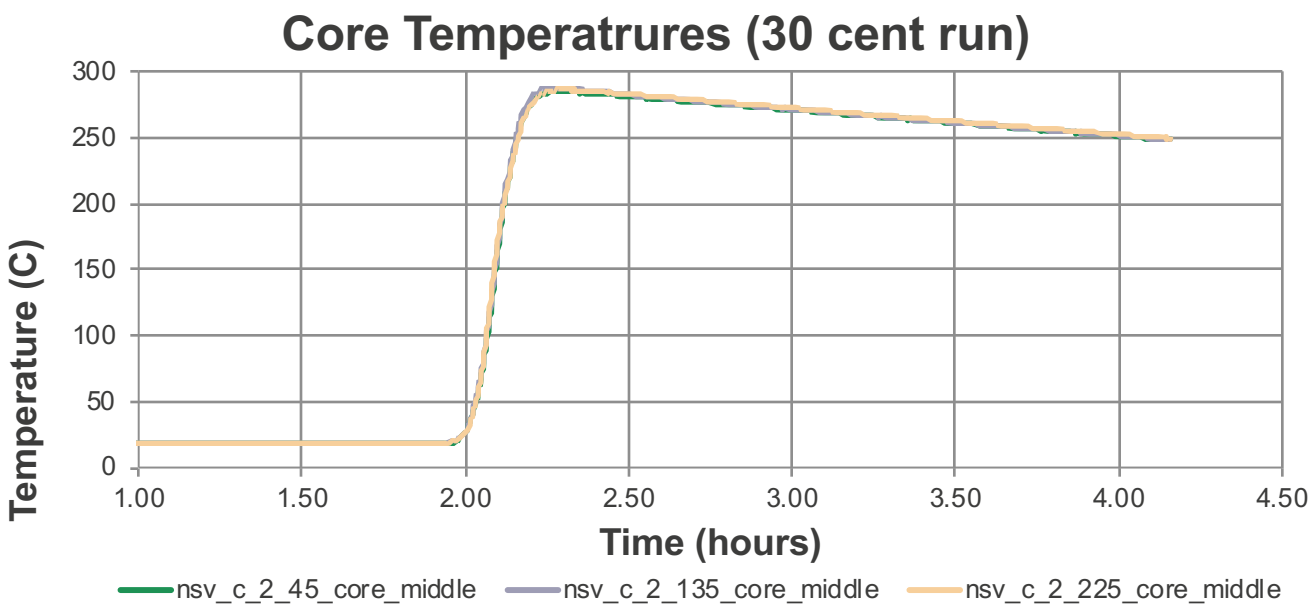

Vacuum chamber
Stirling engines
Heat pipes
SS shield (Top)
B_4C
U(7.65%Mo)
SS shield (radial)
BeO
SS shield (bottom)

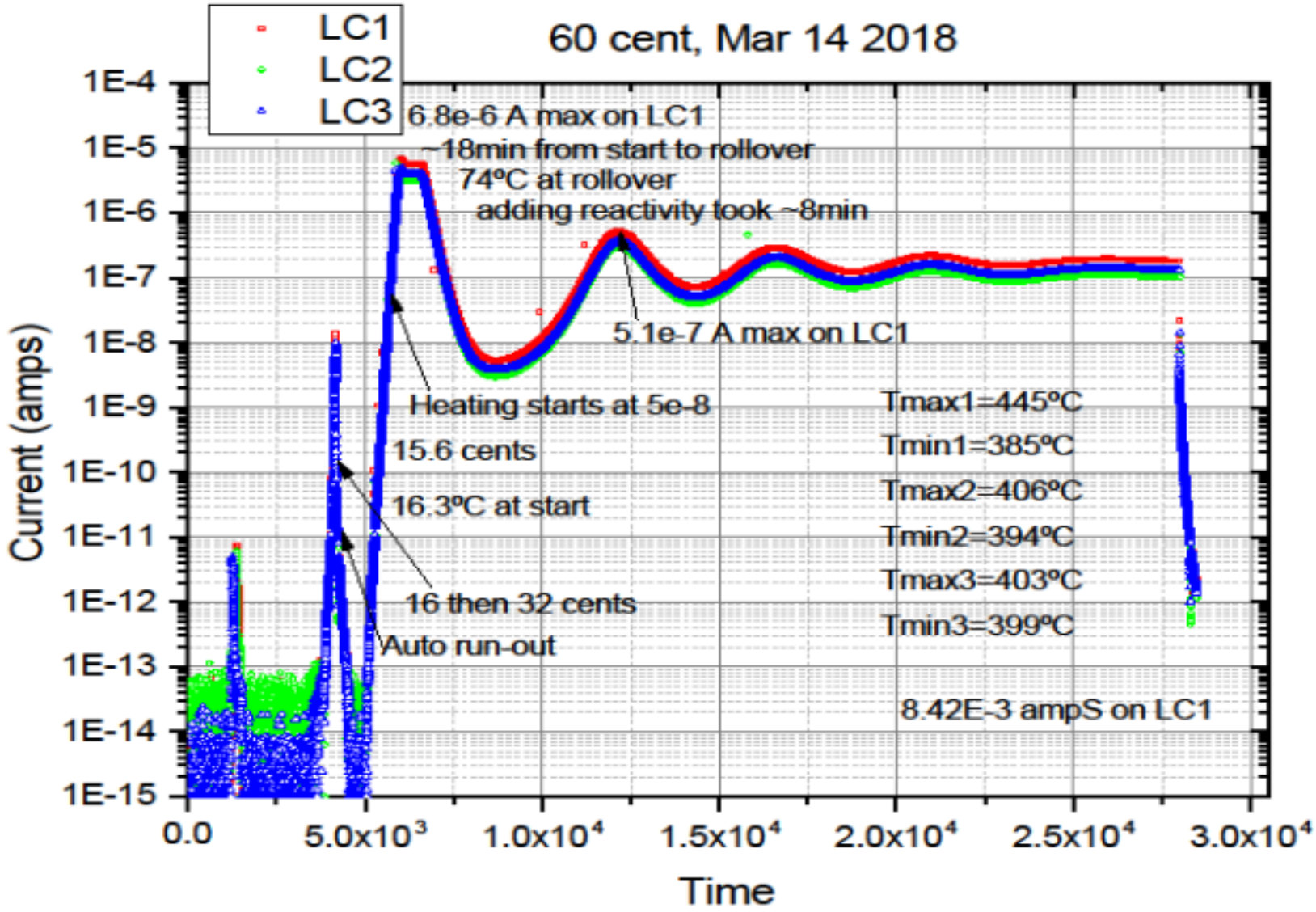
Free Run

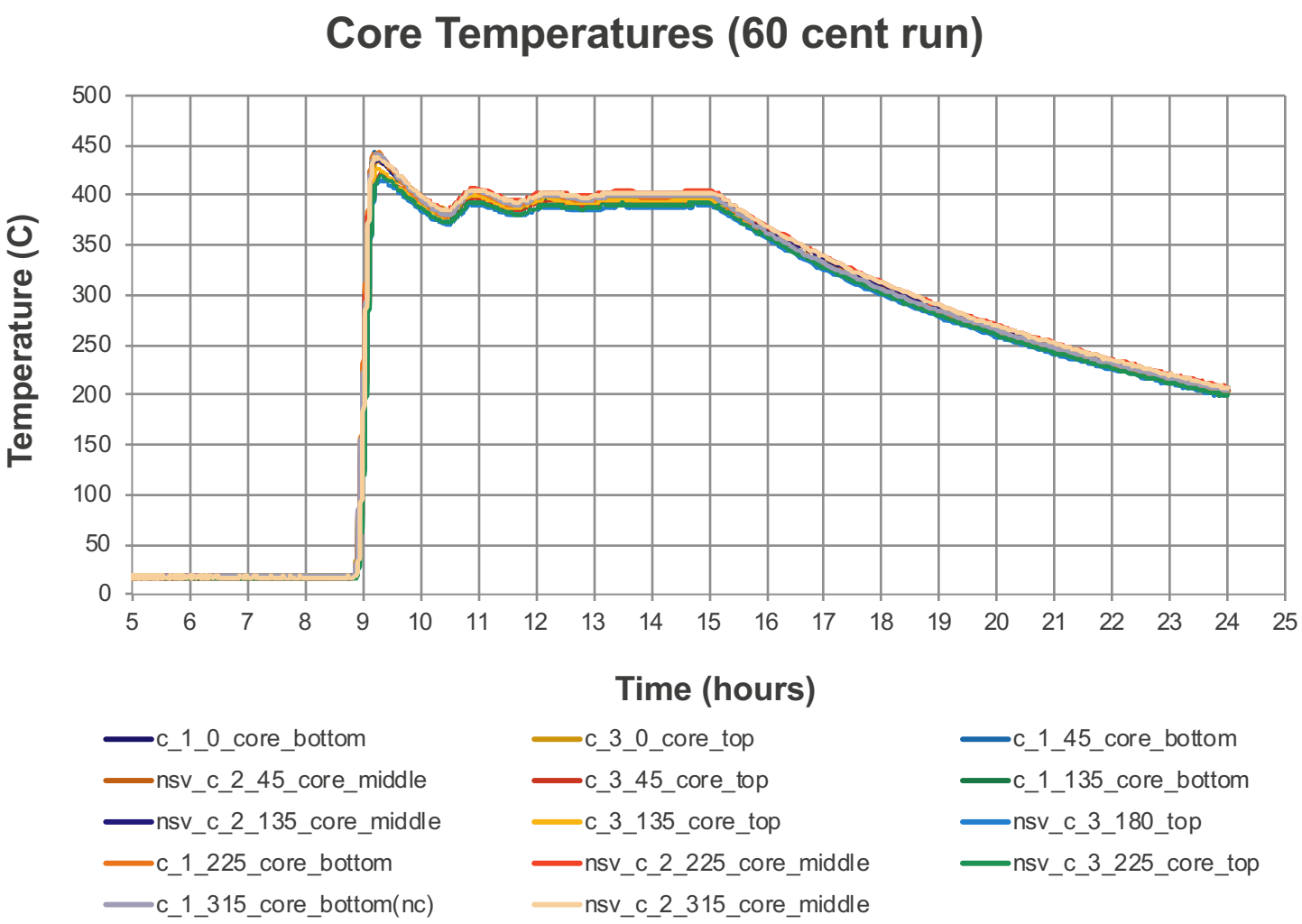

March 7, 2018 (15 Cent Free run)
AMPS
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
1.00E-14
5.00E+06
1.00E+07
1.50E+07
Time (ms)
452 watts = 1e-6
Peak 6.8e-6 = 3.07 kw
Linear 1
Linear 2
Linear 3


Core Tempeartures (15 cent free run)
Temperature (C)
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Time (hours)
c_1_0_core_bottom
c_3_0_core_top
c_1_45_core_bottom
c_3_45_core_top
c_1_135_core_bottom
c_3_135_core_top
c_3_180_core_top(nc)
c_1_225_core_bottom
c_3_225_core_top
c_1_315_core_bottom(nc)
c_2_315_core_middle
nsv_c_2_45_core_middle
nsv_c_2_135_core_middle
nsv_c_2_225_core_middle


30 cent, Mar 08 2018
LC1
LC2
LC3
6.6e-6 A max on LC1
~14min from start to rollover
adding reactivity took ~1min
Auto run-out
Tmax=288ºC on Sim3
at ~32 min from start
15.3 cents
31.5 cents
Sim1=20.45ºC
3.02E-3 ampS on LC1
Current (amps)
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
1E-14
1E-15
0.0
5.0x10³
1.0x10⁴
1.5x10⁴
Time


Core Temperatrures (30 cent run)
Temperature (C)
300
250
200
150
100
50
0
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
Time (hours)
nsv_c_2_45_core_middle
nsv_c_2_135_core_middle
nsv_c_2_225_core_middle


60 cent, Mar 14 2018
LC1
LC2
LC3
6.8e-6 A max on LC1
~18min from start to rollover
74ºC at rollover
adding reactivity took ~8min
5.1e-7 A max on LC1
Heating starts at 5e-8
15.6 cents
16.3ºC at start
16 then 32 cents
Auto run-out
Tmax1=445ºC
Tmin1=385ºC
Tmax2=406ºC
Tmin2=394ºC
Tmax3=403ºC
Tmin3=399ºC
8.42E-3 ampS on LC1
Current (amps)
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
1E-14
1E-15
0.0
5.0x10³
1.0x10⁴
1.5x10⁴
2.0x10⁴
2.5x10⁴
3.0x10⁴
Time


Core Temperatures (60 cent run)
Temperature (C)
500
450
400
350
300
250
200
150
100
50
0
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Time (hours)
c_1_0_core_bottom
c_3_0_core_top
c_1_45_core_bottom
nsv_c_2_45_core_middle
c_3_45_core_top
c_1_135_core_bottom
nsv_c_2_135_core_middle
c_3_135_core_top
nsv_c_3_180_top
c_1_225_core_bottom
nsv_c_2_225_core_middle
nsv_c_3_225_core_top
c_1_315_core_bottom(nc)
nsv_c_2_315_core_middle

NRC uses computer codes

- Fuel behavior
- Reactor kinetics
- Thermal-Hydraulic conditions
- Time-dependent dose for design basis accidents

  - PARCS
  - RELAP 5
  - TRAC

Simulation Model

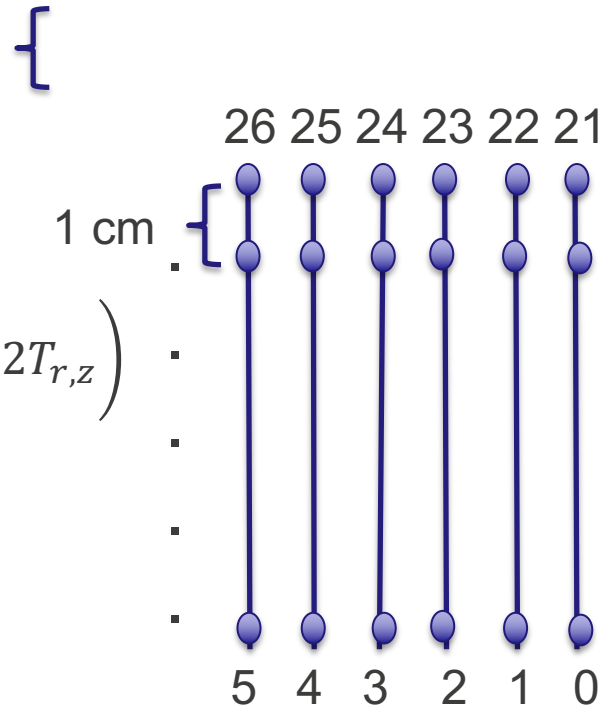
- Combines the point reactor kinetics model with a simple thermal model of the reactor fuel through a reactivity feedback model.
- The reactivity feedback coefficient and neutron importance were calculated using MCNP6.
- The simulation model was solved numerically using the Runge-Kutta method.

$$\frac{dP}{dt} = \frac{\beta}{\Lambda}\left[(R-1)P + \sum_i \left(\frac{\beta_i}{\beta}\right) D_i\right]$$

$$\frac{dD_i}{dt} = \lambda_i (P - D_i)$$

$$R = R_0 + \alpha_T \sum I_{r,z} \Delta T_{r,z}$$

Simulation Model (Cont.)



The fuel temperature at a given node point Is given by:

$$\frac{dT_{r,z}}{dt} = \frac{1}{\rho_f C_{pf}}\left(\frac{k_f}{dr^2}\left(\left(1-\frac{1}{2r}\right)T_{r-1,z}\right) + \left(1-\frac{1}{2r}\right)T_{r+1,z} - 2T_{r,z}\right)$$

$$+ \frac{k_f}{dz^2}\left(T_{r,z-1} + T_{r,z+1} - 2T_{r,z}\right) + \dddot{q}_{r,z})$$

Boundary condition

$$\frac{\partial T}{\partial r} = \frac{\partial T}{\partial z} = 0$$

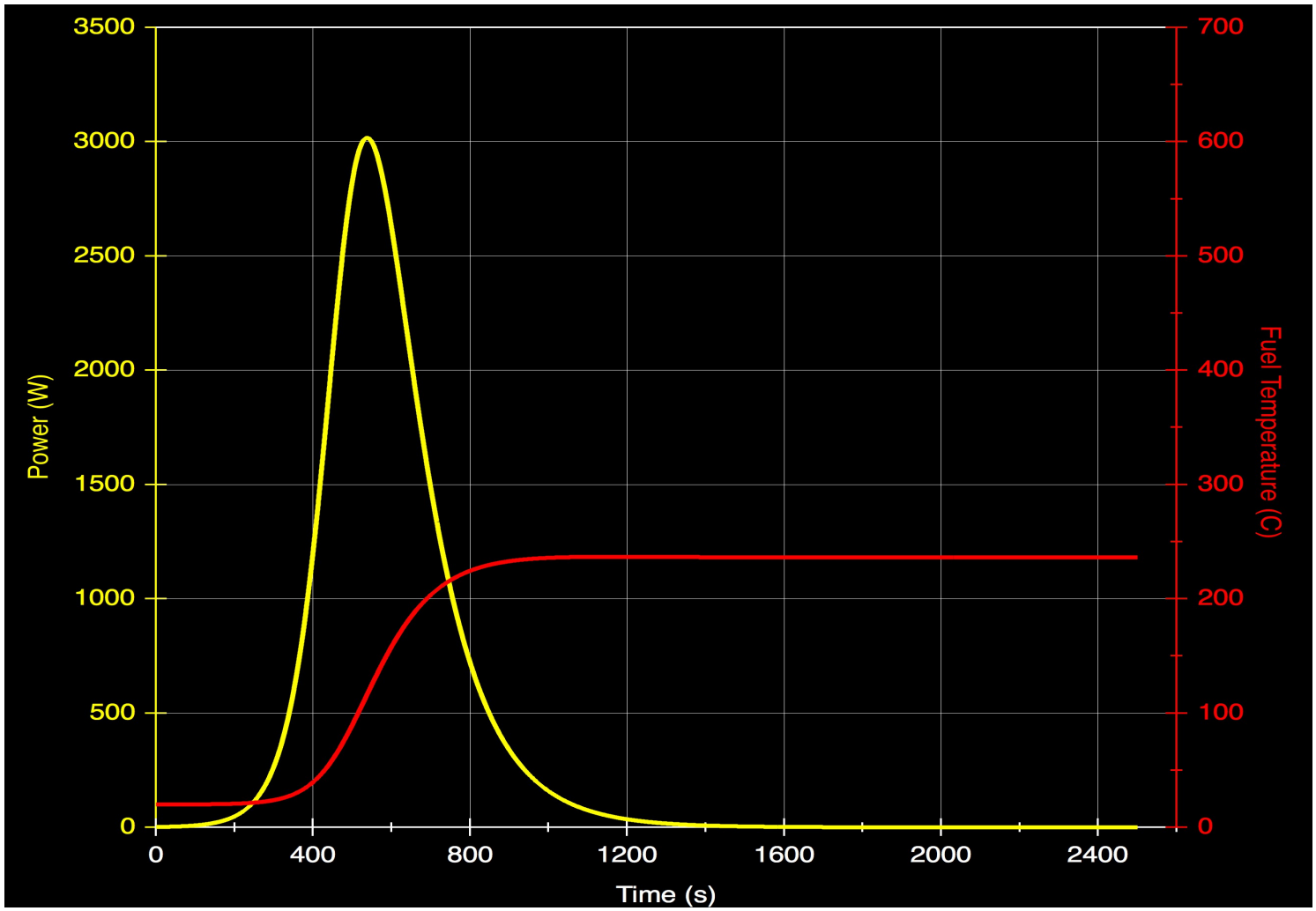
Power (heat generation)

$$\dddot{q}_{r,z} = P_0 P f_{r,z}$$

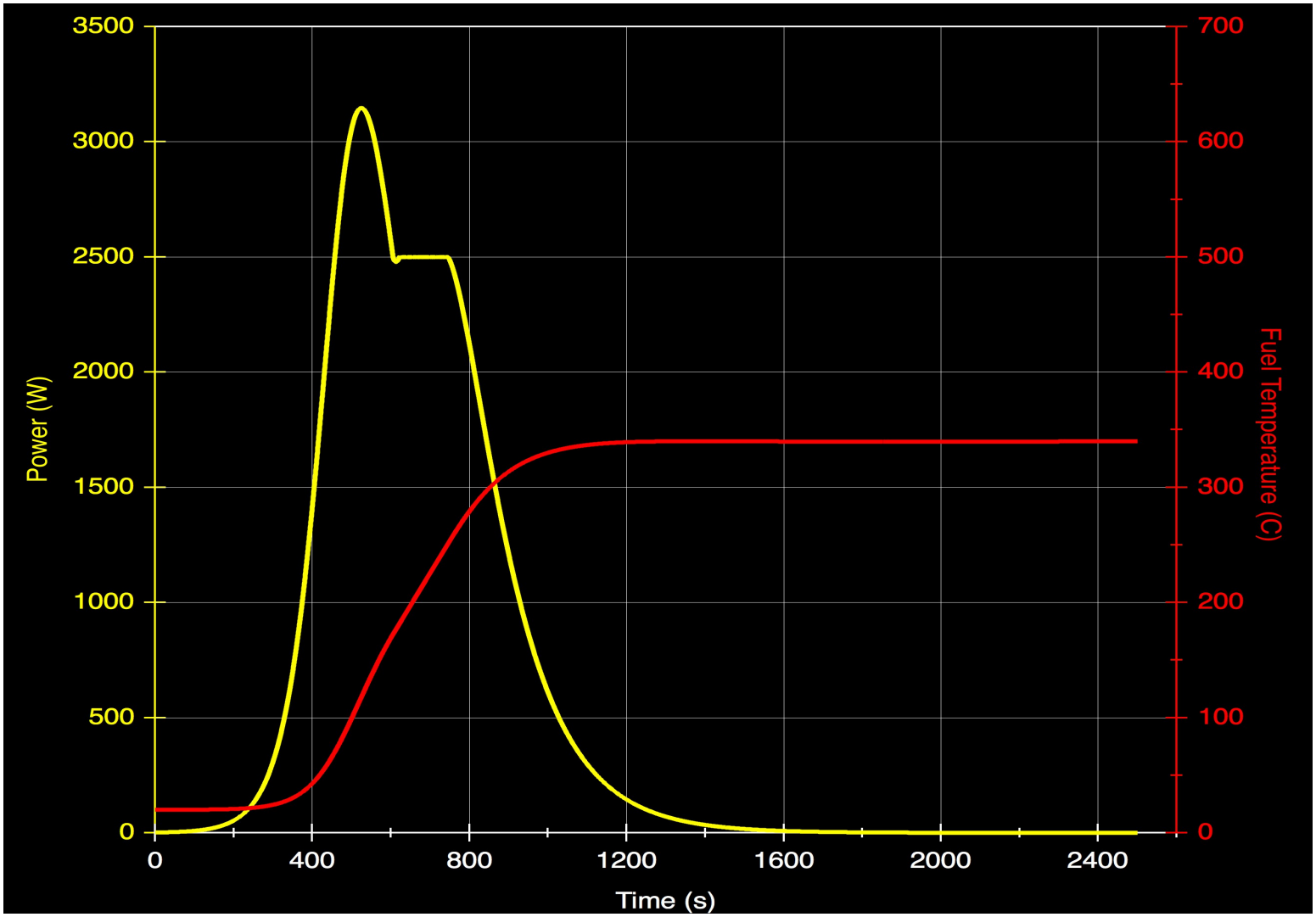
Thermal properties did not change as a function of time and temperature.

The importance function and the energy deposition did not change as a function of time and temperature

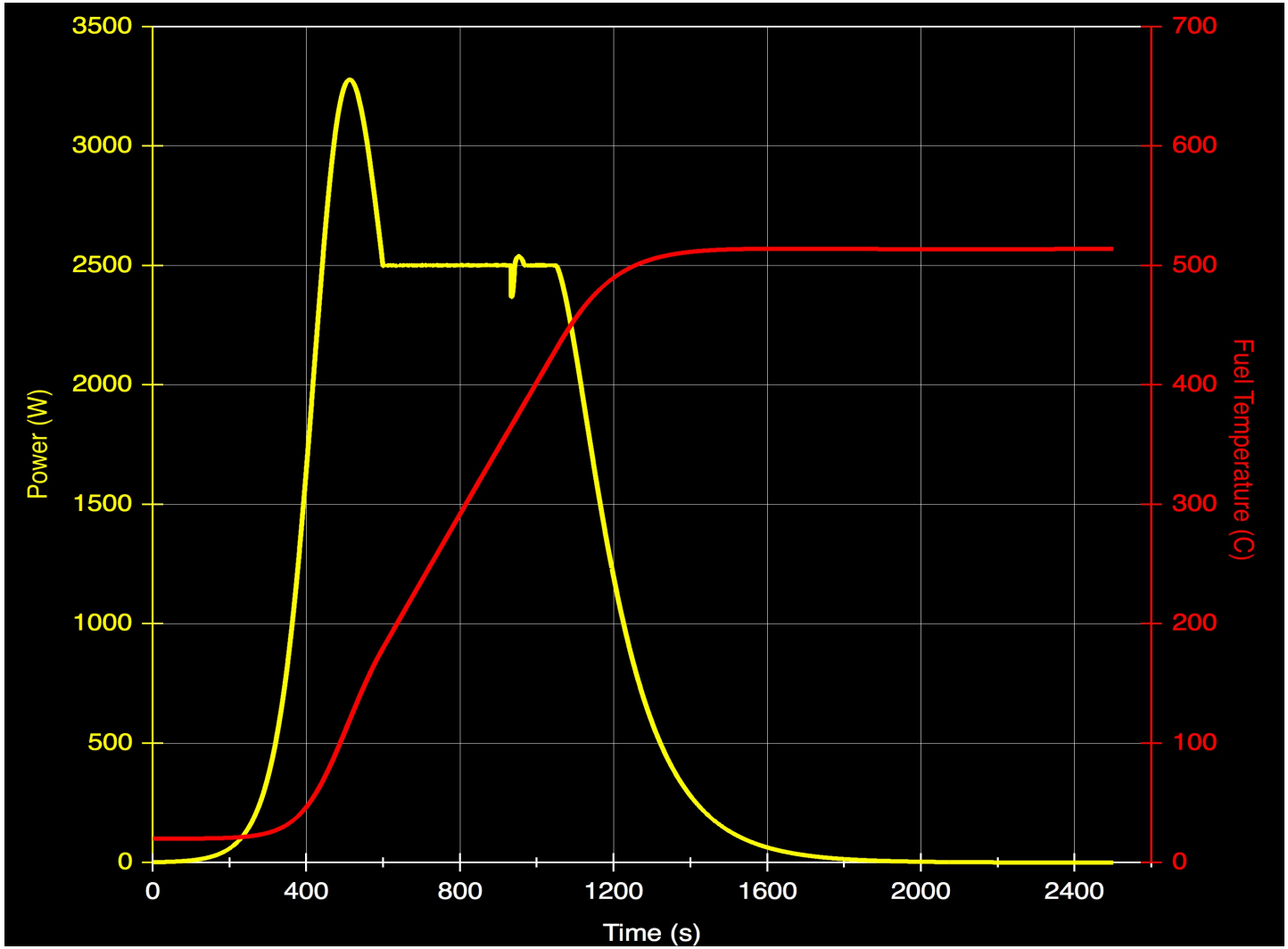
Simulation of the 15 Cent Free run

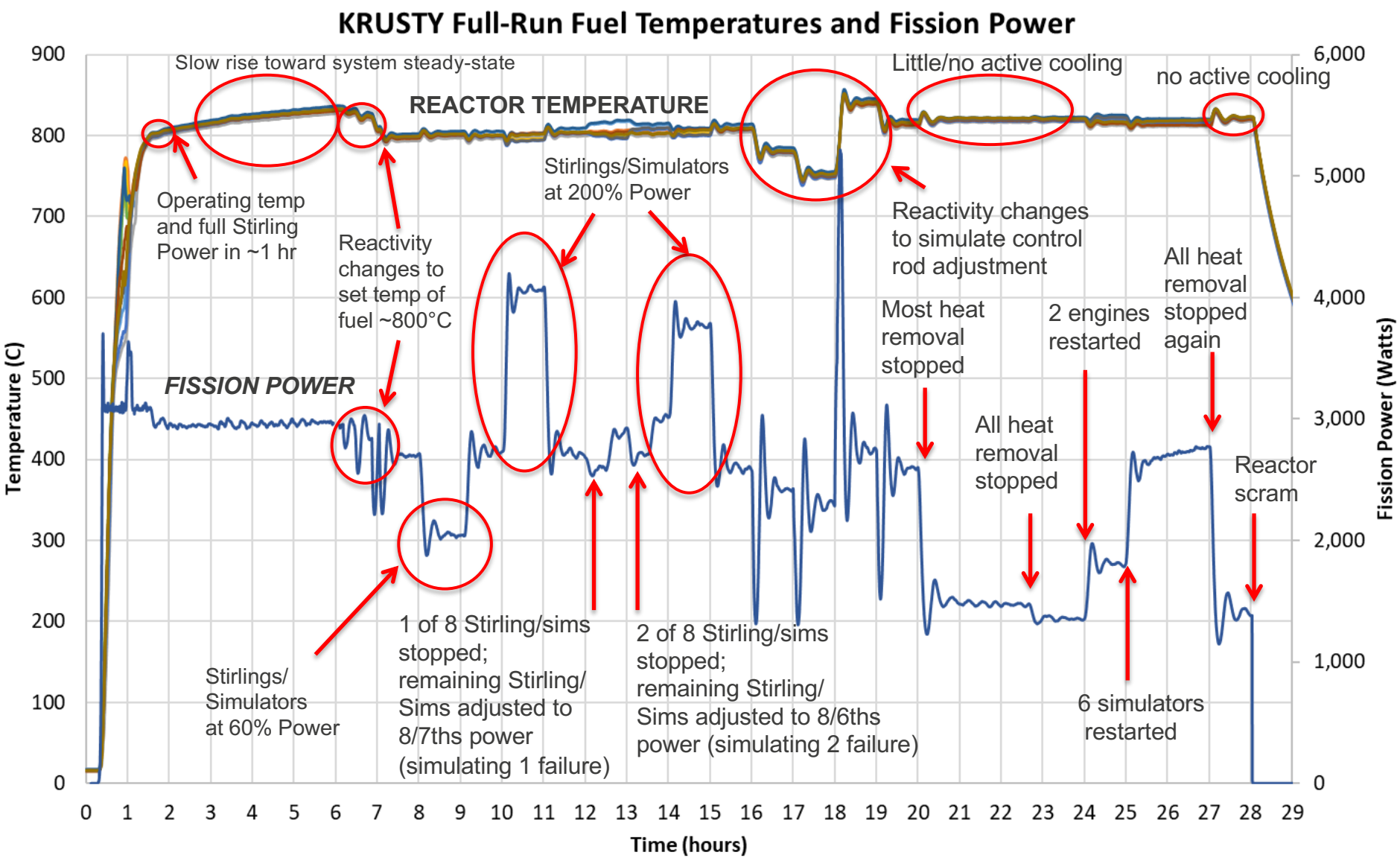


Simulation of the 30 cent run

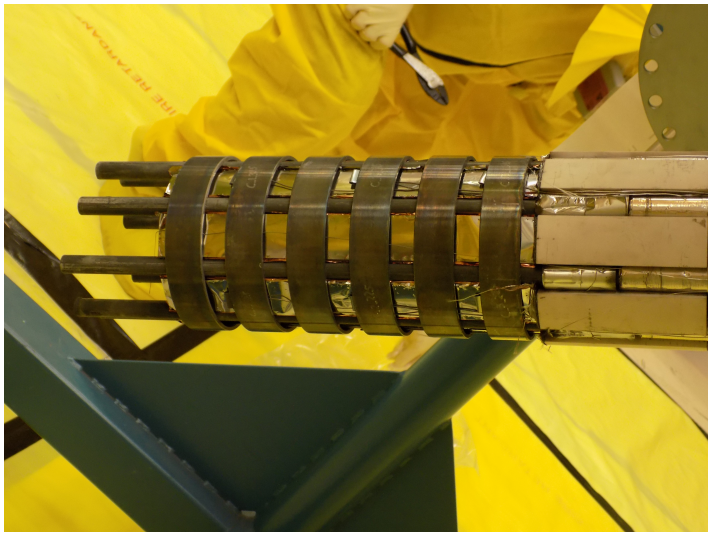


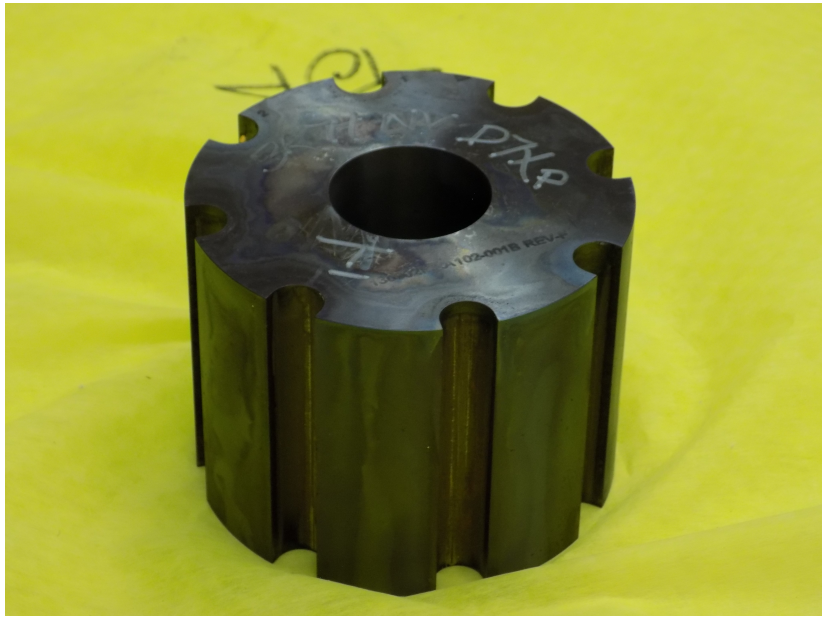
Simulation of the 60 cent run

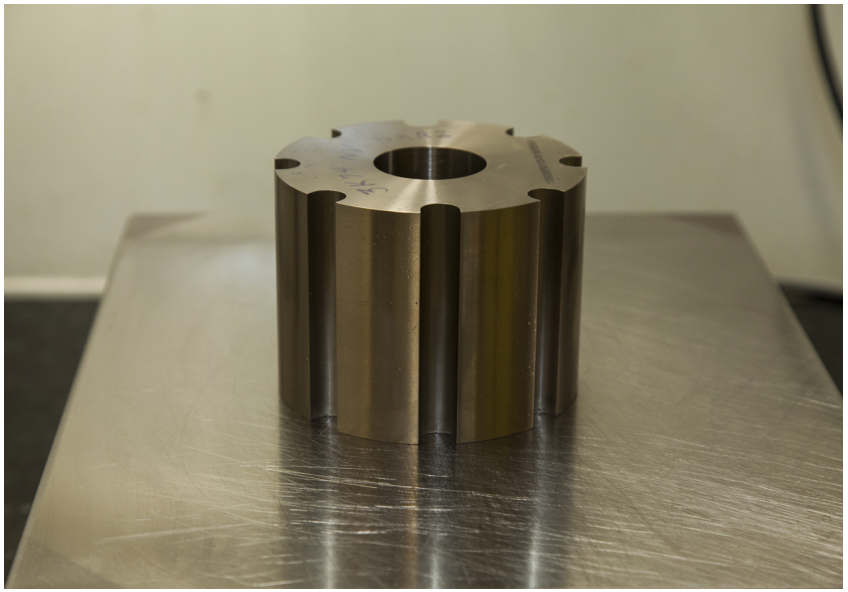



KRUSTY Full-Run Fuel Temperatures and Fission Power
Temperature (C)
Fission Power (Watts)
Time (hours)
REACTOR TEMPERATURE
FISSION POWER
Slow rise toward system steady-state
Operating temp and full Stirling Power in ~1 hr
Reactivity changes to set temp of fuel ~800°C
Stirlings/ Simulators at 60% Power
1 of 8 Stirling/sims stopped; remaining Stirling/ Sims adjusted to 8/7ths power (simulating 1 failure)
Stirlings/Simulators at 200% Power
2 of 8 Stirling/sims stopped; remaining Stirling/ Sims adjusted to 8/6ths power (simulating 2 failure)
Little/no active cooling
Reactivity changes to simulate control rod adjustment
Most heat removal stopped
All heat removal stopped
2 engines restarted
6 simulators restarted
no active cooling
All heat removal stopped again
Reactor scram

Disassembly of KRUSTY







- **Weight 10.741 vs 10.7415 kg**
- **Density** ~ 17.4 g/cc
- **Uranium alloy (~7.5 wt% Mo)**
- **The uranium is isotopically enriched to ~ 93 wt% ^{235}U**
- **400 mR/hr at contact.**
- **70 k DPM**

Summary

- The simulation model results compared favorably to the experimental results (15 cent, 30 cent, and 60 cent).
- Thermal properties must change as a function of temperature.
- Importance function and energy deposition on each node must change as a function of time.
- Other models such natural convection for the heat pipes and radiative heat transfer from the fuel must be added so that the complete point kinetics-heat transfer model can attempt to simulate the 28-hr high temperature run.

Acknowledgement

This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.