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Delivering science and technology
to protect our nation
and promote world stability

NNSA
National Nuclear Security Administration
Operated by Triad National Security for the U.S. Department of Energy's NNSA

National Criticality Experiments Research Center (NCERC) Recent Measurements and Capabilities

GAIN-EPRI-NEI-US NIC Micro-Reactor Workshop

Nicholas Thompson, Rene Sanchez, Jesson Hutchinson, Rian Bahran, David Hayes, William Myers, Jennifer Arthur, John Bounds, Theresa Cutler, Derek Dinwiddie, Joetta Goda, Travis Grove, Robert Little, George McKenzie, Alex McSpaden, Avneet Sood, Morgan White

June 19th, 2019

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NNSA National Nuclear Security Administration

Operated by Triad National Security for the U.S. Department of Energy's NNSA

LA-UR-19-25526

National Criticality Experiments Research Center (NCERC)

- Located at the Device Assembly Facility (DAF) at the Nevada National Security Site (NNSS)
- NCERC is operated by Los Alamos National Laboratory
- Four critical assemblies (including Godiva, which can be operated above prompt critical).
- Subcritical measurements are also performed.

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NEVADA NATIONAL NNSS SECURITY SITE

NCERC NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER

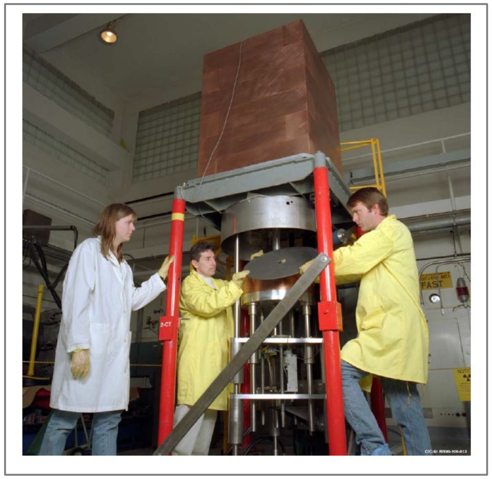
National Criticality Experiments Research Center (NCERC)

- **NCERC is the only general-purpose critical experiments facility in the US and is one of only a few that remain operational throughout the world**

- **Operated from 1946-2004 at Los Alamos National Laboratory, then moved to the Nevada National Security Site (NNSS), previously known as the Nevada Test Site.**

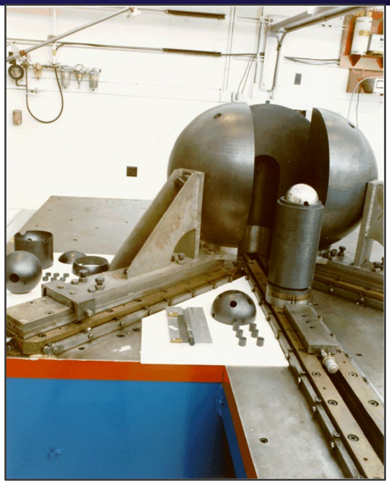
- **NCERC supports US Government programs and missions – also has national and international collaborations**
  - US universities and commercial partners
  - United Kingdom (AWE), France (IRSN, CEA), Japan (JAEA).

Critical Assemblies

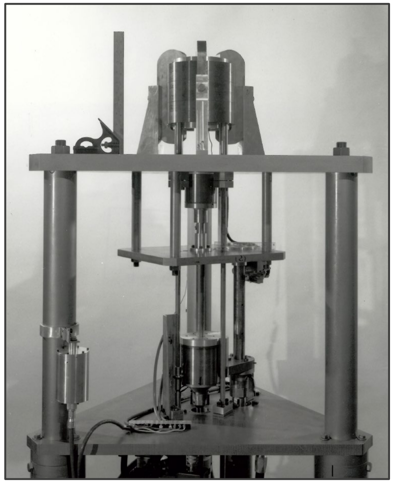


Comet: General purpose heavy duty vertical lift assembly

Planet: General purpose light duty vertical lift assembly



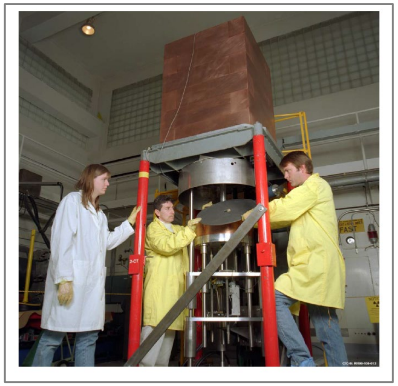
Flat-Top: Fast critical assembly

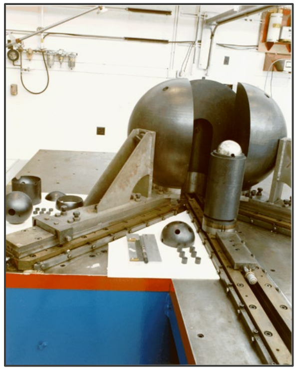


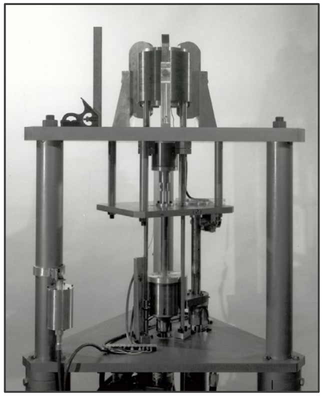
Godiva IV: Fast burst assembly

- **Critical Benchmarks (ICSBEP)**
- **Sample irradiations and reactivity worth measurements**
- **Reactivity ranges from subcritical to above prompt critical**
- **Thermal, intermediate, and fast neutron energy spectrum**
- **HEU, Natural U, Pu, etc.**

Recent Measurements







- **Comet**
  - JAEA U-Lead and Pu-Lead
  - NASA KRUSTY Kilopower
  - Sample irradiations
  - ICSBEP (Zeus, JAEA U-Lead and Pu-Lead)
- **Planet**
  - NCSP training
  - Sample irradiations
  - Alternative nuclear materials
  - ICSBEP (NCSP projects)
  - TEX
- **Flat-Top**
  - NCSP training
  - Sample irradiations
  - NASA DUFF
  - ICSBEP (NCSP projects)
- **Godiva IV**
  - NCSP training
  - Sample irradiations
  - NCSP projects
  - ICSBEP (NCSP projects)
- **Subcritical**
  - NCSP Training
  - University consortia
  - IRSN and AWE measurements

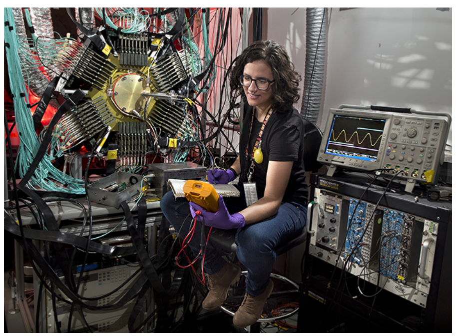
Flexibility

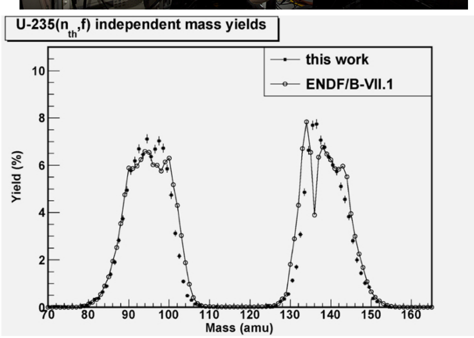
- **HEU, Natural U, Pu**
  - HEU and Natural U can be mixed to get different “effective” enrichments
- **Moderators, reflectors, other materials can be added easily**
- **Energy spectrum can be tuned**

Integral Measurements

Differential Measurements

- Measuring nuclear data, fundamental physics





Integral Measurements

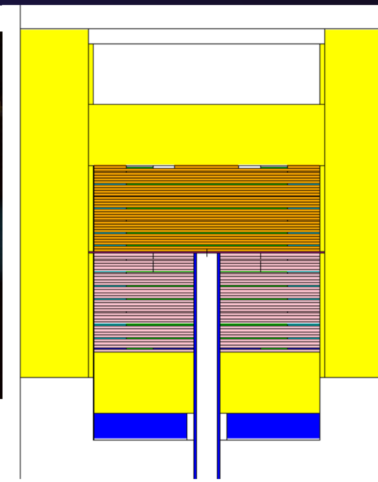
- Core loading/approach to critical
- Low power critical tests
- Flux measurements/mapping
- Void coefficients
- Temperature coefficients
- Reactivity measurements
  - Excess reactivity
  - Shutdown reactivity
- Control rod worth

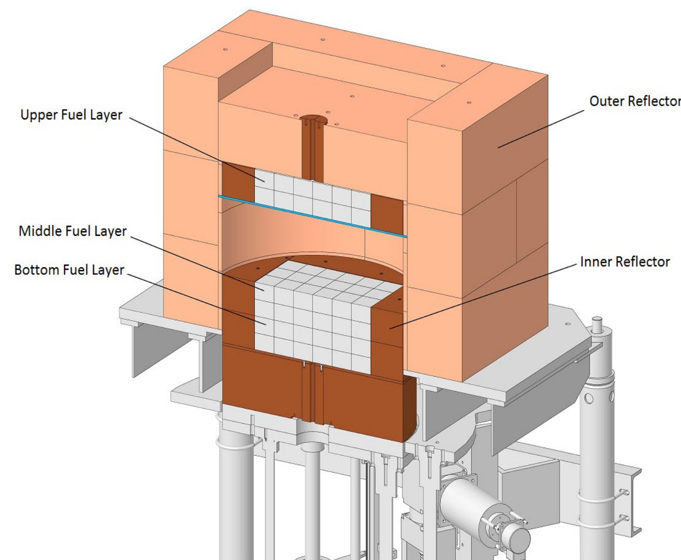
Large Scale Tests

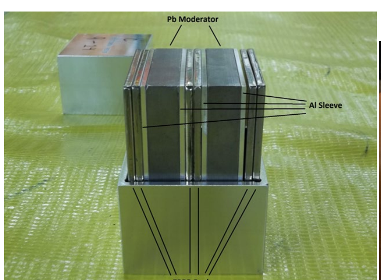
- High power demonstrations

Lead (Pb) Void Coefficient Measurements

- **Recent lead (Pb) measurements**
  - No intermediate-energy Pb benchmarks exist!
  - JAEA was very interested in performing such measurements
    - For applications with future ADS systems
  - Three experimental series (each with multiple configurations) were performed.
    - HEU: “Jemima” plates (~21 kg of HEU) with lead matrix material and Cu reflector.
    - HALEU: “Jemima” plates (~21 kg of HEU) and Nat U plates (to give “effective” enrichment of ~21%) with lead matrix material and Cu reflector.
    - Pu: ZPPR fuel plates (3” x 2” x 0.25”) and lead plates with Cu reflector.
  - Coming to ICSBEP “soon”.

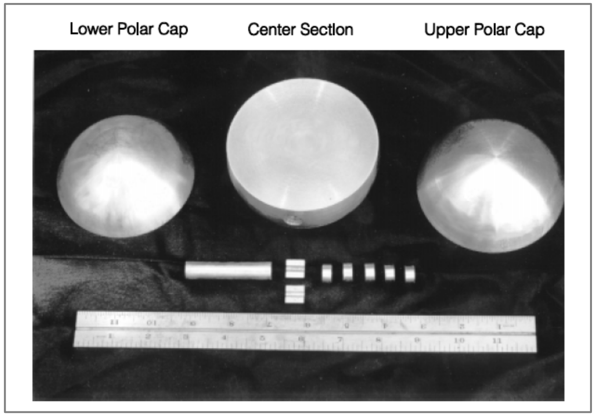






Subcritical mass measurements

- **High neutron multiplication, static objects (bare, reflected, moderated)**
- **Subcritical benchmarks for nuclear data/radiation transport code validation**
  - International Criticality Safety Benchmark Evaluation Project (ICSBEP)



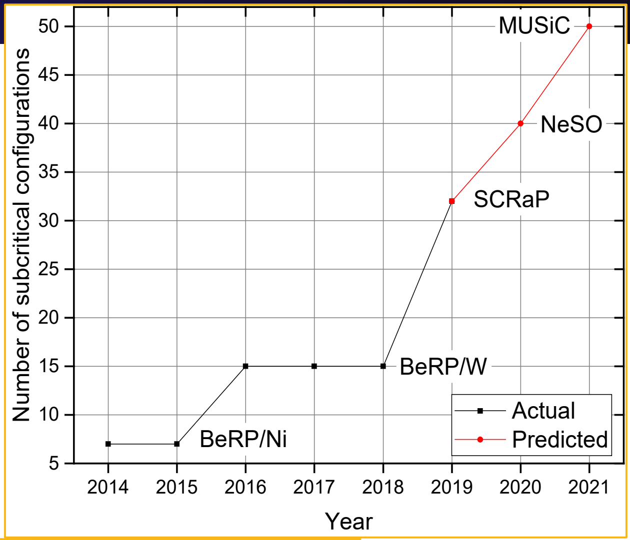
Thor core
9.6 kg delta-phase Pu-239

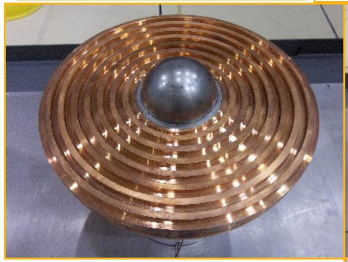
BERP Ball
4.5 kg alpha-phase Pu (94 wt% Pu-239)

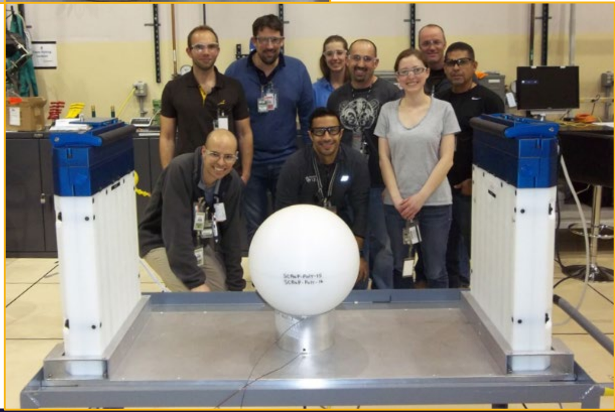
Rocky Flats shells
Metal HEU nesting hemishells

Recent Subcritical Experiments

- **Growing dataset of neutron multiplication benchmarks experiments/evaluations**
  – Culmination of several years of sub-critical experiment research
  – Goal is to validate nuclear data and computational methods
- **BeRP-Ni (published in 2014)**
  – Executed in 2012, ICSBEP evaluation published in 2014
- **BeRP-W (published in 2016)**
  – Sub-critical tungsten-reflected α-phase Pu
  – Executed in 2012, ICSBEP evaluation published in 2016
- **SCRαP (published in 2018)**
  – Sub-critical copper/poly-reflected α-phase Pu
  – Executed in 2016, ICSBEP evaluation published in 2018

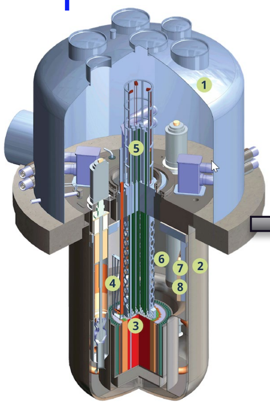






Designing critical experiments

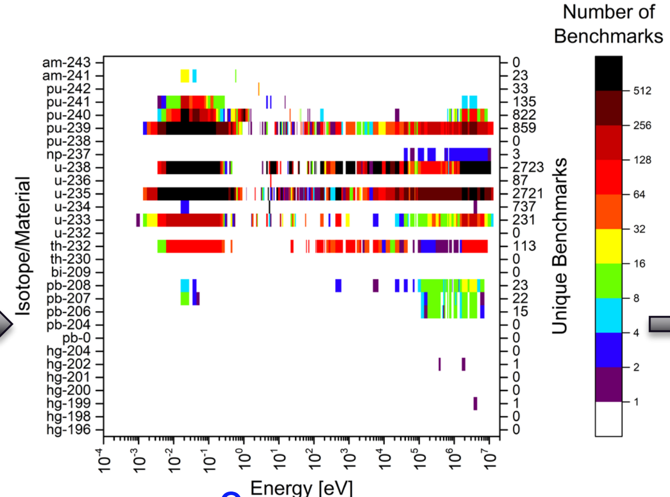
1



2

MCNP6

$$S_{k,x} = \frac{dk/k}{dx/x} = -\frac{\langle \psi^\dagger, (\Sigma_x - S_x - k^{-1}F_x)\psi \rangle}{\langle \psi^\dagger, k^{-1}F\psi \rangle}$$



3

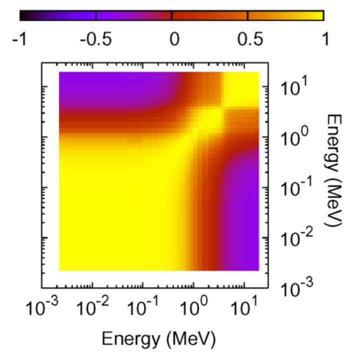


FIG. 6: Correlation matrix for the capture cross section of n+^{235}U.

4

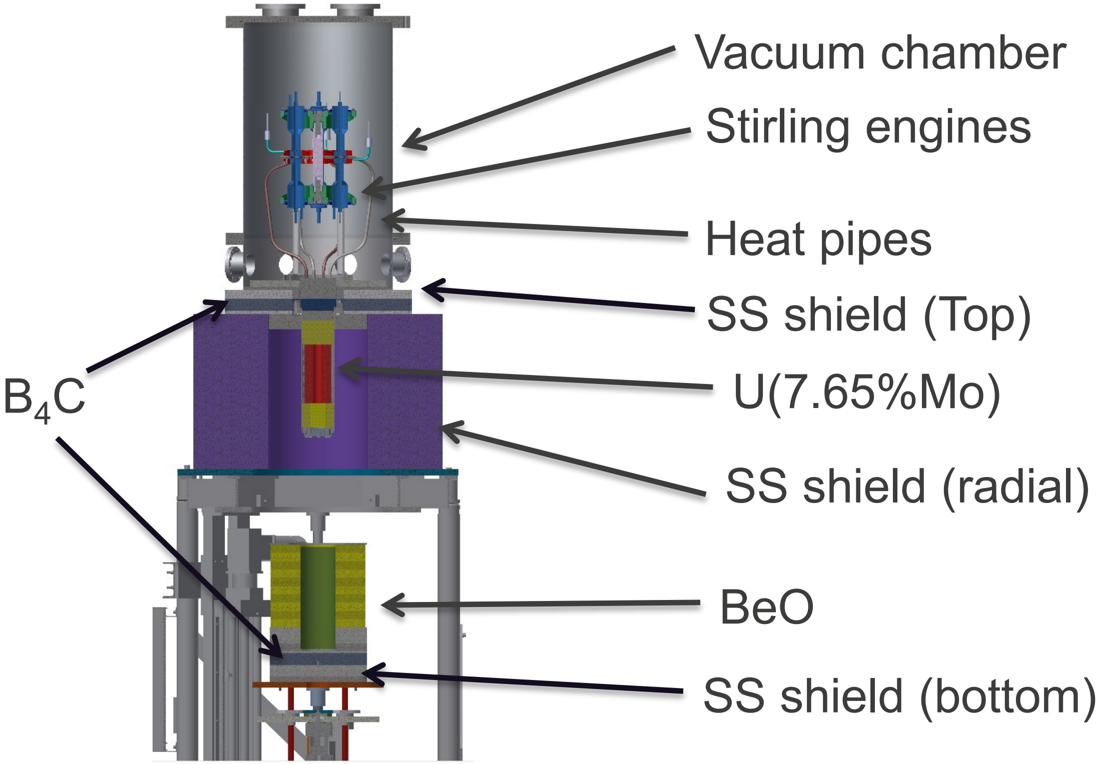
1: **Generate model** (Monte Carlo or deterministic) of application for radiation transport simulations.
2: Perform cross-section **sensitivity simulations**.
3: Perform a **gap analysis** to investigate if similar benchmarks exist.
4: Perform **optimization** to design new experiments that are more sensitive to the application than existing benchmarks.

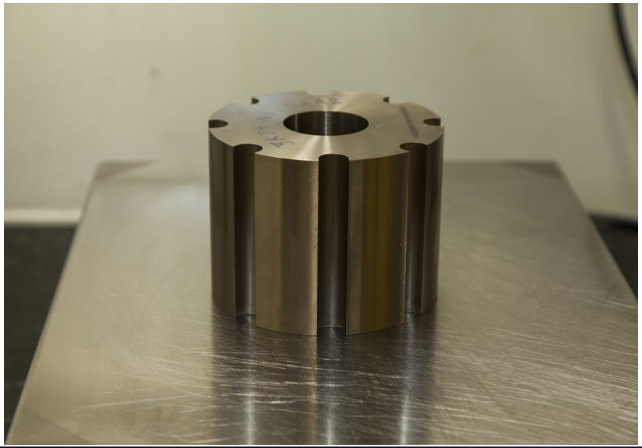
KRUSTY/Kilopower Overview

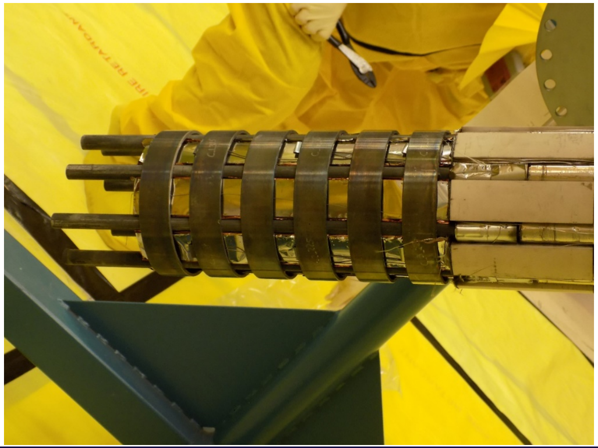
- Joint program with DOE and NASA
- The main objective of the KRUSTY experiment is to evaluate the operational performance of a compact reactor that closely resembles the flight unit NASA will use for deep space exploration missions.
- Test the dynamic behavior of the reactor (transients).
- Verify the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

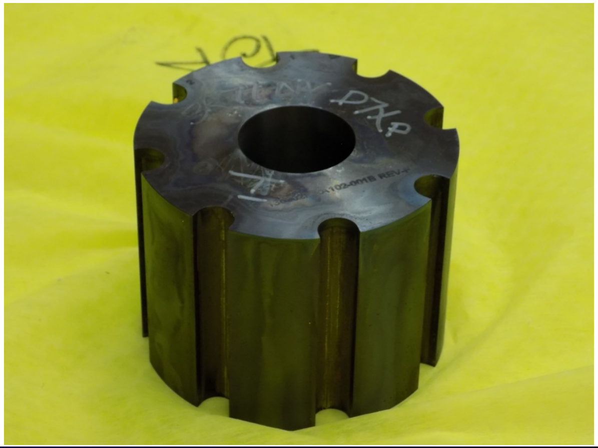
National Nuclear Security Administration

KRUSTY

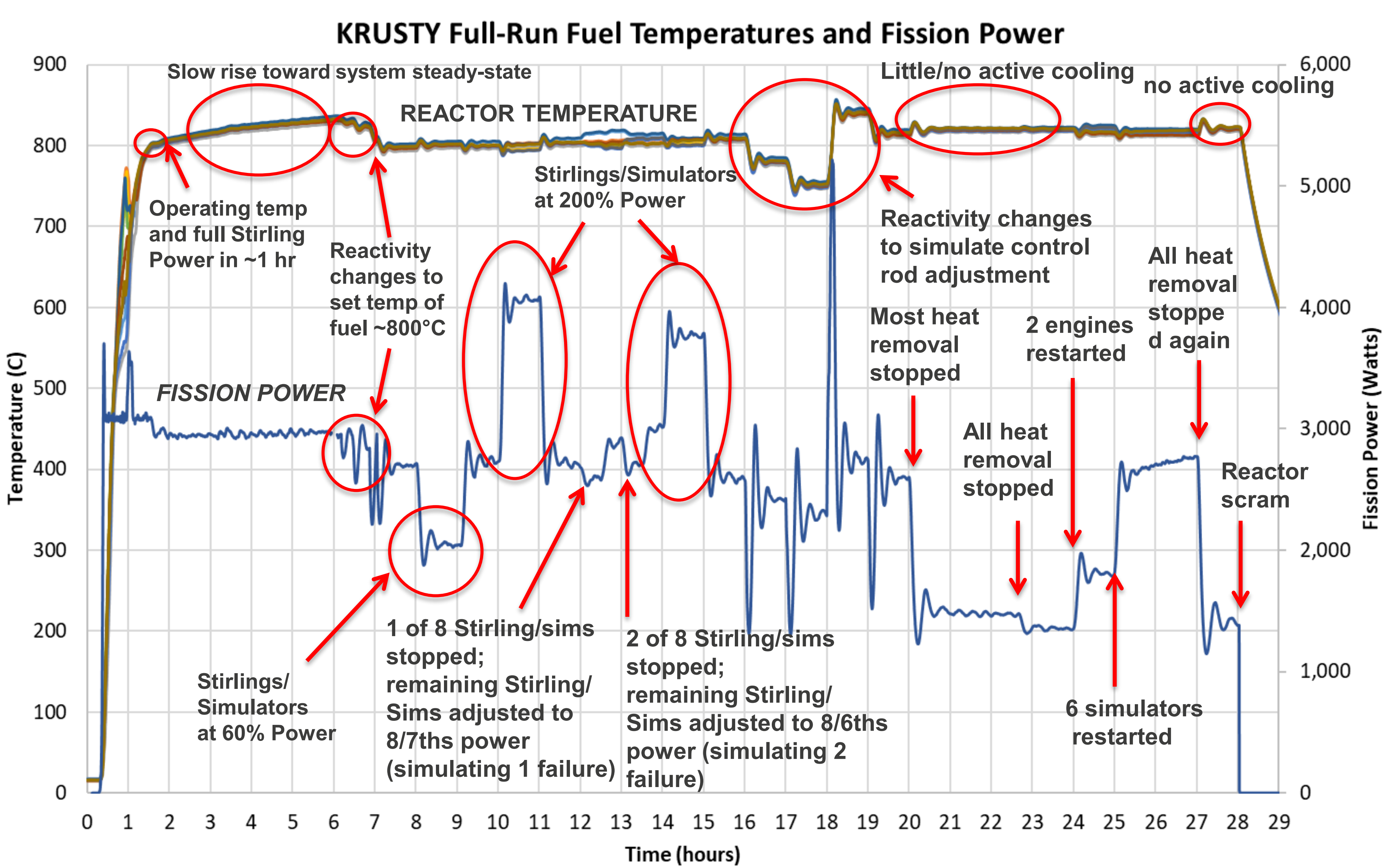

Vacuum chamber
Stirling engines
Heat pipes
SS shield (Top)
B_4C
U(7.65%Mo)
SS shield (radial)
BeO
SS shield (bottom)







High temperature 28 hour run, with transients



Acknowledgements

- NCERC is supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.
- NASA, in collaboration with the DOE, supported the KRUSTY experiments.

To get in touch about questions or collaborations:
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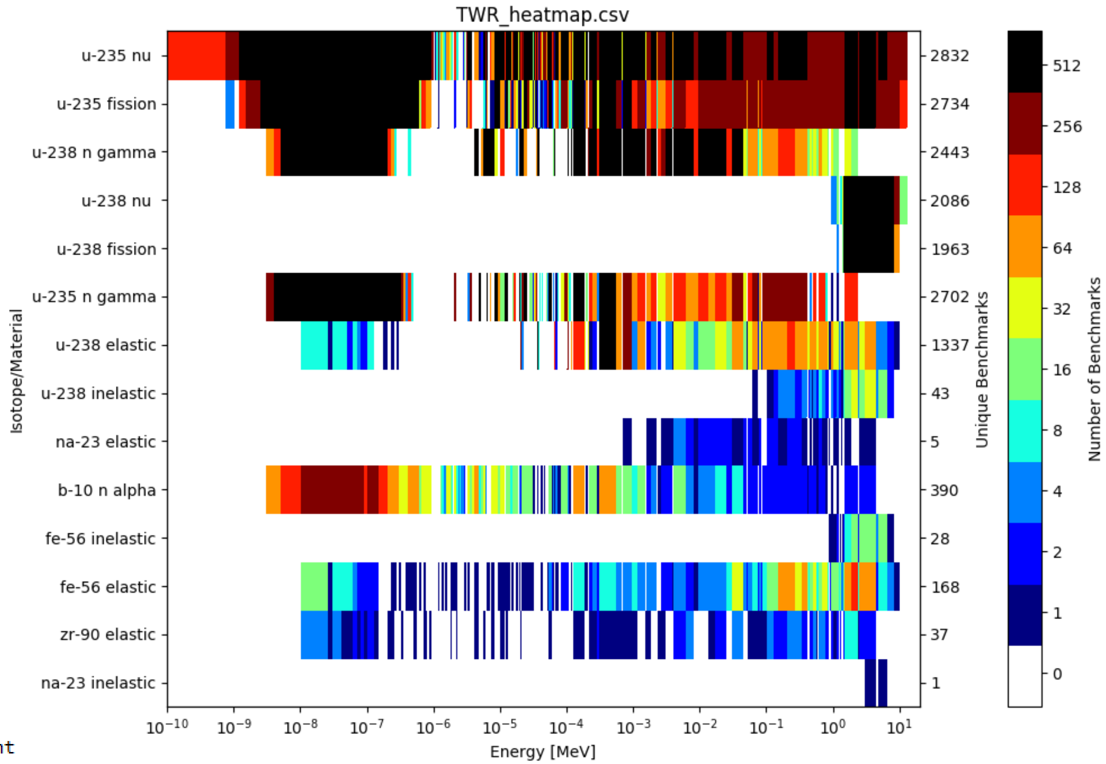
Backup slides

TWR Example

List of ranked reactions for TWR (based on |k_{eff} sensitivities|).

Nuclide	Reaction	keff sensitivity		
92235.80c	nu	8.48E-01	±	6.48E-04
92235.80c	fission	5.48E-01	±	6.53E-04
92238.80c	n,gamma	-2.34E-01	±	1.65E-04
92238.80c	nu	1.52E-01	±	2.70E-04
92238.80c	fission	9.32E-02	±	2.79E-04
92235.80c	n,gamma	-7.16E-02	±	5.83E-05
92238.80c	elastic	4.54E-02	±	2.61E-03
92238.80c	inelastic	-3.98E-02	±	8.97E-04
11023.80c	elastic	1.60E-02	±	2.00E-03
5010.80c	n,alpha	-1.45E-02	±	5.54E-05
26056.80c	inelastic	-1.32E-02	±	2.90E-04
26056.80c	elastic	1.31E-02	±	1.73E-03
40000.58c	elastic	1.31E-02	±	1.44E-03
11023.80c	inelastic	-8.54E-03	±	3.33E-04



benchmark	ck	weight
ZLEU36_0V_endf.i	0.9404	1.0000
ieu-met-fast-005-001.i	0.9304	0.9153
heu-met-fast-038-002.i	0.9235	0.8572
heu-met-fast-030-001.i	0.9135	0.7726
ieu-met-fast-006-001.i	0.9134	0.7712
ieu-met-fast-004-001.i	0.9109	0.7501
ieu-met-fast-002-001.i	0.9086	0.7309
ieu-met-fast-001-004.i	0.8947	0.6127
ieu-met-fast-003-001.i	0.8936	0.6034
heu-met-mixed-004-001.i	0.8914	0.5843

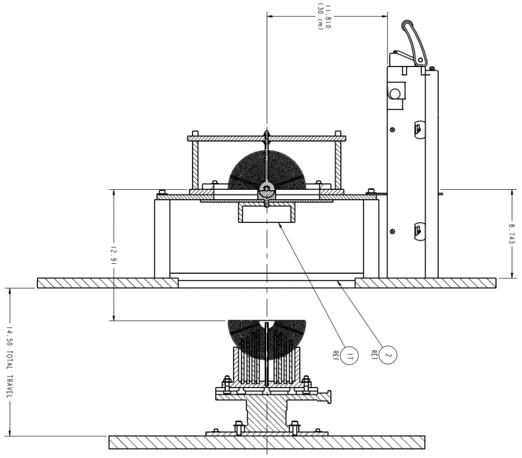
Heatmap for the top 14 reactions. Benchmarks included are those that exceed a sensitivity threshold of > 10^{-3} for that energy bin.

List of ICSBEP cases ranked by c_k for the TWR application.

- The highest c_k is actually from the Comet HEU/Pb experiment (not in ICSBEP yet).

Select Upcoming Measurements

- **NeSO - Neptunium**
  - Sub-critical Neptunium w/various reflectors
- **MUSIC – Rocky Flats shells**
  - Hemishells of HEU and aluminum
- **GODIVA IV Neutron Noise**
  - Fast detectors and electronics
- **CURIE – Uranium URR/Intermediate**
  - Jemima plates layered with Teflon



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)

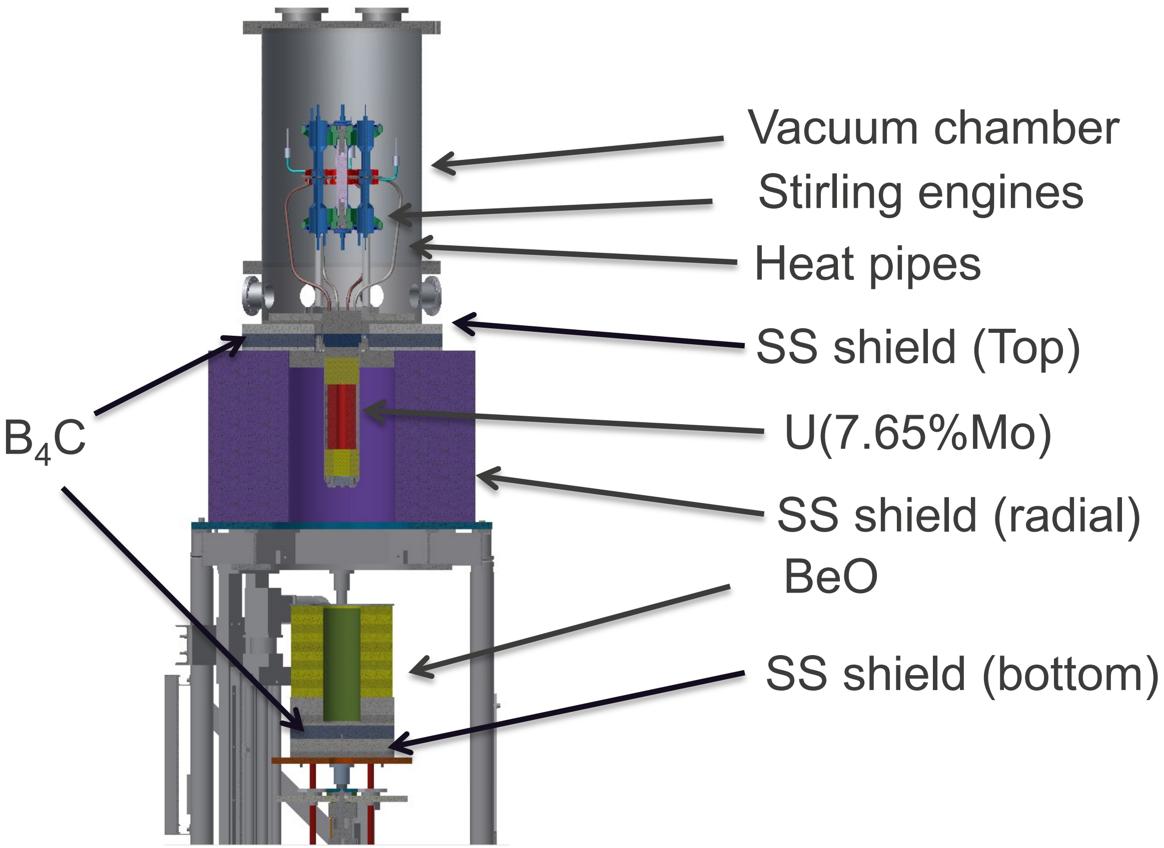
Warm Criticals (Phase 3)

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

High Temperature run (Phase 4)

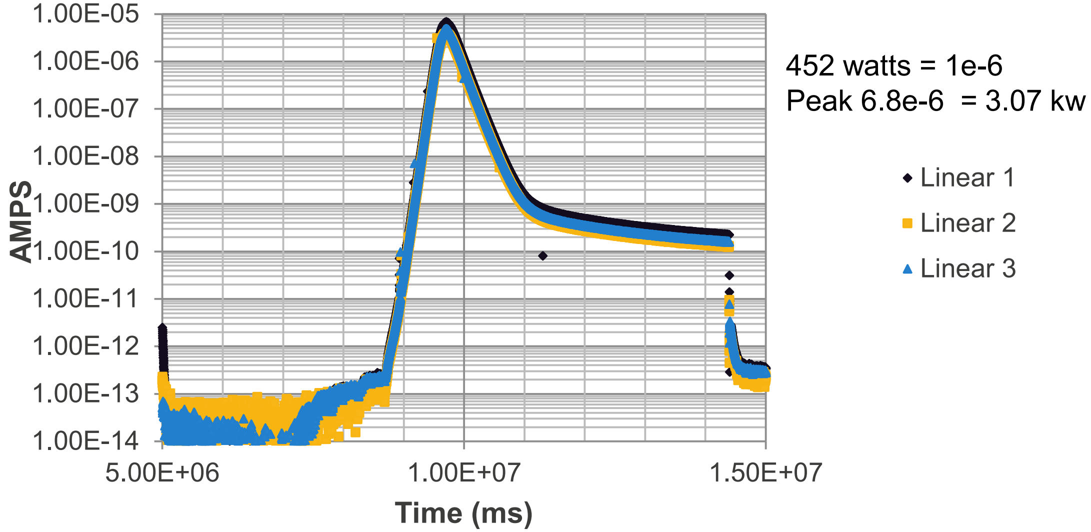
- Operating Reactor at high temperature (800°C) for 28-hr and performing some transients while operating at full power.

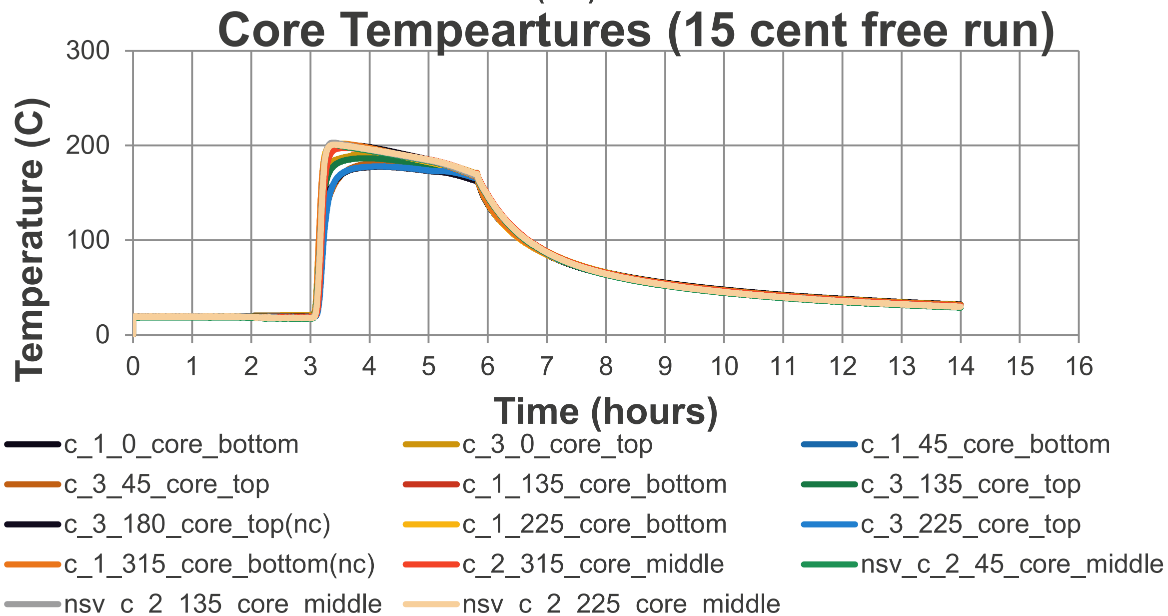
KRUSTY

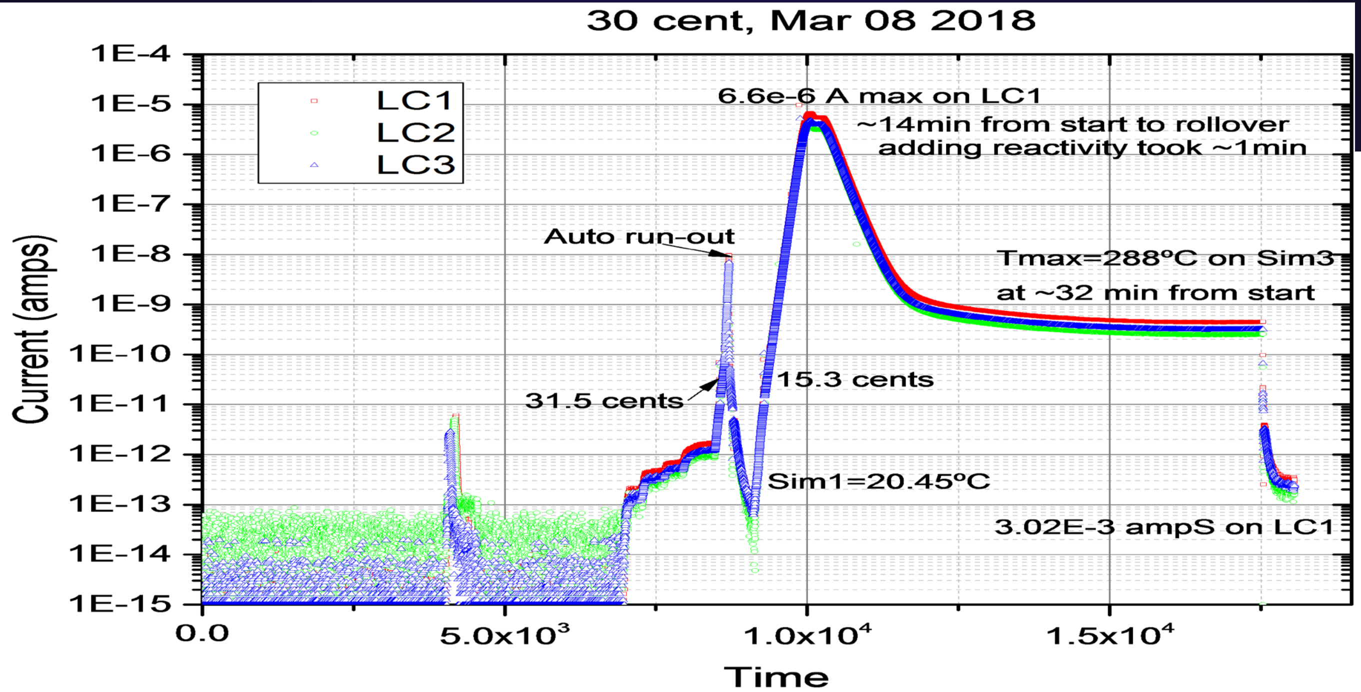

Vacuum chamber
Stirling engines
Heat pipes
SS shield (Top)
B_4C
U(7.65%Mo)
SS shield (radial)
BeO
SS shield (bottom)

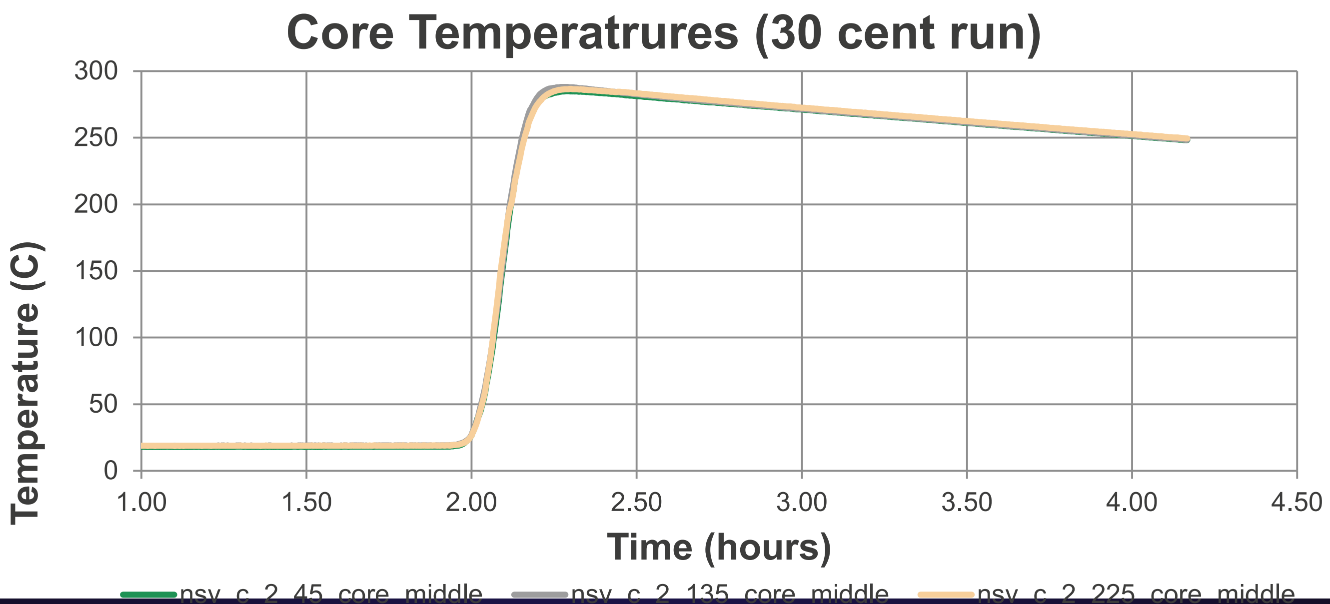
Free Run

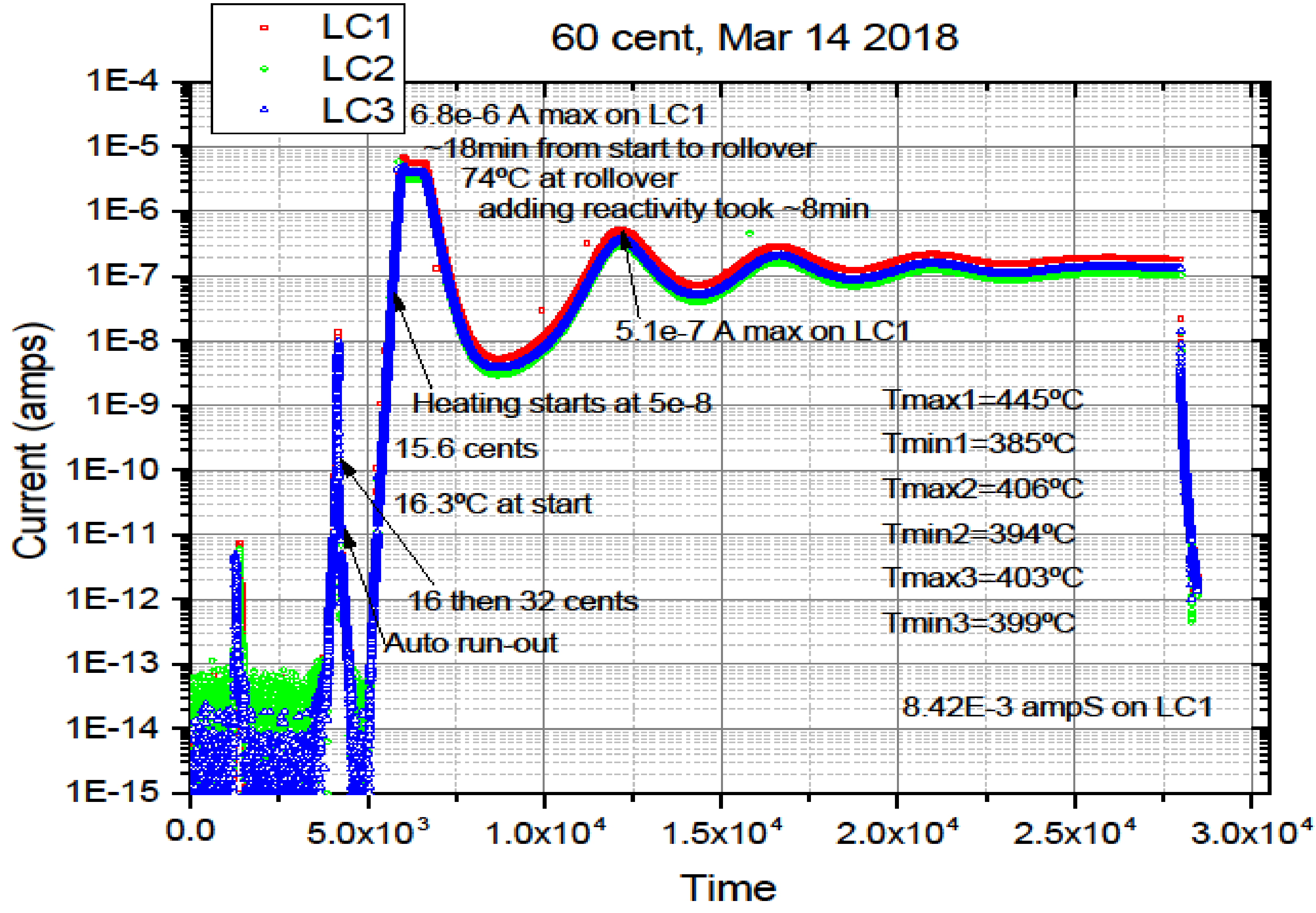
March 7, 2018 (15 Cent Free run)





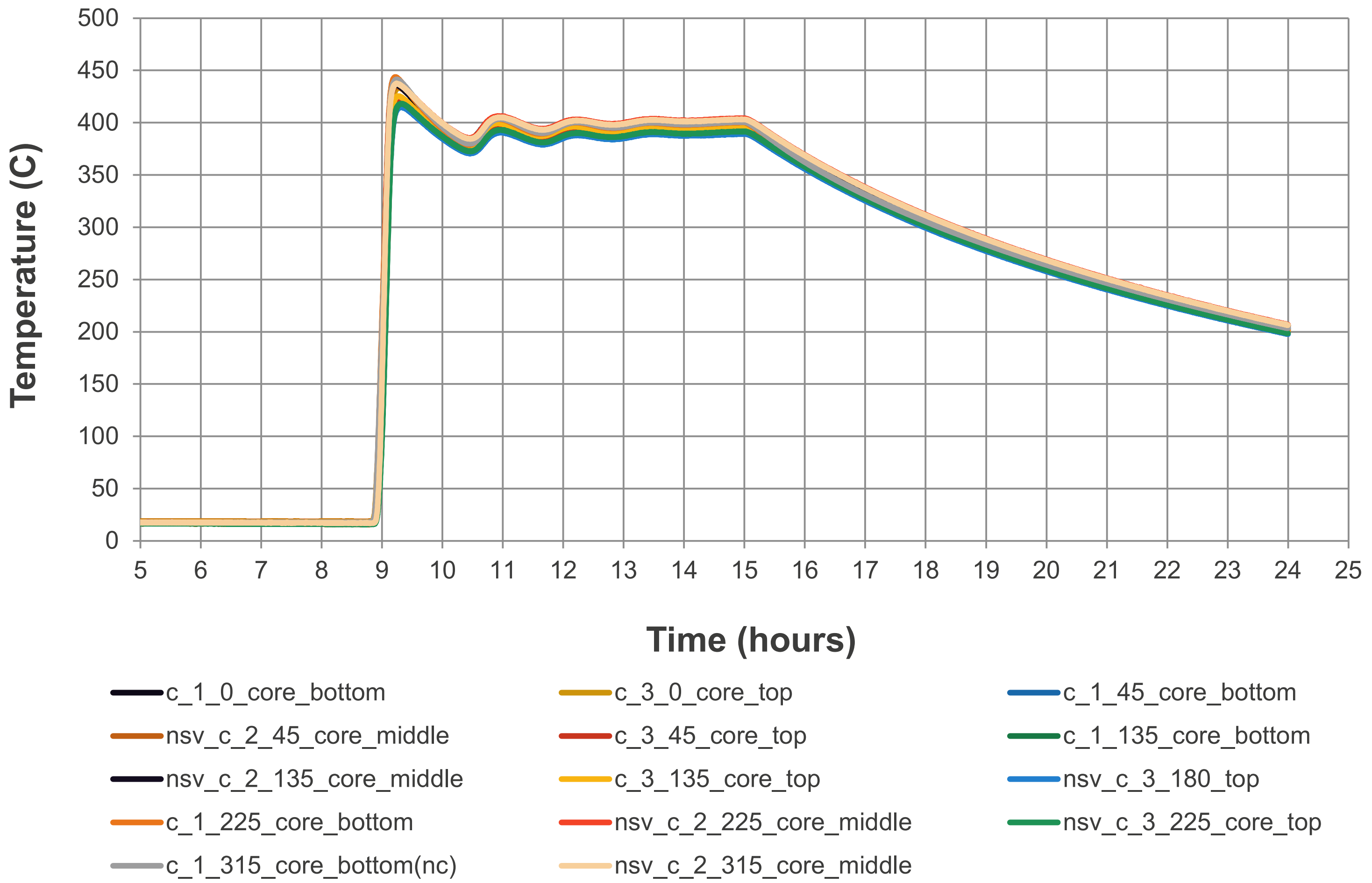

30 cent, Mar 08 2018
LC1
LC2
LC3
6.6e-6 A max on LC1
~14min from start to rollover
adding reactivity took ~1min
Auto run-out
Tmax=288ºC on Sim3
at ~32 min from start
15.3 cents
31.5 cents
Sim1=20.45ºC
3.02E-3 ampS on LC1
Current (amps)
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
1E-14
1E-15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

Core Temperatures (60 cent run)



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.

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

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

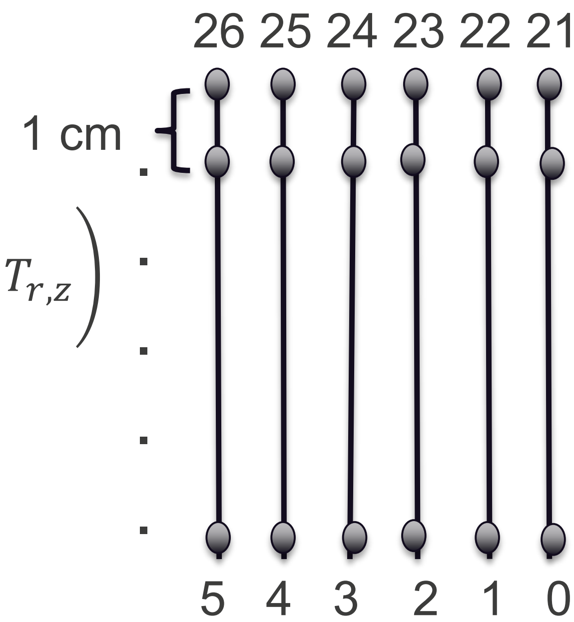
$$R = R_0 + \alpha_T \sum I_{r,z} \Delta T_{r,z}$$

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

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

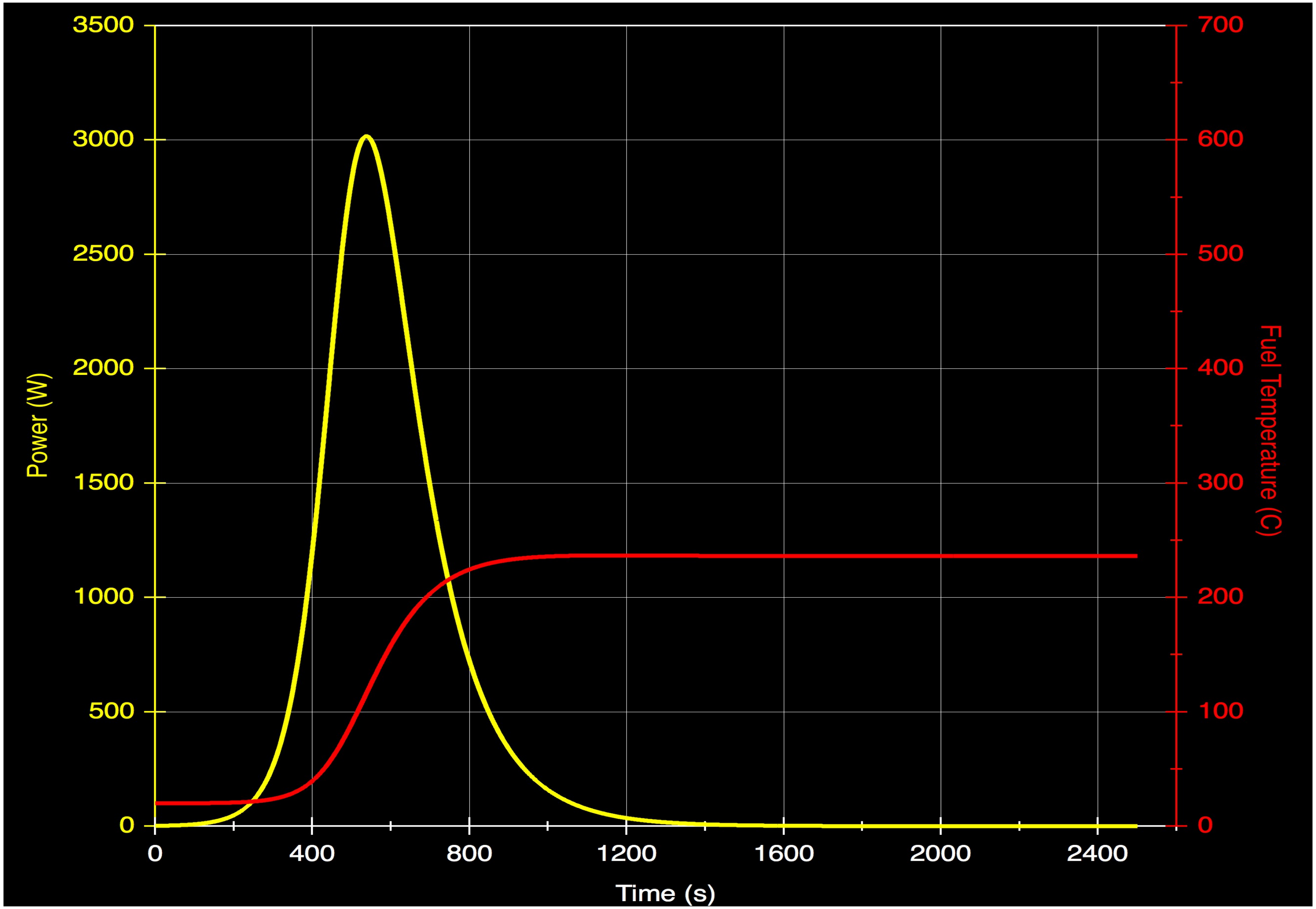
Power (heat generation)

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

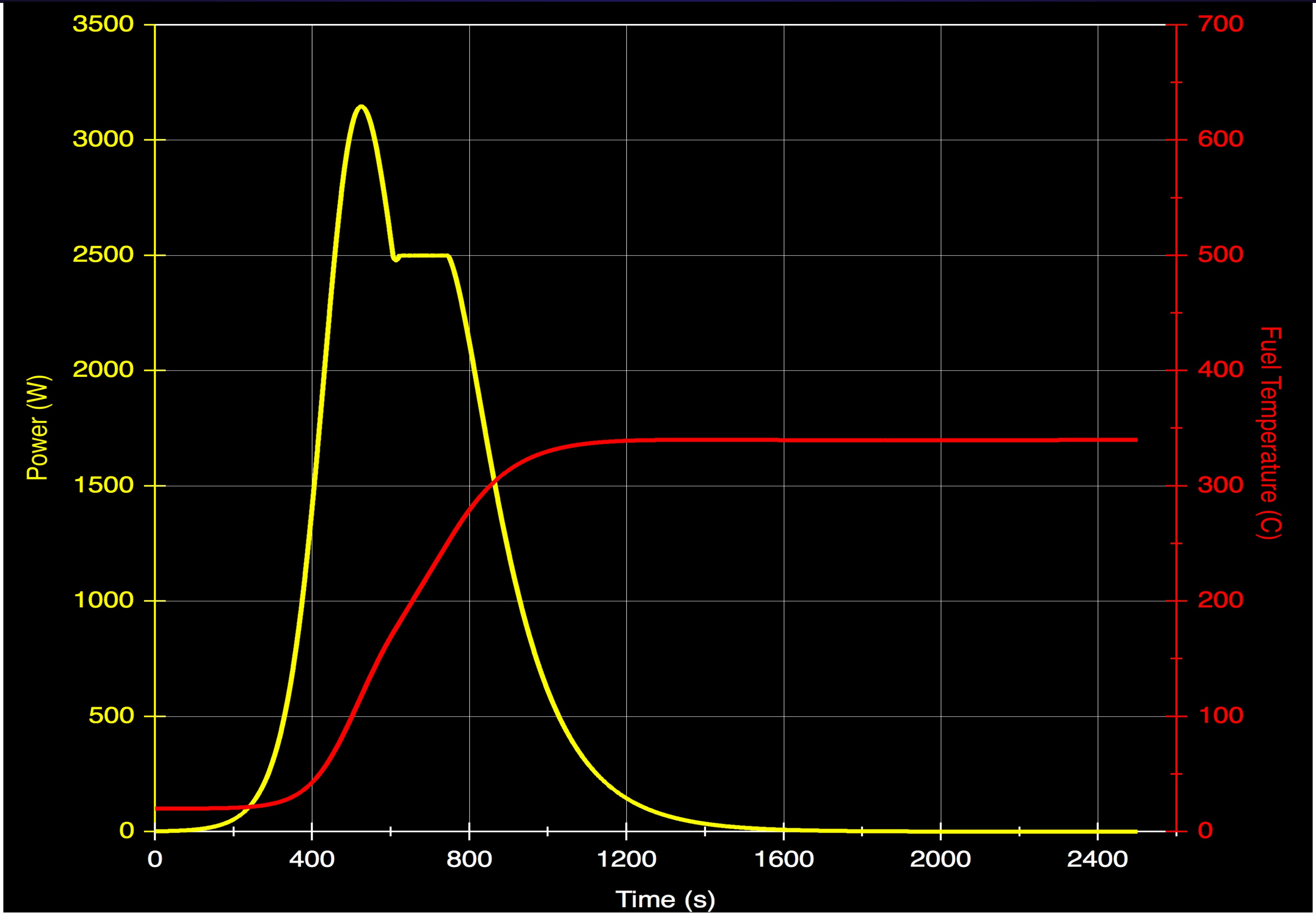
Thermal properties did not change as a function of time and temperature.

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

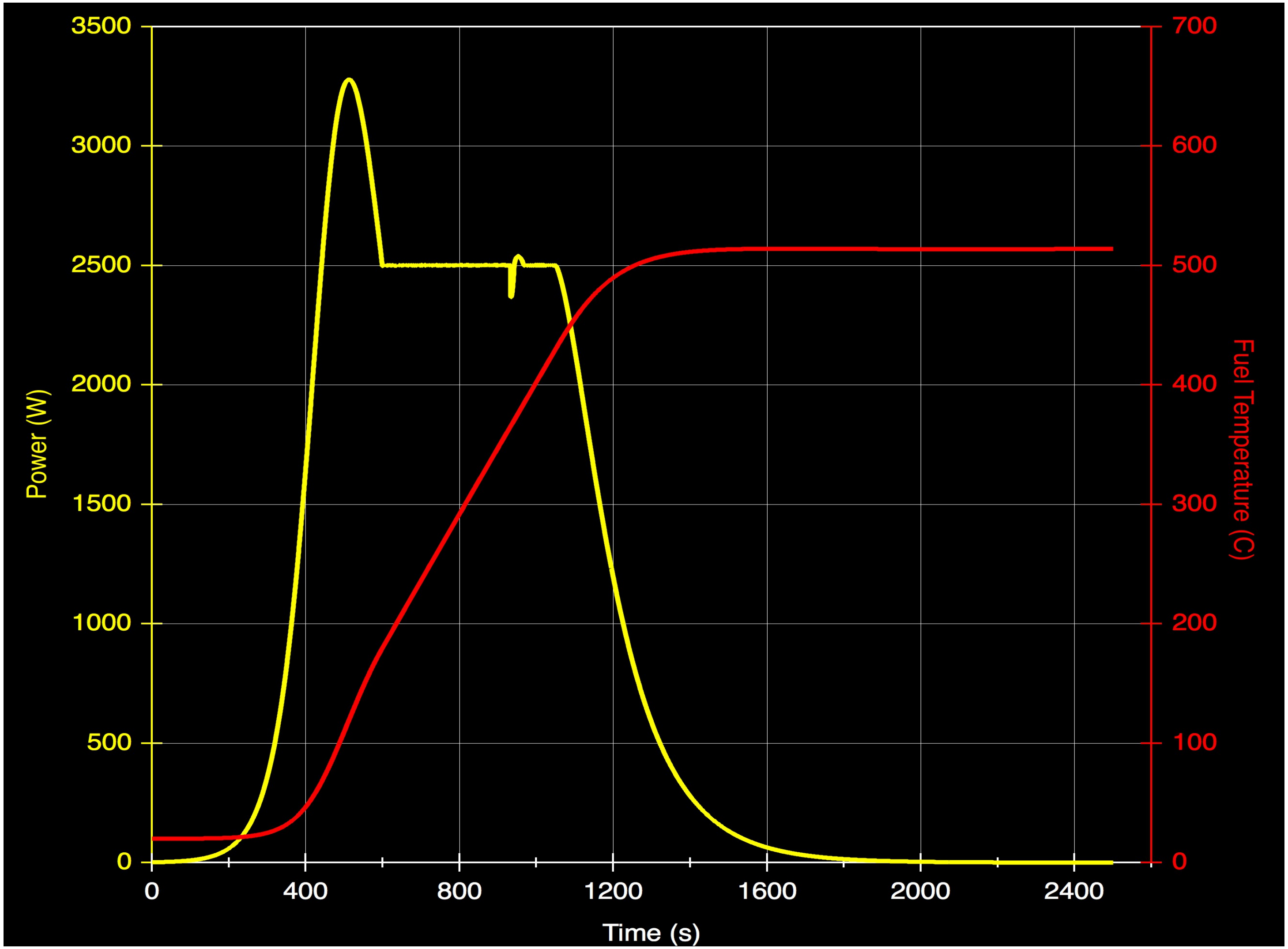
Simulation of the 15 Cent Free run



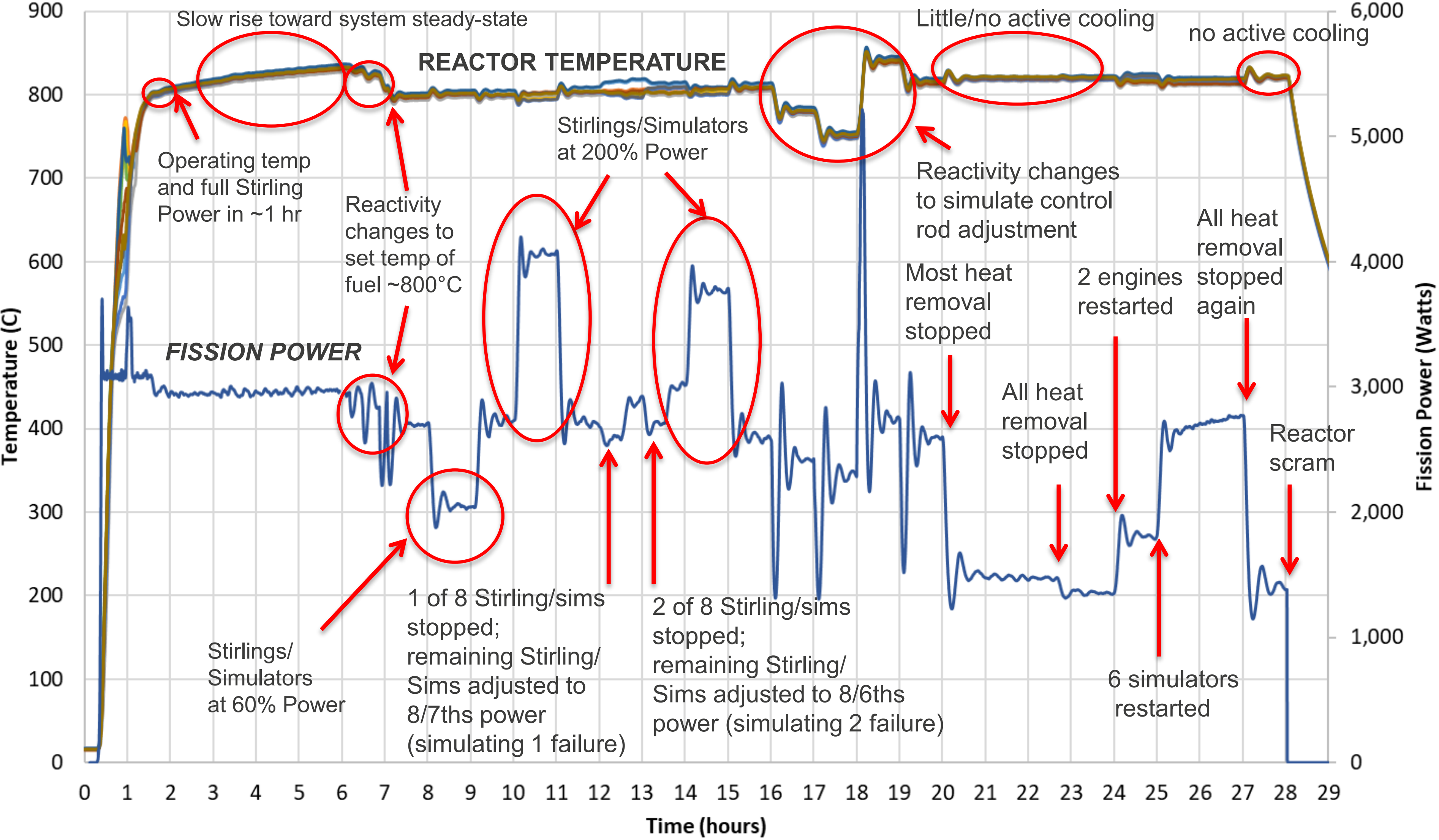
Simulation of the 30 cent run



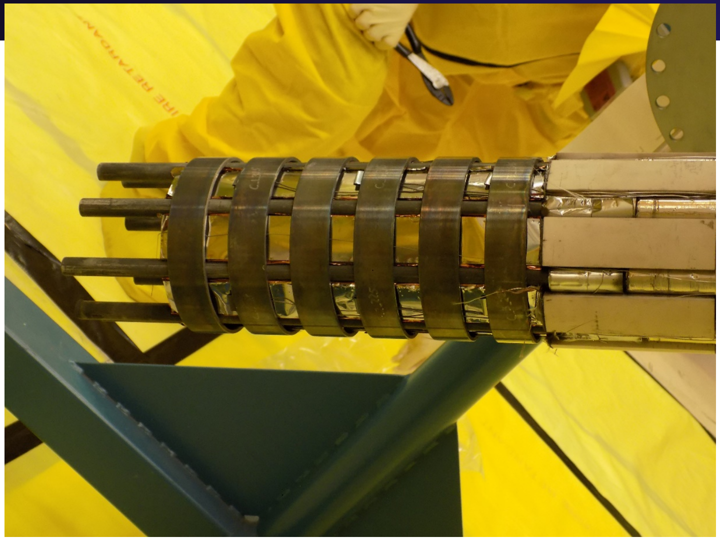
Simulation of the 60 cent run

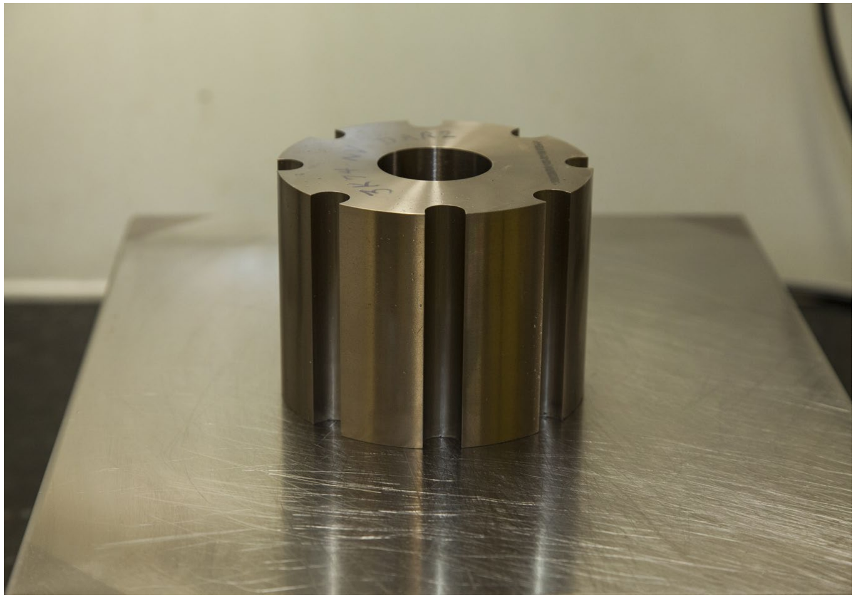


KRUSTY Full-Run Fuel Temperatures and Fission Power



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 sothat the complete point kinetics-heat transfer model can attempt to simulate the 28-hr high temperature run.