NC STATE UNIVERSITY

Design of a HEU Metal Fast Burst Supercritical Assembly

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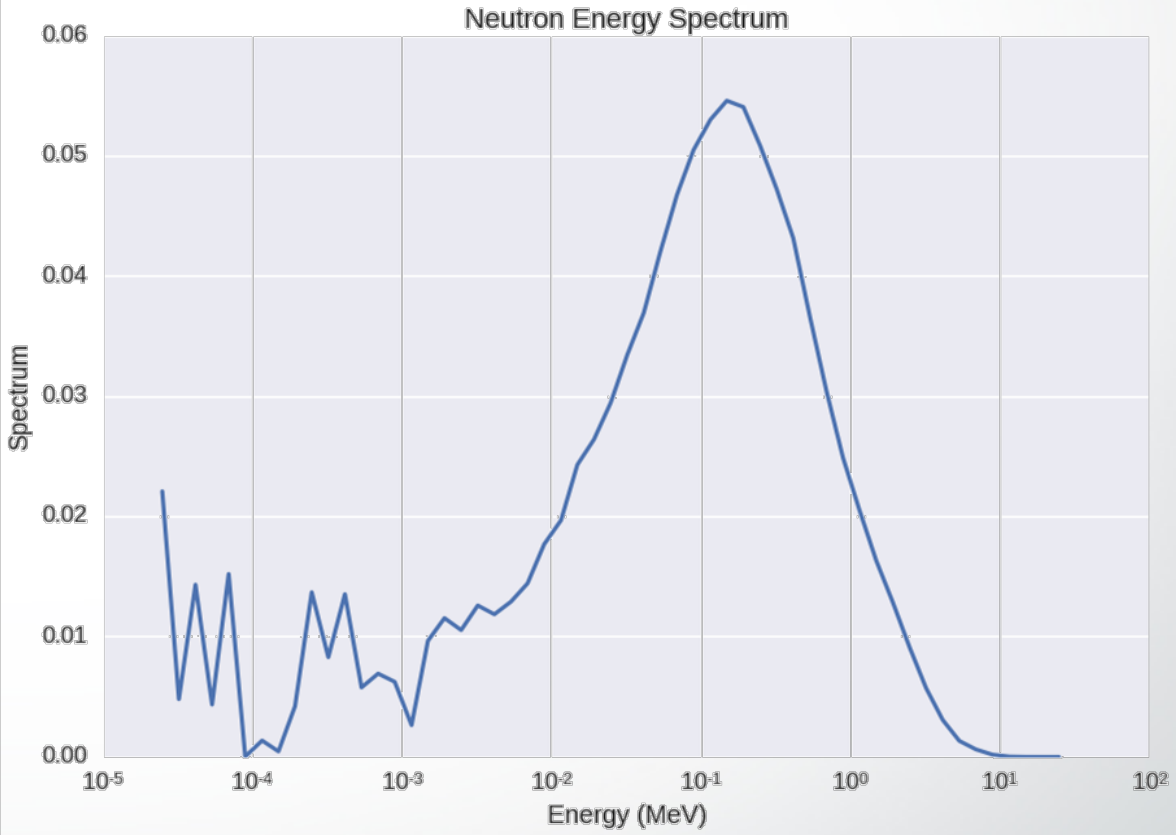
Project Description

Design of a highly enriched uranium (93.5% U-235) metal fast burst supercritical assembly

Applications

- Estimating the reactivity worth of different materials
- Studying neutron-induced damage in various materials
- Conducting forensic analysis of neutron-irradiated nuclear materials
- Testing different types of dosimetry



Project Objective

Surpass the performance of Godiva-IV

Technical Objectives:

- Maintain/improve level of power output (~90,000 MW)
- Minimize pulse duration (≤ 30 μs) while maximizing neutron fluence

Engineering Objective:

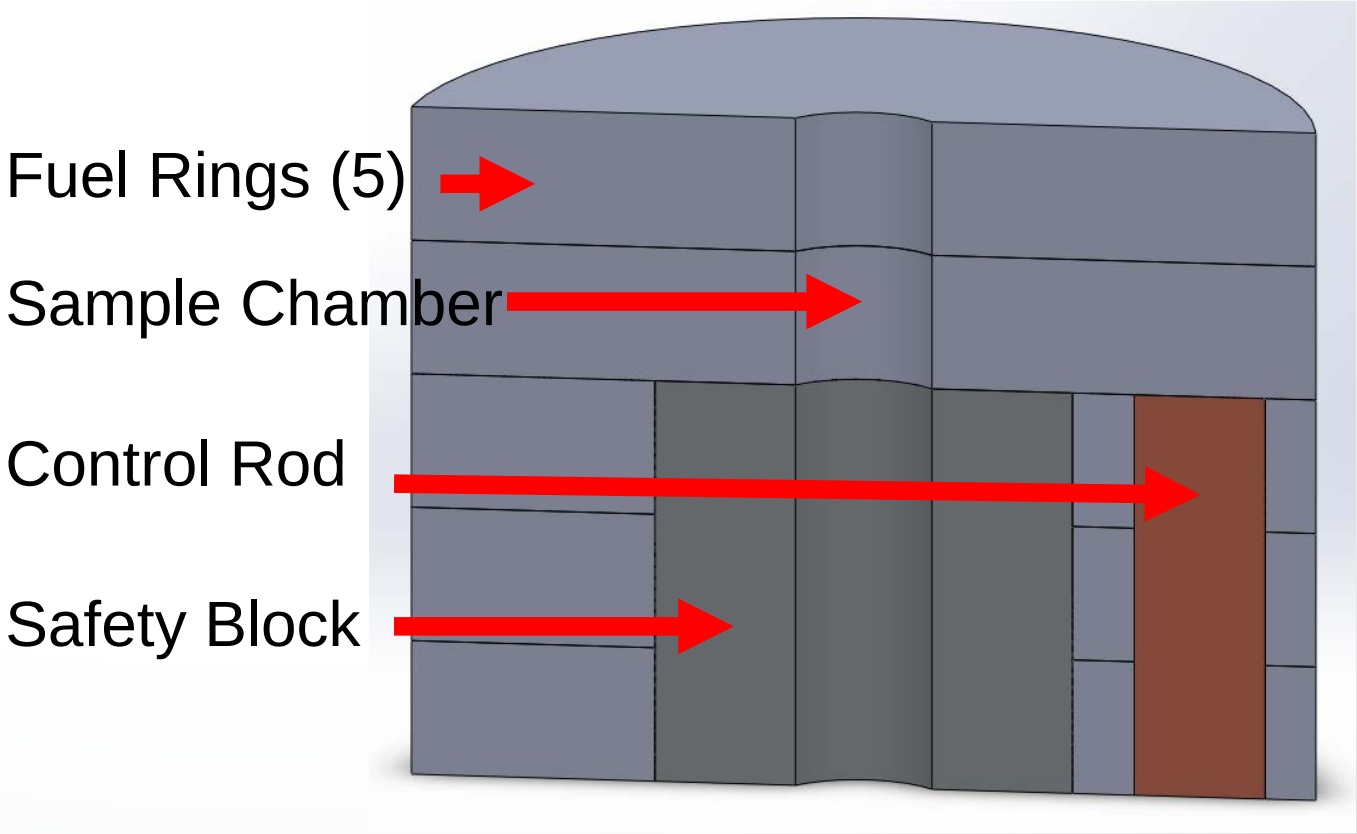
- Maximize sample chamber dimensions
  - Design sample chamber to allow for pneumatic rabbit system for rapid, automated retrieval of irradiated materials

Historical Designs of Fast Burst Assemblies

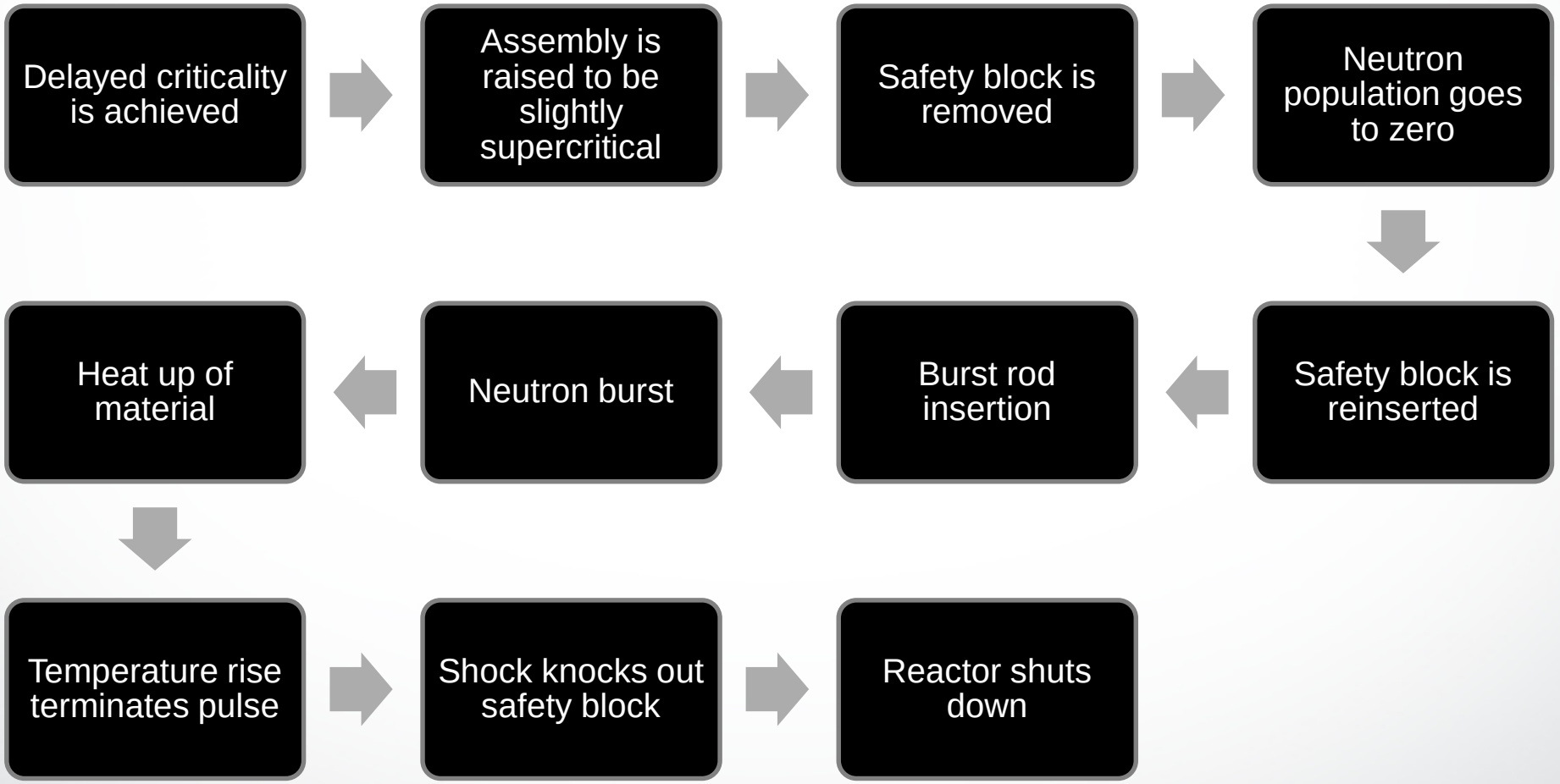
Device	Positive	Negative
Godiva I	• Sphere geometry which allows for less U metal	• Spherical shape requires complicated uranium metal machining • Sphere shape ultimately makes it more difficult to control.
SPR III	• Much larger than the Godiva's sample chamber. • Elimination of control rods makes the creation of the plates simpler.	• Will have a much longer neutron lifetime. • More mass will be required to achieve criticality
Caliban	• Very large test chamber, • Simple design of uranium plates.	• Extremely large size increases the FWHM of neutron burst
Godiva IV	• Simple to model, create, and control.	• More mass will be required to achieve criticality than Godiva I.

Assembly Design

Component	Radius (cm)	Height (cm)
Aspect Ratio (H/D)	0.75	
Mass	74.3 kg	
Core Dimensions	9.60	14.40
Fuel Ring	9.60	2.88
Control Rods	1.50	8.64
Burst Rod	1.50	5.70
Safety Block	4.60	8.64
Sample Chamber	2.00	14.40



Operating Principle



Simulation Algorithm

Solve Point Kinetics – assume $\rho = constant$

Obtain $\phi(t)$

Obtain heat generation $q'''(\vec{r}, t)$

Solve for temperature distribution $T(\vec{r}, t)$

Update reactivity due to ΔT

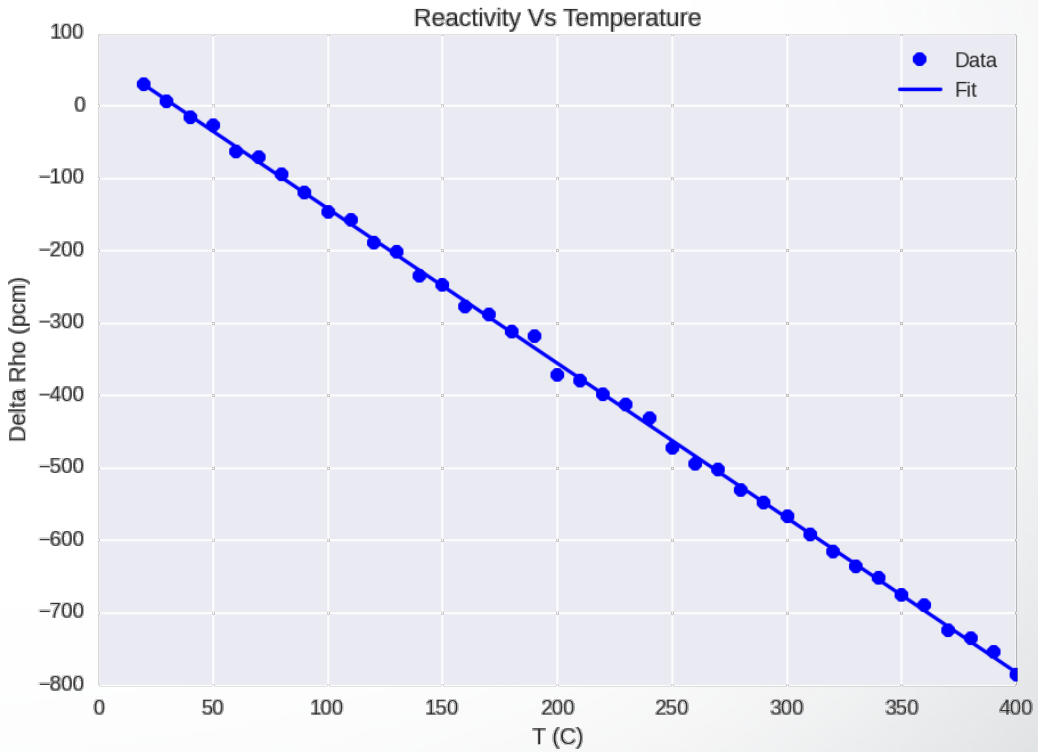
Time Step Complete, Restart Cycle

Reactivity vs. Density vs. Temperature

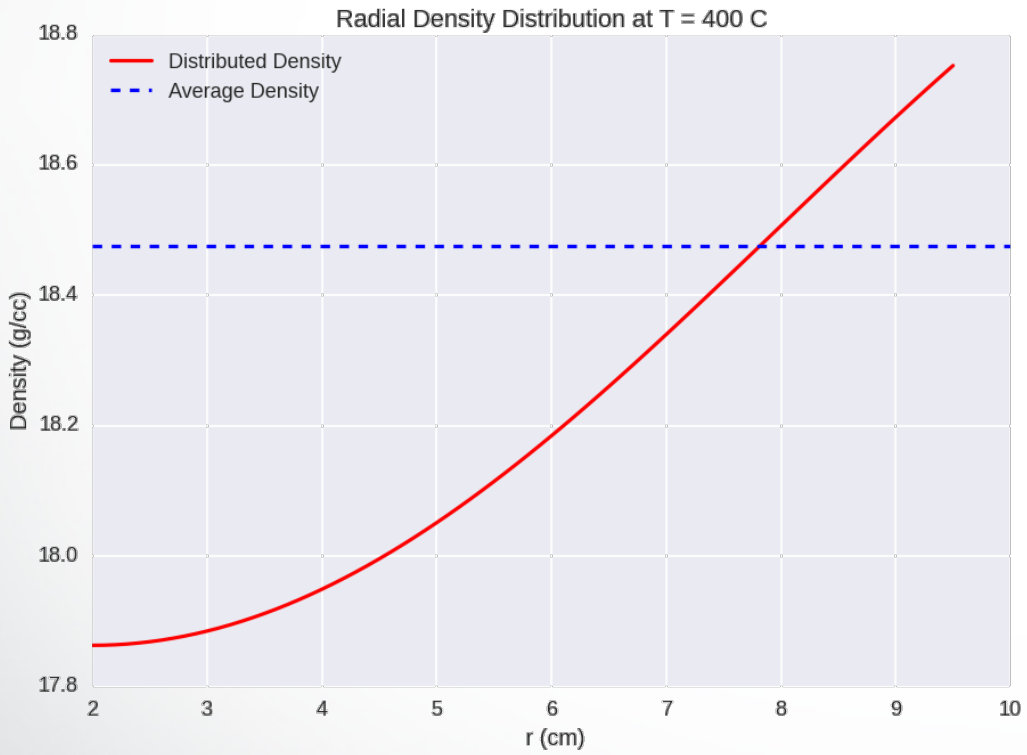
MCNP simulations provided our neutronic parameters

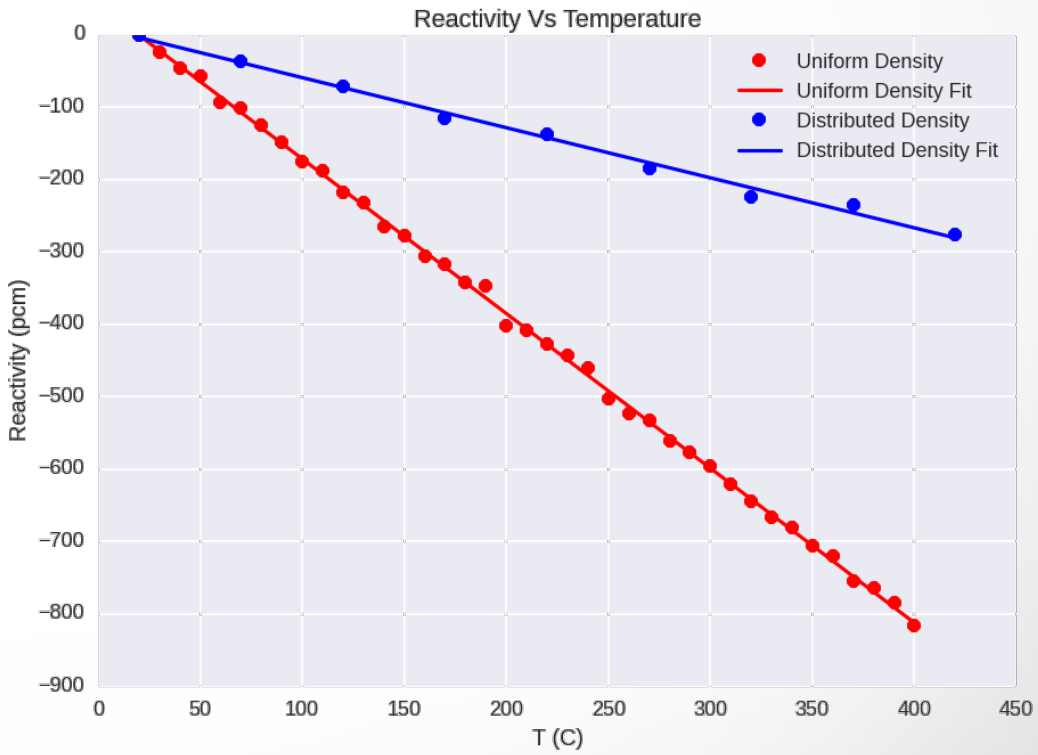
All reactivity effects are assumed to be due to thermal expansion of the fuel only

- $\Delta V = 3\alpha V_0 \Delta T$
- $\rho(T) \approx \rho_0 + \alpha_T \Delta T$
  - $\alpha_T = -2.14 \frac{pcm}{°C}$



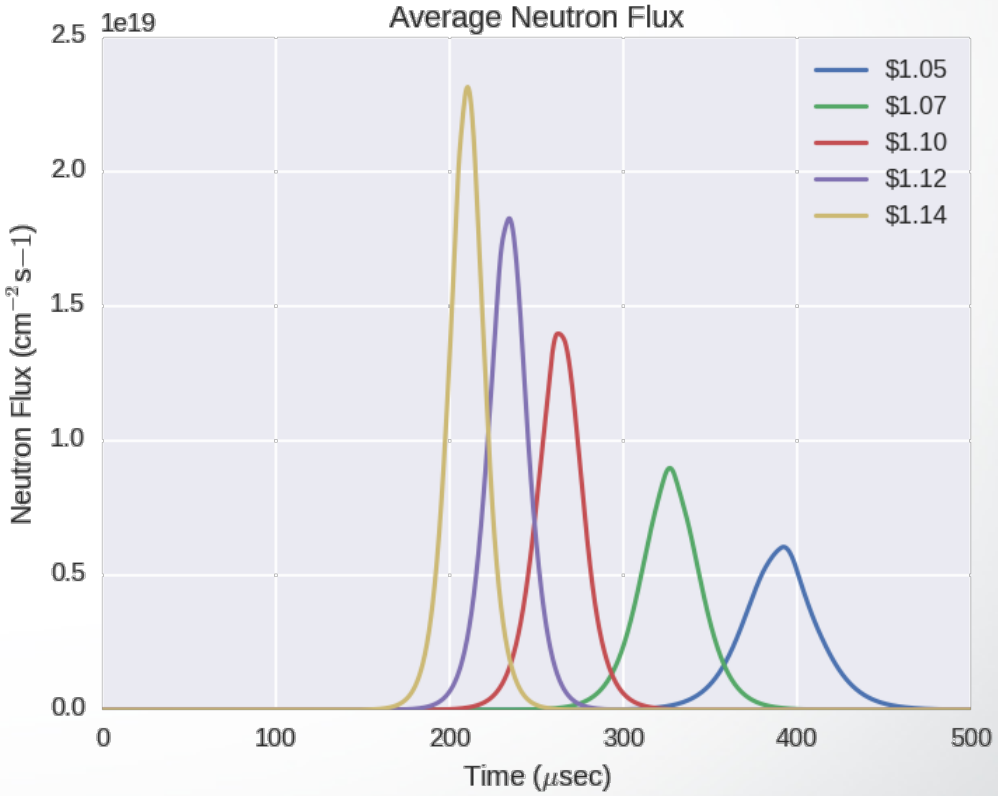
Reactivity Effect Due to Distributed Density





Dynamic Neutronic Behavior

ρ	FWHM µs	Peak $\phi \times 10^{-19}$ cm^{-2}s^{-1}	Sample $\Phi \times 10^{-14}$ cm^{-2}	Average $\Phi \times 10^{-14}$ cm^{-2}
$1.05	44.2	0.61	9.72	3.06
$1.07	36.9	0.90	11.8	3.70
$1.10	29.3	1.40	14.7	4.63
$1.12	25.3	1.82	16.8	5.27
$1.14	22.5	2.31	18.8	5.90



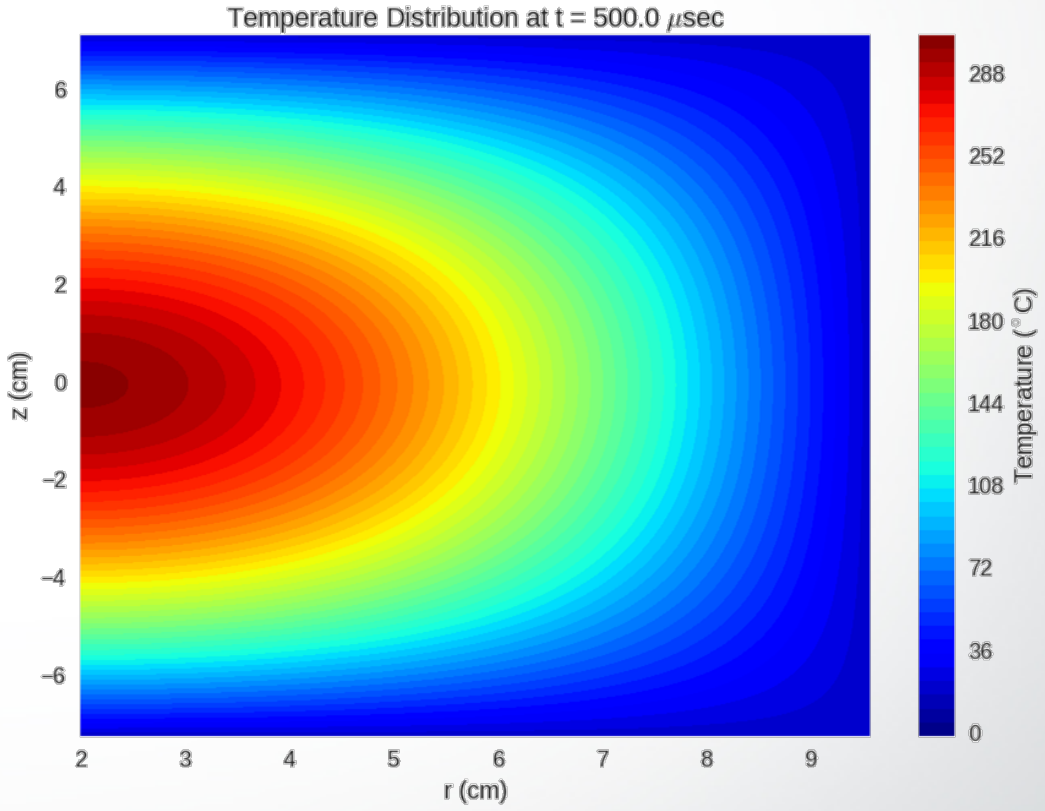
Temperature Response

Temperature is solved for using two approaches:

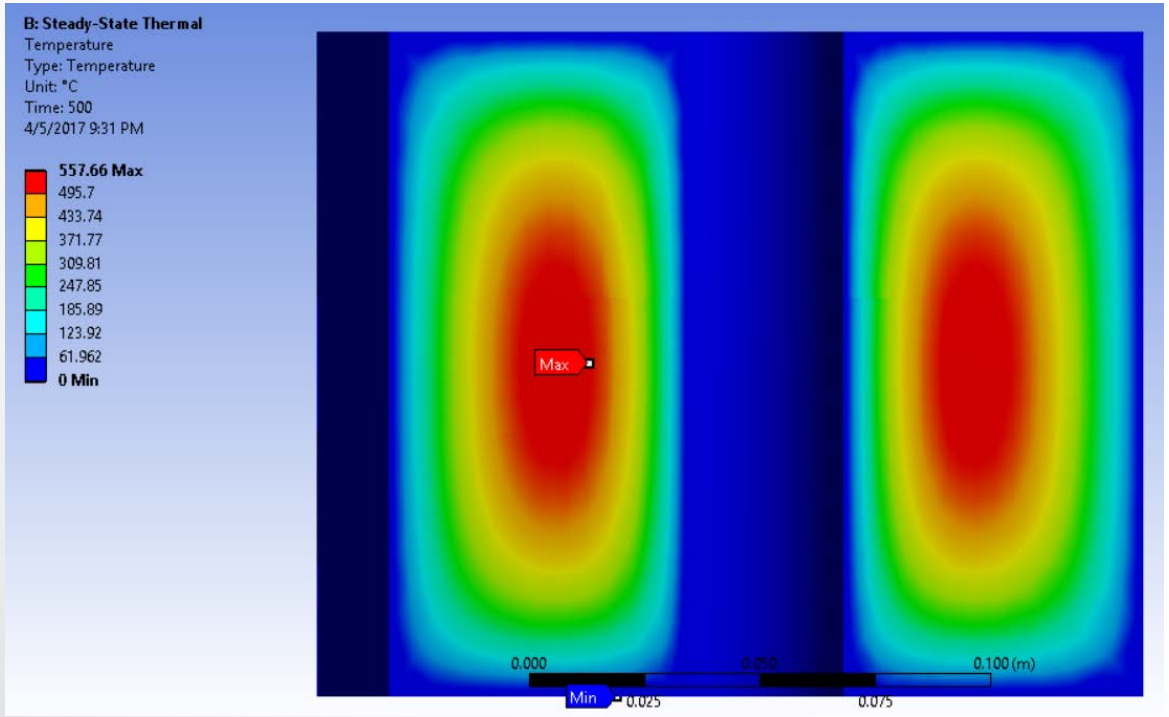
- Analytic solution of Fourier's Law, feeds into simulator
- Numerical simulation in ANSYS, not spatially dependent

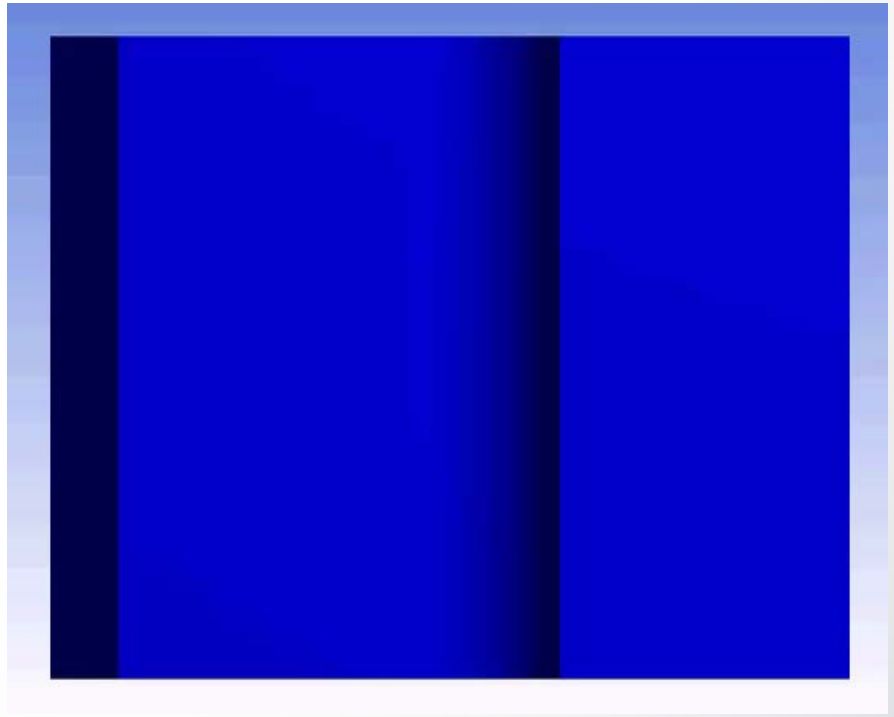
ρ	Peak Power GW	Peak T °C	Peak T_{ave} °C
$1.05	37.3	206	78.3
$1.07	55.3	245	90.8
$1.10	86.1	301	108
$1.12	112	340	121
$1.14	143	378	133

*Initial temperature: 20 °C
**Melt temperature: 1135 °C



ANSYS Temperature Map





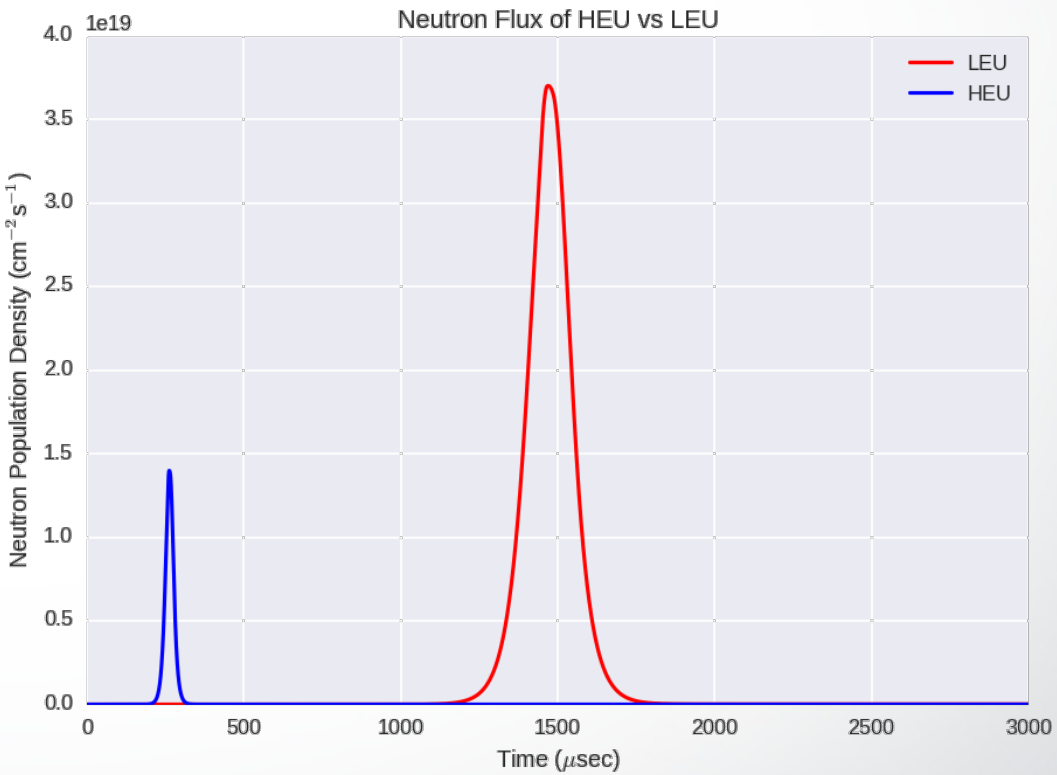
Evaluation of HEU vs LEU

HEU:

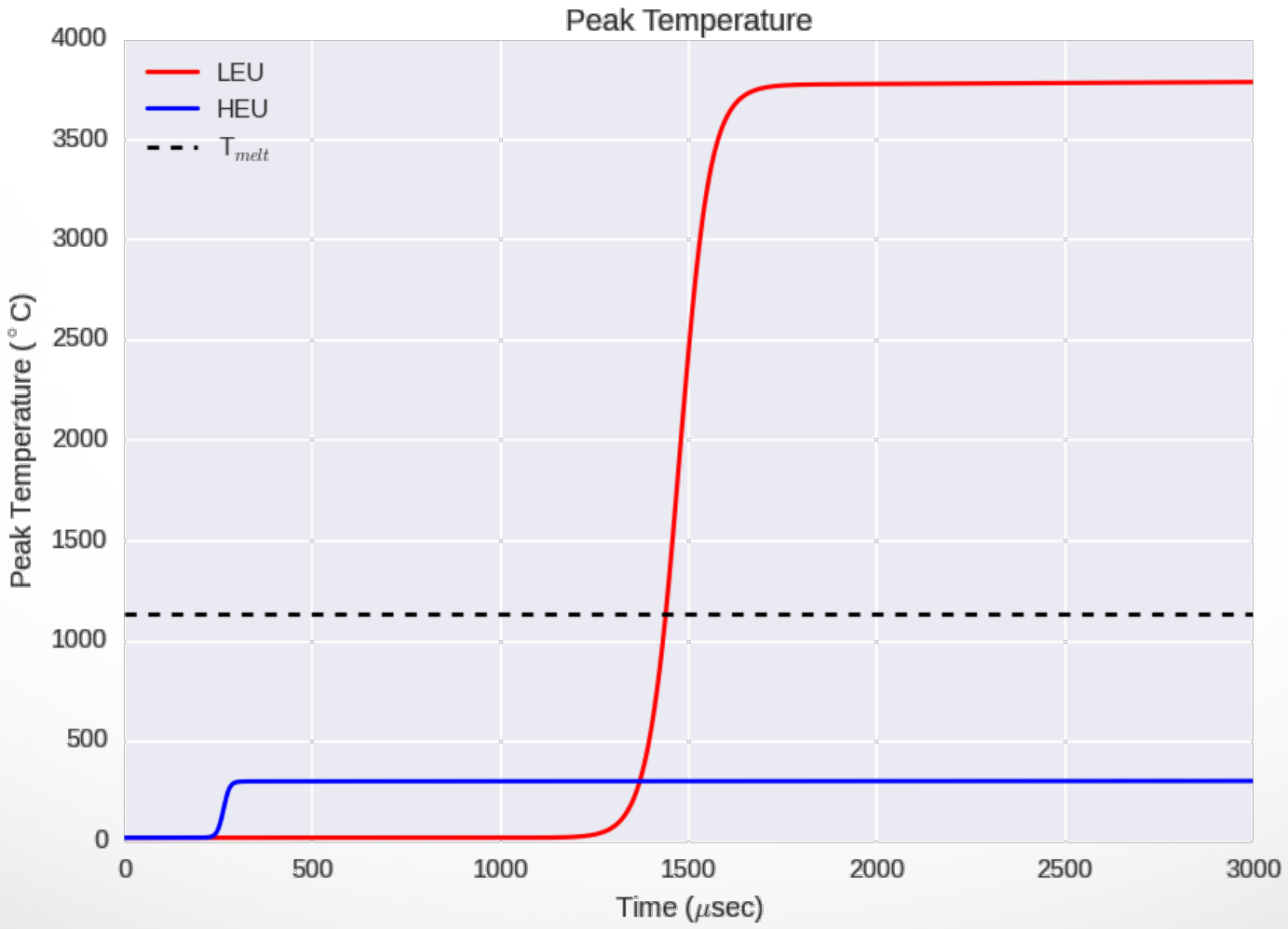
- Fluence: $4.63 \times 10^{14}\ cm^{-2}$
- Peak Power: $86.1\ GW$
- Peak Flux: $1.40 \times 10^{19} cm^{-2} s^{-1}$
- FWHM: $29.3\ \mu s$

LEU:

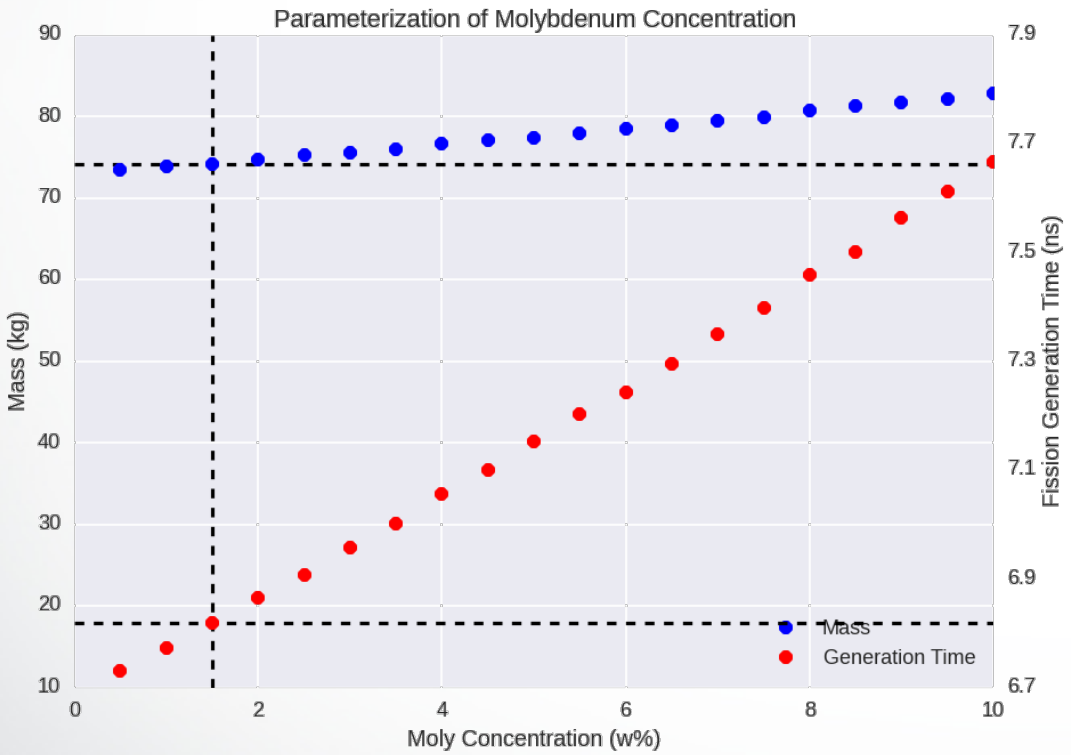
- Fluence: $6.20 \times 10^{15}\ cm^{-2}$
- Peak Power: $3{,}041\ GW$
- Peak Flux: $3.70 \times 10^{19}\ cm^{-2} s^{-1}$
- FWHM: $147.6\ \mu s$

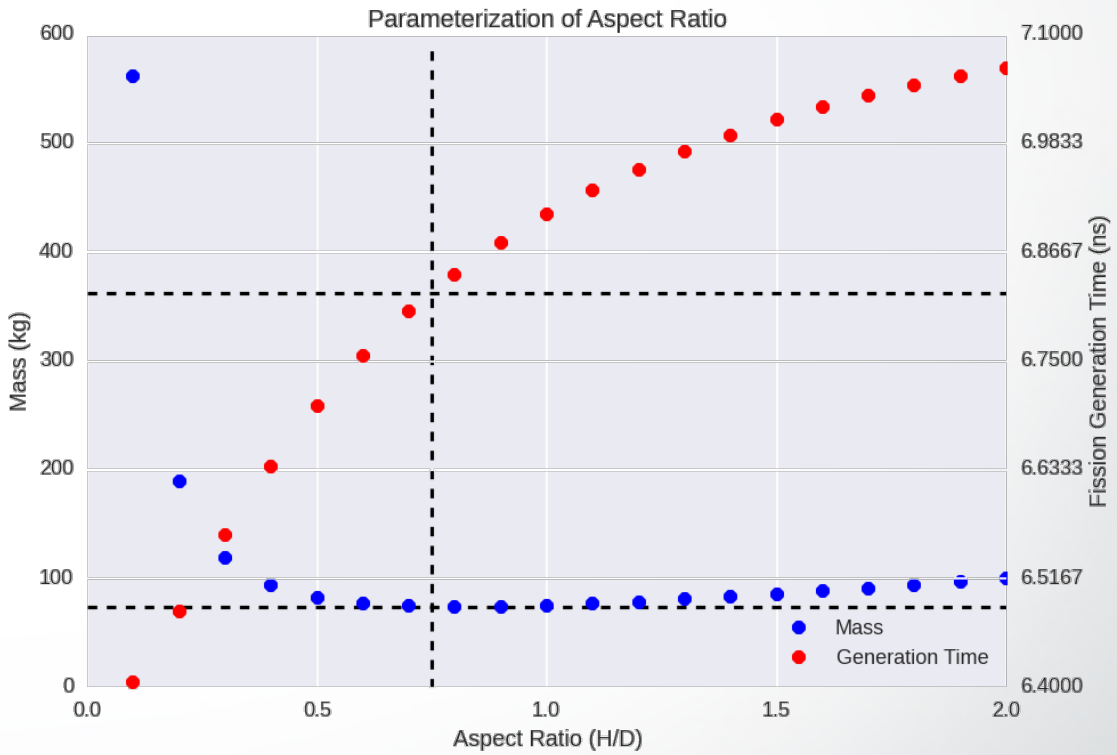


HEU vs LEU Peak Temperature



Design Optimization

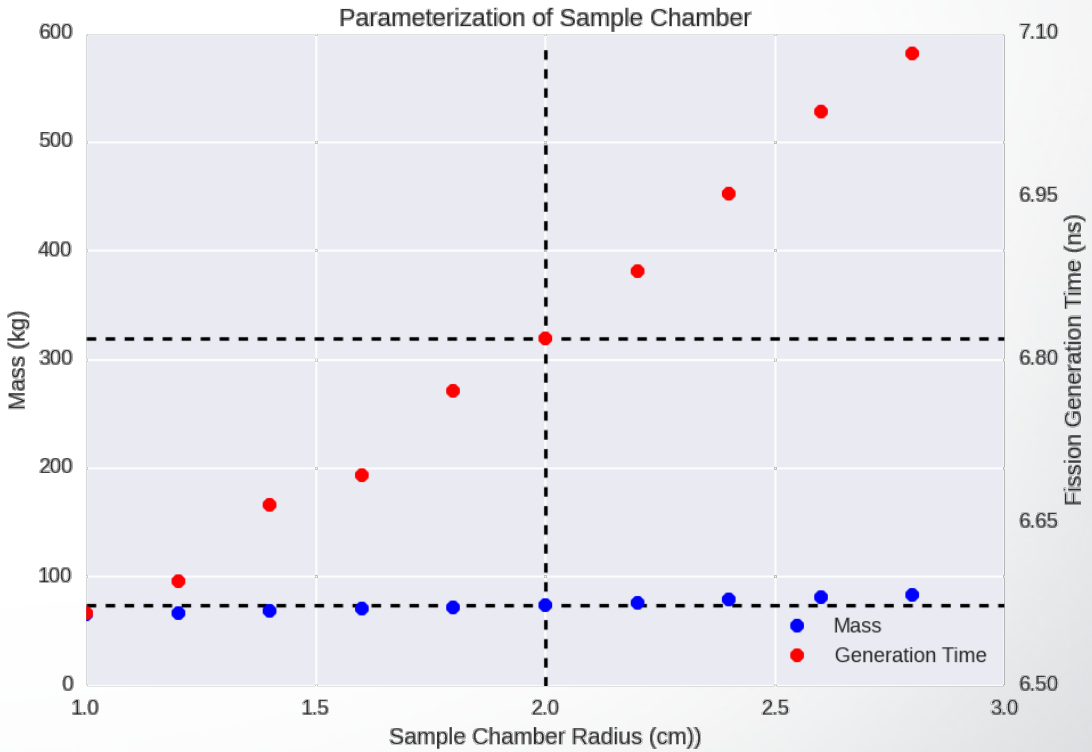




Design Optimization - Cont.

Based on these relationships we decided on:

- Mass: 74.3 kg
- Neutron Generation Time: 6.88 ns
- Aspect ratio (H/D): 0.75
- W% Moly: 1.5
- Sample Chamber Radius: 2 cm



Preinitiation Probability

$$p(n \geq 1) = 1 - \exp\left(-RT\left(\frac{k_i + k_f}{2} - 1\right)\right)$$

$$k_i = 1/(1 - 0.1\beta)$$
$$k_f = 1/(1 - 1.1\beta)$$

Where:

- $p(n \geq 1)$: probability of one or more interactions that begins a chain reaction
- R: neutron injection rate, 60 neutrons per second from U-238 SF
- T: insertion time of burst rod, 70 milliseconds
- k_i: initial reactivity, \$0.10
- k_f: final reactivity, \$1.10

The preinitiation probability of our assembly is about **1.5%**

Goals

Exceed Godiva-IV Performance

- Peak power greater than 90,000 MW
- FWHM less than 30 μs

Safety Analysis

- Examine off-nominal operations
  - Stuck burst/control rod or safety block

Stretch Goals

- Look into other uranium alloys

Completed Work

Developed Numeric Model

- Developed the tools necessary to simulate this device

Improved Performance from Godiva-IV

- Peak power is over 100,000 MW (for $1.12 and $1.14 bursts)
- FWHM is less than 30 μs (for $1.10, $1.12, and $1.14 bursts)

Expanded Sample Chamber from Godiva-IV

- 2 cm radius vs 0.3175 cm in Godiva-IV

Safety Analysis

- Thought experiment as to the potential outcome of a stuck component

Future Work

- Add contamination containment system
  - Research potential alloys for surface application
- Look into other uranium alloys
  - Uranium-Niobium (UNb)
- Continue improving ANSYS models and simulations
  - Evaluate force distribution on the safety block
    - Confirm safety block dislodging after completion of pulse
  - Improve temperature transient simulation

Acknowledgements

Los Alamos National Laboratory

Joetta Goda

Jesson Hutchinson

Robert Kimpland

Robert Margevicius

North Carolina State University

Elisabeth Brown

Joseph Cambareri

Nilesh Kumar

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Hypothesis Regarding Off Nominal Operation

- Pulse occurs
- Safety block fails to fall out of the assembly
- Device cools
  - On the order of minutes
- Reactivity increases
  - Reaches prompt supercritical
- Assembly pulses with lower amplitude