Utilization of Pulsing Research Reactor Experiments for Special Nuclear Material (SNM) Thermomechanical Property Testing

A. Foley, E.S. Lum, and D.T. Olive

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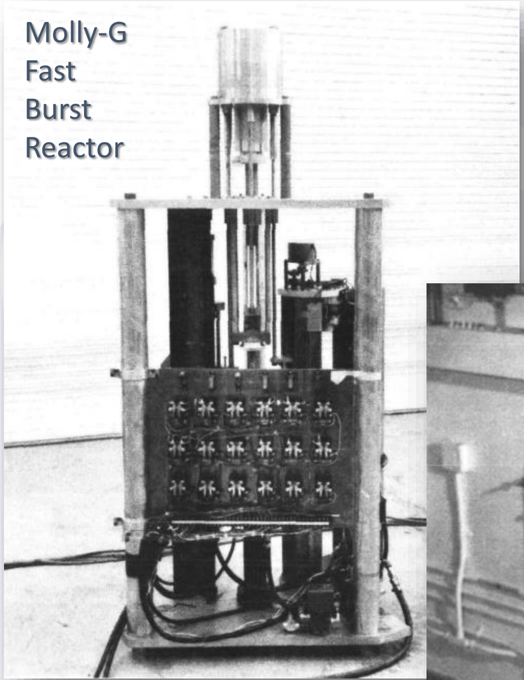
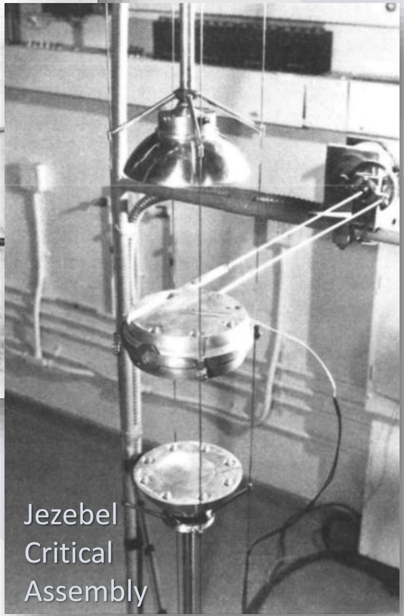
Introduction

- Transient testing of nuclear materials exposes targets to environments that simulate atypical operation conditions
- A multi-laboratory team including is reestablishing capability for transient tests for the thermophysical material analysis of SNM
  - SNM tests not conducted in over a decade
  - Increased safety requirements
  - Personnel change over
- Overview of current research and potential facility needs

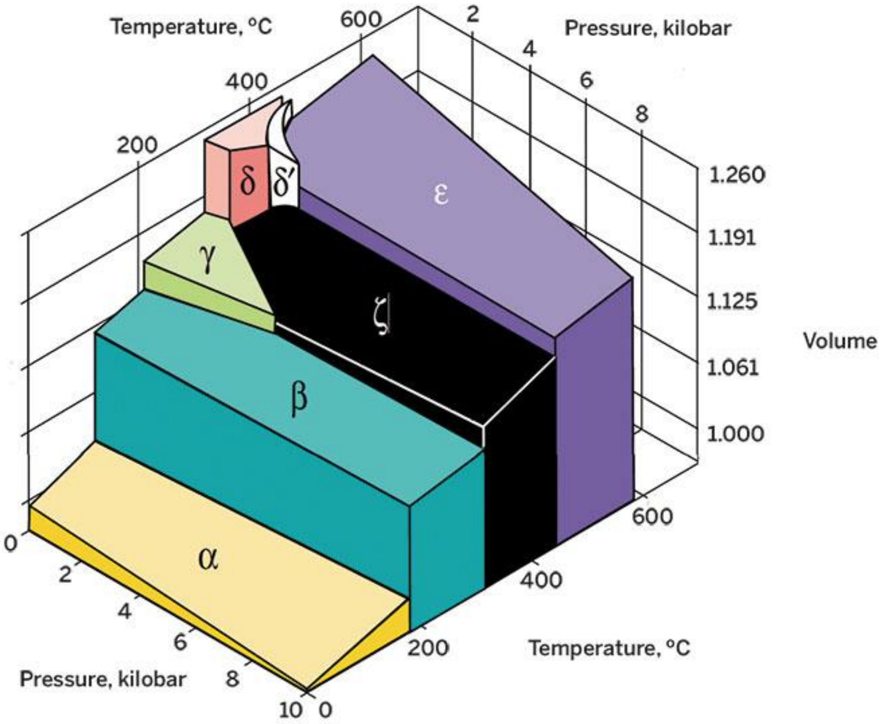




Photos: H.C. Paxton. “A History of Critical Experiments at Pajarito Site”. LA-9685-H

Unique Properties of Plutonium

- Plutonium is a unique element
  - *5f* electron orbital effects on material properties
  - 6 solid allotropes, most of any metal
- >20% change in density across allotropes
- Low melting temperature 638°C, 1254°C boil (at vacuum)
- 5 chemical oxidation states (+metal)
- Self-irradiation damage



Plutonium Phase Diagram showing 6 allotropes and melting point with respect to pressure and temperature[1]

[1]*Los Alamos Science*. 2000, 26 (II), 312

Self-Irradiation Damage in Plutonium

- Plutonium self-irradiation damage:
  - Lattice damage
  - He bubble in-growth
  - Void swelling
- Primary Knock on Atom (PKA) transfers energy to the lattice, displacing atoms from initial configuration
- Annealing process can partially or fully heal self irradiation damage
- How do aging effects impact the thermomechanical properties under these neutron environments?

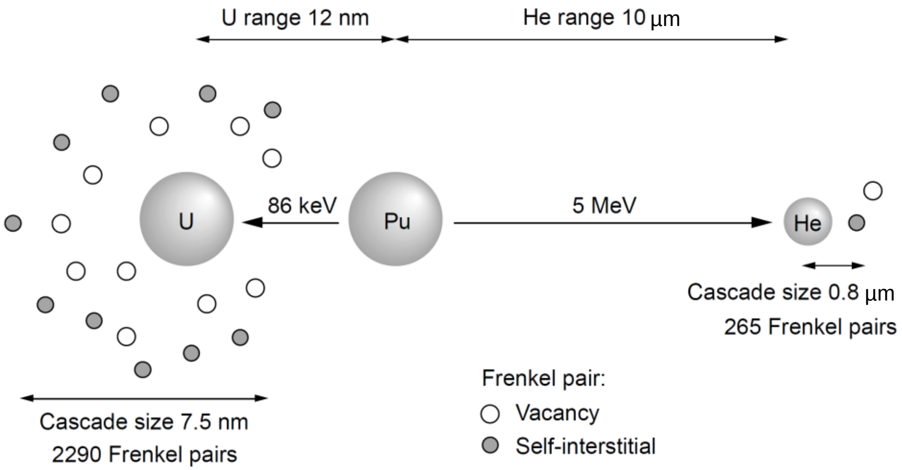


Diagram Illustrating the Self-Irradiation Effects of Plutonium from Alpha Decay to Uranium[2]

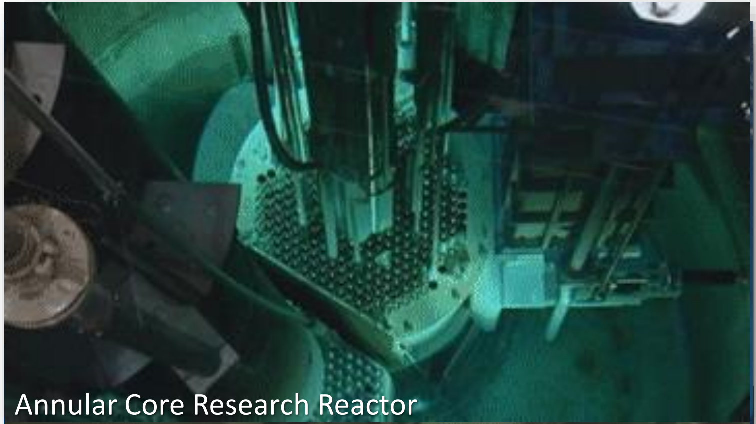
[2]*Los Alamos Science*. 2000, 26 (II), 274-285

Current Experiment Series

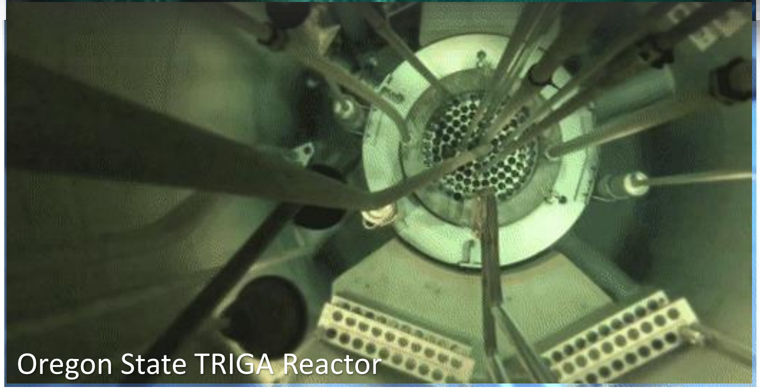
- Our first modern Pu experiment fielded at ACRR August 2022, a major milestone in fielding increasingly complex experiments
- Experiments designed to assess changes in material properties and heating in fissioning materials in neutron environments
  - Sandia National Laboratory's Annular Core Research Reactor (ACRR)
  - Idaho National Laboratory's Transient Reactor Test Facility (TREAT)
- Development work small-scale experiments and instrumentation
  - NSRC Godiva-IV
  - Discussions with university pulsing research reactors

Pulsing Test and Research Reactors

- Ability to achieve supercriticality and safely, rapidly shut down through neutronic effects
- Operational requirements depend on application
  - Pulse Width
  - Pulse Energy
  - Pulse Shape
  - Neutron Fluence
  - Cavity Size
- Many available research facilities for experimenters with varying safety limits for types of materials and forms



Annular Core Research Reactor



Oregon State TRIGA Reactor

GIF of Video: [10,000th cycle of the Annular Core Research Reactor - YouTube]

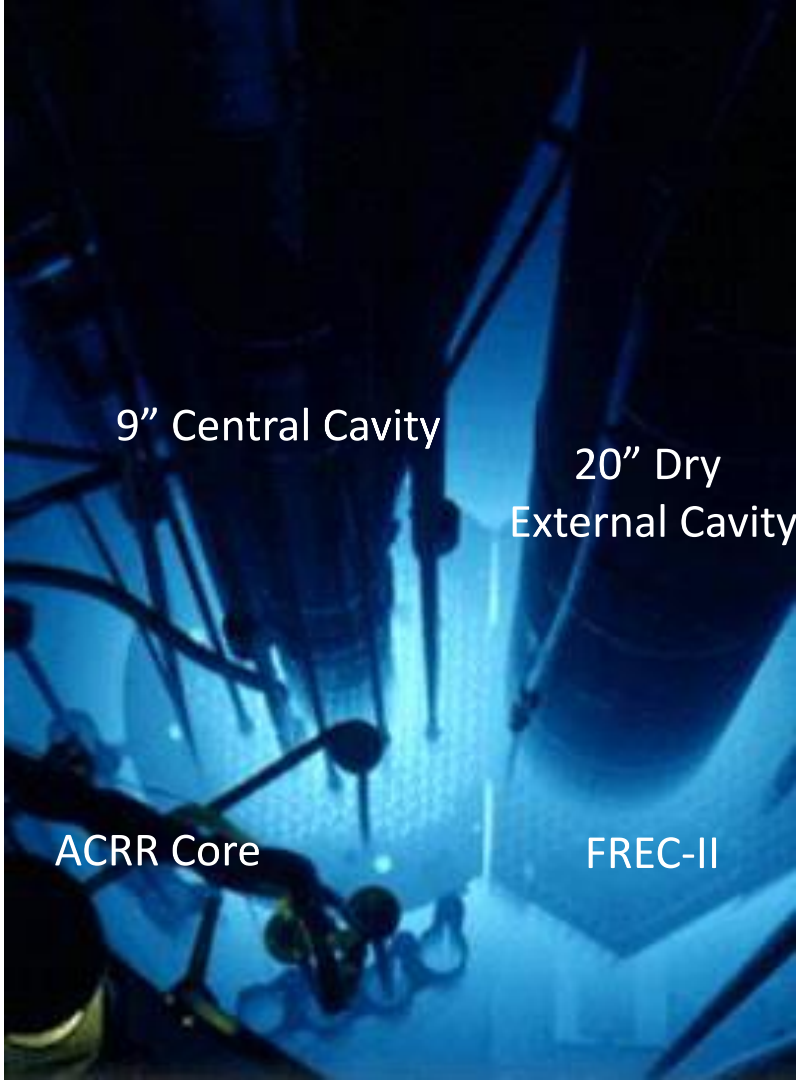
Facility Selection

- Identifying facilities with appropriate operating conditions to execute test matrix
- Pulse width vs. Pulse power
- Integrated energy deposition, temporal effects are important
- Size of cavity for the facility
- Handling of test materials

	TREAT	ACRR	OSTR (TRIGA Mark II)	GODIVA-IV
Max Pulse Size	2600 MJ	275 MJ	23 MJ	1.7 MJ
Pulse Width	70 ms	14 ms	20 ms	0.033 ms
Cavity Size	D 7.8”	D 9” CC D 20” FREC-II	D 0.9”	D 0.25”
Location	Arco, ID	Albuquerque, NM	Corvallis, OR	Mercury, Nevada
Neutron Fluence (Max)	2×10^{16} n/cm^2	5×10^{15} n/cm^2	1.5×10^{15} n/cm	4.5×10^{13} n/cm^2

Annular Core Research Reactor

- Chosen due to neutron fluence, cavity size, proximity, ability to handle SNM
- Water-moderated, pool-type research reactor
  - Steady-state, high-power pulse, and transient operations available
  - UO_2-BeO fuel elements
- Dry 9” Central Cavity
  - Highest fluence
- Dry 20” FREC-II*
  - Radiation gradient across package
  - Optional coupling
- Multiple spectrum modifying buckets

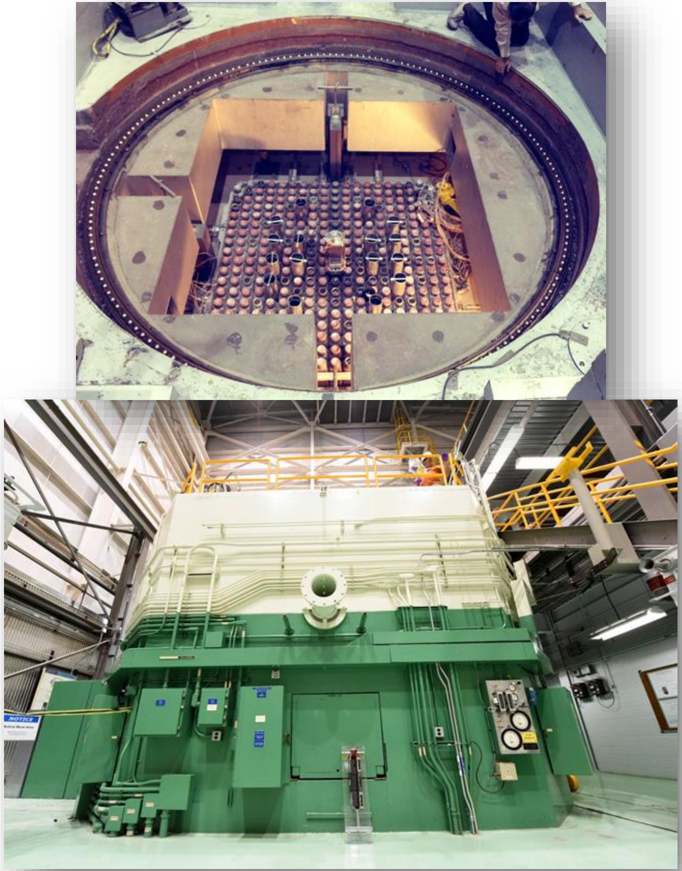


Annular Core Research Reactor (ACRR) and Fuel Ring External Cavity (FREC-II) at Sandia National Laboratory

Los Alamos NATIONAL LABORATORY

Transient Reactor Test Facility

- Unique in safely permitting the melting and even vaporization of SNM
- Air-moderated, graphite moderated, thermal spectrum test reactor
  - Steady-state, high-power pulse, and transient operations available
  - Transient shaping
- Proximity to post-irradiation examination capabilities and security at MFC
- Big-BUSTER
  - 20 cm diameter
  - Characterization of Big-BUSTER prior to first TREAT experiment



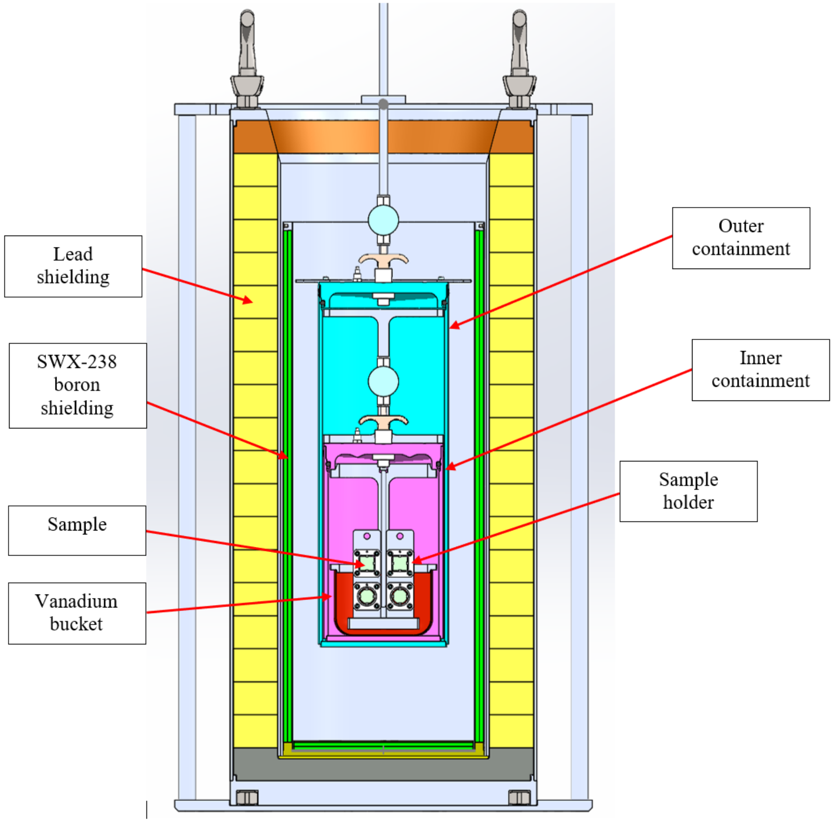
Transient Reactor Test Facility (TREAT) at Idaho National Laboratory

Collaborating on Experiment Design

- SNL/ACRR experiment in a high-hazard category, must work through their own authorization process with multiple levels of readiness
- INL experiment unique in working through the design process as an external party, different than their norm
- Compliance within regulatory structure at that facility
- Triggered internal processes to ensure their QA program can handle analysis and certification of experiment packages
- **With any high-hazard experiment at an external irradiation facility, the process increasingly becomes a collaboration**

ACRR Experimental Can Design

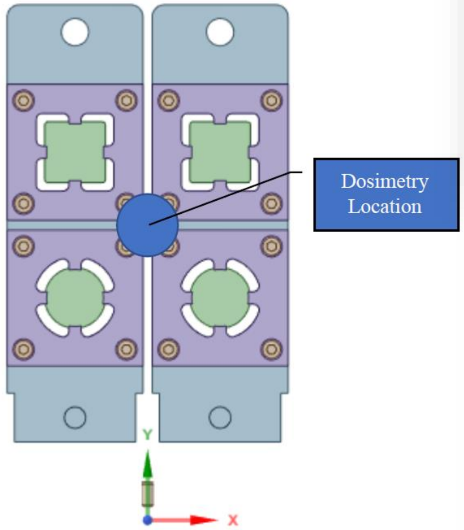
- Consider n-γ environment
- 2” of Lead Shielding
- SWX-238 Flex Boron Shielding
  - ¼” Thickness
  - Equivalent to 0.27 g/cm^2 of natural boron
- Outer and Inner Aluminum Can
- Sample Holder
  - 2 “Stakes”
  - 2 Samples per Stake
  - Spacer rods
- Vanadium Bucket



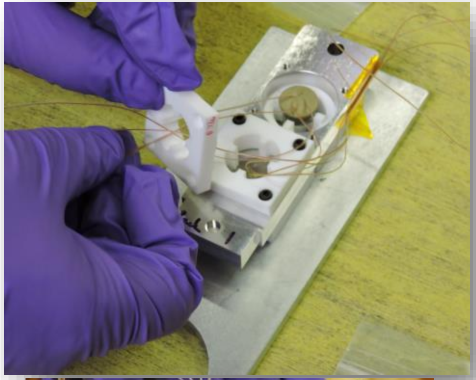
CAD Cutaway of Experimental Package

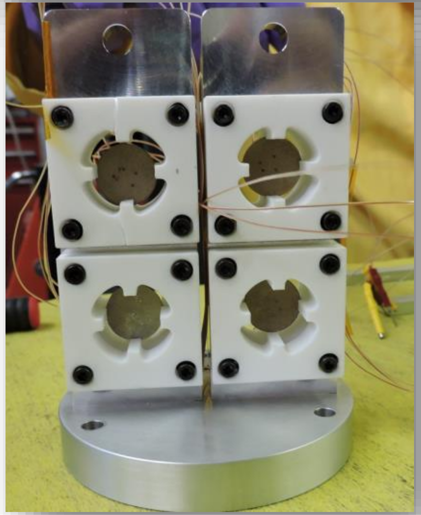
Samples and Sample Holders

- Samples fielded in ACRR
  - 2 Plutonium Coupons
  - 1 HEU Coupon
  - Bismuth coupon for γ heating
- Previous confirmatory tests with DU and Bi
- Bespoke MACOR® low thermal conductivity holders
  - Machinable ceramic to fit each sample individually
- Similar but horizontal design for TREAT experiments



2D Representation of 2 Sample Steaks and (Purple) MACOR holders to hold sample coupons with dosimetry packet in center

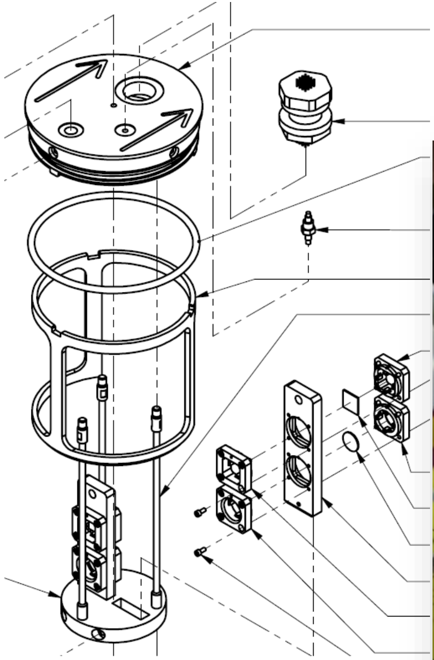




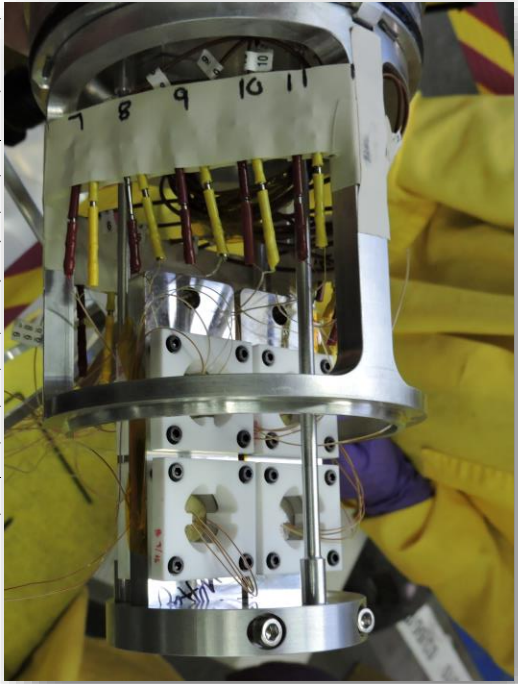
Setup of test sample stakes from earlier DU tests

Instrumentation

- 16 k-type 40 g AWG Thermocouple wires
  - 4-5 per sample welded
  - Mechanical Hold
  - Ceramic adhesive (not epoxy)
- Kulite XTE-190 pressure transducers
  - Required in safety analysis, included redundancy
- TCs welded to face of samples and fastened in two-sided bespoke MACOR® sample holders



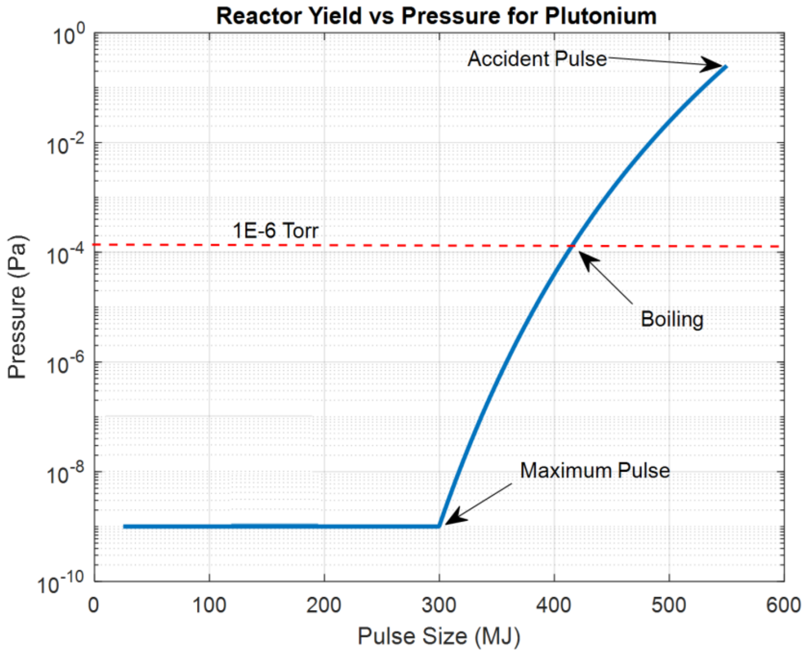
Drawing of Inner Can Design



Strain relief of TCs following assembly of the Bi and DU samples

Accident Scenarios for SNM

- Evaluated credible accident scenarios for the safety review of experiment
  - Sample melt
  - Sample vaporization
  - Release of fission products
  - H and He release from melted samples
  - Vaporization of TC insulation
- ACRR Maximum pulse 250-275 MJ and Accident Pulse 550 MJ

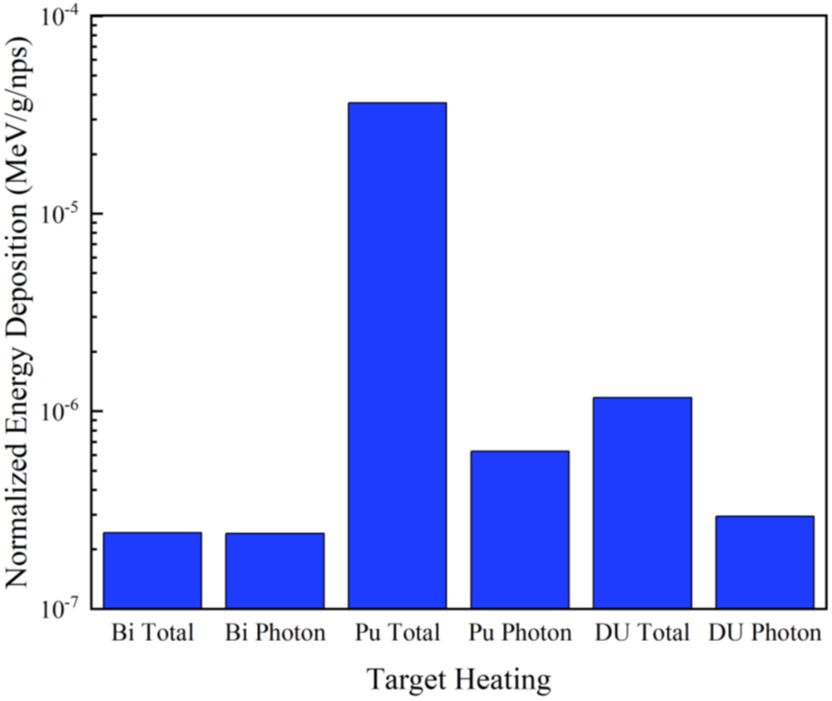


Pressure vs. Reactor Yield Analysis for Maximum Pulse (300 MJ) and Accident Pulse (550 MJ) for Plutonium Sample in ACRR

Neutron and Gamma Heating

- Total fission heating of SNM samples calculated with temperature increase and specific heat capacity
- Bismuth used as a γ heating calorimeter
  - No fission and negligible neutron heating
- Subtraction of gamma heating in Pu, DU, and HEU

$$\Delta\hat{T}_{SNM(n)} = \frac{\Delta\hat{T}_{Bi(\gamma)} \cdot c_{p,Bi}}{c_{p,SNM}}$$

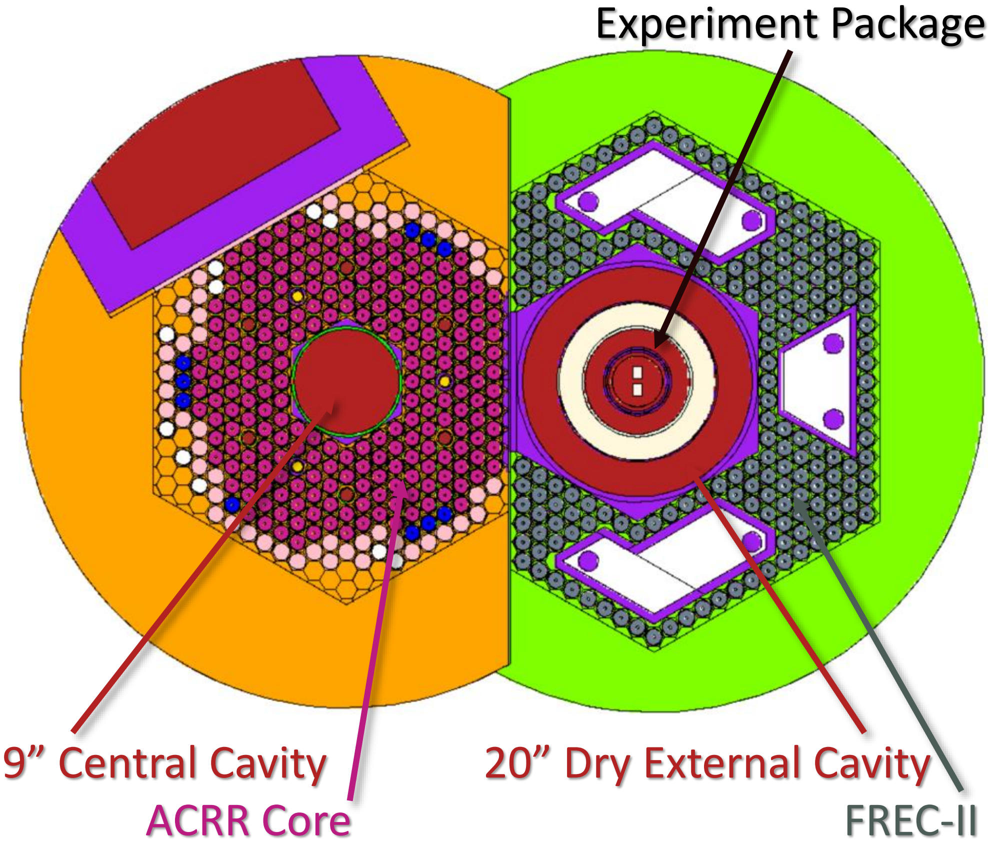


MCNP6.2 Produced Energy Deposition Estimates for ACRR Pulse Operation in Bi, Pu, and DU

Reactivity and Worth Calculations with MCNP6.2

- ACRR provided original model of reactor facility with coupled FREC-II
- For facility approval, calculation of package worth and reactivity characteristics necessary
- Material coupling factor, the sum of energy deposited and generated in that material per MJ of reactor yield

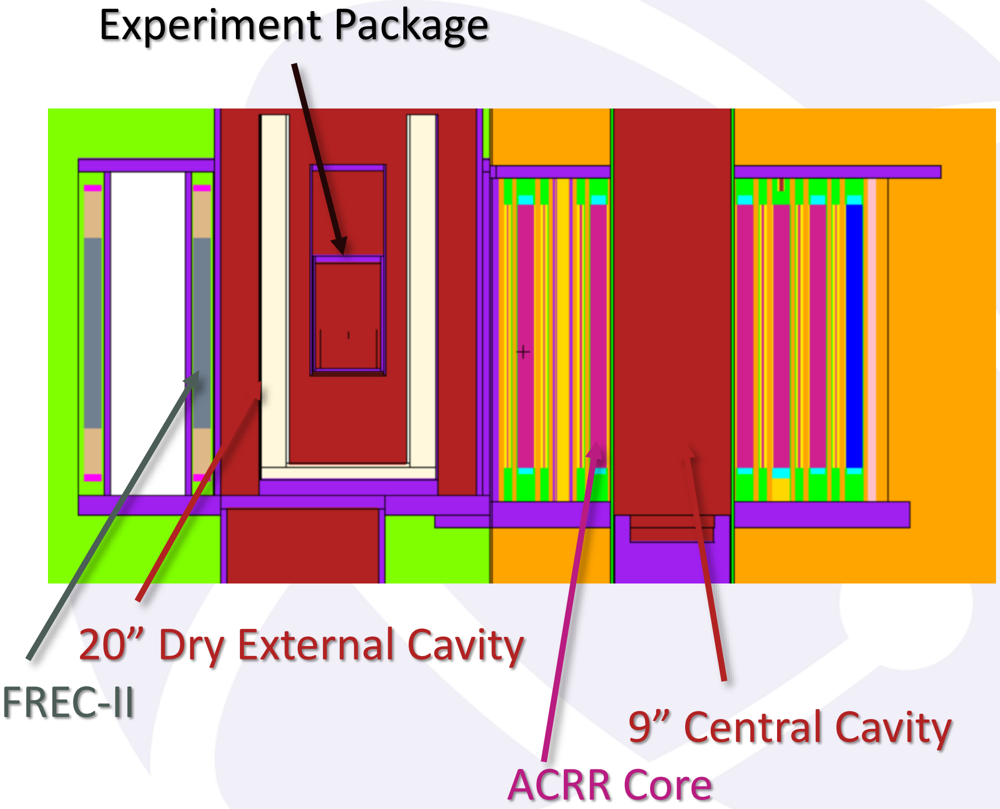
$$F\left\{\frac{J}{g \cdot MJ}\right\} = \frac{C_p \cdot \Delta T}{E_{Pulse}}$$



Simulation of Pulse Heating with MCNP6.2

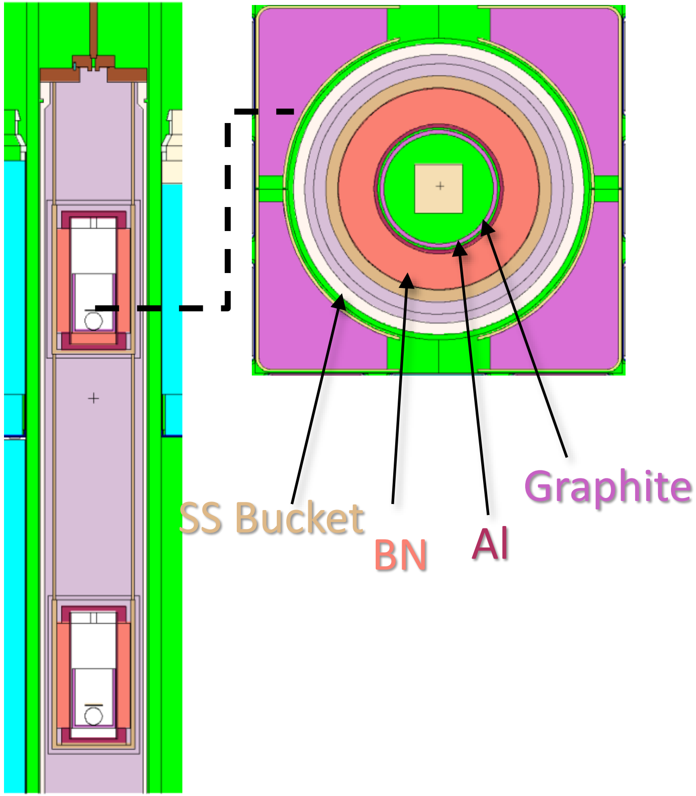
- Enthalpy increase of the samples value of interest for experiment
- Control rods in placement for maximum pulse in model
- +F6 tally in MCNP6.2 utilized in estimating pulse heating
- MCNP provides normalized value of MeV/g/nps

$$E_{Dep} = \frac{\nu \cdot \frac{fissions}{MJ}}{K_{eff}} \cdot \left(\frac{MeV}{g \cdot nps}\right) \cdot E_{Pulse} \cdot \frac{J}{MeV}$$



Neutron Shielding Assessment with MCNP6.2

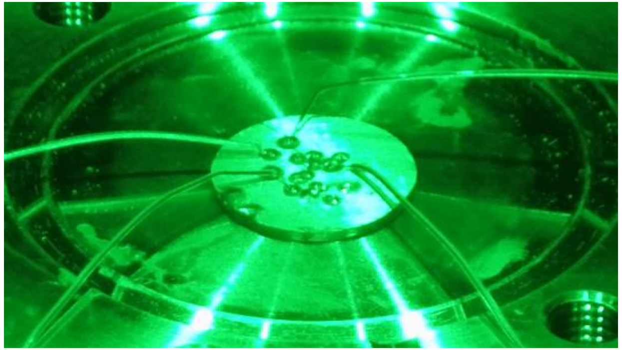
- Shielding required to adjust sample package for neutron energy spectrum, gamma reduction, or reduction in energy absorption
- Use MCNP6.2 to calculate k_{eff} and package environment with adjusting shielding material and thickness
- Balance in neutron heating and ability to pulse
- Consider energy deposition into the shielding as well for structural integrity
  - Non-uniform heating across thick shielding
- TREAT pulse size and energy deposition required special consideration



TRTR Community Involvement

- Interest in performing preparatory experiments at pulsing research reactors
  - Small scale SNM experiments

  With or without SNM:
  - TC attachment methods (e.g, adhesive, spot welding, ultrasonic welding, laser welding)
  - Shielding materials in neutron pulse (e.g., AX05, PCBN1000)
  - Alternative temperature measurement techniques (e.g., pyrometry)
  - Strain gauge attachment methods



Video of laser welding to Bismuth samples

Boron nitride samples: PCBN1000 (square) and AX05 (round) for shielding and ceramic pin connector for future development

Summary

- LANL is investigating pulsed reactor experiments to reestablish plutonium testing capability
- Overview of the design steps and considerations for pulsed reactor experiments with SNM (or other material)
- Discussion of simulation tools to aid in design, evaluation, and defensibility of experimental package
- Desire for cross-facility experiments and development work

Questions?