SAND2014-18133PE

October 1, 2014

Overview of Activities at SNL Technical Area V with a focus on calorimeter studies at the Annular Core Research Reactor

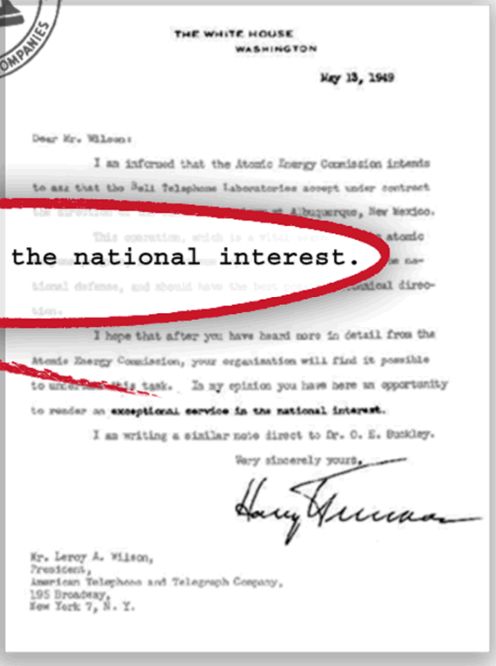
Brian D. Hehr

Senior R&D Scientist and Engineer, Applied Nuclear Technologies Department

Sandia National Laboratories is a multi program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Sandia's history



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract [illegible] at Albuquerque, New Mexico.

This operation, which is a vital [illegible] atomic [illegible] the national defense, and should have the best [illegible] technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an **exceptional service in the national interest.**

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

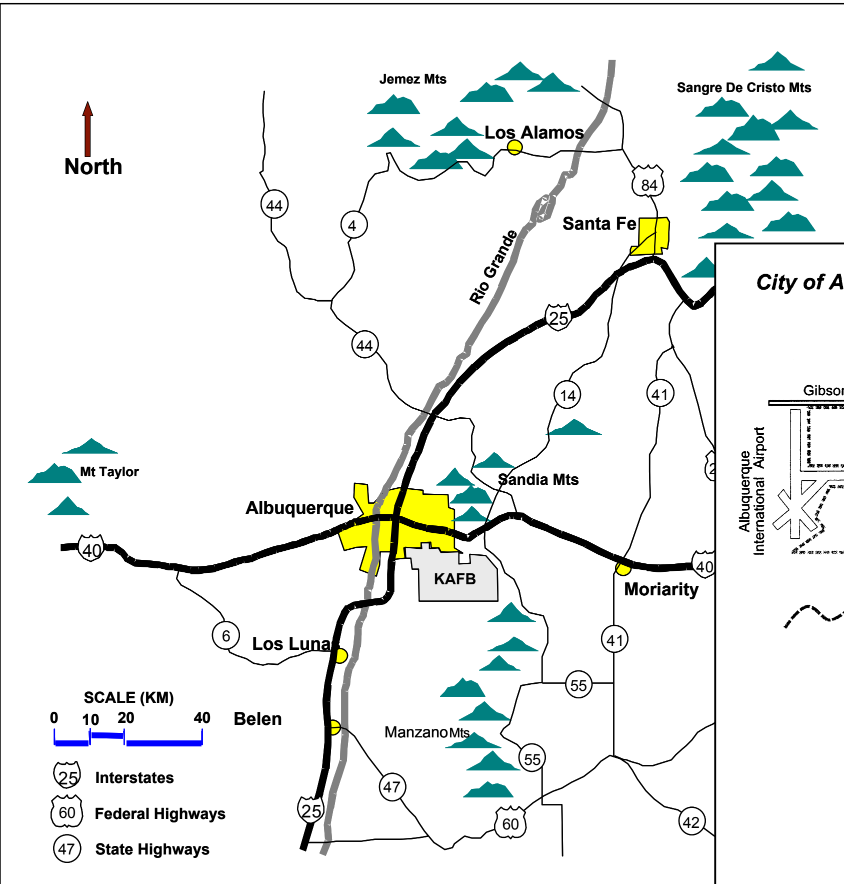
exceptional service in the national interest.

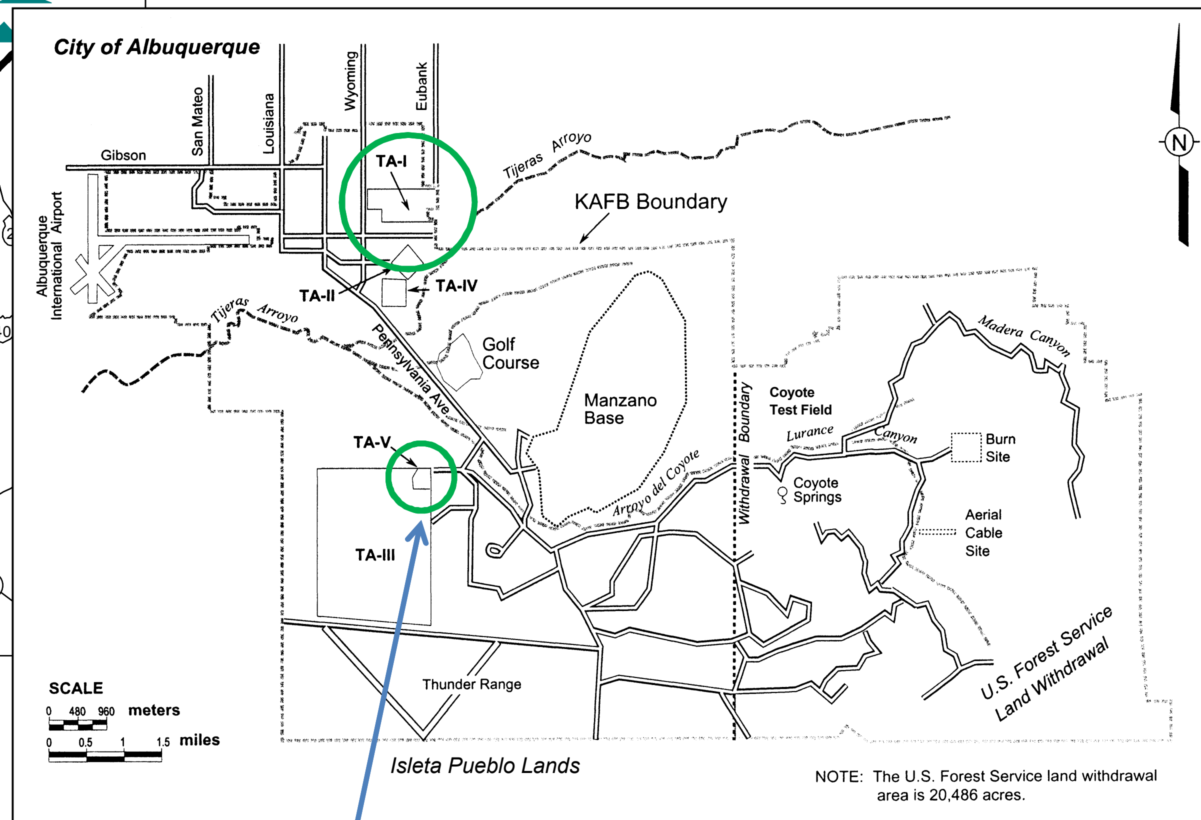
National Laboratories

Sandia National Laboratories

Sandia National Laboratories - ABQ

Sandia National Laboratories (SNL) is located on Kirtland AFB in Albuquerque, NM.

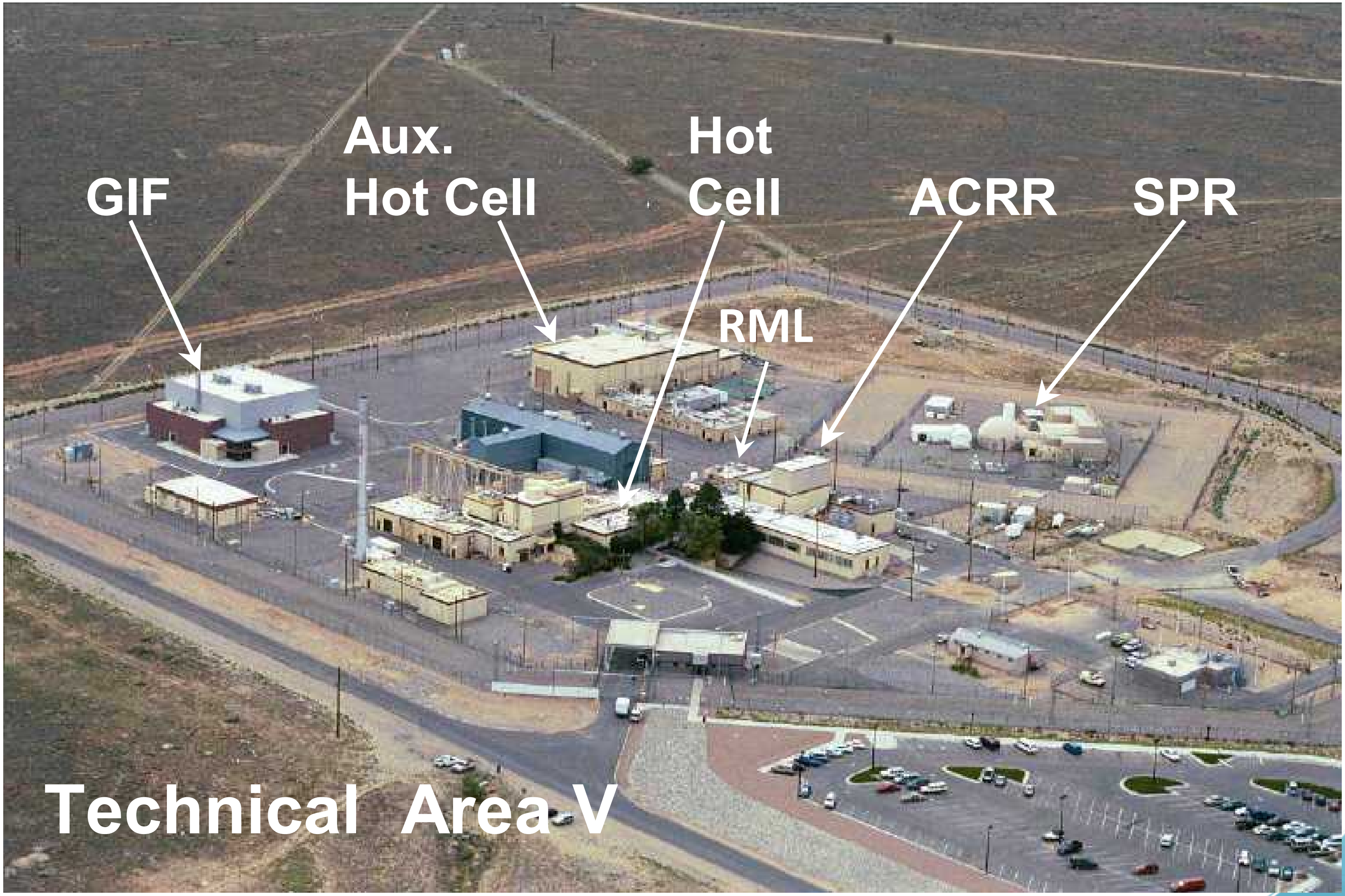




Sandia's nuclear reactor facilities are in Technical Area V - a few miles south of the main research campus.

Sandia National Laboratories

SNL Tech Area V



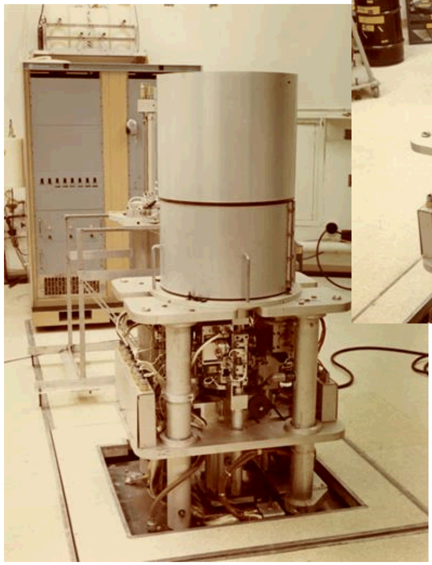
Sandia National Laboratories

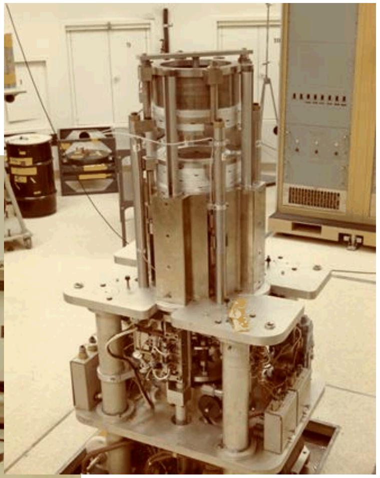
TA-V History

- TAV was constructed in 1959 as part of the Nuclear Airplane Project
  - Sandia Pulse Reactor (SPR-I) – 1961
  - Sandia Pulse Reactor (SPR-II) - 1967
  - Sandia Nuclear Assembly Reactor (SNARE) – 1962
  - Sandia Engineering Reactor (SER) – 1963
  - Annular Core Pulse Reactor (ACPR) 1967

TA-V Recent History

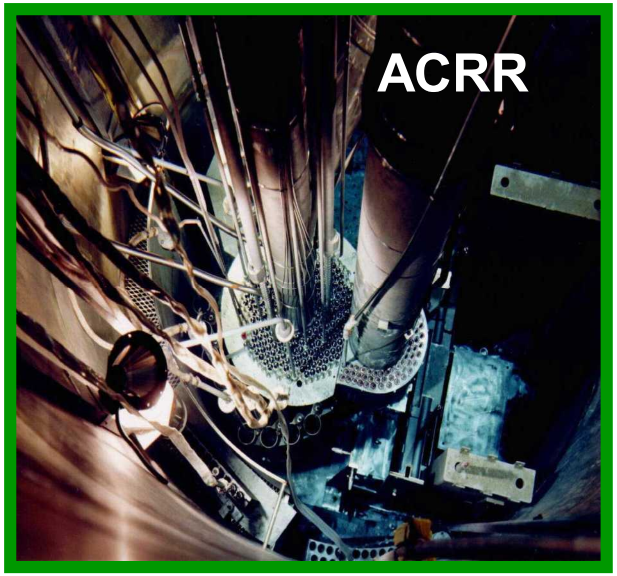
- TAV continued to build on its nuclear reactor success through the ‘70s and ‘80s
  - Sandia Pulse Reactor (SPR-III) - 1976
  - Annular Core Research Reactor (ACRR) – 1978
  - Critical Experiment-Space Nuclear Thermal Power (SNTP-CX) 1989
  - ACRR-Fueled Ringed External Cavity (FREC-II) – 1988



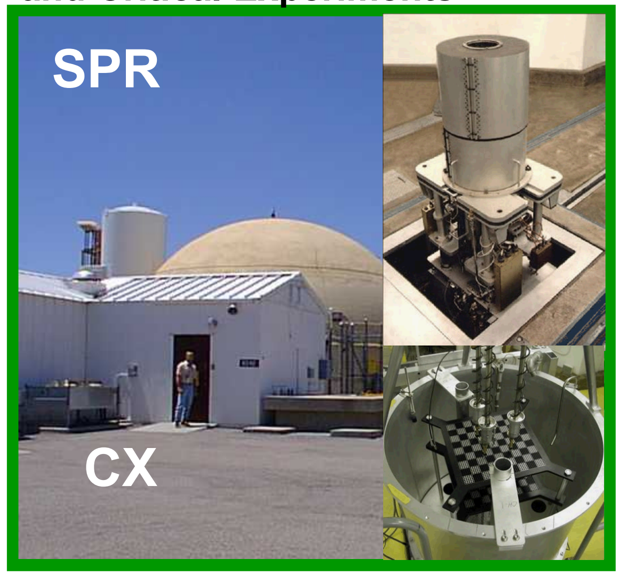


TA-V Facilities Currently Operating

Annular Core Research Reactor



Sandia Pulse Reactor and Critical Experiments

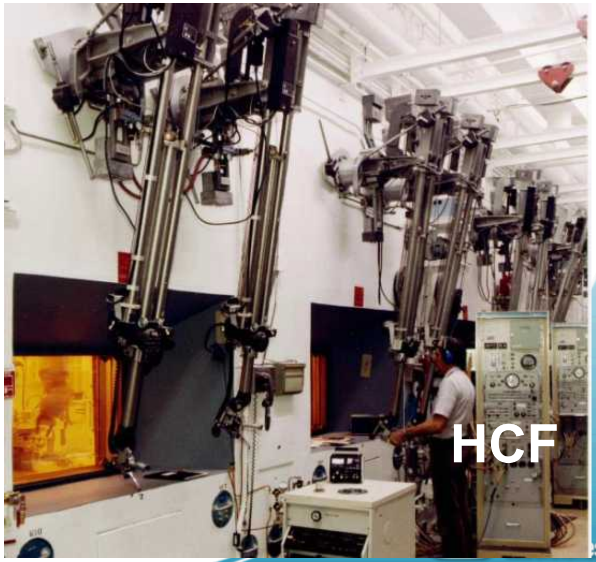


Radiation Metrology Laboratory

Gamma Irradiation Facility

Auxiliary Hot Cell Facility

Hot Cell Facility



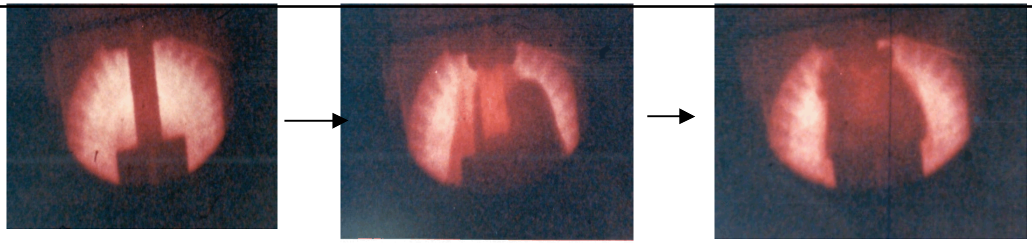
Past Experiment Programs at TAV

- TAV has been involved in many nuclear experiment programs over the years
  - Weapon Component Testing – Our original and continuing mission
  - Radiation Effects Sciences – New methods base on science discovery
  - Fast Reactor Safety – CRBR, Advanced fuel/cladding testing, equation of state
  - Light Water Reactor Safety – TMI, Severe fuel damage and fission product release from debris beds
  - Nuclear Pumped Laser (FALCON) – Part of Reagan's Star Wars Defense
  - Space Thermal Nuclear Power (SNTP) – Critical experiments, particle fuel testing, element testing using hydrogen
  - Medical Isotope Production (Mo-99, I-125) – Domestic production initiative
  - Space Power (JIMO) – Advanced reactors for space power
  - Nuclear Hydrogen Production – Hydrogen as transportation fuel

Sandia National Laboratories

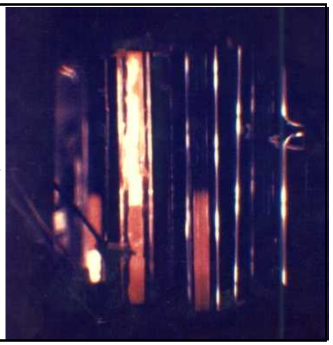
Reactor Safety Testing

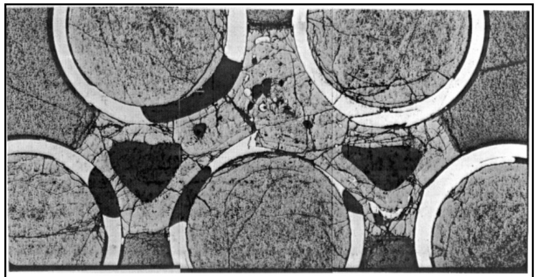
NRC tests of Oxide and Irradiated Mixed Oxide Fuels



Pin heatup, clad melt and FP release, and fuel disruption sequence in LMFBR high burnup fuel pin (FD Program - JNC, UKAEA, KFK, NRC)

Axial clad and fuel relocation in LMFBR pin array (STAR Program - JNC, NRC)

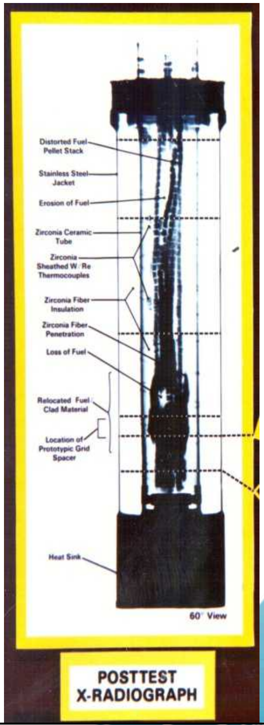




Transition phase studies in LMFBR pin arrays (TRAN Program - JNC, NRC)

ACRR has been used to simulate a wide range of transient fuel test conditions

Severe fuel damage and FP release tests on LWR fuel bundle (SFD Program)

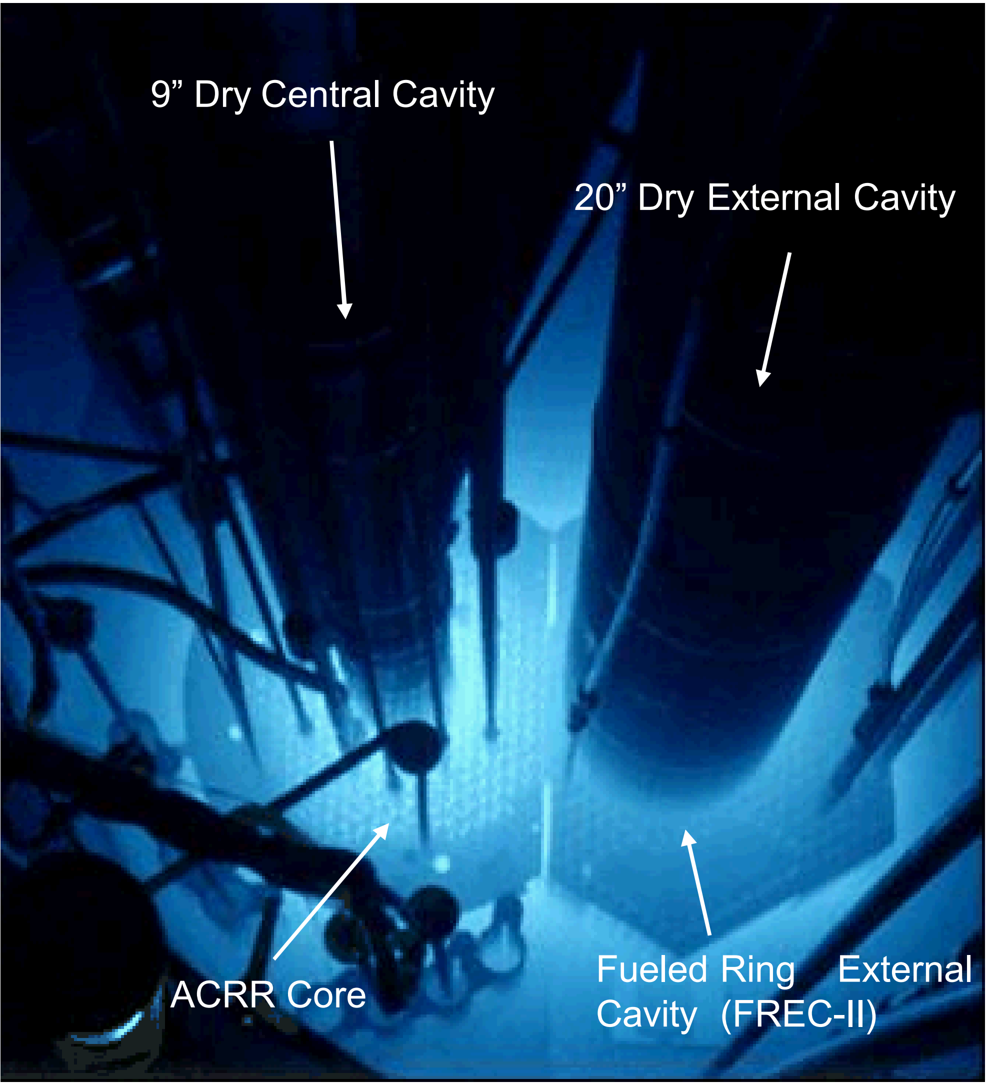


Current Experiment Programs at TAV

- TAV is still relevant – last research reactor standing
  - Weapon Component Testing – Our original and continuing mission
  - Radiation Effects Sciences – New methods base on science discovery
  - Burnup Credit – Critical experiments fission product reactivity effects
  - Criticality Safety – Critical experiments training for the complex
  - Advanced Reactor Concepts – Right Size Reactor Concept (RSR)
  - Advanced Power Generation Cycles – Supercritical CO2 cycle

Sandia National Laboratories

ACRR Description



ACRR and FREC-II

- 236 UO_2-BeO fueled elements
  - 1.5 in (3.8 cm) dia. x 20 in (51 cm)
  - 100 g U-235 per element – 35% enr.
- Operating Power level
  4 MW_{th} Steady State Mode
  - 250 MJ Pulse Mode (6 ms FWHM)
  - 300 MJ Transient Mode (Programmable)
- Dry cavity 9 in (23 cm) diameter
  - Extends full length of pool through core
  - Neutron Flux 4E13 n/cm^2-s at 2 MW
  - 65% > 1 eV, 56% > 10 keV, 45% > 100 keV
- Epithermal Spectrum
  - Flux in cavity can be tailored for desired energy spectrum (Poly, B4C)
- Open-pool type reactor
  - Fuel elements cooled by natural convection
  - Pool cooled by HX and cooling tower
- FREC-II uses previous ACPR fuel
  - TRIGA type (UZrH) – 20 in (51 cm) dia. dry cavity
- Fuel burnup is minimal
- Reactor used for short duration power runs, pulses, and transients

Sandia National Laboratories

Central Cavity Bucket Limitations

Lead melts @ 327 °C

Poly melts @ 120-130°C

Lead Poly (LP-1&LP-2) Bucket (Posey bucket AF&F)

- Designed for a specific set of neutron and gamma requirements
- 6-inch ID
- 200 MJ, un-instrumented
- Payload limited to 250 pounds
- Worth = - $2.50

Total Neutron Fluence n/cm2/MJ	2.50E13
Gamma [Rad/MJ]	5.5E3

↑ η_{th} ↓ γ

PLG Bucket (LP-1 upgrade) (Posey bucket AF&F)

- Designed for a specific set of neutron and gamma requirements
- 7-inch ID
- 200 MJ, un-instrumented
- Payload limited to 300 pounds
- Worth = + $0.42

Total Neutron Fluence [n/cm2/MJ]	2.36E13
Gamma [Rad/MJ]	6.6E3

↑ η_{th} ↓ γ

Pb-B_4C Bucket (and LB-44)

- 4.9-inch ID (5.0 – inch – LB44)
- 500 MJ, un-instrumented
- The container may be used up to a measured temperature of 250 C
- Payload limited to ~250 pounds
- Worth = - ~$5.90 (LB44 (~-$6.07)

Total Neutron Fluence n/cm2/MJ	1.16E13
Gamma [Rad/MJ]	1.02E3

↓ η_{th} ↓ γ

Central Cavity Instrumentation (passive)

- No normally installed instrumentation other than in-core diagnostics, ex-core diagnostics thermocouples.
- Primary CC diagnostics– Passive Nuclear Dosimetry

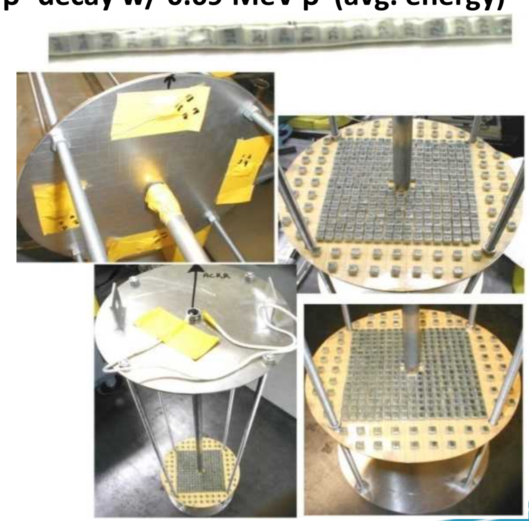
  Ni, S, Fission Foils, Activation Foils ,TLD

<u>Thermal</u>

- $^{45}Sc(n,\gamma)^{46}Sc$, ^{45}Sc 100% abundance, ^{46}Sc $T_{1/2}$ = 83.81 days, β^- decay w/ 1.12, 0.89 MeV γ
- $^{59}Co(n,\gamma)^{60}Co$, ^{59}Co 100% abundance, ^{60}Co $T_{1/2}$ = 5.271 years, β^+ decay w/ 1.33, 1.17 MeV γ
- $^{58}Fe(n,\gamma)^{59}Fe$, ^{58}Fe 0.282% abundance, ^{59}Fe $T_{1/2}$ = 44.51 days, β^- decay w/ 1.29 MeV, 1.10 MeV γ

<u>Fast</u>

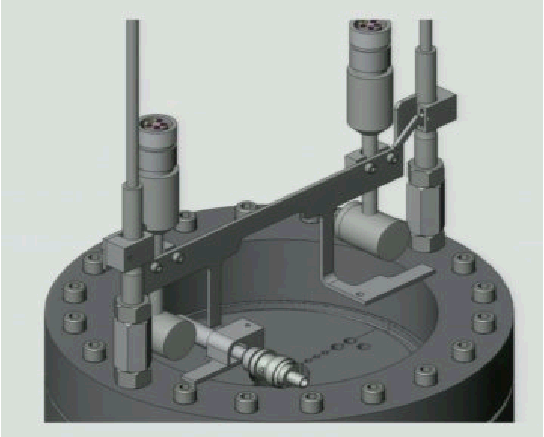
- $^{54}Fe(n,p)^{54}Mn$, ^{54}Fe 5.845% abundance, ^{54}Mn $T_{1/2}$ = 312.2 days, ε decay w/ 0.83 MeV γ
- $^{58}Ni(n,p)^{58}Co$, ^{58}Ni 68.077% abundance, ^{58}Co $T_{1/2}$ = 70.88 days, ε, β^+ decay w/ 0.81 MeV γ
- $^{32}S(n,p)^{32}P$, ^{32}S 95.02% abundance, ^{32}P $T_{1/2}$ = 14.26 days, β^+ decay w/ 0.69 MeV β (avg. energy)



Sandia National Laboratories

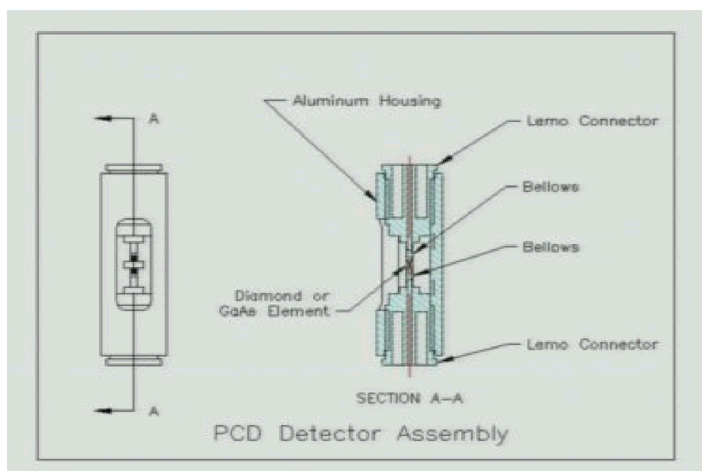
Central Cavity Instrumentation (active)

- PCDs, pin diodes, Calorimeters, Ion Chambers, Fission Chambers,



PCDs – Rate Detectors

- **Radiation Hardened Photo-Conducting Detector**
- **Diamond PCDs used to determine pulse shape.**
- **Useful for many pulses in ACRR Central cavity**
- **Very fast – being used at Hermes III and Z-pinch Accelerators**
- **Diamonds are pre-dosed to 1E16-1E17 n/cm2 in ACRR before fabrication**
- **Have replaced Pin Diodes – Higher survivability rate**



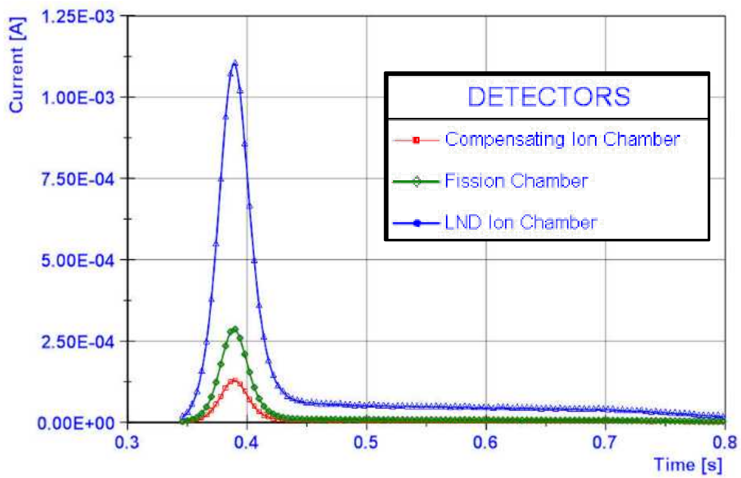
Fission Chambers

- **Fission Chambers (U-235, Np-237, U-238)…Typically microgram (deminimis) quantities.**

Modeling, Calibration and Verification of a Fission Chamber for ACRR Experimenters

Jonathan Coburn (NCSU intern), Summer 2013

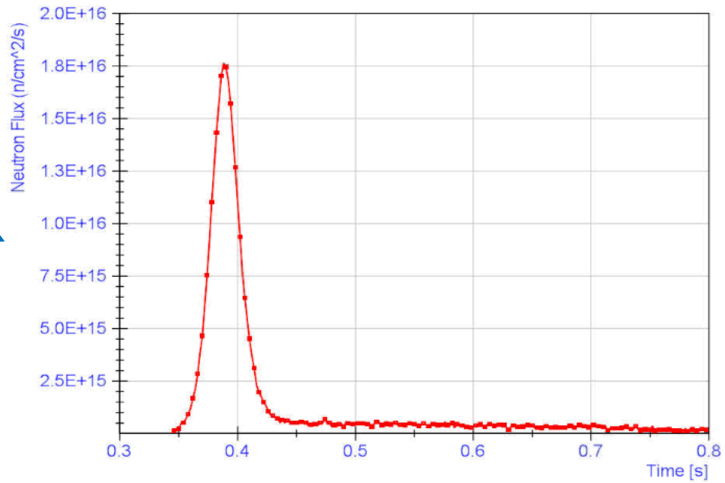
Current Signal for 50 MJ Pulse



$$\overline{\varphi_n}(t) = \frac{I_n(t)}{F \cdot A \cdot x \cdot \overline{\Sigma_f}}$$

Run Number	Type	Energy [MJ]	Time [s]
1	Pulse	36	0.696
2	Pulse	47.3	0.663
3	Pulse	50	0.450
4	Pulse	98	0.455
5	Steady-state	8.5	466
6	Steady-state	22.2	582
7	Steady-state	88.1	557
MCNP Fissions/MJ Constant:	$3.04*10^6$ [Fissions/MJ]		
A_{FC}/A_{LND} Ratio:	0.0977		
G_{FC}/G_{LND} Ratio:	0.844		
$\overline{\Sigma_f}$ for LB36 Environment	0.0679 [cm^{-1}]		

Neutron Flux for 50 MJ Pulse



Calorimetry

- A calorimeter, meaning heat, is a device used for calorimetry – the science of measuring the heat of nuclear (or chemical) reactions or physical changes as well as the heat capacity of a material.

- Absorbed dose calorimetry is a direct method of measuring radiation energy deposition in reactor environments.

- May use a variety of materials (e.g. boron, silicon, tantalum, GaAs, etc…). In fact, virtually any material is intrinsically capable of being employed as a calorimetric sensor.

Objectives of Calorimetry Study

To investigate the responses of a set of elemental calorimeter materials including Si, Zr, Sn, Ta, W, and Bi to pulsed irradiation inside the central cavity of ACRR.

Of particular interest is the measured heating component due to secondary radiation produced within the calorimeters themselves, since this would be highly localized and, consequently, could impact test environment characterization efforts.

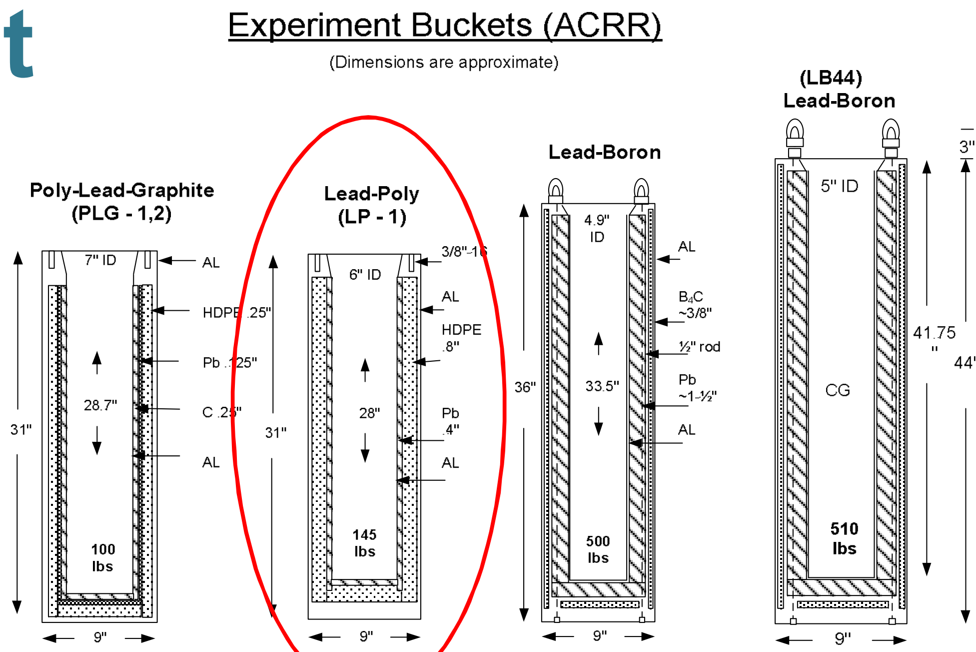
Specific goals are to:

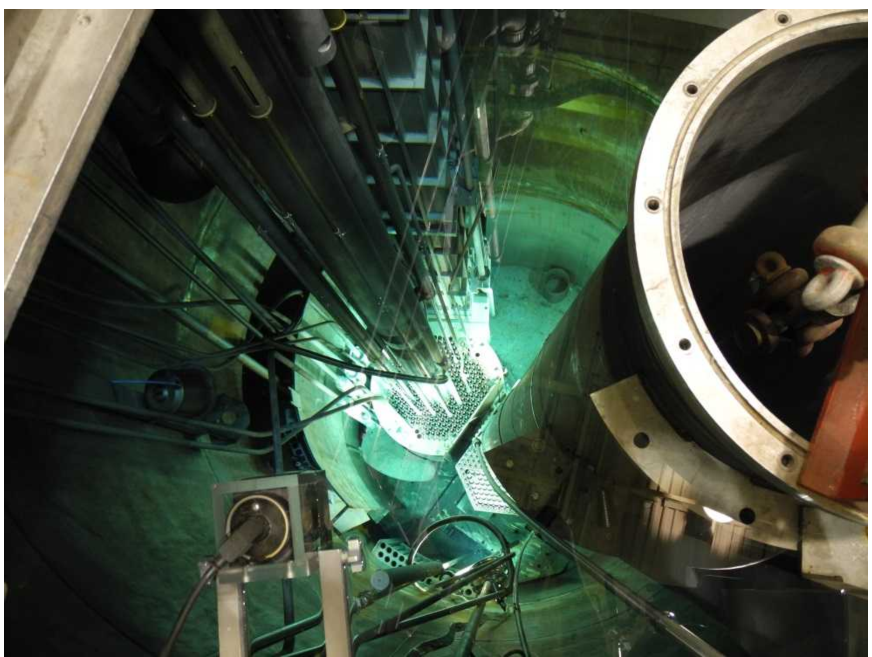
- Examine differences in response behavior among the various materials, including that portion attributable to neutron capture reactions within the calorimeters
- Assess the fidelity of an MCNP model in replicating the observed responses
- Survey the apportionment and origin of significant radiative dose contributions

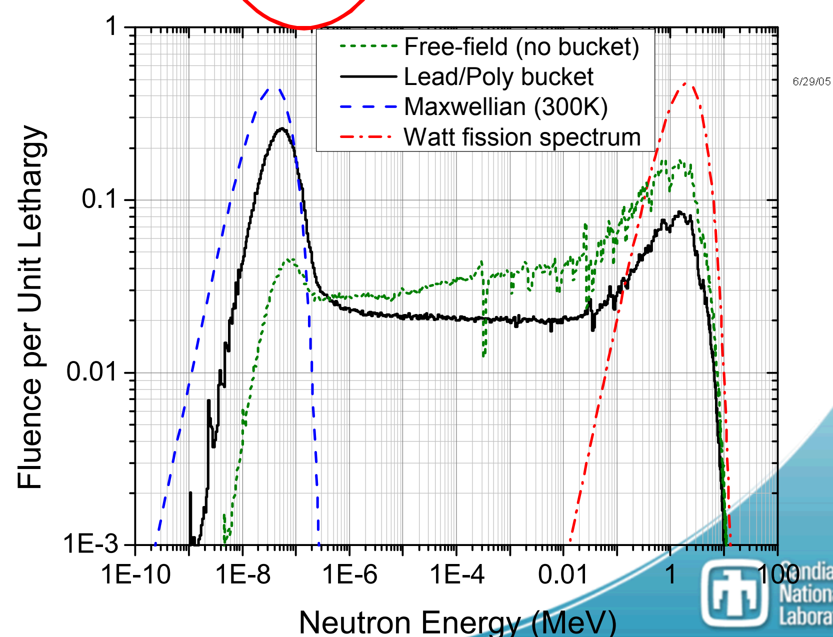
ACRR environment

Four spectrum-modifying buckets are in common use at ACRR. The analysis herein shall focus on the lead-poly bucket (highly moderating) and the free-field cavity.

For reference, the poly-lead-graphite bucket would be intermediate between the above two environments, and the lead-boron bucket would feature fewer gammas and a much harder neutron spectrum.





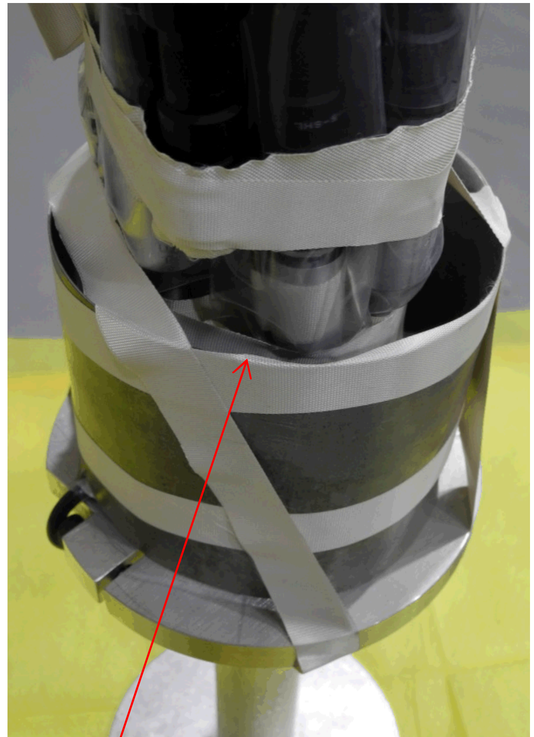


Sandia National Laboratories

Experimental Setup

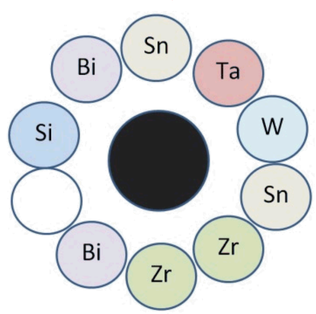
Aluminum stand

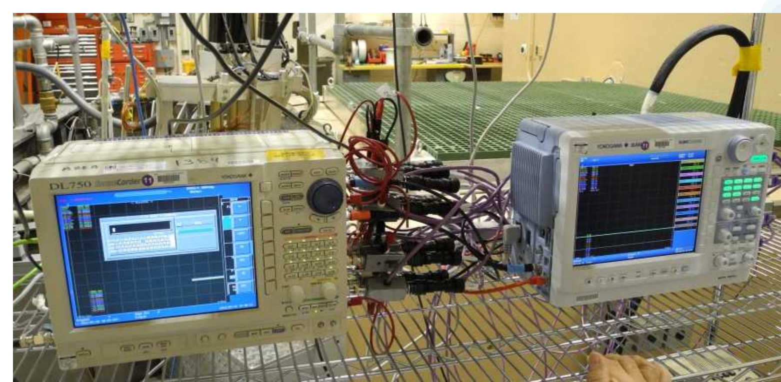
Bare calorimeter array



Cd-covered array

Bucket loading & data acquisition

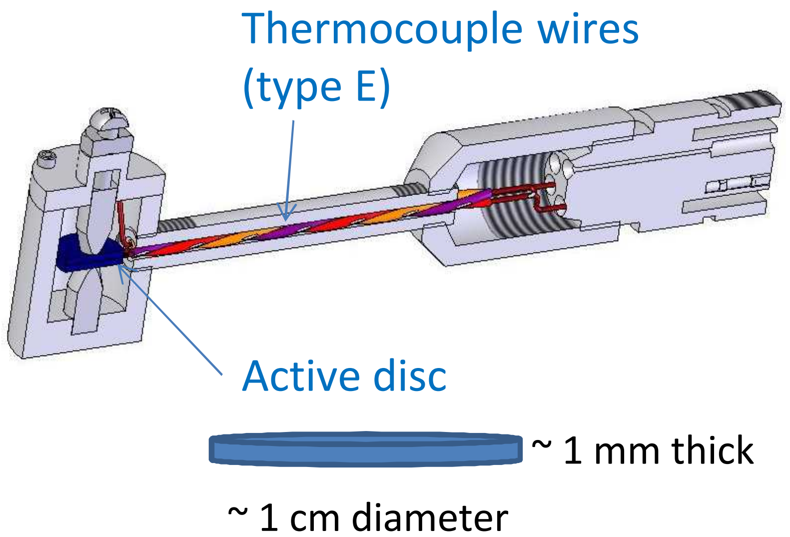


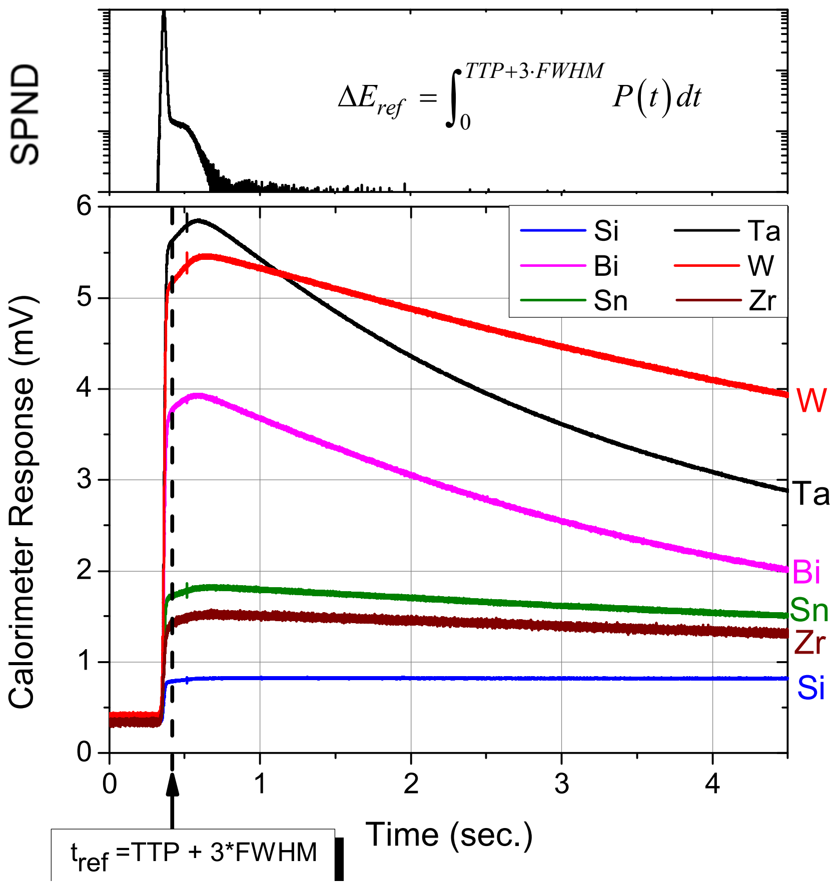


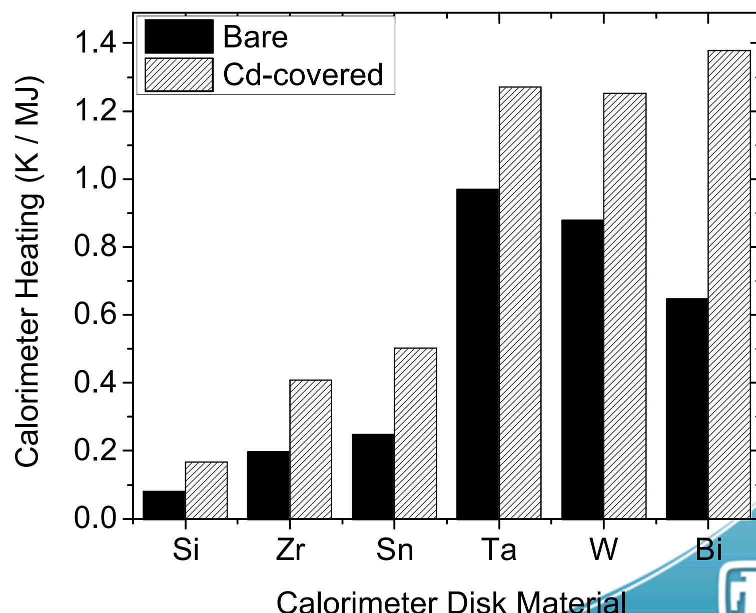
Calorimeters

Signal (in mV) converted to heating (in K) by means of tabulated conversion factors for type E thermocouple

Conversion =~ 0.06 mV/K near room temperature





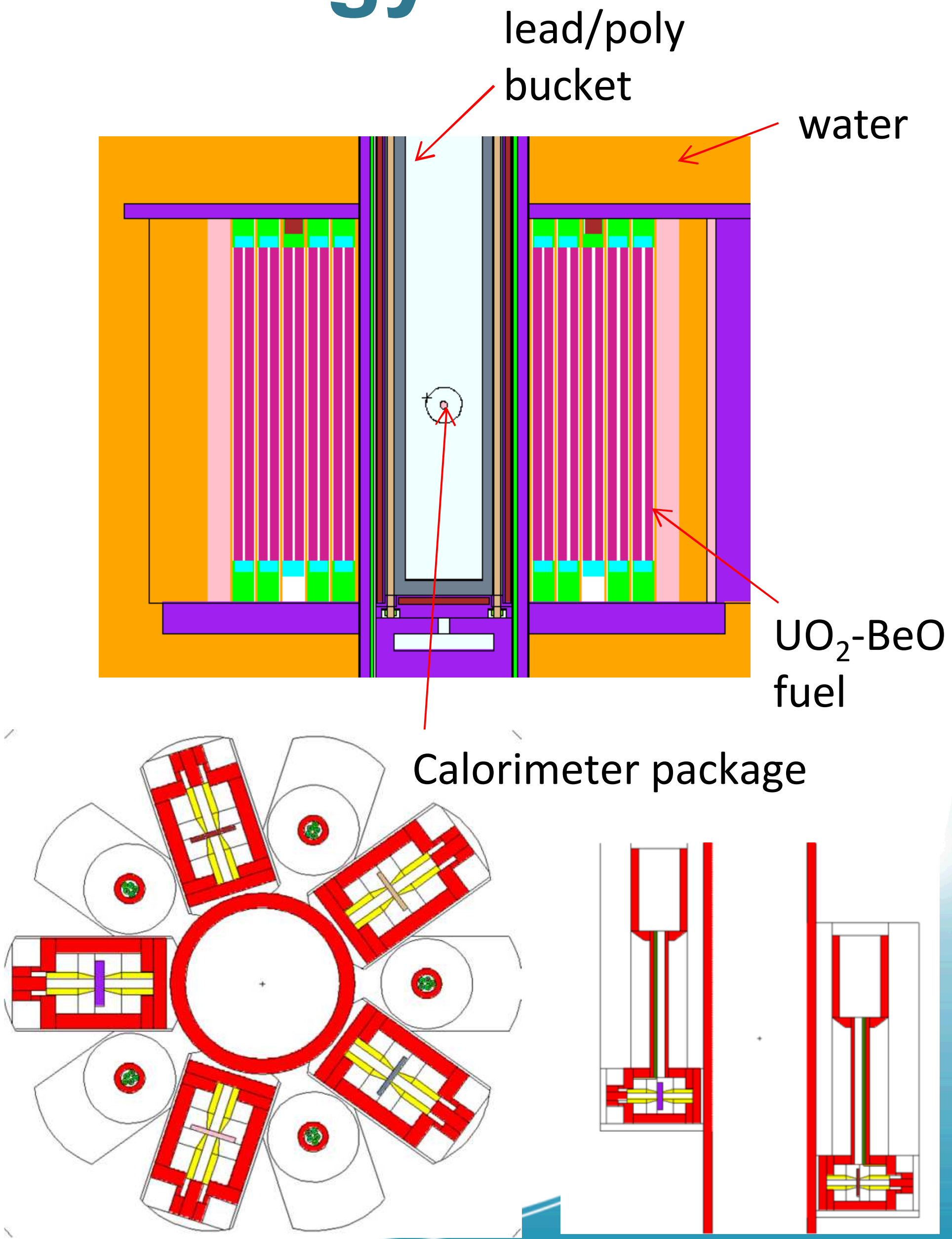


Sandia National Laboratories

Computational Methodology

- Reactor and experimental package modeled in MCNP
- ENDF/B-VII cross sections used except where gamma production data was lacking (e.g. cadmium).
- Temperature set to 300 K for cross section evaluation purposes
- Heating in the active discs was computed from energy deposition tallies in conjunction with appropriate heat capacities.
- Result was normalized to the pulse energy (in MJ) via:

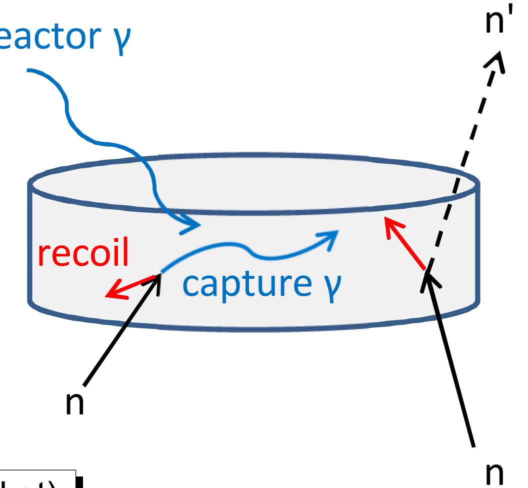
$$\frac{1\ rad}{source-n}\cdot\left(\frac{2.4\ source-n}{fission}\right)\left(\frac{fission}{180\ MeV}\right)\left(\frac{1\ MeV}{1.6\,x\,10^{-19}\ MJ}\right) = 8.33x10^{16}\ \frac{rad}{MJ}$$



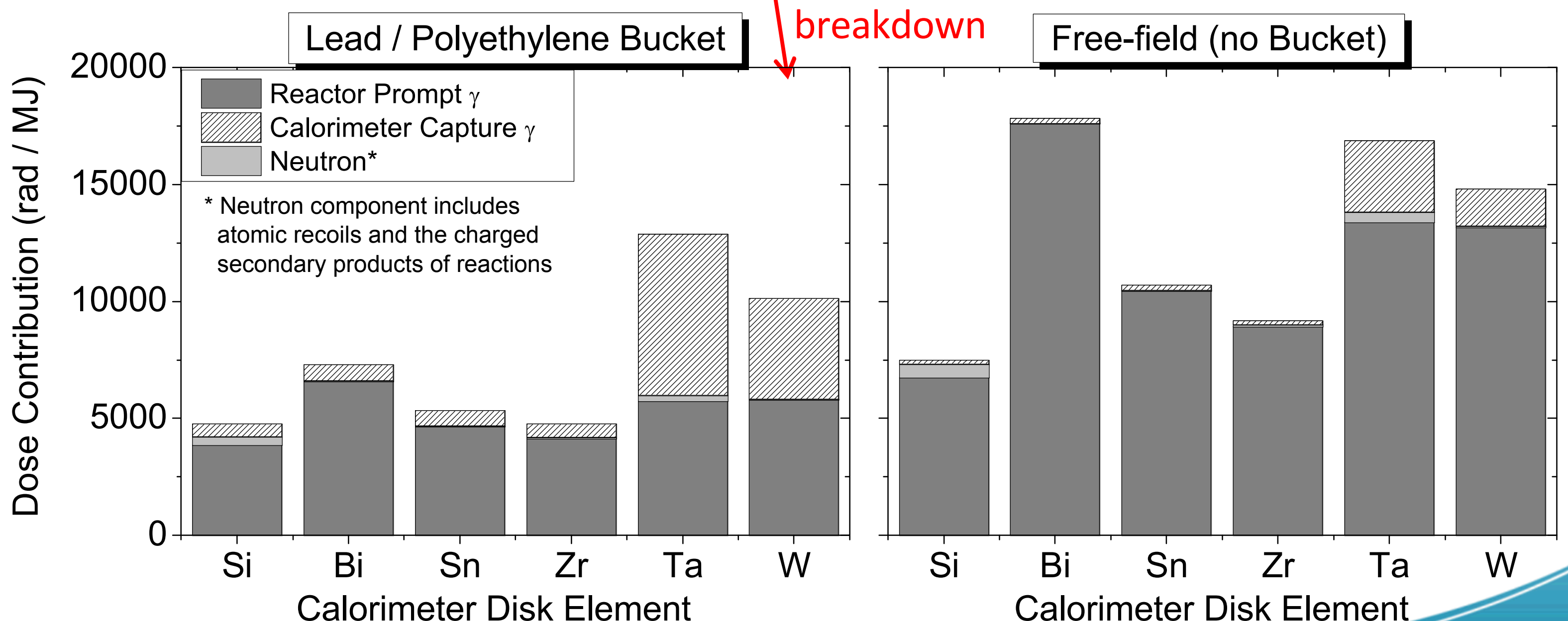
Calculated vs. Experimental Heating

Dose was evaluated using *f8 pulse height tally + electron transport. The kerma was found to overestimate dose substantially due the assumption of charged particle equilibrium.

Disk type	EXPT Heating (K/MJ)			CALC. Heating (K/MJ)		
	Bare	Cd-wrapped	Ratio	Bare	Cd-wrapped	Ratio
Si	0.081	0.167	2.1	0.075	0.158	2.1
Zr	0.198	0.408	2.1	0.185	0.407	2.2
Sn	0.248	0.501	2.0	0.228	0.510	2.2
Ta	0.970	1.270	1.3	1.002	1.244	1.2
W	0.878	1.252	1.4	0.806	1.222	1.5
Bi	0.648	1.378	2.1	0.654	1.402	2.1



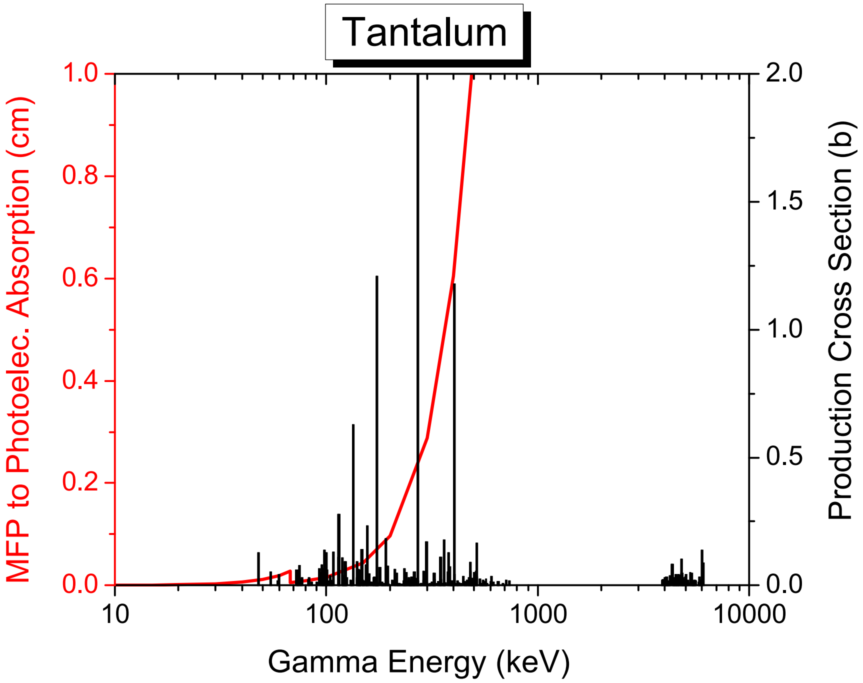
Component breakdown

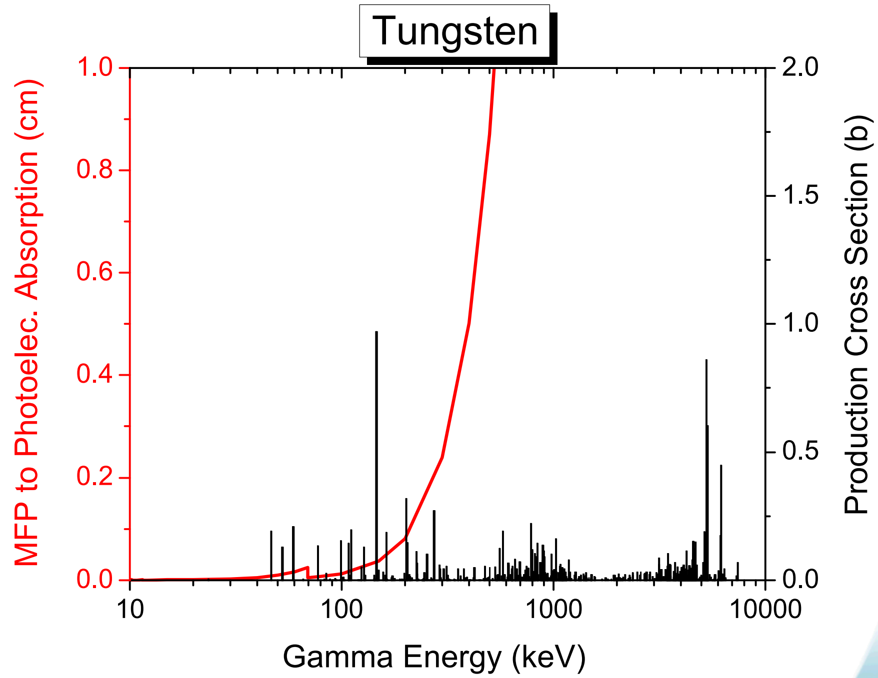


Sandia National Laboratories

Prompt Capture γ – Range in Disc

A significant dose contribution from disc-generated prompt gammas is plausible in tantalum and tungsten given the prompt γ energy spectrum and range.





67% of gammas produced below 300 keV

26% of gammas produced below 300 keV

Photon cross sections from: NIST XCOM photon database

Prompt gamma data from: R.B. Firestone at al., *Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis*, IAEA STI/PUB/1263, 251 pp (2007).

Non-disc Contributions

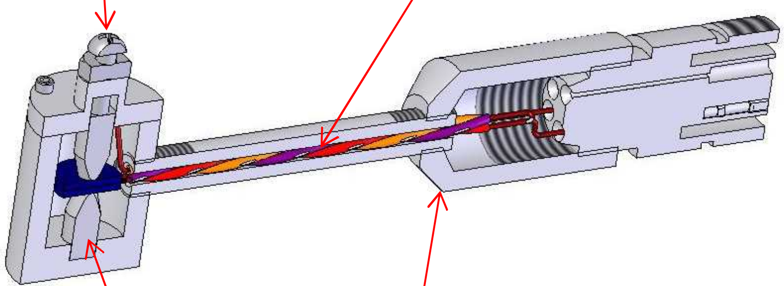
Percent contribution to total response in bismuth:

Steel screw

0.3% lead/poly
< 0.1% free-field

Thermocouple wires

1.8% lead/poly
0.2% free-field



Alumina spacers + Aluminum body

4.3% lead/poly
0.7% free-field

Stand

Not considered (introduces nearly identical perturbation to all test articles)

Conclusions

- Prompt capture gammas generated within the active disc elements can be a major contributor to the measured response.
  - **Pb-poly bucket**: up to 50% of total
  - **Free-field**: up to 20% of total

  with (n,γ) reactions in auxiliary, non-disc components adding an additional several percent in the Pb-poly bucket.

- Simulated heating factors (K/MJ) agree with measured values to within 10% when the dose / kerma offset is taken into account. In particular, comparison of the Cd-wrapped vs. bare response indicates that the model correctly captures secondary radiation effects.

- The results suggest that care must be taken to account for the prompt (n,γ) dose when utilizing certain calorimeter types for dosimetry purposes, since the measured dose can reflect localized perturbations that would not impact other test articles.

Future Work

- Examine response in other buckets (PLG and Pb-B) and test additional disc materials of interest -- especially gold, cadmium, and indium. All three, in fact, have already been tested successfully.

- Incorporate nickel foils and/or sulfur pellets into the dosimetry package for each pulse, so that the pulse energy reported by the reactor ops staff can be corroborated independently.

- Further investigate the validity of imposing an isotropic, spherical source approximation in the MCNP model of the central cavity (used herein only to partition radiative dose contributions in the bare package). There is evidence that this approximation introduces an error of up to ~ 10% in the total dose.

Sandia National Laboratories

Sandia National Laboratories - NCSU/NE Graduates

- **Current Employees**
  - Jonathan Coburn (BS, MS)
  - Charlie Craft (BS, MS)
  - Kevin Hart (BS)
  - Brian Hehr (BS, MS, PhD)

Questions?