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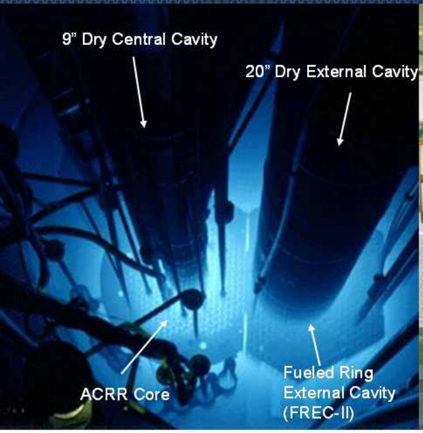

Neutron and Gamma-Ray Radiation Environments for the Annular Core Research Reactor Central Cavity and the FRECII Cavity

Presented at the 16th International Symposium on Reactor Dosimetry – Santa Fe, NM

Ed Parma

May 7-12, 2017

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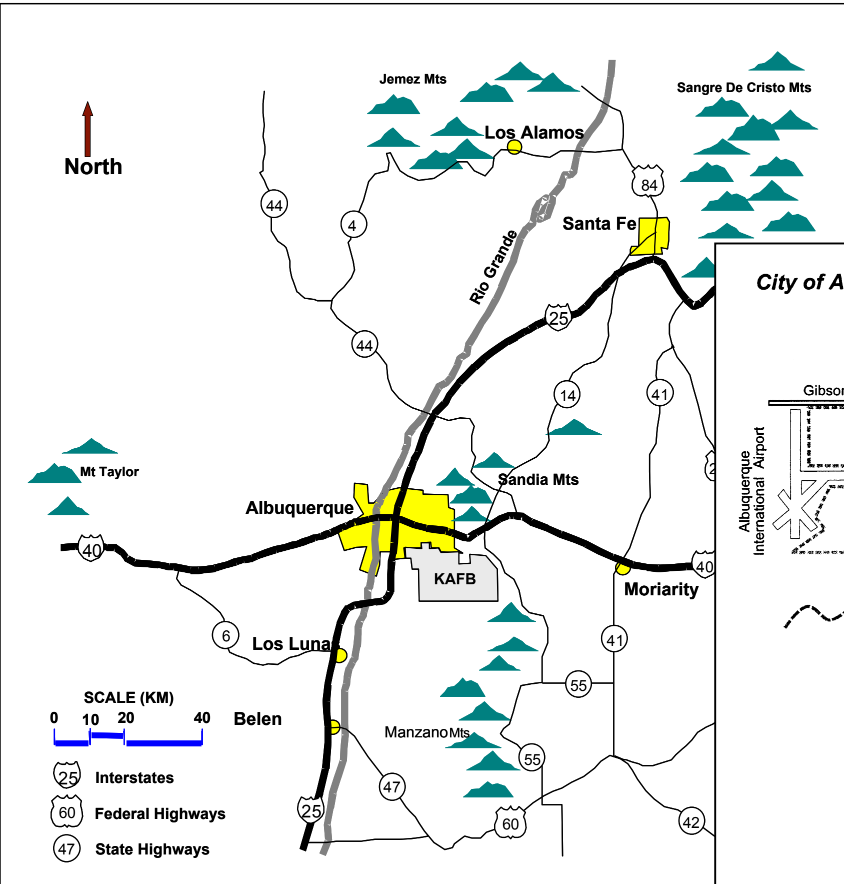

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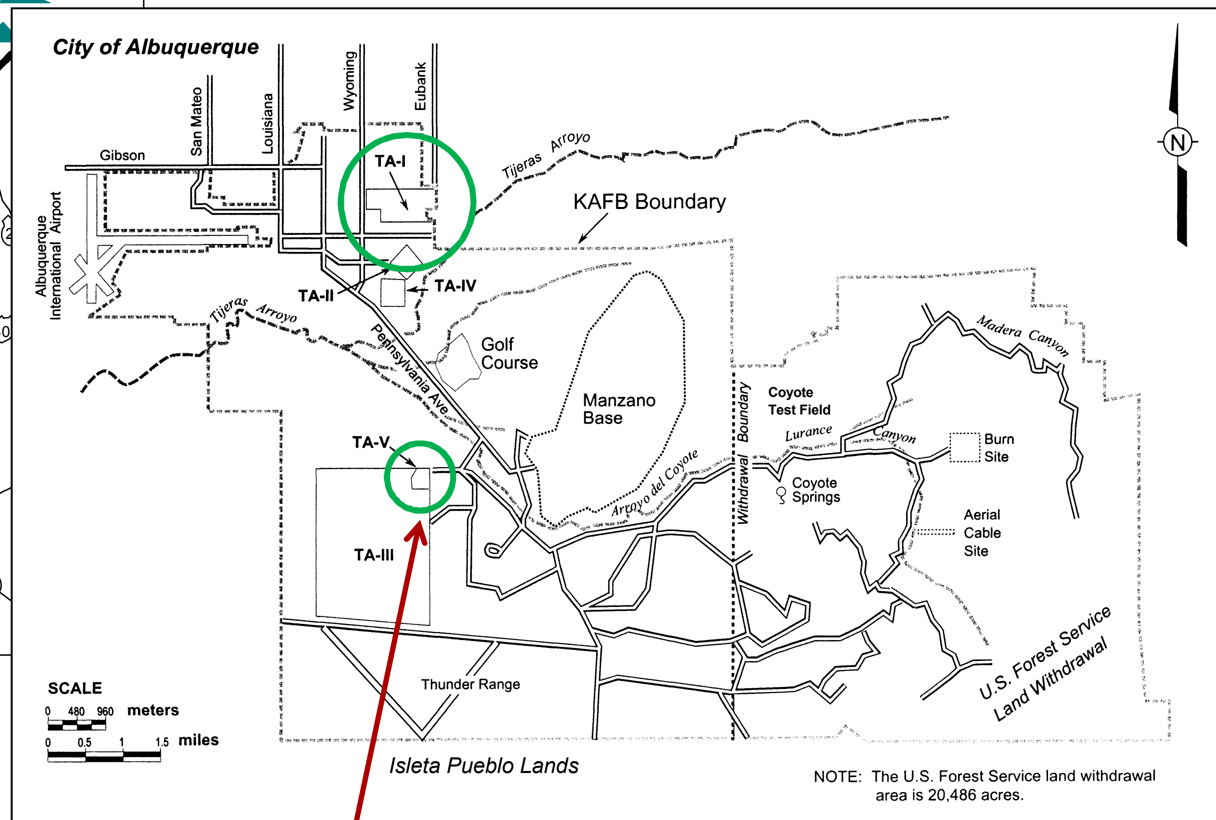
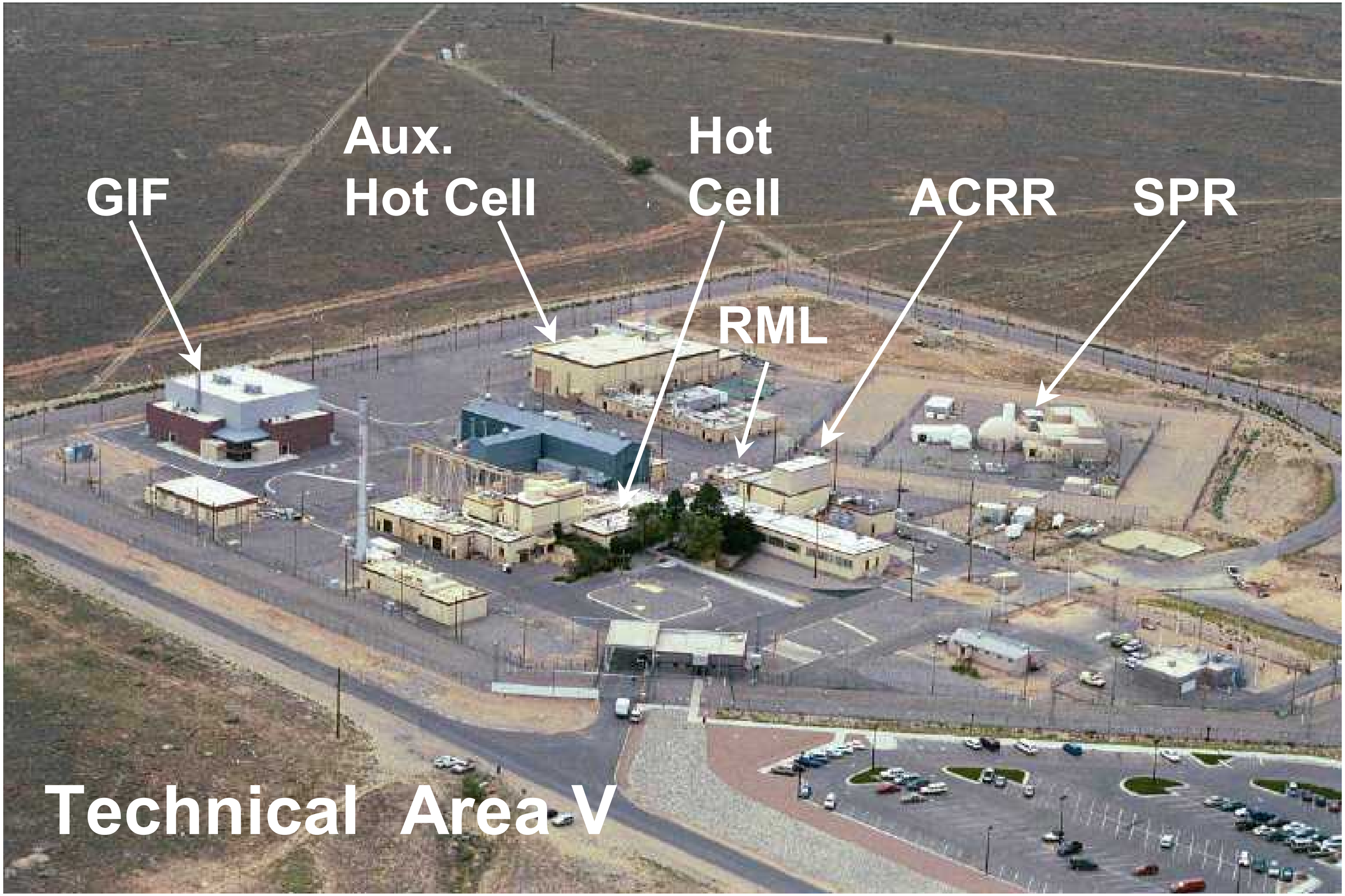


Sandia's nuclear reactor facilities are in Technical Area V - a few miles south of the main technical area.

SNL Tech Area V

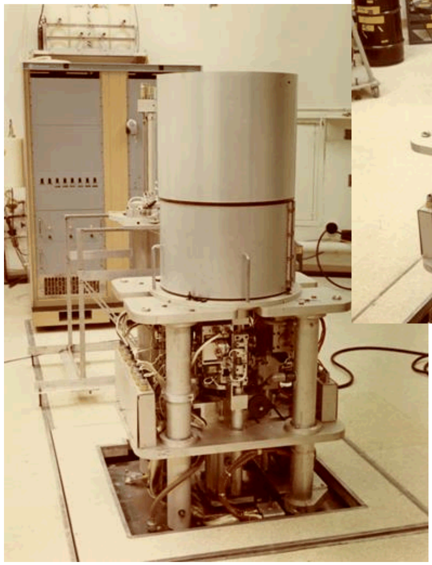


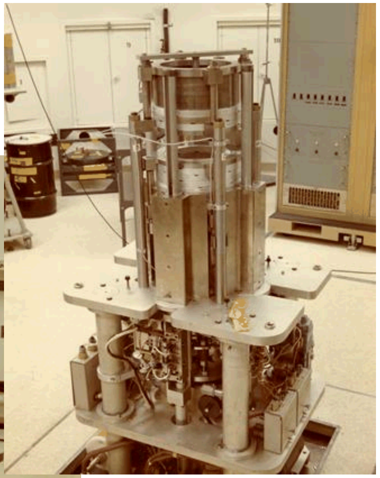
TA-V History

- 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

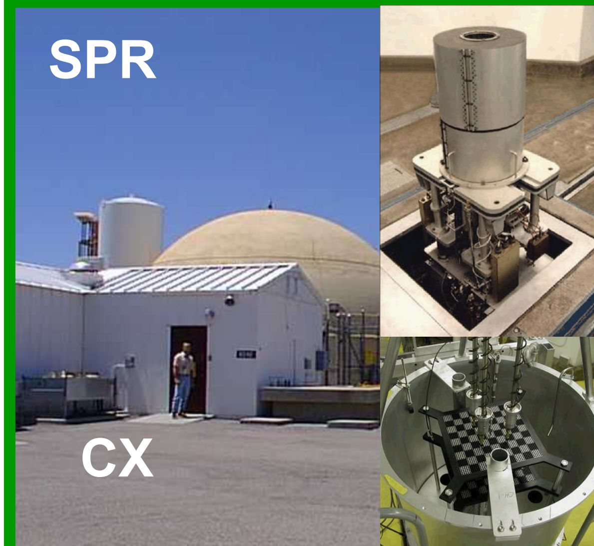




TA-V Facilities Currently Operating

Annular Core Research Reactor

Sandia Pulse Reactor and Critical Experiments

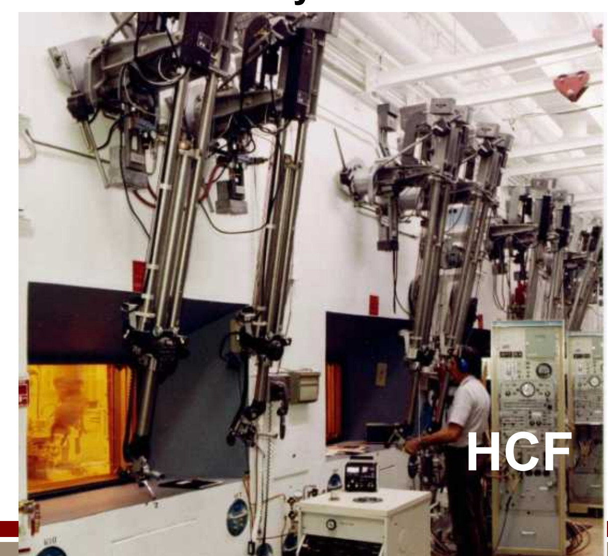


Radiation Metrology Laboratory

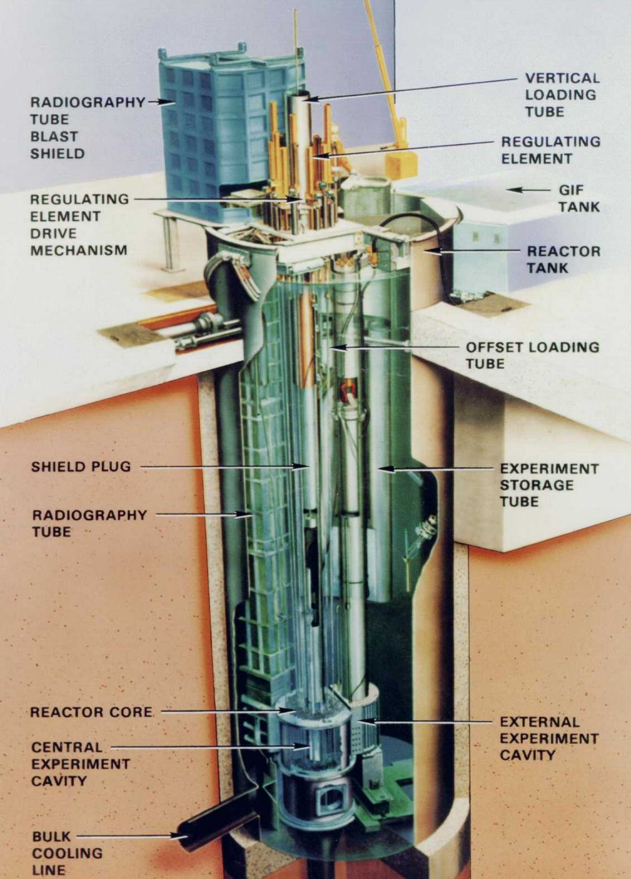
Gamma Irradiation Facility

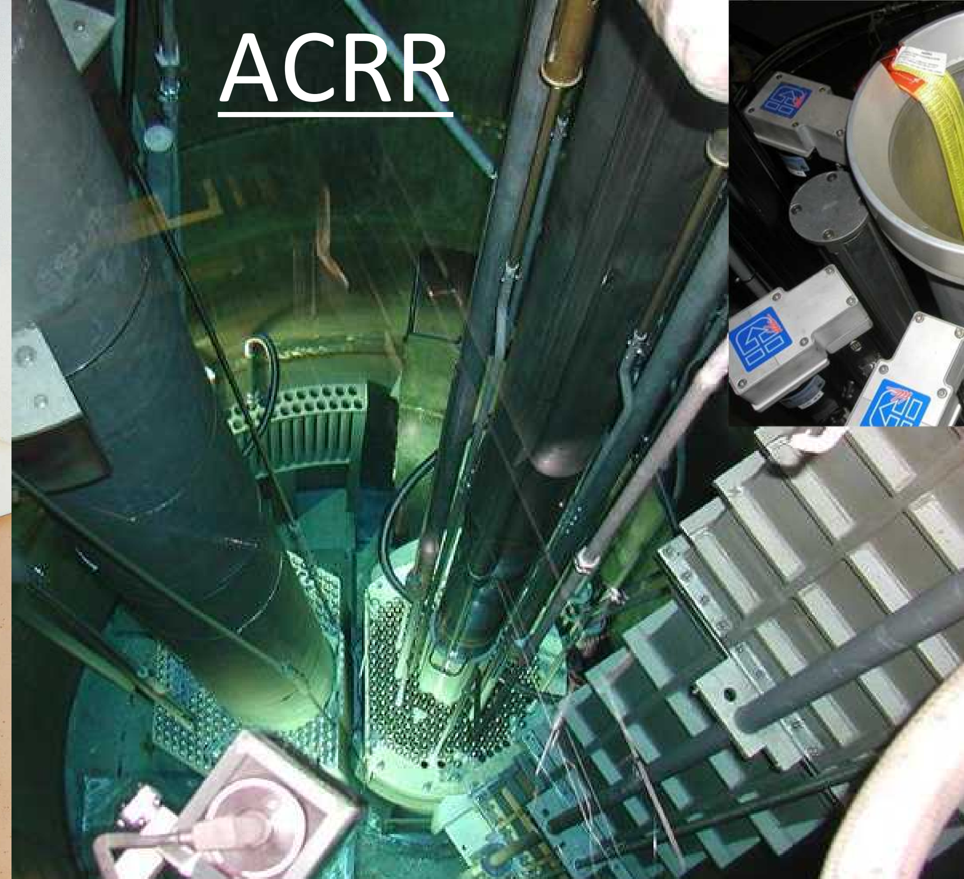
Auxiliary Hot Cell Facility

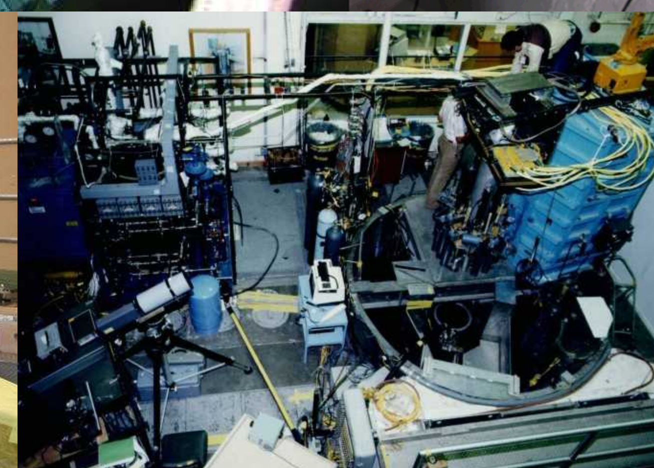
Hot Cell Facility



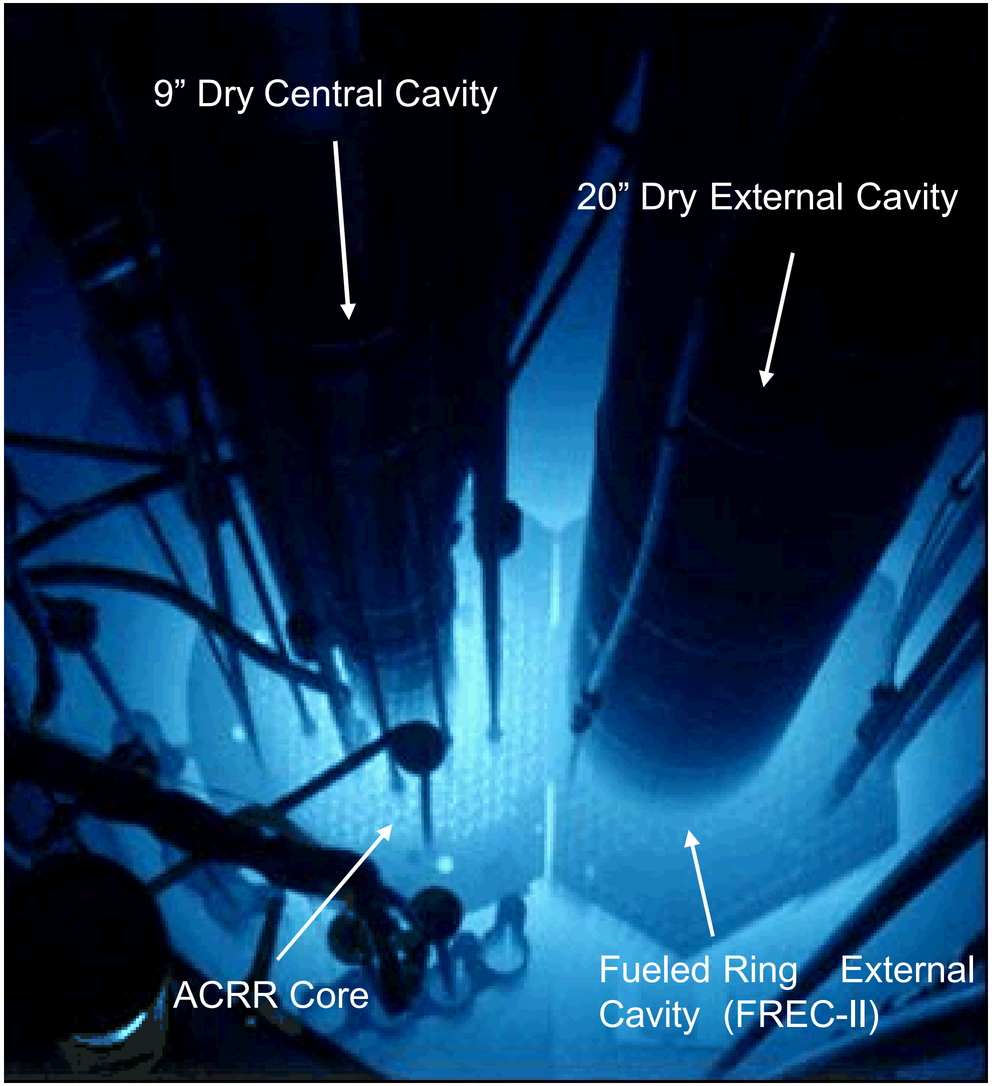
ACRR


RADIOGRAPHY TUBE BLAST SHIELD
VERTICAL LOADING TUBE
REGULATING ELEMENT
GIF TANK
REGULATING ELEMENT DRIVE MECHANISM
REACTOR TANK
OFFSET LOADING TUBE
SHIELD PLUG
EXPERIMENT STORAGE TUBE
RADIOGRAPHY TUBE
REACTOR CORE
EXTERNAL EXPERIMENT CAVITY
CENTRAL EXPERIMENT CAVITY
BULK COOLING LINE





ACRR Description

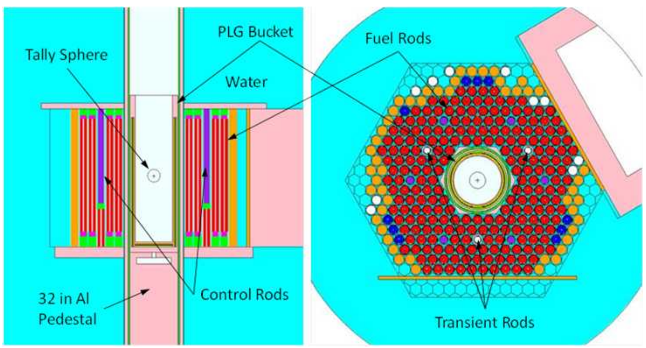


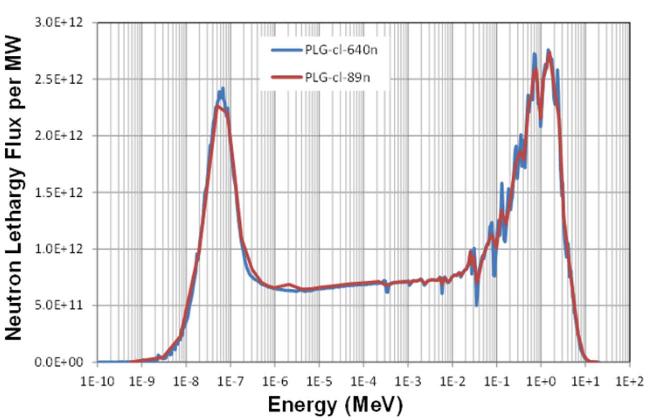
ACRR and FREC-II

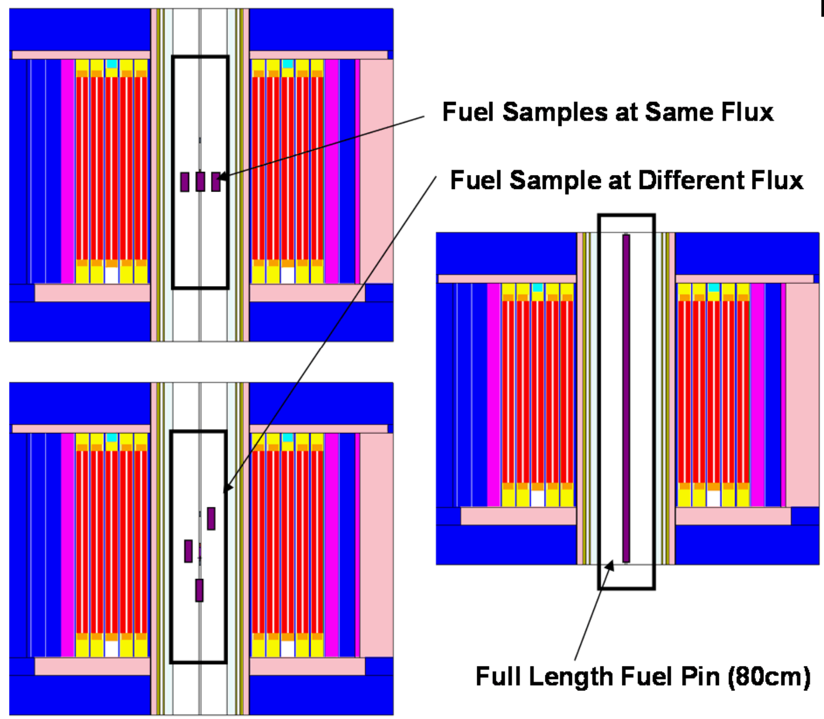
- 236 UO_2-BeO fueled elements
  - 1.5 in (3.8 cm) dia. x 20.5 in (52 cm)
  - 100 g U-235 per element – 35% enriched
- Operating Power level
  - 2-4 MW_{th} Steady-State Mode
  - 300 MJ Pulse Mode (6 ms FWHM)
  - 300 MJ Transient Mode (Programmable)
- Dry cavity 9 in (23 cm) diameter
  - Extends full length of pool through core
  - Neutron Flux 4E13 n/cm^2-s at 2 MW
  - Neutron Fluence 6E15 n/cm^2 at 300 MW
  - 90% > 1 eV, 58% > 10 keV, 46% > 100 keV
- Epithermal/Fast Spectrum
  - Flux in cavity can be tailored for desired energy spectrum (Poly, B4C)
- Open-pool type reactor
  - Core cooled by natural convection
  - Pool cooled by HX and cooling tower
- FREC-II uses previous ACPR fuel
  - TRIGA type (UZrH)
  - Dry cavity 20 in (51 cm) diameter
- Fuel burnup is minimal
- Reactor used for short duration power runs, pulses, and transients

ACRR Modeling

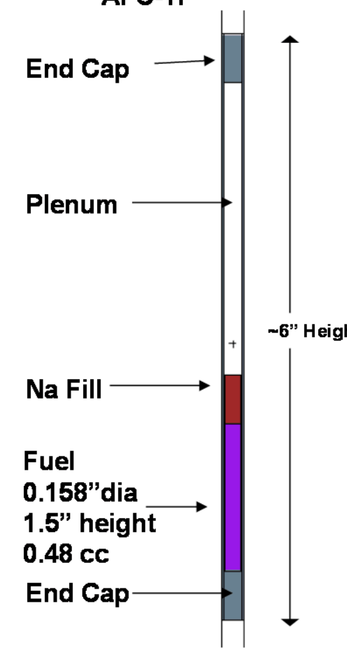
- Modeling the ACRR Core Using MCNP
  - Experiment Response
  - Safety
  - Characterization







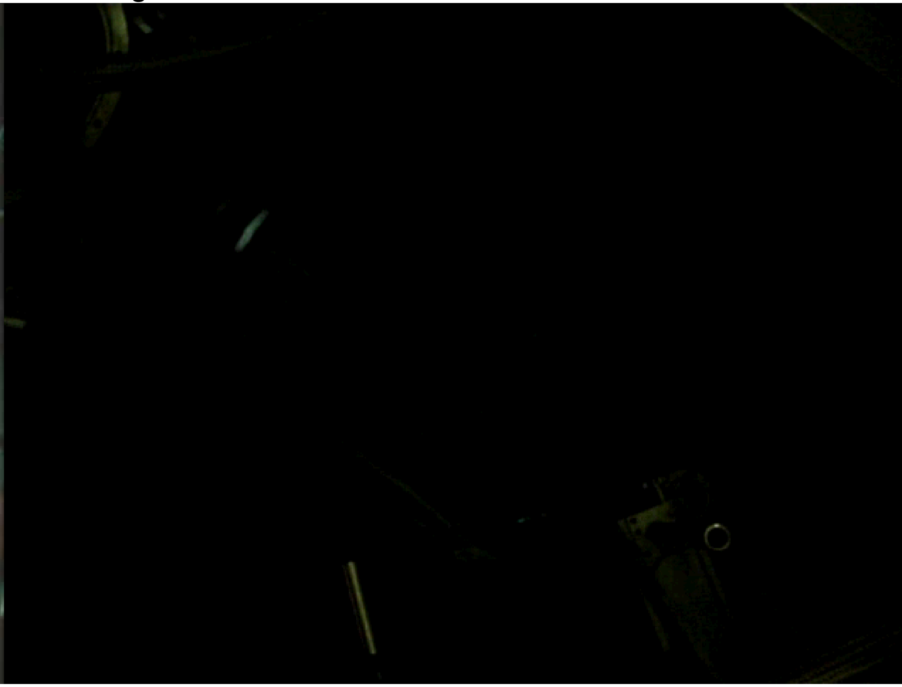
Metal Rodlet from ATR
AFC-1f

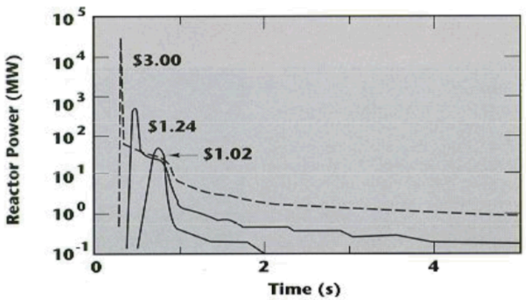


ACRR Pulse and Transient Operating Modes

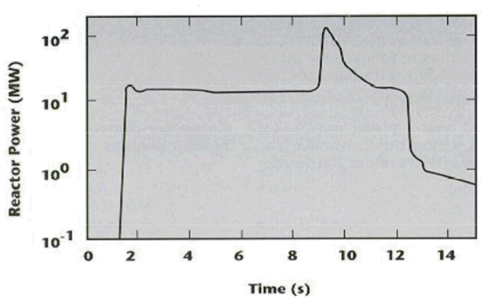
Single Pulse Mode

Programmed Transient Mode

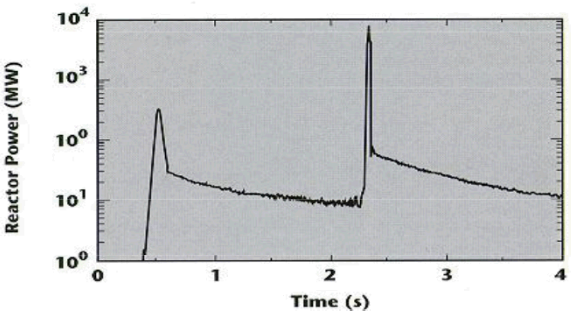




Single Pulse Mode



Programmed Transient Mode



Double Pulse Mode

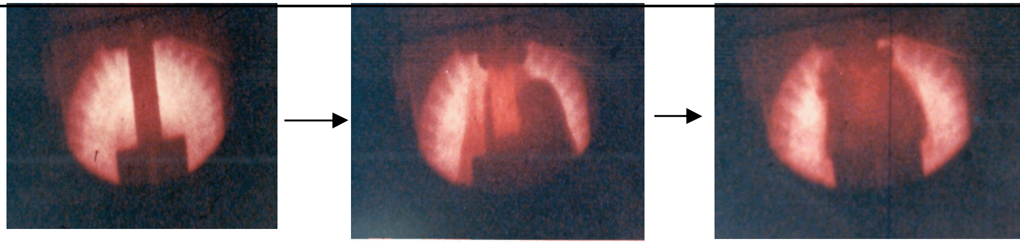
r.wmv

Past/Current Experiment Programs

- ACRR has been used in many nuclear experiment programs over the years
  - Weapon Component Testing – Our original and continuing mission
  - Radiation Effects Sciences – New methods/concepts based on science discovery
  - QASPR – Qualitative Alternatives to SPR
  - 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)
  - Space Thermal Nuclear Power (SNTP) – Critical experiments, particle fuel testing, element testing using hydrogen
  - Medical Isotope Production (Mo-99, I-125) – Domestic production initiative

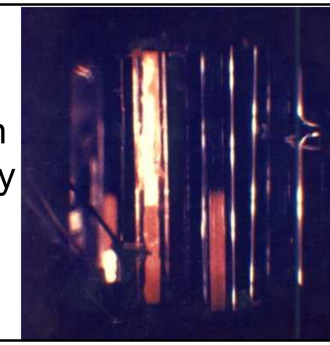
Reactor Safety Testing

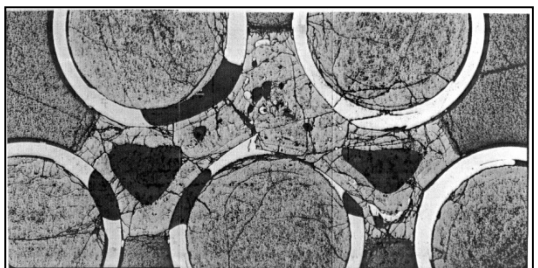
NRC tests of Oxide and Irradiated Mixed Oxide Fuels



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)

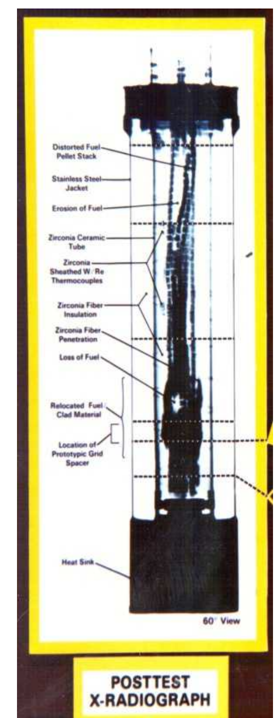




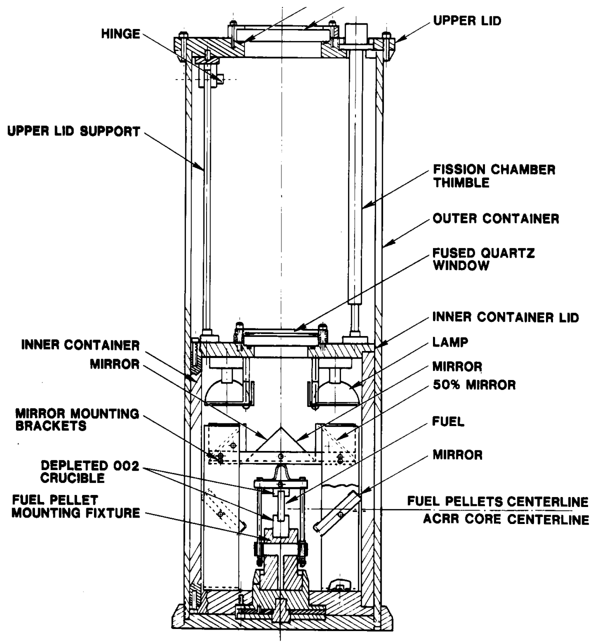
Transition phase studies in LMFBR pin arrays (TRAN Program - JNC, NRC)

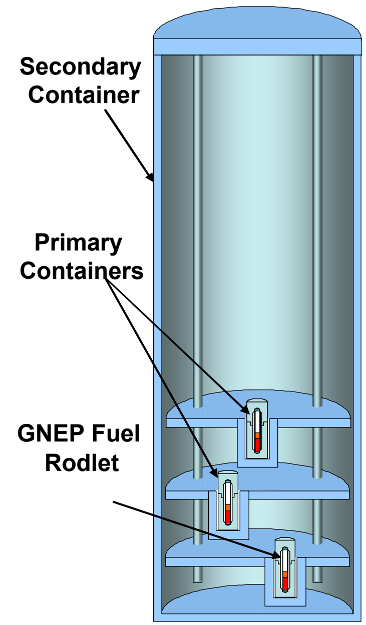
ACRR has been used to simulate a wide range of transient fuel test conditions

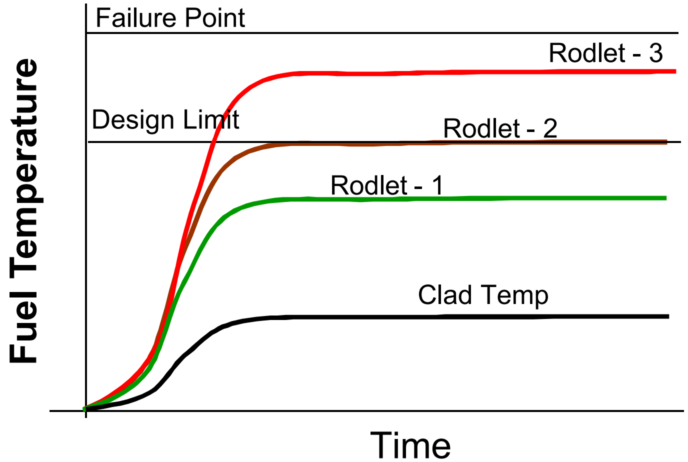
Severe fuel damage and FP release tests on LWR fuel bundle (SFD Program)



Sample Fuel Rodlet Tests

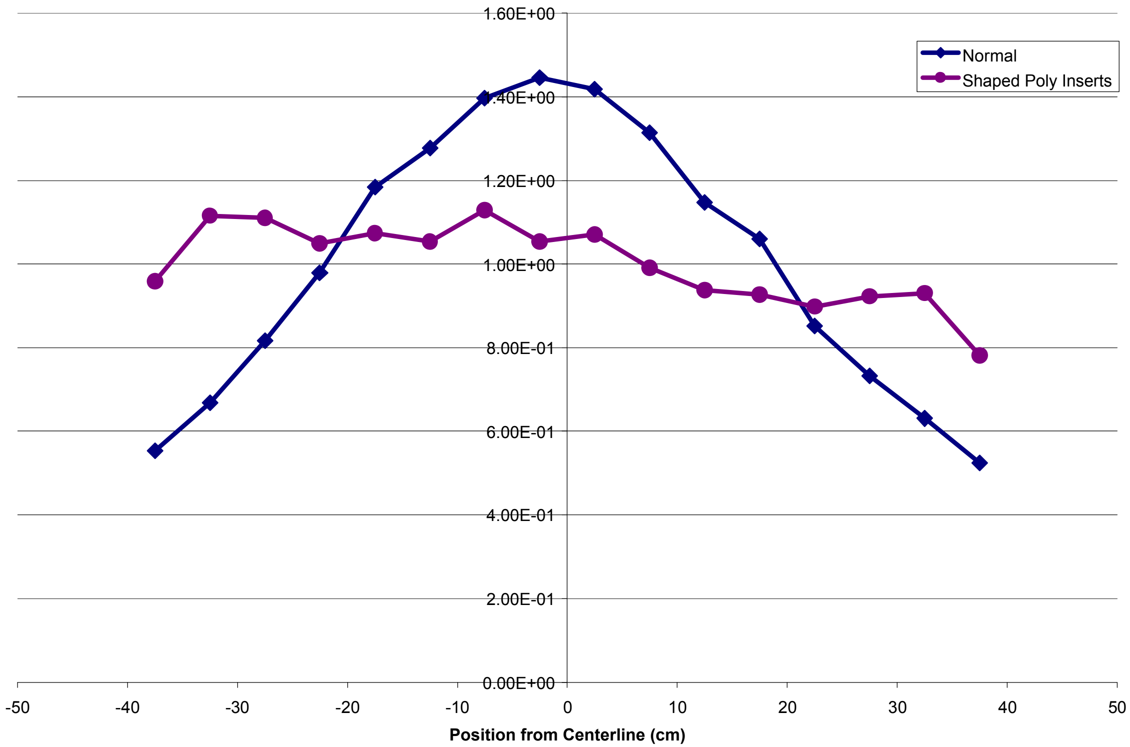




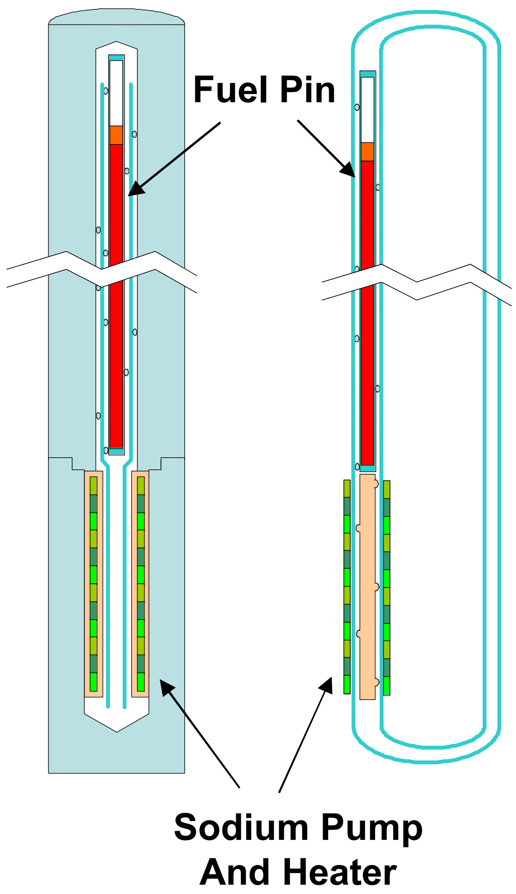


Full Length Fuel Pin Test With Sodium Cooling

Axial Power Shaping Options



Annular or Loop Configuration



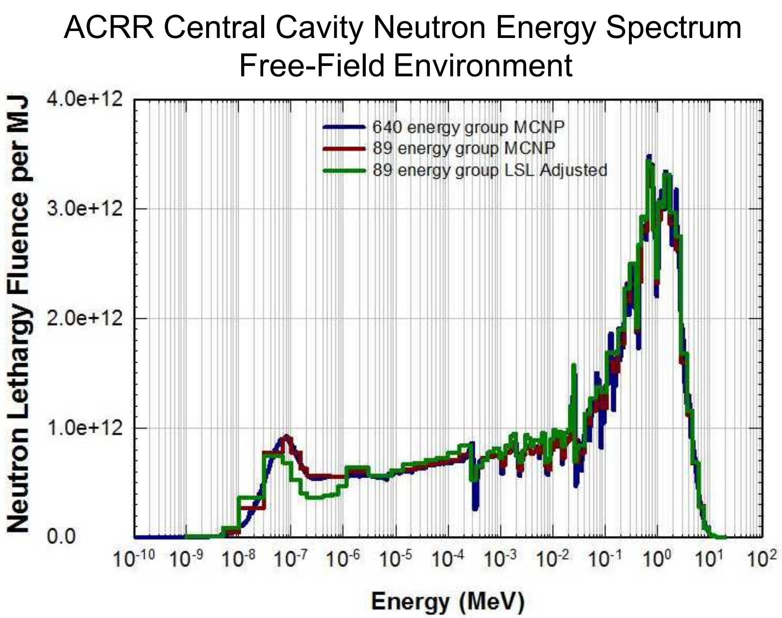
How can the ACRR Neutron/Gamma Flux and Energy Spectrum be Modified?

- Neutronic characteristics can be changed by –
  - Removing the thermal neutrons (B4C)
  - Thermalizing the spectrum (Poly, Water, Graphite)
- Gamma-Ray characteristics can be changed by –
  - Removing gammas – (Lead)
  - Generating more gammas – (Cd, Gd, Cd-Poly, Gd-Poly)

The ACRR is unique in that it maintains a significant epithermal/fast neutron energy spectrum in the cavity in a free-field environment.

This allows for a significant amount of flexibility in using spectrum modifying buckets.

Most research reactors have a highly thermal neutron energy spectrum and don't have this capability.

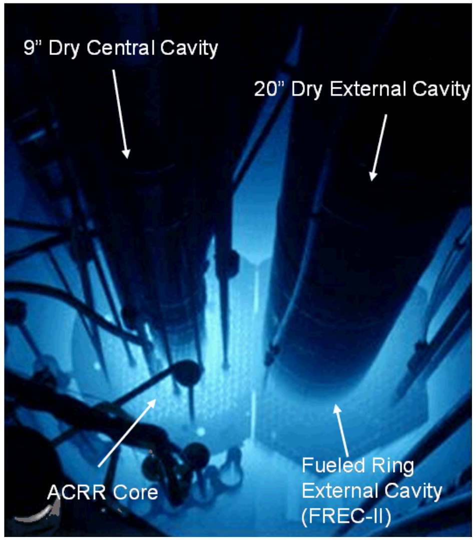


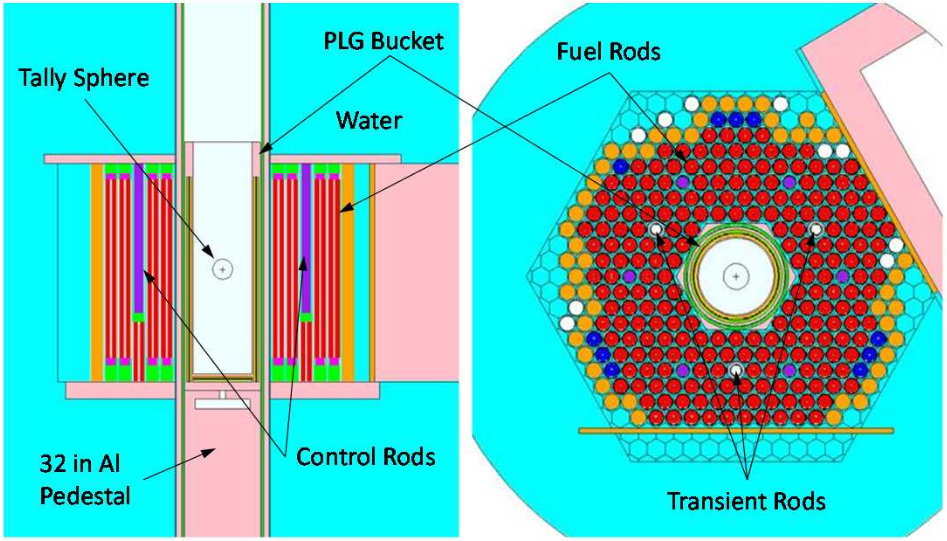
Neutron/Gamma Reactor Environment Characterization

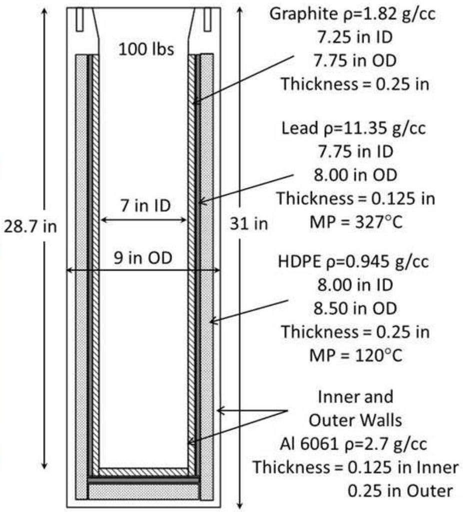
- Characterization of a reactor irradiation space is important in order to know, with some degree of certainty, information about the field where objects are being tested.
- Without characterization, only results from neutronics codes would be available – with little information on uncertainty.
- Characterization can include several facets
  - Neutron and gamma energy spectrum,
  - Neutron and gamma fluence compared to a calibrated activation foil,
  - Neutron and gamma metrics – ie. 1-MeV DES nvt, ionizing dose in Si,
  - Neutron and gamma axial and radial profiles,
  - Neutron to gamma ratios,
  - Delayed gamma time dependent energy spectrum, fluence, etc.
  - Variations with pulse size and steady state conditions,
  - Time dependent measurements and unfolding using PCDs, fission chambers, calorimeters.
- A test object **can change** the characterized environment – Additional dosimetry may be required on test object.

Neutronics Modeling

- Neutronics model (n/γ) of the reactor
  - Develop a relatively high fidelity model of the reactor core
- Neutronics model of the bucket
  - Develop a relatively high fidelity model of the bucket
- Calculate neutron, gamma ray, and delayed gamma ray energy spectra.







Neutron Activation Foils and Setup

- Activation Foils, TLDs
  - Irradiate dosimetry quality neutron activation foils, fission foils, and TLDs
  - 23 Different Foils, 42 Reactions

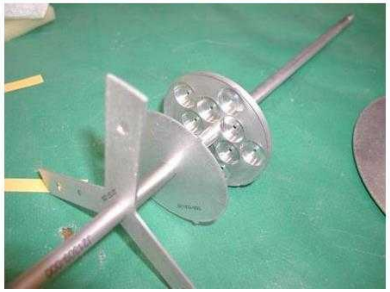








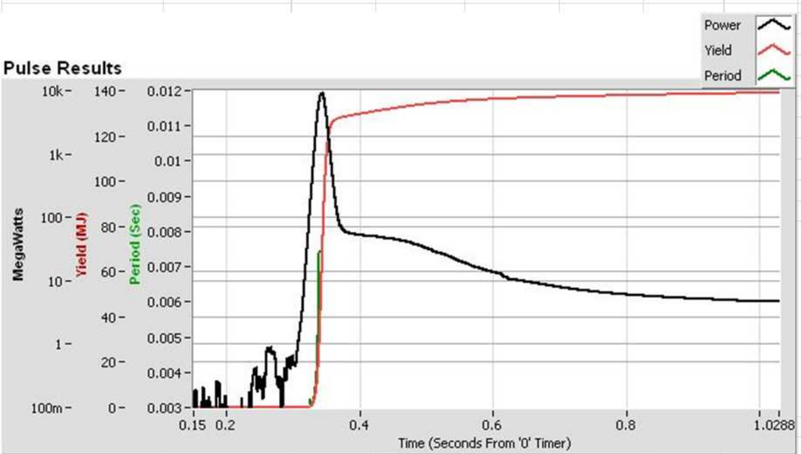


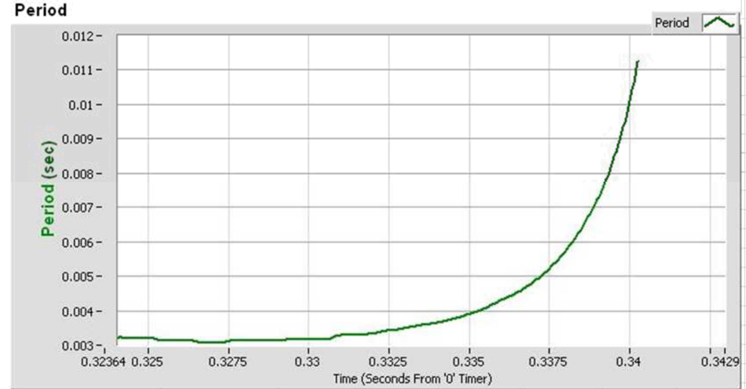


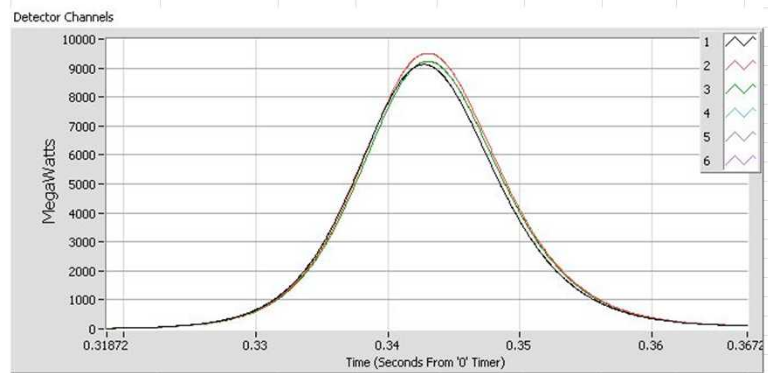
ACRR Shot Diagnostics

Shot Information		Predicted Values	
Run Number	10439	Expected MW	14000
Operator	Joe Greenberg	Expected TTP	0.3280
Date \ Time	11/12/2012 15:53	Expected MJ	160.97
Experimenter Name	Mike Luker	Expected Fuel Temp	509.4
Experiment Plan #	1132	Dialed In MW	10523.61
Package Worth $	0.667		
Shot Worth $	2.249		
Rod Hold Up (sec)	0.35		
FREC Mode	Decoupled		
FREC RODS	DOWN		
Comments	TR Bank worth: $ 3.107. PLG-1		

	Average	CH-1	CH-2	CH-3	CH-4	CH-5	CH-6
Detector		DE2-3	DE4-9	DE5-1			
Detector Calibration		42.6	40.2	40.6			
Channel Type		PXI Amp	SR570 Amp	SR570 Amp			
Average Used		Both	Peak	Peak			
Period Used		Yes	Yes	Yes			
PEAK DATA:							
Peak (MW)	9286.6	9123.5	9509.2	9234.5			
TTP (sec)	0.34296	0.34272	0.34304	0.34296			
FWHM (sec)	0.01212	0.01212	0.01212	0.01212			
LEHM (sec)	0.00588	0.00584	0.00588	0.00576			
TEHM (sec)	0.00624	0.00628	0.00624	0.00636			
Ratio (LE/TE)	0.942	0.93	0.942	0.906			
Shot Worth	2.058	2.234	2.376	2.757			
YIELD DATA:							
Total Yield (MJ)	146.737	145.212	139.834	136.155			
TTP+3fwhm (MJ)	128.489	126.212	131.547	127.663			
Yield @ Peak (MJ)	60.991	59.464	62.423	59.658			
Min Period (sec)	0.003057	0.002619	0.002346	0.001832			







Neutron Activation Results

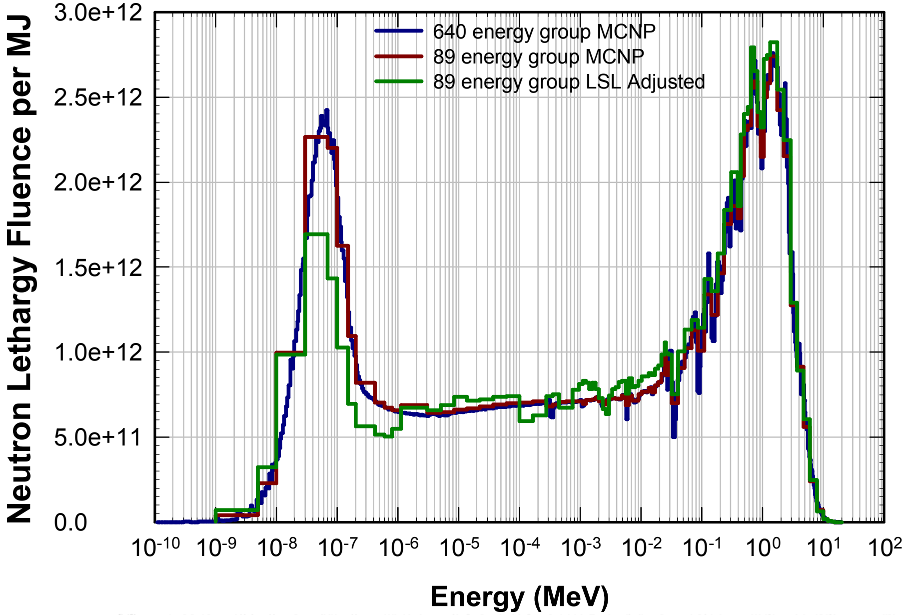
- Activation foils, TLDs
  - Involve a number of operations and foils

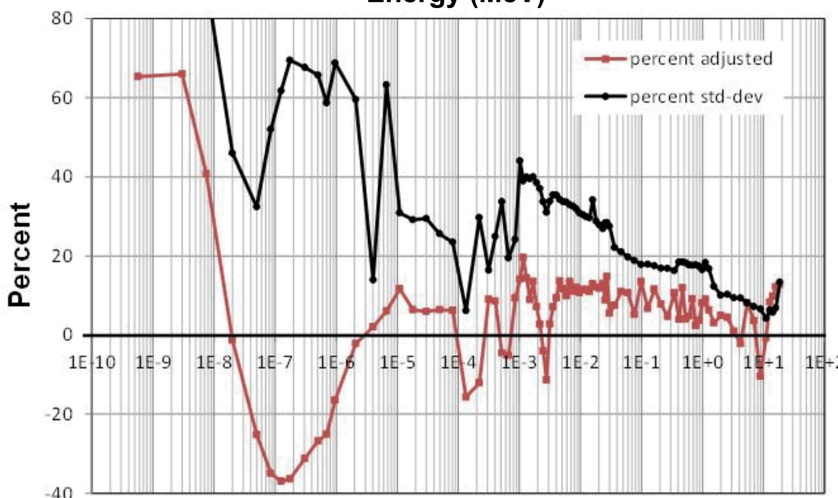
Complete ?	Shot numl	type	Energy (M	bucket	fixture		foils	day	date	wk da
Week 1 - 6/24/13										
x	1	pulse	150	PLG-1	Map		Sulfur Axial	1	25-Jun	T
x	2	pulse	70	PLG-1	Map		TLD Axial	1	25-Jun	T
x	3	pulse	150	PLG-1	Dos-F		Ni all 10 locations	2	26-Jun	W
x	4	pulse	150	PLG-1	Dos-F		Sc all 10 locations	2	26-Jun	W
x	5	pulse	150	PLG-1	Dos-F		Set 1a	3	27-Jun	Th
x	6	pulse	150	PLG-1	Dos-F		Set 2	3	27-Jun	Th
Week 2 - 7/1/13										
x	7	ss	150	PLG-1	Dos-F		Set 1b	4	1-Jul	M
								5	2-Jul	T
x	8	pulse	150	PLG-1	Dos-F	short	Set 3 and 4	6	3-Jul	W
x	9	ss	150	PLG-1	Map		Sulfur Axial	6	3-Jul	W
Week 3 - 7/8/13										
x	10	pulse	150	PLG-1	Dos-F		Set 5 and 6	7	8-Jul	M
x	11	pulse	150	PLG-1	Dos-F	short	Set 7 and 8	8	9-Jul	T
x	12	pulse	150	PLG-1	Dos-B		B-F1	8	9-Jul	T
x	13	pulse	150	PLG-1	Dos-B		B-1	9	10-Jul	W
x	14	pulse	150	PLG-1	Dos-B		B-2	9	10-Jul	W
x	15	pulse	150	PLG-1	Dos-B		B-3	10	11-Jul	Th
x	16	pulse	150	PLG-1	Map		Sulfur and Gold dilute Radial	10	11-Jul	Th
x	17	ss	70	PLG-1	Map		TLD Axial	11	12-Jul	Fri
x	18	pulse	70	PLG-1	Map		TLD Radial	11	12-Jul	Fri
Week 4 - 8/12/13										
x	19	pulse	150	PLG-2	Map		Sulfur Axial	12	13-Aug	T
x	20	pulse	70	PLG-2	Map		TLD Axial	12	13-Aug	T
x	21	pulse	150	PLG-2	Dos-F		Set 1c	13	14-Aug	W
x	22	pulse	70	PLG-2	Map		Sulfur and Gold dilute Radial	13	14-Aug	W
x	23	pulse	70	PLG-2	Map		TLD Radial	14	15-Aug	Th

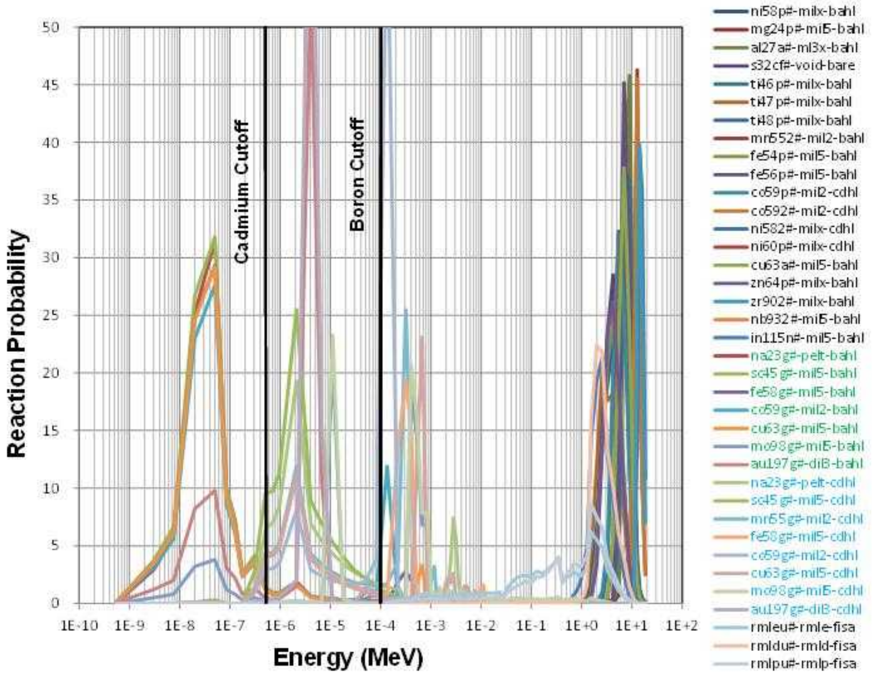
Activation Reaction	Half-Life	Activity (Bq/atom-isotope)	Counting Uncertainty (%)
^{58}Ni(n,p)^{58}Co - Reference	70.83 d	7.7936E-18	1.7
^{24}Mg(n,p)^{24}Na	14.957 h *	9.8561E-18	1.8
^{27}Al(n,α)^{24}Na	14.957 h *	4.8547E-18	2.2
^{32}S(n,p)^{32}P Cf-equ	14.284 d	5.4590E+14 n/cm^2	3.6
^{46}Ti(n,p)^{46}Sc	83.788 d	6.1277E-19	1.6
^{47}Ti(n,p)^{47}Sc	3.349 d	3.0287E-17	3.1
^{48}Ti(n,p)^{48}Sc	43.67 h	7.1657E-19	1.0
^{55}Mn(n,2n)^{54}Mn	312.3 d	3.5325E-21	20.2
^{54}Fe(n,p)^{54}Mn	312.3 d	1.2772E-18	2.7
^{56}Fe(n,p)^{56}Mn	2.579 h *	4.6190E-17	1.8
^{59}Co(n,p)^{59}Fe	44.495 d	1.4707E-19	2.7
^{59}Co(n,2n)^{58}Co	70.83 d	1.2657E-20	18.1
^{58}Ni(n,2n)^{57}Ni	35.9 h	1.1537E-20	6.2
^{60}Ni(n,p)^{60}Co	1925.27 d	5.2239E-21	3.1
^{63}Cu(n,α)^{60}Co	1925.27 d	1.4983E-21	7.9
^{64}Zn(n,p)^{64}Cu	12.701 h *	3.7146E-16	3.0
^{90}Zr(n,2n)^{89}Zr	78.41 h	1.4115E-19	3.0
^{93}Nb(n,2n)^{92m}Nb	10.15 d	1.9054E-19	1.2
^{115}In(n,n')^{115m}In	4.486 h *	7.0790E-15	5.6
^{23}Na(n,γ)^{24}Na	14.957 h *	3.9324E-15	2.1
^{45}Sc(n,γ)^{46}Sc	83.788 d	1.6579E-15	0.7
^{58}Fe(n,γ)^{59}Fe	44.495 d	1.6831E-16	1.4
^{59}Co(n,γ)^{60}Co	1925.27 d	1.1350E-16	1.4
^{63}Cu(n,γ)^{64}Cu	12.701 h *	5.0078E-14	3.1
^{98}Mo(n,γ)^{99}Mo	2.748 d	2.5304E-15	1.2
^{197}Au(n,γ)^{198}Au	2.694 d	7.1560E-13	1.8
^{23}Na(n,γ)^{24}Na - Cd	14.957 h *	4.1746E-16	1.3
^{45}Sc(n,γ)^{46}Sc - Cd	83.788 d	1.2948E-16	1.3
^{55}Mn(n, γ)^{56}Mn - Cd	2.579 h *	1.1075E-13	1.7
^{58}Fe(n,γ)^{59}Fe - Cd	44.495 d	2.6925E-17	2.1
^{59}Co(n,γ)^{60}Co - Cd	1925.27 d	2.2206E-17	1.5
^{63}Cu(n,γ)^{64}Cu - Cd	12.701 h *	7.5389E-15	3.1
^{98}Mo(n,γ)^{99}Mo - Cd	2.748 d	2.3306E-15	1.1
^{197}Au(n,γ)^{198}Au - Cd	2.694 d	5.3238E-13	1.8
^{235}U(n,f)FP - BB	^{140}Ba - 12.752 d	2.5730E-09 #fis	2.0
^{238}U(n,f)FP - BB	^{140}Ba - 12.752 d	2.1936E-10 #fis	2.1
^{239}Pu(n,f)FP - BB	^{140}Ba - 12.752 d	2.5696E-09 #fis	2.0

Neutron Spectrum Adjustment

- Spectrum adjustment using dosimetry cross section library
  - Determine adjusted spectrum, uncertainty, and correlation matrix

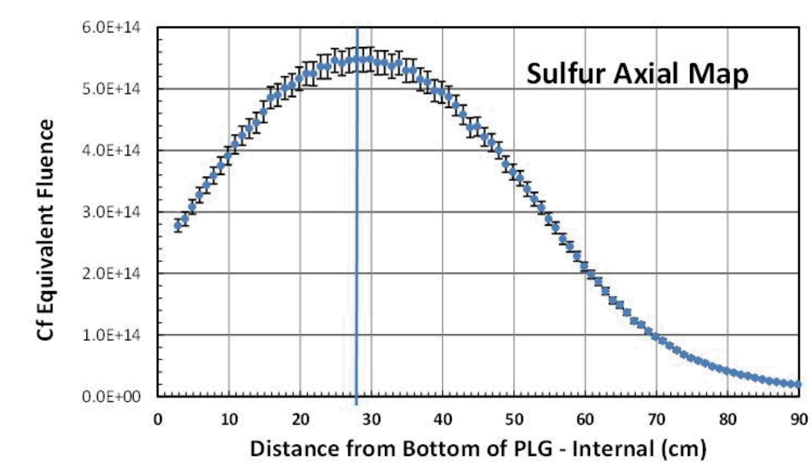


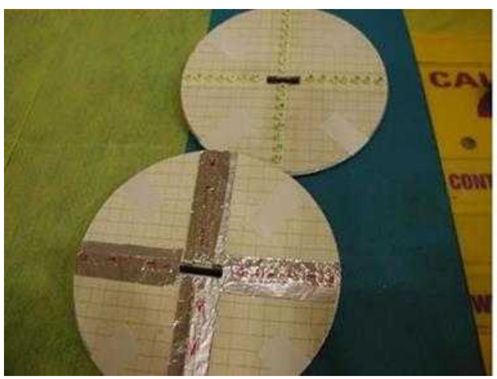


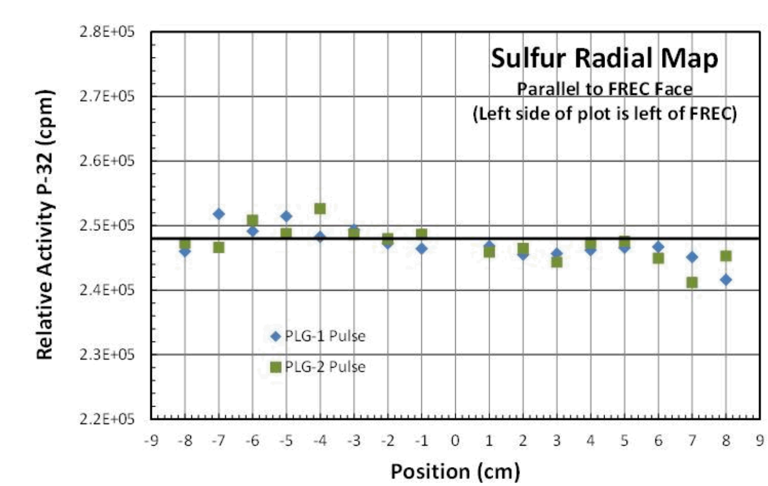


Axial and Radial n/γ Profiles

- Axial and Radial Profiles are important for geometry effects

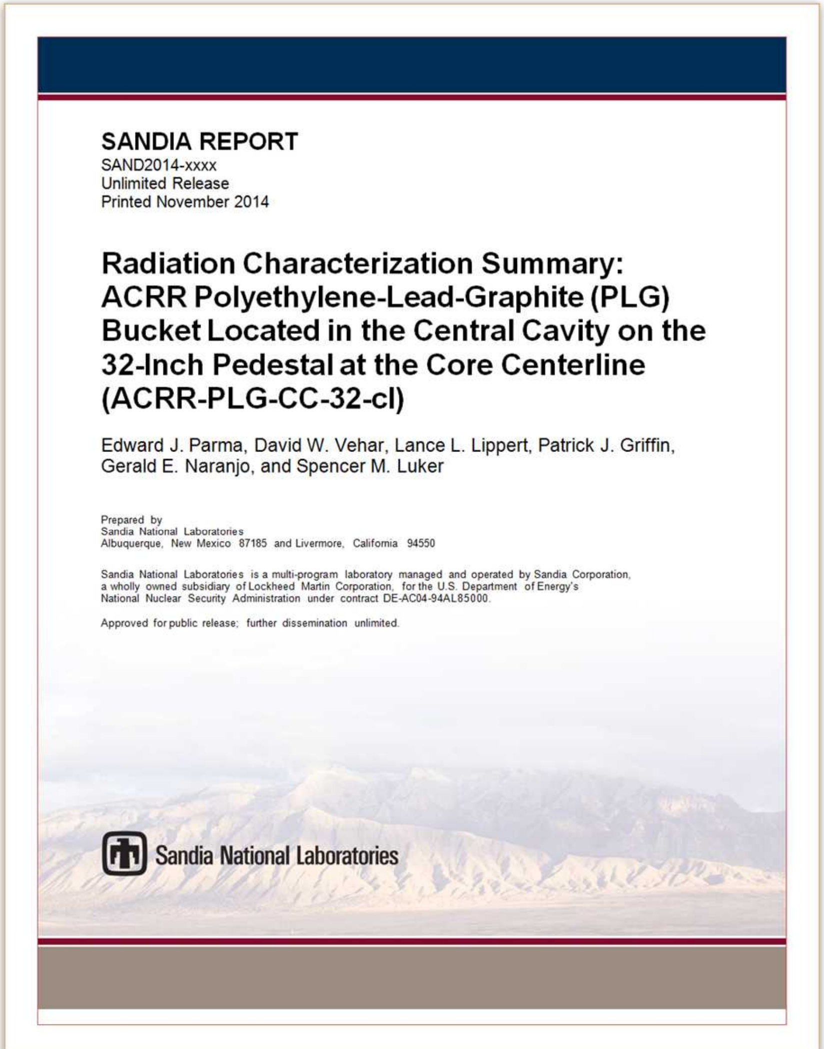






Documentation

- Results are compiled into a SAND report
  - Users will utilize the spectra, uncertainties, correlation matrix, and tables to determine the metrics for their unique test.



SANDIA REPORT
SAND2014-xxxx
Unlimited Release
Printed November 2014

Radiation Characterization Summary: ACRR Polyethylene-Lead-Graphite (PLG) Bucket Located in the Central Cavity on the 32-Inch Pedestal at the Core Centerline (ACRR-PLG-CC-32-cl)

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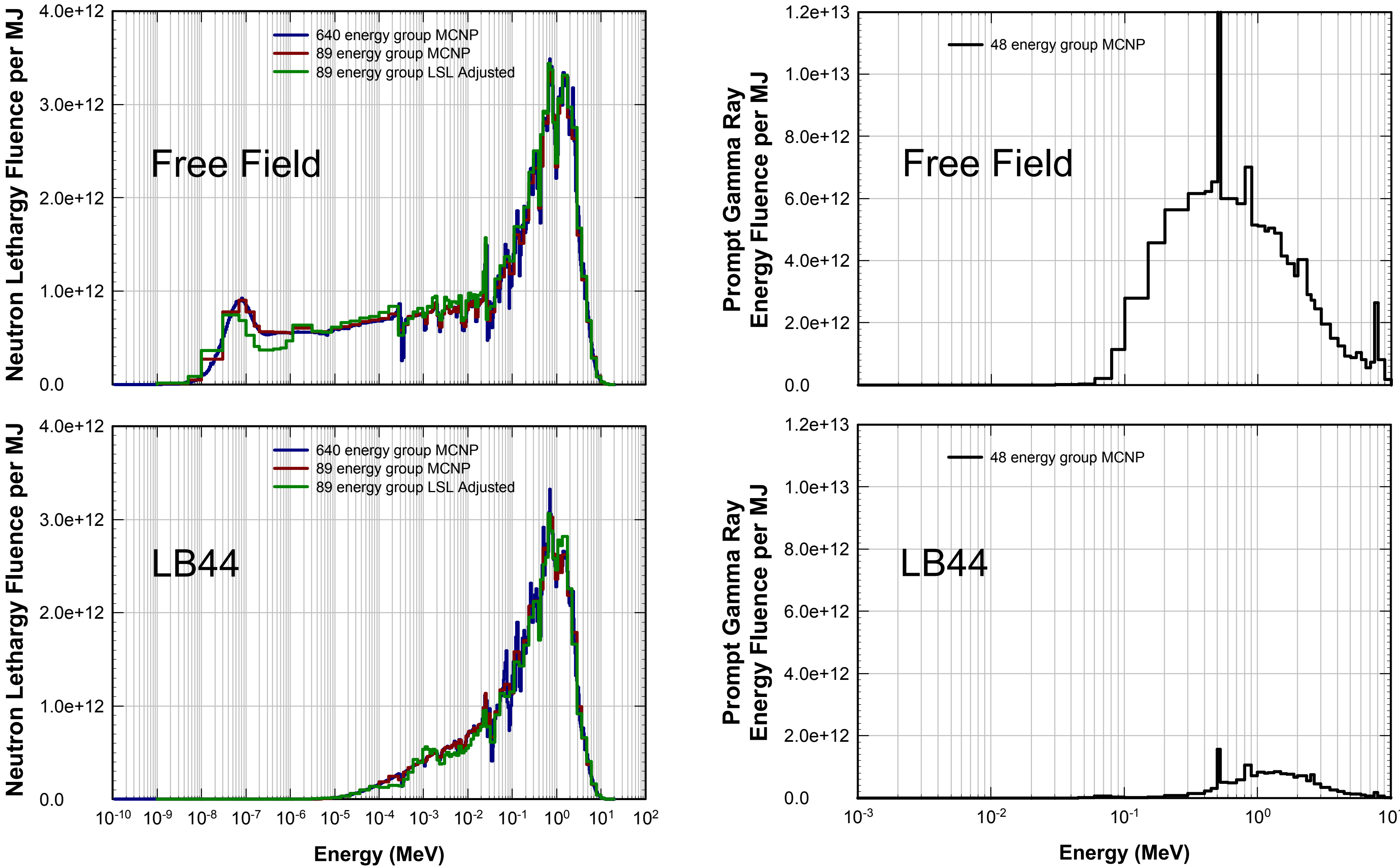
Metric	Integral Response	Standard Deviation (%)
Total Neutron Fluence Average Neutron Energy = 0.481 MeV	1.00	--
Fluence > 3 MeV	0.033	3.9
Fluence > 1 MeV	0.164	4.6
Fluence > 100 keV	0.374	3.3
Fluence > 10 keV	0.479	2.6
Fluence < 1 keV	0.437	2.9
Fluence < 1 eV	0.217	10.6
Fluence 1-MeV(Si) Eqv. E722-94	0.325	3.1
Fluence 1-MeV(GaAs) Eqv. E722-94	0.364	2.8
^{58}Ni(n,p)^{58}Co Spectrum Avg. Cross-Section IRDFF-1.02	18.26 mb	3.4
^{32}S(n,p)^{32}P Spectrum Avg. Cross-Section IRDFF-1.02	11.49 mb	4.0
Total Fluence Conversion ([n/cm^2]/fission)	6.545E-04	0.4
Total Fluence Conversion ([n/cm^2]/MJ)	2.123E+13	2.0
Total Fluence Conversion From Ni Activation ^{58}Ni(n,p)^{58}Co ([n/cm^2]/[Bq/atom$_{Ni-58}$])	4.835E+32	3.4
Total Fluence Conversion From Ni Activation ^{58}Ni(n,p)^{58}Co ([n/cm^2]/[Bq/g$_{Ni-58}$])	4.652E+10	3.4
Power Conversion From Ni Activation ^{58}Ni(n,p)^{58}Co (MJ/[Bq/atom$_{Ni-58}$])	2.277E+19	3.9
Power Conversion From Ni Activation ^{58}Ni(n,p)^{58}Co (MJ/[Bq/g$_{Ni-58}$])	2.191E-03	3.9
Total Fluence Conversion From S Activation ([n/cm^2]/Fluence ^{32}S(n,p) Cf-eqv)	6.449	4.8

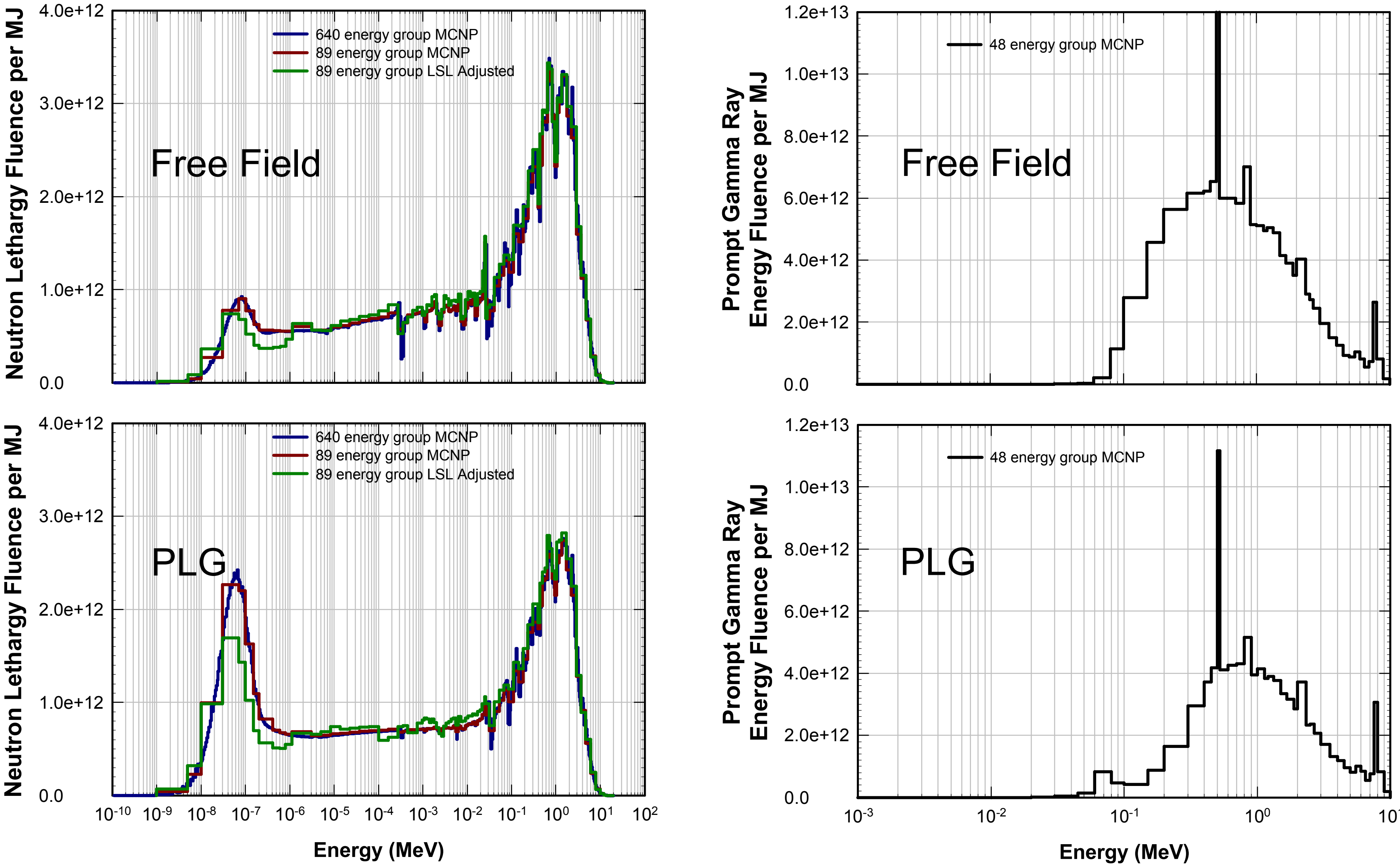
Neutron/Gamma Energy Spectra

- Comparison of Free Field to Lead Boron Bucket (LB44)



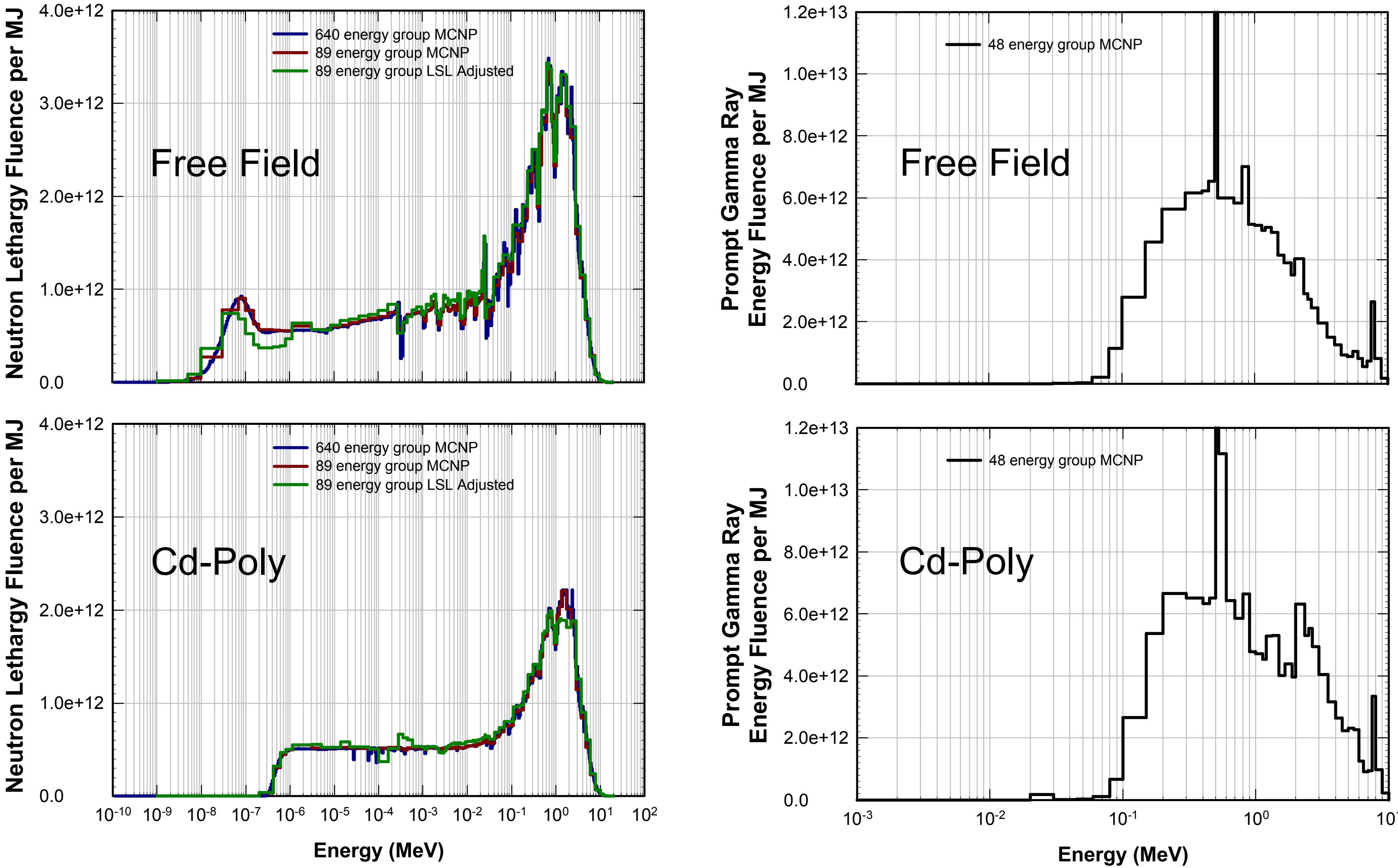
Neutron/Gamma Energy Spectra

- Comparison of Free Field to Poly-Lead-Graphite Bucket (PLG)



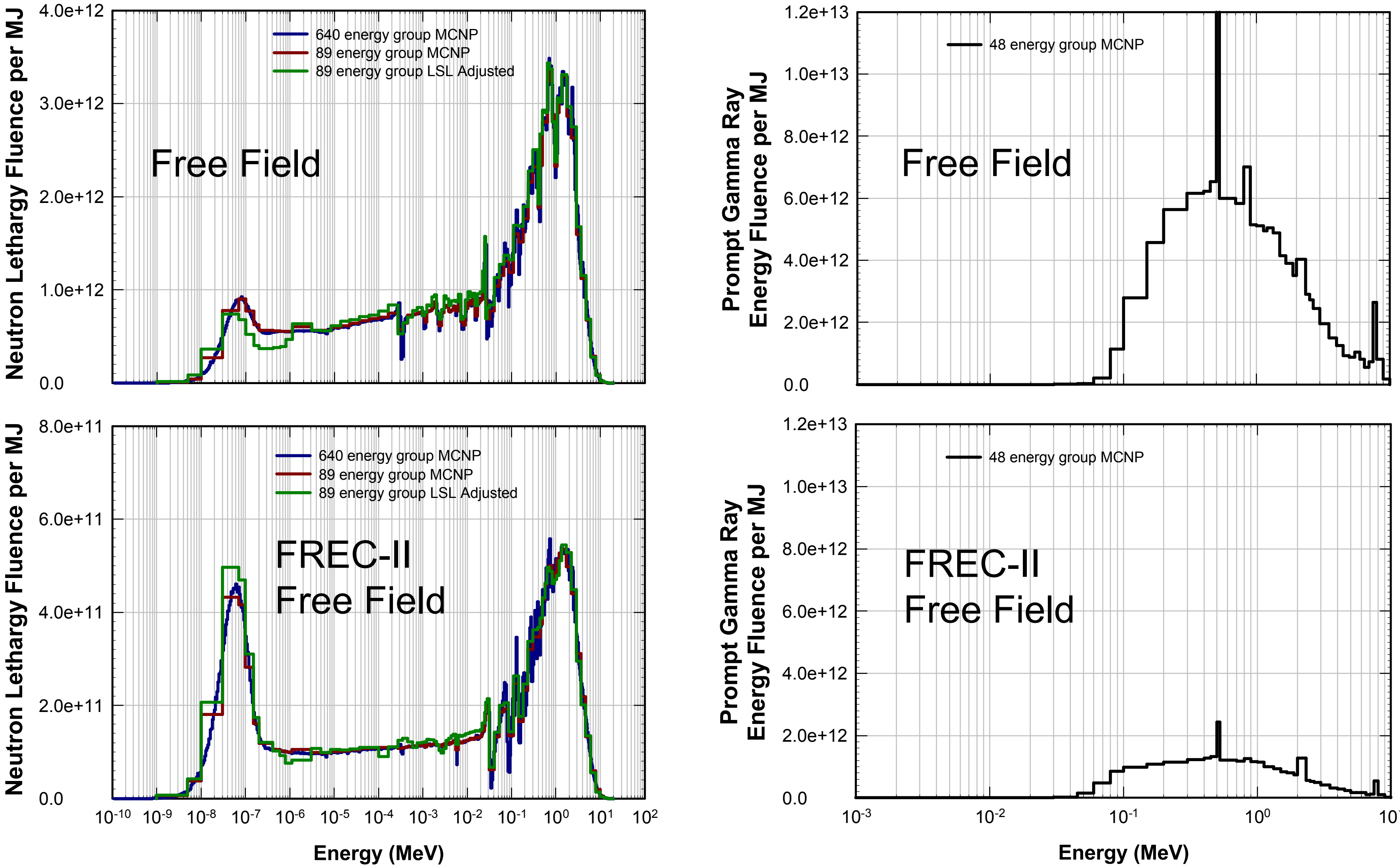
Neutron/Gamma Energy Spectra

- Comparison of Free Field to Cd Poly Bucket (Cd-Poly)



Neutron/Gamma Energy Spectra

- Comparison of Free Field to FREC-II FF



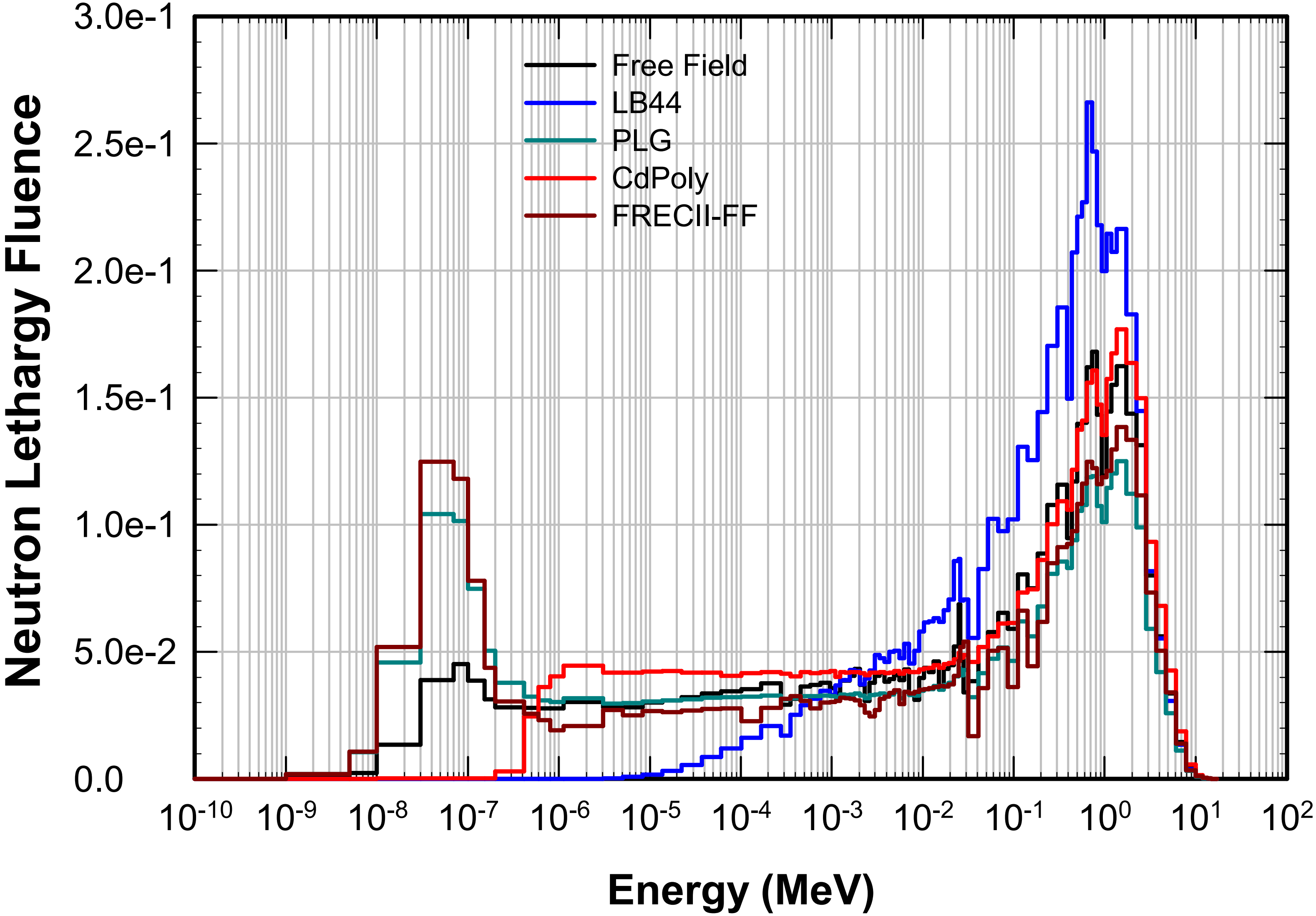
Comparison of ACRR Environments

- Neutron Fluence and Prompt Gamma-Ray Si Dose for the Characterized Environments

Bucket Environment	Neutron Fluence Total (n/cm^2–MJ)	Neutron Fluence 1-MeV DES (n/cm^2–MJ)	Prompt Gamma-Ray Dose in Si (krad/MJ)	Ratio of 1 MeV DES Fluence to Gamma-Ray Dose (Si) x 1E+12	Bucket Internal Diameter
Central Cavity Free Field	2.05E+13	8.19E+12	7.94	1.03	9.0 in
PLG	2.12E+13	6.90E+12	6.10	1.13	7.0 in
LB44	1.15E+13	6.47E+12	0.98	6.60	5.0 in
Cd-Poly	1.26E+13	5.24E+12	11.05	0.47	7.5 in
FREC-II Free Field - FREC Rods Up	3.98E+12	1.34E+12	1.71	0.78	20 in

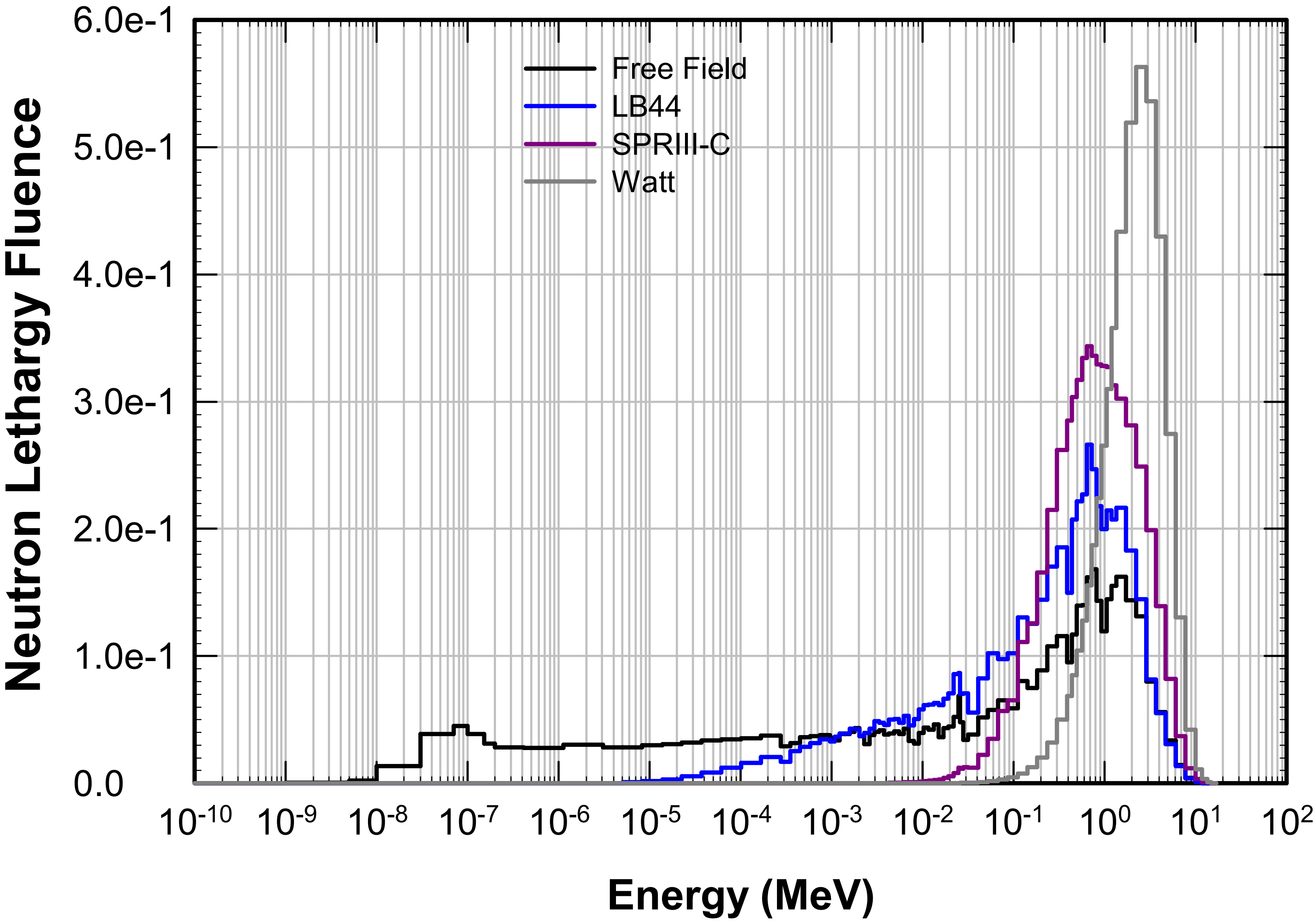
Neutron Energy Spectra

- Comparison of All of the ACRR Environments



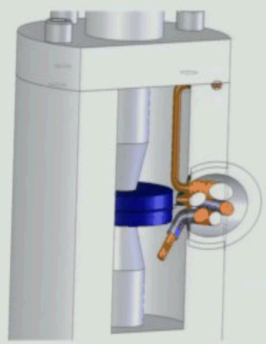
Neutron Energy Spectra

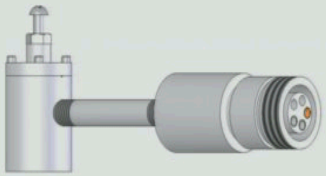
- Comparison of ACRR Environments to SPRIII

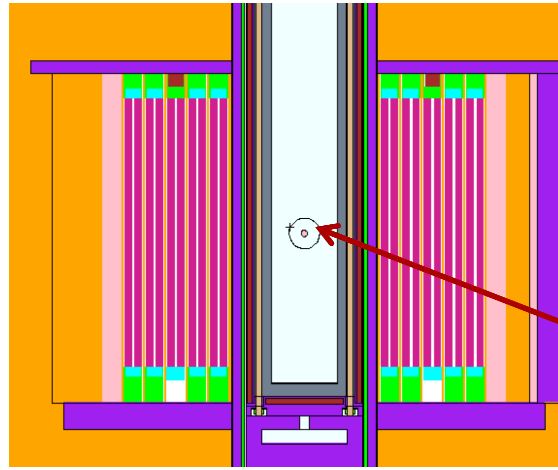


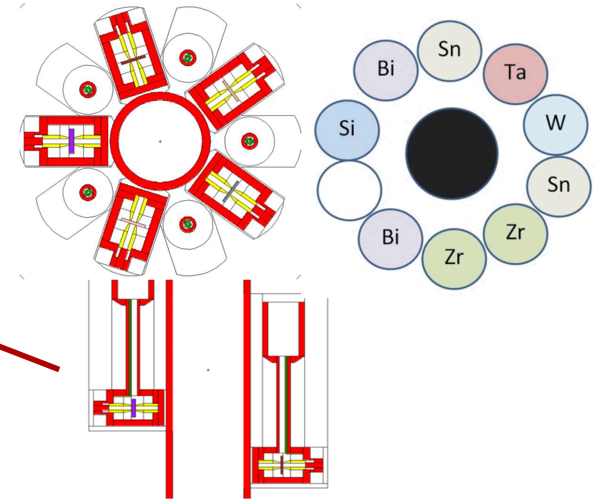
RES Calorimeter Diagnostics

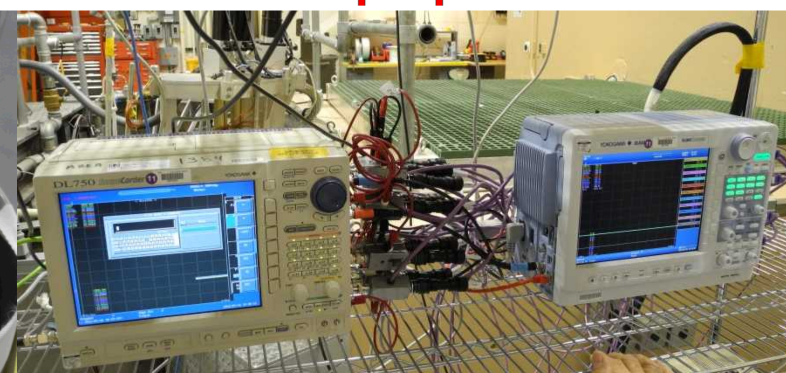
- Real-time total dose measurement in ACRR central cavity for pulse mode operations.
- Can be used for multiple shots.
- As a primary standard, no calibration required.
- Two 0.375" diameter x 0.040" thick undoped silicon wafers
- Type-E thermocouple, 0.001" diameter.
- Fully shielded and twisted-shielded pair up to data acquisition system.



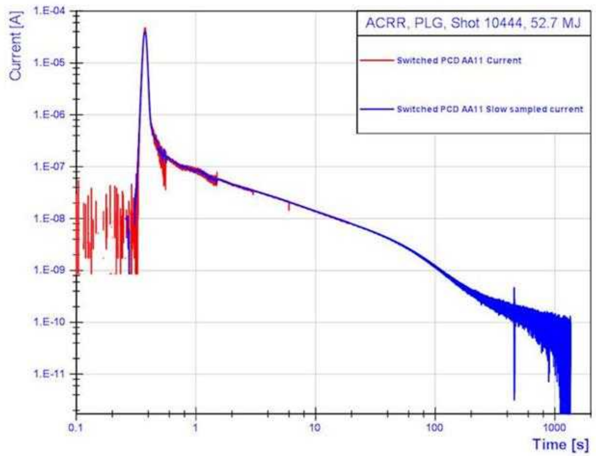


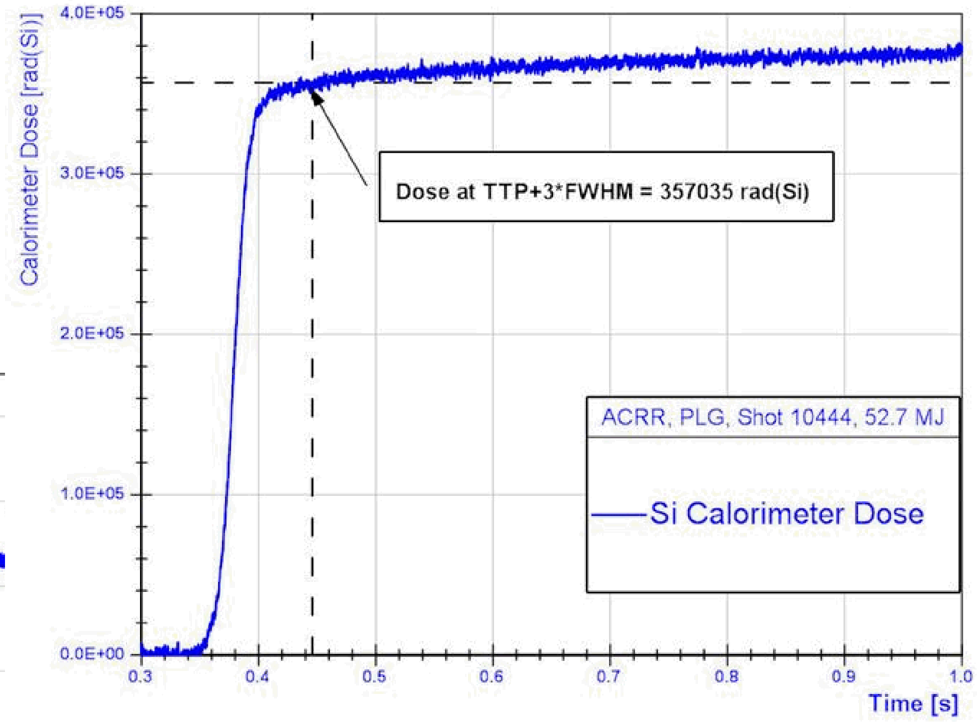


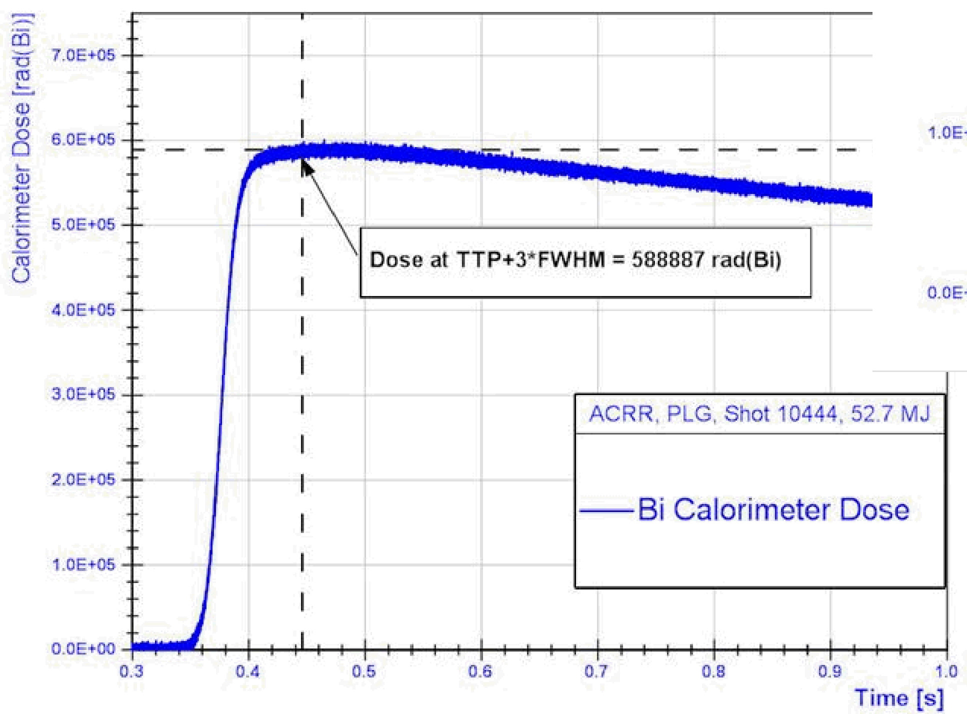




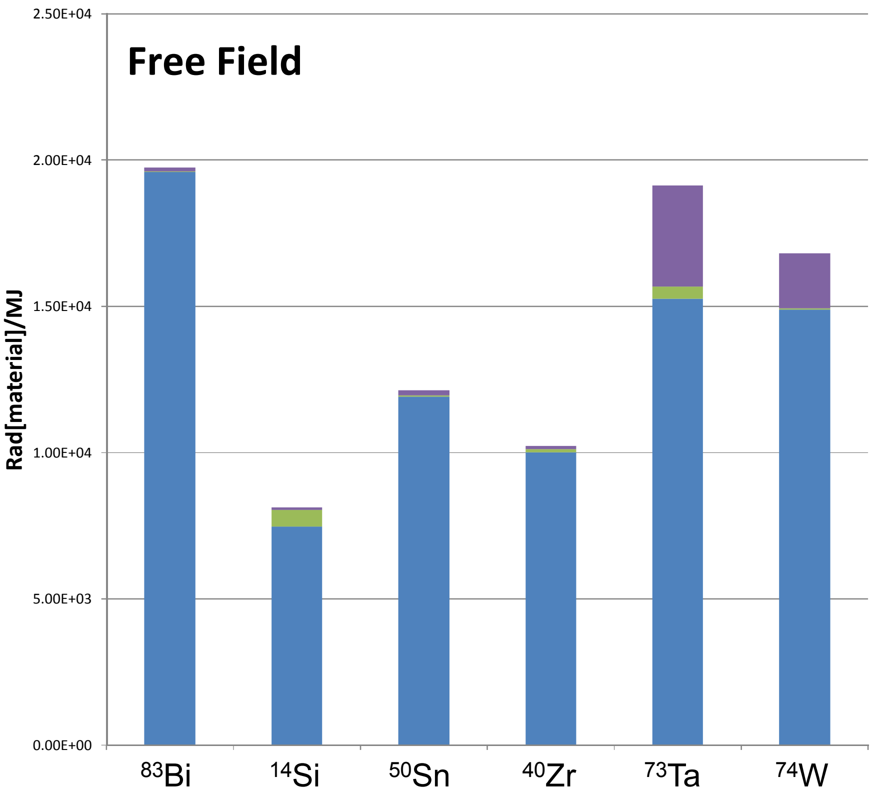
Calorimeter Characterization

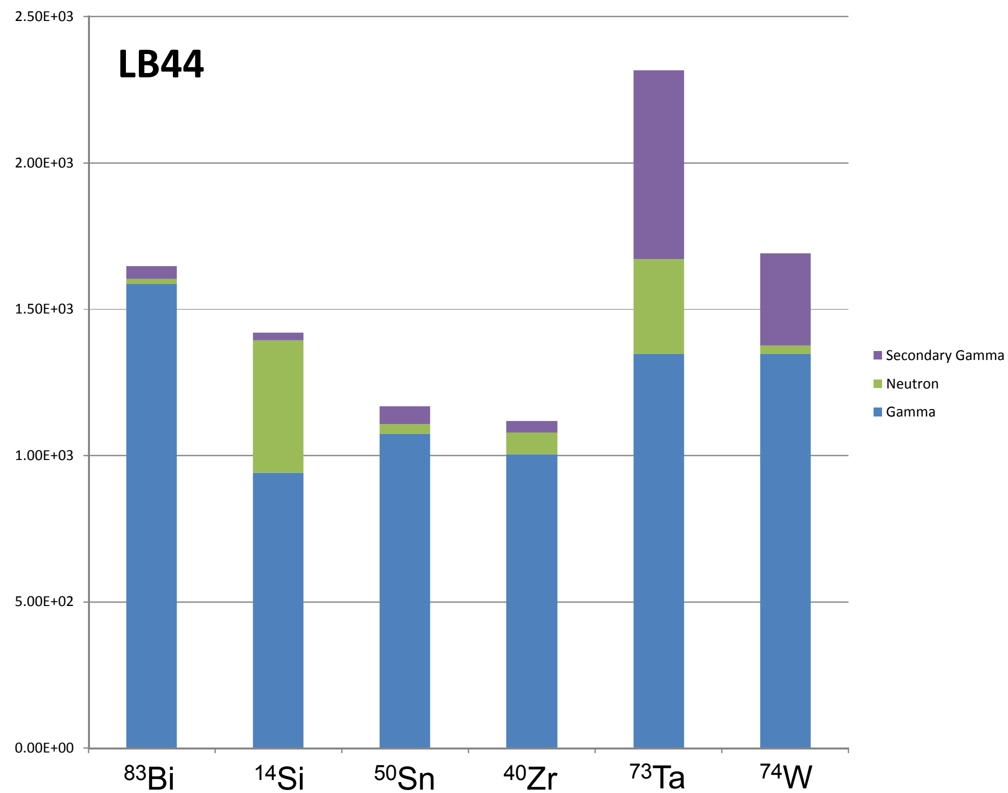






Calorimeter Comparisons





We continue to test different calorimeter materials in the ACRR to understand the gamma-ray spectrum and intensity.

Questions?