SAND2007-6368P

Presentation at JOWOG-6 Meeting:

Characterization of the Time-Dependent Radiation Environment in Pulsed Reactor Operations

By: P. J. Griffin & RES Team

11 October 2007

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy under contract DE-AC04-94AL85000.

Agenda

- Uncertainty contributors
- Previous dosimetry development
- Improved measurement techniques
  - Dynamic PCD resolution
  - Decomposition of PCD temporal response
- Improved dosimeters
  - Silicon calorimeter construction process
  - Resistive-based silicon calorimeter
  - Diamond PCDs reliability
- Experimenter support aspects

Uncertainty Contributors

- Measurement error
  - Signal-to-noise in pulse tail
- Interpretation/use of measurement
  - Knowledge of nuclear data
  - Mixed field dosimeter response
  - Time-dependent source characterization

SNLRML Dosimetry

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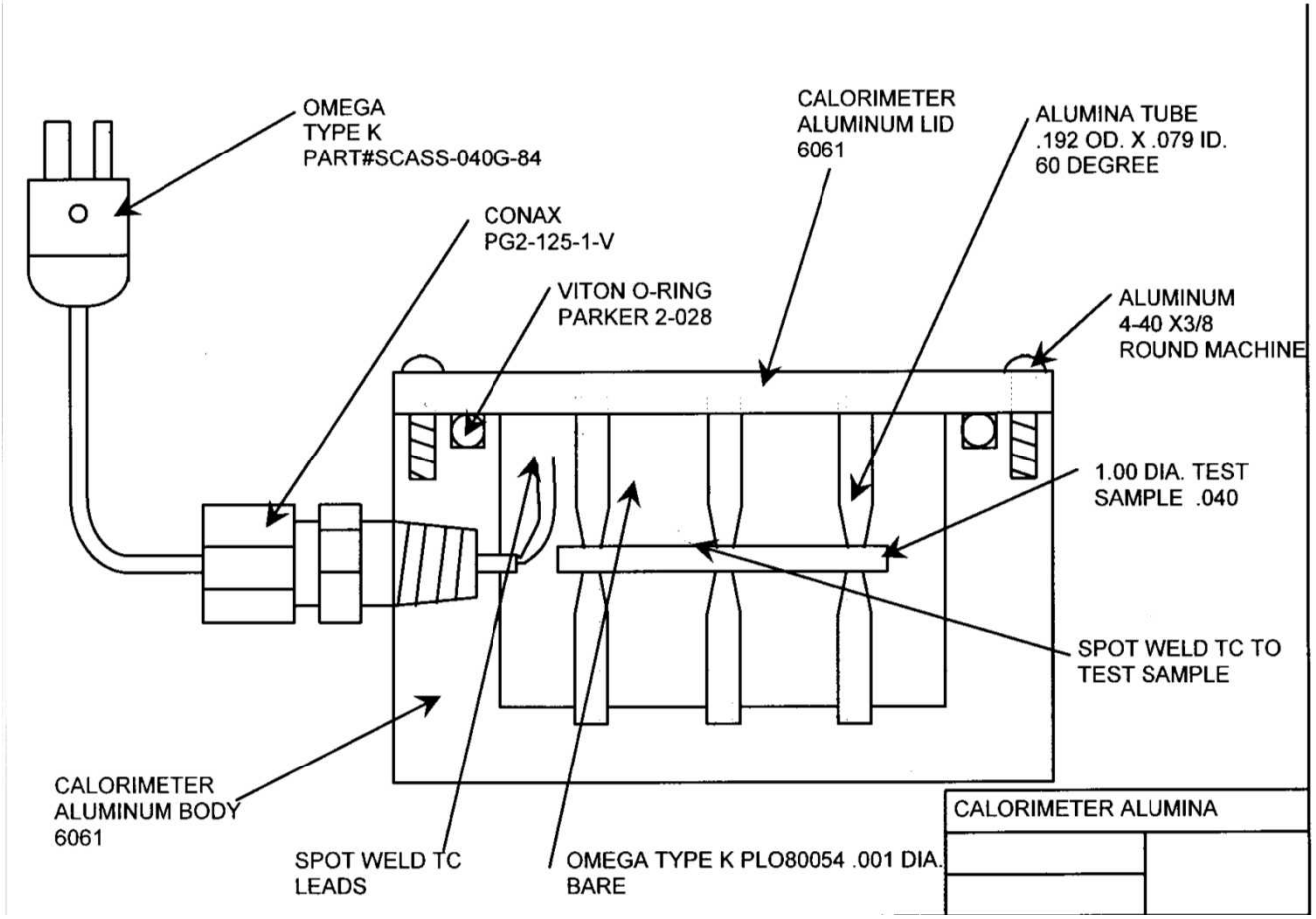
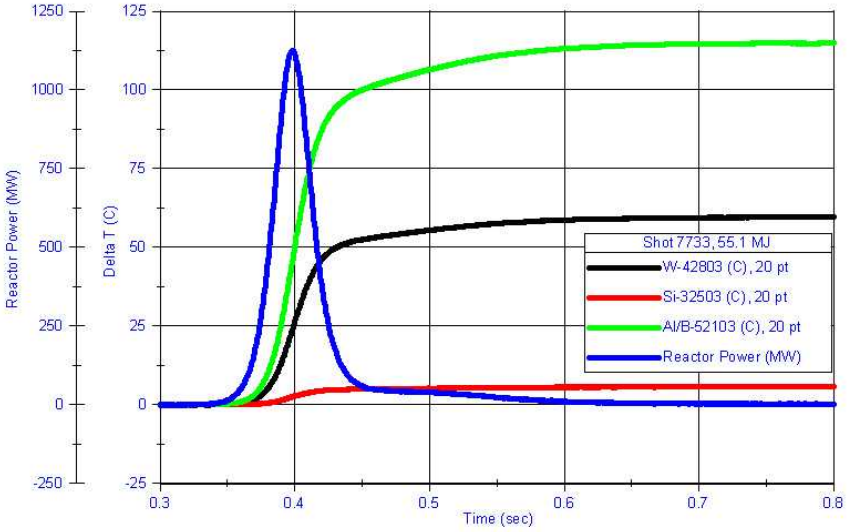
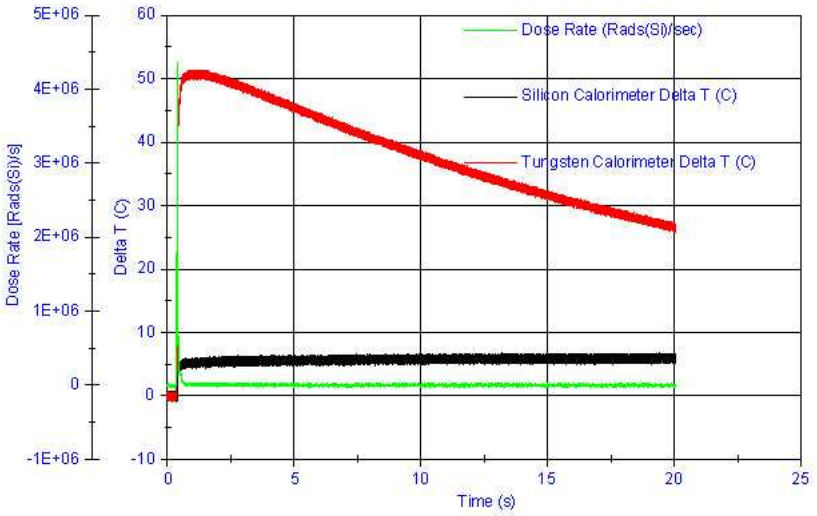
Consistency Testing of PIN/PCD/SPND/IC

Si Calorimeter



Calorimeter Comparison



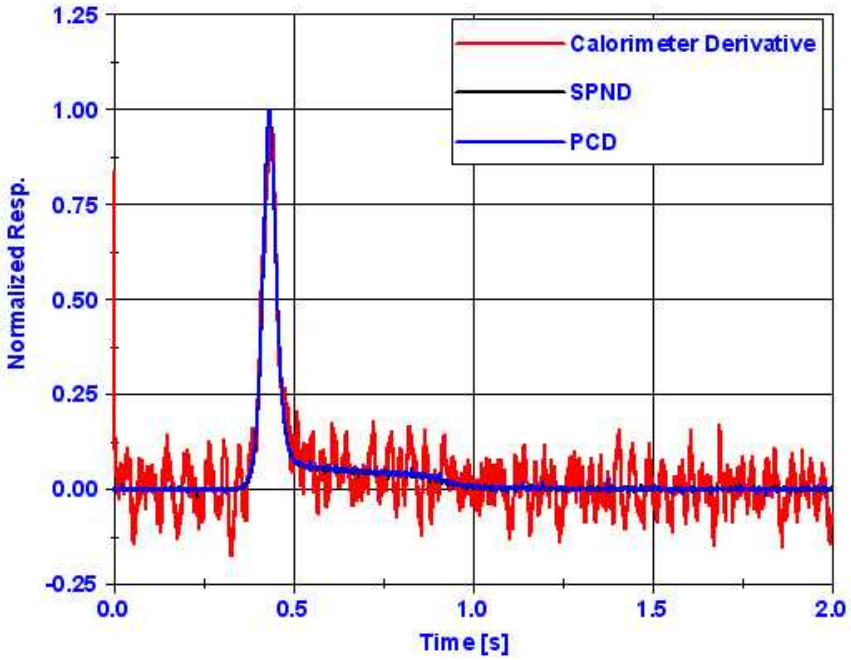


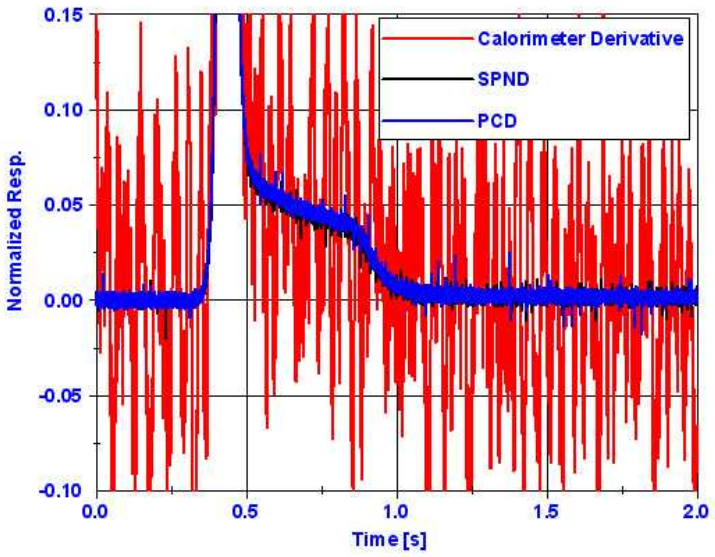
Tungsten and boron give a higher ΔΘ

Higher temperature radiates faster.

Low temperature has signal-to-noise issues

Dosimeter Early-time Agreement





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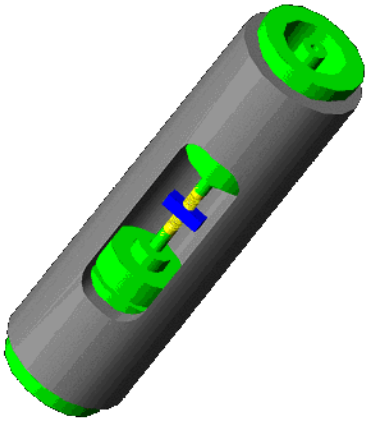
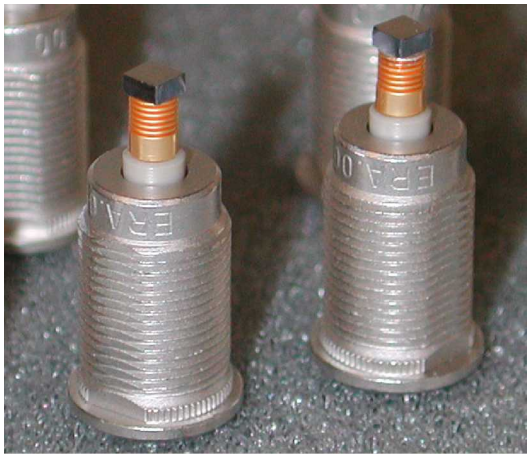
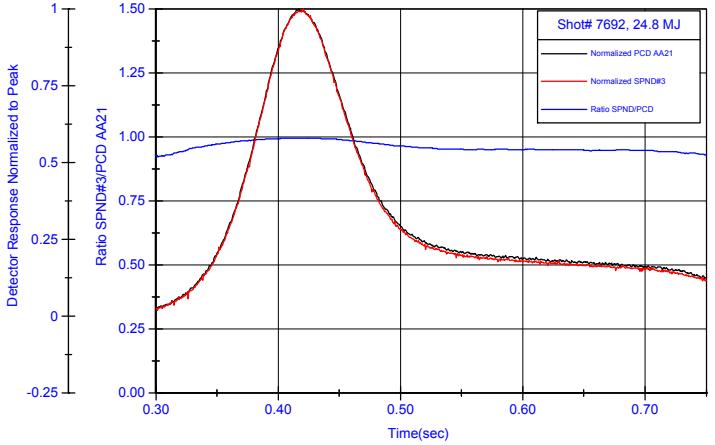
Active Dosimetry for ACRR

- Developed new active dosimeter combination; reduces rate uncertainty from 2X to 25%
  - PCD – picosecond response
  - Si calorimeter – accurate integral dose
- Documented:
  - construction/application
  - uncertainties
- Validated in Hermes-III testing
- Used in support of W76-1 AF&F testing







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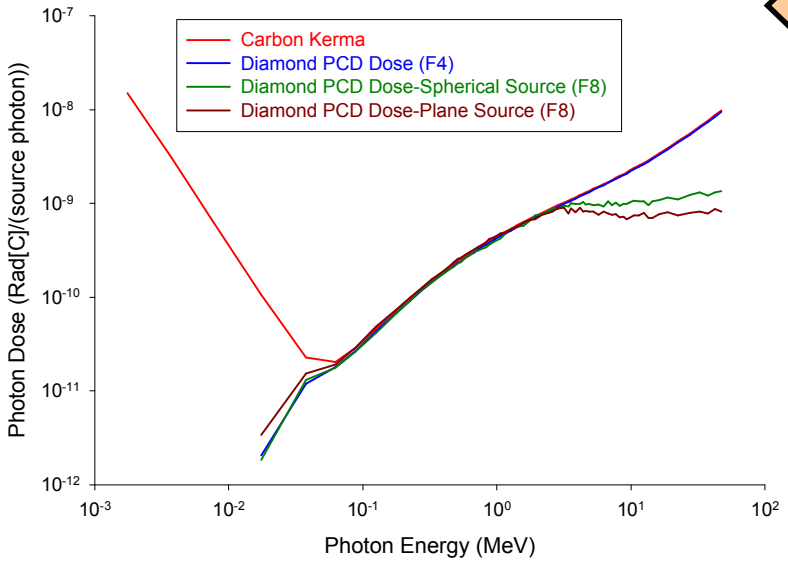
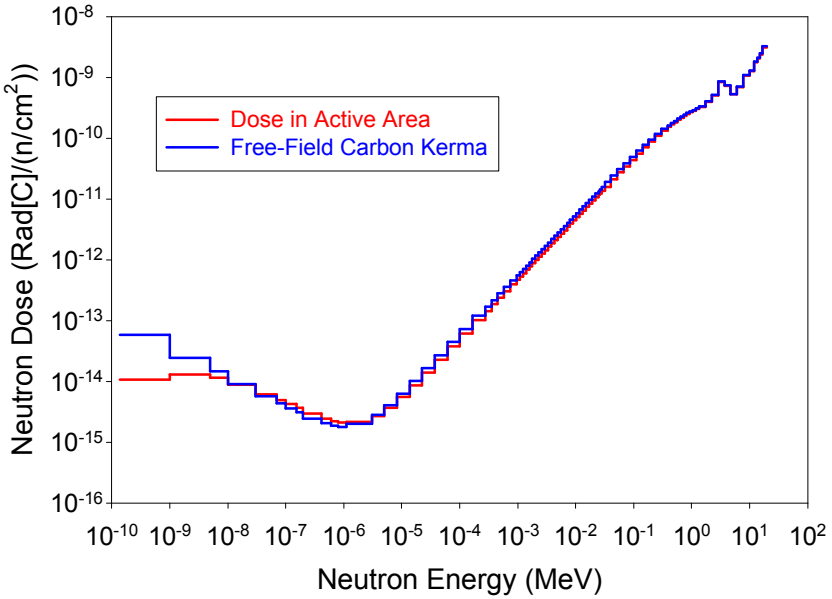
Modeled PCD Response



Photon:

- **low energy attenuation**
- **high energy non-CPE**

Neutron:



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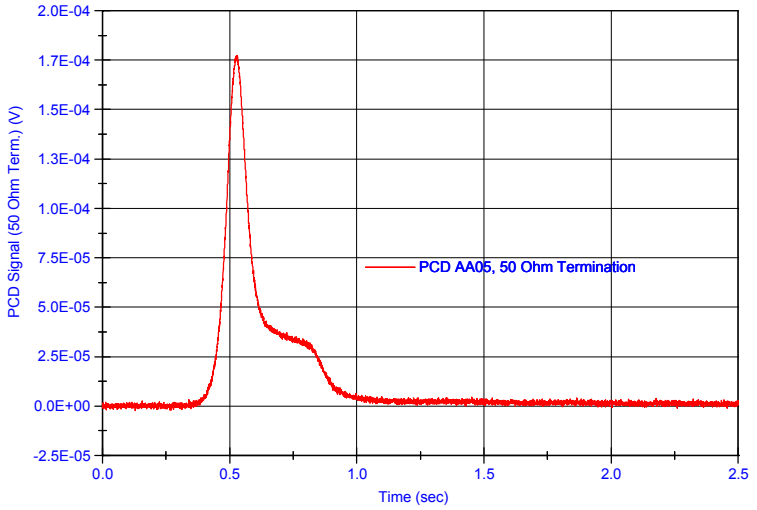
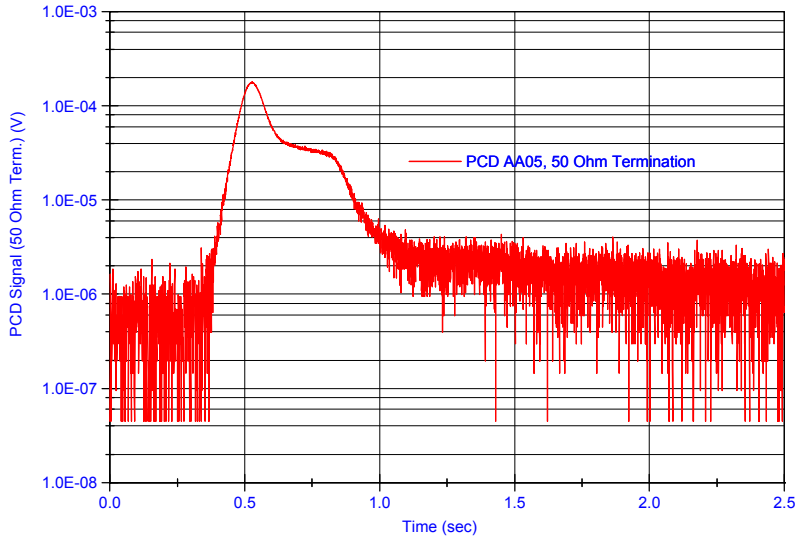
PCD Response in ACRR



Linear View

Logarithmic View



n/γ Response of PCD in ACRR Central Cavity Irradiation

Matl.	Neutron Kerma	Gamma Kerma	% Dose from neutrons
Alanine	469.2	208.2	69%
Diamond	74.3	192.9	28%
Silicon	16.0	203.2	7%
CaF_2:Mn TLD	31.45	202.4	13%

n/γ dose components?

- photon component varies with Z
- neutron component varies with hydrogen content

Only some of the energy is deposited as ionization!

Energy Loss Mechanism	% Energy Loss	
	Primary Ion	Recoil Atoms
Ionization	67.1	9.34
Vacancies	0.22	0.71
Phonons	1.39	21.23

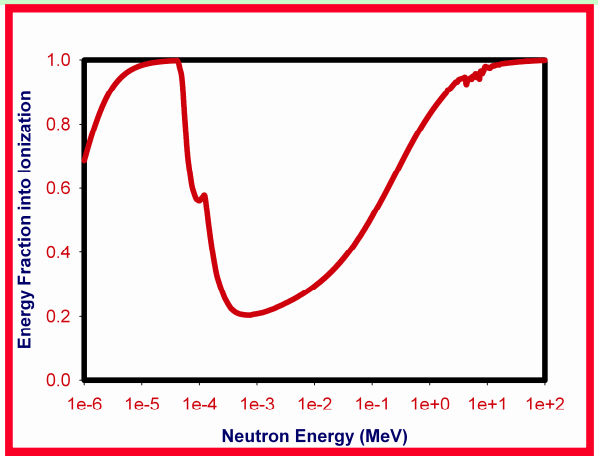
Neutron Ionizing Dose Component

- Total Dose ≠ Ionizing Dose
- Correction factor for C PCD or Si PIN

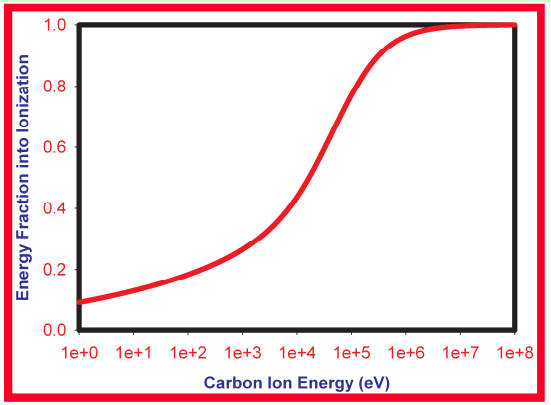
Carbon PCD Neutron Response

Spectrum	% n-dose	% n- dose Ionizing	% Effect on Rsp.
SPR-III CC	59	77	14
SPR-III 17”	69	77	16
ACRR CC	27	61	11
ACRR Pb-B	68	63	25

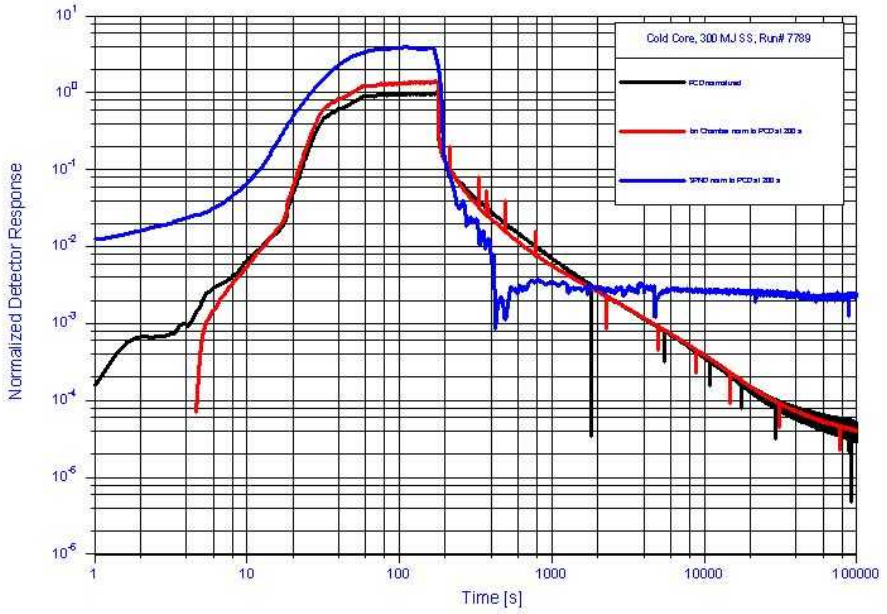
C Neutron Ionization/Total Dose



C Ion Ionization/Total Dose

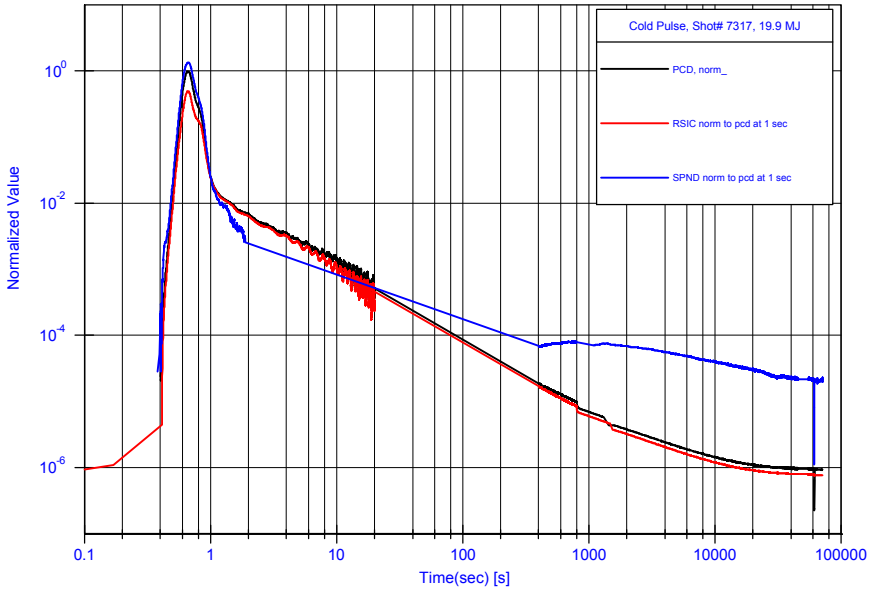


Long-term Dosimeter Comparison in Reactor Environment

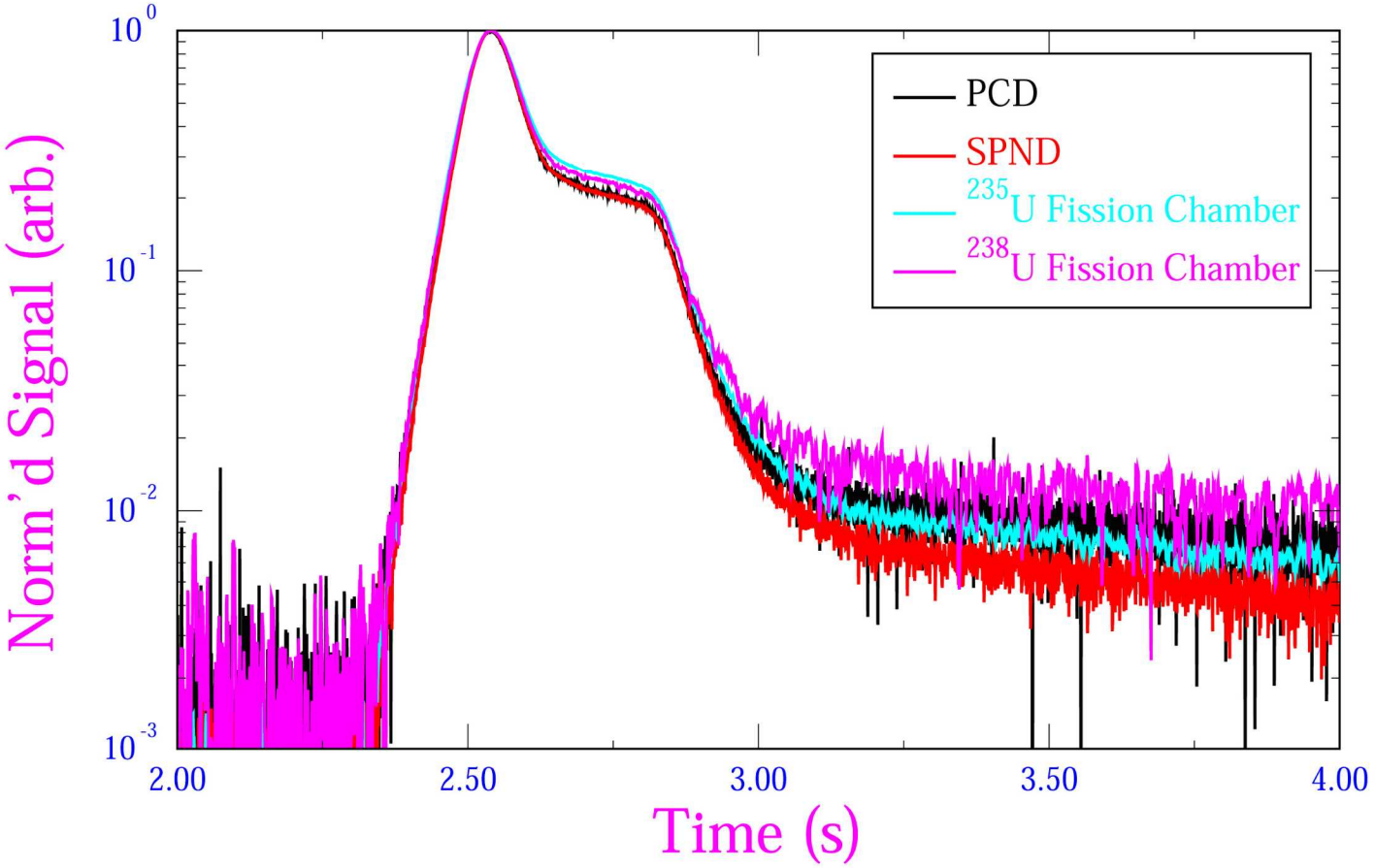


Steady-state operation

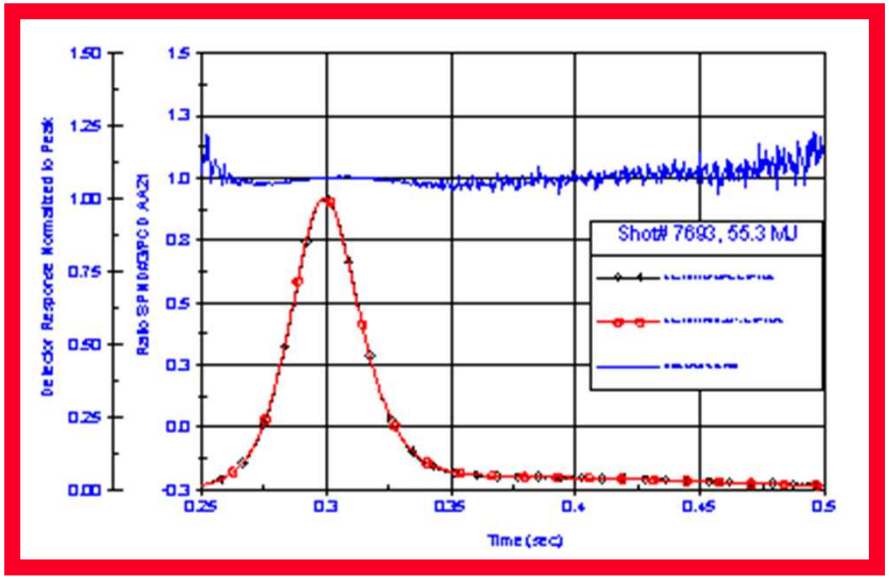
Pulse operation



Comparison of Active Dosimeters at ACRR

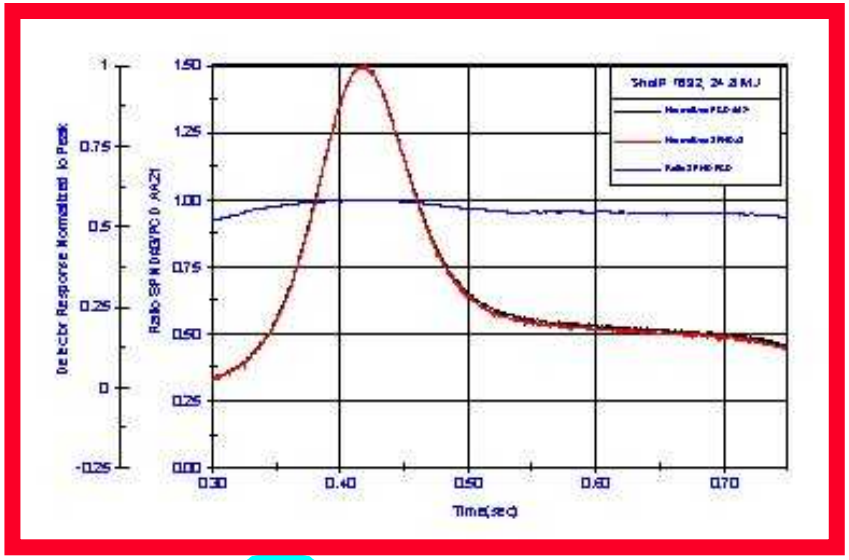


SPND and PCD Response for 55.3 and 24 MJ ACRR Shots



ACRR testing done from 20 – 300 MJs

Agreement with SPND power profile excellent within peak + 3 FWHM



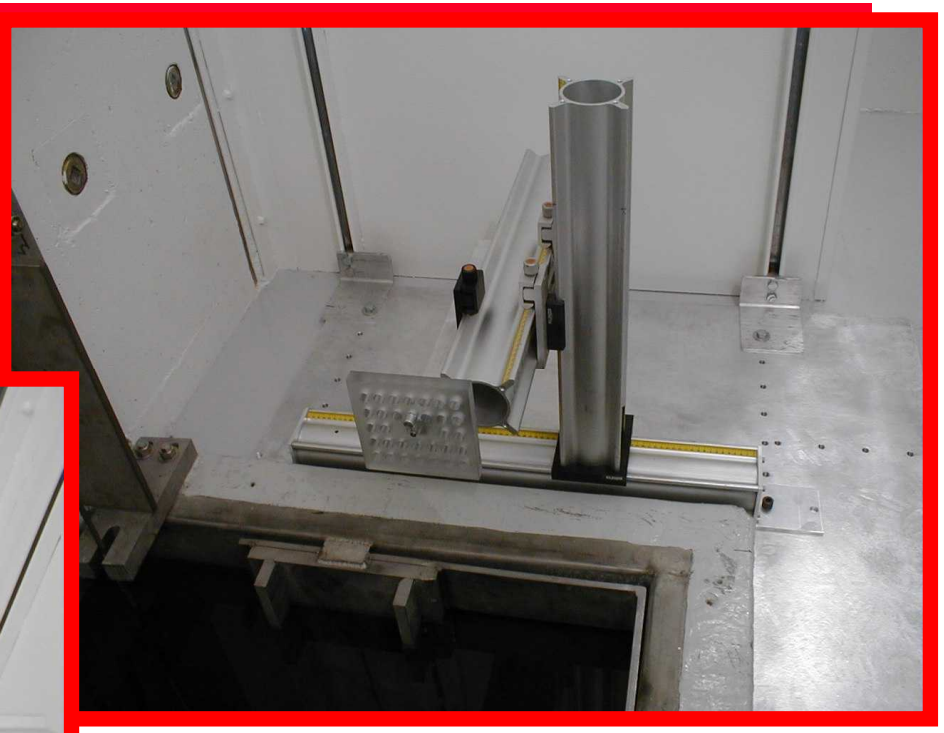
Plots show overlap of normalized pulse profiles

AND

Ratio of time profiles

GIF Fixture for Stability Check

Need: easily and rapidly confirm stability of PCD calibration after neutron irradiation



Reproducible placement of PCDs, alanine dosimetry

High fidelity (2% prec., 4% acc,, 4% field uniformity)

Variation of PCD in 100 rad(Si)/sec GIF Field

- Individual measurements stable to ~0.25%
- Gamma field dosimetry: ~2% precision, ~4% accuracy, ~4% uniformity
- PCD-to-PCD variation in calibration ratio ~8%

PCD #	Rsp. Ratio [mV-s /rad(H2O)]	Std. Dev.
AA22	1.43E-10	0.24%
AA24	1.30E-10	0.31%
AA26	1.46E-10	0.21%
AA28	1.44E-10	0.97%

PCD #	Rsp. Ratio [mV-s /rad(H2O)]	Std. Dev.
AA29	1.64E-10	0.21%
AA30	1.30E-10	0.27%
AA33	1.51E-10	0.22%
AA46	1.34E-10	0.23%

Stable Response for Pre-damaged PCDs

Date	Φ_{int}	Cable Compensated Response Ratio ($x10^{-10}$)			
		AA05	AA11	AA15	AA28
7/29/2003	1.79E14	1.65	1.78	1.75	---
8/6/2003	3.65E14	1.71	1.83	1.77	1.64
8/11/2003	5.51E14	1.69	1.84	1.82	1.65
8/21/2003	7.33E14	1.69	1.83	1.83	1.65
8/25/2003	1.09E15	1.68	1.91	---	1.64
9/3/2003	1.46E15	1.69	1.80	1.80	1.64
9/24/2003	2.26E15	1.68	1.80	1.79	1.63
10/23/2003	3.06E15	1.69	1.80	1.90	1.72
12/1/2003	3.86E15	1.68	1.77	1.77	1.62
2/14/2004	4.65E15	1.67	1.77	1.77	1.62
3/9/2004	5.43E15	1.61	1.73	1.77	1.60
Std. Dev.		1.53%	2.63%	2.50%	2.05%

Variation of PCD with Different GIF Dose Rates

- GIF calibration consistent over available dose rates
- Uncertainty includes variation in gamma field and associated alanine field calibration dosimetry uncertainty

PCD #	Dose Rate [rad(H_2O)/sec]			Average	Uncertainty (Dos. + Std.)
	100	50	10		
112D1	2.63E-10	2.91E-10	2.94E-10	2.89E-10	5.8%
AA26	1.46E-10	1.77E-10	1.83E-10	1.66E-10	10.1%
AA29	1.64E-10	--	1.91E-10	1.78E-10	9.05%
AA28	1.44E-10	--	1.44E-10	1.44E-10	4.01%

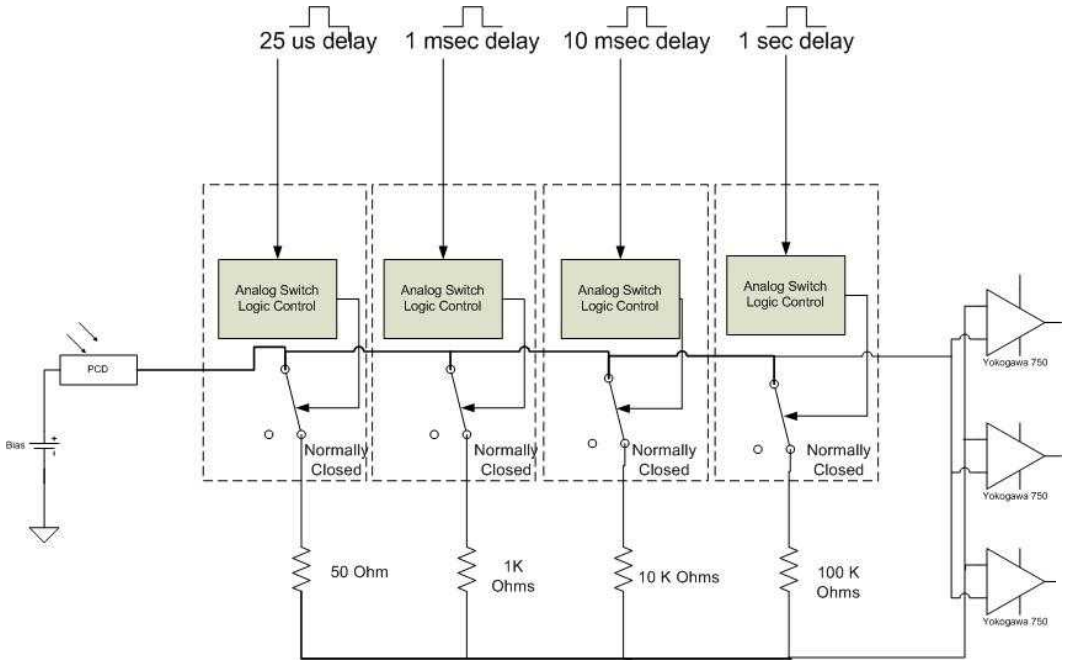
Hermes-III Full and Half Power Calibration

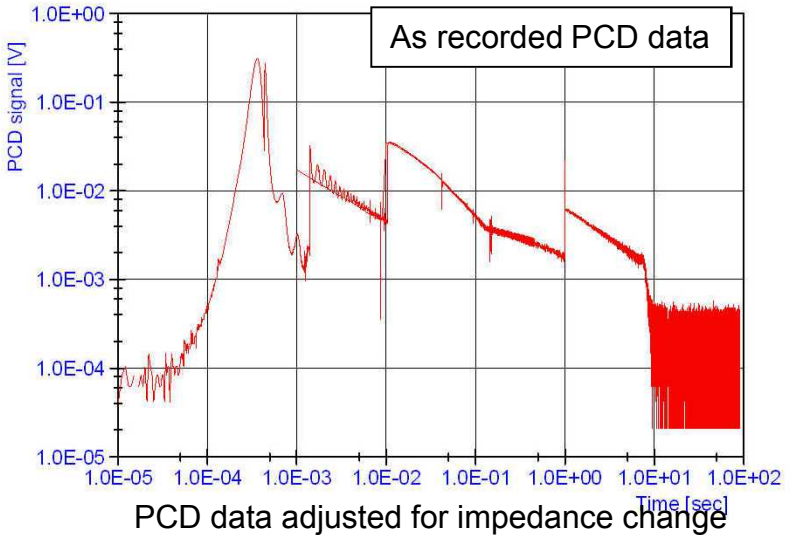
Agreement consistent with calibration uncertainties

- Calibration basis: integral PCD response wrt TLD
- Full power Hermes-III, $1 \times 10^{10} - 2 \times 10^{12}$ rad(Si)/s
- Half power Hermes-III, $5 \times 10^{8} - 2 \times 10^{11}$ rad(Si)/s

PCD #	Full Power		Half Power		Var. of Cal.
	Rsp.	Cal.	Rsp.	Cal.	
	mV-s /rad(TLD)	mV-s /rad(C)	mV-s /rad(TLD)	mV-s /rad(C)	
AA02	1.772E-7	2.20E-7	1.876E-7	2.26E-7	2.6%
AA12	1.555E-7	1.93E-7	1.848E-7	2.23E-7	15%

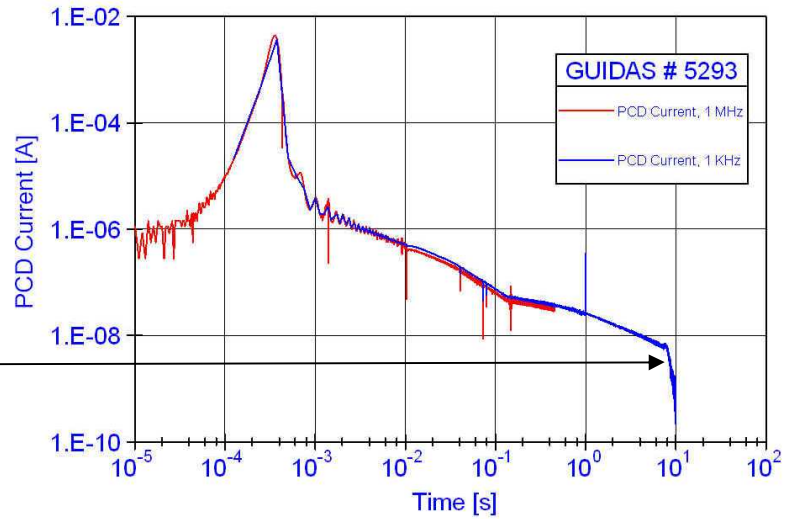
High Resolution Dynamic Range PCD Measurement PCD





PCD data adjusted for impedance change

$\delta PCD = 50\ \mu V$ for $V_{PCD} < 10$ mV
$= 1$ mV for $V_{PCD} > 10$ mV



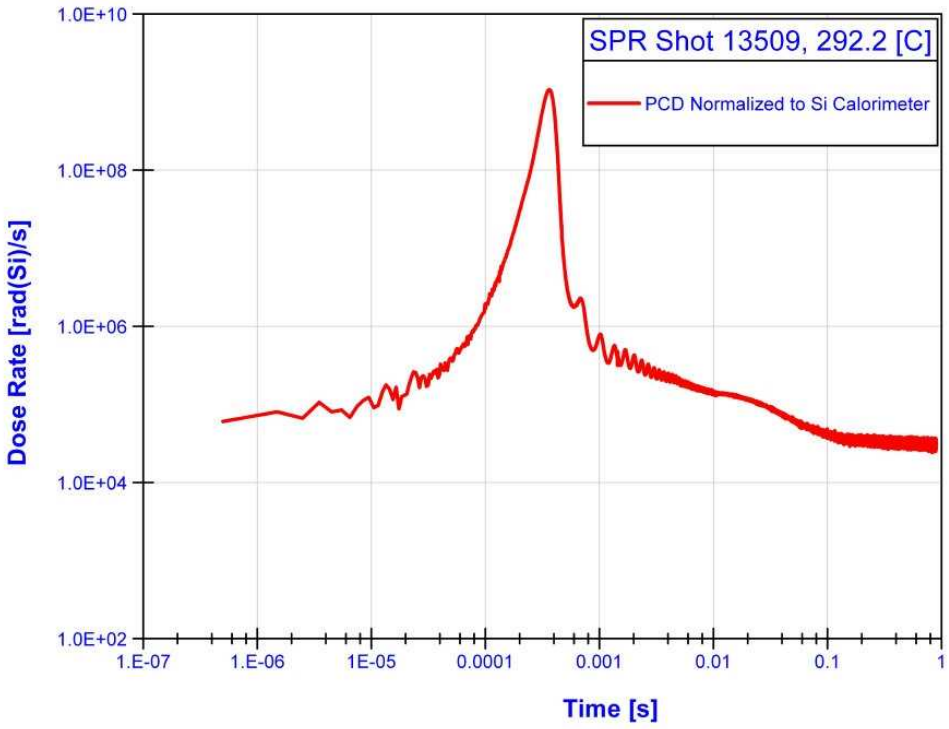
Reactor lowered Into floor

Unlimited Distribu

S. M. Luker

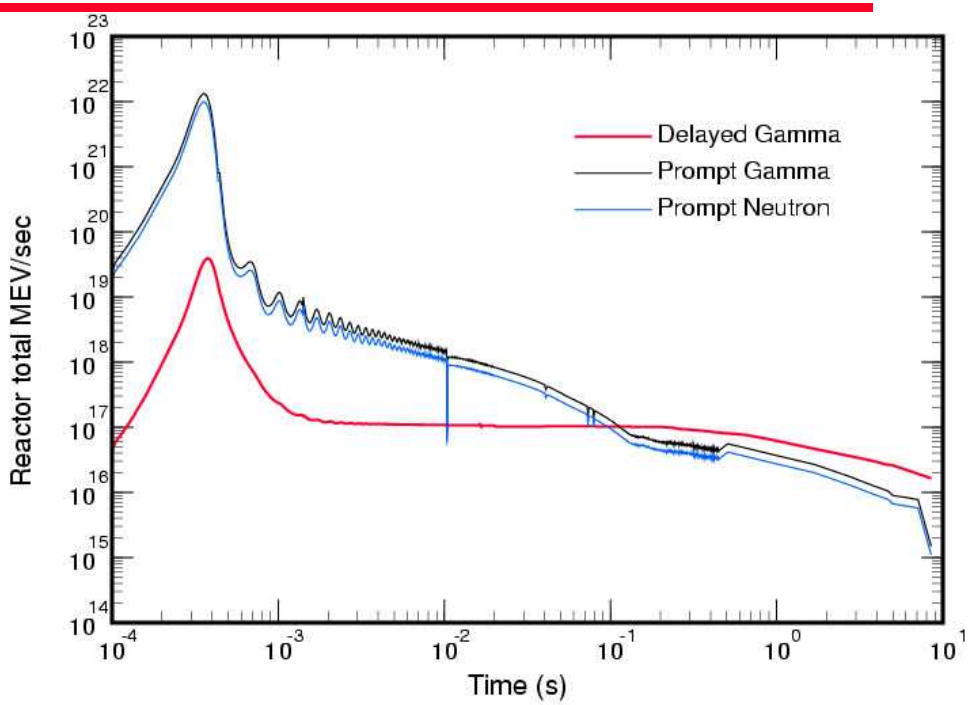
SPR-III Shot 13509 Dosimetry

- **Neutron fluence:**
  - **^{58}Ni(n,p) activity: 2.84E4 Bq/gm**
  - **Total Fluence: 3.51E14 n/cm^2**
- **Silicon ionizing dose**
  - **Si calorimeter: 117.7 krad(Si)**
- **PCD Time Profile**



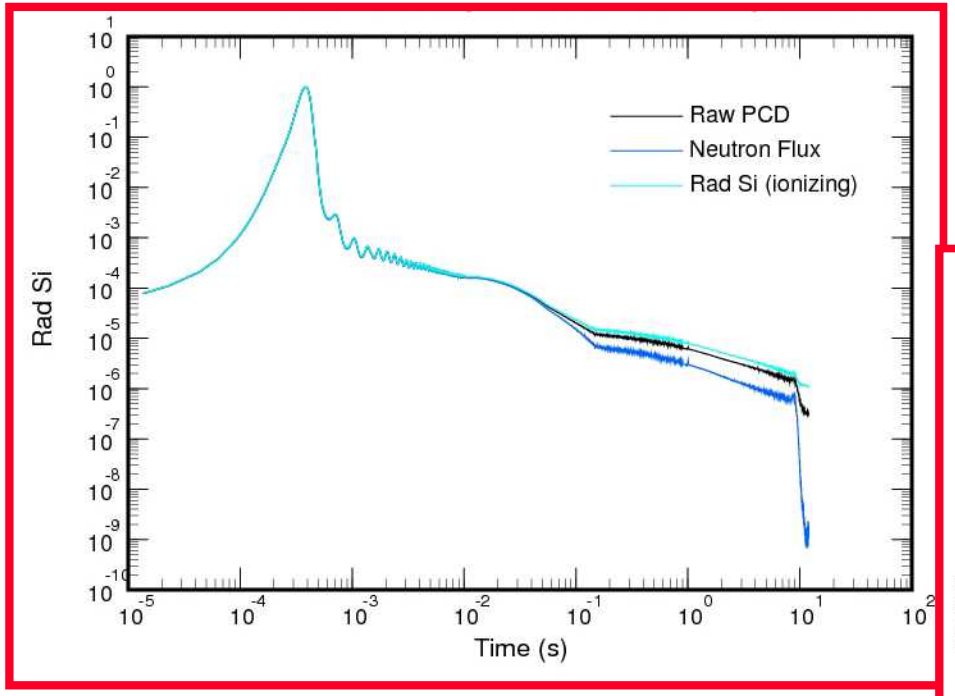
Decomposition of Late-time Reactor Environment

- Use diamond PCD to unfold the reactor power time history
- Used to support:
  - QASPR testing
  - NG and AF&F test environment selection
  - RES dosimeter response studies



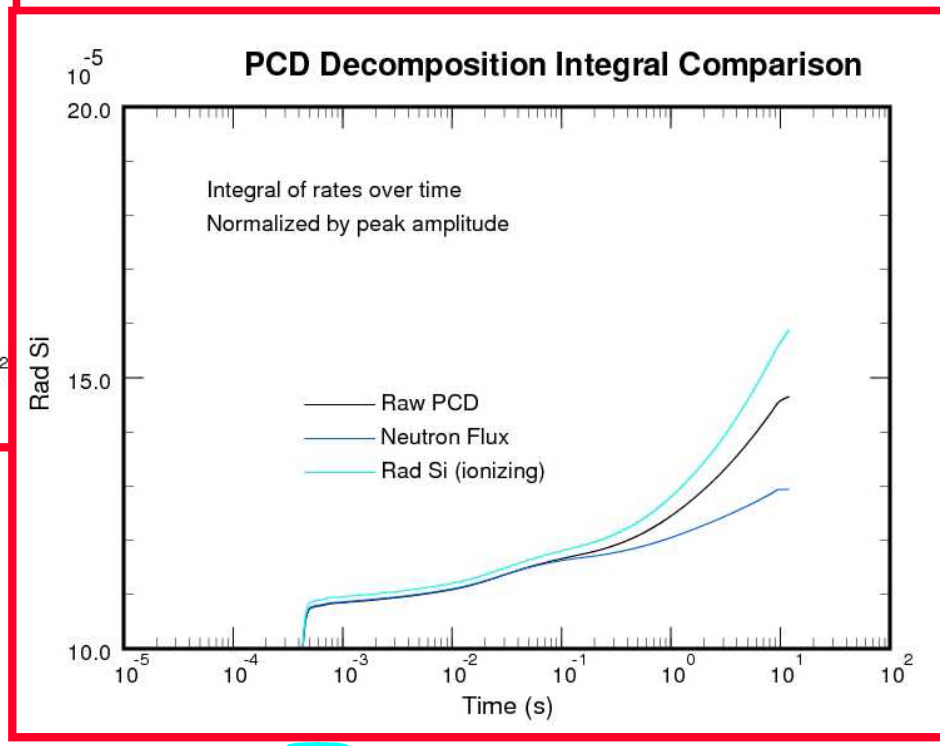
A. J. Suo-Anttila, Org. 1384

pdf and cdf for SPR-III Temporal Profiles

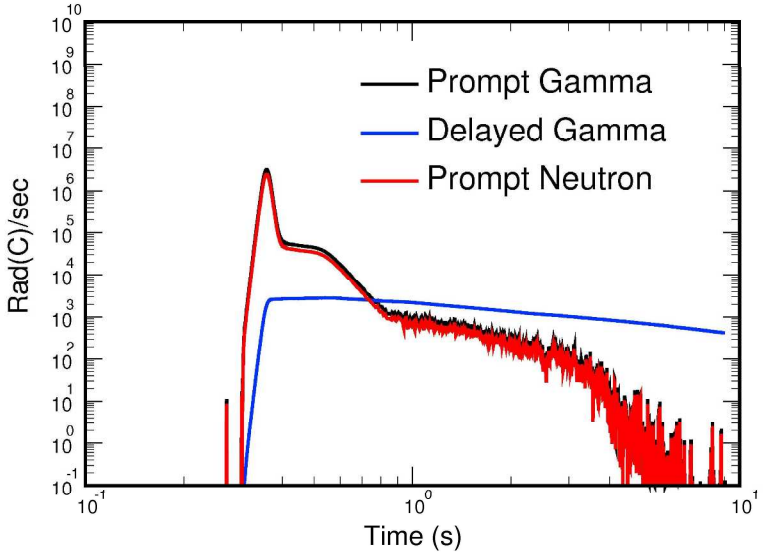


Normalized pdf temporal profiles

cdf temporal profiles with peak match

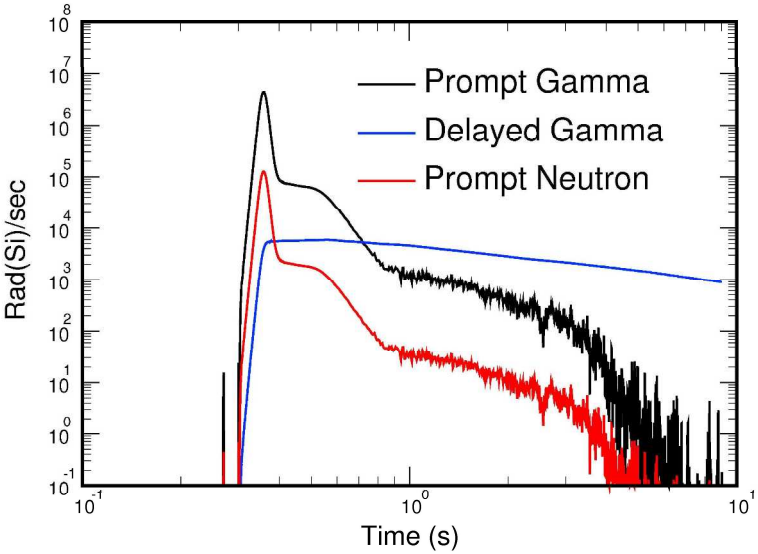


ACRR Pb-B Bucket Decomposed Environment

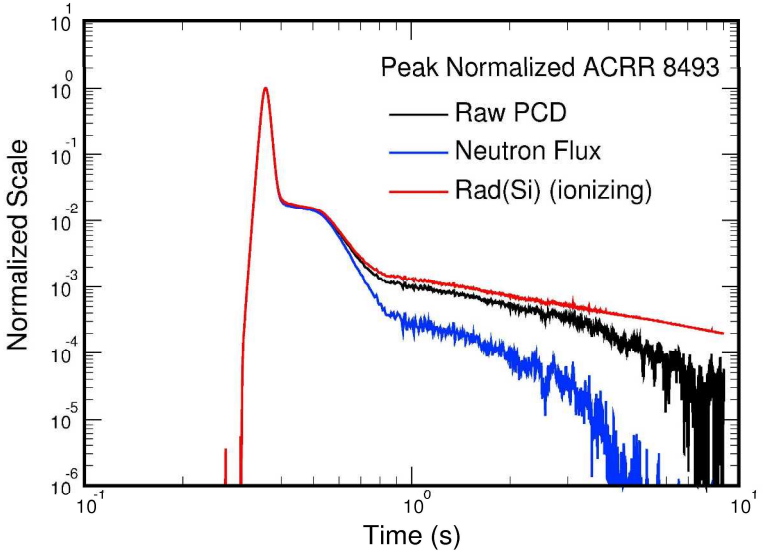


Rad(C) temporal profiles

Rad(Si) temporal profiles

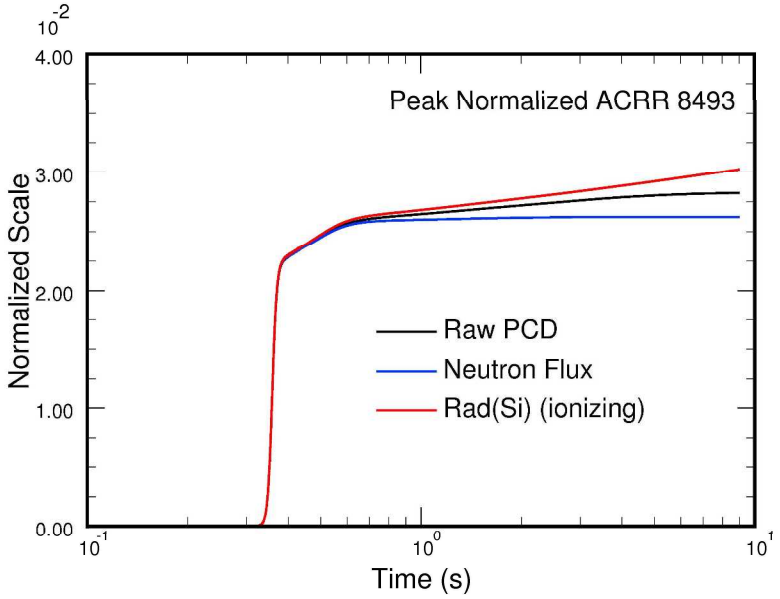


ACRR Pb-B Bucket Time Profiles



Scaled temporal profiles

Cumulative distributions



Active Dosimeters for DP Testing

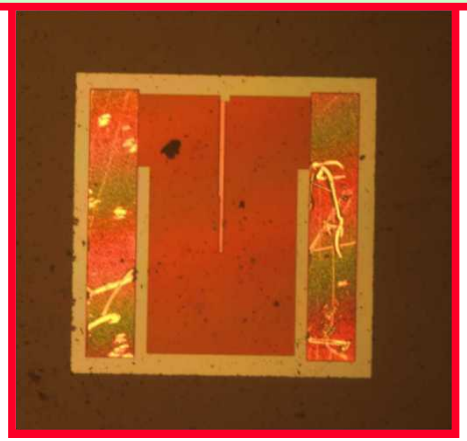
- Construct, document inventory of dosimeters for experimenter non-destructive use.
  - Si calorimeters
  - Boron calorimeter
  - Diamond PCD

Dosimeter Improvements

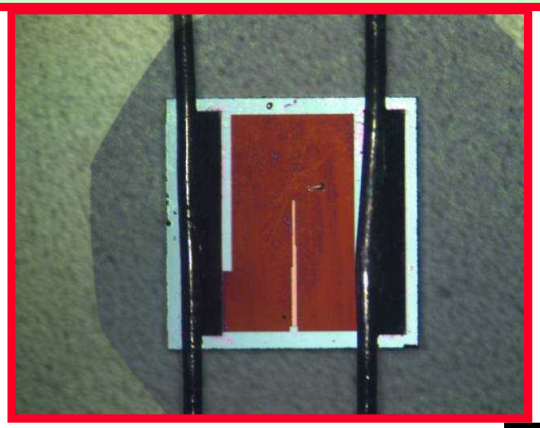
- Modern silicon calorimeter construction methods
- Improved boron calorimeter
- ^{237}Np fission chamber
- Investigations:
  - In-situ active temperature measurements
    - » issue of measurement time
    - » Issue of damaged device response
  - Cooled PIN
  - Silicon PCD – under consideration

Improvement and Validation of Si Calorimeter

Si chip with TaN thin film resistor



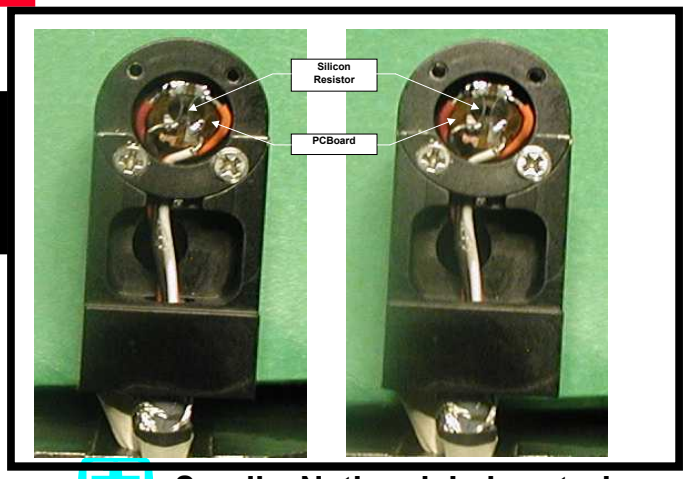
Wires on gold bond pads



Si chip suspended over hole in PC Board

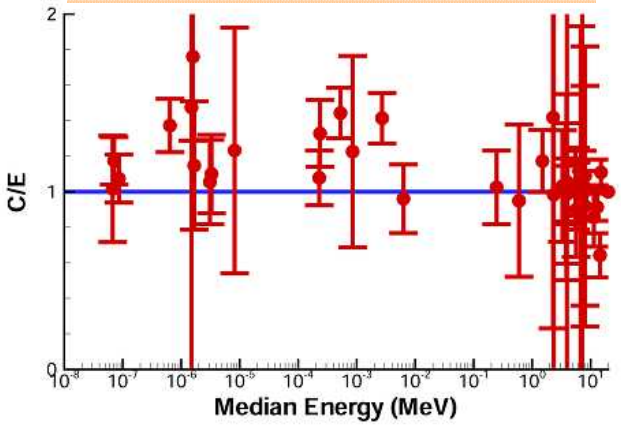
- **Explore use of a thin film resistor for a resistance measurement of temperature.**
- **50 mil sq. area**
- **10 mil thick**
- **~0.5 μm TaN layer**

Assembled calorimeter

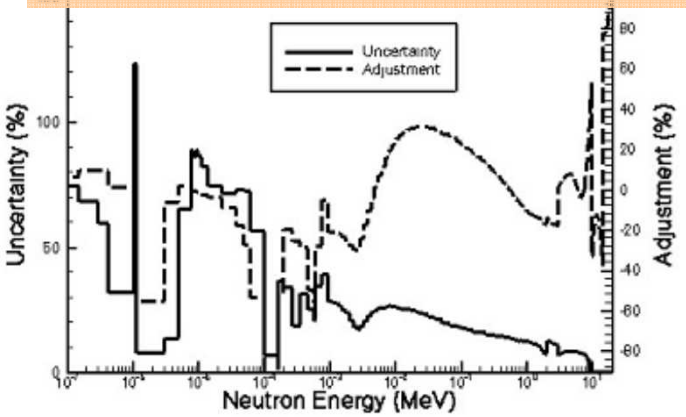


Uncertainty/Dosimetry Approach: ACRR Spectrum Characterization

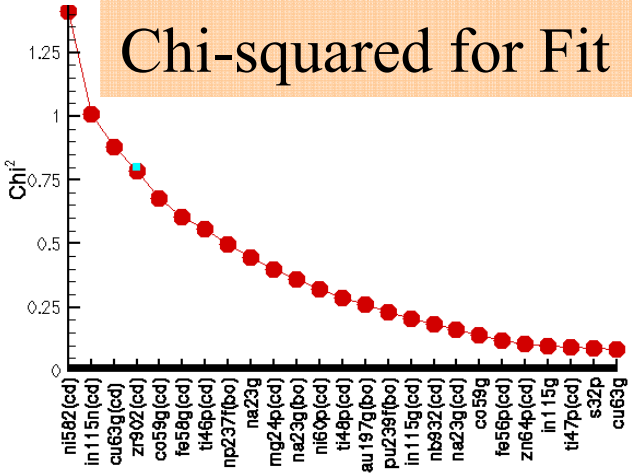
C/E for Activities



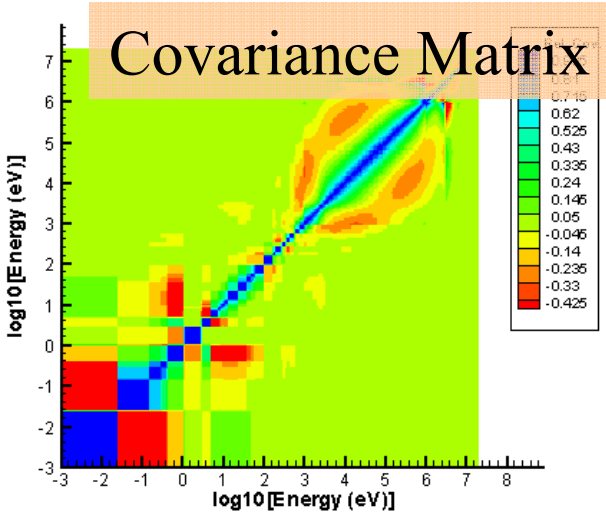
Adjustment/Uncertainty



Chi-squared for Fit

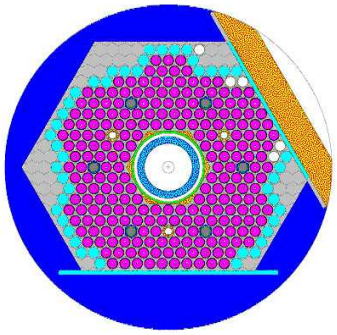


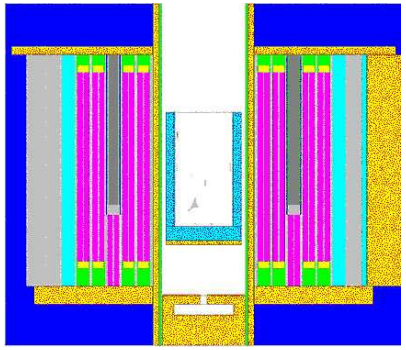
Covariance Matrix

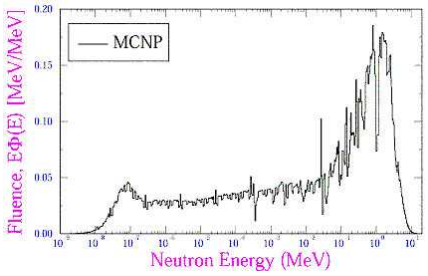


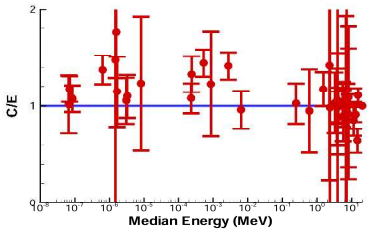
Reactor Test Fidelity Resource Support

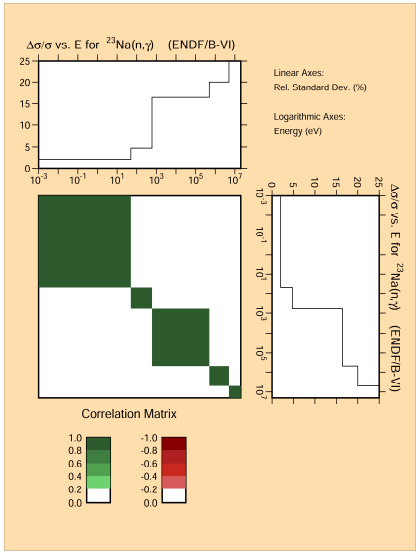
- **Evaluation of latest dosimetry cross sections**
  - **ENDF/B-VII, Jan. 2007 release**
  - **Integrate into ASTM cross section library for community**
- **Upgrade spectrum determination tools**
  - **LSL – covariance interface**
  - **SAND – UQ**











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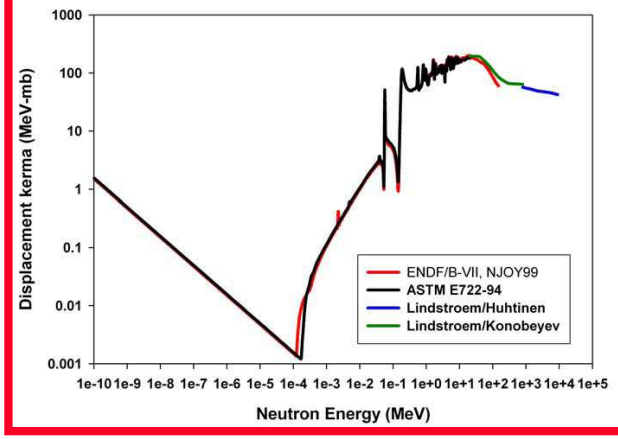
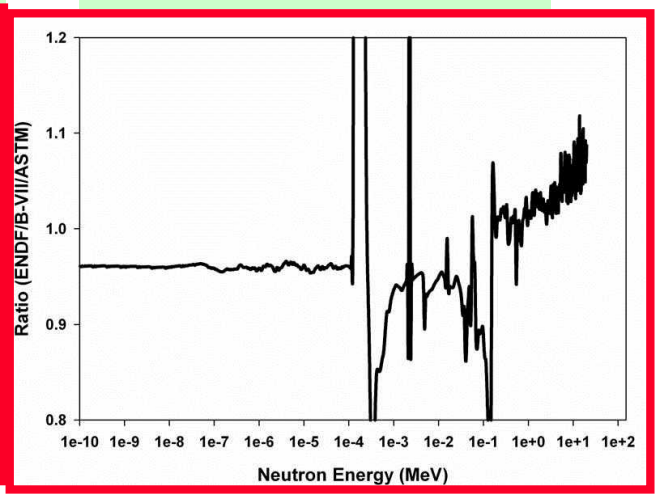
Updated Silicon 1-MeV(Si) Damage Function

- ENDF/B-VII xsec
- NRT dpa formalism
- All isotopes
- Submitted to ASTM, published by DOD

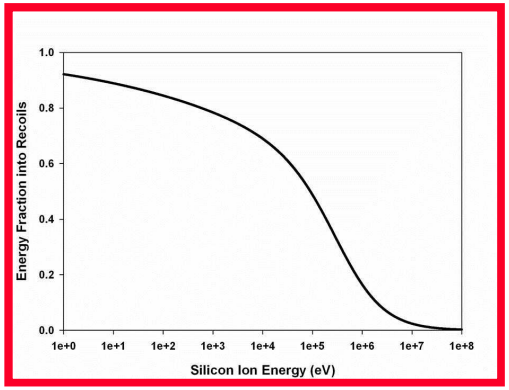
ENDF/B-VII 1-MeV(Si)



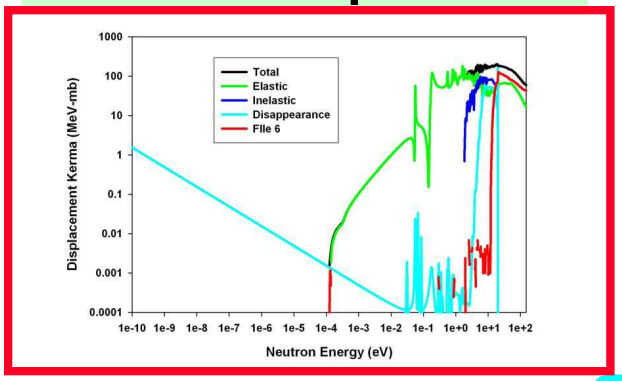
Ratio: New/Old



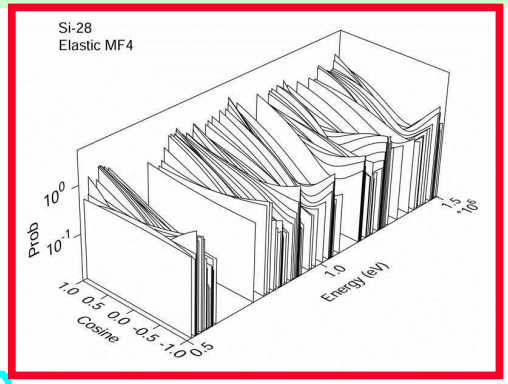
Fraction dpa/total



Si DPA Components



Angular Distribution



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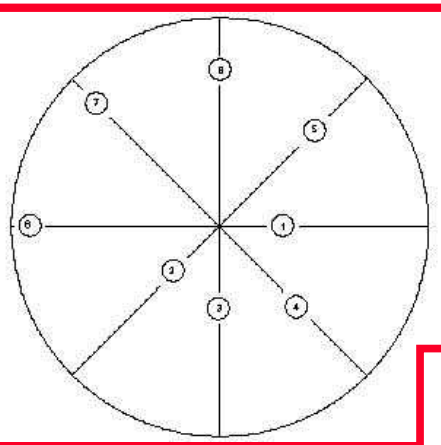
Questions???

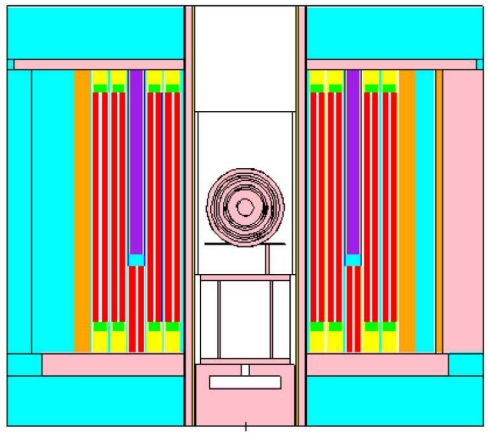
Improvements in Experimenter Test Fixtures

- New ACRR shield plug
  - Reduce radiation exposure to experimenter when handling cable bundles and cryo cooling
  - Improved safety in rigging and handling
- New GIF exposure fixture
  - Improved test object position, reproducibility, field uniformity
  - Permit heavier test articles
  - Permit active cooling

Uncertainty Propagation in Reactor Test Objects

- Research into uncertainty propagation in reactor test environments
  - Supported dissertation work
- Used in 2007 ASC V&V Level 2 milestone





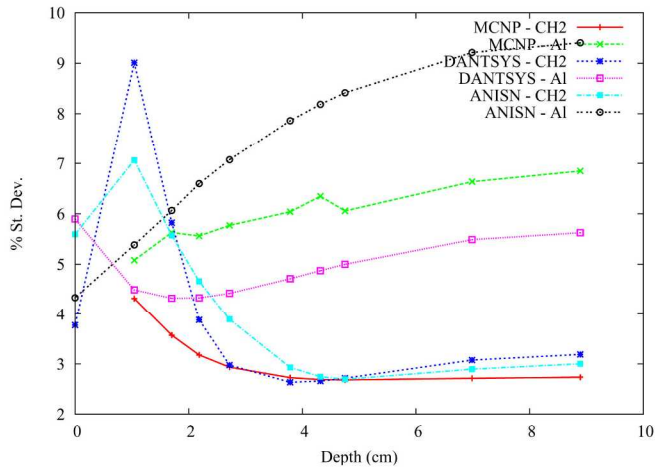
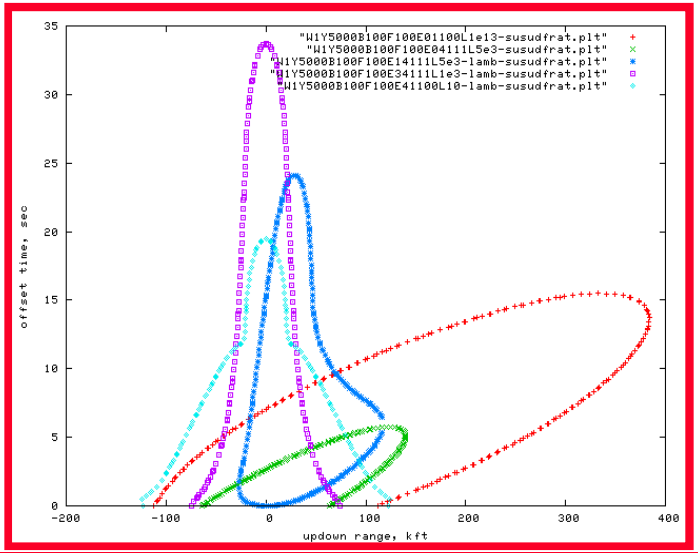


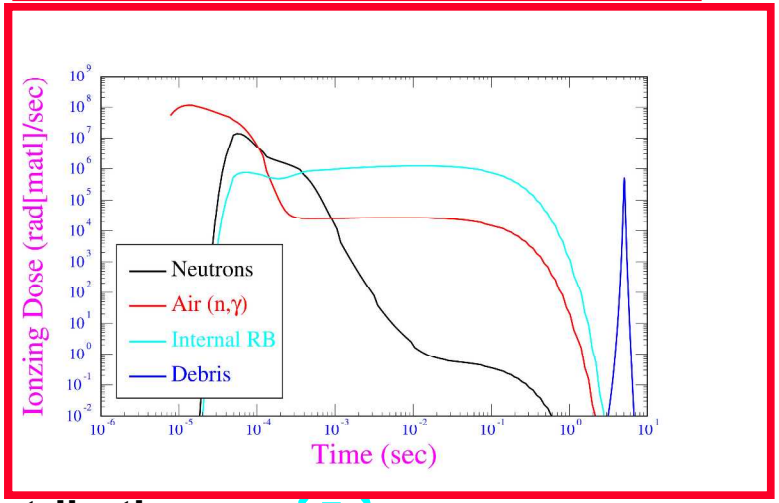
Figure shows source uncertainty contribution to $^{45}Sc(n,\gamma)$ response vs. depth for various calculational methods

R. Keith, ITT

How do reactor environments compare to threat environments?

- Explored a generic classified threat space and looked at time profile for stressing encounters
  - Documented results for threat type, yield, and encounter geometry
- Compared to range of ACRR, SPR-III, WSMR time/environment profiles that could be simulated
- HEART 2007 oral presentation
  - JRE paper pending



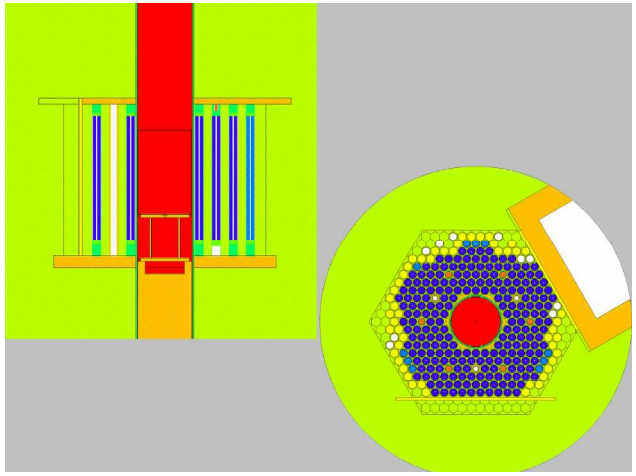


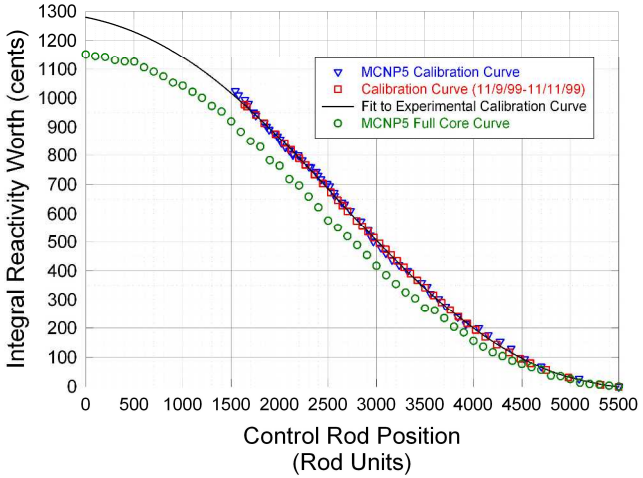
W. C. Cheng, Org. 1384

P. J. Griffin, Org. 1384

ACRR Rod Worth Model & Predictive Worth Validation

- Issue: bootstrap worth measurement technique did not fit prediction of large of package worth
- Resolution: Simulate rod worth measurement technique, not measuring true worth. Package DC measurement was accurate. Predictive issue.
- ANS Winter 2006 paper, “Bootstrap Techniques Versus Full Core Model for Control Rod Calibration”





K. R. DePriest, Org. 1384

Characterization of the Thermal Neutron Environment in ACRR Radiography Tube

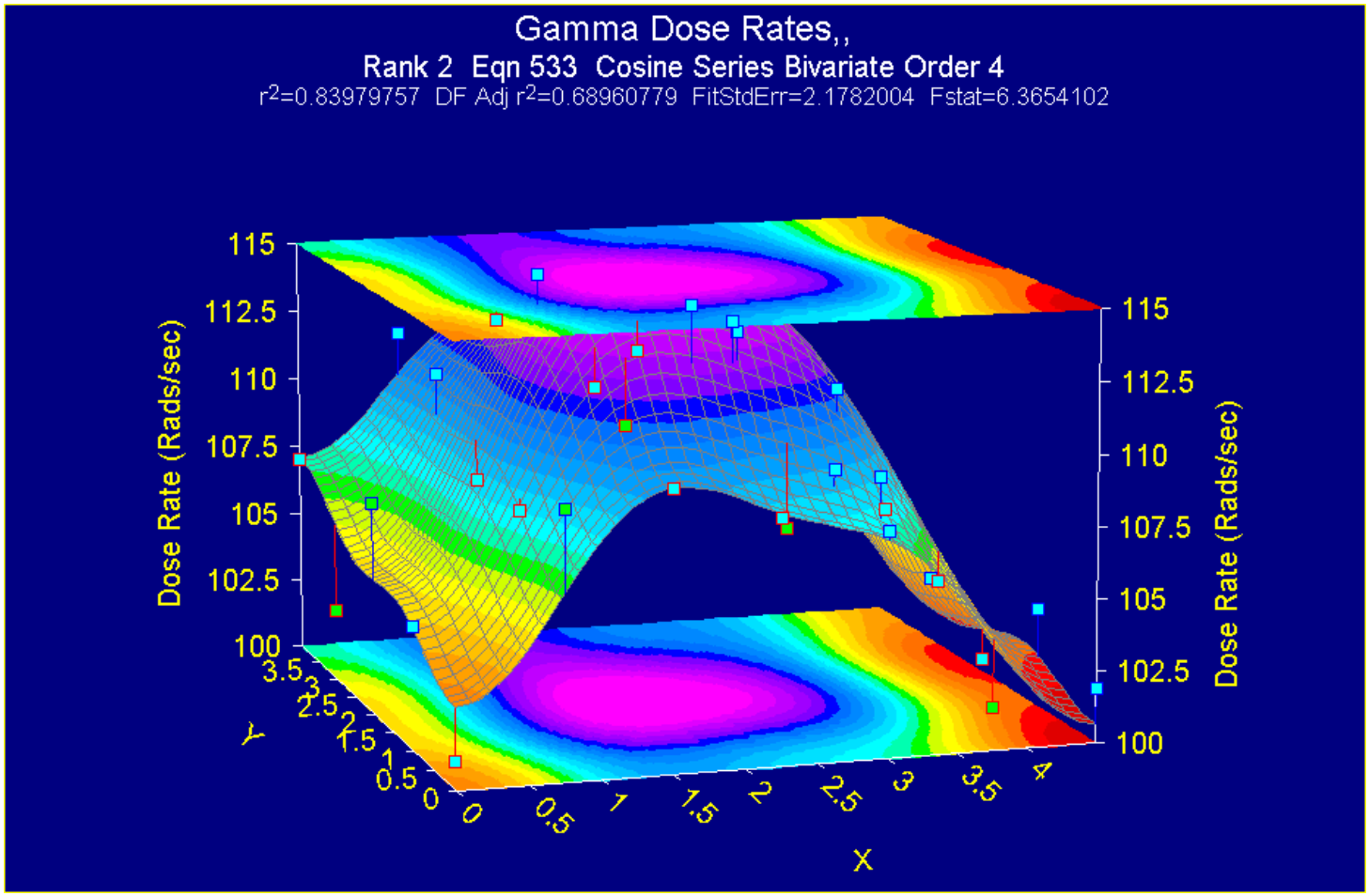
- Investigated $^{164}Dy(n,\gamma)$ monitor for thermal neutron flux
  - Different reactor aperture settings and power levels
- Used to support DOE applications
  - LANL satellite monitor performance
  - PANTEX weapon monitor
  - SEU semiconductor testing

S. M. Luker, Org. 1384

P. J. Griffin, Org. 1384

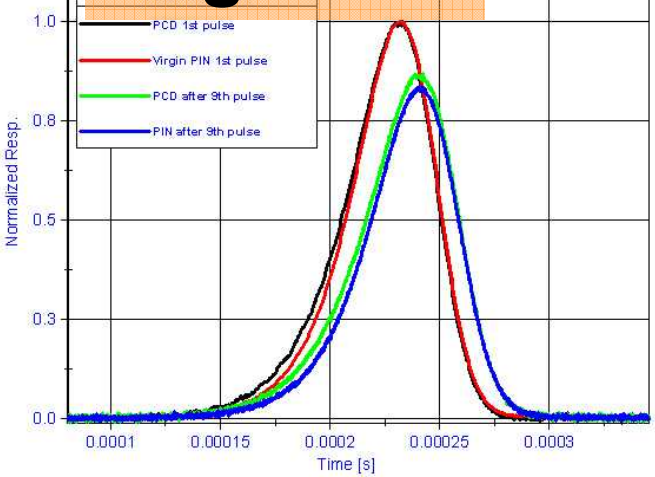
D. W. Vehar, Org. 1382

We Are Carefully Mapping Fixture Uniformity

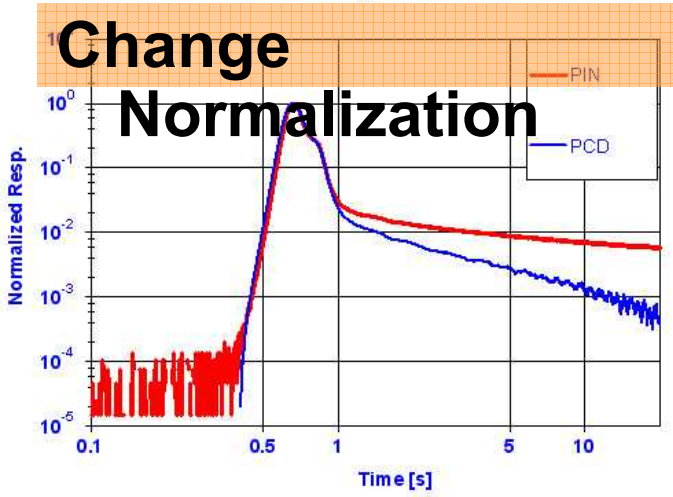


PIN Degradation/Failure

Degrade

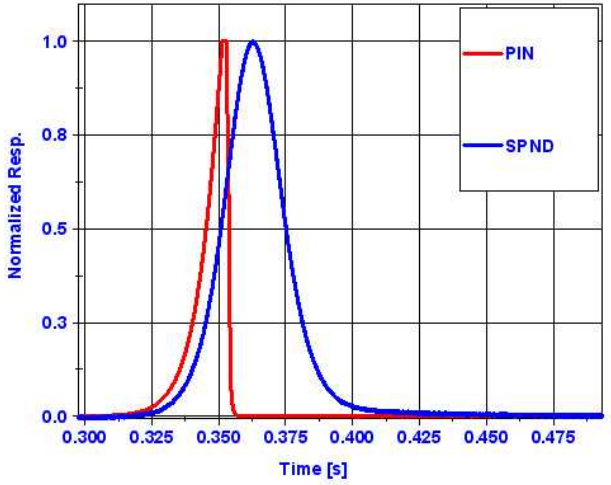


Change Normalization



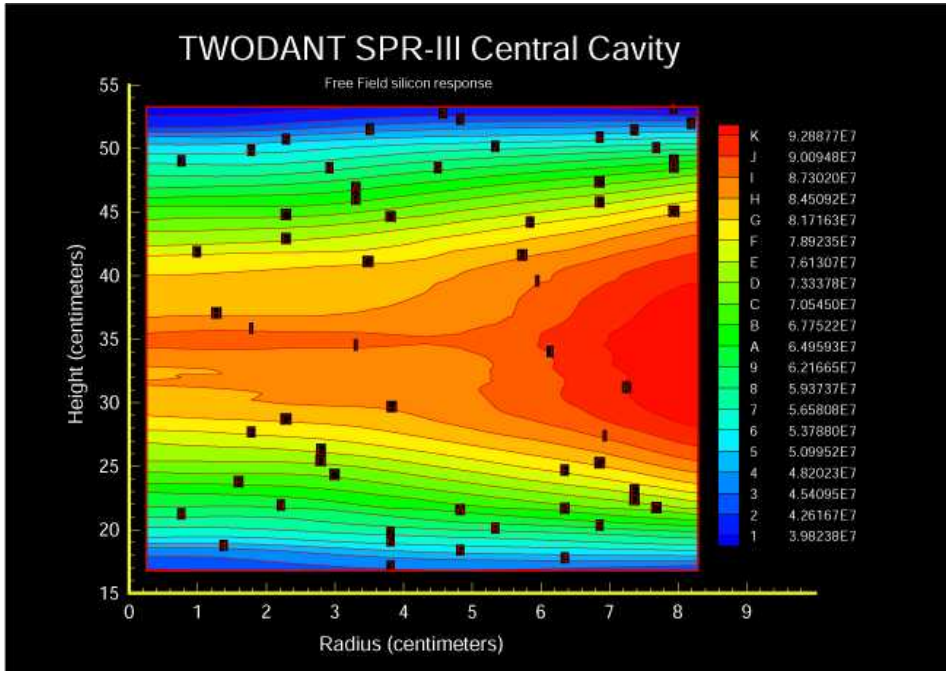
- PINs are not reliable as multi-use dosimeters at reactors. They:
  - Degrade
  - Change normalization
  - Catastrophically fail

Catastrophically fail



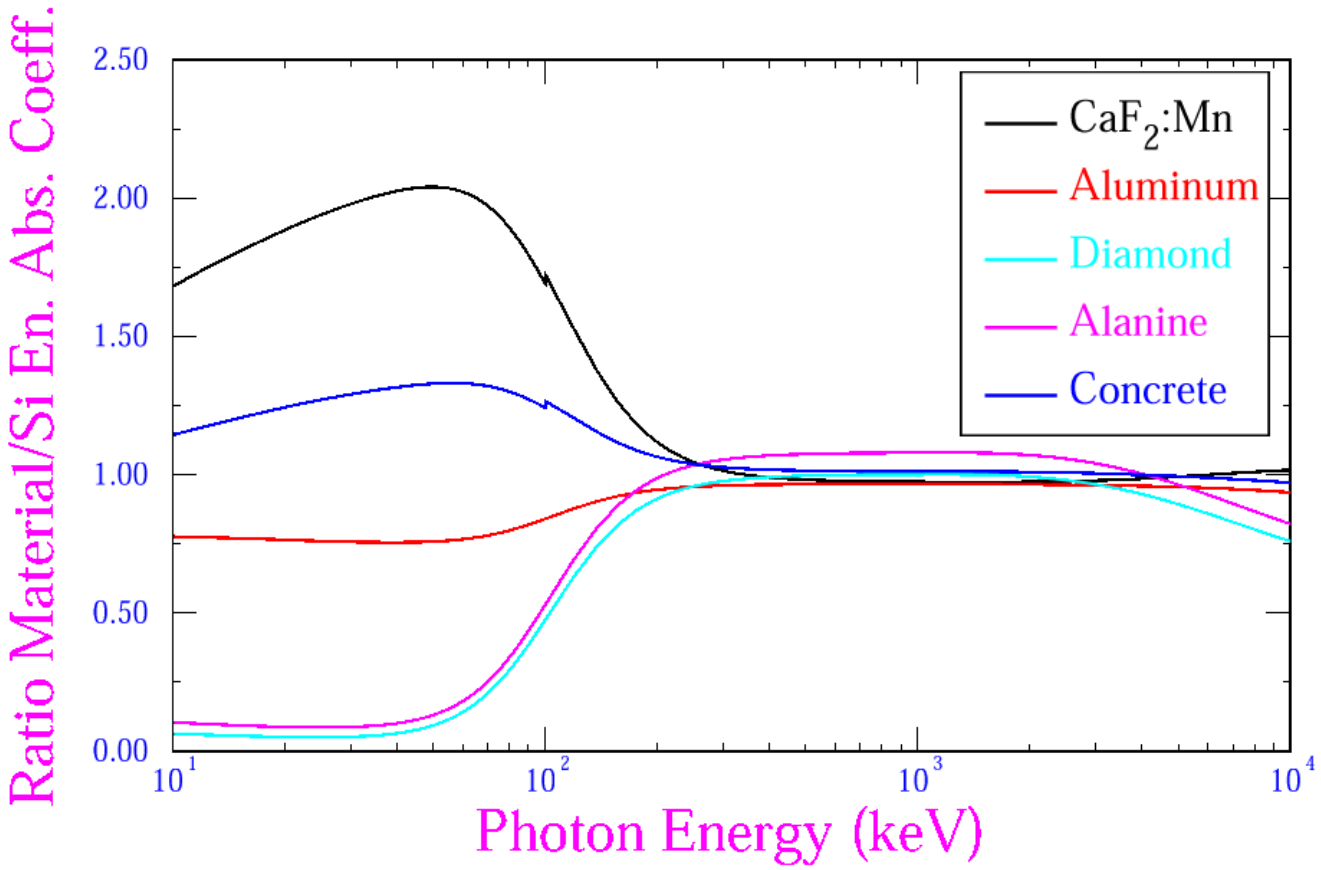
SPR-III Central Cavity Characterization

- Neutron Total Fluence
  - Ni activity
- Neutron Spectrum
- Gamma Dose
  - Si calorimeter
- Gamma Spectrum
- Time Profile
  - Diamond PCD
- Uncertainty Quantification

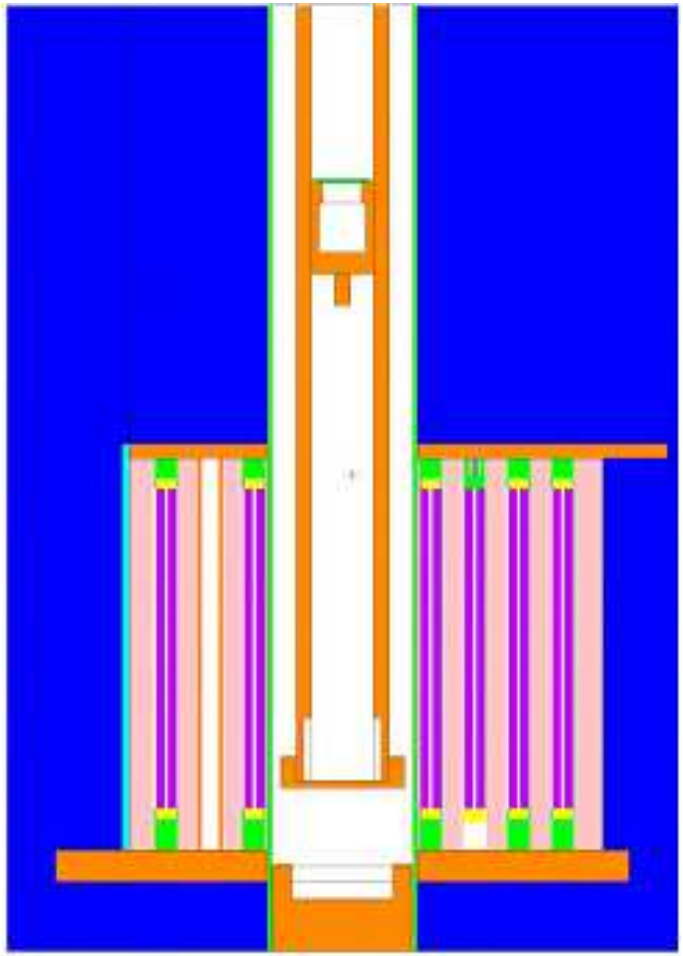


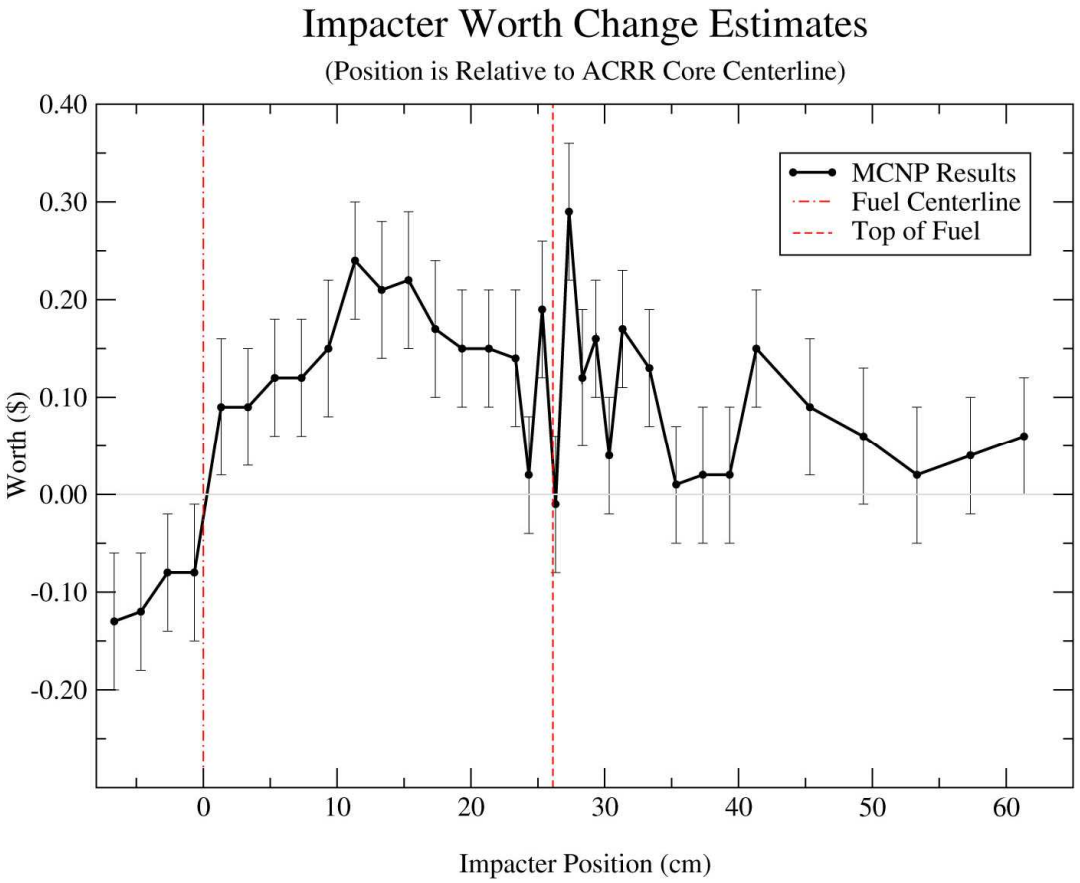
ESR Read-out of Alanine

Photon kerma

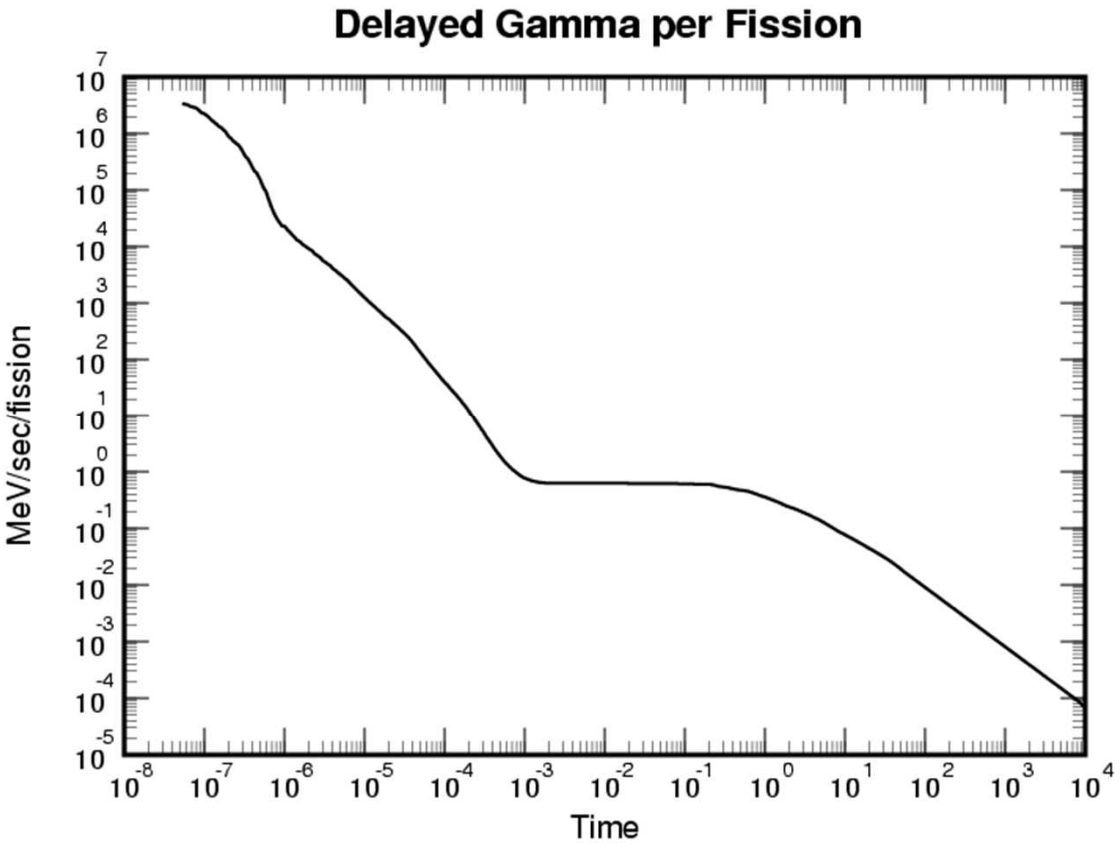


Predictions of Worth During Active Experiments

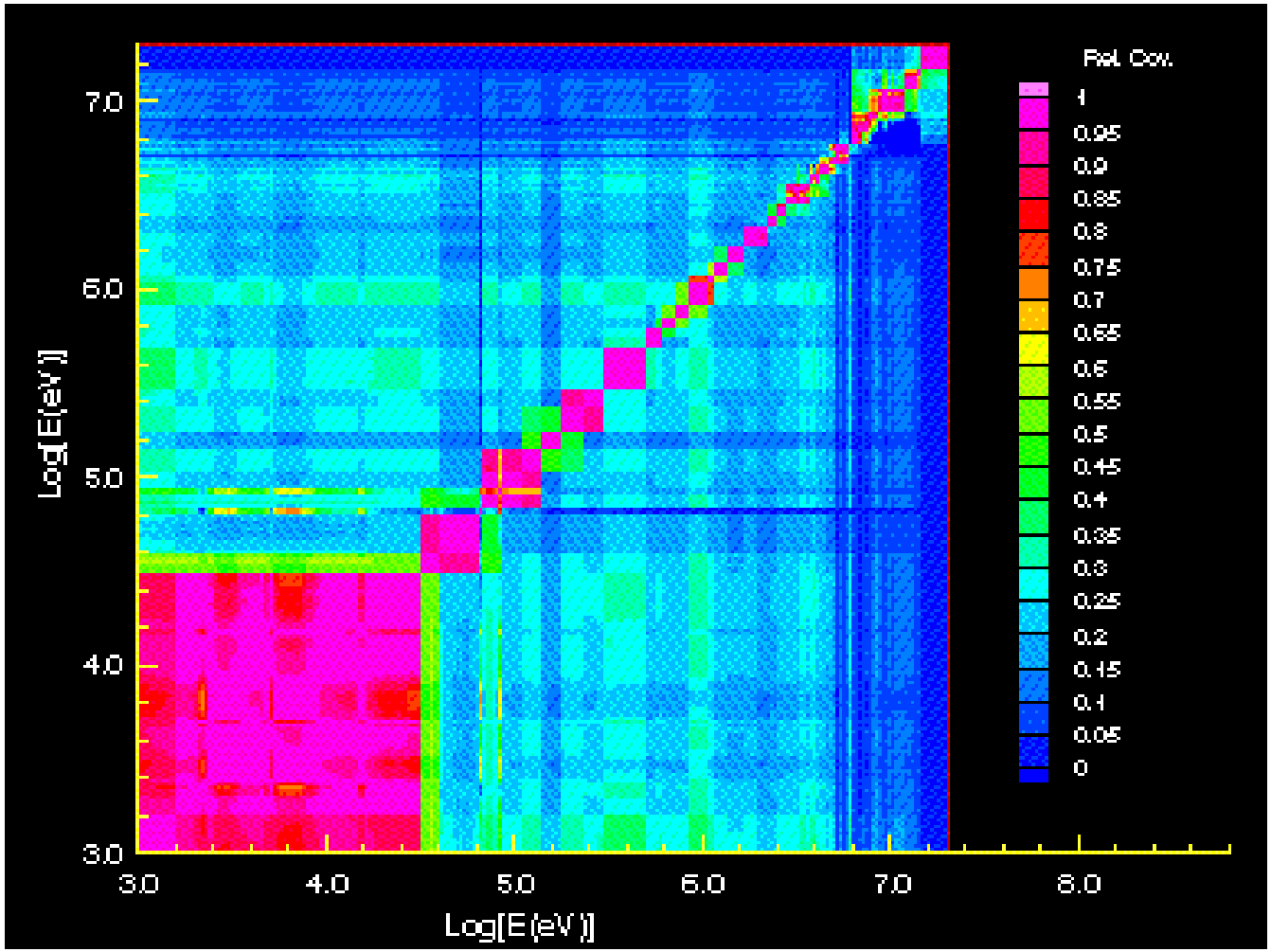




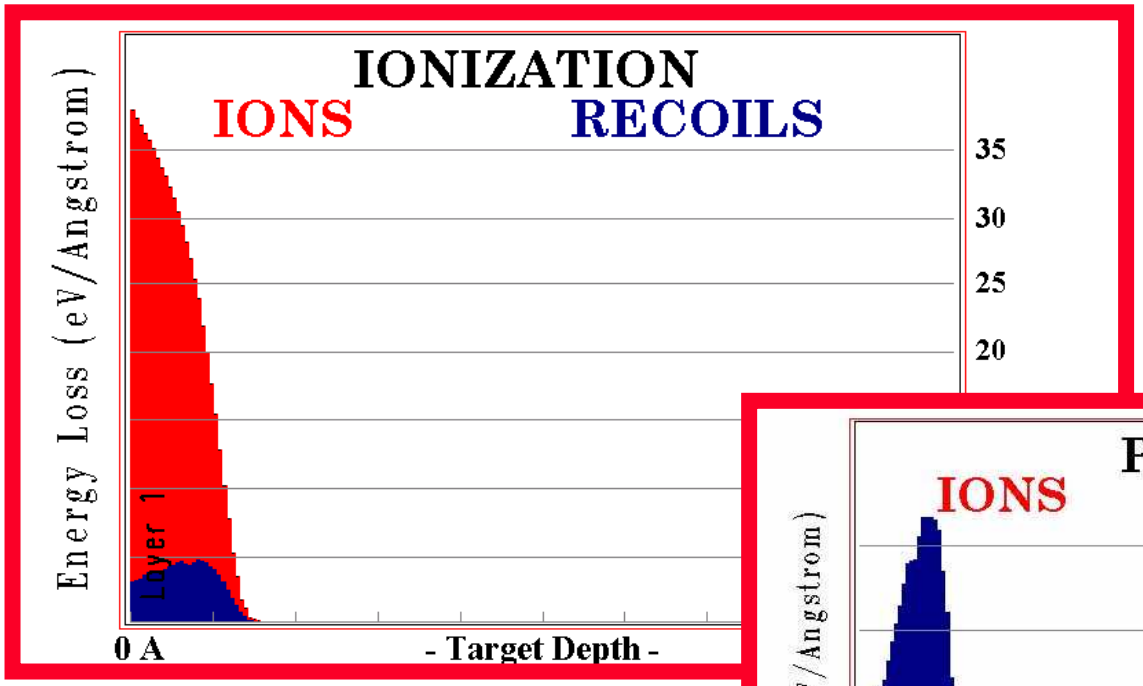
Time-dependence of Delayed Fission Gammas



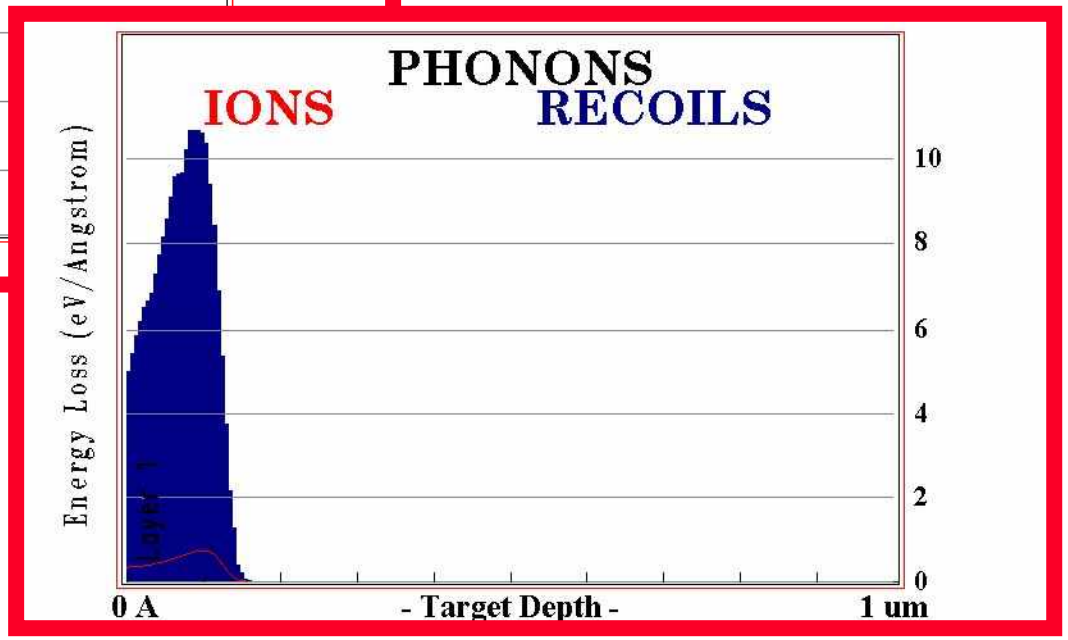
1-MeV(Si) Covariance



Diamond Recoil Damage

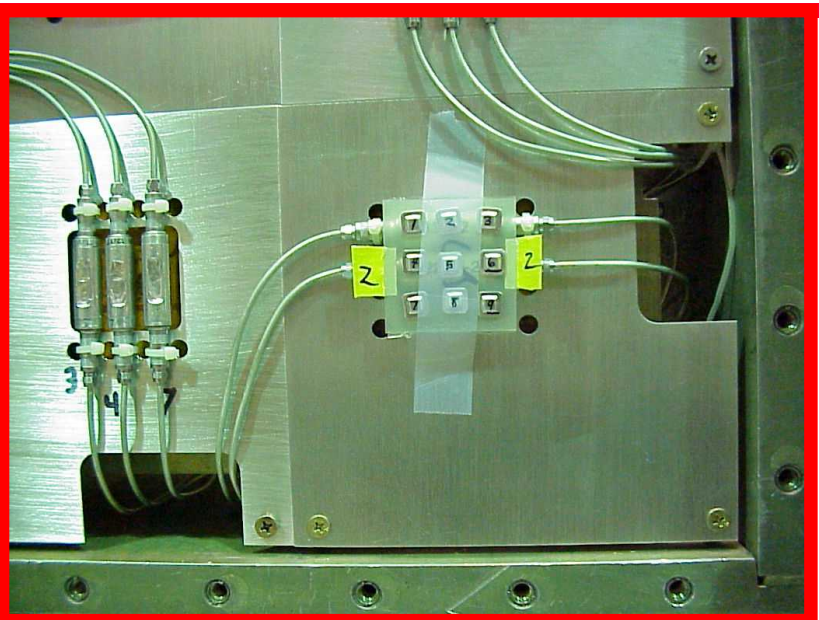


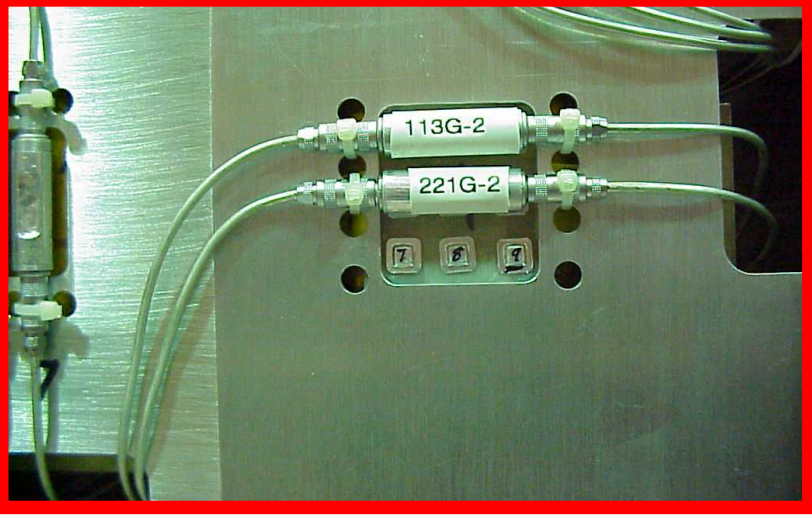
Ionization generation is dominated by initial recoil ion



Phonons generation is dominated by secondary recoils

PCD Calibration at Hermes-III





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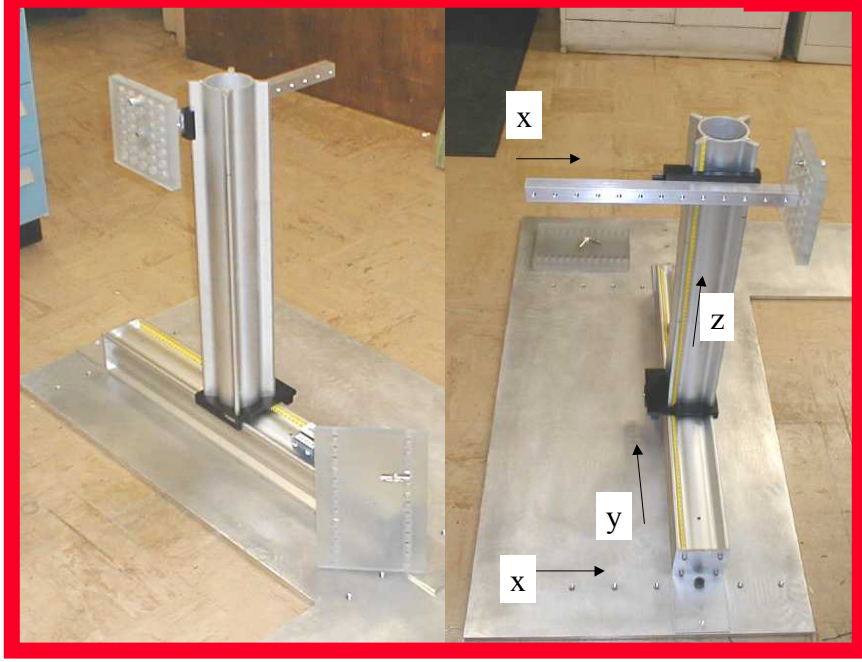
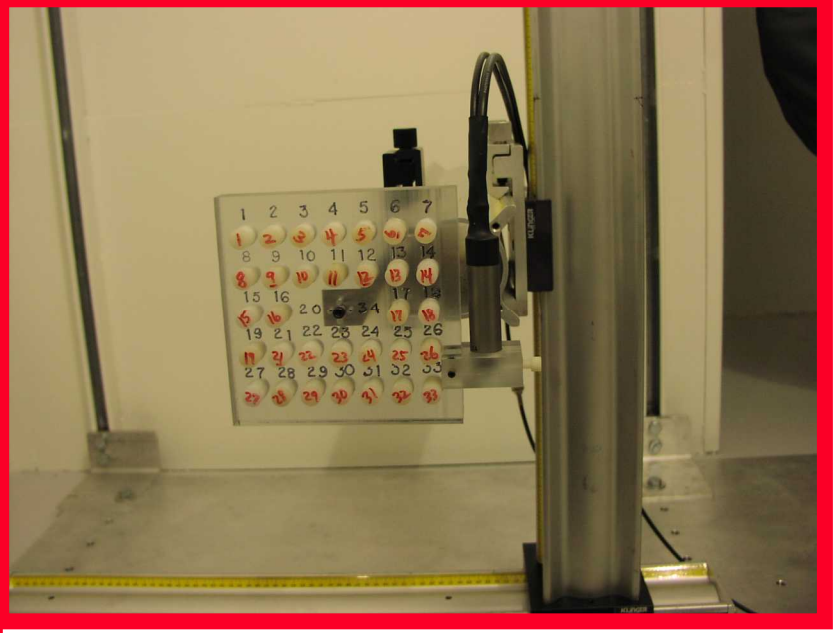
GIF PCD Calibration/Stability Test Fixture

10 – 100 rad(Si)/sec – as seen here

Up to 900 rad(Si)/sec – in design





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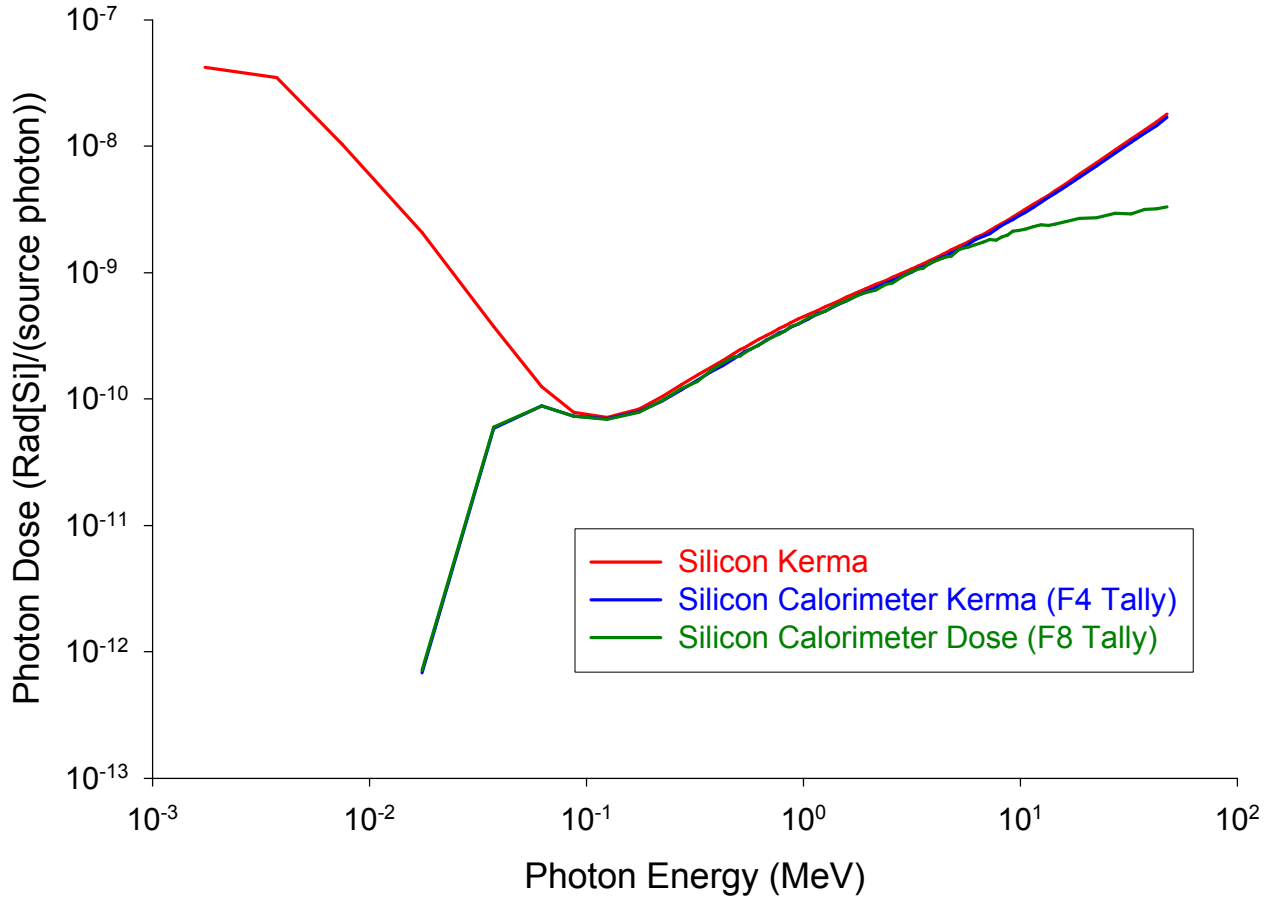
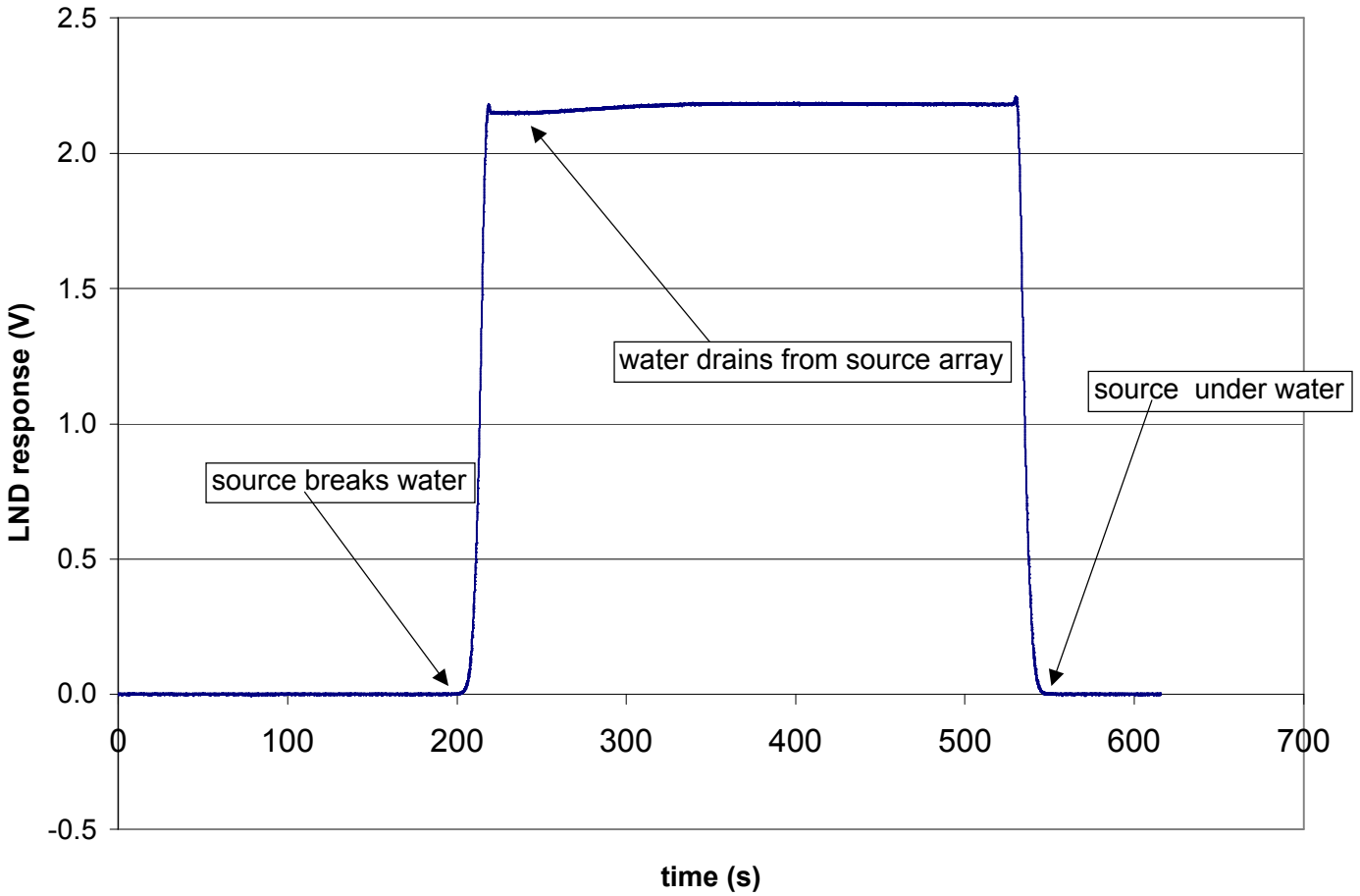
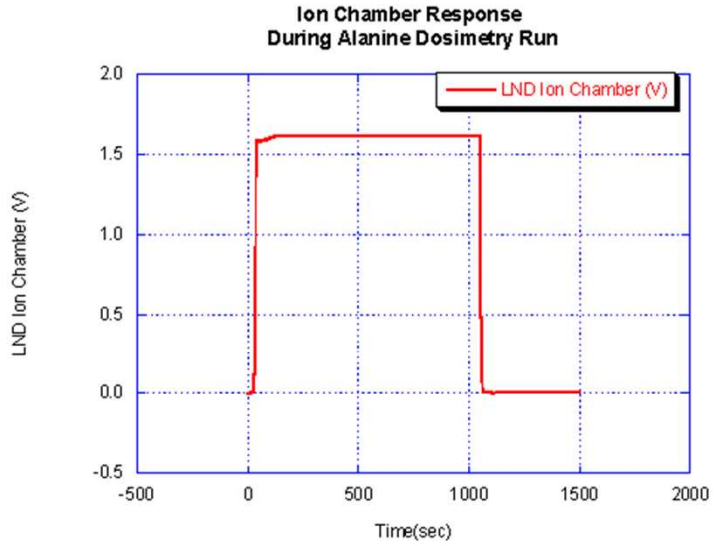
Si Calorimeter Kerma

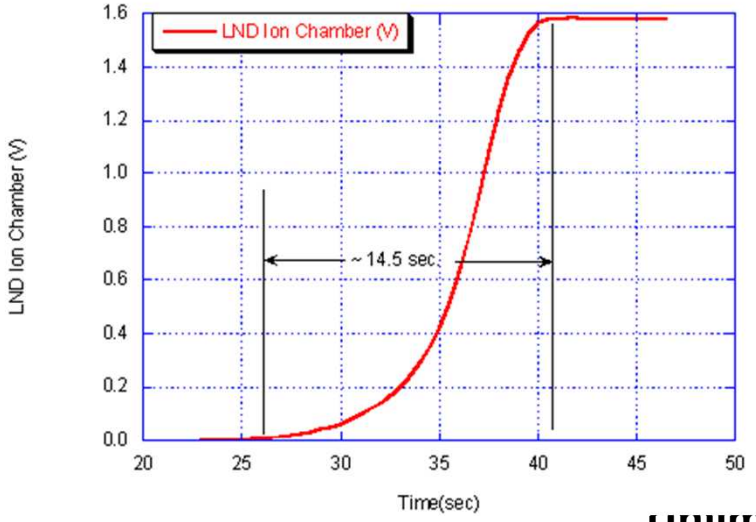


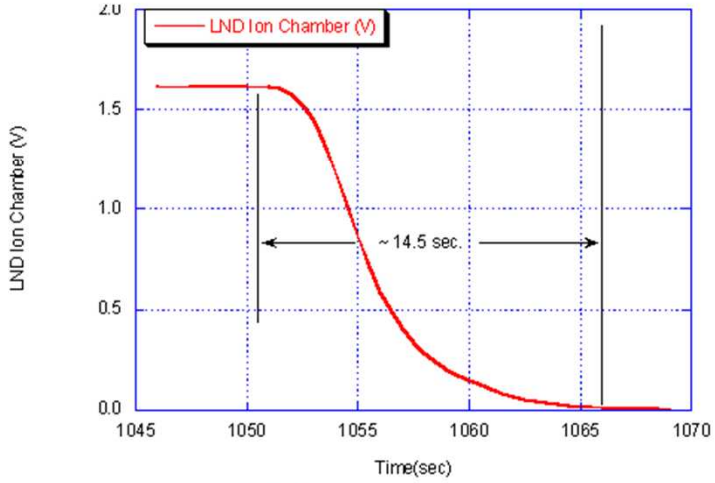
PCD in ^{60}Co GIF



Compensating ^{60}Co Source Position

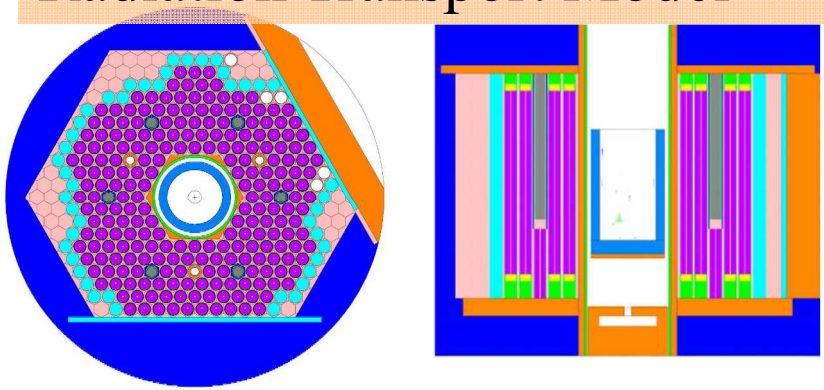






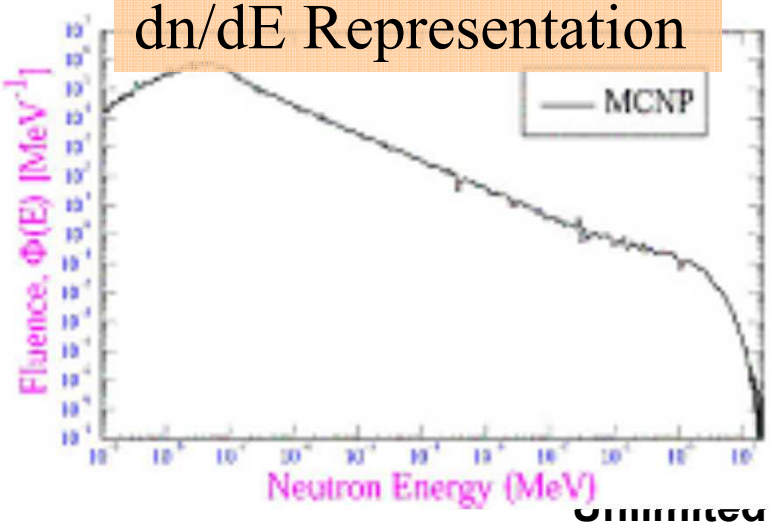
Dosimetry Approach: ACRR Spectrum

Radiation Transport Model

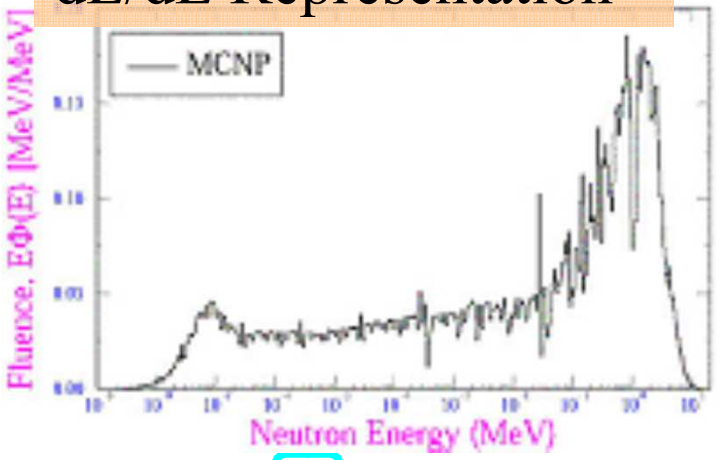


- **Calculate *a priori* values**
  - **<1% statistical unc.**
- **Least squares spectrum adjustment**
- **Analysis of χ^2**

dn/dE Representation



dE/dE Representation



Carbon Kerma