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Radiation Characterization Summary: ACRR Central Cavity Free-Field Environment with the 32-Inch Pedestal at the Core Centerline (ACRR-FF-CC-32-cl)

Edward J. Parma, Gerald E. Naranjo, Richard M. Vega, Lance L. Lippert, David W. Vehar, and Patrick J. Griffin

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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David W. Vehar, and Patrick J. Griffin
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Abstract

This document presents the facility-recommended characterization of the neutron, prompt gamma-ray, and delayed gamma-ray radiation fields in the Annular Core Research Reactor (ACRR) for the central cavity free-field environment with the 32-inch pedestal at the core centerline. The designation for this environment is ACRR-FF-CC-32-cl. The neutron, prompt gamma-ray, and delayed gamma-ray energy spectra, uncertainties, and covariance matrices are presented as well as radial and axial neutron and gamma-ray fluence profiles within the experiment area of the cavity. Recommended constants are given to facilitate the conversion of various dosimetry readings into radiation metrics desired by experimenters. Representative pulse operations are presented with conversion examples.

Acknowledgements

The authors wish to thank the Annular Core Research Reactor staff and the Radiation Metrology Laboratory staff for their support of this work. Also thanks to David Ames for his assistance in running MCNP on the Sandia parallel machines.

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Nomenclature / Acronyms

ASTM	American Society for Testing and Materials
ACRR	Annular Core Research Reactor
Al	aluminum
B	boron
B_4C	boron carbide
Bq	Becquerel (disintegrations/second)
C/E	calculated to experiment ratio
Cd	cadmium
dc	delayed critical
E_{th}	threshold energy
eV	electron volt
FP	Frenkel Pair
FREC-II	Fueled Ring External Cavity – version 2
FWHM	full-width at half-maximum
Gy	Gray – unit of absorbed dose equal to 100 rad
keff	k-effective multiplying constant
keV	kilo-electron volt
krad	kilorad – unit of absorbed dose equal to 1000 rad
lbs	pounds
LB36	36-inch-long lead-boron bucket
LB44	44-inch-long lead-boron bucket
LSL-M2	Least-Squares Logarithmic Adjustment code
mb	millibarns
MCNP	Monte Carlo N-Particle
MeV	mega-electron volt
MJ	megajoule
ms	milliseconds
MW	megawatts
n/cm^2	units of fluence (neutrons per cm^2)
NuGET	Neutron-Gamma Environment Transport code
Pb	lead
PCD	photo-conducting detector
PKA	primary knock-on atom
PLG	polyethylene-lead-graphite
rad	unit of absorbed dose equal to 100 erg/g in a specified material
SNL	Sandia National Laboratories
TA-V	Technical Area V
TC	thermocouple
TLD	thermoluminescent dosimeter
TRIGA	Training, Research, Isotopes, General Atomics
UO_2-BeO	uranium dioxide – beryllium oxide
UZrH	uranium zirconium hydride

1. Introduction

Characterization of the neutron and gamma-ray environments in the Annular Core Research Reactor (ACRR) central cavity and the Fueled Ring External Cavity (FREC-II) is important in order to maintain a high degree of fidelity in performing qualification and other testing at the ACRR. Characterization includes both modeling and experimental efforts. Building accurate neutronic models of the ACRR and "bucket" environments that can be used by experimenters is important in planning and designing experiments as well as in assessing experimental results. Experimental observations, including passive and active dosimetry, are important in order to determine the accuracy of the models, the energy dependent neutron fluence, the conversion constants for radiation metrics, the axial and radial neutron and gamma-ray fluence profiles, and the time-dependent responses for different pulse sizes.

There are several existing neutron and gamma-ray spectrum modifying "buckets" that can be used in the ACRR central cavity. Since the ACRR neutron energy spectrum in the central cavity has a large epithermal component, buckets with a moderating material, like polyethylene, can be used to thermalize the neutron spectrum. Thermal neutron absorbing materials, like boron carbide, can be used to remove the thermal neutron component of the spectrum. Buckets with lead can be used to attenuate some of the prompt and delayed gamma rays in the cavity. Typically, some combination of materials is used to create the desired neutron and gamma-ray environment desired by the experimenter.

This document presents the facility-recommended characterization of the radiation fields in the ACRR central cavity free-field environment with the 32-inch pedestal at the core centerline. The designation for this environment is ACRR-FF-CC-32-cl. The central cavity of the ACRR has a 9-inch-diameter. The free-field environment is the radiation environment within this central cavity without the presence of any spectrum modifying bucket.

The neutron, prompt gamma-ray, and delayed gamma-ray energy spectra, uncertainties, and covariance matrices are presented at the radial centerline of the central cavity at the axial fuel centerline at the peak neutron fluence location. In addition, radial and axial neutron and gamma-ray fluence profiles are given within the available experiment area inside of the central cavity. Recommended constants are given that facilitate the conversion of various dosimetry readings into radiation metrics desired by experimenters. Temporal profiles for representative pulse operations are presented with conversion examples for the radiation metrics.

The neutronics model for the ACRR used in the free-field characterization was developed for the Monte Carlo N-Particle Transport Code (MCNP, 2003). The original ACRR MCNP model was assembled by Wesley Fan and later modified by Phil Cooper and Ed Parma. Russell DePriest modified the model in 2006 to include a macrobody geometry description of the reactor core instead of the standard surface description (DePriest, 2006). The macrobody description, with the free-field environment and the 32-inch pedestal, is included in Appendix A. Other models, including the ACRR with the FREC-II coupled, are available. Details of the ACRR model and calculations are described later in this document. A 640-group and 89-group neutron energy spectrum and a 48-group gamma-ray energy spectrum were calculated using MCNP5 Version 1.6 and the ENDF/B-VII cross sections for the ACRR model with a scoring sphere at the radial centerline of the central cavity and at the axial centerline of the core. The calculated neutron spectrum can then be used with activation foil measurements and dosimetry cross sections, as the trial function in the unfolding codes SAND-IV (Griffin, 1994a, McElroy, 1967), LSL-M2 (Stallmann, 1985), or other code.

For this work a total of 21 different foil types, resulting in 35 different reactions, were irradiated at the ACRR-FF-CC-32-cl location. The LSL-M2 code and the IRDFF, version 1.02 dosimetry cross sections (IRDFF, 2014; Capote, 2012; Zsolnay, 2012), were used in the unfolding analysis.

2. Environment Description

2.1 ACRR Description

The ACRR is a pulse and steady-state, pool-type research reactor that maintains a large, dry irradiation cavity at the center of its core. The ACRR is typically used to perform irradiation testing where a high neutron fluence is required for a short period of time. Historically, the ACRR has been used for a wide variety of experiment campaigns including weapons effects testing, nuclear fuels testing, nuclear pumped laser experiments, space nuclear thermal propulsion testing, and medical isotopes production. The ACRR is currently fully operational. The ACRR's main attributes include a large, dry central irradiation cavity, epithermal neutron fluence, and large pulsing capabilities.

The ACRR is located in Technical Area V (TA-V) at Sandia National Laboratories in Albuquerque, New Mexico. The reactor, in its current configuration, was assembled in 1978 to accommodate large experiments at the center of its core and have large pulsing capabilities. The fuel elements for the ACRR are similar in size and shape to TRIGA fuel. However, the fuel is unique in that the form of the fuel is uranium dioxide/beryllium oxide (UO_2-BeO) that was specially designed to have a large heat capacity and, thus, larger pulsing capabilities.

Figure 1 shows the ACRR looking into the pool during a 2 MW steady-state power operation. The ACRR core is shown on the left in the figure. The 9-inch-diameter dry cavity extends from above the pool through the center of the core. The reactor facility also accommodates the fueled ring external cavity-II (FREC-II), shown on the right in the figure, which maintains a larger dry cavity (20-inch diameter) and uses uranium/zirconium-hydride (U-ZrH) TRIGA fuel as a subcritical multiplier. FREC-II provides the user with a larger experimental volume and the fuel arrangement limits the neutron fluence gradient across the test volume.

The ACRR tank and high bay are shown in Figure 2 at floor level. The shield plug, shown on the left in the figure, is a borated polyethylene and lead cylinder that is inserted into the central cavity after a bucket and/or experiment package is loaded. The shield plug is about five feet in length and sits on a lip inside the central cavity that is located about 10 feet below the pool surface. The dry central cavity, shown in Figure 3, extends from above the pool and goes directly through and below the core region. Another view of the ACRR and FREC-II is shown in Figure 4, with the reactor shut down and the FREC-II (on the left) tilted back in its "decoupled" configuration. Shown on the right in Figure 4 is the radiography tube.

The ACRR maintains an epithermal neutron fluence spectrum in the core and central cavity. This allows for the neutron energy fluence spectrum to be tailored to the desired specifications of an experiment. Moderators can be used within the cavity to thermalize the neutron spectrum. Boron and lead can be used to increase the fast neutron fluence ratio and decrease the gamma-ray fluence, respectively. For an unmoderated condition, the neutron fluence at the center of the central cavity, at the core axial centerline, is ~2.0E13 n/cm^2 per MJ of reactor energy. About 46% of the neutron fluence is above 100 keV and 58% above 10 keV. The 1-MeV damage-equivalent silicon fluence is ~7.6E12 n/cm^2 per MJ of reactor energy. The prompt gamma-ray dose at the same position is ~7.9E3 rad(Si) per MJ. The delayed gamma-ray dose is ~3.4E3 rad(Si) per MJ.

- 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

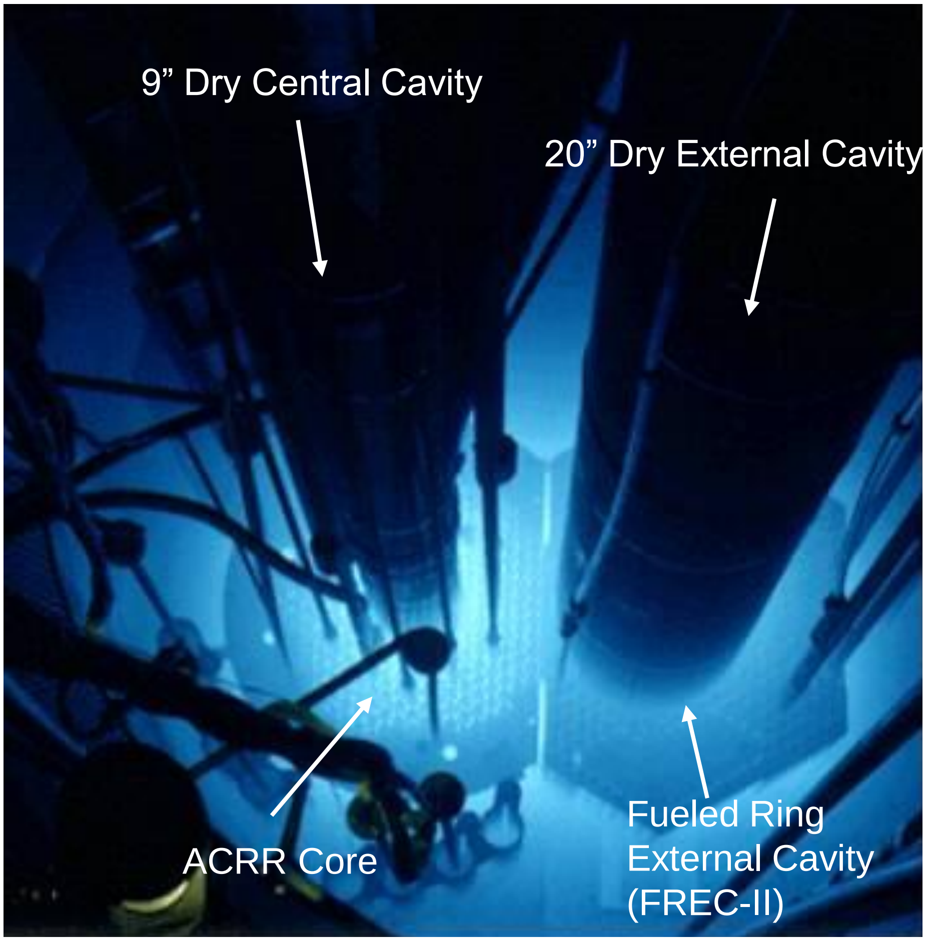


Figure 1. The ACRR and FREC-II Operating at 2-MW Steady-State Power.

Figure 2. The ACRR Tank and High Bay.

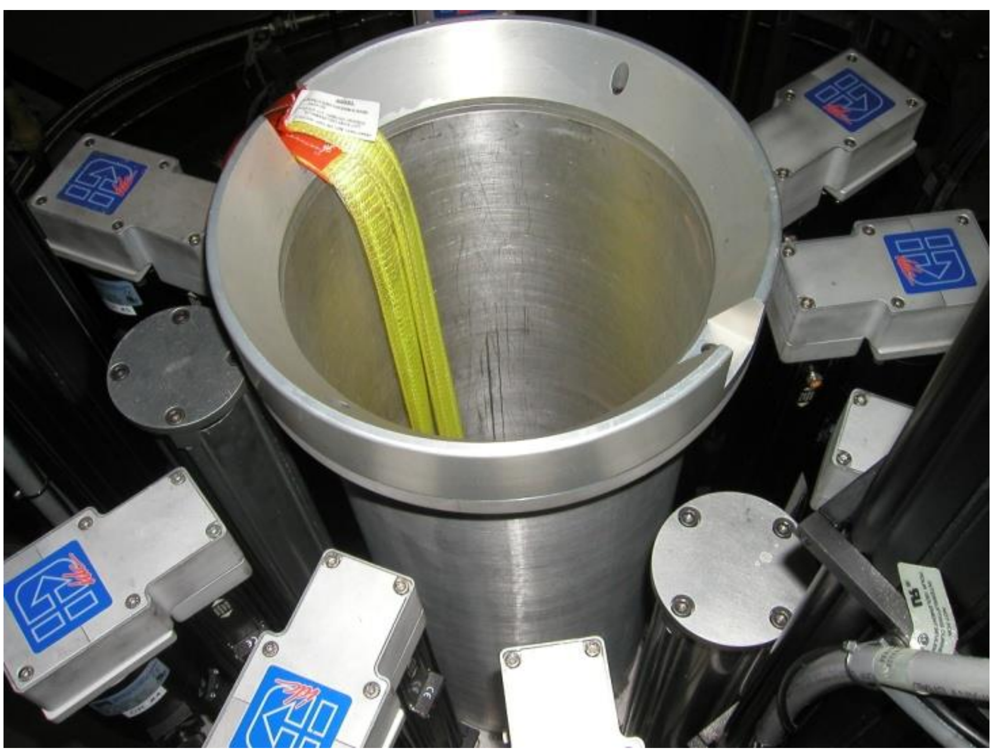


Figure 3. The ACRR Dry Central Cavity and Control Rod Drives.

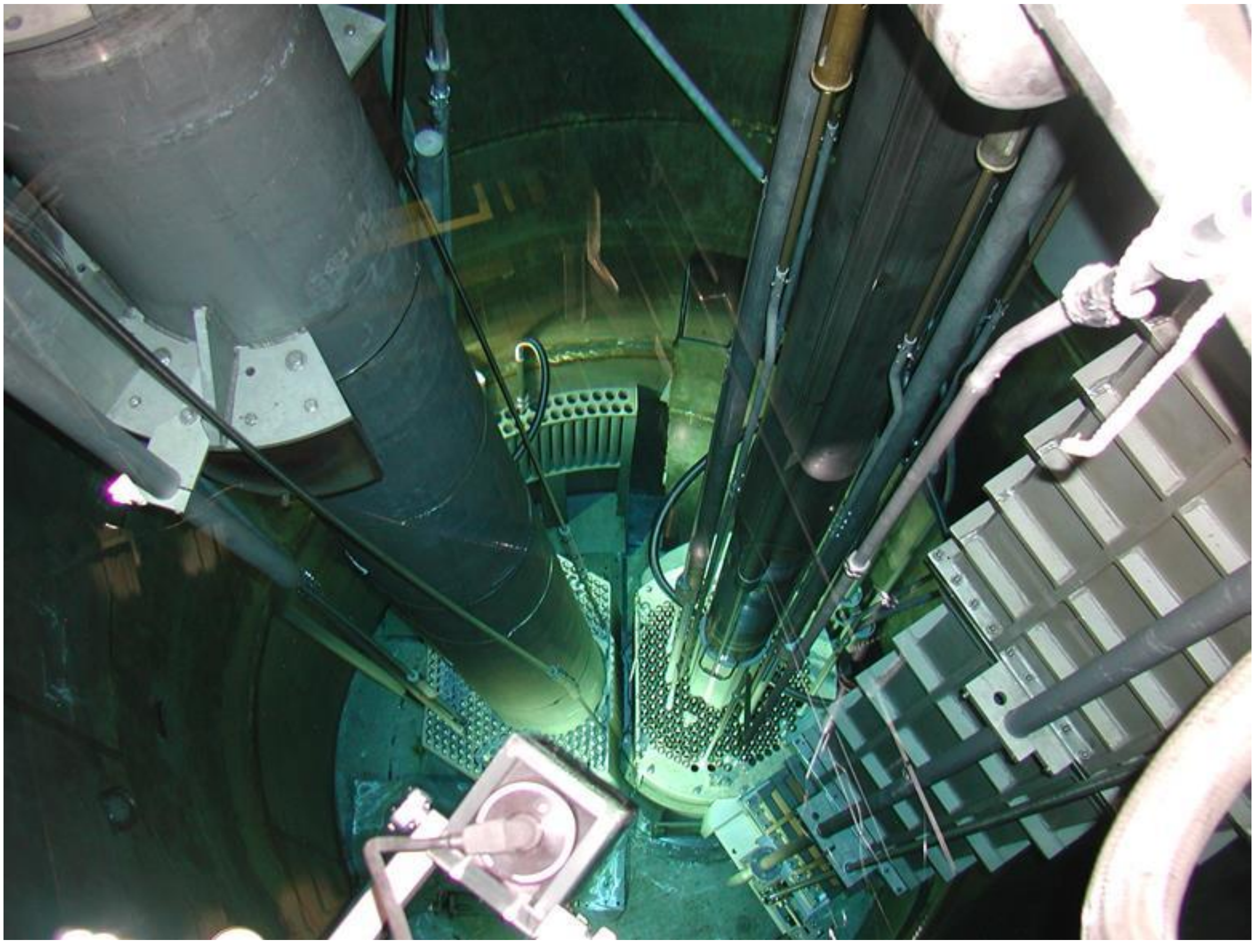


Figure 4. ACRR with FREC-II Decoupled.

The ACRR can operate in a steady-state, transient, or pulse mode. In the steady-state mode, the operating power level is limited to ~4 MW. In the pulse mode, a maximum pulse size of ~250 MJ with a full-width half-maximum (FWHM) of 6 ms can be attained. In the transient mode, the reactor power shape can be tailored to the desired requirements for a total reactor energy deposition of ~300 MJ. The transient mode can be used to increase the reactor power quickly; for example a ramp increase in power level linear with time from low power to high power.

The coupling factor is defined as the amount of fission energy that can be produced in a fissile experiment per gram of fissile fuel and per MJ of reactor power. The coupling factor for an unmoderated cavity is ~18 J/g-MJ, and ~90 J/g-MJ for the moderated condition. These coupling factors allow for fueled experiments to be designed for a wide variety of test conditions for steady-state, transient, and pulse operations.

The ACRR is fueled by a 236-element array of UO_2-BeO fuel elements. The fuel is uranium enriched to 35 weight percent U-235, with 21.5 weight percent UO_2 and 78.5 weight percent BeO. The ACRR fuel elements are stainless steel clad, 1.5 inches in diameter and 21 inches in fuel length. Within the elements are niobium cups that hold the UO_2-BeO fuel pieces.

The ACRR is controlled by two fuel-followed safety rods, three poison (void-followed) transient rods, and six fuel-followed control rods. The control rods (safety and control) make up part of the 236 elements for the normal core configuration.

The ACRR central cavity and FREC-II cavity allow for a high degree of experiment flexibility, along with in-situ and real-time experiment instrumentation and diagnostics. The large size of the cavities allows for the possibility of flow loops and other complex experimental hardware to be fielded within the high-fluence region of the core. Because the ACRR is under-moderated, the neutron spectrum has a large epithermal component within the central cavity. This epithermal spectrum can be modified by the use of thermal absorbers to give a harder spectrum or by the use of moderator materials to give a softer spectrum. Spectrum-modifying cavity inserts or buckets, such as lead-boron and lead-polyethylene, provide the facility with the ability to change the inherent neutron spectrum found in the reactor as well as allowing adjustment of the neutron-to-gamma dose ratio. The normal mode of operation for the ACRR is to have the FREC-II tilted back and decoupled from the ACRR using a nickel plate on the FREC-II side of the core.

The ACRR core is located in an open pool 10 feet (3.0 m) in diameter and 28 feet (8.5 m) deep. The pool is filled with 64,000 liters of deionized water. The core is cooled by natural convection of the pool water. The pool water is cooled by a heat exchanger and cooling tower. For steady-state mode operations, the ACRR operates continuously at up to 4 MW. The pool is cooled using a heat rejection system rated to support steady-state operations up to 5 MW.

2.2 ACRR-FF-CC-32-cl Environment

Free-Field Description

The most prominent feature of the ACRR is the large (9.17 inch inside diameter) dry, central irradiation cavity at the center of the core. While there are several buckets used to alter the spectrum of the ACRR in the central cavity for experimenters, occasionally it is desired to perform an experiment with the epithermal spectrum of the reactor without modification. In this case, all of the metrics presented in the previous section for the unmoderated central cavity remain valid such as the 1-MeV damage-equivalent silicon fluence and the delayed gamma ray dose.

The central irradiation space is formed by hexagonal cutouts in the upper and lower core grid plates. The space allows installation of experiment assemblies at the center of the core where neutron fluence levels are highest. The central cavity is a stainless steel cavity liner with aluminum "corners" to produce its hexagonal shape. A schematic of the central cavity is found below in Figure 5. Figure 5 is also a presentation of the MCNP model of the central cavity. Within the central cavity, the height of experiments can be adjusted through the use of pedestals. Two such pedestals are shown in the MCNP model in Figure 6.

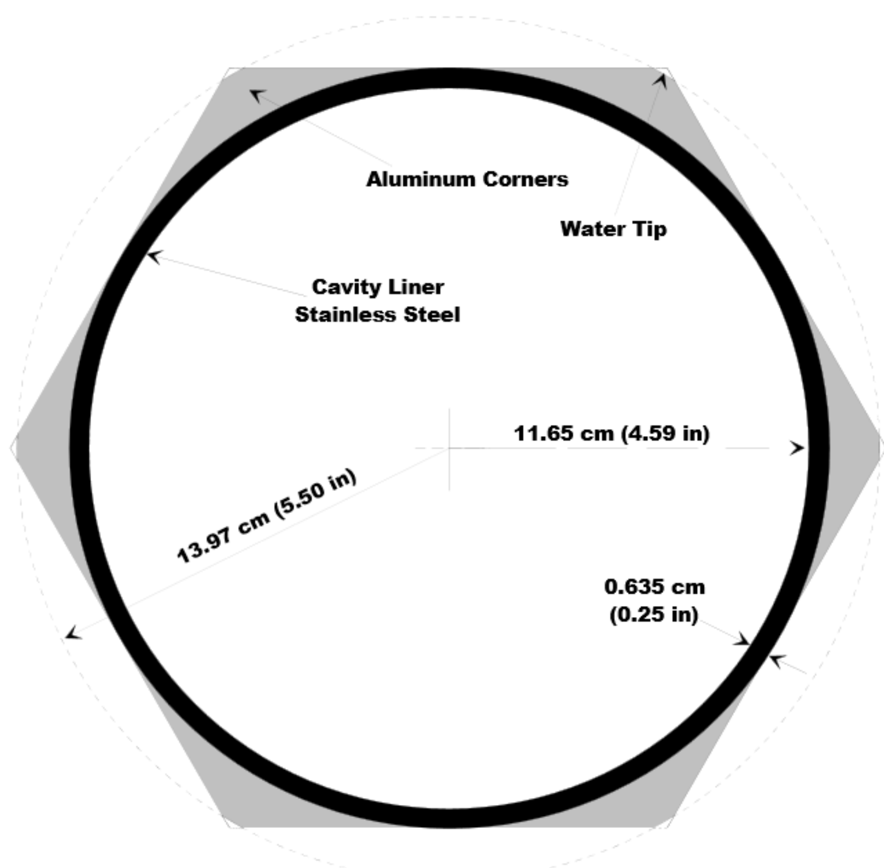


Figure 5. Schematic of the ACRR Central Cavity.

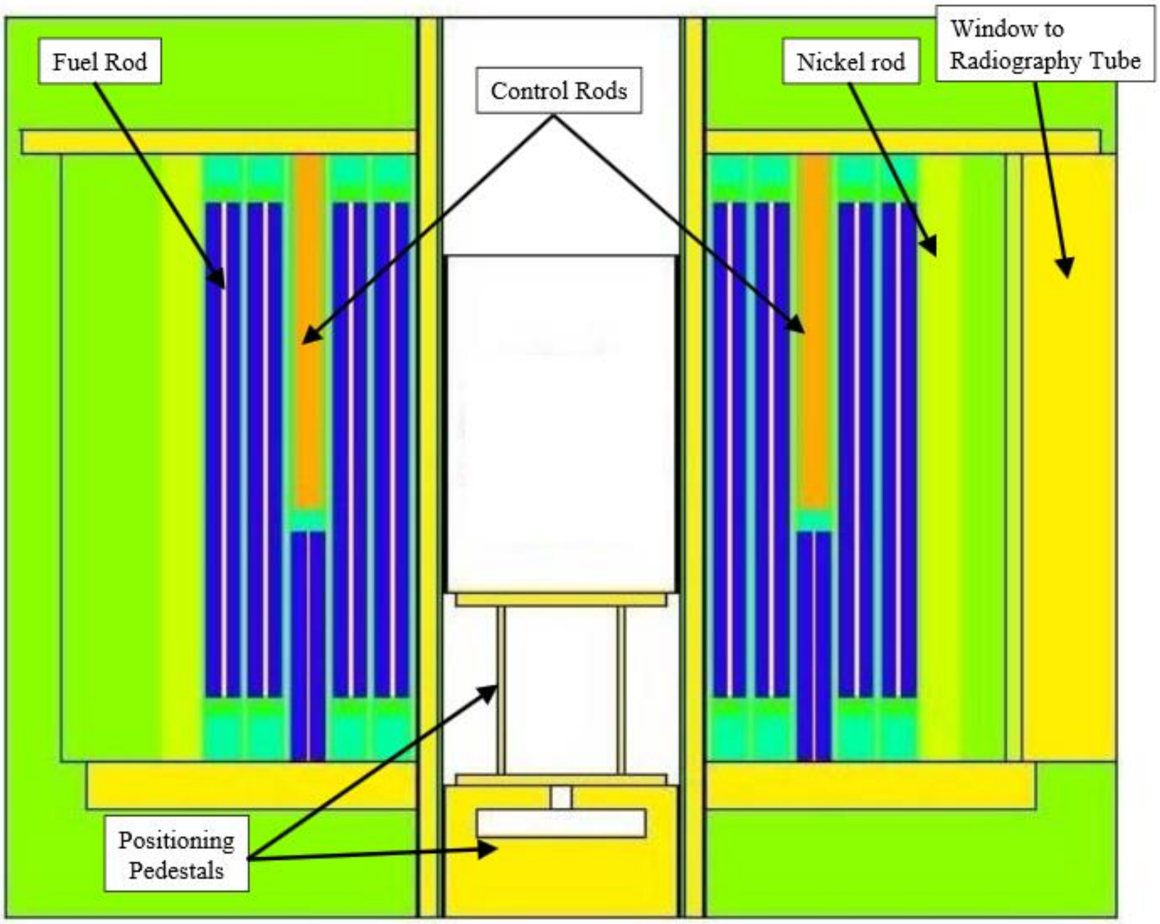


Figure 6. MCNP Model Showing Positioning Pedestals Within the Central Cavity.

The free-field environment does not provide any attenuation of gamma rays that accompany fission. Thus, if the desire is to attempt to isolate the effect of neutron irradiation in an experiment, one of the spectrum altering bucket environments that contain lead should be used. A more detailed drawing of the central cavity can be seen in Figure 7, and Figure 8 shows a picture of the one of the spectrum altering buckets being loaded into the central cavity via steel cables and the penthouse crane (left). Also shown is the shield plug being loaded into the central cavity after the bucket has been installed (right).

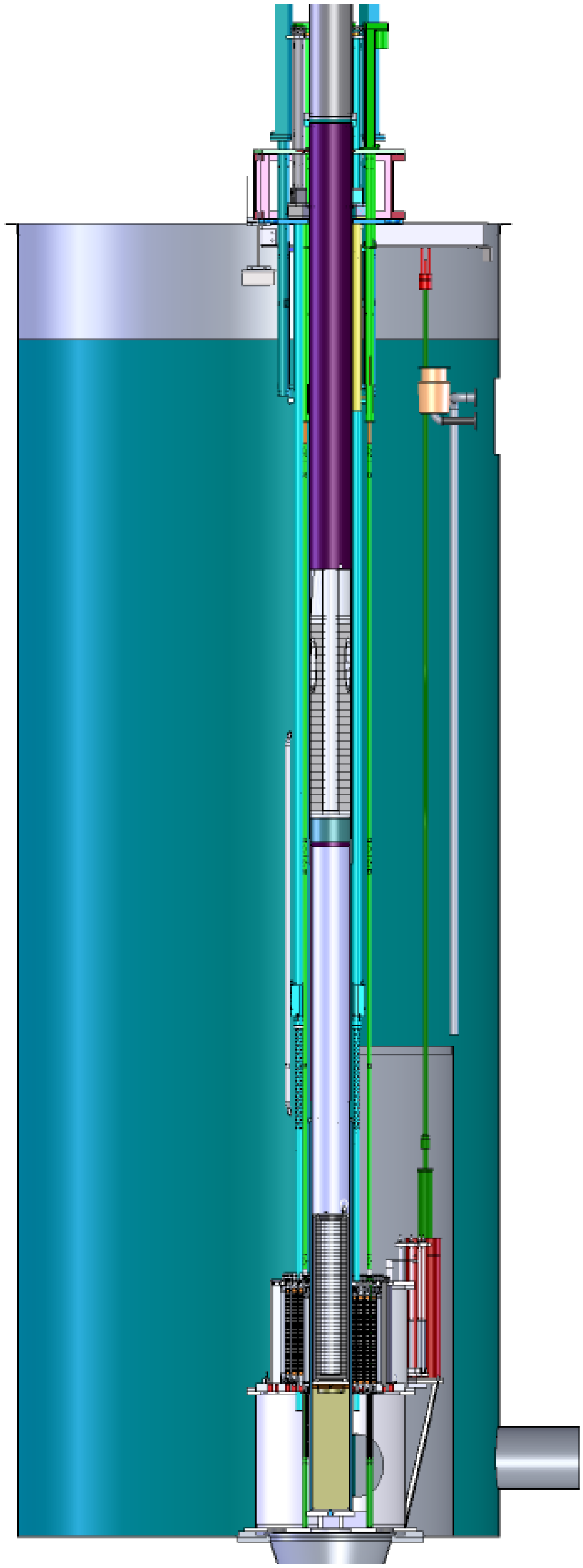


Figure 7. Detailed Engineering Drawing of the ACRR Pool and Central Cavity.

Figure 8. Installing a Spectrum Altering Bucket (left) and the Shield Plug (right) Into the ACRR Central Cavity.

MCNP Model

The MCNP model of the ACRR central cavity with the 32-inch pedestal is shown in Figure 9. The input model is included in Appendix A of this document. The model does not include the FREC-II. The reason for this is that, although the FREC-II is located within the core tank, the normal operating mode is to have it tilted back and decoupled from the core using a nickel plate. In this position the FREC-II has only a small effect on the neutronic behavior of the ACRR. The MCNP model of the ACRR includes all of the fuel elements and the control, safety, and transient rods that make up the core. The control, safety, and transient rods can be adjusted in the vertical direction in the model to whatever position is desired. Typically, the model is run with the safety and transient rods in the full-out position and the control rods in the full-out, full-in, or delayed critical (dc) position. The calculated dc position can be found for the model by iterating on the control rod position until k_{eff} is equal to one. The model is typically run using room-temperature (300 K) cross sections, $S(\alpha,\beta)$ values, and water density. All cross-section temperatures can be modeled if desired.

Neutron, prompt gamma-ray, and delayed gamma-ray energy spectra and fluence per fission were calculated using a 6-cm diameter tally sphere. For the ACRR-FF-CC-32-cl position, the sphere was positioned at the radial center of the cavity and at the axial centerline of the core. Calculations were performed using the MCNP k-code mode for the neutron and prompt gamma-ray environments, and in the source mode for the delayed gamma-ray environment.

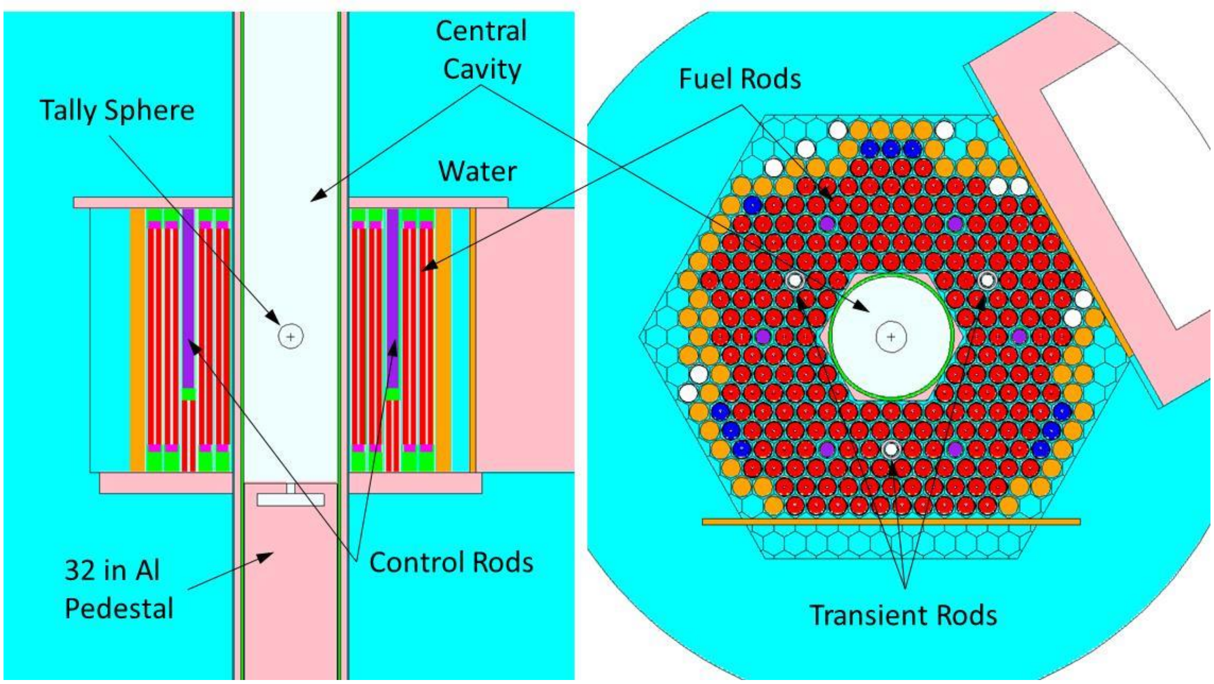


Figure 9. MCNP Model of the ACRR and the Central Cavity With the 32-inch Pedestal.

3. Spectrum Characterization

3.1 Neutron

The neutron environment includes both prompt and delayed neutrons from the ACRR core. The neutron energy spectrum is first calculated using MCNP and then a least-squares spectrum adjustment is performed using passive neutron activation dosimetry measurements to produce a "characterized" neutron spectrum. The process for determining a characterized neutron spectrum is to first generate an *a priori* 640-energy group and an 89-energy group neutron trial spectrum from the MCNP model presented in Section 2 for the 6-cm diameter tally sphere. In order to have reasonable statistics in all of the energy groups, the model was run on a parallel machine for 20 billion source neutrons. The 89-group MCNP result represents the trial function that is then adjusted using a least-squares-based unfolding code. For this work a total of 21 different dosimetry foil types, resulting in 35 different transmutation reactions, were irradiated at the ACRR-FF-CC-32-cl location. The LSL-M2 code (Stallmann, 1985) and the IRDFF, version 1.02 dosimetry cross sections (IRDFF, 2014; Capote, 2012; Zsolnay, 2012), were used in the unfolding analysis to determine the characterized neutron energy spectrum.

<u>MCNP Model Results – 640-Group and 89-Group Neutron Energy Spectra</u>

The neutron energy spectrum was calculated for a 640-energy group and an 89-energy group structure using the MCNP model presented in Section 2 for the 6-cm diameter tally sphere. MCNP5 version 1.60 was used with the ENDF/B-VII cross sections. The MCNP model with the free-field environment is included in Appendix A of this report. Room temperature cross sections were used for the calculations. The model was run in the k-code mode using both neutrons and photons. This allowed for both the neutron energy spectrum and the prompt gamma-ray energy spectrum to be generated in one run. The gamma-ray spectrum used a 48-energy group structure. In order to have reasonable statistics in all of the energy groups, the model was run on a parallel machine for 20 billion source neutrons. The results generated in the tally sphere were in units of neutron fluence per source neutron. These results were then converted to fluence per fission in a spreadsheet. The neutron fluence results were converted from fluence per fission to fluence per MJ of reactor power using 192.4 MeV per fission. This value represents the fission fragment, neutron, prompt gamma-ray, capture gamma-ray and delayed gamma-ray energy deposition in the reactor core and surrounding water, per fission event. These energy deposition values were calculated using MCNP with the exception of the delayed gamma-ray energy, which was assumed to be the total delayed gamma energy of 6.33 MeV per fission as characterized in the ENDF/B-VII nuclear data file. The 89-energy group neutron spectrum result was used as the trial function for the LSL-M2 code.

Figures 10 and 11 show the MCNP generated 640-energy group and 89-energy group neutron fluence on a linear and logarithmic y-axis, respectively. The units on the y-axis are in lethargy fluence or energy fluence, equal to $E d\phi/dE$ (MeV/MeV-cm^2-MJ). With the energy fluence represented linearly on the y-axis and the neutron energy on the x-axis represented logarithmically, the area under the curve represents the total neutron fluence. This representation allows for the best visual depiction of the fluence over the complete neutron energy range.

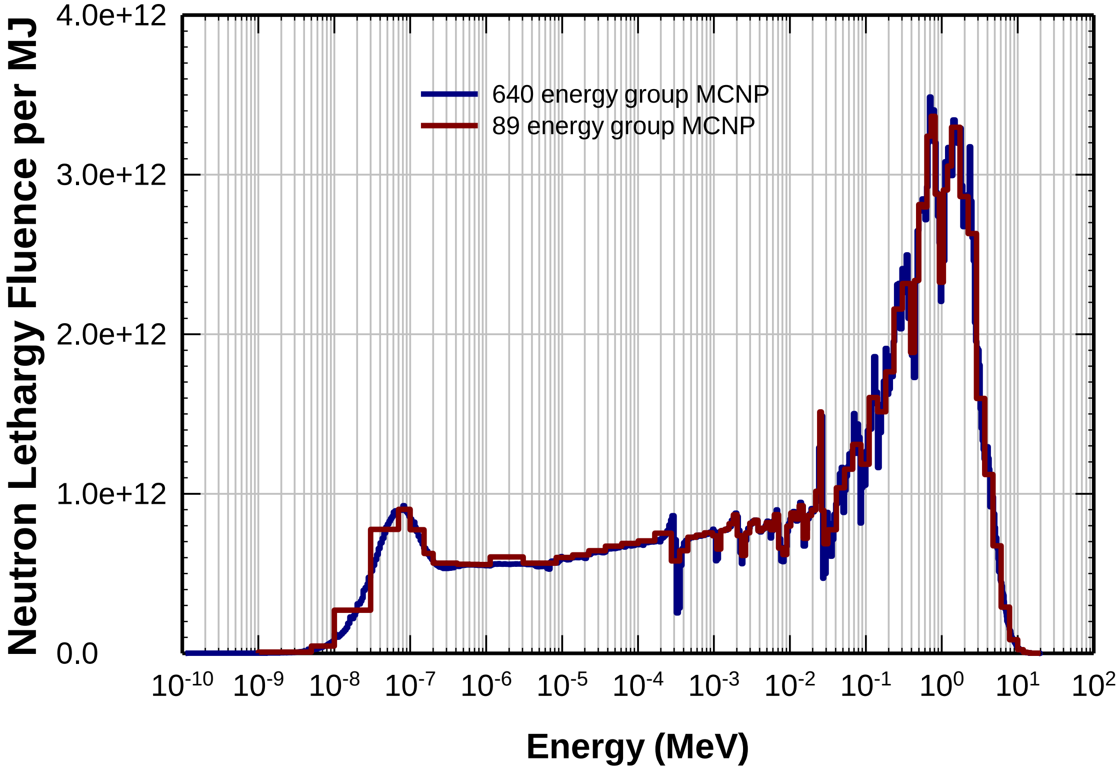


Figure 10. MCNP 640-Group and 89-Group Neutron Lethargy Fluence Energy Spectra (linear–log).

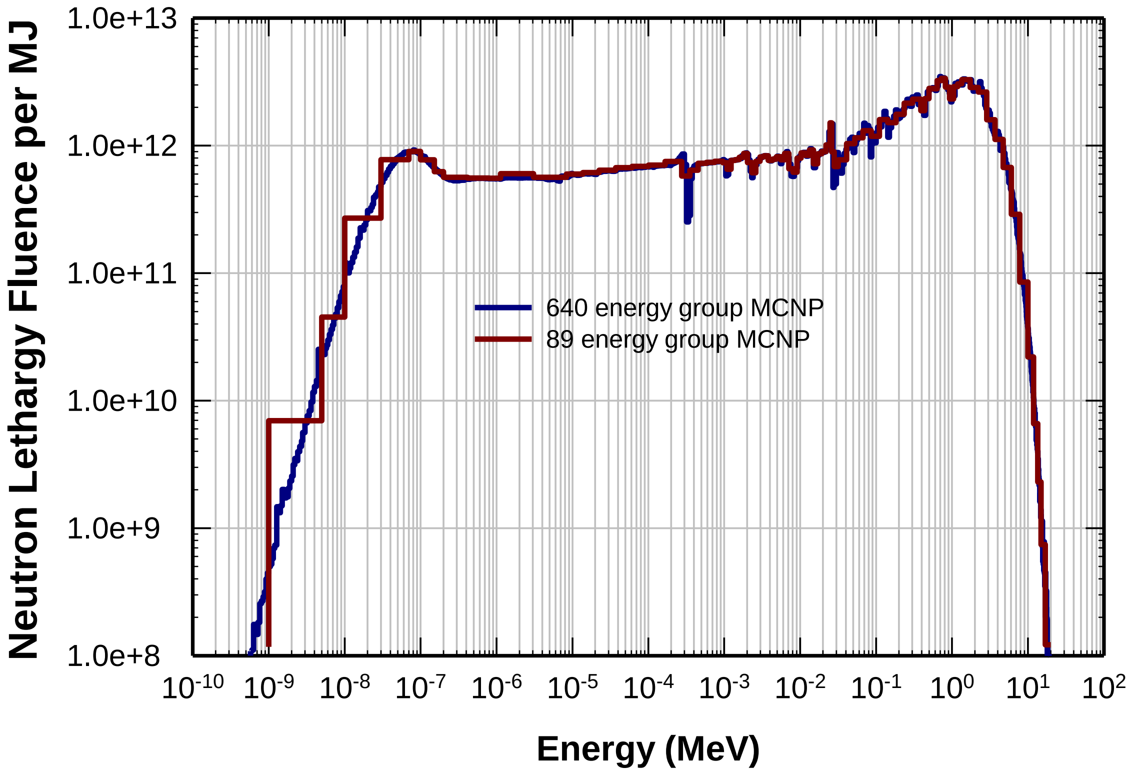


Figure 11. MCNP 640-Group and 89-Group Neutron Lethargy Fluence Energy Spectra (log–log).

The energy fluence is found to peak near 1 MeV. The thermal peak occurs at ~0.07 eV (7.0E-8 MeV). The results for the 640-energy group and 89-energy group neutron fluence are in very close agreement, as expected. The 640-energy group calculation shows more structure in the fluence spectrum, which is more notably observed in the energy range of 1E-4 to 1 MeV. This structure is considered to be real and not an artifact of the code or cross-section set. It is caused by resonances in the cross sections, especially from the oxygen elastic scattering cross section. The structure in the energy range below 0.01 eV (1.0E-8 MeV) is not understood. The uncertainty in the MCNP results in this energy range are greater than 10%, and hence cannot be trusted. The calculated standard deviation for each energy bin in the 640-energy group fluence in the energy range from 0.005 eV (5.0E-9 MeV) to 6 MeV is less than 1%. A similar but less resolved structure is also seen in the 89-energy group fluence. The 89-energy group structure is the energy grouping used in the NuGET code (DePriest, 2004).

Dosimetry Foils

The results of the MCNP calculation of the ACRR with the free-field environment represent a good initial representation for the neutron spectrum characterization. However, a considerable uncertainty in the results can exist due to model representation uncertainty (geometry, density, and composition) and uncertainty in the transport cross sections. An improved spectrum can be obtained by combining this initial trial spectrum with measured integral values that correspond to the reactions rates from high-fidelity passive dosimetry reactions. The resulting least-squares adjusted neutron fluence spectrum includes an energy-dependent uncertainty. The spectrum can then be considered "characterized," in that it quantifies the "true" neutron-fluence energy spectrum with a stated accuracy, including energy dependent uncertainties and a covariance matrix. If the least-squares spectrum is found to have inconsistent inputs in comparing the MCNP *a priori* trial spectrum and the measured dosimetry results, as determined by a measure of the chi-squared per degree of freedom (χ^2/dof) in the spectrum adjustment, the dosimetry measurements would be reexamined and/or the MCNP model for the ACRR would be reexamined and modified or modeled with greater fidelity. In addition to the adjusted neutron spectrum, uncertainty and covariance results are found from the least-squares analysis using the LSL-M2 code. The characterized neutron spectrum can be used, with the corresponding uncertainty values and the correlation matrix, to support the evaluation of various damage and dose metrics relevant to users of the ACRR free-field environment. The characterized spectrum can be used directly by the NuGET code or as an isotropic shell source in MCNP to calculate the radiation internal to a complex test object. For this work, the LSL-M2 code was used to generate an 89-energy group neutron spectrum that is used in the NuGET code. The SAND-IV code can also be used to determine an adjusted 640-energy group spectrum. This may be performed in the future for comparison purposes, but is beyond the scope of this work.

The selection of passive dosimetry foils and activation reactions has been studied and evaluated over many years. A summary of the work can be found in ASTM E720, Griffin (2011a), Griffin (2011b) and references therein. No complete and perfect set of activation reactions exists that allows the neutron fluence energy spectrum to be calculated by dosimetry alone. However, there are enough reactions to cover the relevant energy range with high-fidelity dosimetry cross sections to allow for adjusted neutron fluence results to be generated with a quantified accuracy. The passive dosimetry foils and the associated neutron activation reactions used to perform the neutron fluence characterization for the free-field environment are shown in Table 1.

Table 1. Neutron Activation Dosimetry Used for ACRR-FF-CC-32-cl.

Activation Reaction	Half-Life	Activity (Bq/atom-isotope)	Counting Uncertainty (%)
^{58}Ni(n,p)^{58}Co - Reference	70.83 d	9.7808E-18	2.9
^{24}Mg(n,p)^{24}Na	14.957 h *	1.2890E-17	2.3
^{27}Al(n,α)^{24}Na	14.957 h *	6.1585E-18	2.3
^{32}S(n,p)^{32}P Cf-equ	14.284 d	7.0703E+14 n/cm^2	3.6
^{46}Ti(n,p)^{46}Sc	83.788 d	7.8515E-19	2.3
^{47}Ti(n,p)^{47}Sc	3.349 d	3.8055E-17	3.1
^{48}Ti(n,p)^{48}Sc	43.67 h	8.8424E-19	1.4
^{55}Mn(n,2n)^{54}Mn	312.3 d	--	--
^{54}Fe(n,p)^{54}Mn	312.3 d	1.6954E-18	2.2
^{56}Fe(n,p)^{56}Mn	2.579 h *	5.8136E-17	1.8
^{59}Co(n,p)^{59}Fe	44.495 d	1.7965E-19	5.8
^{59}Co(n,2n)^{58}Co	70.83 d	--	--
^{58}Ni(n,2n)^{57}Ni	35.9 h	--	--
^{60}Ni(n,p)^{60}Co	1925.27 d	6.3203E-21	5.3
^{63}Cu(n,α)^{60}Co	1925.27 d	--	--
^{64}Zn(n,p)^{64}Cu	12.701 h *	4.7963E-16	3.1
^{90}Zr(n,2n)^{89}Zr	78.41 h	1.7102E-19	5.1
^{93}Nb(n,2n)^{92m}Nb	10.15 d	2.5526E-19	2.0
^{115}In(n,n')^{115m}In	4.486 h *	--	--
^{23}Na(n,γ)^{24}Na	14.957 h *	1.8587E-15	2.2
^{45}Sc(n,γ)^{46}Sc	83.788 d	7.3161E-16	2.2
^{55}Mn(n, γ)^{56}Mn	2.579 h *	3.4622E-13	1.8
^{58}Fe(n,γ)^{59}Fe	44.495 d	8.3270E-17	2.2
^{59}Co(n,γ)^{60}Co	1925.27 d	5.6707E-17	1.4
^{63}Cu(n,γ)^{64}Cu	12.701 h *	--	--
^{98}Mo(n,γ)^{99}Mo	2.748 d	2.4853E-15	1.7
^{109}Ag(n,γ)^{110m}Ag	249.78 d	8.7524E-17	0.81
^{186}W(n,γ)^{187}W	23.72 h *	2.2104E-13	1.5
^{197}Au(n,γ)^{198}Au	2.694 d	5.6538E-13	3.2
^{23}Na(n,γ)^{24}Na - Cd	14.957 h *	4.2940E-16	2.2
^{45}Sc(n,γ)^{46}Sc - Cd	83.788 d	1.1446E-16	2.2
^{55}Mn(n, γ)^{56}Mn - Cd	2.579 h *	9.1556E-14	1.9
^{58}Fe(n,γ)^{59}Fe - Cd	44.495 d	2.5208E-17	1.8
^{59}Co(n,γ)^{60}Co - Cd	1925.27 d	1.8963E-17	1.4
^{63}Cu(n,γ)^{64}Cu - Cd	12.701 h *	--	--
^{98}Mo(n,γ)^{99}Mo - Cd	2.748 d	2.3502E-15	1.6
^{109}Ag(n,γ)^{110m}Ag	249.78 d	5.7839E-17	0.8
^{197}Au(n,γ)^{198}Au - Cd	2.694 d	4.7342E-13	3.2
^{235}U(n,f)FP - BB	^{140}Ba - 12.752 d	3.1399E-09 #fis	3.5
^{238}U(n,f)FP - BB	^{140}Ba - 12.752 d	2.8531E-10 #fis	3.5
^{239}Pu(n,f)FP - BB	^{140}Ba - 12.752 d	3.1557E-09 #fis	3.5
^{239}Np(n,f)FP - BB	^{140}Ba - 12.752 d	1.5815E-09 #fis	3.5

* half life less than one day ** half life less than one hour #fiss = units are fissions per atom isotope
Cd = foil is located within a standard Cd cup BB = foil is located within a thick Cd cup and within a B_4C ball
Reference – all foil activities are normalized to a ^{58}Ni(n,p)^{58}Co activity for each irradiation

The foils and activation reactions chosen for the analysis represent expert judgment and references to previous work, including characterization of the LB44 bucket on the 32-inch pedestal (Parma, 2013), and historical characterization of the ACRR free-field condition and the LB36 bucket (Griffin, 2011b; Griffin, 1994b). A complete set of dosimetry foils and reaction data will vary for a given neutron environment being characterized. Typically, neutron activation resulting in the emission of protons (n,p), neutrons (n,2n), (n,n'), or alpha particles (n,α) represent high neutron-energy reactions of 1 MeV or greater. Neutron activation resulting in prompt gamma-ray emission from radiative capture (n,γ) or fission reactions determine the shape of the thermal and epithermal region of the neutron spectrum. Covering foils with cadmium (Cd) and/or boron (B) can allow for resonances above the associated cutoff energies to become more prominent, allowing for additional information to be included in the analysis.

A total of 21 different foil types, resulting in 35 different reactions, were irradiated at the ACRR-FF-CC-32-cl location. The foils were irradiated in 10 different pulse (150 MJ) operations. The four fission foils (U-235, U-238, Pu-239, and Np-237) were irradiated individually in a cadmium and boron ball configuration in four separate steady-state operations. Two additional (n,γ) foils (Co and Ag) were also irradiated but were not used in the analysis due to significant inconsistencies in the unfolding results. It is unsure at this time if there are problems in the measurement technique for these reactions or if there are issues with the dosimetry cross sections. Figure 12 shows a picture of some of the dosimetry foils used, from left to right: Co, Sc, Ni, and Fe. For reference, the Ni foil is 1.27 cm in diameter. The irradiations were all performed at the peak axial fast neutron fluence location within the cavity. From sulfur tablet irradiations, presented in Section 4 of this report, the peak axial fast neutron fluence is located 13 inches from the top of the 32 inch pedestal. Multiple foils were irradiated on a specially designed aluminum stand, which held the foils at the 13 inch position in the cavity. The dosimetry stand, tray and holder are shown in Figure 13. Figure 14 shows the 10-slot dosimetry foil tray and foil packets. The tray was designed with the slots large enough to accommodate foils and Cd covered foils. In order to minimize any self-shielding effects, the foils were never stacked. Instead, the foils were arranged randomly on the tray and held in place with an aluminum cover. Figure 15 shows the boron ball and stand used for the irradiations. For each irradiation, at least one Ni foil was irradiated and used to normalize all of the irradiations. Several foils were run for each operation, and multiple foils of the same type were tested during the campaign.

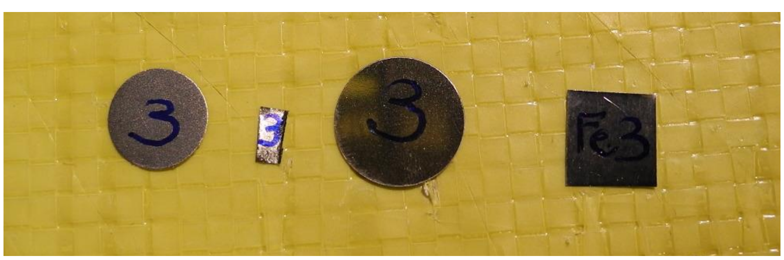


Figure 12. Typical Dosimetry Foils - Left to Right: Co, Sc, Ni, and Fe.

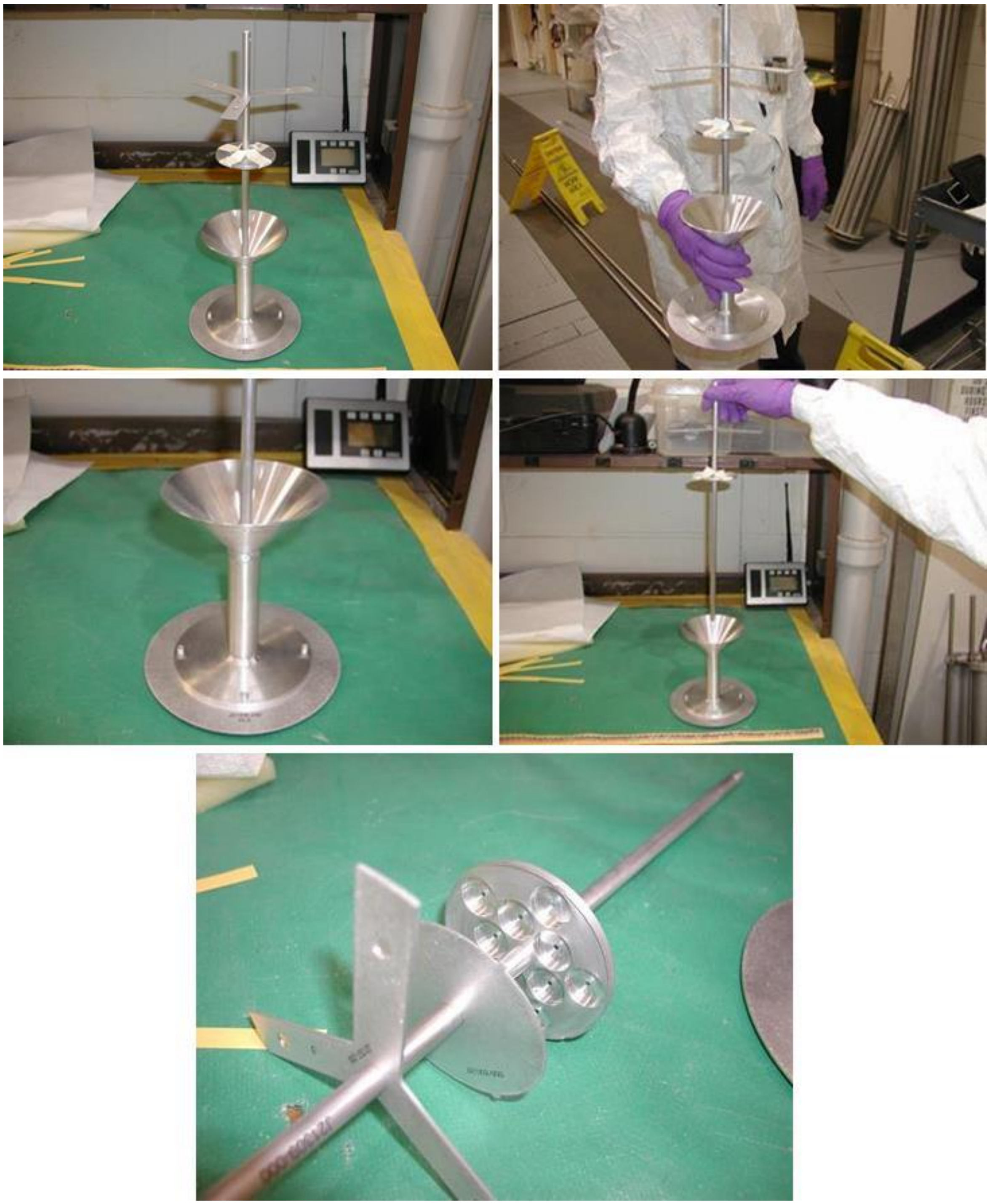


Figure 13. Drop-In Dosimetry Stand Used to Irradiate Foils in the Central Cavity.

Figure 14. Aluminum Dosimetry Tray and Foil Packets Awaiting Irradiation.

The free-field environment was used to perform all of the foil irradiations identified in Table 1. Steady-state operations and lower pulse irradiations were also performed using the free-field environment to determine any temperature or steady-state effects on the neutron spectrum. Again, no statistically significant differences could be determined from these tests. No variation was found radially or azimuthally in the neutron fluence at the central region of the bucket, as presented in Section 4. The radial and azimuthal fluence variations are considered negligible for the free-field environment at the 13-inch position. Additional uncertainty in the analysis was included to account for possible variation due to geometry effects.

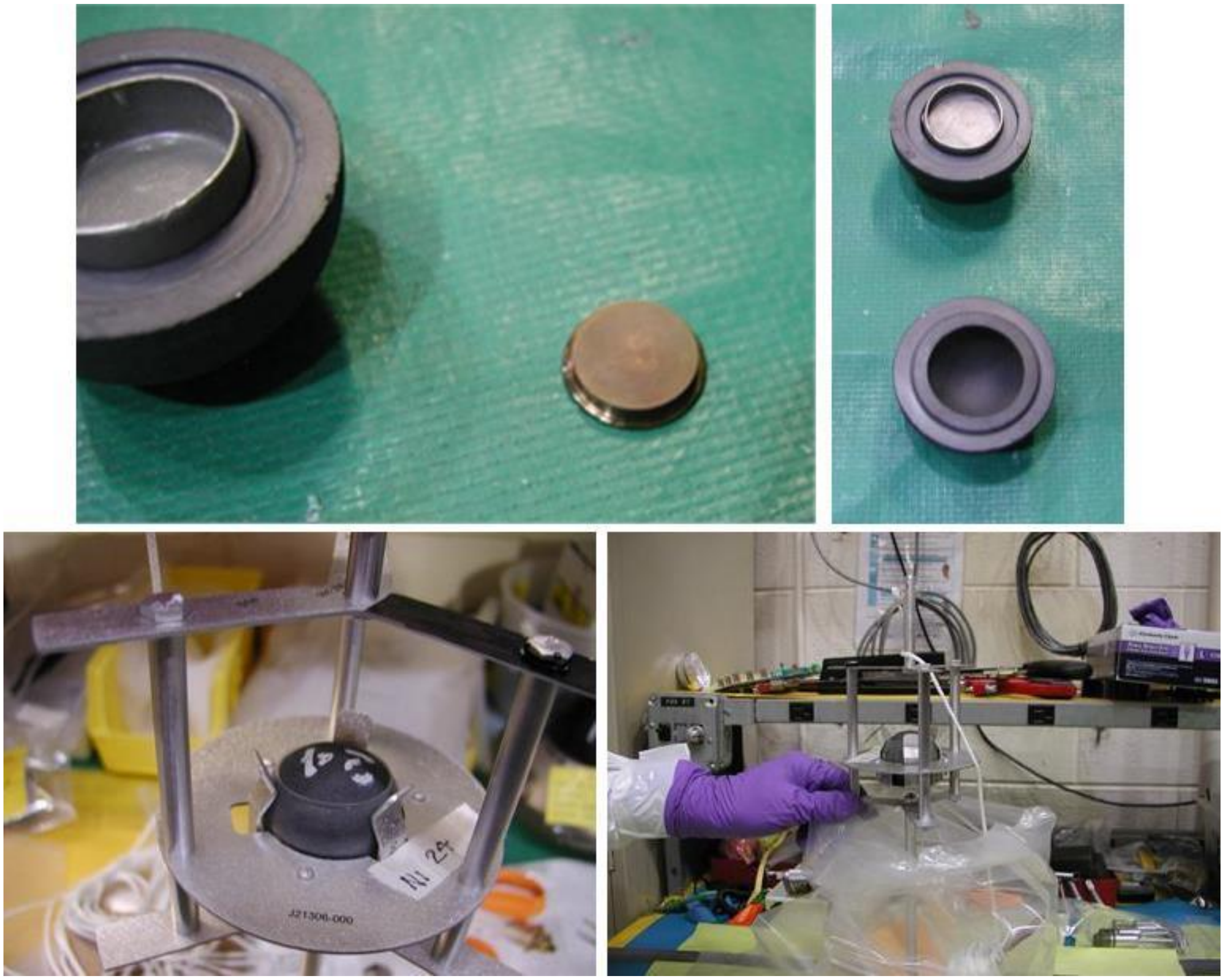


Figure 15. Boron Ball Configuration and Stand.

The free-field environment requires good coverage of the thermal, epithermal, and high-energy neutron reactions in order to perform an adequate adjustment to the neutron fluence energy spectrum. Cd and B_4C covers can be used to discriminate energy regions in some reactions. Table 1 shows each activation reaction used in the analysis, as well as the half-life for the transmuted isotope, the measured activity decay corrected to the end of the irradiation, and the counting uncertainty. The reactions are grouped in order of reaction type. The first group represents the high-energy (n,p), (n,2n), (n,n') and (n, α) reactions. The second group represents the low-energy radiative capture reactions for bare foils. The third group represents the radiative capture reactions with each individual foil placed in a cadmium cover. The fourth group represents the fission foils placed in a cadmium cup within a boron ball configuration. Reactions identified with a light-gray colored box represent reactions that were not identified from the dosimetry report for these tests. Reactions identified with a dark-gray colored box represent reactions that were not used in the final spectrum adjustment do to inconsistencies in the results.

LSL Spectrum Unfold Results

LSL-M2 was run using the *a priori* 640-energy group trial spectrum from MCNP converted to the NuGET 89 group structure, and the dosimetry data presented in Table 1. Also required in the analysis was an initial uncertainty estimate in the neutron spectrum as a function of energy, an initial energy-dependent correlation matrix, the energy dependent self-shielding factors, and the dosimetry cross section library that also included uncertainties and covariance matrices. The input deck used for the LSL calculation is included in Appendix B of this report. In addition to the counting uncertainty, an additional 2% uncertainty was included for the foils to address uncertainty contributions due to positioning and possible geometrical effects in the central region of the core. The output was in the 89-energy group NuGET format described earlier.

The resulting value for χ^2/dof is 0.80, which represents an acceptable value. Figures 16 and 17 show the same representation of the neutron energy spectra as previously shown in Figures 10 and 11, with the additional 89-energy group adjusted spectrum result from the LSL analysis (green curve). Figure 18 shows the percent adjustment made to the trial spectrum (red curve), and the percent standard deviation in the adjusted spectrum (black curve). The adjusted neutron fluence in Figure 16 shows a lower value in the thermal energy range (1E-8 to 3E-6 MeV) than calculated using the MCNP model. This difference could be due to a number of factors including accuracy of the geometry and density of materials in the ACRR MCNP model, cross section or scattering model discrepancies in MCNP.

Figures 19 to 23 show the dosimetry foil relative reaction probabilities as a function of energy from the LSL analysis. Each relative reaction probability sums to 100%. It is desirable to have diverse coverage over the complete energy range. Peaks represent areas of higher probability that allow for energy discrimination in the analysis. Figure 21 shows all of the reactions used in the analysis. Figures 20 through 23 represent the high-energy reactions, the radiative capture reactions, the Cd covered radiative capture reactions, and the fission reactions, respectively. The reactions that are green in the legend represent those in the thermal region less than 1 eV. The blue legend reactions represent those that are Cd covered. The cadmium cutoff value is at 0.5 eV. Although a B-10 cutoff energy does not exist, an effective value is shown at 100 eV that represents a nominal value. Figure 21 shows that there is good coverage with many peaks in the energy range between 0.001 eV and 1 keV, and 1 MeV to 10 MeV. There is less coverage in the range 1 keV to 1 MeV.

Table 2 shows the result of the calculated to experimental (C/E) dosimetry results for the trial spectrum and the adjusted spectrum. Also shown is the factor adjusted from the trial spectrum to the adjusted spectrum for the dosimetry reactions. For the high-energy reactions, the C/E-1 values are found to be both positive and negative for the trial spectrum, and are reduced for the adjusted spectrum. For the radiative capture reactions, the C/E-1 values are all positive, with the exception of a single reaction, for the trial spectrum. This infers that the thermal/epithermal calculated fluence is too high. After the adjustment, the results become much closer to zero for C/E-1.

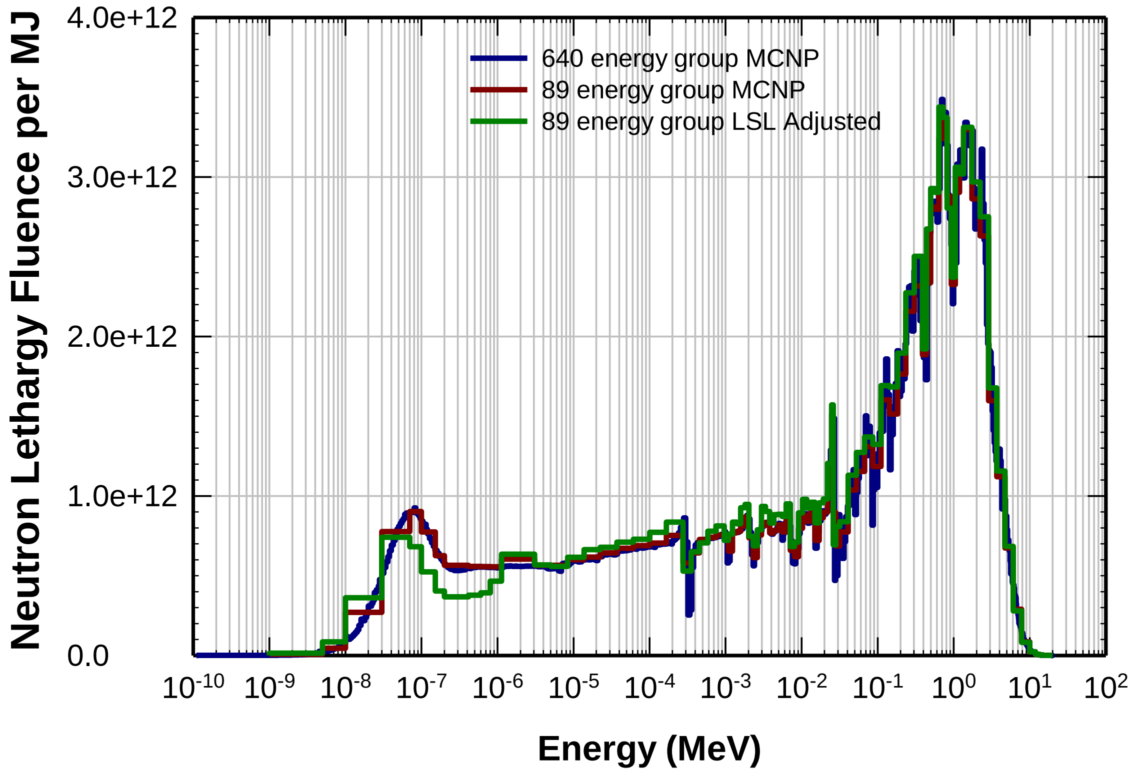


Figure 16. LSL Adjusted 89-Group Neutron Lethargy Fluence Energy Spectrum Compared to the MCNP Calculated Results (linear–log).

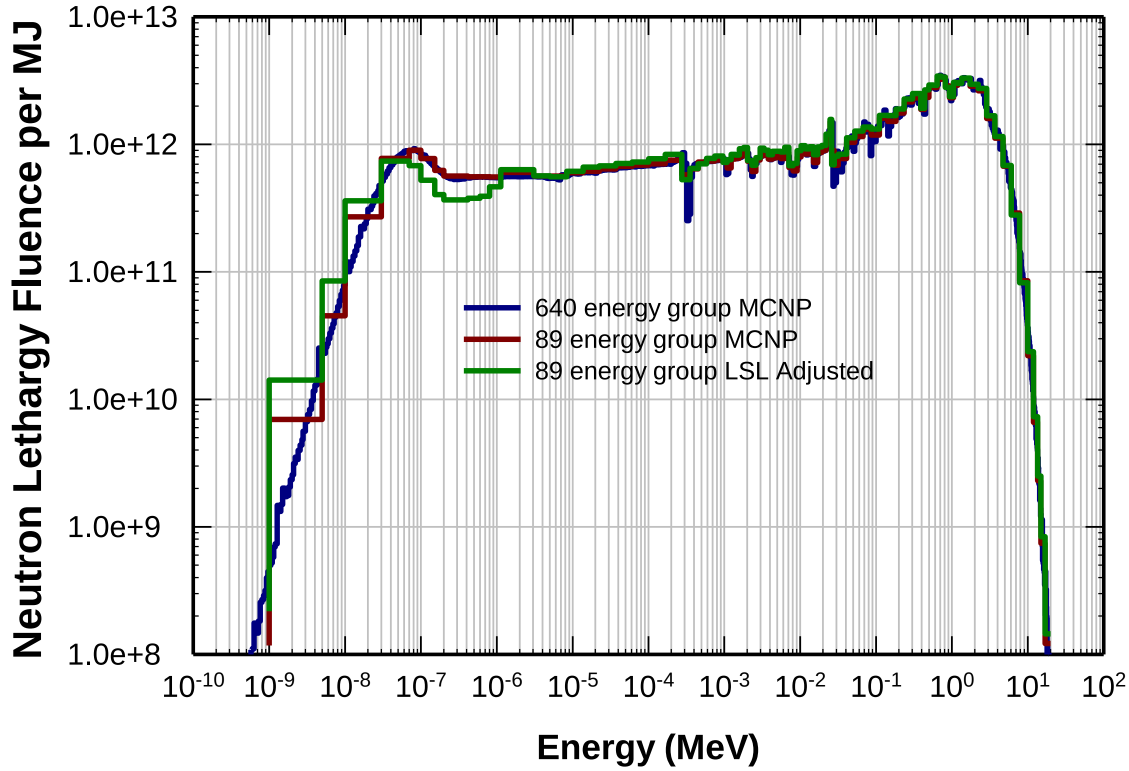


Figure 17. LSL Adjusted 89-Group Neutron Lethargy Fluence Energy Spectrum Compared to the MCNP Calculated Results (log–log).

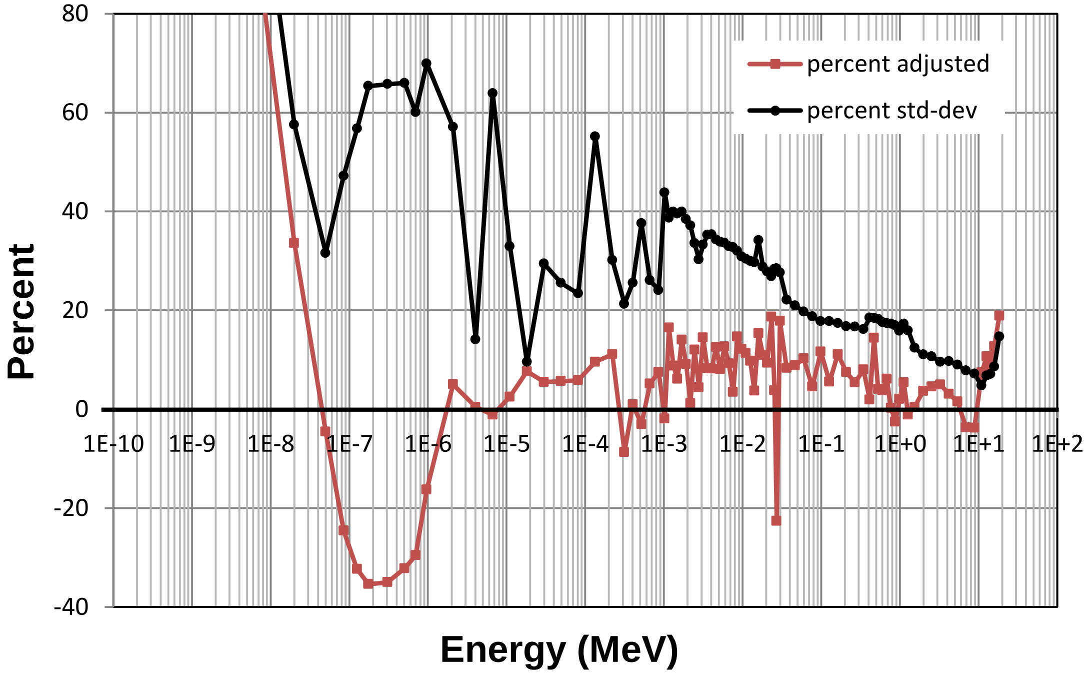


Figure 18. LSL Percent Adjustment to the Trial Spectrum and Standard Deviation Results for the 89-Group Adjusted Neutron Spectrum.

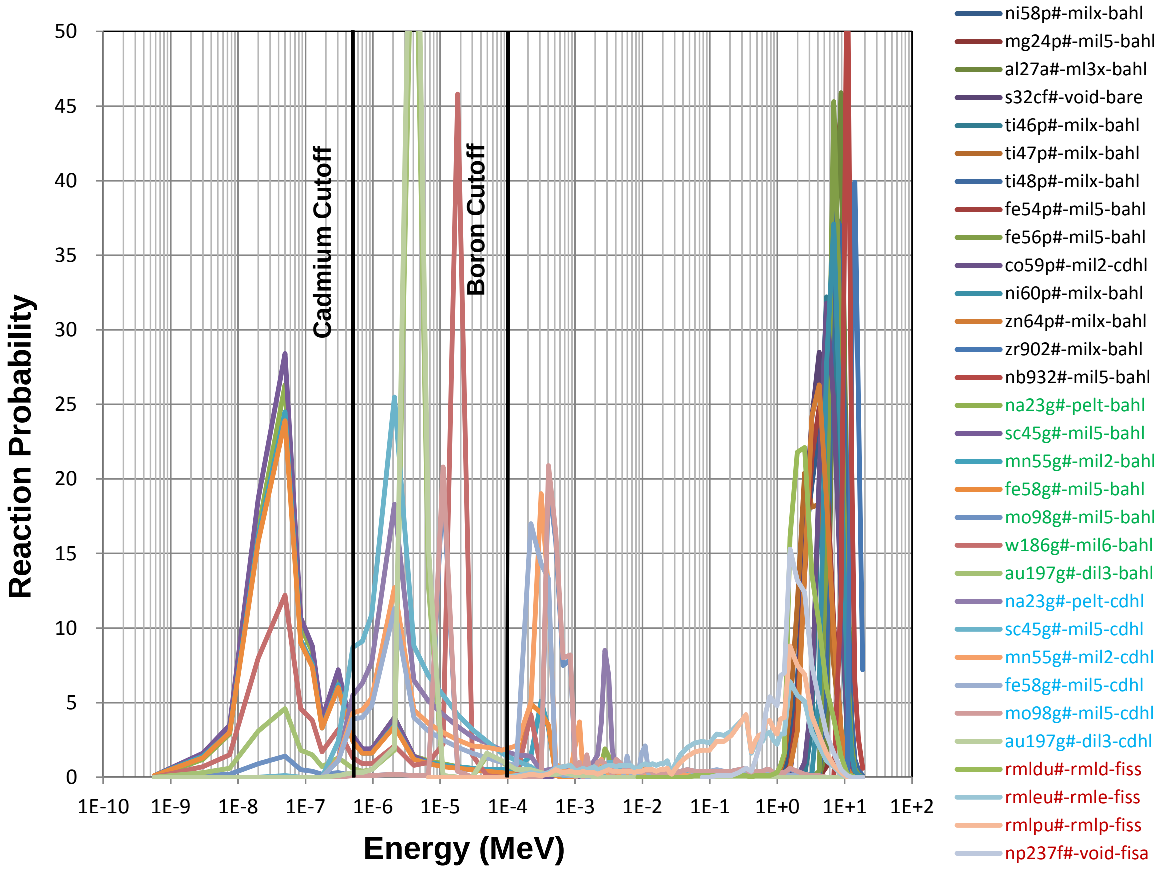


Figure 19. Relative Reaction Probabilities for the Complete Dosimetry Reaction Set.

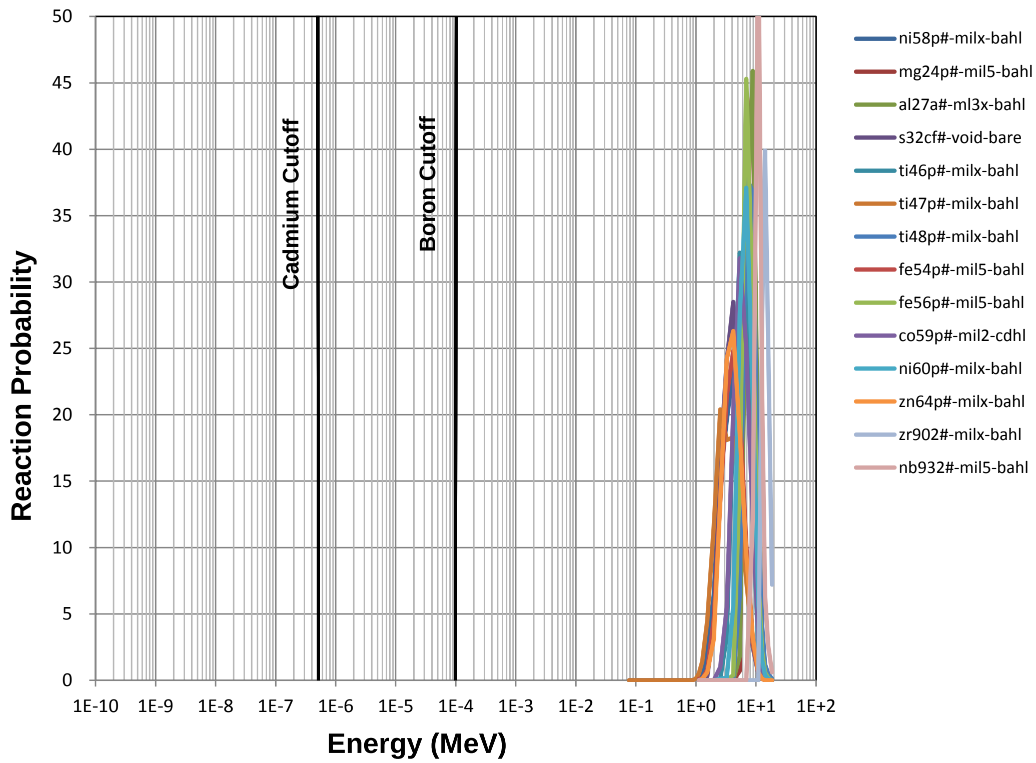


Figure 20. Relative Reaction Probabilities for the High Energy Dosimetry Reaction Set.

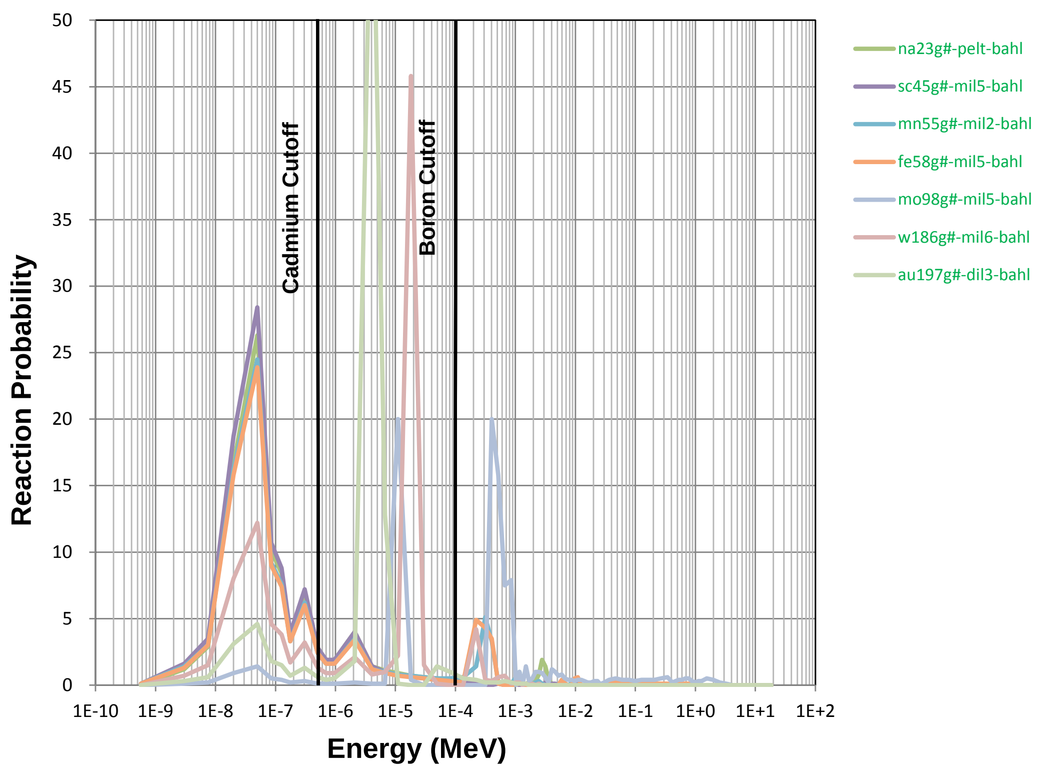


Figure 21. Relative Reaction Probabilities for the Radiative Capture Dosimetry Reaction Set.

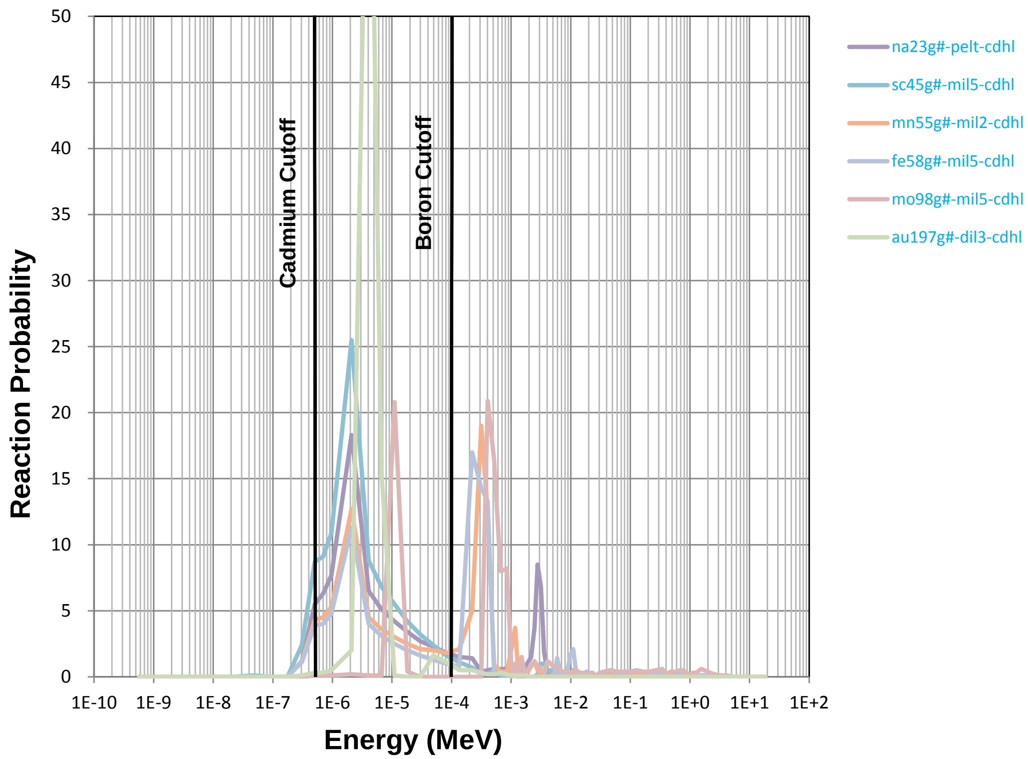


Figure 22. Relative Reaction Probabilities for the Radiative Capture Dosimetry Reaction Set With Cd Covers.

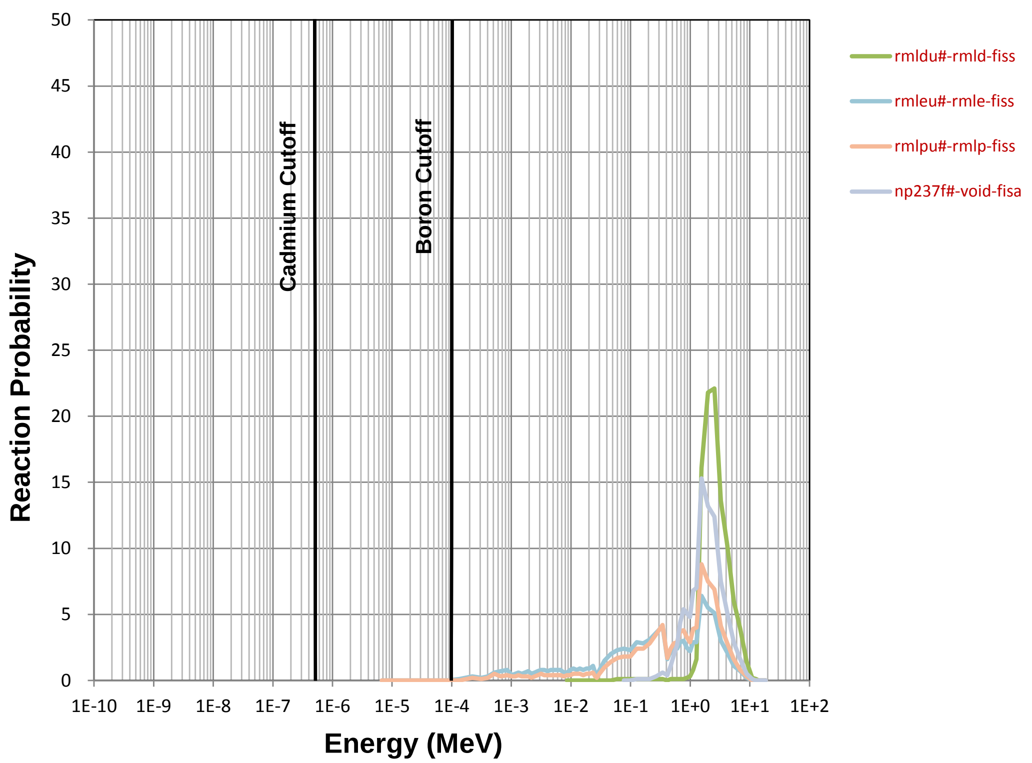


Figure 23. Relative Reaction Probabilities for the Fission Dosimetry Reaction Set.

Table 2. C/E Values for the Trial and Adjusted LSL Neutron Energy Spectrum.

Activation Reaction	C/E-1 Trial Spectrum (%)	C/E-1 Adjusted Spectrum (%)	Factor Adjusted (%)
^{58}Ni(n,p)^{58}Co - Reference	0.00	1.50	1.50
^{24}Mg(n,p)^{24}Na	4.03	1.20	-2.83
^{27}Al(n,α)^{24}Na	1.76	-0.40	-2.13
^{32}S(n,p)^{32}P Cf-equ	5.06	4.60	-0.43
^{46}Ti(n,p)^{46}Sc	2.07	0.80	-1.27
^{47}Ti(n,p)^{47}Sc	-2.87	-0.80	2.06
^{48}Ti(n,p)^{48}Sc	4.75	1.10	-3.59
^{54}Fe(n,p)^{54}Mn	-4.10	-2.30	1.82
^{56}Fe(n,p)^{56}Mn	-0.85	-2.20	-1.34
^{59}Co(n,p)^{59}Fe	3.15	2.30	-0.82
^{60}Ni(n,p)^{60}Co	2.50	0.70	-1.79
^{64}Zn(n,p)^{64}Cu	-4.07	-2.30	1.79
^{90}Zr(n,2n)^{89}Zr	-9.16	1.20	10.21
^{93}Nb(n,2n)^{92m}Nb	-7.05	-0.70	6.40
^{23}Na(n,γ)^{24}Na	12.80	3.20	-9.34
^{45}Sc(n,γ)^{46}Sc	10.45	0.30	-10.15
^{55}Mn(n, γ)^{56}Mn	4.07	-3.00	-7.33
^{58}Fe(n,γ)^{59}Fe	6.76	0.10	-6.65
^{98}Mo(n,γ)^{99}Mo	-0.23	-1.00	-0.76
^{186}W(n,γ)^{187}W	0.99	0.00	-1.02
^{197}Au(n,γ)^{198}Au	1.49	-1.70	-3.19
^{23}Na(n,γ)^{24}Na - Cd	4.23	-0.60	-4.85
^{45}Sc(n,γ)^{46}Sc - Cd	8.23	-0.10	-8.36
^{55}Mn(n,γ)^{56}Mn - Cd	5.01	1.00	-4.00
^{58}Fe(n,γ)^{59}Fe - Cd	2.29	-0.20	-2.46
^{98}Mo(n,γ)^{99}Mo - Cd	1.41	1.00	-0.41
^{197}Au(n,γ)^{198}Au - Cd	3.61	1.40	-2.14
^{235}U(n,f)FP - BB	-2.87	-0.70	2.16
^{238}U(n,f)FP - BB	-9.31	-6.10	3.41
^{239}Pu(n,f)FP - BB	4.87	5.50	0.63
^{239}Np(n,f)FP - BB	0.23	1.10	0.89

Table 3 shows the adjusted neutron fluence spectrum in a tabular format for the 89-energy group NuGET structure. Column 5 represents the number fraction, column 6 the energy fraction, column 7 the differential number fraction, column 8 the differential energy fraction, and column 9 the percent standard deviation for the adjusted spectrum. The number fraction, represented as a histogram, can be used in MCNP source calculations as an isotropic spherical surface source. The average neutron energy is calculated to be 0.595 MeV. The peak differential number fraction occurs in energy group 4 at 0.02 eV. The differential fluence at 1 MeV (Group 74) is almost seven orders of magnitude lower than the peak. The differential energy fluence for the same comparison is about the same order of magnitude as for the 1 MeV value. The LSL adjusted results for the number fraction, percent standard deviation, and covariance as a function of the 89-group energy structure are included in an LSL format in Appendix C of this report.

Table 3. Neutron 89-Energy Group Adjusted Spectrum for ACRR-FF-CC-32-cl.

Group	Lower Energy (MeV)	Upper Energy (MeV)	Midpoint Energy (MeV)	Number Fraction	Energy Fraction	Differential Number dN/dE	Differential Energy dE/dE	Standard Deviation (%)
1	1.0000E-10	1.0000E-09	5.5000E-10	1.74E-05	1.60576E-14	1.93012E+04	1.06157E-05	262.15
2	1.0000E-09	5.0000E-09	3.0000E-09	9.20E-04	4.63873E-12	2.30001E+05	6.90002E-04	138.74
3	5.0000E-09	1.0000E-08	7.5000E-09	2.76E-03	3.47646E-11	5.51590E+05	4.13693E-03	107.76
4	1.0000E-08	3.0000E-08	2.0000E-08	1.76E-02	5.92284E-10	8.81010E+05	1.76202E-02	57.56
5	3.0000E-08	7.0000E-08	5.0000E-08	2.89E-02	2.42734E-09	7.22123E+05	3.61061E-02	31.60
6	7.0000E-08	1.0000E-07	8.5000E-08	1.17E-02	1.67364E-09	3.90510E+05	3.31934E-02	47.21
7	1.0000E-07	1.5230E-07	1.2615E-07	1.06E-02	2.24542E-09	2.02497E+05	2.55450E-02	56.75
8	1.5230E-07	2.0000E-07	1.7615E-07	5.33E-03	1.57918E-09	1.11826E+05	1.96981E-02	65.35
9	2.0000E-07	4.1400E-07	3.0700E-07	1.25E-02	6.44622E-09	5.83799E+04	1.79226E-02	65.75
10	4.1400E-07	6.0000E-07	5.0700E-07	6.76E-03	5.76189E-09	3.63542E+04	1.84316E-02	65.97
11	6.0000E-07	8.0000E-07	7.0000E-07	5.47E-03	6.43063E-09	2.73298E+04	1.91308E-02	60.05
12	8.0000E-07	1.1250E-06	9.6250E-07	7.66E-03	1.23902E-08	2.35670E+04	2.26832E-02	69.93
13	1.1250E-06	3.0590E-06	2.0920E-06	2.86E-02	1.00531E-07	1.47840E+04	3.09282E-02	57.06
14	3.0590E-06	5.0430E-06	4.0510E-06	1.36E-02	9.22736E-08	6.83100E+03	2.76724E-02	14.12
15	5.0430E-06	8.3150E-06	6.6790E-06	1.33E-02	1.49711E-07	4.07604E+03	2.72239E-02	63.90
16	8.3150E-06	1.3710E-05	1.1013E-05	1.47E-02	2.72015E-07	2.72411E+03	2.99993E-02	32.94
17	1.3710E-05	2.2600E-05	1.8155E-05	1.58E-02	4.82976E-07	1.78048E+03	3.23247E-02	9.55
18	2.2600E-05	3.7270E-05	2.9935E-05	1.62E-02	8.15522E-07	1.10494E+03	3.30762E-02	29.43
19	3.7270E-05	6.1440E-05	4.9355E-05	1.69E-02	1.40529E-06	7.00923E+02	3.45940E-02	25.56
20	6.1440E-05	1.0130E-04	8.1370E-05	1.74E-02	2.38036E-06	4.36668E+02	3.55317E-02	23.42
21	1.0130E-04	1.6700E-04	1.3415E-04	1.84E-02	4.15583E-06	2.80551E+02	3.76359E-02	55.13
22	1.6700E-04	2.7540E-04	2.2120E-04	2.00E-02	7.42440E-06	1.84229E+02	4.07514E-02	30.16
23	2.7540E-04	3.5360E-04	3.1450E-04	6.40E-03	3.38478E-06	8.18867E+01	2.57534E-02	21.30
24	3.5360E-04	4.5400E-04	4.0380E-04	7.87E-03	5.33913E-06	7.83576E+01	3.16408E-02	25.58
25	4.5400E-04	5.8300E-04	5.1850E-04	8.55E-03	7.45125E-06	6.62829E+01	3.43677E-02	37.58
26	5.8300E-04	7.4850E-04	6.6575E-04	9.43E-03	1.05512E-05	5.69777E+01	3.79329E-02	26.08
27	7.4850E-04	9.6110E-04	8.5480E-04	9.84E-03	1.41347E-05	4.62776E+01	3.95581E-02	24.10
28	9.6110E-04	1.0890E-03	1.0251E-03	4.39E-03	7.56453E-06	3.43303E+01	3.51902E-02	43.84
29	1.0890E-03	1.2340E-03	1.1615E-03	4.63E-03	9.03090E-06	3.19047E+01	3.70573E-02	38.73
30	1.2340E-03	1.3980E-03	1.3160E-03	5.07E-03	1.12219E-05	3.09370E+01	4.07130E-02	39.96
31	1.3980E-03	1.5850E-03	1.4915E-03	5.04E-03	1.26415E-05	2.69678E+01	4.02225E-02	39.52
32	1.5850E-03	1.7960E-03	1.6905E-03	5.63E-03	1.59990E-05	2.66873E+01	4.51149E-02	39.94
33	1.7960E-03	2.0350E-03	1.9155E-03	5.76E-03	1.85415E-05	2.40977E+01	4.61592E-02	38.48
34	2.0350E-03	2.3060E-03	2.1705E-03	4.54E-03	1.65744E-05	1.67656E+01	3.63897E-02	37.17
35	2.3060E-03	2.6130E-03	2.4595E-03	4.18E-03	1.72776E-05	1.36147E+01	3.34854E-02	33.59
36	2.6130E-03	2.9600E-03	2.7865E-03	4.79E-03	2.24102E-05	1.37901E+01	3.84261E-02	30.30
37	2.9600E-03	3.3550E-03	3.1575E-03	5.69E-03	3.02118E-05	1.44127E+01	4.55082E-02	33.24
38	3.3550E-03	3.8010E-03	3.5780E-03	5.48E-03	3.29765E-05	1.22953E+01	4.39926E-02	35.30
39	3.8010E-03	4.3070E-03	4.0540E-03	5.05E-03	3.44045E-05	9.97911E+00	4.04553E-02	35.34
40	4.3070E-03	4.8810E-03	4.5940E-03	5.38E-03	4.15011E-05	9.36413E+00	4.30188E-02	34.32
41	4.8810E-03	5.5310E-03	5.2060E-03	5.39E-03	4.71362E-05	8.28795E+00	4.31471E-02	33.82
42	5.5310E-03	6.2670E-03	5.8990E-03	5.30E-03	5.25620E-05	7.20321E+00	4.24917E-02	33.64
43	6.2670E-03	7.1020E-03	6.6845E-03	5.78E-03	6.49581E-05	6.92450E+00	4.62868E-02	32.97
44	7.1020E-03	8.0470E-03	7.5745E-03	4.15E-03	5.28121E-05	4.38994E+00	3.32516E-02	32.72
45	8.0470E-03	9.1190E-03	8.5830E-03	4.32E-03	6.23487E-05	4.03185E+00	3.46053E-02	32.03
46	9.1190E-03	1.0330E-02	9.7245E-03	5.42E-03	8.86575E-05	4.47935E+00	4.35594E-02	30.89
47	1.0330E-02	1.1710E-02	1.1020E-02	5.97E-03	1.10588E-04	4.32670E+00	4.76802E-02	30.39
48	1.1710E-02	1.3270E-02	1.2490E-02	5.62E-03	1.18070E-04	3.60548E+00	4.50325E-02	29.93
49	1.3270E-02	1.5030E-02	1.4150E-02	5.82E-03	1.38390E-04	3.30632E+00	4.67845E-02	29.68
50	1.5030E-02	1.7040E-02	1.6035E-02	5.08E-03	1.36887E-04	2.52701E+00	4.05207E-02	34.20
51	1.7040E-02	1.9300E-02	1.8170E-02	5.80E-03	1.77229E-04	2.56792E+00	4.66592E-02	28.77

52	1.9300E-02	2.1880E-02	2.0590E-02	5.99E-03	2.07444E-04	2.32346E+00	4.78400E-02	27.84
53	2.1880E-02	2.4790E-02	2.3335E-02	7.32E-03	2.87049E-04	2.51516E+00	5.86912E-02	26.87
54	2.4790E-02	2.6060E-02	2.5425E-02	3.82E-03	1.63410E-04	3.01110E+00	7.65573E-02	28.34
55	2.6060E-02	2.8090E-02	2.7075E-02	2.53E-03	1.15225E-04	1.24736E+00	3.37723E-02	28.50
56	2.8090E-02	3.1830E-02	2.9960E-02	4.92E-03	2.47751E-04	1.31557E+00	3.94144E-02	27.64
57	3.1830E-02	4.0870E-02	3.6350E-02	1.02E-02	6.20837E-04	1.12413E+00	4.08620E-02	22.10
58	4.0870E-02	5.2480E-02	4.6675E-02	1.37E-02	1.07372E-03	1.17892E+00	5.50262E-02	20.99
59	5.2480E-02	6.7380E-02	5.9930E-02	1.54E-02	1.55348E-03	1.03511E+00	6.20340E-02	19.71
60	6.7380E-02	8.6520E-02	7.6950E-02	1.66E-02	2.14673E-03	8.67236E-01	6.67338E-02	18.79
61	8.6520E-02	1.1110E-01	9.8810E-02	1.60E-02	2.66258E-03	6.52274E-01	6.44512E-02	17.76
62	1.1110E-01	1.4260E-01	1.2685E-01	2.05E-02	4.36432E-03	6.49870E-01	8.24360E-02	17.78
63	1.4260E-01	1.8320E-01	1.6290E-01	2.04E-02	5.59475E-03	5.03320E-01	8.19909E-02	17.38
64	1.8320E-01	2.3520E-01	2.0920E-01	2.30E-02	8.07517E-03	4.41669E-01	9.23972E-02	16.74
65	2.3520E-01	3.0200E-01	2.6860E-01	2.76E-02	1.24462E-02	4.12728E-01	1.10859E-01	16.68
66	3.0200E-01	3.8770E-01	3.4485E-01	3.03E-02	1.75744E-02	3.53818E-01	1.22014E-01	16.16
67	3.8770E-01	4.3940E-01	4.1355E-01	1.17E-02	8.14226E-03	2.26588E-01	9.37055E-02	18.47
68	4.3940E-01	4.9790E-01	4.6865E-01	1.63E-02	1.28176E-02	2.78171E-01	1.30365E-01	18.47
69	4.9790E-01	5.6420E-01	5.3105E-01	1.78E-02	1.59001E-02	2.68697E-01	1.42691E-01	18.22
70	5.6420E-01	6.3930E-01	6.0175E-01	1.77E-02	1.78650E-02	2.35210E-01	1.41538E-01	17.62
71	6.3930E-01	7.2440E-01	6.8185E-01	2.09E-02	2.39748E-02	2.45837E-01	1.67624E-01	17.41
72	7.2440E-01	8.2080E-01	7.7260E-01	2.05E-02	2.66438E-02	2.12851E-01	1.64448E-01	17.25
73	8.2080E-01	9.3010E-01	8.7545E-01	1.71E-02	2.51123E-02	1.56151E-01	1.36702E-01	16.93
74	9.3010E-01	1.0540E+00	9.9205E-01	1.44E-02	2.40858E-02	1.16592E-01	1.15665E-01	15.86
75	1.0540E+00	1.1940E+00	1.1240E+00	1.86E-02	3.51103E-02	1.32755E-01	1.49217E-01	17.29
76	1.1940E+00	1.3530E+00	1.2735E+00	1.84E-02	3.93256E-02	1.15555E-01	1.47160E-01	15.93
77	1.3530E+00	1.7380E+00	1.5455E+00	4.02E-02	1.04445E-01	1.04441E-01	1.61413E-01	12.41
78	1.7380E+00	2.2310E+00	1.9845E+00	3.59E-02	1.19892E-01	7.29126E-02	1.44695E-01	11.04
79	2.2310E+00	2.8650E+00	2.5480E+00	3.34E-02	1.42856E-01	5.26162E-02	1.34066E-01	10.65
80	2.8650E+00	3.6790E+00	3.2720E+00	2.03E-02	1.11799E-01	2.49753E-02	8.17192E-02	9.60
81	3.6790E+00	4.7240E+00	4.2015E+00	1.40E-02	9.89083E-02	1.34036E-02	5.63154E-02	9.67
82	4.7240E+00	6.0650E+00	5.3945E+00	8.29E-03	7.51704E-02	6.18268E-03	3.33525E-02	9.01
83	6.0650E+00	7.7880E+00	6.9265E+00	3.39E-03	3.94394E-02	1.96626E-03	1.36193E-02	7.81
84	7.7880E+00	1.0000E+01	8.8940E+00	9.96E-04	1.48819E-02	4.50077E-04	4.00299E-03	7.17
85	1.0000E+01	1.1910E+01	1.0955E+01	2.01E-04	3.70489E-03	1.05351E-04	1.15412E-03	4.77
86	1.1910E+01	1.3500E+01	1.2705E+01	4.45E-05	9.50946E-04	2.80088E-05	3.55852E-04	6.78
87	1.3500E+01	1.4920E+01	1.4210E+01	1.22E-05	2.90827E-04	8.57556E-06	1.21859E-04	7.12
88	1.4920E+01	1.6900E+01	1.5910E+01	5.07E-06	1.35664E-04	2.56235E-06	4.07670E-05	8.58
89	1.6900E+01	2.0000E+01	1.8450E+01	1.18E-06	3.67198E-05	3.81990E-07	7.04772E-06	14.70

The results for a number of integral metrics and conversion factors are shown in Table 4. The total neutron fluence is normalized to 1.00 and the other values for fluence are in reference to this value. These values were calculated as part of the LSL analysis. Conversion values to translate to n/cm^2 are given for fissions in the reactor, MJ of reactor energy, and ^{58}Ni(n,p)^{58}Co activity at the characterized location in the cavity. In order to maintain consistency, the experimenter should always use a reference fast neutron reaction or reactions, e.g. ^{58}Ni(n,p)^{58}Co and ^{32}S(n,p) ^{32}P, as a normalizing metric between operations. Typically, Ni, S, and TLD sensors are included in an experiment package in order to normalize the results of the experiment. Figure 18 showed the energy-dependent spectrum uncertainty. It must be noted that portions of the energy spectrum are highly correlated, so the uncertainty in the integral metric can be much less than the average uncertainty. Users should perform uncertainty propagation using the full energy-dependent covariance matrix given in Appendix C in order to determine the correlated uncertainty.

Table 4. Integral Neutron Spectrum Metrics and Associated Uncertainties.

Metric	Integral Response	Standard Deviation (%)
Total Neutron Fluence Average Neutron Energy = 0.595 MeV	1.00	--
Fluence > 3 MeV	0.044	4.3
Fluence > 1 MeV	0.200	4.6
Fluence > 100 keV	0.460	3.0
Fluence > 10 keV	0.579	2.4
Fluence < 1 keV	0.328	4.0
Fluence < 1 eV	0.106	12.1
Fluence 1-MeV(Si) Eqv. E722-94	0.381	2.8
Fluence 1-MeV(GaAs) Eqv. E722-94	0.310	2.4
^{58}Ni(n,p)^{58}Co Spectrum Avg. Cross-Section IRDFF-1.02	23.06 mb	3.6
^{32}S(n,p)^{32}P Spectrum Avg. Cross-Section IRDFF-1.02	14.66 mb	4.2
Total Fluence Conversion ([n/cm^2]/fission)	6.326E-04	0.4
Total Fluence Conversion ([n/cm^2]/MJ)	2.052E+13	2.0
Total Fluence Conversion From Ni Activation ^{58}Ni(n,p)^{58}Co ([n/cm^2]/[Bq/atom$_{Ni-58}$])	3.829E+32	3.6
Total Fluence Conversion From Ni Activation ^{58}Ni(n,p)^{58}Co ([n/cm^2]/[Bq/g$_{Ni-58}$])	3.683E+10	3.6
Power Conversion From Ni Activation ^{58}Ni(n,p)^{58}Co (MJ/[Bq/atom$_{Ni-58}$])	1.866E+19	4.1
Power Conversion From Ni Activation ^{58}Ni(n,p)^{58}Co (MJ/[Bq/g$_{Ni-58}$])	1.795E-03	4.1
Total Fluence Conversion From S Activation ([n/cm^2]/Fluence ^{32}S(n,p) Cf-eqv)	5.054	4.9

Table 5 shows representative integral metrics that may be useful to the experimenter. These values were calculated using the LSL adjusted 89-energy group neutron spectrum and the NuGET code with various response functions. Included are responses for Si dose, Si damage, C dose, GaAs dose, GaAs damage, TLD dose, Alanine dose, and Teflon dose.

Table 5. Other Neutron Spectrum Metrics.

Metric	Integral Response
Total Si Dose (rad[Si]/[n/cm^2])	2.972E-11
Ionizing Si Dose (rad[Si]/[n/cm^2])	1.647E-11
Percent Neutron Si Dose Ionizing (%)	55.4
Si PKA Average Energy (keV) - SPECTER	28.7
Si Frenkel Pair (FP) Generation Efficiency ([FP/cm^3]/[n/cm^2]) – SPECTER/MARLOWE Single Crystal – 15 eV E_{th}	22.126
Si FP density (FP/cascade)	161.6
Total Carbon Dose (rad[C]/[n/cm^2])	1.383E-10
Ionizing C Dose (rad[C]/[n/cm^2])	1.172E-10
Percent Neutron C Dose Ionizing (%)	84.7
Total GaAs Dose (rad[GaAs]/[n/cm^2])	6.029E-12
Ionizing GaAs Dose (rad[GaAs]/[n/cm^2])	1.836E-12
Percent Neutron GaAs Dose Ionizing (%)	30.4
GaAs PKA Average Energy (keV) - EMPIRE	5.7 Ga-69 5.8 Ga-71 4.4 As-75
GaAs FP Generation Efficiency ([FP/cm^3]/[n/cm^2]) – EMPIRE/MARLOWE Single Crystal - 15 eV E_{th}	20.0 Ga-69 35.0 Ga-71 21.6 As-75 23.8 wt-avg.
GaAs FP density (FP/cascade)	55.0 Ga-69 56.0 Ga-71 47.4 As-75
Total CaF_2:Mn (TLD) Dose (rad[CaF_2:Mn]/[n/cm^2])	5.987E-11
Effective Ionizing CaF_2:Mn Dose (rad[CaF_2:Mn]/[n/cm^2])	5.875E-12
Percent Neutron CaF_2:Mn Dose total light (%)	9.8
Total Alanine Dose (rad[Alanine]/[n/cm^2])	9.068E-10
Effective Alanine EPR Dose – Waligorski (rad[CaF_2:Mn]/[n/cm^2])	4.592E-10
Percent Neutron Alanine EPR Dose (%)	50.6
Effective Alanine EPR Dose – Gerstenberg (rad[CaF_2:Mn]/[n/cm^2])	4.136E-10
Percent Neutron Alanine EPR Dose (%)	45.6
Total Teflon Dose (rad[Teflon]/[n/cm^2])	9.926E-11

3.2 Prompt Gamma Ray

The gamma-ray environment includes both prompt and delayed gamma rays. Prompt gamma rays are generated from the direct fission process in the ACRR fuel, and from radiative capture and inelastic scattering of neutrons in the ACRR fuel and structure, the central cavity, and the bucket. Delayed gamma rays are generated by fission-product decay in the ACRR fuel and decay from activated materials in the core. All gamma rays are considered to fall into one of these two categories, prompt or delayed. Gamma rays generated from the direct fission process as the reactor power decreases following a pulse are considered prompt gamma rays.

It is not currently practical to use experimental integral measurements to adjust the gamma-ray energy spectrum as it is for neutrons, using the current state-of-the-art technology in gamma-ray detection and energy-deposition measurements. For photon energies above the K-edges for photon cross sections (~80 keV), most material response functions fail to show any strong energy-dependent structure that can be used to resolve the spectrum. There is simply no effective way to discriminate energy groups in a gamma-ray fluence within a small volume in a reactor core. Integral dose measurements can be performed and are used as benchmarks for calculated integral responses. These integral measurements have value in validation, but are not useful for spectrum adjustment. However, both passive dosimeters (e.g., TLDs) and active dosimeters (e.g., calorimeters) have some neutron and delayed gamma-ray contribution effects that make deciphering the results much more complex.

MCNP Model Results – 48-Group Prompt Gamma-Ray Energy Spectrum

The prompt gamma-ray fluence can be calculated in a similar way as was performed for the neutron environment. With both neutrons and photons (gamma rays) turned "on" in the k-code mode of MCNP, the prompt gamma rays generated by fission, neutron radiative capture, and neutron inelastic scattering will be tracked properly, without any additional input from the user. The production and energy spectrum for the source fission gamma rays are modeled for the MCNP5-supplied 70c fissile and fissionable cross sections. The radiative capture cross sections for neutron absorption are also modeled, but one must be sure that the gamma-ray production cross section is included in the cross-section data for each reaction of interest. For example, radiative capture gamma-ray production for the naturally occurring cadmium isotopes is not included in the 70c or other cross sections available in the MCNP library. This information for each individual isotope can be found in Appendix G – MCNP Data Libraries of the MCNP manual. Typically, it is estimated that there are about seven gamma rays generated in the fission process at energies of about 1 MeV each. Another 1 to 12 MeV of radiative capture gamma rays can be emitted. This value is dependent on the type of reactor and absorbing materials in the fuel elements, structure, and control elements. For the ACRR, the total energy calculated for the prompt gamma rays (fission, radiative capture, and inelastic scattering) is ~13 MeV per fission.

Figures 24 and 25 show the MCNP-generated 48-energy group prompt gamma-ray fluence on a linear and logarithmic y-axis, respectively. The units on the y-axis are in energy fluence, equal to $E d\phi/dE$ (MeV/MeV-cm^2-MJ). With the energy fluence represented linearly on the y-axis and the photon energy on the x-axis represented logarithmically, the area under the curve represents the total prompt gamma-ray fluence. The gamma-ray energy fluence has a prominent peak at ~0.5 MeV and another peak at ~0.8 MeV.

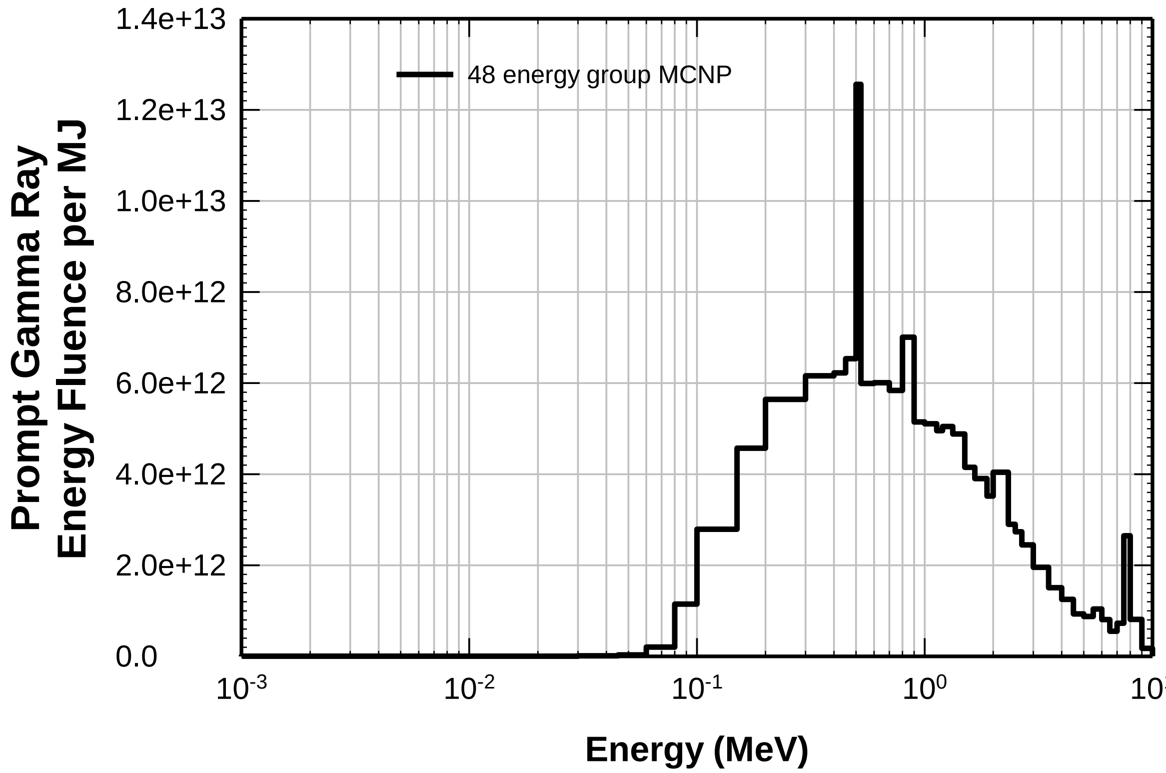


Figure 24. MCNP 48-Group Prompt Gamma-Ray Energy Spectrum (linear–log).

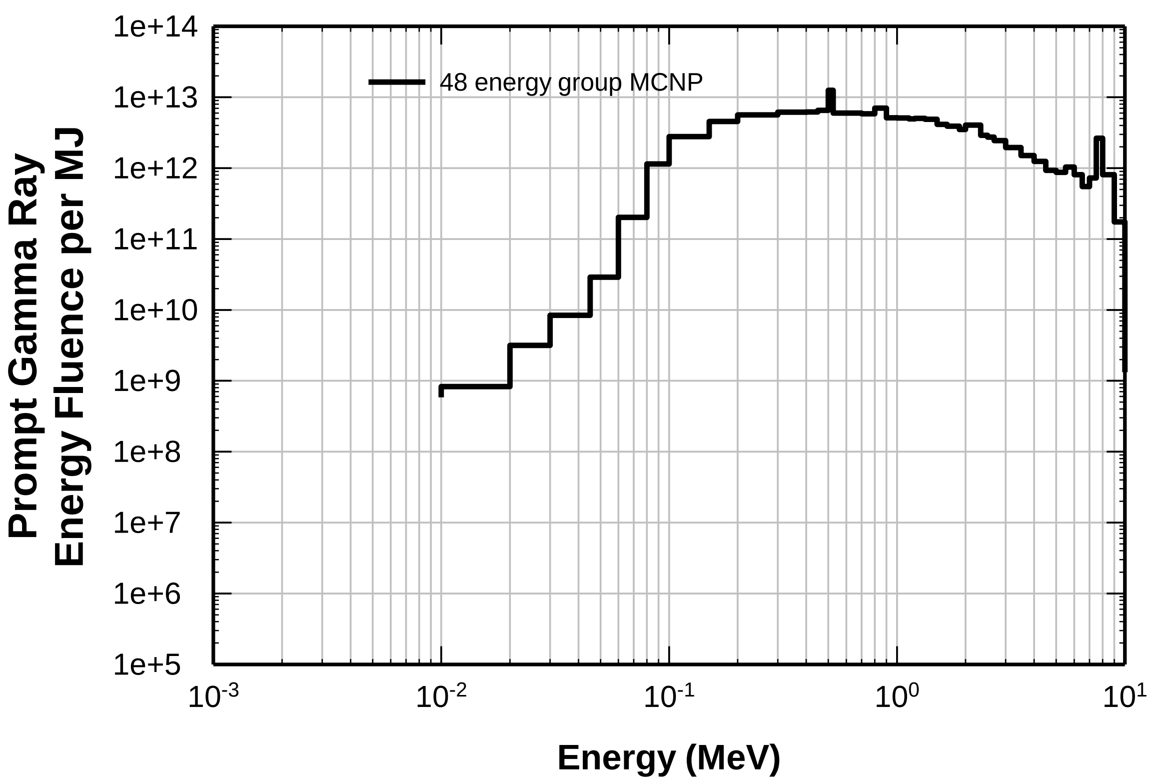


Figure 25. MCNP 48-Group Prompt Gamma-Ray Energy Spectrum (log–log).

Table 6 shows the prompt gamma-ray fluence spectrum in a tabular format for the 48-energy group NuGET structure. Column 5 represents the number fraction, column 6 the energy fraction, column 7 the differential number fraction, column 8 the differential energy fraction, and column 9 the percent standard deviation. The number fraction, represented as a histogram, can be used in MCNP source calculations as an isotropic spherical surface source. The average gamma-ray energy is calculated to be 1.086 MeV. The peak differential energy fluence occurs in energy group 14 at 0.5125 MeV. This is the large peak seen in Figure 24 and represents the electron-positron annihilation photon energy (0.511 MeV).

Table 6. Prompt Gamma-Ray 48-Energy Group Spectrum for ACRR-FF-CC-32-cl.

Group	Lower Energy (MeV)	Upper Energy (MeV)	Midpoint Energy (MeV)	Number Fraction	Energy Fraction	Differential Number dN/dE	Differential Energy dE/dE	Standard Deviation (%)
1	1.0000E-03	1.0000E-02	5.5000E-03	5.15736E-05	2.61255E-07	5.73040E-03	3.15172E-05	81.49
2	1.0000E-02	2.0000E-02	1.5000E-02	2.98099E-05	4.11838E-07	2.98099E-03	4.47149E-05	64.92
3	2.0000E-02	3.0000E-02	2.5000E-02	6.87775E-05	1.58366E-06	6.87775E-03	1.71944E-04	52.23
4	3.0000E-02	4.5000E-02	3.7500E-02	1.83031E-04	6.32164E-06	1.22020E-02	4.57577E-04	42.15
5	4.5000E-02	6.0000E-02	5.2500E-02	4.48487E-04	2.16862E-05	2.98991E-02	1.56970E-03	34.78
6	6.0000E-02	8.0000E-02	7.0000E-02	3.13358E-03	2.02029E-04	1.56679E-01	1.09675E-02	33.52
7	8.0000E-02	1.0000E-01	9.0000E-02	1.38005E-02	1.14396E-03	6.90024E-01	6.21022E-02	32.41
8	1.0000E-01	1.5000E-01	1.2500E-01	6.04916E-02	6.96434E-03	1.20983E+00	1.51229E-01	30.96
9	1.5000E-01	2.0000E-01	1.7500E-01	7.07061E-02	1.13964E-02	1.41412E+00	2.47471E-01	29.48
10	2.0000E-01	3.0000E-01	2.5000E-01	1.22278E-01	2.81555E-02	1.22278E+00	3.05695E-01	27.90
11	3.0000E-01	4.0000E-01	3.5000E-01	9.52927E-02	3.07187E-02	9.52927E-01	3.33525E-01	26.42
12	4.0000E-01	4.5000E-01	4.2500E-01	3.96581E-02	1.55237E-02	7.93163E-01	3.37094E-01	25.56
13	4.5000E-01	5.0000E-01	4.7500E-01	3.72878E-02	1.63130E-02	7.45756E-01	3.54234E-01	25.07
14	5.0000E-01	5.2500E-01	5.1250E-01	3.31967E-02	1.56698E-02	1.32787E+00	6.80532E-01	24.74
15	5.2500E-01	6.0000E-01	5.6250E-01	4.32663E-02	2.24154E-02	5.76884E-01	3.24497E-01	24.33
16	6.0000E-01	7.0000E-01	6.5000E-01	5.00434E-02	2.99595E-02	5.00434E-01	3.25282E-01	23.69
17	7.0000E-01	8.0000E-01	7.5000E-01	4.21569E-02	2.91209E-02	4.21569E-01	3.16177E-01	23.06
18	8.0000E-01	9.0000E-01	8.5000E-01	4.46685E-02	3.49699E-02	4.46685E-01	3.79682E-01	22.50
19	9.0000E-01	1.0000E+00	9.5000E-01	2.93463E-02	2.56774E-02	2.93463E-01	2.78790E-01	22.01
20	1.0000E+00	1.1250E+00	1.0625E+00	3.37624E-02	3.30398E-02	2.70099E-01	2.86980E-01	21.52
21	1.1250E+00	1.2000E+00	1.1625E+00	1.61247E-02	1.72647E-02	2.14995E-01	2.49932E-01	21.12
22	1.2000E+00	1.3300E+00	1.2650E+00	2.80830E-02	3.27196E-02	2.16023E-01	2.73269E-01	20.75
23	1.3300E+00	1.5000E+00	1.4150E+00	3.17871E-02	4.14268E-02	1.86983E-01	2.64581E-01	20.26
24	1.5000E+00	1.6600E+00	1.5800E+00	2.27706E-02	3.31365E-02	1.42317E-01	2.24860E-01	20.00
25	1.6600E+00	1.8750E+00	1.7675E+00	2.62815E-02	4.27843E-02	1.22239E-01	2.16058E-01	20.00
26	1.8750E+00	2.0000E+00	1.9375E+00	1.17851E-02	2.10305E-02	9.42808E-02	1.82669E-01	20.00
27	2.0000E+00	2.3330E+00	2.1665E+00	3.33717E-02	6.65905E-02	1.00215E-01	2.17117E-01	20.00
28	2.3330E+00	2.5000E+00	2.4165E+00	1.10588E-02	2.46133E-02	6.62204E-02	1.60022E-01	20.00
29	2.5000E+00	2.6600E+00	2.5800E+00	9.73780E-03	2.31396E-02	6.08613E-02	1.57022E-01	20.00
30	2.6600E+00	3.0000E+00	2.8300E+00	1.54334E-02	4.02274E-02	4.53923E-02	1.28460E-01	20.00
31	3.0000E+00	3.5000E+00	3.2500E+00	1.62952E-02	4.87772E-02	3.25904E-02	1.05919E-01	20.00
32	3.5000E+00	4.0000E+00	3.7500E+00	1.08777E-02	3.75701E-02	2.17554E-02	8.15826E-02	20.00
33	4.0000E+00	4.5000E+00	4.2500E+00	7.96836E-03	3.11912E-02	1.59367E-02	6.77311E-02	20.00
34	4.5000E+00	5.0000E+00	4.7500E+00	5.31217E-03	2.32402E-02	1.06243E-02	5.04656E-02	20.00
35	5.0000E+00	5.5000E+00	5.2500E+00	4.50661E-03	2.17913E-02	9.01322E-03	4.73194E-02	20.00
36	5.5000E+00	6.0000E+00	5.7500E+00	4.89178E-03	2.59065E-02	9.78355E-03	5.62554E-02	20.00
37	6.0000E+00	6.5000E+00	6.2500E+00	3.49738E-03	2.01325E-02	6.99477E-03	4.37173E-02	22.00
38	6.5000E+00	7.0000E+00	6.7500E+00	2.21312E-03	1.37589E-02	4.42625E-03	2.98772E-02	25.76
39	7.0000E+00	7.5000E+00	7.2500E+00	2.71146E-03	1.81057E-02	5.42292E-03	3.93162E-02	29.26
40	7.5000E+00	8.0000E+00	7.7500E+00	9.25132E-03	6.60359E-02	1.85026E-02	1.43396E-01	32.53
41	8.0000E+00	9.0000E+00	8.5000E+00	5.16339E-03	4.04230E-02	5.16339E-03	4.38888E-02	37.05
42	9.0000E+00	1.0000E+01	9.5000E+00	9.94072E-04	8.69794E-03	9.94072E-04	9.44368E-03	42.49
43	1.0000E+01	1.2000E+01	1.1000E+01	1.30536E-05	1.32251E-04	6.52682E-06	7.17950E-05	48.26
44	1.2000E+01	1.4000E+01	1.3000E+01	2.24649E-07	2.68981E-06	1.12324E-07	1.46022E-06	53.97
45	1.4000E+01	1.7000E+01	1.5500E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	59.98
46	1.7000E+01	2.0000E+01	1.8500E+01	2.12631E-08	3.62304E-07	7.08770E-09	1.31122E-07	66.02
47	2.0000E+01	3.0000E+01	2.5000E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	76.31
48	3.0000E+01	5.0000E+01	4.0000E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	92.37

The results for the number fraction, percent standard deviation, and covariance as a function of the 48-group energy structure are included in an LSL format in Appendix D of this report. The uncertainty and covariance matrix represents a combination of expert judgment and perturbation analyses using MCNP. The covariance matrix satisfies the spectrum normalization condition and is positive semi-definite, with non-negative eigenvalues.

The results for a number of integral metrics and conversion factors are shown in Table 7. Conversion values to translate to γ/cm^2 are given relative to fissions in the core, MJ of reactor energy, and $^{58}Ni(n,p)^{58}Co$ activity at the characterized location in the bucket. The same caveats presented in the neutron discussion using reactor power apply to the prompt gamma-rays. Table 7 also shows additional integral metrics that may be useful to the experimenter. These values were calculated using the 48-energy group gamma-ray spectrum and the NuGET code with various response functions. Included are responses for Si dose, C dose, GaAs dose, TLD dose, Alanine dose, and Teflon dose.

Table 7. Prompt Gamma-Ray Spectrum Metrics.

Metric	Integral Response
Average gamma-ray energy (MeV)	1.086
Fluence Conversion ($[\gamma/cm^2]/[n/cm^2]$)	0.922
Fluence Conversion ($[\gamma/cm^2]$/fission)	5.833E-04
Fluence Conversion ($[\gamma/cm^2]$/MJ)	1.892E+13
Fluence Conversion From Ni Activation $^{58}Ni(n,p)^{58}Co$ ($[\gamma/cm^2]/[Bq/atom_{Ni\text{-}58}]$)	3.530E+32
Fluence Conversion From Ni Activation $^{58}Ni(n,p)^{58}Co$ ($[\gamma/cm^2]/[Bq/g_{Ni\text{-}58}]$)	3.396E+10
Total (Ionizing) Si Dose (rad[Si]/$[\gamma/cm^2]$)	4.197E-10
Total (Ionizing) Carbon Dose (rad[C]/$[\gamma/cm^2]$)	3.975E-10
Total (Ionizing) GaAs Dose (rad[GaAs]/$[\gamma/cm^2]$)	4.844E-10
Total (Ionizing) CaF_2:Mn (TLD) Dose (rad[CaF_2:Mn]/$[\gamma/cm^2]$)	4.170E-10
Total Alanine Dose (rad[Alanine]/$[\gamma/cm^2]$)	4.463E-10
Total Teflon Dose (rad[Teflon]/$[\gamma/cm^2]$)	4.018E-10

3.3 Delayed Gamma Ray

Delayed gamma rays are generated by fission-product decay in the ACRR fuel and by the decay of activated materials in the reactor core. MCNP does not intrinsically calculate the source for these gamma rays. MCNPX or MCNP6 could be used with the burnup feature of the code to generate fission products and activation products in defined regions of the core. But in order to generate the decay gamma-ray source, a separate calculation would need to be performed that would generate the time-dependent or time-integrated gamma-ray energy spectrum from the unique isotopic inventory and gamma-ray lines. For the analysis presented in this report, a much simpler approach was taken. The assumption was made that only early-time fission product generated decay gamma rays would be modeled. This model ignores the gamma-ray contribution from neutron activation in the core. A generic fission product decay gamma-ray energy spectrum was used in the MCNP analysis and transported the gamma rays from the fission distribution in the ACRR fuel to the detector sphere in the central cavity.

MCNP Model Results – 48-Group Delayed Gamma-Ray Energy Spectrum

The decay gamma-ray fluence was calculated with MCNP using the source mode and with photons only. The same model of the ACRR and bucket configuration was used with a represented fission product gamma-ray source energy spectrum. The same 48-energy group structure was used as for prompt gamma rays. The fission-product delayed gamma-ray energy spectrum used was for fast U-235 fission in the time interval from 0.2 to 0.5 seconds as given in Engle (1962) and Fisher (1964). The gamma-ray source distribution within the ACRR fuel was radially by row in the core. The distribution function was generated from a separate MCNP k-code calculation by tallying the number of fissions in each row of fuel. A constant axial source distribution was assumed. The results gave the transported delayed gamma-ray fluence spectrum per source photon.

The total delayed gamma-ray energy released from the fission products used was 6.33 MeV per fission for U-235 fission from ENDF/B-VII.1. This value is about half of the value emitted as prompt gamma rays, and therefore cannot be ignored as a trivial quantity. The number of delayed gamma rays emitted per fission was then calculated to be 6.57 delayed photons/fission, using the source delayed gamma-ray energy spectrum for fast U-235 fission.

Figure 26 shows the delayed gamma-ray energy source distribution in units of gamma rays per MeV as a function of energy. This spectrum was used in a histogram format for the source calculation in MCNP described above. The resulting transported gamma-ray fluence to the tally sphere is in units of fluence per source delayed gamma ray. Figure 27 shows the time-integrated energy fraction from the emission of the delayed gamma rays on a per fission basis. Although fission products continue to decay over many years, the majority of the energy (~85%) is released from the shorter-lived products over 1E4 seconds (2.8 hours). The fractional energy release up to 0.1 s is ~1%, ~6.5% up to 1 s, ~23.2% up to 10 s, and ~55% up to 300 s (5 minutes).

Figures 28 and 29 show the MCNP-generated 48-energy group delayed gamma-ray fluence on a linear and logarithmic y-axis, respectively. The units on the y-axis are in energy fluence, equal to $E d\phi/dE$ (MeV/MeV-cm^2-MJ). With the energy fluence represented linearly on the y-axis and the photon energy on the x-axis represented logarithmically, the area under the curve represents the total gamma-ray fluence. The scale of the plots is the same as presented for the prompt gamma rays. The delayed gamma-ray energy fluence has a prominent peak at ~0.5 MeV.

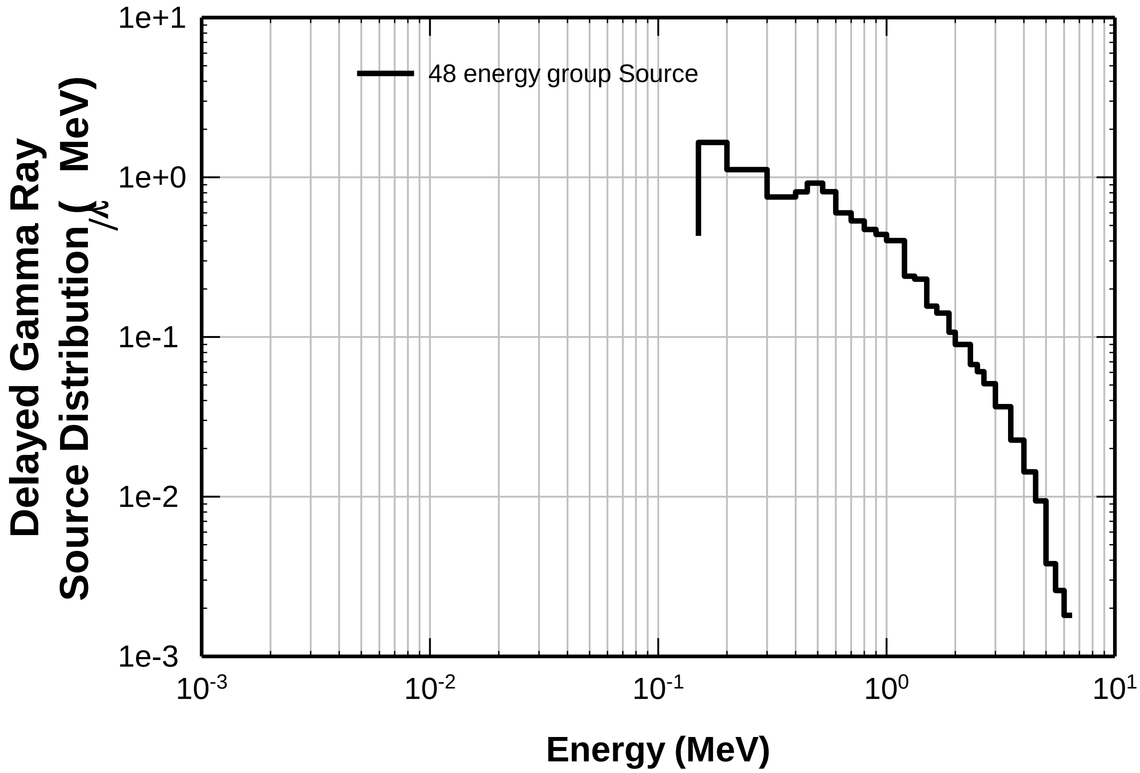


Figure 26. Delayed Gamma-Ray Source Distribution Used for MCNP Analysis.

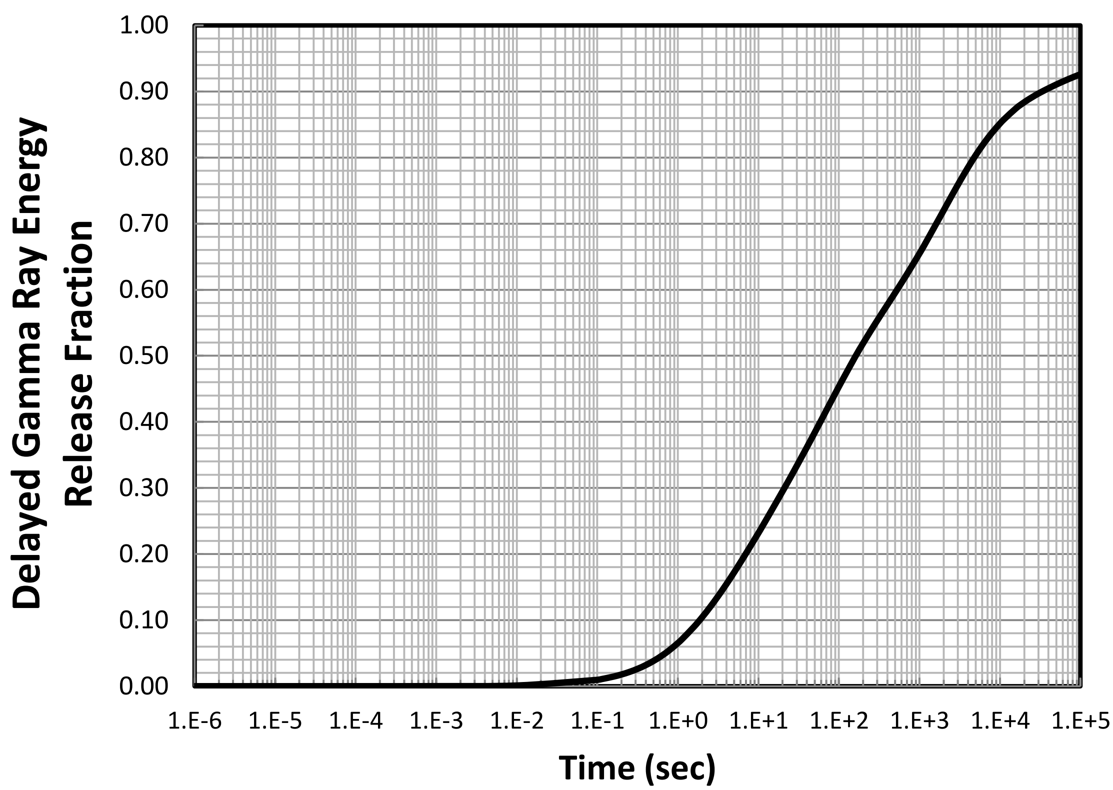


Figure 27. Time Dependent Delayed Gamma-Ray Energy Release Fraction from Fission.

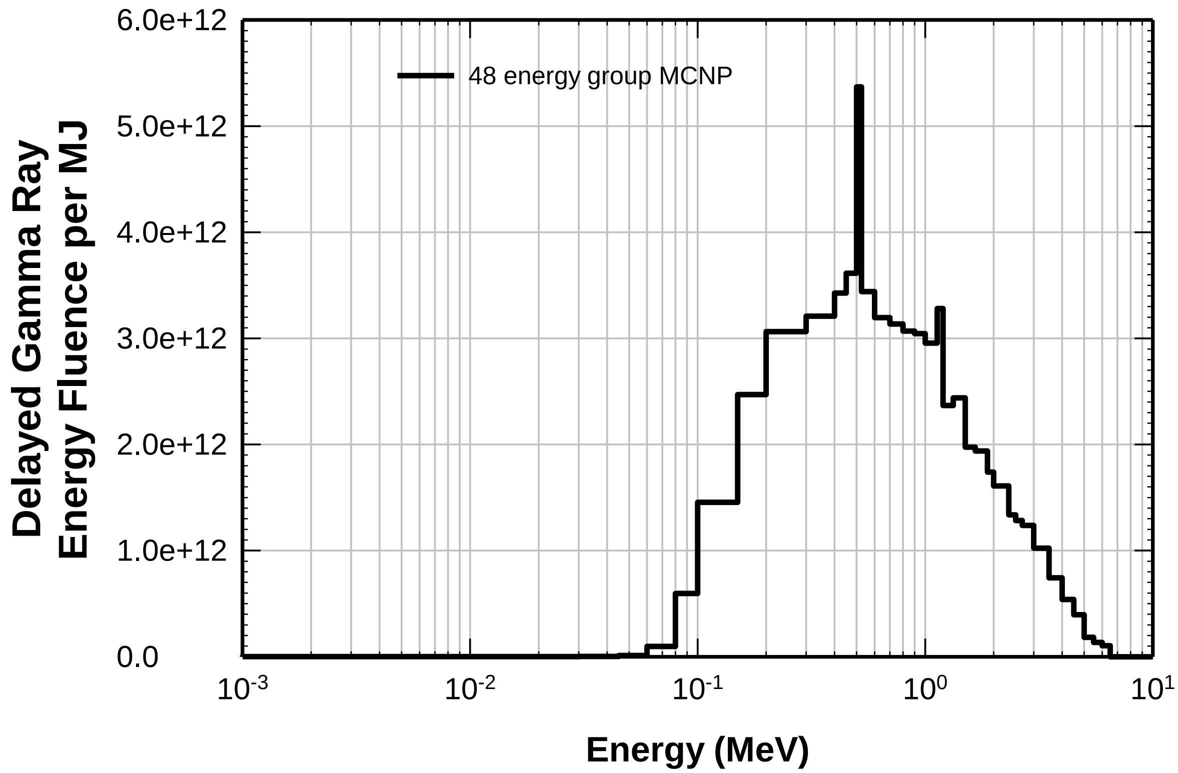


Figure 28. MCNP 48-Group Delayed Gamma-Ray Energy Spectrum (lin–log).

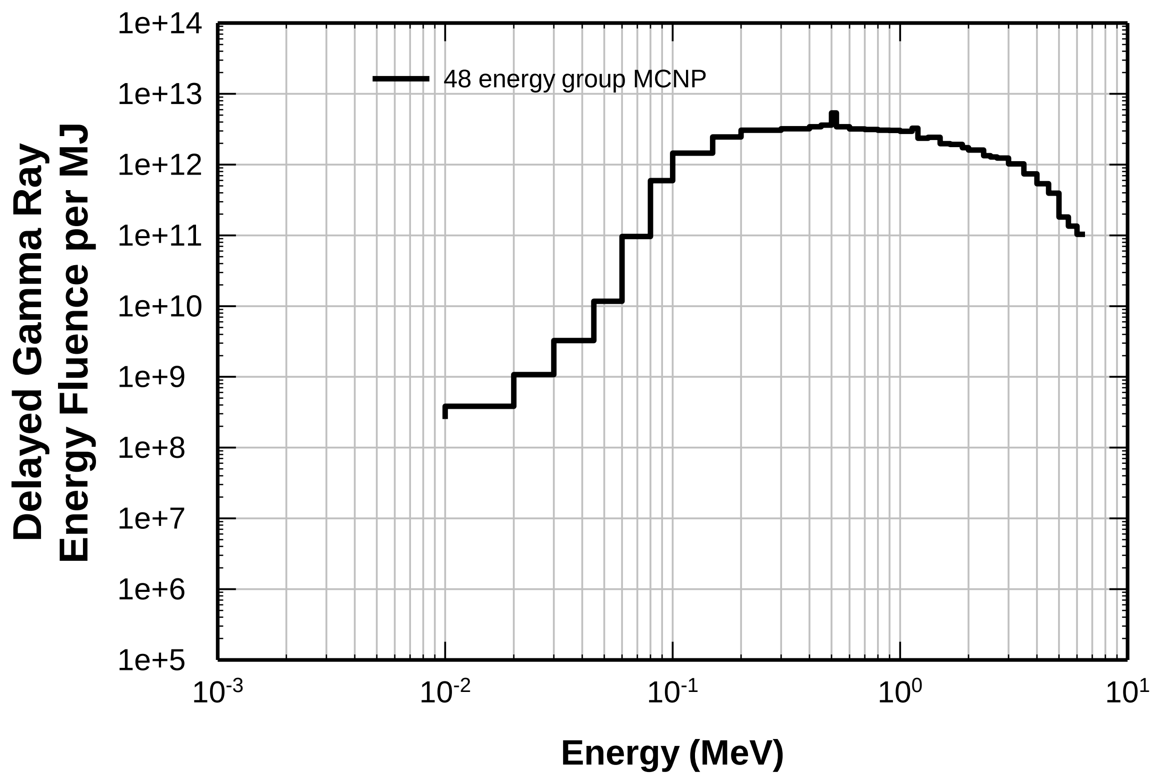


Figure 29. MCNP 48-Group Delayed Gamma-Ray Energy Spectrum (log–log).

Table 8 shows the delayed gamma-ray fluence spectrum in a tabular format for the 48-energy group NuGET structure. Column 5 represents the number fraction, column 6 the energy fraction, column 7 the differential number fraction, column 8 the differential energy fraction, and column 9 the percent standard deviation. The number fraction, represented as a histogram, can be used in MCNP source calculations as an isotropic spherical surface source. The average delayed gamma-ray energy is calculated to be 0.866 MeV. The peak differential energy fluence again occurs in energy group 14 at 0.5125 MeV. This is the large peak seen in Figure 28 and represents the electron-positron annihilation photon energy (0.511 MeV).

Table 8. Delayed Gamma-Ray 48-Energy Group Spectrum for ACRR-FF-CC-32-cl.

Group	Lower Energy (MeV)	Upper Energy (MeV)	Midpoint Energy (MeV)	Number Fraction	Energy Fraction	Differential Number dN/dE	Differential Energy dE/dE	Standard Deviation (%)
1	1.0000E-03	1.0000E-02	5.5000E-03	4.44752E-05	2.82401E-07	4.94169E-03	2.71793E-05	102.26
2	1.0000E-02	2.0000E-02	1.5000E-02	2.74447E-05	4.75265E-07	2.74447E-03	4.11671E-05	101.64
3	2.0000E-02	3.0000E-02	2.5000E-02	4.60495E-05	1.32908E-06	4.60495E-03	1.15124E-04	101.50
4	3.0000E-02	4.5000E-02	3.7500E-02	1.40194E-04	6.06939E-06	9.34624E-03	3.50484E-04	74.71
5	4.5000E-02	6.0000E-02	5.2500E-02	3.60116E-04	2.18267E-05	2.40077E-02	1.26041E-03	53.46
6	6.0000E-02	8.0000E-02	7.0000E-02	2.96827E-03	2.39877E-04	1.48414E-01	1.03890E-02	53.39
7	8.0000E-02	1.0000E-01	9.0000E-02	1.42310E-02	1.47864E-03	7.11550E-01	6.40395E-02	54.04
8	1.0000E-01	1.5000E-01	1.2500E-01	6.25204E-02	9.02231E-03	1.25041E+00	1.56301E-01	46.59
9	1.5000E-01	2.0000E-01	1.7500E-01	7.58651E-02	1.53273E-02	1.51730E+00	2.65528E-01	42.42
10	2.0000E-01	3.0000E-01	2.5000E-01	1.31755E-01	3.80271E-02	1.31755E+00	3.29387E-01	42.26
11	3.0000E-01	4.0000E-01	3.5000E-01	9.86136E-02	3.98465E-02	9.86136E-01	3.45147E-01	42.27
12	4.0000E-01	4.5000E-01	4.2500E-01	4.33565E-02	2.12730E-02	8.67131E-01	3.68531E-01	44.29
13	4.5000E-01	5.0000E-01	4.7500E-01	4.09018E-02	2.24296E-02	8.18036E-01	3.88567E-01	41.90
14	5.0000E-01	5.2500E-01	5.1250E-01	2.81616E-02	1.66624E-02	1.12647E+00	5.77313E-01	38.54
15	5.2500E-01	6.0000E-01	5.6250E-01	4.93459E-02	3.20450E-02	6.57946E-01	3.70095E-01	38.97
16	6.0000E-01	7.0000E-01	6.5000E-01	5.28658E-02	3.96710E-02	5.28658E-01	3.43627E-01	14.55
17	7.0000E-01	8.0000E-01	7.5000E-01	4.49723E-02	3.89396E-02	4.49723E-01	3.37292E-01	10.71
18	8.0000E-01	9.0000E-01	8.5000E-01	3.88241E-02	3.80984E-02	3.88241E-01	3.30005E-01	9.11
19	9.0000E-01	1.0000E+00	9.5000E-01	3.44577E-02	3.77917E-02	3.44577E-01	3.27349E-01	7.97
20	1.0000E+00	1.1250E+00	1.0625E+00	3.88060E-02	4.76008E-02	3.10448E-01	3.29851E-01	7.17
21	1.1250E+00	1.2000E+00	1.1625E+00	2.12077E-02	2.84625E-02	2.82770E-01	3.28720E-01	5.45
22	1.2000E+00	1.3300E+00	1.2650E+00	2.61554E-02	3.81977E-02	2.01195E-01	2.54512E-01	4.59
23	1.3300E+00	1.5000E+00	1.4150E+00	3.15041E-02	5.14648E-02	1.85318E-01	2.62226E-01	4.72
24	1.5000E+00	1.6600E+00	1.5800E+00	2.14963E-02	3.92109E-02	1.34352E-01	2.12276E-01	5.08
25	1.6600E+00	1.8750E+00	1.7675E+00	2.58940E-02	5.28378E-02	1.20437E-01	2.12873E-01	5.12
26	1.8750E+00	2.0000E+00	1.9375E+00	1.15650E-02	2.58687E-02	9.25202E-02	1.79258E-01	5.32
27	2.0000E+00	2.3330E+00	2.1665E+00	2.63613E-02	6.59343E-02	7.91631E-02	1.71507E-01	6.01
28	2.3330E+00	2.5000E+00	2.4165E+00	1.01160E-02	2.82215E-02	6.05747E-02	1.46379E-01	6.89
29	2.5000E+00	2.6600E+00	2.5800E+00	9.07285E-03	2.70240E-02	5.67053E-02	1.46300E-01	7.48
30	2.6600E+00	3.0000E+00	2.8300E+00	1.54827E-02	5.05847E-02	4.55374E-02	1.28871E-01	8.42
31	3.0000E+00	3.5000E+00	3.2500E+00	1.69224E-02	6.34936E-02	3.38447E-02	1.09995E-01	9.95
32	3.5000E+00	4.0000E+00	3.7500E+00	1.06446E-02	4.60836E-02	2.12892E-02	7.98344E-02	11.56
33	4.0000E+00	4.5000E+00	4.2500E+00	6.81681E-03	3.34469E-02	1.36336E-02	5.79429E-02	12.94
34	4.5000E+00	5.0000E+00	4.7500E+00	4.47654E-03	2.45483E-02	8.95308E-03	4.25271E-02	14.12
35	5.0000E+00	5.5000E+00	5.2500E+00	1.86439E-03	1.13001E-02	3.72878E-03	1.95761E-02	15.14
36	5.5000E+00	6.0000E+00	5.7500E+00	1.26474E-03	8.39565E-03	2.52948E-03	1.45445E-02	16.02
37	6.0000E+00	6.5000E+00	6.2500E+00	8.92766E-04	6.44174E-03	1.78553E-03	1.11596E-02	100.00
38	6.5000E+00	7.0000E+00	6.7500E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
39	7.0000E+00	7.5000E+00	7.2500E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
40	7.5000E+00	8.0000E+00	7.7500E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
41	8.0000E+00	9.0000E+00	8.5000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
42	9.0000E+00	1.0000E+01	9.5000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
43	1.0000E+01	1.2000E+01	1.1000E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
44	1.2000E+01	1.4000E+01	1.3000E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
45	1.4000E+01	1.7000E+01	1.5500E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
46	1.7000E+01	2.0000E+01	1.8500E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
47	2.0000E+01	3.0000E+01	2.5000E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00
48	3.0000E+01	5.0000E+01	4.0000E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	100.00

The results for the number fraction, percent standard deviation, and covariance as a function of the 48-group energy structure are included in an LSL format in Appendix E of this report. The covariance matrix represents a combination of expert judgment and perturbation analyses using MCNP. The covariance matrix satisfies the spectrum normalization condition and is positive definite, with non-negative eigenvalues.

The results for a number of integral metrics and conversion factors are shown in Table 9. Conversion values to translate to γ/cm^2 are given for fissions in the core, MJ of reactor energy, and $^{58}Ni(n,p)^{58}Co$ activity at the characterized location in the bucket. The same caveats presented in the neutron discussion using reactor power apply to the delayed gamma rays. Table 9 also shows additional integral metrics that may be useful to the experimenter. These values were calculated using the 48-energy group gamma-ray spectrum and the NuGET code with various response functions. Included are responses for Si dose, C dose, GaAs dose, TLD dose, Alanine dose, and Teflon dose.

Table 9. Delayed Gamma-Ray Spectrum Metrics.

Metric	Integral Response
Average delayed gamma-ray (dγ) energy (MeV)	0.866
Fluence Conversion ([dγ/cm^2]/[source dγ])	4.366E-05
Source Delayed Gamma Rays (source dγ/fission)	6.567
Fluence Conversion ([dγ/cm^2]/[γ/cm^2])	0.504
Fluence Conversion ([dγ/cm^2]/fission)	2.938E-04
Fluence Conversion ([dγ/cm^2]/MJ)	9.536E+12
Fluence Conversion From Ni Activation $^{58}Ni(n,p)^{58}Co$ ([dγ/cm^2]/[Bq/$atom_{Ni-58}$])	1.781E+32
Fluence Conversion From Ni Activation $^{58}Ni(n,p)^{58}Co$ ([dγ/cm^2]/[Bq/g_{Ni-58}])	1.712E+10
Total (Ionizing) Si Dose (rad[Si]/[dγ/cm^2])	3.548E-10
Total (Ionizing) Carbon Dose (rad[C]/[dγ/cm^2])	3.443E-10
Total (Ionizing) GaAs Dose (rad[GaAs]/[dγ/cm^2])	4.061E-10
Total (Ionizing) CaF_2:Mn (TLD) Dose (rad[CaF_2:Mn]/[dγ/cm^2])	3.527E-10
Total Alanine Dose (rad[Alanine]/[dγ/cm^2])	3.892E-10
Total Teflon Dose (rad[Teflon]/[dγ/cm^2])	3.468E-10

4. Radial and Axial Fluence Profiles

Passive dosimetry was used to determine the axial and radial neutron and gamma-ray fluence profiles for the free-field environment. From these profiles, the peak axial fluence location can be determined as well as any radial variation. For these runs, the reactor was operated in both pulse and steady-state modes. Sulfur tablets and TLDs were used for the axial profiles, and sulfur tablets, Au foils, and TLDs were used for the radial profiles. The axial profiles were performed at the radial centerline of the central cavity. The radial profiles were performed at an axial position 13 inches from the top of the 32 inch pedestal. Figure 30 shows the axial dosimetry fixture with sulfur tablets and TLDs at 1 cm increments along the axial height within the central cavity. Figure 31 shows the radial dosimetry fixture used for sulfur tablets, Au foils, and TLDs.

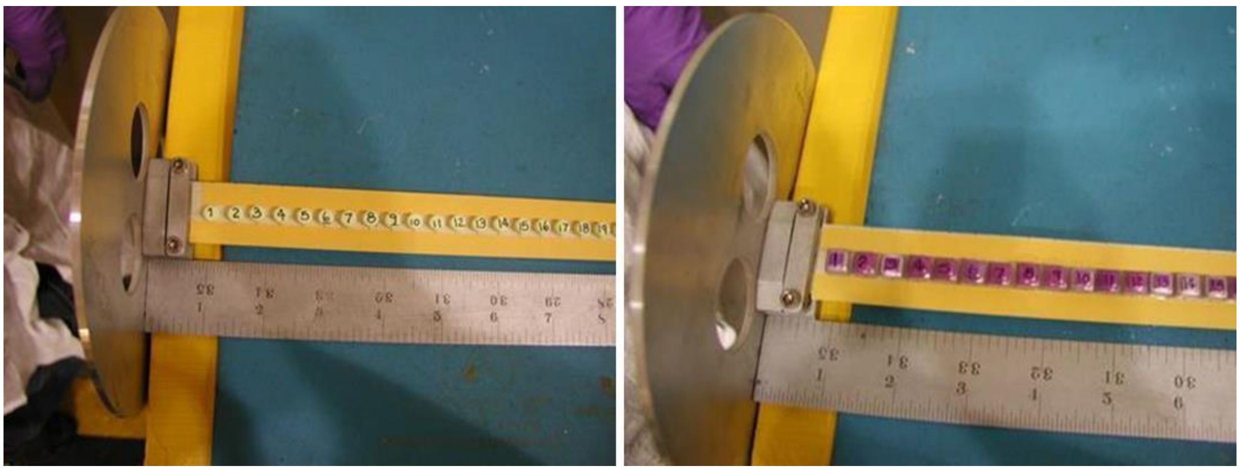


Figure 30. Axial Profile Mapping Fixture for Sulfur Tablets (left) and TLDs (right).

Figure 31. Radial Profile Mapping Fixture for Sulfur Tablets and Gold Foils.

4.1 Neutron-Sulfur Map

Figure 32 shows the results for the sulfur axial (vertical) neutron fast fluence profile along the axis of the central cavity. The sulfur activation reaction is $^{32}S(n,p)^{32}P$, which is a fast neutron reaction. The ^{32}P decays by β- emission with a 14.3 day half-life. The y-axis is in units of californium (^{252}Cf) equivalent fluence, which is related to how a transfer calibration from NIST is used to calibrate the sulfur beta counter. The results show that the peak occurs at about 33 cm (~13 in.) from the top of the 32 inch pedestal. The peak is relatively flat between the regions of 30 cm to 35 cm, covering a range of about 5 cm (~2 in.). For reference, the axial fuel centerline is ~33 cm (13 inches) from the top of the 32 inch pedestal. The ACRR fuel is 52.25 cm in length (20.57 inches). The range in which the fuel extends in Figure 32 is from ~7 cm to ~59 cm.

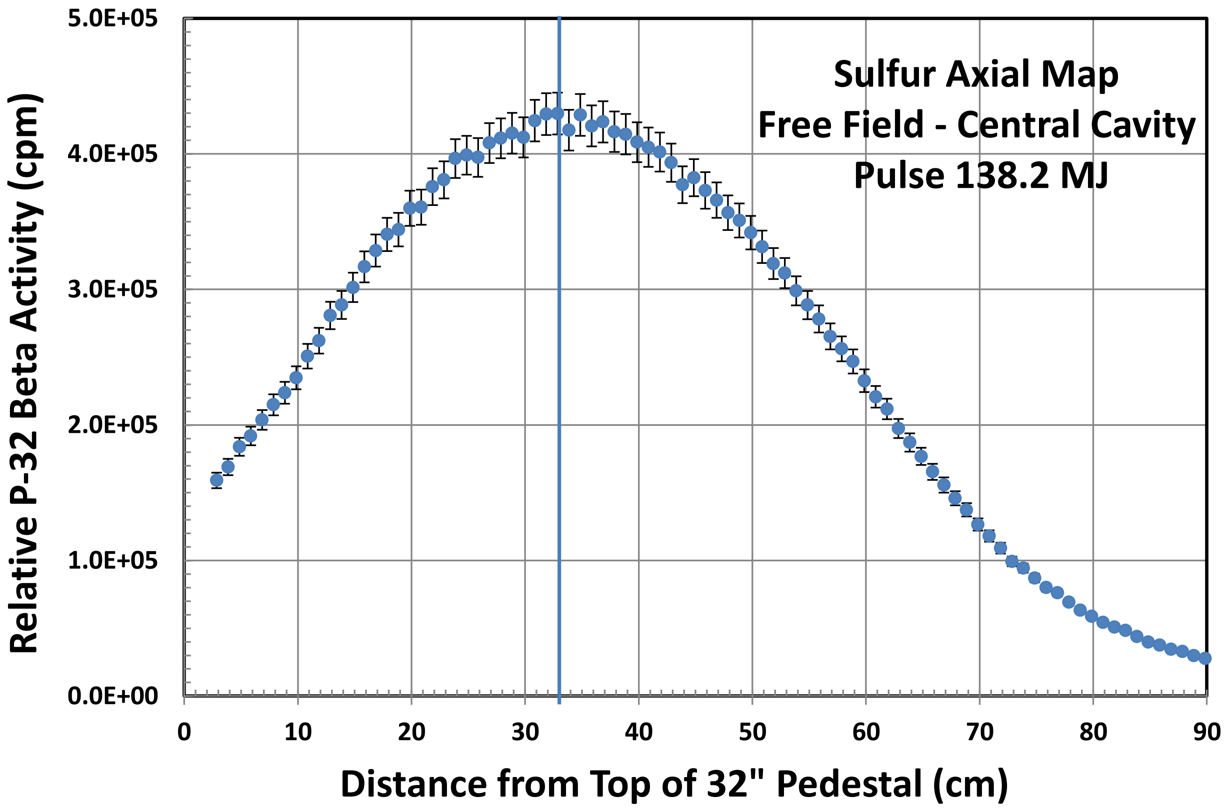


Figure 32. Sulfur Axial Neutron Fluence Profile for FF-CC-32.

Figure 33 shows the results comparing the axial (vertical) sulfur fluence maps for the free-field environment using pulse versus steady-state operations. No differences are found in the results. This indicates that the pulse and steady-state conditions are the same.

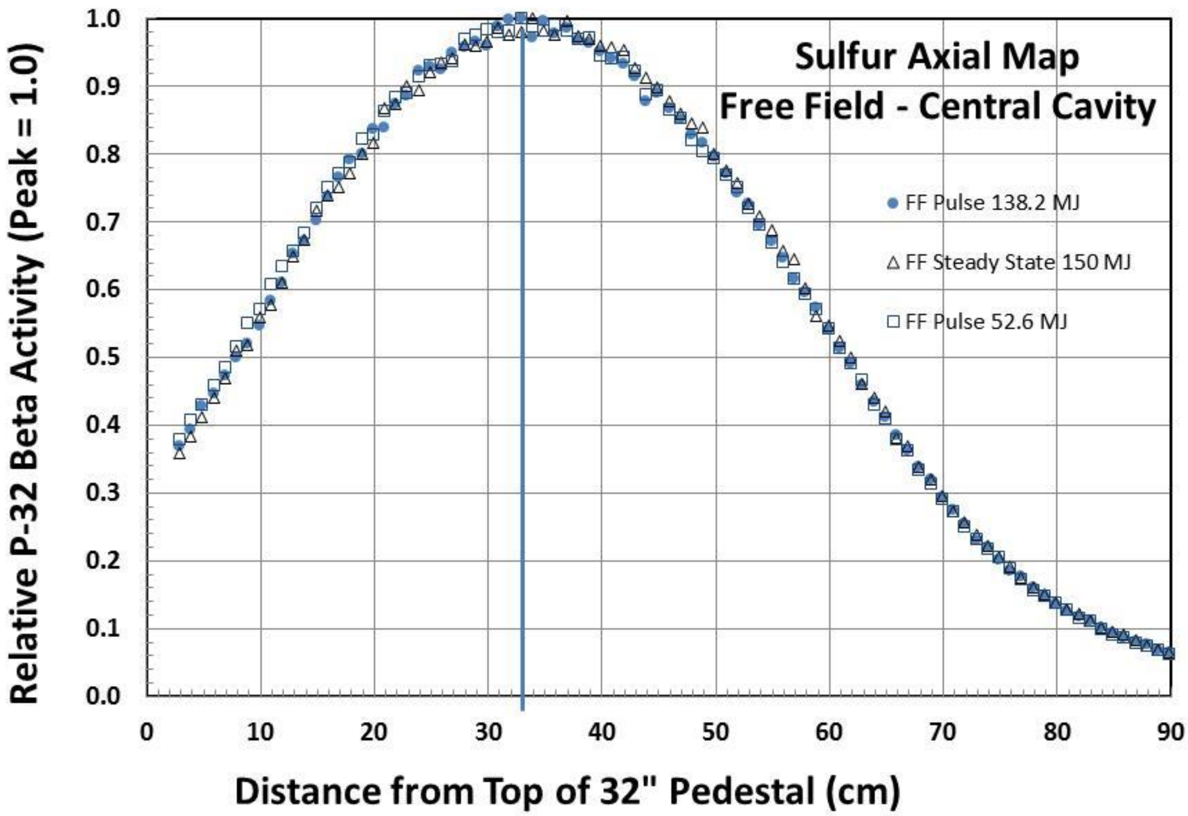


Figure 33. Sulfur Axial Neutron Fluence Profile Comparisons.

Figures 34 and 35 show the results for the sulfur radial neutron fluence profile for the free-field environment at an axial position of 13 inches from the top of the 32 inch pedestal for the sulfur tables arranged perpendicular and parallel to the front face of the FREC-II, respectively. The sulfur tablets were arranged on a plate that covered the complete area within the 9-inch-diameter cavity. Both plots have the same y-axis scaling. The solid line represents the average value for all of the tablets measured on the plate. The counting uncertainties are within each data point symbol. Each major unit represents a 1% change in the fluence. The results show that for the sulfur activation reactions, there is no significant variation in the fast neutron fluence across the internal diameter of the cavity at the peak axial location.

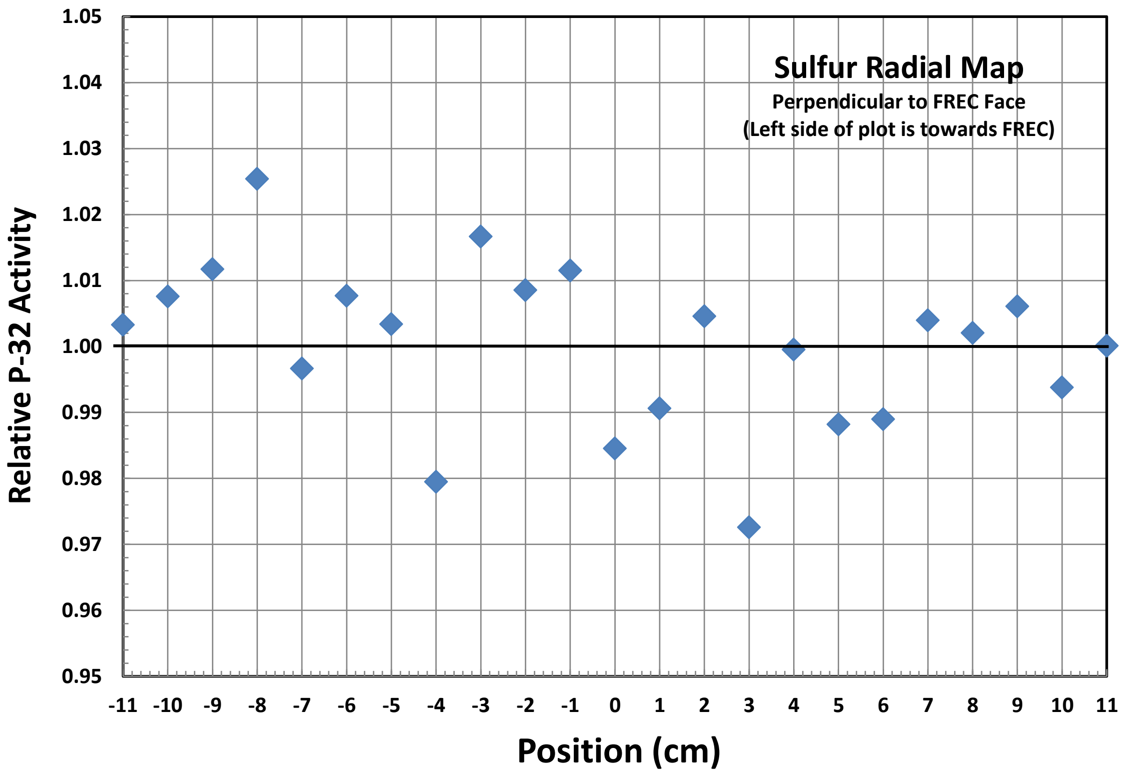


Figure 34. Sulfur Radial Neutron Fluence Profile for FF-CC-32-cl Perpendicular to FREC.

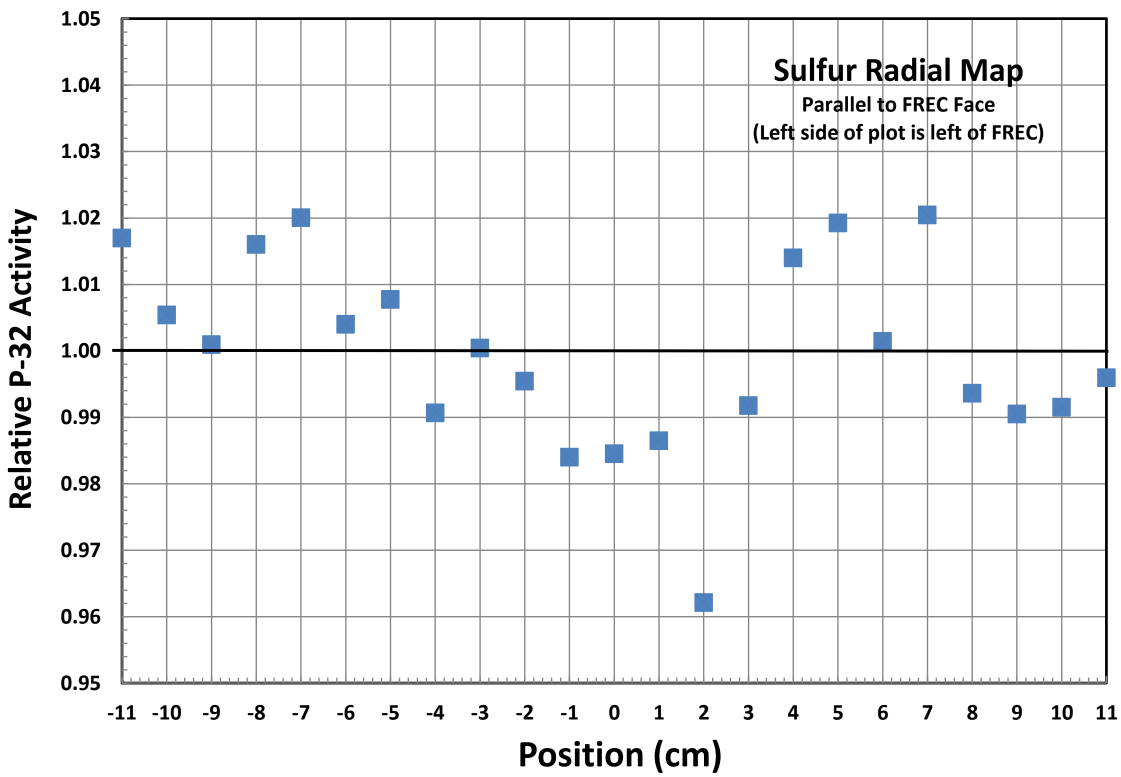


Figure 35. Sulfur Radial Neutron Fluence Profile for FF-CC-32-cl Parallel to FREC.

4.2 Neutron-Gold Map

Figures 36 and 37 show the results for the radial thermal neutron fluence profile as measured with the $^{197}Au(n,\gamma)$ reaction for the free-field environment at an axial position 13 inches from the top of the 32 inch pedestal for the foils arranged perpendicular and parallel to the front face of FREC-II, respectively. The $^{197}Au(n,\gamma)$ reaction is a thermal neutron reaction and hence, the results represent the thermal neutron fluence profile. The foils were arranged on a plate that covered the complete area within the 9-inch-diameter cavity. Both plots have the same y-axis scaling. The solid line represents the average value for all of the foils measured on the plate. Each major unit represents a 1% change. The results show that for the gold activation reactions, there is no statistically significant variation in the thermal neutron fluence across the internal diameter of the bucket at the peak axial location.

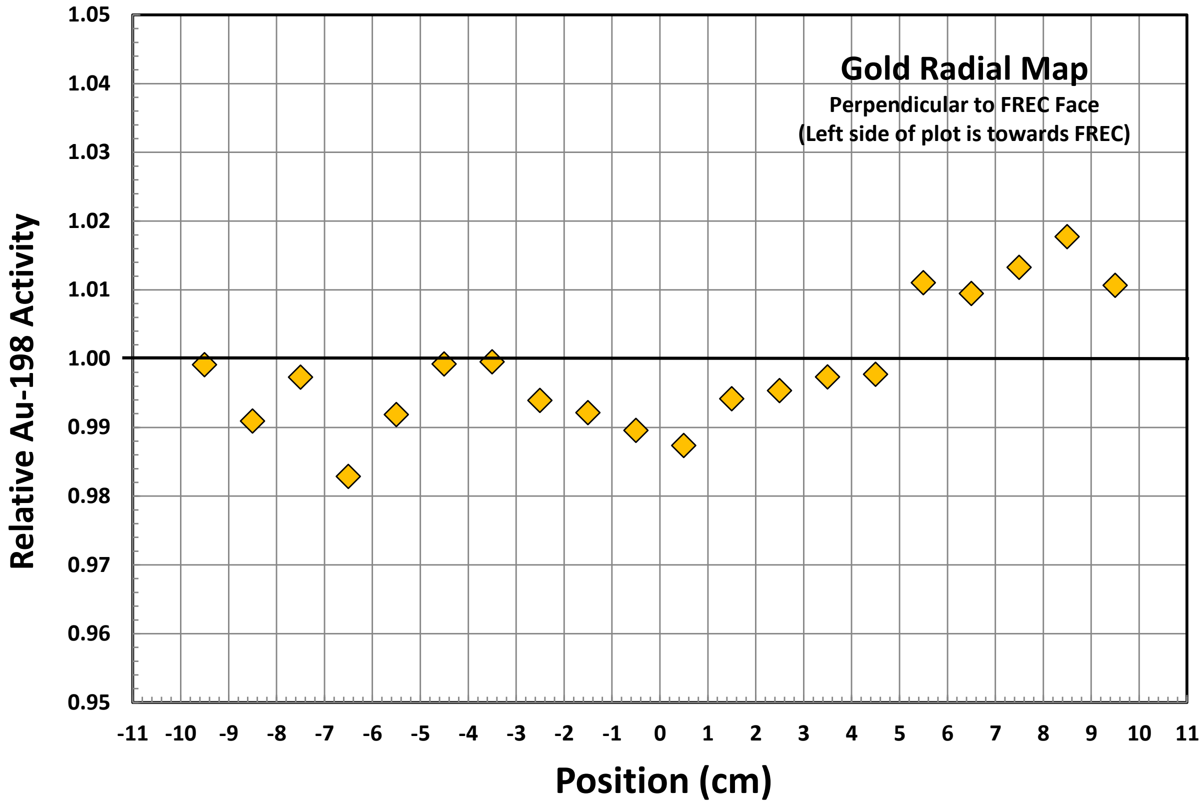


Figure 36. Gold Radial Neutron Fluence Profile for FF-CC-32-cl Perpendicular to FREC.

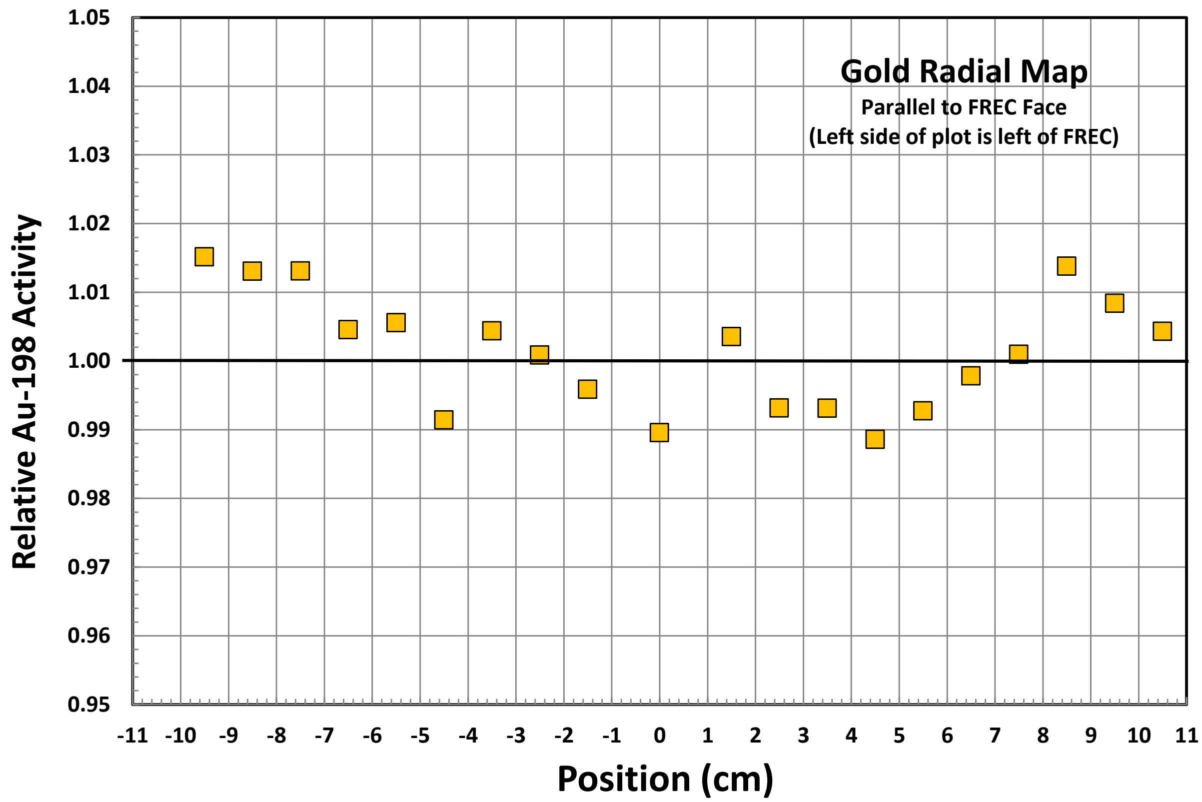


Figure 37. Gold Radial Neutron Fluence Profile for FF-CC-32-cl Parallel to FREC.

4.3 Gamma-Ray TLD Map

Figure 38 shows the results for the TLD axial gamma fluence profile for the free-field environment. The y-axis is in units of absorbed dose in Gray (Gy) for the TLD material CaF_2:Mn. One Gy is equal to 100 rads. Note that the CaF_2:Mn TLDs have a small sensitivity to neutrons. The CaF_2:Mn TLD responds to absorbed dose induced by neutron deposited energy with about a factor of 10 less light emission than seen for a similar photon-induced deposited dose. Again, this scale is completely arbitrary for the purposes of this analysis. The results show that, as for the sulfur results, the peak occurs at about 33 cm (~13 inches) from the top of the 32 inch pedestal. The peak is relatively flat between the regions of 25 cm to 45 cm, covering a range of about 20 cm (~8 in.).

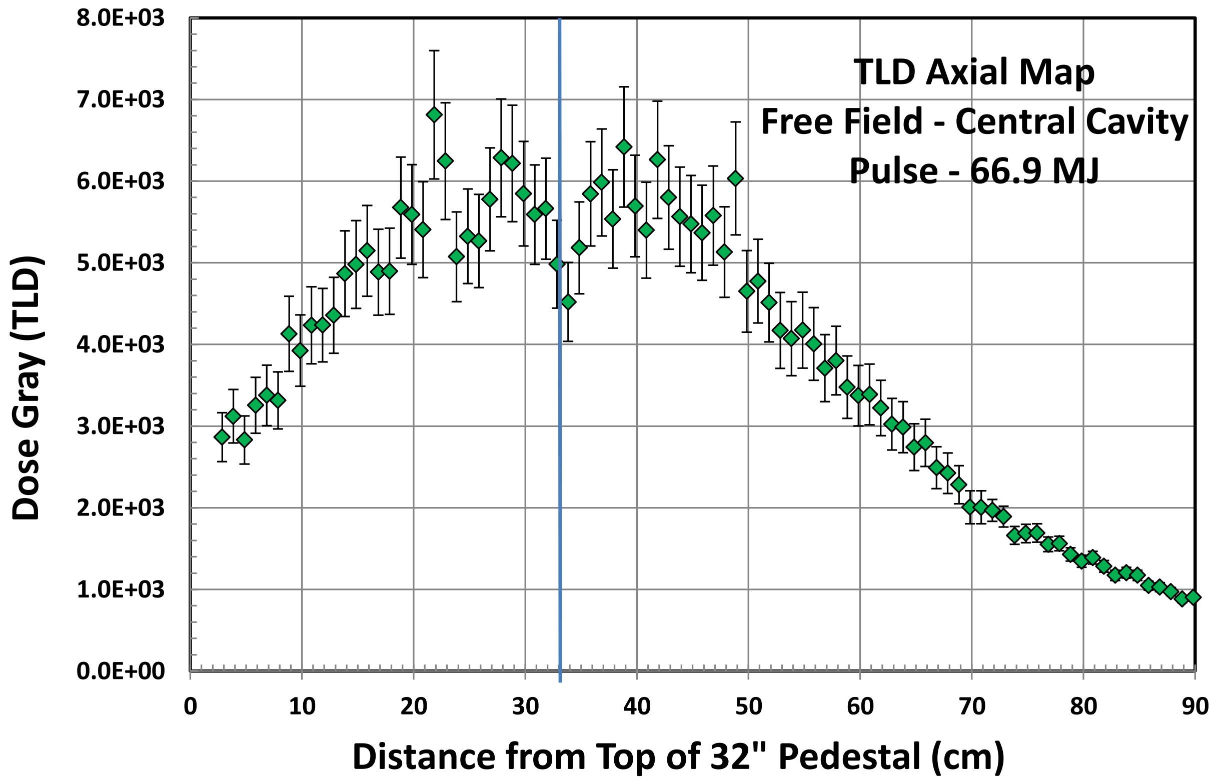


Figure 38. TLD Axial Gamma-Ray Fluence Profile for FF-CC-32.

Figure 39 shows the results comparing the TLD axial gamma fluence profile for a steady-state operation. No statistically significant differences are found in the results. This indicates that the pulse and steady-state conditions are the same.

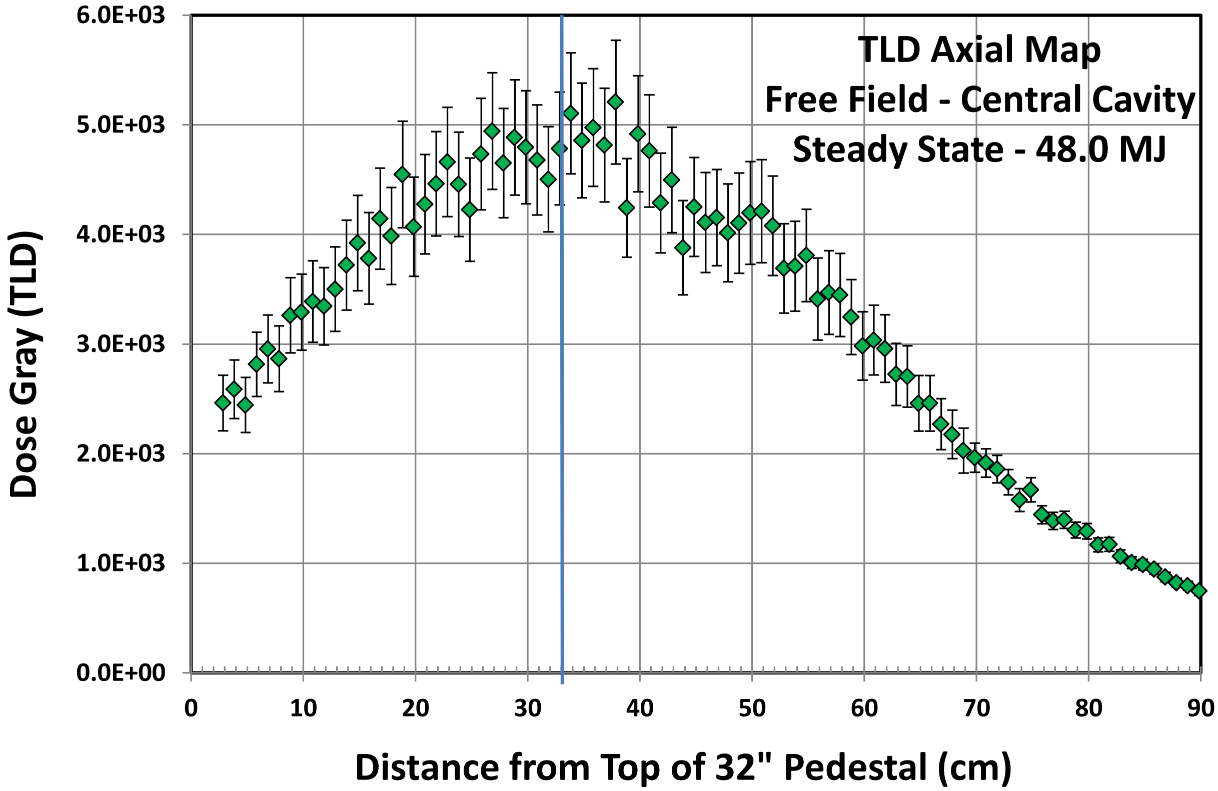


Figure 39. TLD Axial Gamma-Ray Fluence Profile Comparisons.

Figures 40 and 41 show the results for the TLD radial gamma fluence profile for the free-field environment at an axial position of 13 inches for the TLDs arranged perpendicular and parallel to the front face of the FREC-II, respectively. The TLDs were arranged on a plate that covered the complete area within the 9-inch-diameter cavity. Both plots have the same y-axis scaling. The solid line in each figure represents the average value for all of the TLDs measured in the perpendicular or parallel direction on the plate and the dashed line the average for all of the TLDs measured. Each major unit represents a 2% change. The results show that for the TLD response, there is no statistically significant variation in the fluence across the internal diameter of the cavity at the peak axial location.

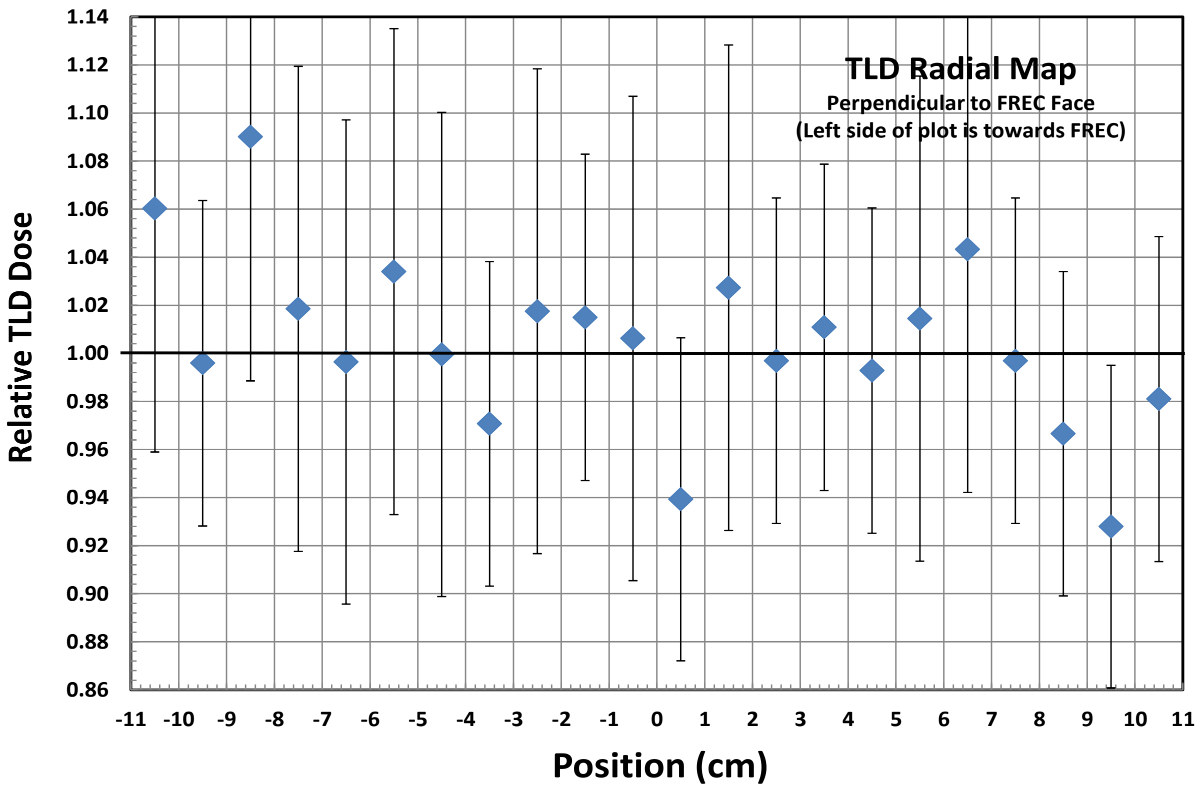


Figure 40. TLD Radial Gamma Fluence Profile for FF-CC-32-cl Perpendicular to FREC.

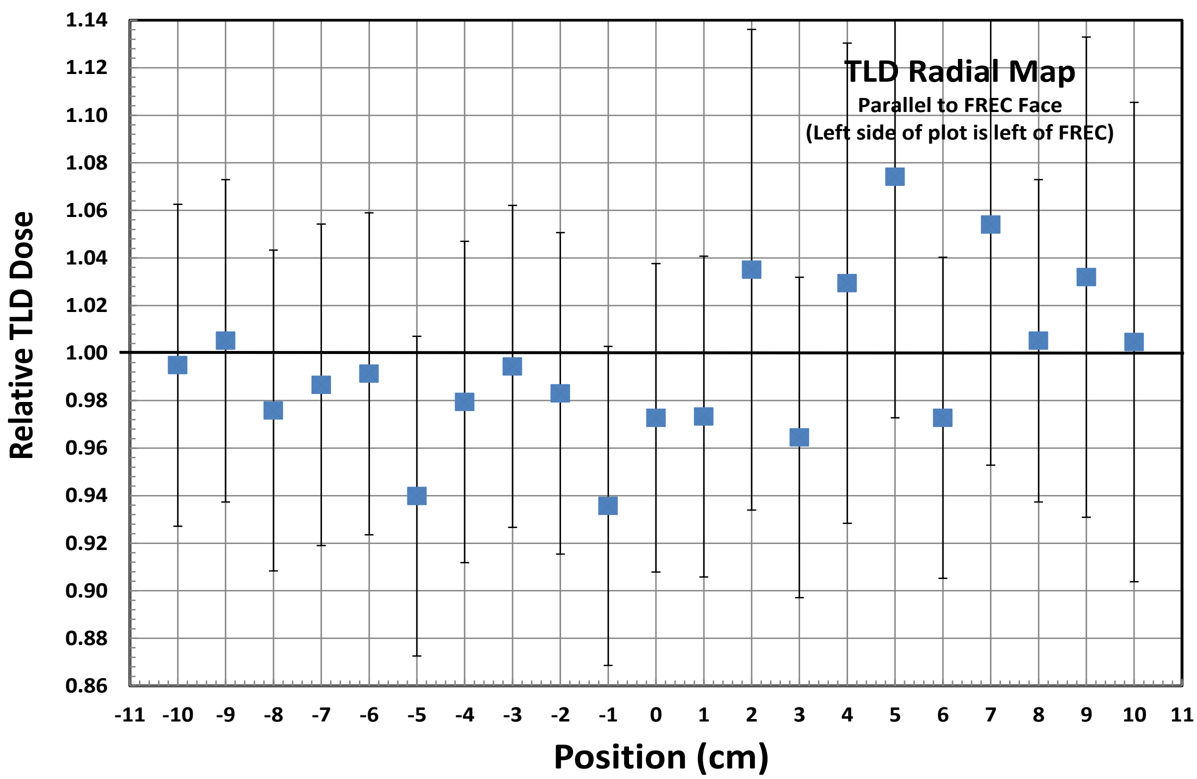


Figure 41. TLD Radial Gamma Fluence Profile for FF-CC-32-cl Parallel to FREC.

5. Sample Operations

Three sample ACRR operations are presented for ACRR-FF-CC-32-cl to show how dosimetry data can be used to determine the derived metrics, such as neutron fluence, 1-MeV Si equivalent fluence, prompt and delayed gamma-ray fluence, and dose. The radiation environment conversion factors and metrics used are those presented in Tables 4 and 5 for neutrons, Table 7 for prompt gamma rays, and Table 9 for delayed gamma rays. Typically Ni foils and/or sulfur tablets are used to establish the normalization factors for comparative experiments. Of course, once an experiment is placed in the bucket, the irradiation conditions can, and will change depending on many factors, such as experiment neutron moderation, absorption, etc. Due diligence must be paid to ensure that the results of the experiment are valid within uncertainty bounds. Both experimental and analytical work must be performed along with expert judgment to ensure the integrity of the results.

The sample operations represent a small, medium, and large pulse operation for the free-field environment. For each operation active dosimetry was fielded that included a diamond photoconductive detector (PCD), Si calorimeter, and Bi calorimeter at the axial centerline of the ACRR. Passive dosimetry included a Ni foil, sulfur tablets, and TLDs. The PCD fielded was a 1 mm x 2 mm x 1 mm diamond biased to 750 VDC.

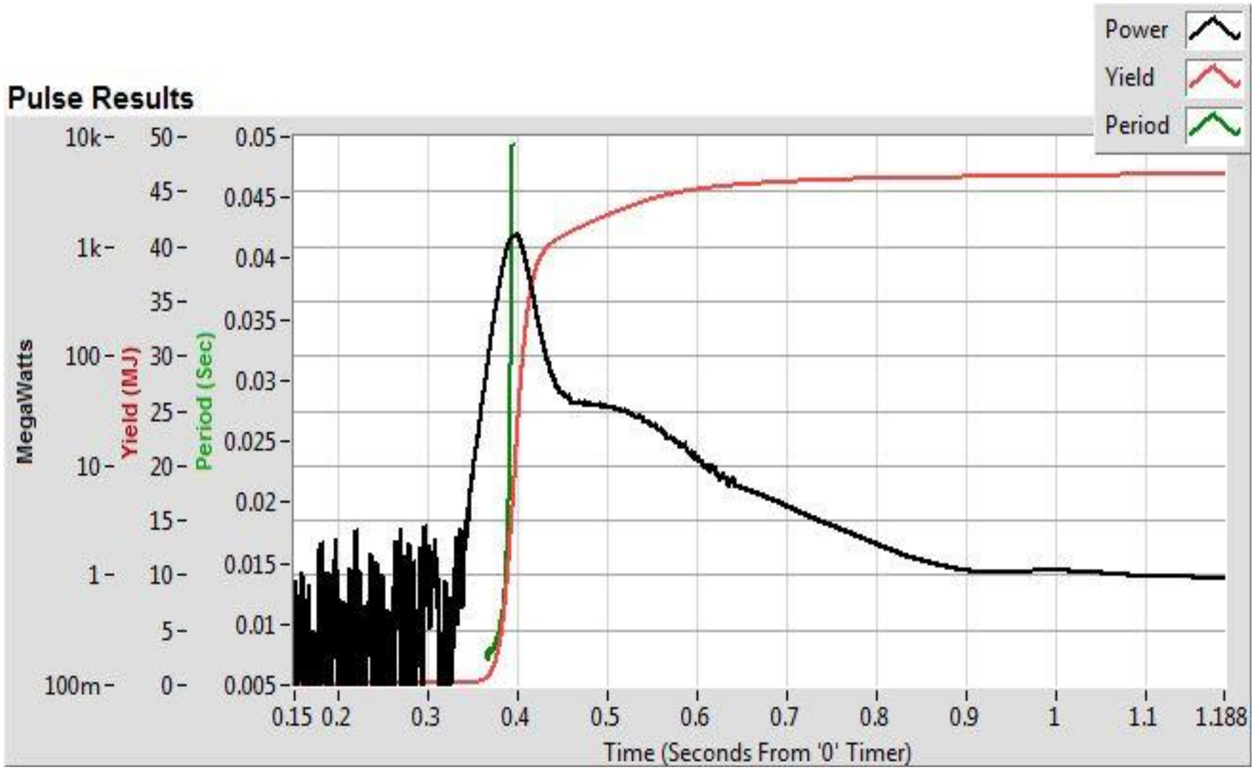
5.1 Small Pulse Operation

A small pulse operation (~50 MJ) was performed on 11/19/2013 for ACRR-FF-CC-32-cl using both active and passive dosimetry. The reactor was operated in the pulse mode with a reactivity addition of $1.45. The reactor shot number was #10724. Figure 42 shows the shot information for the run. Figure 43 shows the power history and cumulative reactor energy from the ACRR pulse diagnostic system. The reported reactor energy was 42.074 MJ taken at the peak of the pulse plus three full-width half maximum (FWHM) time values. The reported total reactor energy was 50.981 MJ from the pulse diagnostics information. Figure 44 shows the results for the switched PCD transient response after the data was renormalized. Figure 45 and 46 show the results for the Bi and Si calorimeters transient response, respectively.

Shot Information			Predicted Values		
Run Number	10724		Expected MW		1000
Operator	Krista Kaiser		Expected TTP		0.4180
Date \ Time	11/19/2013 9:58		Expected MJ		57.96
Experimenter Name	Brain Hehr		Expected Fuel Temp		195.9
Experiment Plan #	1137		Dialed In MW		534.72
Package Worth $	0.012				
Shot Worth $	1.47				
Rod Hold Up (sec)	0.4				
FREC Mode	Decoupled				
FREC RODS	DOWN				
Comments	Secondary Gamma				

	Average	CH-1	CH-2	CH-3	CH-4
Detector		DE2-3	DE4-9		DE5-8
Detector Calibration		48	42.5		54
Channel Type		PXI Amp	SR570 Amp		PXI Amp
Average Used		Both	Both		Both
Period Used		Yes	Yes		Yes
PEAK DATA:					
Peak (MW)	**1280.9**	1218.1	1358.7		1256.3
TTP (sec)	0.396	0.39676	0.3968		0.39604
FWHM (sec)	0.0274	0.02736	0.02748		0.02744
LEHM (sec)	0.01288	0.01368	0.01352		0.013
TEHM (sec)	0.01452	0.01368	0.01396		0.01444
Ratio (LE/TE)	0.887	1	0.968		0.9
Shot Worth	1.453	1.941	1.86		1.88
YIELD DATA:					
Total Yield (MJ)	**50.981**	49.303	55.158		48.692
TTP+3fwhm (MJ)	42.074	40.033	44.601		41.104
Yield @ Peak (MJ)	18.842	18.84	20.714		18.472
Min Period (sec)	0.007127	0.003439	0.003762		0.003679

Figure 42. Shot Information for Pulse Operation #10724 – 50.981 MJ.



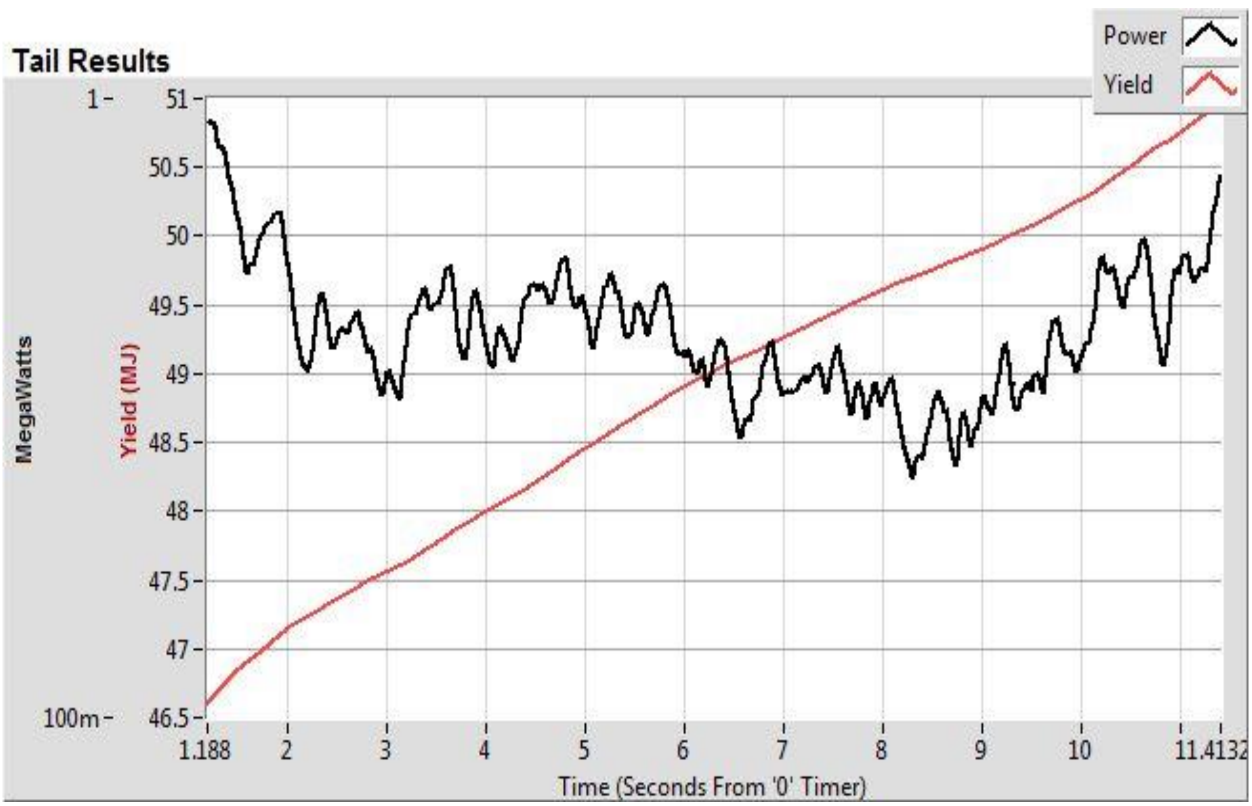


Figure 43. Power and Energy Trace for Pulse Operation #10724 – 50.981 MJ.

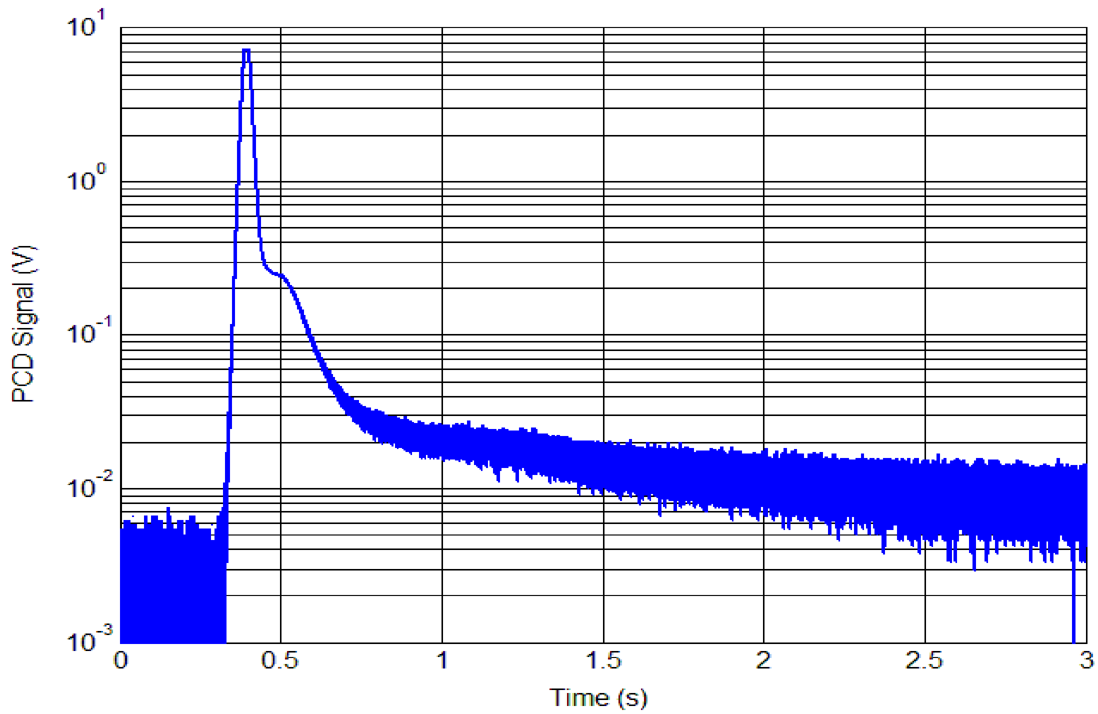


Figure 44. Switched PCD Transient Response for Pulse Operation #10724 – 50.981 MJ.

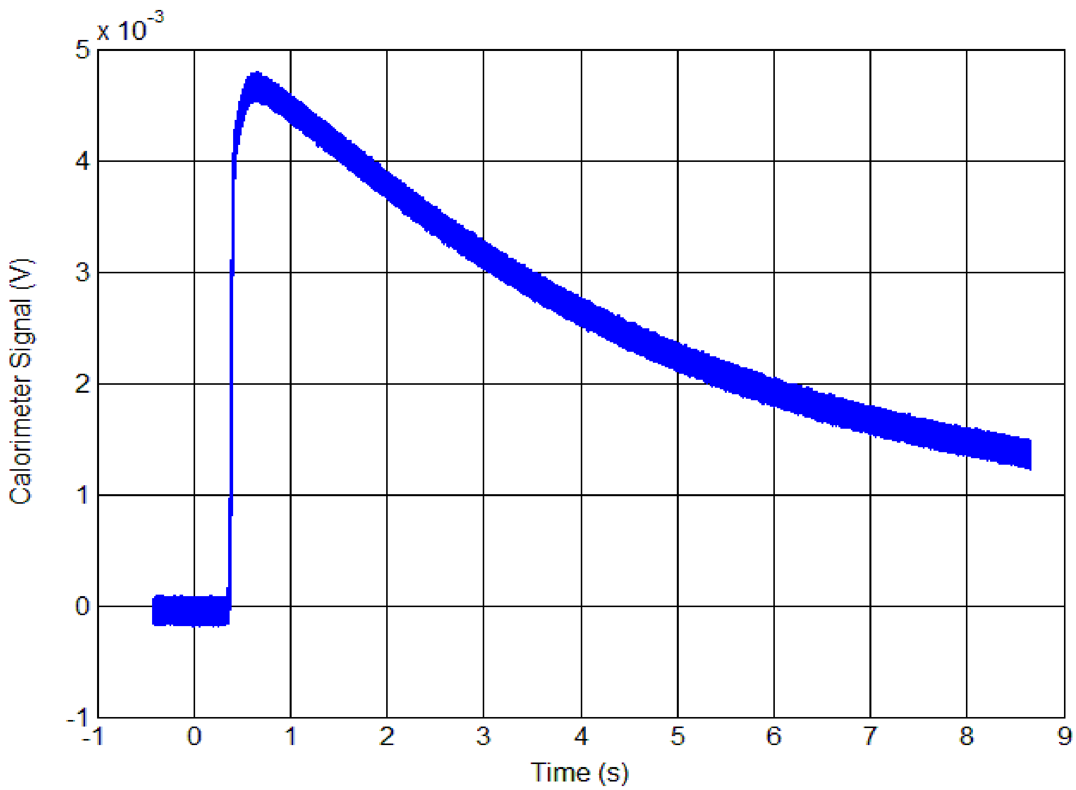


Figure 45. Bi Calorimeter Transient Response for Pulse Operation #10724 – 50.981 MJ.

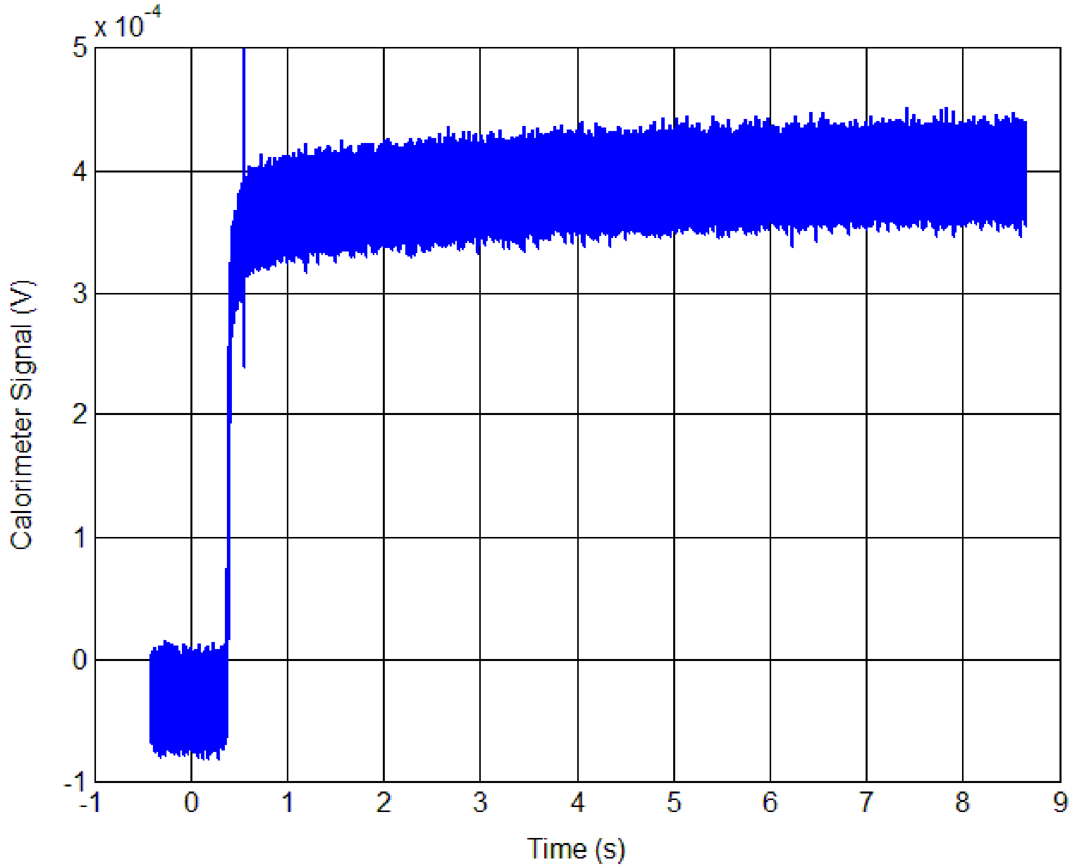


Figure 46. Si Calorimeter Transient Response for Pulse Operation #10724 – 50.981 MJ.

Shot Number ACRR 10724 – Summary

Shot Date: 11/19/2013
Description: Small pulse operation, $1.453, FWHM = 27.4 ms
Experiment: ACRR-FF-CC-32-cl, passive dosimetry Ni, S, TLDs, active PCD, Bi, Si
Reported ACRR Energy: 42.074 MJ at Peak+3FWHM, 50.981 MJ total

Dosimetry Results

Measured ^{58}Ni(n,p)^{58}Co Activity:		3.233E+04 Bq/g_{Ni-58} ± 3.1%
Measured ^{32}S(n,p)^{32}P Activity (Avg of 4):		2.270E+14 Cf equ ± 3.6%
Measured TLD Response (Average of 4):		7.263E+03 Gy(CaF_2:Mn)
		726.3 krad(CaF_2:Mn)
Uncertainty:	Type A (statistical) one TLD	± 5.5%
	Type B (other) one TLD	± 10.2%

Derived Conversion Metrics

Total Neutron Fluence (Ni):	1.191E+15 n/cm^2
Total Neutron Fluence (S):	1.147E+15 n/cm^2
1-MeV Si Equivalent Neutron Fluence:	4.454E+14 n/cm^2
>1 MeV Neutron Fluence:	2.338E+14 n/cm^2
Total prompt γ Fluence:	1.078E+15 γ/cm^2
Total delayed γ Fluence:	5.432E+14 γ/cm^2
Calculated ACRR Energy (Ni):	58.0 MJ
Calculated ACRR Energy (S):	55.9 MJ
Total Si Dose (neutron):	3.474E+04 rad(Si)
Ionizing Si Dose (neutron):	1.925E+04 rad(Si)
Total/Ionizing Si Dose (prompt γ):	4.524E+05 rad(Si)
Total/Ionizing Si Dose (delayed γ):	1.927E+05 rad(Si)
Total C Dose (neutron):	1.617E+05 rad(C)
Ionizing C Dose (neutron):	1.370E+05 rad(C)
Total/Ionizing C Dose (prompt γ):	4.285E+05 rad(C)
Total/Ionizing C Dose (delayed γ):	1.870E+05 rad(C)
Total CaF_2:Mn (TLD) Dose (neutron):	6.999E+04 rad(CaF_2:Mn)
Effective Ionizing CaF_2:Mn Dose (neutron):	6.868E+03 rad(CaF_2:Mn)
Total (Ionizing) CaF_2:Mn (TLD) Dose (prompt γ):	4.495E+05 rad(CaF_2:Mn)
Total (Ionizing) CaF_2:Mn (TLD) Dose (delayed γ):	1.916E+05 rad(CaF_2:Mn)
Sum (Ionizing) CaF_2:Mn (TLD) Dose (n-eff+pγ+dγ):	647.9 krad(CaF_2:Mn)
Calculated to Measured TLD Dose Response:	0.892

Comments: The derived Ni and S reactor energies are within 4% of each other, which is similar to the measurement uncertainty and spectrum adjusted uncertainty. The derived reactor energy (avg Ni and S) is within 12% of the pulse diagnostic measured value with the pulse diagnostic measured value being smaller than the derived value. The calculated-to-measured TLD response is within 11%, which is similar to the type B uncertainty.

5.2 Medium Pulse Operation

A medium pulse operation (~100 MJ) was performed on 11/19/2013 for ACRR-FF-CC-32-cl using both active and passive dosimetry. The reactor was operated in the pulse mode with a reactivity addition of $1.86. The reactor shot number was #10725. Figure 47 shows the shot information for the run. Figure 48 shows the power history and cumulative reactor energy from the ACRR pulse diagnostic system. The reported reactor energy was 85.17 MJ taken at the peak of the pulse plus three full-width half maximum (FWHM) time values. The reported total reactor energy was 98.581 MJ from the pulse diagnostics information. Figure 49 shows the results for the switched PCD transient response after the data was renormalized. Figure 50 and 51 show the results for the Bi and Si calorimeters transient response, respectively.

Shot Information			Predicted Values		
Run Number	10725		Expected MW		5000
Operator	Krista Kaiser		Expected TTP		0.3473
Date \ Time	11/19/2013 10:52		Expected MJ		119.52
Experimenter Name	Brain Hehr		Expected Fuel Temp		368.1
Experiment Plan #	1137		Dialed In MW		4711.42
Package Worth $	0.012				
Shot Worth $	1.89				
Rod Hold Up (sec)	0.4				
FREC Mode	Decoupled				
FREC RODS	DOWN				
Comments	Secondary Gamma				
	Average	CH-1	CH-2	CH-3	CH-4
Detector		DE2-3	DE4-9		DE5-8
Detector Calibration		48	42.5		54
Channel Type		PXI Amp	SR570 Amp		PXI Amp
Average Used		Both	Both		Both
Period Used		Yes	Yes		Yes
PEAK DATA:					
Peak (MW)	**4889.1**	4654.5	5189.7		4795.5
TTP (sec)	0.3536	0.3536	0.35388		0.35368
FWHM (sec)	0.01516	0.01516	0.01516		0.01512
LEHM (sec)	0.0072	0.00728	0.00728		0.00732
TEHM (sec)	0.00796	0.00788	0.00788		0.0078
Ratio (LE/TE)	0.905	0.924	0.924		0.938
Shot Worth	1.857	2.358	2.522		2.134
YIELD DATA:					
Total Yield (MJ)	**98.581**	95.451	103.807		96.92
TTP+3fwhm (MJ)	85.17	80.992	90.136		83.358
Yield @ Peak (MJ)	39.728	37.982	42.355		39.443
Min Period (sec)	0.003778	0.002378	0.002119		0.002852

Figure 47. Shot Information for Pulse Operation #10725 – 98.581 MJ.

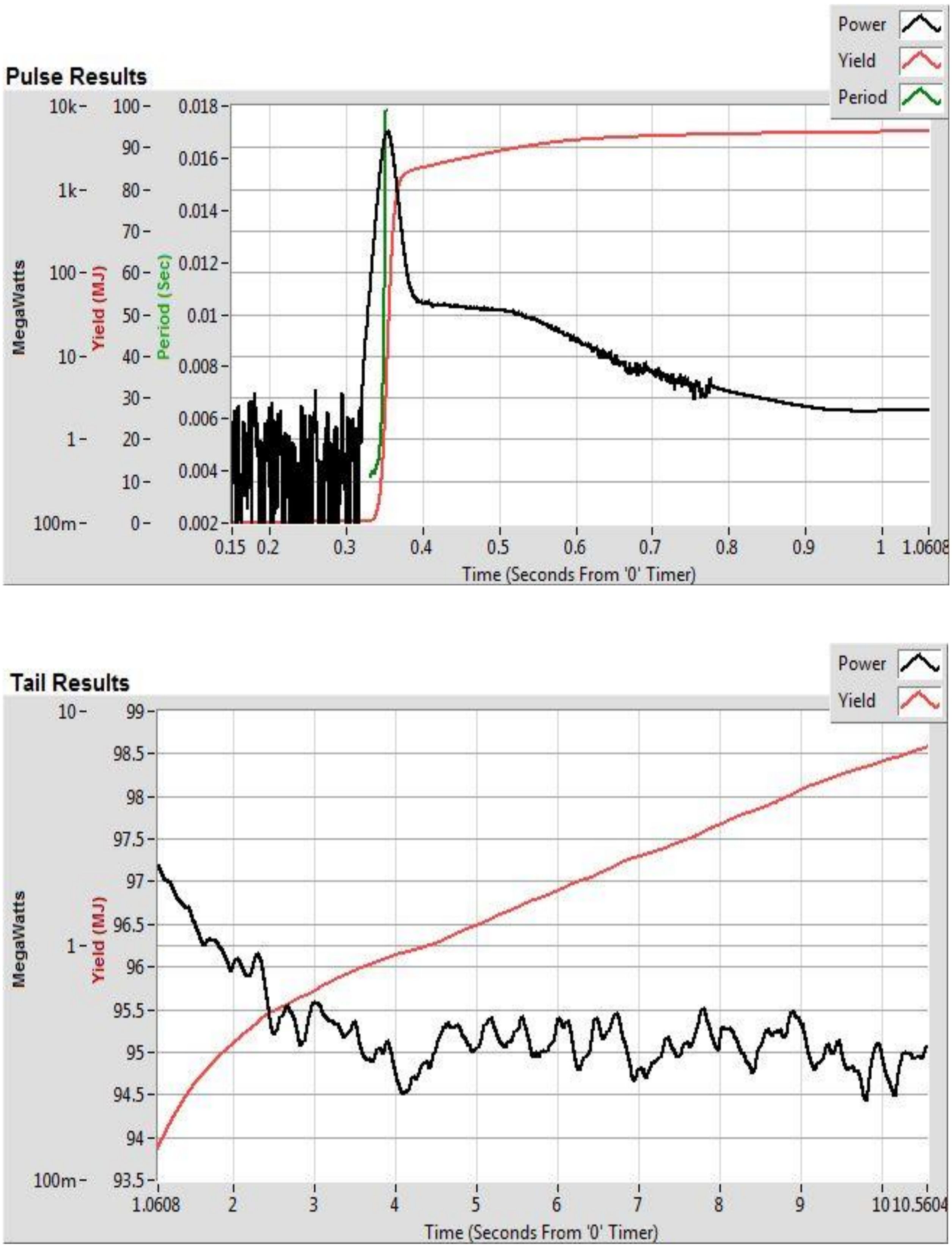


Figure 48. Power and Energy Trace for Pulse Operation #10725 – 98.581 MJ.

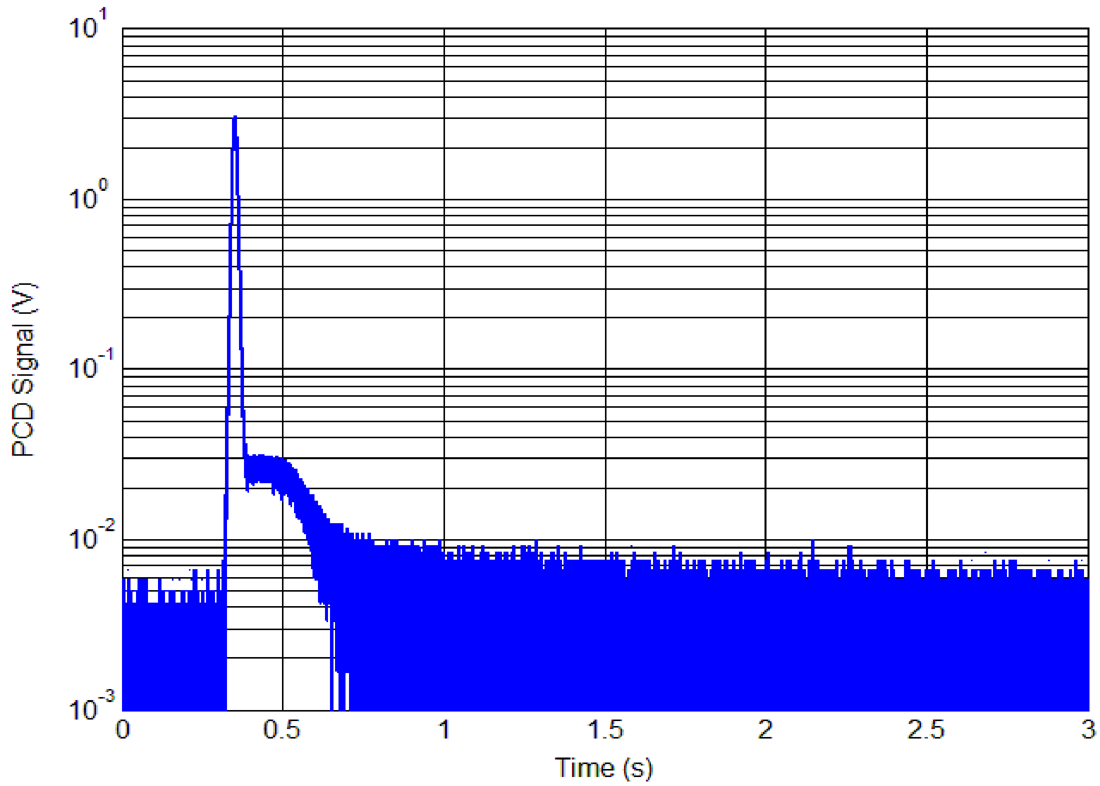


Figure 49. Switched PCD Transient Response for Pulse Operation #10725 – 98.581 MJ.

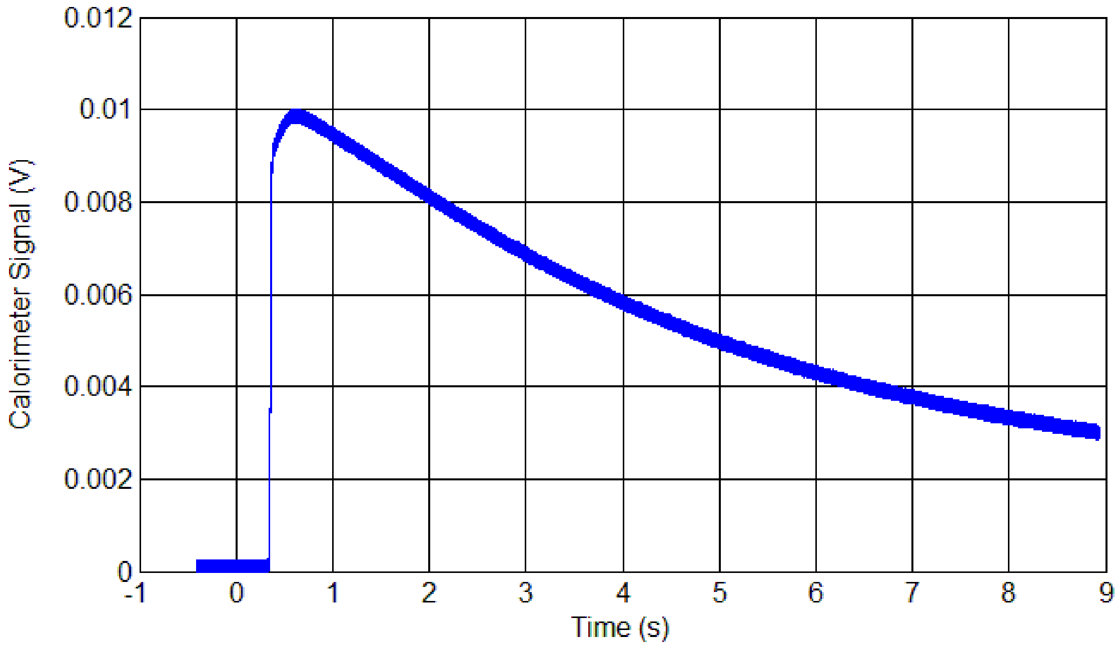


Figure 50. Bi Calorimeter Transient Response for Pulse Operation #10725 – 98.581 MJ.

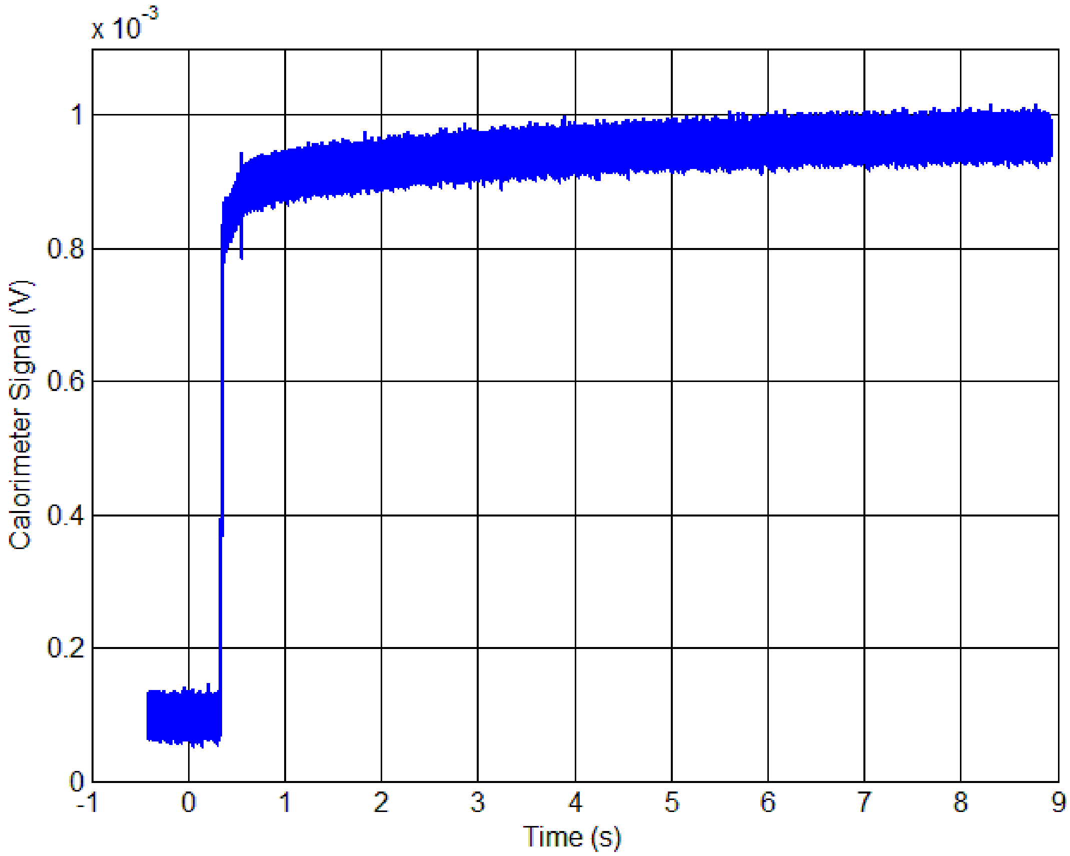


Figure 51. Si Calorimeter Transient Response for Pulse Operation #10725 – 98.581 MJ.

Shot Number ACRR 10725 - Summary

Shot Date: 11/19/2013
Description: Medium pulse operation, \$1.86, FWHM = 15.2 ms
Experiment: ACRR-FF-CC-32-cl, passive dosimetry Ni, S, TLDs, active PCD, Bi, Si
Reported ACRR Energy: 85.17 MJ at Peak+3FWHM, 98.581 MJ total

Dosimetry Results

Measured ^{58}Ni(n,p)^{58}Co Activity:	6.422E+04 Bq/g$_{Ni\text{-}58}$ ± 3.0%
Measured ^{32}S(n,p)^{32}P Activity (Avg of 4):	4.435E+14 Cf equ ± 3.6%
Measured TLD Response (Average of 4):	Not readable – limit exceeded

Derived Conversion Metrics

Total Neutron Fluence (Ni):	2.365E+15 n/cm^2
Total Neutron Fluence (S):	2.241E+15 n/cm^2
1-MeV Si Equivalent Neutron Fluence:	8.776E+14 n/cm^2
>1 MeV Neutron Fluence:	4.607E+14 n/cm^2
Total prompt γ Fluence:	2.124E+15 γ/cm^2
Total delayed γ Fluence:	1.070E+15 γ/cm^2
Calculated ACRR Energy (Ni):	115.3 MJ
Calculated ACRR Energy (S):	109.2 MJ
Total Si Dose (neutron):	6.845E+04 rad(Si)
Ionizing Si Dose (neutron):	3.794E+04 rad(Si)
Total/Ionizing Si Dose (prompt γ):	8.913E+05 rad(Si)
Total/Ionizing Si Dose (delayed γ):	3.797E+05 rad(Si)
Total C Dose (neutron):	3.185E+05 rad(C)
Ionizing C Dose (neutron):	2.699E+05 rad(C)
Total/Ionizing C Dose (prompt γ):	8.441E+05 rad(C)
Total/Ionizing C Dose (delayed γ):	3.685E+05 rad(C)
Total CaF_2:Mn (TLD) Dose (neutron):	1.379E+05 rad(CaF_2:Mn)
Effective Ionizing CaF_2:Mn Dose (neutron):	1.353E+04 rad(CaF_2:Mn)
Total (Ionizing) CaF_2:Mn (TLD) Dose (prompt γ):	8.856E+05 rad(CaF_2:Mn)
Total (Ionizing) CaF_2:Mn (TLD) Dose (delayed γ):	3.775E+05 rad(CaF_2:Mn)
Sum (Ionizing) CaF_2:Mn (TLD) Dose (n-eff+pγ+dγ):	1276.6 krad(CaF_2:Mn)
Calculated to Measured TLD Dose Response:	Measured not readable

Comments: The derived Ni and S reactor energies are within 5% of each other, similar to the measurement uncertainty and spectrum adjusted uncertainty. The derived reactor energy (avg Ni and S) is within 14% of the pulse diagnostic measured value with the pulse diagnostic measured value being smaller than the derived value. The measured TLD response was not readable since the TLD dose exceeded 700 krad.

5.3 Large Pulse Operation

A large pulse operation (~150 MJ) was performed on 11/19/2013 for ACRR-FF-CC-32-cl using both active and passive dosimetry. The reactor was operated in the pulse mode with a reactivity addition of $2.12. The reactor shot number was #10726. Figure 52 shows the shot information for the run. Figure 53 shows the power history and cumulative reactor energy from the ACRR pulse diagnostic system. The reported reactor energy was 130.228 MJ taken at the peak of the pulse plus three full-width half maximum (FWHM) time values. The reported total reactor energy was 150.672 MJ from the pulse diagnostics information. Figure 54 shows the results for the switched PCD transient response after the data was renormalized. Figure 55 and 56 show the results for the Bi and Si calorimeters transient response, respectively.

Shot Information			**Predicted Values**		
Run Number	10726		**Expected MW**		15000
Operator	Krista Kaiser		**Expected TTP**		0.3262
Date \ Time	11/19/2013 13:01		**Expected MJ**		179.62
Experimenter Name	Brain Hehr		**Expected Fuel Temp**		536.5
Experiment Plan #	1137		**Dialed In MW**		11729.49
Package Worth $	0.012				
Shot Worth $	2.301				
Rod Hold Up (sec)	0.4				
FREC Mode	Decoupled				
FREC RODS	DOWN				
Comments	Secondary Gamma				
	Average	**CH-1**	**CH-2**	**CH-3**	**CH-4**
Detector		DE2-3	DE4-9		DE5-8
Detector Calibration		48	42.5		54
Channel Type		PXI Amp	SR570 Amp		PXI Amp
Average Used		Both	Both		Both
Period Used		Yes	Yes		Yes
PEAK DATA:					
Peak (MW)	**10782.6**	10255.9	11451.5		10569.4
TTP (sec)	0.34176	0.34184	0.3416		0.34188
FWHM (sec)	0.0106	0.01056	0.01056		0.01056
LEHM (sec)	0.00496	0.00508	0.00456		0.00512
TEHM (sec)	0.00564	0.00548	0.006		0.00544
Ratio (LE/TE)	0.879	0.927	0.76		0.941
Shot Worth	2.117	2.514	2.537		2.333
YIELD DATA:					
Total Yield (MJ)	**150.672**	139.618	168.666		144.458
TTP+3fwhm (MJ)	130.228	123.682	138.174		127.345
Yield @ Peak (MJ)	60.167	58.513	59.679		60.596
Min Period (sec)	0.002894	0.00213	0.002098		0.002422

Figure 52. Shot Information for Pulse Operation #10726 – 150.672 MJ.

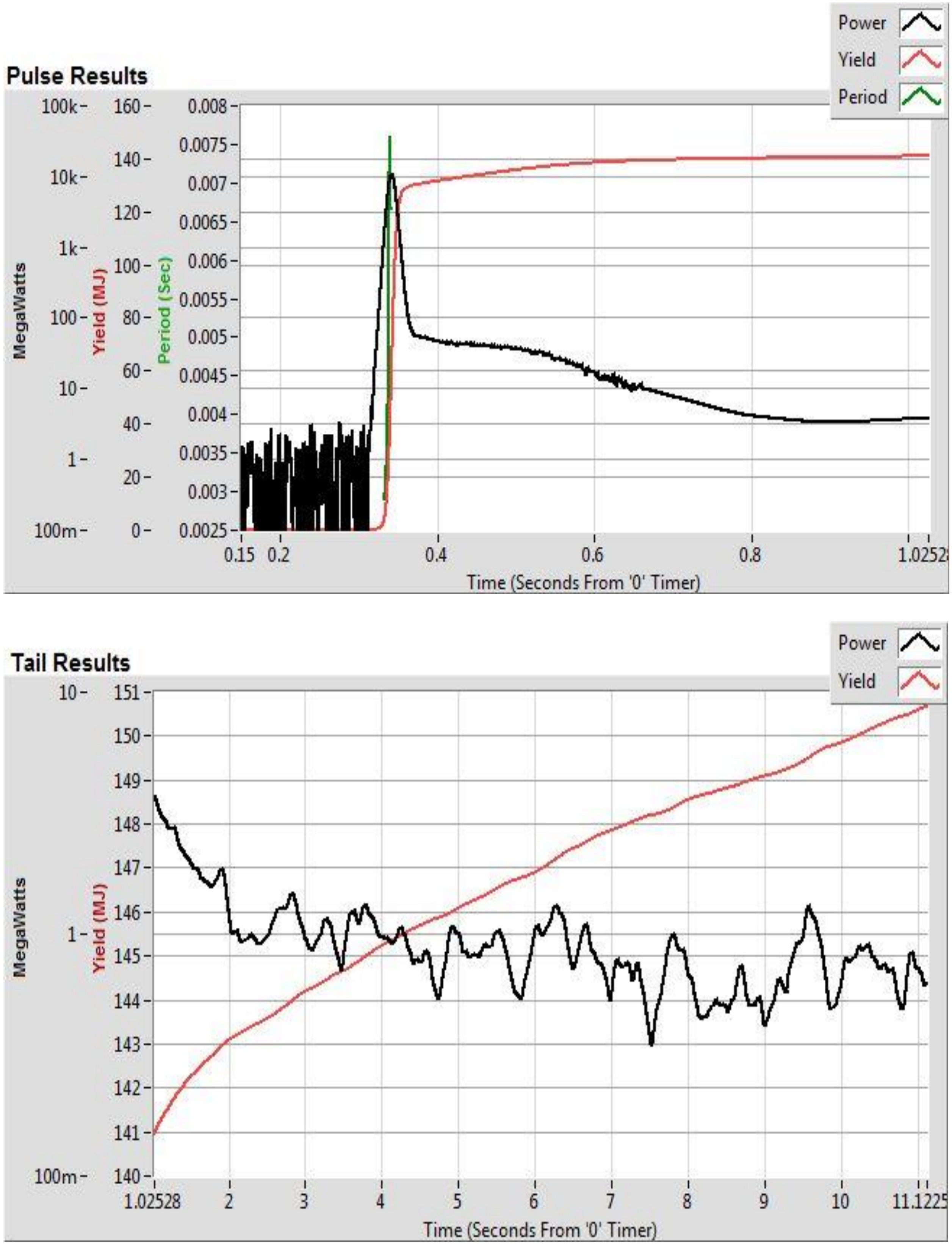


Figure 53. Power and Energy Trace for Pulse Operation #10726 – 150.672 MJ.

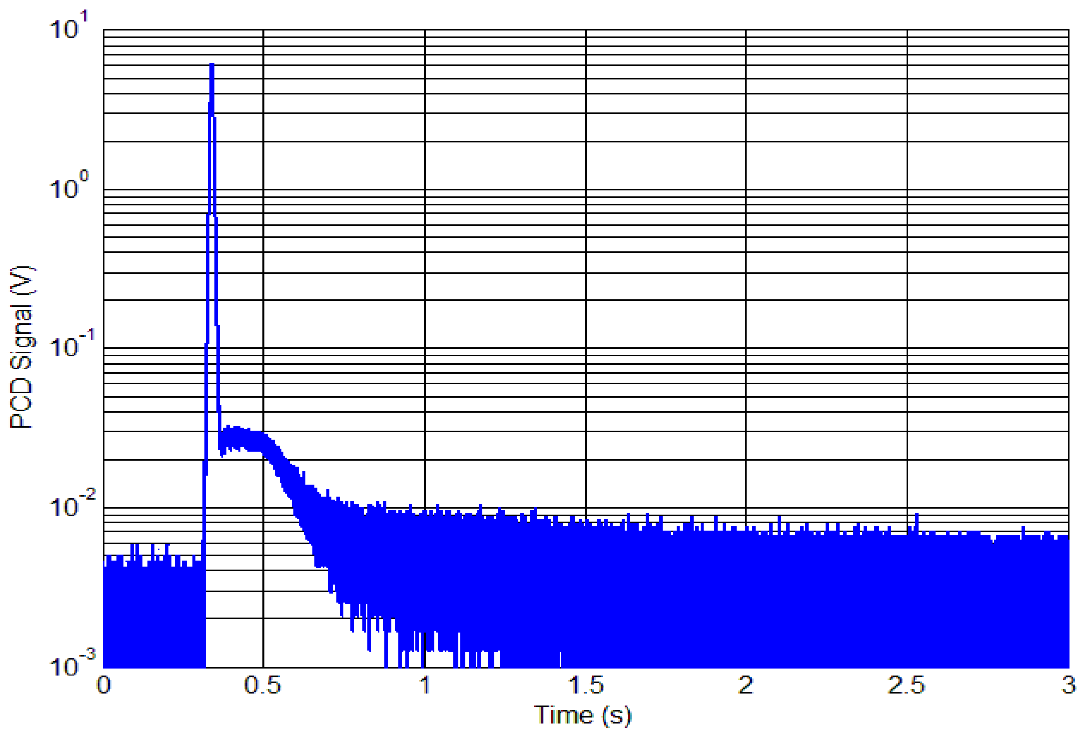


Figure 54. Switched PCD Transient Response for Pulse Operation #10726 – 150.672 MJ.

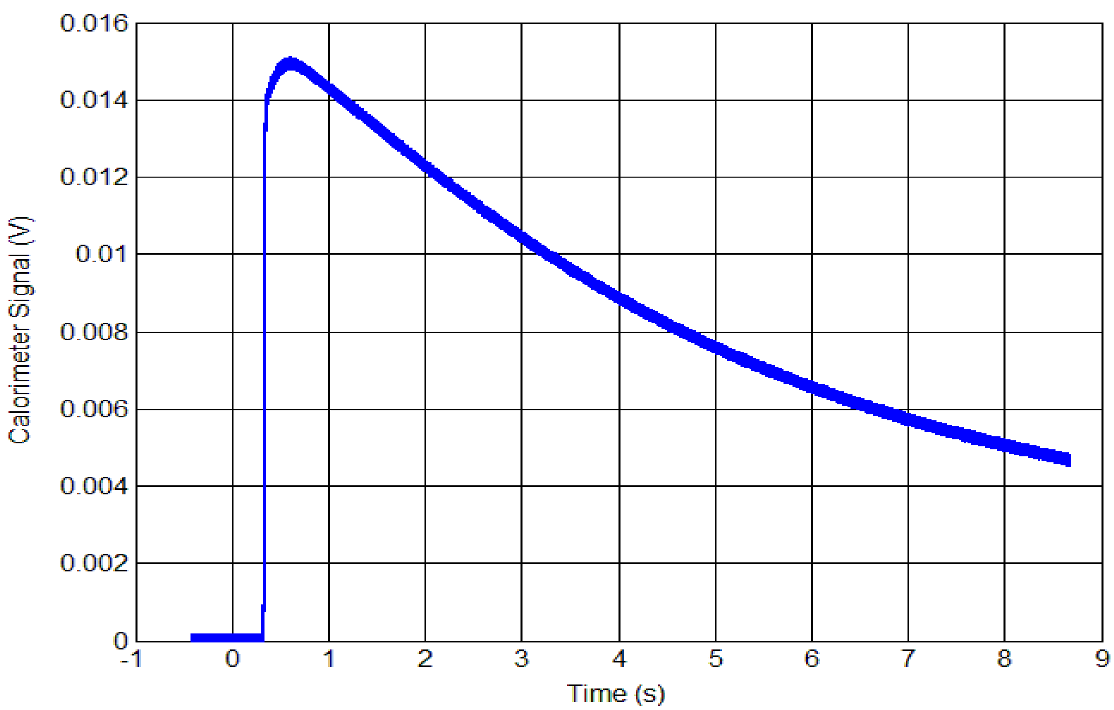


Figure 55. Bi Calorimeter Transient Response for Pulse Operation #10726 – 150.672 MJ.

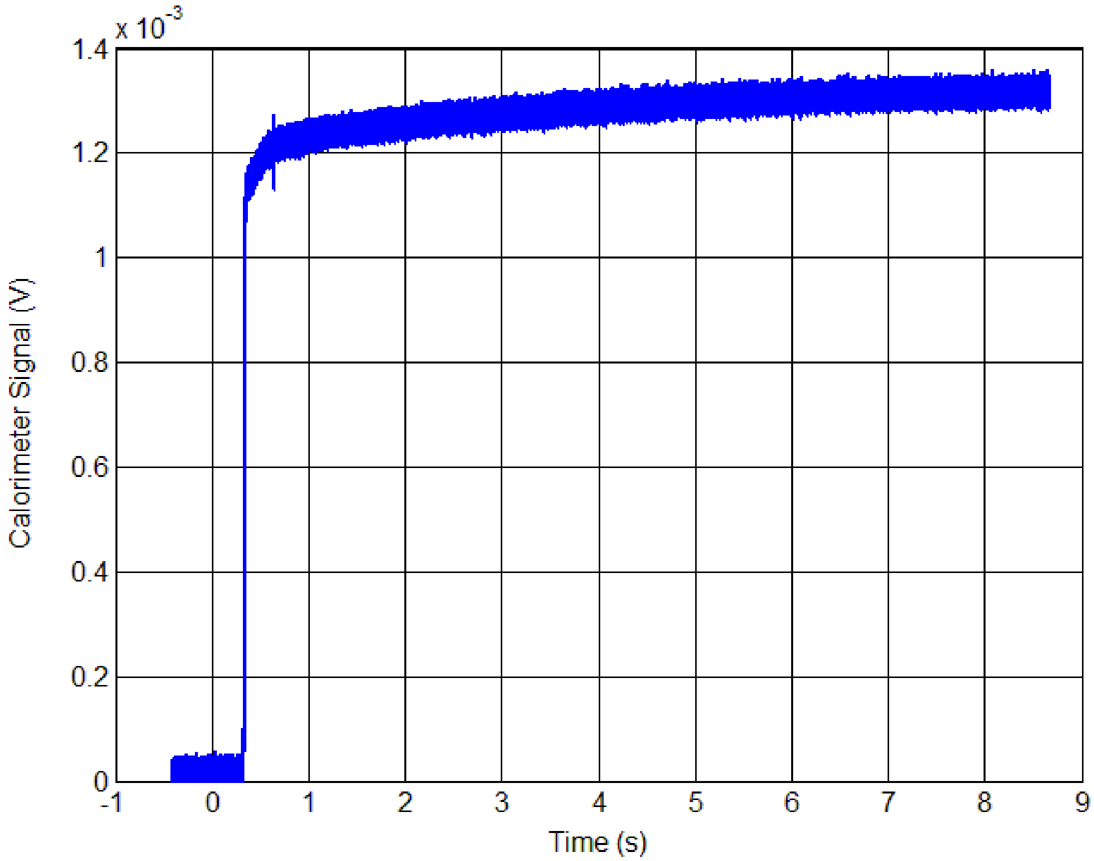


Figure 56. Si Calorimeter Transient Response for Pulse Operation #10726 – 150.672 MJ.

Shot Number ACRR 10726 - Summary

Shot Date: 11/19/2013
Description: Large pulse operation, $2.12, FWHM = 10.6 ms
Experiment: ACRR-FF-CC-32-cl, passive dosimetry Ni, S, TLDs, active PCD, Bi, Si
Reported ACRR Energy: 130.228 MJ at Peak+3FWHM, 150.672 MJ total

Dosimetry Results

Measured ^{58}Ni(n,p)^{58}Co Activity:	9.545E+04 Bq/g_{Ni-58} ± 3.0%
Measured ^{32}S(n,p)^{32}P Activity (Avg of 4):	6.485E+14 Cf equ ± 3.6%
Measured TLD Response (Average of 4):	Not readable – limit exceeded

Derived Conversion Metrics

Total Neutron Fluence (Ni):	3.516E+15 n/cm^2
Total Neutron Fluence (S):	3.278E+15 n/cm^2
1-MeV Si Equivalent Neutron Fluence:	1.294E+15 n/cm^2
>1 MeV Neutron Fluence:	6.793E+14 n/cm^2
Total prompt γ Fluence:	3.132E+15 γ/cm^2
Total delayed γ Fluence:	1.578E+15 γ/cm^2
Calculated ACRR Energy (Ni):	171.3 MJ
Calculated ACRR Energy (S):	159.7 MJ
Total Si Dose (neutron):	1.009E+05 rad(Si)
Ionizing Si Dose (neutron):	5.594E+04 rad(Si)
Total/Ionizing Si Dose (prompt γ):	1.314E+06 rad(Si)
Total/Ionizing Si Dose (delayed γ):	5.600E+05 rad(Si)
Total C Dose (neutron):	4.697E+05 rad(C)
Ionizing C Dose (neutron):	3.981E+05 rad(C)
Total/Ionizing C Dose (prompt γ):	1.245E+06 rad(C)
Total/Ionizing C Dose (delayed γ):	5.434E+05 rad(C)
Total CaF_2:Mn (TLD) Dose (neutron):	2.034E+05 rad(CaF_2:Mn)
Effective Ionizing CaF_2:Mn Dose (neutron):	1.995E+04 rad(CaF_2:Mn)
Total (Ionizing) CaF_2:Mn (TLD) Dose (prompt γ):	1.306E+06 rad(CaF_2:Mn)
Total (Ionizing) CaF_2:Mn (TLD) Dose (delayed γ):	5.567E+05 rad(CaF_2:Mn)
Sum (Ionizing) CaF_2:Mn (TLD) Dose (n-eff+pγ+dγ):	1882.5 krad(CaF_2:Mn)
Calculated to Measured TLD Dose Response:	Measured not readable

Comments: The derived Ni and S reactor energies are within 8% of each other. The derived reactor energy (avg Ni and S) is within 10% of the pulse diagnostic measured value with the pulse diagnostic measured value being smaller than the derived value. The measured TLD response was not readable since the TLD dose exceeded 700 krad.

6. Conclusions

This report presents the characterized neutron, prompt gamma-ray, and delayed gamma-ray radiation environments for the free-field environment in the central cavity of the ACRR. The characterized location is 13 inches from the top of the 32-inch pedestal. The designation for this location is ACRR-FF-CC-32-cl. A 640-energy group and 89-energy group neutron spectrum, a 48-energy group prompt gamma-ray spectrum, and a 48-energy group delayed gamma-ray spectrum were calculated using MCNP using a high-fidelity model of the ACRR. The neutron spectrum was adjusted to align more closely with neutron activation dosimetry. The adjustment was performed using the least-squares code LSL-M2. Neutron, prompt gamma ray, and delayed gamma ray conversion factors are presented to facilitate the conversion of various dosimetry readings into radiation metrics desired by the experimenter.

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A Appendix – MCNP ACRR Model With Free-field Environment on 32-inch Pedestal

```
STANDARD ACRR Model (Extended Cavity, 32" Pedestal, Pb-B4C Bucket)
C
C  Origianl Model Developed by W. Fan
C  Modified by P. Cooper and E. Parma with new cavity
C  Macrobody Model Developed by R. DePriest
C  New 44" Pb-B4C Bucket LB44 Model Developed by T. Trinh
C
C
C     standard 236-element core configuration with new cavity
C     no FREC
C     room temp 70c cross sections with S(a,b)
C     LB-44-cl-32 - 44inch lead/boron bucket on 32inch pedestal
C     tally is a 6cm diameter sphere at fuel centerline
C         89 and 640 neutron energy groups
C         48 gamma energy groups
C
C       control rods   : variable
C       safety rods    : variable
C       transient rods : variable
C
C
C       1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C ******************************************************************************
C *                                CELL CARDS                                  *
C ******************************************************************************
C
C
C  Universe definitions for the standard 236-element core.
C
C     U=1:fuel rods              U=2:water rods
C     U=3:control rods           U=4:safety rods
C     U=5:transient rods         U=6:nickel rods
C     U=7:90% fuel rods          U=9:al rods (empty)
C
C   ********  U=8 is the reactor core fill.  *******
C
C
C  Regular Fuel Elements
C
10  0             -10              U=1  IMP:N,P=1 $Void
11  1   -3.3447    10 -11          U=1  IMP:N,P=1 $UO2-BeO fuel
14  0              11 -14          U=1  IMP:N,P=1 $Void
15  2   -8.4000    14 -15          U=1  IMP:N,P=1 $Niobium
16  0              15 -16          U=1  IMP:N,P=1 $Void Gap
17  4   -2.8000   -17              U=1  IMP:N,P=1 $Lower BeO Plug
18  4   -2.8000   -18              U=1  IMP:N,P=1 $Upper BeO Plug
19  3   -8.0300    17 -19          U=1  IMP:N,P=1 $Lower SS Plug
20  3   -8.0300    18 -20          U=1  IMP:N,P=1 $Upper SS Plug
21  3   -8.0300    19  20  16 -21  U=1  IMP:N,P=1 $SS304
22  5   -1.0000    21 -22          U=1  IMP:N,P=1 $Water
C
C
C  Water Rods
C
23  5   -1.0000   -22              U=2  IMP:N,P=1 $Water
C
C
C  Control Rods:  Poison section
C
25  8   -2.4800   -25              U=3  IMP:N,P=1 $B4C poison
26  0              25 -26          U=3  IMP:N,P=1 $Void Cap
27  3   -8.0300    26 -27          U=3  IMP:N,P=1 $Poison sleeve
28  3   -8.0300   -28              U=3  IMP:N,P=1 $Magnaform plug
29  5   -1.0000    27  28 -29      U=3  IMP:N,P=1 $Water
C
C  Control Rods:  Fuel follower
C
30  0             -30              U=3  IMP:N,P=1 $Void
31  1   -3.3447    30 -31          U=3  IMP:N,P=1 $UO2-BeO fuel
32  0              31 -32          U=3  IMP:N,P=1 $Void
33  2   -8.4000    32 -33          U=3  IMP:N,P=1 $Niobium
34  0              33 -34          U=3  IMP:N,P=1 $Void gap
```

```
35  4   -2.8000   -35              U=3  IMP:N,P=1 $BeO plug
36  0             -36              U=3  IMP:N,P=1 $Void
37  3   -8.0300    34  35 36 -37   U=3  IMP:N,P=1 $SS304
38  5   -1.0000    37 -38          U=3  IMP:N,P=1 $Water
C
C
C  Safety Rods:  Poison section
C
39  8   -2.4800   -39              U=4  IMP:N,P=1 $B4C poison
40  0              39 -40          U=4  IMP:N,P=1 $Void cap
41  3   -8.0300    40 -41          U=4  IMP:N,P=1 $Poison sleeve
42  3   -8.0300   -42              U=4  IMP:N,P=1 $Magnaform plug
43  5   -1.0000    41  42 -43      U=4  IMP:N,P=1 $Water
C
C  Safety Rods:  Fuel follower
C
44  0             -44              U=4  IMP:N,P=1 $Void
45  1   -3.3447    44 -45          U=4  IMP:N,P=1 $UO2-BeO fuel
46  0              45 -46          U=4  IMP:N,P=1 $Void
47  2   -8.4000    46 -47          U=4  IMP:N,P=1 $Niobium
48  0              47 -48          U=4  IMP:N,P=1 $Void gap
49  4   -2.8000   -49              U=4  IMP:N,P=1 $BeO plug
50  0             -50              U=4  IMP:N,P=1 $Void
51  3   -8.0300    48 49  50 -51   U=4  IMP:N,P=1 $SS304
52  5   -1.0000    51 -52          U=4  IMP:N,P=1 $Water
C
C
C  Transient Rods:  Void section
C
53  0             -53              U=5  IMP:N,P=1 $Void
54  7   -2.7000    53 -54 58 60 61 U=5  IMP:N,P=1 $Al tubing
55  5   -1.0000    54 -55          U=5  IMP:N,P=1 $Water
56  7   -2.7000    55 -56          U=5  IMP:N,P=1 $Al guidex
57  5   -1.0000    56 -57          U=5  IMP:N,P=1 $Water
58  7   -2.7000   -58              U=5  IMP:N,P=1
C
C  Transient Rods:  Poison section
C
59  8   -2.4800   -59              U=5  IMP:N,P=1 $Poison
60  7   -2.7000    59 -60          U=5  IMP:N,P=1 $Inner sleeve
61  0             -61              U=5  IMP:N,P=1 $Void
62  7   -2.7000   -62  54          U=5  IMP:N,P=1 $End plug
C
C
C  Nickel Rods
C
65  6   -8.9000   -21              U=6  IMP:N,P=1 $Nickel
66  5   -1.0000    21 -22          U=6  IMP:N,P=1 $Water
C
C
C  90% Fuel Element
C
70  0             -10              U=7  IMP:N,P=1 $Void
71  11  -3.0102    10 -11          U=7  IMP:N,P=1 $UO2-BeO fuel
74  0              11 -14          U=7  IMP:N,P=1 $Void
75  2   -8.4000    14 -15          U=7  IMP:N,P=1 $Niobium
76  0              15 -16          U=7  IMP:N,P=1 $Void Gap
77  4   -2.8000   -17              U=7  IMP:N,P=1 $Lower BeO Plug
78  4   -2.8000   -18              U=7  IMP:N,P=1 $Upper BeO Plug
79  3   -8.0300    17 -19          U=7  IMP:N,P=1 $Lower SS Plug
80  3   -8.0300    18 -20          U=7  IMP:N,P=1 $Upper SS Plug
81  3   -8.0300    19  20  16 -21  U=7  IMP:N,P=1 $SS304
82  5   -1.0000    21 -22          U=7  IMP:N,P=1 $Water
C
C
C  Empty Aluminum Rod
C
600  0             -90              U=25  IMP:N,P=1 $Void
601  7   -2.7000    90 -21          U=25  IMP:N,P=1 $Al Rod
602  5   -1.0000    21 -22          U=25  IMP:N,P=1 $Water
C
C
C  Empty Aluminum Rod
C
90  0             -90              U=9  IMP:N,P=1 $Void
91  7   -2.7000    90 -21          U=9  IMP:N,P=1 $Al Rod
92  5   -1.0000    21 -22          U=9  IMP:N,P=1 $Water
C
C
C  Core  (UNIVERSE = 8)
C
```

```
  1  0  -300 311 210 211 213 220  fill=8   IMP:N,P=1
C
  2  5   -1.0000  -320     lat=2   U=8  IMP:N,P=1
            fill -12:12 -12:12 0:0
C
C
C  This fuel loading reflects the board as of May 2003.
C
C        1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890123456789 0
C
                 2 24r
                2 24r
               2 24r
              2 9r 2  6  1      1  1  1  1  1  1  1  1     1  6  2 2   $ interface with frec
             2 8r 6  6  1  1     1  1  1  1  1  1  1     1  1  6  6 2
            2 7r 6  1  1  1  1     1  1  1  1  1  1    1  1  1  1  6 2
           2 6r 6  7  1  1  1  3   1   1  5   1   1  3  1  1  1  7  6 2
          2 5r 6  7  1  1  1  1  1   1  1  1  1  1    1  1  1  1  7  6 2
         2 4r 6  7  1  1  1  1  1   1  1  1  1  1   1  1  1  1  1  7  6 2
        2 3r 9  6  1  1  1  4  1   1   2 2 2 2   1   1  1  1  1  1  6  2 2
       2 2r 2  9  6  1  1  1  1   1   2 2 2 2 2   1   1  1  1  1  6  6  2 2
      2  2 2  6  6  1  1  1  1   1   2 2 2 2 2 2   1   1  1  1  1  6  2  2 2
        2 2  2  6  1  1  3  1   1   2 2 2 2 2 2 2   1   1  3  1  1  6  2  2 2   $ center line
         2 2  6  6  1  1  1  1   1   2 2 2 2 2 2   1   1  1  1  1  9  6  2 2 2
          2 2  6  1  1  1  1  1   1   2 2 2 2 2   1   1  1  1  1  1  9  2 2 2r
           2 6  1  1  1  1  5  1   1   2 2 2 2   1   1  5  1  1  1  1  2 2 3r
            2 6  1  1  1  1  1  1   1  1  1  1  1   1  1  1  1  1  1  2 2 4r
             2 6  1  1  1  1  1  1    1  1  1  1   1  1  1  1  1  1  2 2 5r
              2 6  1  1  1  1  3   1   1  4   1   1  3  1  1  1  1  2 2 6r
               2 6  7  1  1  1     1  1  1  1  1  1    1  1  1  1  2 2 7r
                2 6  6  6  1     1  1  1  1  1  1  1     1  9  9  2 2 8r
                 2 2  9  6      6  6  1  1  1  1  6  6     6  6  2 2 9r
                  2 2  2      9  2  6  7  7  7  6  2  6      2  2 2 10r
                   2 2 2 2       25  6  6  6  6  9         2 2 2 2 11r
                    2 24r
C
C
C ********  END OF UNIVERSE DEFINITIONS AND CORE FILL  ********
C
C
C  NEW CENTRAL CAVITY
C
C   To add 32-in pedestal, remove C from line 2.
C   To add 8-in pedestal, remove C from line 2 and 3.
C   You must also remove the C's from the cells in the pedestal
C    descriptions (Cells 110-116).
C
C    Use Line 4 of Cell 100 to exclude surface of buckets and experiments.
C     Exclude surface 706 for Pb-B4C; Exclude surface 711 for Al dosimetry bucket;
C     Exclude surface 725 for LP-1
C     Exclude surfaces 730, 731, and 734 for Boom Box
C
100  702 -1.0245e-3  -100
                      110
C                     113 114 116
                      1001              IMP:N,P=1 $Void
C   for LB44                      899               IMP:N,P=1 $Void
101  3  -8.0300    100 -101             IMP:N,P=1 $Stainless liner
102  7  -2.7000   -311  101 -102        IMP:N,P=1 $Aluminum
103  5  -1.0000   -311  102             IMP:N,P=1 $Water
C
C
C  Central Cavity Additions (32" and 8" Pedestals)
C
C  32-in pedestal
C
110  7  -2.7000      -110  111  112        IMP:N,P=1 $32-in pedestal
111  702 -1.0245e-3  -111                  IMP:N,P=1 $32-in pedestal inset
112  702 -1.0245e-3  -112                  IMP:N,P=1 $Inset Notch
C
C
C  8-in pedestal
C
C 113  7  -2.7000   -113                  IMP:N,P=1 $Bottom plate
C 114  7  -2.7000   -114                  IMP:N,P=1 $Top plate
C 115  702 -1.0245e-3   -115                 IMP:N,P=1 $Center Void
C 116  7  -2.7000   -116  115            IMP:N,P=1 $Support Tube
C
C
C   End of Central Cavity Additions
```

```
C
C
C  Top and Bottom Grid Plates
C
200  7  -2.7000   -200  311  201        IMP:N,P=1 $Top plate
201  5  -1.0000   -200  220 -201        IMP:N,P=1 $Water
202  7  -2.7000   -202  311             IMP:N,P=1 $Bottom plate
C
C
C  Nickel Plate and Window to the Radiography Lab
C
210  6  -8.9000   -210                  IMP:N,P=1 $Nickel Plate
211  5  -1.0000   -211  210 -900        IMP:N,P=1 $Water
212  0            -212 -900             IMP:N,P=1 $Void
213  7  -2.7000   -213  212 -900        IMP:N,P=1 $Aluminum
C
C
C  FREC-II Side Ni Plate
C
220  6  -8.9000   -220                  IMP:N,P=1
C
C
C  Surrounding Water
C
230  5  -1.0000   -900  220 213 212 211 202 200
                        300 311         IMP:N,P=1
C
C
C
C   EXPERIMENTAL or SPECTRUM MODIFYING BUCKETS  (700's)
C
C  Pb-B4C Bucket  (700-706)
C  Weight of Bucket per L. Martin (8/21/2003) - 446 lbs
C  Weight of Model Bucket                     - 450.81
C  Density of B4C layer changed to 2.12 g/cc to make weight 446.19 lbs
C
C
C 700  702  -1.0245e-3  -700              IMP:N,P=1 $Inside Bucket
C 701   7   -2.7100  -701  700            IMP:N,P=1 $1/16" Al liner
C 702  700  -11.350  -702 701 7091 7092   IMP:N,P=1 $1" Pb on bottom
C 703  701  -2.5300  -703  7091 7092      IMP:N,P=1 $Boral on bottom
C 707   0            -707  702            IMP:N,P=1 $Slop between Cannister and Pb
C 708   8   -2.1200  -708                 IMP:N,P=1 $B4C layer on the bottom
C
C 704   7   -2.7100  -704  703  707  708
C                          7091 7092      IMP:N,P=1 $Al layer
C 705   8   -2.1200  -705  704            IMP:N,P=1 $B4C layer
C 706   7   -2.7100 -706 705 7091 7092    IMP:N,P=1 $Al exterior
C 7091  3   -8.0300 -7091                 IMP:N,P=1 $Dowel 1
C 7092  3   -8.0300 -7092                 IMP:N,P=1 $Dowel 2
C
C
C
C
C  Standard Aluminum Experiment Bucket (710-711)
C   Add -900 to 710 and 711 if using 24" Bucket
C
C 710  702 -1.0245e-3  -710                IMP:N,P=1 $Inside Bucket
C 711  7   -2.7000     -711  710           IMP:N,P=1 $Aluminum Bucket
C
C
C
C
C  Pb-Poly Bucket (720-725) -- Designated as LP-1
C
C 720  702 -1.0245e-3  -720                IMP:N,P=1 $Bottom of Inside
C 721  7   -2.7000  -721  720  726         IMP:N,P=1 $1/16" Al Liner
C 722  700 -11.350  -722  721  724  726    IMP:N,P=1 $0.4" Pb Layer
C 723  704 -0.9450  -723  722  726         IMP:N,P=1 $0.8" HDPE
C 724  704 -0.9450  -724                   IMP:N,P=1 $HDPE fill-in
C 725  7   -2.7000  -725  721  723  726    IMP:N,P=1 $Al Container
C 726  702 -1.0245e-3  -726               IMP:N,P=1 $Top of Inside
C
C
C
C
C
C  Boombox for NG testing (730-738)
C
C 730  765 -7.28    -730  736  737  738    IMP:N,P=1 $Lower Boom Box
C 731  765 -7.28    -731  733              IMP:N,P=1 $Upper part of clamping ring
```

```
C 732  765 -7.28    -732  733              IMP:N,P=1 $Lower part of clamping ring
C 733  702 -1.0245e-3  -733                IMP:N,P=1 $"Void" in clamping ring
C 734  702 -1.0245e-3  -734 732            IMP:N,P=1 $"Void" at ring lip
C 735  765 -7.28    -735                   IMP:N,P=1 $Plug
C 736  702 -1.0245e-3  -736 735            IMP:N,P=1 $"Void" around the plug
C 737  702 -1.0245e-3  -737                IMP:N,P=1 $Lower "void"
C 738  702 -1.0245e-3  -738                IMP:N,P=1 $Lip "void"
C
C
C
C
C
C
C New 44" Pb-B4C Bucket
C Base Plate w/ B4C Volume
C From Ktech drawing labeled "PbB BASEII"
C  800  8   -1.274704138 (-802):(817 -815):(818 -816)       IMP:N,P=1 $ B4C Cavity
C  801  766 -7.83 -803:-809                                 IMP:N,P=1 $ All-threads
C    From McMaster-Carr catalog, Item # 98914A033, Threaded Rods and Studs, General Purpose Steel
C  802  767 -7.82 (805 -806):(811 -812)                     IMP:N,P=1 $ Washers
C    From McMaster-Carr catalog, Item #94744A285, Zinc-Plated Steel Washer for Soft Materials (Type
C  803  767 -7.82 (803 -807):(809 -813)                     IMP:N,P=1 $ All-thread nuts
C    From McMaster-Carr catalog, Item # 93939A823, Hex Nut, Grade 8 Steel
C  804  702 -1.0245e-3 (803 -804):(809 -810):(803 -805):(809 -811):
C                   (806 807 803 -808):(812 813 809 -814) IMP:N,P=1 $ Void inside this thread, washe
C  805  7 -2.704  (-817 819):(-818 820)                     IMP:N,P=1 $ Al6061 plugs
C    From McMaster-Carr catalog, Item # 44705K334, Low-Pressure Aluminum Threaded Square-Socket Plug
C  806  702 -1.0245e-3 (-819):(-820)                        IMP:N,P=1 $ Void in this area
C  807  7 -2.704       (-800:-801) 802 804 808 810 814 815 816
C                                                         IMP:N,P=1 $ Al6061 Base Plate
C Containment Base
C From Ktech drawing labeled "CONTAINMENT BASE II"
C  830  702 -1.0245e-3  801 -830                            IMP:N,P=1 $ Void
C  831  7 -2.704       (830 833 834 -831):(831 -832)        IMP:N,P=1 $ Al6061 Containment Base
C  832  766 -7.83      -833:-834                            IMP:N,P=1 $ All-threads, General Purpose St
C Lead Material
C Unchamfered lead rings
C  840  702 -1.0245e-3 -853                                 IMP:N,P=1 $ Void inside lead rings
C  841  766 -7.83      -847:-848                            IMP:N,P=1 $ All-threads, General Purpose St
C  842  702 -1.0245e-3 (847 -843):(848 -844)                IMP:N,P=1 $ Void between All-threads and Pb
C  843  702 -1.0245e-3 -849:-851                            IMP:N,P=1 $ Void inside Al6061 tubing
C  844  7 -2.704  (849 -850):(851 -852)                     IMP:N,P=1 $ Al6061 tubing
C  845  702 -1.0245e-3 (850 -845):(852 -846)                IMP:N,P=1 $ Void between tubing and Pb hole
C  846  700 -11.35     (862 863 860 843 844 845 846 -842):(-840 843 844 845 846):
C                   (853 -854 843 844 845 846)           IMP:N,P=1 $ Unchamfered lead rings
C Inner Aluminum 6061 Sleeves (Items #14 and 15 in DWG titled "LEAD BORON BUCKET ASSEMBLY II")
C  860  7 -2.704       -860                                 IMP:N,P=1 $ Al6061 bottom plate
C  861  702 -1.0245e-3 (-861 1001):-863                     IMP:N,P=1 $ Aluminum sleeve void
C  862  7 -2.704        861 -862                            IMP:N,P=1 $ Al6061 sleeve
C Al6061 Double Wall Weldment (Item #9 in DWG titled "LEAD BORON BUCKET ASSEMBLY II")
C  870  702 -1.0245e-3 (840 842 831 854 -868):
C                   (840 842 831 854 -870):
C                   (840 842 831 854 -872)               IMP:N,P=1 $ Void Between Pb Ring and Double
C  871  7 -2.704       (868 -869):(870 -871):(872 -873):
C                   (874 -875):(876 -877):(878 -879)     IMP:N,P=1 $ Al6061 Inner and Outer Skins
C  872  8 -1.449249072 (869 -874):(871 -885):(886 -876):
C                             (873 -883):(-878 884)      IMP:N,P=1 $ B4C Powder
C PbB Top: Top Plate (Item #1 in DWG titled "LEAD BORON BUCKET ASSEMBLY II")
C  880  702 -1.0245e-3 -880:-881:(-887 848):(-888 847):
C                   -891:-892:-893:-894                  IMP:N,P=1 $ Voids
C  881  7 -2.704       (880 881 -882 887 888 889 890 891 892 893 894):
C                   (883 -884):(885 -886)                IMP:N,P=1 $ Top Plate
C Modified Hex Head Plugs, 1/4 NPT, AL6061-T6 (Item #16 in DWG titled "LEAD BORON BUCKET ASSEMBLY")
C From McMaster-Carr catalog, Item # 3867T65, High-Pressure Aluminum Pipe Fitting
C  882  7 -2.704       (-821 852):(-822 852):(-823 850):(-824 850)
C                                                        IMP:N,P=1 $ Modified Hex Head Plugs
C Outside World
C  889  702 -1.0245e-3 -899 800 831 832 875 877 879 821 822 823 824
C                    882 847 848 850 852                 IMP:N,P=1 $ Enclosing surface
C
C     EXPERIMENT PACKAGES (1000's)
C   1001  702 -1.0245e-3 -1001 1002                         IMP:N,P=1 $ 6 cm dia scoring sphere
C   1002  6   -8.902     -1002                              IMP:N,P=1 $ Ni Foil
1001  702 -1.0245e-3 -1001                               IMP:N,P=1 $ 6 cm dia scoring sphere
C
C
C
C
C     EXTERNAL WORLD
C
C
```

```
C
900 0             900                     IMP:N,P=0 $Outside world

C        1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C ****************************************************************************
C *                              SURFACE CARDS                               *
C ****************************************************************************
C
C    Fuel Elements
C
10  RCC  0.000  0.000  23.32  0.000  0.000  52.25  0.2413  $Void
11  RCC  0.000  0.000  23.32  0.000  0.000  52.25  1.6840  $Fuel
14  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
15  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
16  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
17  RCC  0.000  0.000 21.415  0.000  0.000  1.905 1.48700  $Lower plug
18  RCC  0.000  0.000  75.57  0.000  0.000  1.905 1.48700  $Upper plug
19  RCC  0.000  0.000  16.32  0.000  0.000  7.000 1.82225  $Lower plug
20  RCC  0.000  0.000  75.57  0.000  0.000  5.000 1.82225  $Upper plug
21  RCC  0.000  0.000  16.32  0.000  0.000  98.89 1.87325  $
22  RCC  0.000  0.000  16.32  0.000  0.000  98.89 5.00000  $Water
C
C   Control Rods
C
25 3 RCC 0.000  0.000  78.11  0.000  0.000  52.25 1.46050  $B4C poison
26 3 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.50495  $Void cap
27 3 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.74625  $poison sleeve
28 3 RCC 0.000  0.000  75.57  0.000  0.000   2.54 1.74625  $Magnaform plug
29 3 RCC 0.000  0.000  75.57  0.000  0.000 101.43 5.00000  $Water
30 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 0.24130  $Void
31 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.68400  $Fuel
32 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
33 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
34 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
35 3 RCC 0.000  0.000  20.78  0.000  0.000   2.54 1.82225  $BeO plug
36 3 RCC 0.000  0.000 -79.22  0.000  0.000 100.00 1.82225  $Void
37 3 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 1.87325  $SS304
38 3 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 5.00000  $Water
C
C    Safety Rods
C
39 4 RCC 0.000  0.000  78.11  0.000  0.000  52.25 0.57150  $B4C poison
40 4 RCC 0.000  0.000  78.11  0.000  0.000  98.89 0.83185  $Void cap
41 4 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.74625  $Poison sleeve
42 4 RCC 0.000  0.000  75.57  0.000  0.000   2.54 1.74625  $Magnaform plug
43 4 RCC 0.000  0.000  75.57  0.000  0.000 101.43 5.00000  $Water
44 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 0.24130  $Void
45 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.68400  $Fuel
46 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
47 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
48 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
49 4 RCC 0.000  0.000  20.78  0.000  0.000   2.54 1.82225  $BeO plug
50 4 RCC 0.000  0.000 -79.22  0.000  0.000 100.00 1.82225  $Void
51 4 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 1.87325  $SS304
52 4 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 5.00000  $Water
C
C    Transient Rods
C
53 5 RCC 0.000  0.0 -76.2762  0.000  0.0  73.1012 1.20000  $Void
54   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 1.27000  $Al tubing
55   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 1.49860  $Water
56   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 2.02438  $Al guidex
57   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 5.00000  $Water
58 5 RCC 0.000  0.000 -3.175  0.000  0.000  3.174 1.20000
59 5 RCC 0.000  0.000 -0.001  0.000  0.000 76.201 0.88000  $Poison
60 5 RCC 0.000  0.000 -0.001  0.000  0.000 76.201 1.20000  $Inner sleeve
61 5 RCC 0.000  0.000  76.20  0.000  0.000 123.80 1.20000  $Void
62 5 RCC 0.000  0.000 -100.0  0.000  0.00 23.7238 1.20000  $End plug
C
C    Aluminum Rods
C
90  RCC  0.000  0.000  15.41  0.000  0.000  66.14 1.77125  $Void in Al rod
C
C    Central Cavity Surfaces
C
100 RCC  0.000  0.000  -67.395  0.000  0.000  202.395 11.6450  $Void
101 RCC  0.000  0.000  -67.395  0.000  0.000  202.395 12.2800
102 RCC  0.000  0.000  -67.395  0.000  0.000  202.395 13.9700
C
C   Cavity Additions
```

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C
110 RCC  0.000  0.000 -67.395  0.000  0.000 81.28 11.4300  $32-in pedestal
111 RCC  0.000  0.000 8.4748  0.000  0.000 2.8702  8.2550  $32-in inset
112 RPP -0.9525 0.9525  -8.255  8.255  11.345  13.885      $Inset Notch
113 RCC  0.000  0.000 13.885  0.000  0.000  1.270 10.3188  $Bottom plate (8-in)
114 RCC  0.000  0.000 32.935  0.000  0.000  1.270 10.3188  $Top plate (8-in)
115 RCC  0.000  0.000 15.155  0.000  0.000  17.78  5.7150  $Center void (8-in)
116 RCC  0.000  0.000 15.155  0.000  0.000  17.78  6.3500  $Support tube (8-in)
C
C    Top and Bottom Grid Plates
C
200 RCC  0.000  0.000  80.55  0.000  0.000   2.54 53.3500  $Top plate
201 PY  -34.925                                            $Cutoff of top plate
202 RCC  0.000  0.000  11.33  0.000  0.000   5.08 47.0000  $Bottom plate
C
C
C    Window to Radiography Lab
C
210  1 RPP  38.100 39.370  -26.670 26.670  16.41 80.55     $Ni plate
211  1 RPP  38.100 39.370  -38.100 38.100  16.41 80.55     $Water
212  1 RPP  48.895 100.00  -26.670 26.670  16.41 80.55     $Void
213  1 RPP  39.370 100.00  -38.100 38.100  16.41 80.55     $Aluminum
C
C   Nickel Plate near FREC-II
C
220  RPP  -36.830 36.830  -36.195 -34.925  16.41 83.09     $Nickel Plate
C
C    Hexes for the lattice, inner and outer core, and core boundary
C
320  RHP  0.0 0.0 -132.0  0.0 0.0 400.0 2.0855 0.0 0.0    $Lattice element
300  1 RHP  0.0 0.0 16.41 0.0 0.0 64.14 42.7 0.0 0.0      $outer core bound
310  1 RHP  0.0 0.0 -67.395  0.000  0.000  202.395 11.65 0. 0.0      $Inner liner of cavity
311  1 RHP  0.0 0.0 -67.395  0.000  0.000  202.395 12.285 0. 0.      $Outer liner of cavity
C
C
C   Buckets  (700's)
C
C  Pb-B4C Bucket
C
 700 7 RCC  0.0 0.0 6.35     0.0 0.0 85.09    6.27380 $Void
 701 7 RCC  0.0 0.0 6.26872  0.0 0.0 85.17128 6.35508 $0.032" Al liner
 702 7 RCC  0.0 0.0 3.65125  0.0 0.0 87.78875 9.76630 $Pb layers
 703 7 RCC  0.0 0.0 3.01625  0.0 0.0  0.63500 9.17575 $Boral
 704 7 RCC  0.0 0.0 1.90500  0.0 0.0 89.53500 10.1600 $Al layer
 705 7 RCC  0.0 0.0 1.90500  0.0 0.0 89.53500 11.1125 $B4C
 706 7 RCC  0.0 0.0 0.00000  0.0 0.0 91.44000 11.4300 $Al layer
 707 7 RCC  0.0 0.0 3.65125  0.0 0.0 87.78875 9.84250
 708 7 RCC  0.0 0.0 1.90500  0.0 0.0  0.63500 7.62000 $B4C bottom
7091 7 RCC  0.0 -8.890 0.00  0.0 0.0 91.44000 0.31750 $Dowel 1
7092 7 RCC  0.0  8.890 0.00  0.0 0.0 91.44000 0.31750 $Dowel 2
C
C  14" Aluminum Bucket
C
 710 7 RCC  0.0 0.0 0.15875  0.0 0.0 35.40125 11.27125   $Void
 711 7 RCC  0.0 0.0 0.00000  0.0 0.0 35.56000 11.43000   $Al bucket
C
C USE these for a 24" Aluminum Bucket
C
C 710 7 RCC  0.0 0.0 0.15875  0.0 0.0 60.80125 11.27125   $Void
C 711 7 RCC  0.0 0.0 0.00000  0.0 0.0 60.96000 11.43000   $Al bucket
C
C  LP-1 Surfaces
C
 720 7 RCC  0.0 0.0 5.74675  0.0 0.0 62.18825  7.46125   $Inside
 721 7 RCC  0.0 0.0 5.58800  0.0 0.0 73.15200  7.62000   $Al liner
 722 7 RCC  0.0 0.0 3.55600  0.0 0.0 64.37900  8.63600   $Pb
 723 7 RCC  0.0 0.0 2.54000  0.0 0.0 65.39500 10.66800   $HDPE
 724 7 RCC  0.0 0.0 3.55600  0.0 0.0  1.01600  7.62000   $HDPE fill-in
 725 7 RCC  0.0 0.0 0.00000  0.0 0.0 78.74000 11.43000   $Al Container
 726 7 RCC  0.0 0.0 67.9350  0.0 0.0 10.80500  7.46125
C
C  Boom Box Surfaces
C
 730   7 RCC  0.0 0.0 0.0       0.0 0.0 65.786   9.8425
 731   7 RCC  0.0 0.0 65.913    0.0 0.0  3.048   9.8425
 732   7 RCC  0.0 0.0 65.786    0.0 0.0  0.127   8.1280
 733   7 RCC  0.0 0.0 65.786    0.0 0.0  3.175   5.0800
 734   7 RCC  0.0 0.0 65.786    0.0 0.0  0.127   9.8425
 735   7 RCC  0.0 0.0 59.436    0.0 0.0  6.350   6.6675
 736   7 RCC  0.0 0.0 59.436    0.0 0.0  6.350   6.7945
 737   7 RCC  0.0 0.0  2.540    0.0 0.0 54.864   7.9375
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 738  7 RCC  0.0 0.0 57.404   0.0 0.0  2.032   5.0800
C
C
C New 44" Pb-B4C Bucket
C Base Plate w/ B4C Volume
C From Ktech drawing labeled "PbB BASEII"
C
800  7 RCC  0.000  0.000  0.000  0.000  0.000  1.905  11.43  $ Base Plate Bottom
801  7 RCC  0.000  0.000  1.905  0.000  0.000  1.905  7.9375 $ Base Plate Top
802  7 RCC  0.000  0.000  2.2225 0.000  0.000  1.27   7.62   $ B4C Cavity
C Bolts/Bolt Holes
C Big Bolts/Bolt Holes
C From McMaster-Carr catalog, Item # 98914A033, Threaded Rods and Studs
803  7 RCC  8.890  0.000  0.000  0.000  0.000  1.905  0.53594  $ All-Thread #1
804  7 RCC  8.890  0.000  1.524  0.000  0.000  0.381  0.65151  $ All-Thread Hole #1
805  7 RCC  8.890  0.000  1.2954 0.000  0.000  0.2286 0.674688 $ All-Thread Washer Void #1
806  7 RCC  8.890  0.000  1.2954 0.000  0.000  0.2286 1.27     $ All-Thread Washer #1
807  7 RCC  8.890  0.000  0.50165 0.000 0.000  0.79375 0.9525  $ All-Thread Nut #1
808  7 RCC  8.890  0.000  0.000  0.000  0.000  1.524  1.5875   $ All-Thread Nut Hole #1
809  7 RCC -8.890  0.000  0.000  0.000  0.000  1.905  0.53594  $ All-Thread #2
810  7 RCC -8.890  0.000  1.524  0.000  0.000  0.381  0.65151  $ All-Thread Hole #2
811  7 RCC -8.890  0.000  1.2954 0.000  0.000  0.2286 0.674688 $ All-Thread Washer Void #2
812  7 RCC -8.890  0.000  1.2954 0.000  0.000  0.2286 1.27     $ All-Thread Washer #2
813  7 RCC -8.890  0.000  0.50165 0.000 0.000  0.79375 0.9525  $ All-Thread Nut #2
814  7 RCC -8.890  0.000  0.000  0.000  0.000  1.524  1.5875   $ All-Thread Nut Hole #2
C Small Bolts/Bolt Holes
C From McMaster-Carr catalog, Item # 44705K334, Low-Pressure Aluminum Threaded Square-Socket Plug
815  7 RCC  0.000  5.3975 0.000  0.000  0.000  2.2225 0.71374 $ Small Hole #1
816  7 RCC  0.000 -5.3975 0.000  0.000  0.000  2.2225 0.71374 $ Small Hole #2
817  7 RCC  0.000  5.3975 0.000  0.000  0.000  1.2192 0.71374 $ Plug #1
818  7 RCC  0.000 -5.3975 0.000  0.000  0.000  1.2192 0.71374 $ Plug #2
819  7 RPP -0.357188 0.357188  5.040313  5.754688 0.000 0.862648 $ Plug #1 9/32" Hole
820  7 RPP -0.357188 0.357188 -5.754688 -5.040313 0.000 0.862648 $ Plug #2 9/32" Hole
C
C Containment Base
C From Ktech drawing labeled "CONTAINMENT BASE II"
C
830  7 RCC  0.000  0.000  1.905  0.000  0.000  1.905  7.9883 $ Inner void
831  7 RCC  0.000  0.000  1.905  0.000  0.000  1.905  9.779  $ Inner Disc Region
832  7 RCC  0.000  0.000  1.905  0.000  0.000  0.635  11.43  $ Outer Disc Region
833  7 RCC  8.890  0.000  1.905  0.000  0.000  1.905  0.53594 $ All-thread #1, General purpose steel
834  7 RCC -8.890  0.000  1.905  0.000  0.000  1.905  0.53594 $ All-thread #2, General purpose steel
C
C Lead Bottom, Floor, and Rings (Items #4, 5, and 6 in DWG titled "LEAD BORON BUCKET ASSEMBLY II")
C Drawn March 22, 2010 by S. Padias
C Unchamfered lead components
C
840  7 RCC  0.000  0.000  3.810  0.000  0.000  2.540  9.7663  $ Lead bottom disc
C 841  7 RCC  0.000  0.000  6.350  0.000  0.000  100.33 6.477   $ Inner lead void
842  7 RCC  0.000  0.000  6.350  0.000  0.000  100.33 9.7663  $ Lead ring
843  7 RCC  8.89   0.000  3.810  0.000  0.000  106.68 0.65532 $ Right-side big lead hole
844  7 RCC -8.89   0.000  3.810  0.000  0.000  106.68 0.65532 $ Left-side big lead hole
845  7 RCC  0.000  8.89   3.810  0.000  0.000  106.68 0.32639 $ Top-side small lead hole
846  7 RCC  0.000 -8.89   3.810  0.000  0.000  106.68 0.32639 $ Bottom-side small lead hole
C From McMaster-Carr catalog, Item # 98914A033, Threaded Rods and Studs
847  7 RCC  8.89   0.000  3.810  0.000  0.000  113.665 0.53594 $ Right-side All-Thread
848  7 RCC -8.89   0.000  3.810  0.000  0.000  113.665 0.53594 $ Left-side All-Thread
C General Purpose Aluminum Tubing
C From McMaster-Carr catalog, Item # 89965K42, General Purpose Aluminum Tubing
849  7 RCC  0.000  8.89   3.810  0.000  0.000  111.76  0.2286  $ Top-side inner radius Al6061 Tubing
850  7 RCC  0.000  8.89   3.810  0.000  0.000  111.76  0.3175  $ Top-side outer radius Al6061 Tubing
851  7 RCC  0.000 -8.89   3.810  0.000  0.000  111.76  0.2286  $ Bottom-side inner radius Al6061 Tub
852  7 RCC  0.000 -8.89   3.810  0.000  0.000  111.76  0.3175  $ Bottom-side outer radius Al6061 Tub
C Chamfered lead components
853  7 TRC  0.000  0.000  106.68 0.000  0.000  3.81   6.477  7.62  $ Chamfered lead ring void
854  7 RCC  0.000  0.000  106.68 0.000  0.000  3.81   9.7663  $ Chamfered lead ring radius
C
C Inner Aluminum 6061 Sleeves (Items #14 and 15 in DWG titled "LEAD BORON BUCKET ASSEMBLY II")
C
860  7 RCC  0.000  0.000  6.35   0.000  0.000  0.08255 6.477  $ Al6061 Base Plate
861  7 RCC  0.000  0.000  6.43255 0.000 0.000  100.1776 6.39445 $ Al6061 Sheet void
862  7 RCC  0.000  0.000  6.43255 0.000 0.000  100.1776 6.477 $ Al6061 Sheet
863  7 RCC  0.000  0.000  106.6102 0.000 0.000 0.0698   6.477 $ Void
C
C PbB base II Double Wall Weldment (Item #9 in DWG titled "LEAD BORON BUCKET ASSEMBLY II")
C
868  7 RCC  0.000  0.000  2.54   0.000  0.000  107.315 9.8425 $ Inner Surface of Inner Skin II L1
869  7 RCC  0.000  0.000  2.54   0.000  0.000  107.315 10.16  $ Inner Skin II L1
870  7 RCC  0.000  0.000  109.855 0.000  0.000  0.254  9.8425 $ Inner Surface of Inner Skin II L2
871  7 RCC  0.000  0.000  109.855 0.000  0.000  0.254  10.16  $ Inner Skin II L2
872  7 RCC  0.000  0.000  110.109 0.000  0.000  0.381  9.8425 $ Inner Surface of Inner Skin II L3
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873  7 RCC  0.000  0.000  110.109 0.000  0.000  0.381  10.16  $ Inner Skin II L3
874  7 RCC  0.000  0.000  2.54   0.000  0.000  107.315 11.1125 $ B4C Powder Region L1
875  7 RCC  0.000  0.000  2.54   0.000  0.000  107.315 11.43  $ Outer Skin II L1
876  7 RCC  0.000  0.000  109.855 0.000  0.000  0.254  11.1125 $ B4C Powder Region L2
877  7 RCC  0.000  0.000  109.855 0.000  0.000  0.254  11.43  $ Outer Skin II L2
878  7 RCC  0.000  0.000  110.109 0.000  0.000  0.381  11.1125 $ B4C Powder Region L3
879  7 RCC  0.000  0.000  110.109 0.000  0.000  0.381  11.43  $ Outer Skin II L3
C
C PbB Top: Top Plate (Item #1 in DWG titled "LEAD BORON BUCKET ASSEMBLY II")
C
880  7 RCC  0.000  0.000  110.49 0.000  0.000  0.4318 7.62    $ Lower void
881  7 TRC  0.000  0.000  110.9218 0.000 0.000 0.8382 7.62 8.103935 $ Upper void
882  7 RCC  0.000  0.000  110.49 0.000  0.000  1.27   11.43   $ Al6061 Disc
883  7 RCC  0.000  0.000  110.49 0.000  0.000 -0.381  10.1727 $ Lower B4C Cap void
884  7 RCC  0.000  0.000  110.49 0.000  0.000 -0.381  11.0998 $ B4C Cap
885  7 TRC  0.000  0.000  109.855 0.000 0.000  0.254  10.4267 10.1727 $ Inner chamfer
886  7 TRC  0.000  0.000  109.855 0.000 0.000  0.254  10.8458 11.0998 $ Outer chamfer
C Top Plate holes
887  7 RCC -8.89   0.000  110.49 0.000  0.000  1.27   0.65151 $ Left Large hole
888  7 RCC  8.89   0.000  110.49 0.000  0.000  1.27   0.65151 $ Right Large hole
889  7 RCC  0.000 -8.89   110.49 0.000  0.000  1.27   0.65151 $ Bottom Large hole
890  7 RCC  0.000  8.89   110.49 0.000  0.000  1.27   0.65151 $ Top Large hole
891  7 RCC  -2.54  8.89   110.49 0.000  0.000  1.27   0.3175  $ Small Hole #1
892  7 RCC   2.54  8.89   110.49 0.000  0.000  1.27   0.3175  $ Small Hole #2
893  7 RCC  -2.54 -8.89   110.49 0.000  0.000  1.27   0.3175  $ Small Hole #1
894  7 RCC   2.54 -8.89   110.49 0.000  0.000  1.27   0.3175  $ Small Hole #2
C Modified Hex Head Plugs, 1/4 NPT, AL6061-T6 (Item #16 in DWG titled "LEAD BORON BUCKET ASSEMBLY")
C From McMaster-Carr catalog, Item # 3867T65, High-Pressure Aluminum Pipe Fitting
821  7 RCC  0.000 -8.89   111.76 0.000  0.000 -1.27   0.65151 $ Bottom Hex Thread
822  7 RCC  0.000 -8.89   111.76 0.000  0.000  0.635  0.79375 $ Bottom Hex Head
823  7 RCC  0.000  8.89   111.76 0.000  0.000 -1.27   0.65151 $ Top Hex Thread
824  7 RCC  0.000  8.89   111.76 0.000  0.000  0.635  0.79375 $ Top Hex Head
C
C Enclosing surface for the 44" Pb-B4C bucket
C
899  7 RCC  0.000  0.000  0.000  0.000  0.000  117.475 11.43  $ Enclosing surface
C
C
C  EXPERIMENT SURFACES
C
1001 6 SO   3.                                    $ 6 cm dia scoring sphere
1002 6 rcc  0. -0.013301675 0.   0. 0.026603351 0.   0.635     $ Nickel Foil
C
C    External Cutoff
C
900 RCC  0.000  0.000 -67.395  0.000  0.000  202.395 72.0000

C ***************************
C *     TRANSFORMATIONS     *
C ***************************
C
C  TR1 rotates the hexes for the outer core bound and the cavity liner
C
*TR1   0 0 0 30 60 90 120 30 90
C
C  TR3-->Movement of control rods -0.001 (full up) to -55.001 (full down)
C
C
C   Measured Up DC with 32-in pedestal is -39.731               (03/03/2004)
C   Measured Down DC is -30.851                                 (03/03/2004)
C    -->Up DC position of 1527 Rod Units
C    -->Down DC position of 2415 Rod Units
C   Measured Up DC with 8-in + 32-in pedestal is -40.421        (03/01/2004)
C   Measured Down DC with 8-in + 32-in pedestal is -31.291      (03/01/2004)
C    -->Up DC position of 1428 Rod Units
C    -->Down DC position of 2371 Rod Units
C   Measured Up DC with Pb-B4C on 32-in pedestal is -22.951     (03/09/2004)
C   Measured Down DC with Pb-B4C on 32-in pedestal is -10.741   (03/09/2004)
C    -->Up DC position of 3205 Rod Units
C    -->Down DC position of 4426 Rod Units
C   Measured DC with LP-1 on 32-in pedestal is -31.941          (03/11/2004)
C   Measured Down DC with LP-1 on 32-in pedestal is -23.721     (03/11/2004)
C    -->Up DC position of 2306 Rod Units
C    -->Down DC position of 3128 Rod Units
C
*TR3   0 0 -41.50
C
C  TR4-->Movement of safety rods 0.001 (full up) to -54.999 (full down)
C
C    Measured worth of safety rods:  -$2.12                     (03/30/2004)
C
```

```
*TR4   0 0  0.001
C
C  TR5-->Movement of transient rods 0 (full down) to 90 (full up)
C
C    Measured worth of transient rods:  -$4.14                   (03/30/2004)
C
*TR5   0 0  90
C
C  TR6-->Moves experiment package from origin (0 0 0) to fuel centerline
C
*TR6   0  0  49.445
C
C  TR7-->Puts buckets on 8" (34.205) or 32" (13.885) pedestals
C   Use 32" pedestal for LP-1
C   Use 8" for Standard Al buckets
C
*TR7   0  0  13.885
C
C ********************
C *  MATERIAL CARDS  *
C ********************
C  Materials cards use the latest available cross sections
C
C  UO2-BeO fuel (3.3447 g/cc)  (XSEC Temp - 293.6 K)
C
C
M1      4009.70c -0.2827602   8016.70c -0.5277690  92235.70c -0.0662957
       92238.70c -0.1222844  92234.70c -0.0004547  92236.70c -0.0004358
MT1     beo.60t      $ S(alpha, beta) for UO2-BeO (Temp - 294 K)
C
C
C  UO2-BeO fuel (3.0102 g/cc)  -- This is the 90% fuel
C                                 (XSEC Temp - 293.6 K)
C   Included as a separate material to avoid warning message
C
C
M11     4009.70c -0.2827602   8016.70c -0.5277690  92235.70c -0.0662957
       92238.70c -0.1222844  92234.70c -0.0004547  92236.70c -0.0004358
MT11    beo.60t      $ S(alpha, beta) for BeO (Temp - 294 K)
C
C     NIOBIUM (8.4 g/cc)
C
M2     41093.70c  1.0000
C
C
C  SS-304L from Ktech Materials Database Rev. 118
C   Material Number:  3410
C     Values are weight %
C      Si: 0.0100  Cr: 0.1900  Mn: 0.0200  Fe: 0.6800  Ni: 0.1000
C
C FM multiplier (neutrons):  1.76109641E-10  3410  -4   1
C FM multiplier (photons):   1.76109641E-10  3410  -5  -6
C
C  Density:  7.896 g/cc
C
M3     14028.70c -0.009187  14029.70c -0.000483  14030.70c -0.000329
       24050.70c -0.007930  24052.70c -0.159029  24053.70c -0.018380
       24054.70c -0.004661  25055.70c -0.020000  26054.70c -0.038390
       26056.70c -0.624930  26057.70c -0.014691  26058.70c -0.001989
       28058.70c -0.067198  28060.70c -0.026776  28061.70c -0.001183
       28062.70c -0.003834  28064.70c -0.001009
C
C
C     BeO (2.8 g/cc)
C
M4      4009.70c  0.5000     8016.70c  0.4998096    8017.70c  0.0001904
MT4     beo.60t      $ S(alpha, beta) for BeO (Temp - 294 K)
C
C     Water (1 g/cc)
C
M5    1001.70c  0.6665667    1002.70c  0.000100
      8016.70c  0.3332063    8017.70c  0.000127
MT5    lwtr.60t     $ S(alpha, beta) for water (Temp - 294 K)
C
C
C  Ni reflector
C           Values are weight %
C           Ni-58: 67.19780  Ni-60: 26.77586  Ni-61:  1.18346
C           Ni-62:  3.83429  Ni-64:  1.00859
C    Converted Data from Nuclear Wallet Card to w/o with "Weight_Frac" program
C  Density:  8.9020 g/cc
```

```
C
C
M6    28058.70c -0.6719780 28060.70c -0.2677586 28061.70c -0.0118346
      28062.70c -0.0383429 28064.70c -0.0100859
C
C
C  Al-6061 from Ktech Materials Database Rev. 118
C    Material Number:  3110
C     Values are weight %
C      Mg: 0.0110  Al: 0.9670  Si: 0.0080  Ti: 0.0007
C      Cr: 0.0020  Mn: 0.0013  Fe: 0.0056  Ni: 0.0004
C      Cu: 0.0030  Zn: 0.0010
C
C FM multiplier (neutrons):  3.55249469E-10  3110  -4   1
C FM multiplier (photons):   3.55249469E-10  3110  -5  -6
C
C  Density:  2.704 g/cc
C
M7     12000.66c -0.011000  13027.70c -0.967000  14028.70c -0.007350
       14029.70c -0.000387  14030.70c -0.000263  22000.66c -0.000700
       24050.70c -0.000084  24052.70c -0.001674  24053.70c -0.000193
       24054.70c -0.000049  25055.70c -0.001300  26054.70c -0.000316
       26056.70c -0.005147  26057.70c -0.000121  26058.70c -0.000016
       28058.70c -0.000269  28060.70c -0.000107  28061.70c -0.000005
       28062.70c -0.000015  28064.70c -0.000004  29063.70c -0.002055
       29065.70c -0.000945  30000.42c -0.001000
C
C
C    B4C poison (2.48 g/cc)
C    Composition data taken from Jeff Wemple (KTech) Memo dated June 18, 2010
C    and titled "Re: Drawing of new Lead-boron bucket"
C    Manufacturer of powder is READE ADVANCED MATERIALS
C    Density of packed powder in the 44" Pb-B4C bucket is 1.2505 (half of 2.51 g/cc)
C
M8      6000.70c  0.20000   5010.70c  0.159200   5011.70c  0.640800
C
C
C  Natural Lead
C  True Weight %:  Pb-204:  1.37808  Pb-206: 23.95550
C                  Pb-207: 22.07430  Pb-208: 52.59212
C  Weight % based on Available MCNP XSEC:
C                  Pb-206: 24.29024  Pb-207: 22.38275
C                  Pb-208: 53.32701
C
C    Converted Data from Nuclear Wallet Card to w/o with "Weight_Frac" program
C  Density is 11.35 g/cc from Nuclear Wallet Cards.
C
C
M700  82206.70c -0.2429024  82207.70c -0.2238275
      82208.70c -0.5332701
C
C
C Boral Plate Composition
C
C  Composition found in Nuclear Science and Engineering
C   Vol. 65, No. 1, pgs. 41-48, January 1978.
C   Values are weight %
C         B: 27.40   C:  7.61  Al: 63.68
C        Cu:  0.09  Zn:  0.16  Fe:  0.45
C        Cr:  0.10  Mn:  0.10  Mg:  0.05
C        Ti:  0.10  Li:  0.26
C
C   Density:  2.53 g/cc
C
C
M701   5010.70c -0.050242   5011.70c -0.223758    6000.70c -0.076100
      13027.70c -0.636800  29063.70c -0.000616   29065.70c -0.000284
      30000.42c -0.001600  26056.70c -0.004500   24050.70c -0.000042
      24052.70c -0.000837  24053.70c -0.000097   24054.70c -0.000024
      25055.70c -0.001000  12000.66c -0.000500   22000.66c -0.001000
       3006.70c -0.000171   3007.70c -0.002429
C
C
C
C  Air
C   Standard Density:  1.205e-3 g/cc @ 20 deg C, 1 atm
C   Albuquerque:       1.0245e-3 g/cc in ABQ
C  See Attix p.531-532
C
M702   7014.70c -0.752308   7015.70c -0.002960   8016.70c -0.231687
       8017.70c -0.000094   6000.70c -0.000124  18000.42c -0.012827
```

```
C
C
C   HELIUM  For Leak Test
C    @ 2 atm density = 3.57e-4 g/cc
C
M703   2003.70c 0.00000137  2004.70c  0.99999863
C
C
C HDPE-> (C2H4)n    --          --
C                   |   H    H   |
C                   |   |    |   |
C                  -|-  C -- C  -|-
C                   |   |    |   |
C                   |   H    H   |
C                   --          --
C
M704   1001.70c  0.666667   6000.70c  0.333333
MT704  poly.60t
C
C
C   A517 Carbon Steel  (den = 7.28 g/cc)
C     Modified to match the mill test cert.
C     from Tubos de Acero de Mexico, S.A.
C
C   Summary of MatMCNP Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   C-12       0.0118115          0.0025688          0.0009385
C   C-13       0.0001326          0.0000312          0.0000105
C  Si-28       0.0048924          0.0024807          0.0003887
C  Si-29       0.0002484          0.0001305          0.0000197
C  Si-30       0.0001638          0.0000890          0.0000130
C  Cr-50       0.0000184          0.0000167          0.0000015
C  Cr-52       0.0003557          0.0003348          0.0000283
C  Cr-53       0.0000403          0.0000387          0.0000032
C  Cr-54       0.0000100          0.0000098          0.0000008
C  Mn-55       0.0078340          0.0078003          0.0006225
C  Fe-54       0.0568920          0.0556172          0.0045205
C  Fe-56       0.8930822          0.9053674          0.0709617
C  Fe-57       0.0206252          0.0212829          0.0016388
C  Fe-58       0.0027448          0.0028820          0.0002181
C  Cu-63       0.0007628          0.0008700          0.0000606
C  Cu-65       0.0003400          0.0004001          0.0000270
C  Mo-92       0.0000068          0.0000114          0.0000005
C  Mo-94       0.0000043          0.0000072          0.0000003
C  Mo-95       0.0000073          0.0000126          0.0000006
C  Mo-96       0.0000077          0.0000133          0.0000006
C  Mo-97       0.0000044          0.0000077          0.0000003
C  Mo-98       0.0000111          0.0000197          0.0000009
C  Mo-100      0.0000044          0.0000080          0.0000004
C
C  The total compound atom density (atom/b-cm):  0.07945702
C
M765    06000.70c  0.0119440  14028.70c  0.0048924  14029.70c  0.0002484
        14030.70c  0.0001638  24050.70c  0.0000184  24052.70c  0.0003557
        24053.70c  0.0000403  24054.70c  0.0000100  25055.70c  0.0078340
        26054.70c  0.0568920  26056.70c  0.8930822  26057.70c  0.0206252
        26058.70c  0.0027448  29063.70c  0.0007628  29065.70c  0.0003400
        42000.66c  0.0000460
C
C
C
C  General Purpose Steel, Grade B7
C   7 Comment Cards
C
C  1
C  2 The weight fraction for elements of General Purpose Steel, Grade B7 is
C  3 The weight fractions are used for each element.
C  4 The density of natural cadmium is 7.83 g/cc,
C  5 The MCNP material number is found after the material.
C  6 The line below "7" gives the density.
C  7
C
C   Summary of MatMCNP Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   C-12       0.0194064          0.0042483          0.0016694
C   C-13       0.0002178          0.0000517          0.0000187
C  Mn-55       0.0087306          0.0087500          0.0007510
C   P-31       0.0006194          0.0003500          0.0000533
C   S-32       0.0006498          0.0003790          0.0000559
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C   S-33       0.0000051          0.0000031          0.0000004
C   S-34       0.0000288          0.0000178          0.0000025
C   S-36       0.0000001          0.0000001          0.0000000
C  Si-28       0.0045003          0.0022968          0.0003871
C  Si-29       0.0002285          0.0001208          0.0000197
C  Si-30       0.0001506          0.0000824          0.0000130
C  Cr-50       0.0004466          0.0004069          0.0000384
C  Cr-52       0.0086125          0.0081607          0.0007409
C  Cr-53       0.0009766          0.0009432          0.0000840
C  Cr-54       0.0002431          0.0002392          0.0000209
C  Mo-92       0.0001696          0.0002843          0.0000146
C  Mo-94       0.0001057          0.0001811          0.0000091
C  Mo-95       0.0001819          0.0003150          0.0000157
C  Mo-96       0.0001906          0.0003335          0.0000164
C  Mo-97       0.0001091          0.0001929          0.0000094
C  Mo-98       0.0002758          0.0004925          0.0000237
C  Mo-100      0.0001101          0.0002006          0.0000095
C  Fe-54       0.0557637          0.0548720          0.0047968
C  Fe-56       0.8753707          0.8932369          0.0753001
C  Fe-57       0.0202161          0.0209977          0.0017390
C  Fe-58       0.0026904          0.0028434          0.0002314
C
C  The total compound atom density (atom/b-cm):  0.08602087
C
C  This material contains an isotope that is often
C  modified by an S(alpha,beta). Check MCNP
C  Manual Appendix G to see if an
C  S(alpha,beta) is required.
C
C  MCNP Material 766
C
M766    06000.70c  0.0196242
        25055.70c  0.0087306
        15031.70c  0.0006194
        16000.66c  0.0006838
        14028.70c  0.0045003
        14029.70c  0.0002285
        14030.70c  0.0001506
        24050.70c  0.0004466
        24052.70c  0.0086125
        24053.70c  0.0009766
        24054.70c  0.0002431
        42000.66c  0.0011428
        26054.70c  0.0557637
        26056.70c  0.8753707
        26057.70c  0.0202161
        26058.70c  0.0026904
C
C  Caution: The natural zaid is used for Carbon.
C
C  Caution: The natural zaid is used for Sulfur.
C
C  Caution: The natural zaid is used for Molybdenum.
C
C  If the natural zaid is used for any element, the atom fractions of each isotope
C  of that element are added together and listed with the natural zaid just once.
C
C  To convert a particle flux to rad[Material]
C  use FM  1.76023016E-10 766  -4 1 for neutrons
C   or FM  1.76023016E-10 766  -5 -6 for photons.
C
C
C  Carbon Steel
C   8 Comment Cards
C
C  1
C  2 The weight fraction for elements of carbon steel is used.
C  3 The weight fractions are used for each element.
C  4 Data obtained from MCNP Primer by C.D. Harmon and R.D. Busch (1994)
C  5 The density of natural cadmium is 7.82 g/cc,
C  6 The MCNP material number is found after the material.
C  7 The line below "8" gives the density.
C  8
C
C   Summary of MatMCNP Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   C-12       0.0225772          0.0049399          0.0019386
C   C-13       0.0002534          0.0000601          0.0000218
C  Fe-54       0.0571155          0.0561733          0.0049043
C  Fe-56       0.8965919          0.9144202          0.0769875
```

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C  Fe-57       0.0207062          0.0214957          0.0017780
C  Fe-58       0.0027556          0.0029108          0.0002366
C
C  The total compound atom density (atom/b-cm):  0.08586678
C
C  This material contains an isotope that is often
C  modified by an S(alpha,beta). Check MCNP
C  Manual Appendix G to see if an
C  S(alpha,beta) is required.
C
C  MCNP Material 767
C
M767    06000.70c  0.0228306
        26054.70c  0.0571155
        26056.70c  0.8965919
        26057.70c  0.0207062
        26058.70c  0.0027556
C
C  Caution: The natural zaid is used for Carbon.
C
C  If the natural zaid is used for any element, the atom fractions of each isotope
C  of that element are added together and listed with the natural zaid just once.
C
C  To convert a particle flux to rad[Material]
C  use FM  1.75917531E-10 767  -4 1 for neutrons
C   or FM  1.75917531E-10 767  -5 -6 for photons.
C
C
C ********************
C * TALLIES  *
C ********************
C
F14:P   1001
FC14    gamma fluence  g/cm**2/source neutron - 48 group
E14    1.38880e-10
        1.00E-03 1.00E-02 2.00E-02 3.00E-02 4.50E-02
        6.00E-02 8.00E-02 1.00E-01 1.50E-01 2.00E-01
        3.00E-01 4.00E-01 4.50E-01 5.00E-01 5.25E-01
        6.00E-01 7.00E-01 8.00E-01 9.00E-01 1.00E+00
        1.13E+00 1.20E+00 1.33E+00 1.50E+00 1.66E+00
        1.88E+00 2.00E+00 2.33E+00 2.50E+00 2.67E+00
        3.00E+00 3.50E+00 4.00E+00 4.50E+00 5.00E+00
        5.50E+00 6.00E+00 6.50E+00 7.00E+00 7.50E+00
        8.00E+00 9.00E+00 1.00E+01 1.20E+01 1.40E+01
        1.70E+01 2.00E+01 3.00E+01 5.00E+01
C
F24:N   1001
FC24    neutron fluence  n/cm**2/source neutron - 640 group
E24     1.050e-10   1.100e-10   1.150e-10   1.200e-10   1.275e-10
       1.350e-10   1.425e-10   1.500e-10   1.600e-10   1.700e-10   1.800e-10
       1.900e-10   2.000e-10   2.100e-10   2.200e-10   2.300e-10   2.400e-10
       2.550e-10   2.700e-10   2.800e-10   3.000e-10   3.200e-10   3.400e-10
       3.600e-10   3.800e-10   4.000e-10   4.250e-10   4.500e-10   4.750e-10
       5.000e-10   5.250e-10   5.500e-10   5.750e-10   6.000e-10   6.300e-10
       6.600e-10   6.900e-10   7.200e-10   7.600e-10   8.000e-10   8.400e-10
       8.800e-10   9.200e-10   9.600e-10   1.000e-09   1.050e-09   1.100e-09
       1.150e-09   1.200e-09   1.275e-09   1.350e-09   1.425e-09   1.500e-09
       1.600e-09   1.700e-09   1.800e-09   1.900e-09   2.000e-09   2.100e-09
       2.200e-09   2.300e-09   2.400e-09   2.550e-09   2.700e-09   2.800e-09
       3.000e-09   3.200e-09   3.400e-09   3.600e-09   3.800e-09   4.000e-09
       4.250e-09   4.500e-09   4.750e-09   5.000e-09   5.250e-09   5.500e-09
       5.750e-09   6.000e-09   6.300e-09   6.600e-09   6.900e-09   7.200e-09
       7.600e-09   8.000e-09   8.400e-09   8.800e-09   9.200e-09   9.600e-09
       1.000e-08   1.050e-08   1.100e-08   1.150e-08   1.200e-08   1.275e-08
       1.350e-08   1.425e-08   1.500e-08   1.600e-08   1.700e-08   1.800e-08
       1.900e-08   2.000e-08   2.100e-08   2.200e-08   2.300e-08   2.400e-08
       2.550e-08   2.700e-08   2.800e-08   3.000e-08   3.200e-08   3.400e-08
       3.600e-08   3.800e-08   4.000e-08   4.250e-08   4.500e-08   4.750e-08
       5.000e-08   5.250e-08   5.500e-08   5.750e-08   6.000e-08   6.300e-08
       6.600e-08   6.900e-08   7.200e-08   7.600e-08   8.000e-08   8.400e-08
       8.800e-08   9.200e-08   9.600e-08   1.000e-07   1.050e-07   1.100e-07
       1.150e-07   1.200e-07   1.275e-07   1.350e-07   1.425e-07   1.500e-07
       1.600e-07   1.700e-07   1.800e-07   1.900e-07   2.000e-07   2.100e-07
       2.200e-07   2.300e-07   2.400e-07   2.550e-07   2.700e-07   2.800e-07
       3.000e-07   3.200e-07   3.400e-07   3.600e-07   3.800e-07   4.000e-07
       4.250e-07   4.500e-07   4.750e-07   5.000e-07   5.250e-07   5.500e-07
       5.750e-07   6.000e-07   6.300e-07   6.600e-07   6.900e-07   7.200e-07
       7.600e-07   8.000e-07   8.400e-07   8.800e-07   9.200e-07   9.600e-07
       1.000e-06   1.050e-06   1.100e-06   1.150e-06   1.200e-06   1.275e-06
       1.350e-06   1.425e-06   1.500e-06   1.600e-06   1.700e-06   1.800e-06
       1.900e-06   2.000e-06   2.100e-06   2.200e-06   2.300e-06   2.400e-06
```

```
        2.550e-06   2.700e-06   2.800e-06   3.000e-06   3.200e-06   3.400e-06
        3.600e-06   3.800e-06   4.000e-06   4.250e-06   4.500e-06   4.750e-06
        5.000e-06   5.250e-06   5.500e-06   5.750e-06   6.000e-06   6.300e-06
        6.600e-06   6.900e-06   7.200e-06   7.600e-06   8.000e-06   8.400e-06
        8.800e-06   9.200e-06   9.600e-06   1.000e-05   1.050e-05   1.100e-05
        1.150e-05   1.200e-05   1.275e-05   1.350e-05   1.425e-05   1.500e-05
        1.600e-05   1.700e-05   1.800e-05   1.900e-05   2.000e-05   2.100e-05
        2.200e-05   2.300e-05   2.400e-05   2.550e-05   2.700e-05   2.800e-05
        3.000e-05   3.200e-05   3.400e-05   3.600e-05   3.800e-05   4.000e-05
        4.250e-05   4.500e-05   4.750e-05   5.000e-05   5.250e-05   5.500e-05
        5.750e-05   6.000e-05   6.300e-05   6.600e-05   6.900e-05   7.200e-05
        7.600e-05   8.000e-05   8.400e-05   8.800e-05   9.200e-05   9.600e-05
        1.000e-04   1.050e-04   1.100e-04   1.150e-04   1.200e-04   1.275e-04
        1.350e-04   1.425e-04   1.500e-04   1.600e-04   1.700e-04   1.800e-04
        1.900e-04   2.000e-04   2.100e-04   2.200e-04   2.300e-04   2.400e-04
        2.550e-04   2.700e-04   2.800e-04   3.000e-04   3.200e-04   3.400e-04
        3.600e-04   3.800e-04   4.000e-04   4.250e-04   4.500e-04   4.750e-04
        5.000e-04   5.250e-04   5.500e-04   5.750e-04   6.000e-04   6.300e-04
        6.600e-04   6.900e-04   7.200e-04   7.600e-04   8.000e-04   8.400e-04
        8.800e-04   9.200e-04   9.600e-04   1.000e-03   1.050e-03   1.100e-03
        1.150e-03   1.200e-03   1.275e-03   1.350e-03   1.425e-03   1.500e-03
        1.600e-03   1.700e-03   1.800e-03   1.900e-03   2.000e-03   2.100e-03
        2.200e-03   2.300e-03   2.400e-03   2.550e-03   2.700e-03   2.800e-03
        3.000e-03   3.200e-03   3.400e-03   3.600e-03   3.800e-03   4.000e-03
        4.250e-03   4.500e-03   4.750e-03   5.000e-03   5.250e-03   5.500e-03
        5.750e-03   6.000e-03   6.300e-03   6.600e-03   6.900e-03   7.200e-03
        7.600e-03   8.000e-03   8.400e-03   8.800e-03   9.200e-03   9.600e-03
        1.000e-02   1.050e-02   1.100e-02   1.150e-02   1.200e-02   1.275e-02
        1.350e-02   1.425e-02   1.500e-02   1.600e-02   1.700e-02   1.800e-02
        1.900e-02   2.000e-02   2.100e-02   2.200e-02   2.300e-02   2.400e-02
        2.550e-02   2.700e-02   2.800e-02   3.000e-02   3.200e-02   3.400e-02
        3.600e-02   3.800e-02   4.000e-02   4.250e-02   4.500e-02   4.750e-02
        5.000e-02   5.250e-02   5.500e-02   5.750e-02   6.000e-02   6.300e-02
        6.600e-02   6.900e-02   7.200e-02   7.600e-02   8.000e-02   8.400e-02
        8.800e-02   9.200e-02   9.600e-02   1.000e-01   1.050e-01   1.100e-01
        1.150e-01   1.200e-01   1.275e-01   1.350e-01   1.425e-01   1.500e-01
        1.600e-01   1.700e-01   1.800e-01   1.900e-01   2.000e-01   2.100e-01
        2.200e-01   2.300e-01   2.400e-01   2.550e-01   2.700e-01   2.800e-01
        3.000e-01   3.200e-01   3.400e-01   3.600e-01   3.800e-01   4.000e-01
        4.250e-01   4.500e-01   4.750e-01   5.000e-01   5.250e-01   5.500e-01
        5.750e-01   6.000e-01   6.300e-01   6.600e-01   6.900e-01   7.200e-01
        7.600e-01   8.000e-01   8.400e-01   8.800e-01   9.200e-01   9.600e-01
        1.000e+00   1.100e+00   1.200e+00   1.300e+00   1.400e+00   1.500e+00
        1.600e+00   1.700e+00   1.800e+00   1.900e+00   2.000e+00   2.100e+00
        2.200e+00   2.300e+00   2.400e+00   2.500e+00   2.600e+00   2.700e+00
        2.800e+00   2.900e+00   3.000e+00   3.100e+00   3.200e+00   3.300e+00
        3.400e+00   3.500e+00   3.600e+00   3.700e+00   3.800e+00   3.900e+00
        4.000e+00   4.100e+00   4.200e+00   4.300e+00   4.400e+00   4.500e+00
        4.600e+00   4.700e+00   4.800e+00   4.900e+00   5.000e+00   5.100e+00
        5.200e+00   5.300e+00   5.400e+00   5.500e+00   5.600e+00   5.700e+00
        5.800e+00   5.900e+00   6.000e+00   6.100e+00   6.200e+00   6.300e+00
        6.400e+00   6.500e+00   6.600e+00   6.700e+00   6.800e+00   6.900e+00
        7.000e+00   7.100e+00   7.200e+00   7.300e+00   7.400e+00   7.500e+00
        7.600e+00   7.700e+00   7.800e+00   7.900e+00   8.000e+00   8.100e+00
        8.200e+00   8.300e+00   8.400e+00   8.500e+00   8.600e+00   8.700e+00
        8.800e+00   8.900e+00   9.000e+00   9.100e+00   9.200e+00   9.300e+00
        9.400e+00   9.500e+00   9.600e+00   9.700e+00   9.800e+00   9.900e+00
        1.000e+01   1.010e+01   1.020e+01   1.030e+01   1.040e+01   1.050e+01
        1.060e+01   1.070e+01   1.080e+01   1.090e+01   1.100e+01   1.110e+01
        1.120e+01   1.130e+01   1.140e+01   1.150e+01   1.160e+01   1.170e+01
        1.180e+01   1.190e+01   1.200e+01   1.210e+01   1.220e+01   1.230e+01
        1.240e+01   1.250e+01   1.260e+01   1.270e+01   1.280e+01   1.290e+01
        1.300e+01   1.310e+01   1.320e+01   1.330e+01   1.340e+01   1.350e+01
        1.360e+01   1.370e+01   1.380e+01   1.390e+01   1.400e+01   1.410e+01
        1.420e+01   1.430e+01   1.440e+01   1.450e+01   1.460e+01   1.470e+01
        1.480e+01   1.490e+01   1.500e+01   1.510e+01   1.520e+01   1.530e+01
        1.540e+01   1.550e+01   1.560e+01   1.570e+01   1.580e+01   1.590e+01
        1.600e+01   1.610e+01   1.620e+01   1.630e+01   1.640e+01   1.650e+01
        1.660e+01   1.670e+01   1.680e+01   1.690e+01   1.700e+01   1.710e+01
        1.720e+01   1.730e+01   1.740e+01   1.750e+01   1.760e+01   1.770e+01
        1.780e+01   1.790e+01   1.800e+01   1.810e+01   1.820e+01   1.830e+01
        1.840e+01   1.850e+01   1.860e+01   1.870e+01   1.880e+01   1.890e+01
        1.900e+01   1.910e+01   1.920e+01   1.930e+01   1.940e+01   1.950e+01
        1.960e+01   1.970e+01   1.980e+01   1.990e+01   2.000e+01
C
F34:N   1001
FC34    neutron fluence  n/cm**2/source neutron - 89 group
E34     1.39E-10 1.00E-09 5.00E-09 1.00E-08 3.00E-08 7.00E-08 1.00E-07
        1.52E-07 2.00E-07 4.14E-07 6.00E-07 8.00E-07 1.13E-06 3.06E-06
        5.04E-06 8.32E-06 1.37E-05 2.26E-05 3.73E-05 6.14E-05 1.01E-04
        1.67E-04 2.75E-04 3.54E-04 4.54E-04 5.83E-04 7.49E-04 9.61E-04
```

```
        1.09E-03 1.23E-03 1.40E-03 1.58E-03 1.80E-03 2.03E-03 2.31E-03
        2.61E-03 2.96E-03 3.35E-03 3.80E-03 4.31E-03 4.88E-03 5.53E-03
        6.27E-03 7.10E-03 8.05E-03 9.12E-03 1.03E-02 1.17E-02 1.33E-02
        1.50E-02 1.70E-02 1.93E-02 2.19E-02 2.48E-02 2.61E-02 2.81E-02
        3.18E-02 4.09E-02 5.25E-02 6.74E-02 8.65E-02 1.11E-01 1.43E-01
        1.83E-01 2.35E-01 3.02E-01 3.88E-01 4.39E-01 4.98E-01 5.64E-01
        6.39E-01 7.24E-01 8.21E-01 9.30E-01 1.05E+00 1.19E+00 1.35E+00
        1.74E+00 2.23E+00 2.87E+00 3.68E+00 4.72E+00 6.07E+00 7.79E+00
        1.00E+01 1.19E+01 1.35E+01 1.49E+01 1.69E+01 2.00E+01
C
F44:N  1001
FC44   total neutron fluence  n/cm**2/source neutron
C
C
MODE N P
C  20B
KCODE 10000000 1.0 3 2000
c  KCODE 10000 1.0 3 200
KSRC   20 0 50  0 20 60  30 0 40  0 30 60
C    PRINT  10 60 100 110
RAND  GEN=2 SEED=19073486328125 STRIDE=152917
PRDMP  50 50 0 1 0
```

B Appendix – Input Deck for Neutron Spectrum Adjustment Using the LSL-M2 Code

```
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 ACRR Free Field on 32in pedestal at centerline 11.0in
---------------------------------------------------------------
t
t       ACRR Free Field Spectrum
t       used on a 32-inch pedestal and measured at fuel centerline 11.0 inches
t
t       Activites normalized to shot number 10639 143.8MJ Pulse (reported by pulse
diagnostics)
t       Ni 58Ni(n,p)58Co activity reference normalization 9.7808E-18 Bq/atom-iso +/-
2.93%
t
t       dosimetry cross section library = irdffv1p02.lib
t
t   Cu shot but not counted
t   In not irradiated
t   Au irradiated as dilute only
t   59Co(n,g)60Co (bare and Cd covered) left out due to significant inconsistencies
t   109Ag(n,g)110mAg (bare and Cd covered) left out due to significant inconsistencies
t   fission foils used Ni foil irradiated inside of ball as reference
t   55Mn(n,2n)54Mn not found
t   59Co(n,2n)58Co not found
t   58Ni(n,2n)57Ni not found
t
t
------------------------------------------------
@actv
 1.0e+0   (activities given in bq/nucleus-parent)
ejp_FF_32in_cl
@end
@description
 ni58p:sld    milx  bahl  -9.7808E-18   0.029  *
 mg24p:sld    mil5  bahl  -1.2890E-17   0.023
 al27a:sld    ml3x  bahl  -6.1585E-18   0.023
 s32cf:sld    void  bare   7.0703E+14   0.036
 ti46p:sld    milx  bahl  -7.8515E-19   0.023
 ti47p:sld    milx  bahl  -3.8055E-17   0.031
 ti48p:sld    milx  bahl  -8.8424E-19   0.014
 fe54p:sld    mil5  bahl  -1.6954E-18   0.022
 fe56p:sld    mil5  bahl  -5.8136E-17   0.018
 co59p:sld    mil2  cdhl  -1.7965E-19   0.058
 ni60p:sld    milx  bahl  -6.3203E-21   0.053
 zn64p:sld    milx  bahl  -4.7963E-16   0.031
 zr902:sld    milx  bahl  -1.7102E-19   0.051
 nb932:sld    mil5  bahl  -2.5526E-19   0.020
 na23g:sld    pelt  bahl  -1.8587E-15   0.022
 sc45g:sld    mil5  bahl  -7.3161E-16   0.022
 mn55g:sld    mil2  bahl  -3.4622E-13   0.018
 fe58g:sld    mil5  bahl  -8.3270E-17   0.022
 mo98g:sld    mil5  bahl  -2.4853E-15   0.017
 w186g:sld    mil6  bahl  -2.2104E-13   0.015
 au197g:sld   dil3  bahl  -5.6538E-13   0.032
 na23g:sld    pelt  cdhl  -4.2940E-16   0.022
 sc45g:sld    mil5  cdhl  -1.1446E-16   0.022
 mn55g:sld    mil2  cdhl  -9.1556E-14   0.019
 fe58g:sld    mil5  cdhl  -2.5208E-17   0.018
 mo98g:sld    mil5  cdhl  -2.3502E-15   0.016
```

```
 au197g:sld   dil3  cdhl  -4.7342E-13   0.032
 rmldu:sld    rmld  fiss  -2.8531E-10   0.035
 rmleu:sld    rmle  fiss  -3.1399E-09   0.035
 rmlpu:sld    rmlp  fiss  -3.1557E-09   0.035
 np237f:sld   void  fisa  -1.5815E-09   0.035
@end
@posit
0.02
@end
@actcov
@end
@outgrd
= nug89
@end
@trlgrd
= sandii
@end
@calf
group fluences
 89  1
1.00
@end
@hsty
1,3600
dosimetry position
  10  26  17  00   1.000000E+0  1
  10  26  17  01   0.000000000  1
  -1  26  17  01   0.000000000  1
@end
@cora
correction file not needed
end
@end
@refflx
ref640 watt1m
@end
@trlflx
= ejp_FF_32in_cl sandii
@end
@covf
new
@end
```

C Appendix – LSL Format Neutron Output

```
*cor    (library)    (mat.#)    (temp)k
*number of energies plus 1
   90
*energy grid ( ev )
  1.00000E-04  1.00000E-03  5.00000E-03  1.00000E-02  3.00000E-02  7.00000E-02  1.00000E-01  1.52300E-01
  2.00000E-01  4.14000E-01  6.00000E-01  8.00000E-01  1.12500E+00  3.05900E+00  5.04300E+00  8.31500E+00
  1.37100E+01  2.26000E+01  3.72700E+01  6.14400E+01  1.01300E+02  1.67000E+02  2.75400E+02  3.53600E+02
  4.54000E+02  5.83000E+02  7.48500E+02  9.61100E+02  1.08900E+03  1.23400E+03  1.39800E+03  1.58500E+03
  1.79600E+03  2.03500E+03  2.30600E+03  2.61300E+03  2.96000E+03  3.35500E+03  3.80100E+03  4.30700E+03
  4.88100E+03  5.53100E+03  6.26700E+03  7.10200E+03  8.04700E+03  9.11900E+03  1.03300E+04  1.17100E+04
  1.32700E+04  1.50300E+04  1.70400E+04  1.93000E+04  2.18800E+04  2.47900E+04  2.60600E+04  2.80900E+04
  3.18300E+04  4.08700E+04  5.24800E+04  6.73800E+04  8.65200E+04  1.11100E+05  1.42600E+05  1.83200E+05
  2.35200E+05  3.02000E+05  3.87700E+05  4.39400E+05  4.97900E+05  5.64200E+05  6.39300E+05  7.24400E+05
  8.20800E+05  9.30100E+05  1.05400E+06  1.19400E+06  1.35300E+06  1.73800E+06  2.23100E+06  2.86500E+06
  3.67900E+06  4.72400E+06  6.06500E+06  7.78800E+06  1.00000E+07  1.19100E+07  1.35000E+07  1.49200E+07
  1.69000E+07  2.00000E+07
*number fraction
  1.28118E-04 4.31573E-03 1.01319E-02 4.63256E-02 6.38443E-02 2.38102E-02 2.00176E-02 8.87691E-03
  1.85092E-02 8.87994E-03 6.78536E-03 8.73483E-03 2.92370E-02 1.51680E-02 1.58436E-02 1.70433E-02
  1.64519E-02 1.66604E-02 1.69565E-02 1.71013E-02 1.36971E-02 1.44466E-02 8.68397E-03 8.78788E-03
  7.89460E-03 7.87530E-03 9.11521E-03 4.76606E-03 4.89456E-03 4.82057E-03 4.61224E-03 4.81256E-03
  4.60608E-03 4.29358E-03 3.90216E-03 3.72225E-03 4.39087E-03 4.57948E-03 4.65618E-03 4.84014E-03
  4.89676E-03 4.43949E-03 4.98109E-03 4.66946E-03 4.70892E-03 4.87304E-03 5.05037E-03 5.03241E-03
  5.13129E-03 5.09598E-03 5.27794E-03 5.42928E-03 5.79021E-03 2.49024E-03 3.50350E-03 5.80217E-03
  8.79175E-03 1.17702E-02 1.32731E-02 1.39194E-02 1.33808E-02 1.67388E-02 1.59745E-02 1.85035E-02
  2.15142E-02 2.41131E-02 1.09478E-02 1.34078E-02 1.41197E-02 1.43655E-02 1.64185E-02 1.55931E-02
  1.41973E-02 1.36729E-02 1.59919E-02 1.61492E-02 3.31252E-02 2.97829E-02 2.63556E-02 1.50975E-02
  1.04552E-02 7.08919E-03 2.91683E-03 7.40874E-04 1.52886E-04 3.41923E-05 9.84257E-06 4.33286E-06
  9.35970E-07
*% standard deviation
  2.52302E+02  1.19602E+02  8.97692E+01  4.59933E+01  3.23887E+01  5.20077E+01  6.17616E+01  6.94860E+01
  6.76723E+01  6.57181E+01  5.86366E+01  6.87944E+01  5.95694E+01  1.39022E+01  6.32380E+01  3.08789E+01
  2.91414E+01  2.94733E+01  2.55891E+01  2.34477E+01  6.14116E+00  2.96688E+01  1.63902E+01  2.49427E+01
  3.37138E+01  1.94742E+01  2.41441E+01  4.39992E+01  3.89400E+01  3.99640E+01  3.95143E+01  3.99881E+01
  3.84726E+01  3.70709E+01  3.37175E+01  3.10387E+01  3.37917E+01  3.54103E+01  3.53523E+01  3.42730E+01
  3.37268E+01  3.35866E+01  3.29085E+01  3.25852E+01  3.18950E+01  3.08138E+01  3.03620E+01  2.99025E+01
  2.96500E+01  3.41421E+01  2.87289E+01  2.78285E+01  2.68882E+01  2.83248E+01  2.84390E+01  2.75287E+01
  2.20733E+01  2.10035E+01  1.97301E+01  1.88327E+01  1.78157E+01  1.78589E+01  1.74919E+01  1.68525E+01
  1.68210E+01  1.62554E+01  1.84548E+01  1.84482E+01  1.82289E+01  1.76934E+01  1.76612E+01  1.76973E+01
  1.73588E+01  1.64913E+01  1.83241E+01  1.67553E+01  1.23017E+01  1.00382E+01  1.02484E+01  9.38720E+00
  9.35999E+00  8.11655E+00  7.22679E+00  6.56342E+00  4.21132E+00  6.32615E+00  5.66138E+00  6.83828E+00
  1.33585E+01
*correlation coefficient -- upper triangular
  1.00000E+02  4.34552E+01  2.63476E+01  1.15710E+00 -2.08244E+01 -1.33419E+01 -9.61716E+00 -7.17102E+00
 -4.80086E+00 -3.07227E+00 -2.07473E+00  1.11498E+00  2.97717E+00  2.00174E+00  6.29562E-01  1.00332E+00
  1.11120E+00  1.07848E+00  1.26213E+00  1.29830E+00  6.09188E+00  2.28643E+00  3.39543E+00  2.27660E+00
  1.48759E+00  2.08706E+00  1.35819E+00  5.14813E-01  6.08513E-01  6.81928E-01  7.94449E-01  6.93716E-01
  7.53060E-01  6.17597E-01  3.75560E-01  2.04486E-01  3.77317E-01  7.80572E-01  9.52039E-01  9.75200E-01
  1.08564E+00  1.08683E+00  1.10516E+00  1.11651E+00  1.14090E+00  1.27945E+00  1.29616E+00  1.20803E+00
  1.21679E+00  1.06721E+00  1.25149E+00  1.28917E+00  1.33056E+00  1.26773E+00  1.26491E+00  1.30602E+00
  1.60890E+00  1.68581E+00  1.78914E+00  1.86871E+00  1.96834E+00  1.96188E+00  1.99873E+00  2.06925E+00
  2.07297E+00  2.14899E+00  1.90833E+00  1.91332E+00  1.93947E+00  2.00141E+00  2.01097E+00  2.01370E+00
  2.05528E+00  2.08460E+00  1.91270E+00  2.10826E+00  2.89141E+00  3.54249E+00  3.46166E+00  3.76830E+00
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  2.64028E+00
  1.00000E+02  7.40136E+01  1.20237E+01 -5.09285E+01 -3.64060E+01 -2.75092E+01 -2.07120E+01 -1.46491E+01
 -9.75197E+00 -7.21740E+00  3.30370E+00  8.70536E+00  4.68288E+00  1.41423E+00  2.25415E+00  2.59771E+00
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  4.96242E+00  3.18593E+00  1.18646E+00  1.30714E+00  1.54463E+00  1.67235E+00  1.56944E+00  1.60282E+00
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  1.00000E+02  3.34831E+01 -6.16766E+01 -5.02191E+01 -3.92093E+01 -3.11921E+01 -2.26305E+01 -1.50824E+01
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 5.30774E+00  5.85097E+00  8.02514E+00  9.83217E+00  9.60756E+00  1.04582E+01  1.04972E+01  1.20989E+01
 1.36840E+01  1.49775E+01  2.34278E+01  1.55484E+01  1.74102E+01  1.43163E+01  7.32733E+00
 1.00000E+02 -4.09415E+01 -7.51315E+01 -6.61101E+01 -5.60302E+01 -4.40315E+01 -3.08542E+01 -2.38022E+01
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 1.00000E+02 -4.59101E+01  1.22128E+01 -5.70520E+00 -5.00533E+00 -3.42044E+00 -2.61428E+00 -1.09639E+00
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 1.00000E+02  4.92274E+01  1.85152E+01 -1.38468E-01 -8.31236E+00 -3.38576E+00  3.02492E+00  4.81339E+00
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```

```
1.00000E+02  6.32608E+01  1.99720E+01 -1.52477E+01 -1.21103E+01  2.54849E+00  8.64851E+00  3.86754E+00
3.52386E+00  3.69755E+00  7.67990E+00  4.17189E+00  5.48784E+00  2.85450E+00  1.59270E+00
1.00000E+02  4.85430E+01 -2.04278E+01 -2.10943E+01  1.91702E+00  1.26895E+01  5.15909E+00  3.84662E+00
4.77004E+00  9.54444E+00  5.05459E+00  6.86942E+00  3.53139E+00  1.98386E+00
1.00000E+02 -1.69056E+00 -3.82179E+01 -2.86239E+00  1.91368E+01  9.49729E+00  4.68889E+00  7.96412E+00
1.40424E+01  7.72510E+00  1.01860E+01  5.59547E+00  3.03164E+00
1.00000E+02 -1.06270E+00 -2.39235E+01  2.25543E+00  1.43441E+01  9.39343E+00  7.61542E+00  1.60925E+01
9.98195E+00  1.14768E+01  8.62990E+00  4.40604E+00
1.00000E+02 -2.81081E+00 -3.56915E+01  9.60349E+00  1.70405E+01  3.09821E+00  1.35154E+01  1.09714E+01
1.00103E+01  1.02550E+01  4.83067E+00
1.00000E+02 -1.67876E+01 -1.88178E+01  1.98833E+01  5.90695E+00  1.36871E+01  1.13980E+01  1.03505E+01
1.04110E+01  5.09931E+00
1.00000E+02 -2.77174E+01 -5.88862E+00  2.50763E+01  1.77487E+01  6.11669E+00  1.38912E+01  4.44481E+00
3.16971E+00
1.00000E+02 -2.32840E+01  1.84864E+01  2.56859E+01  7.07720E+00  1.65589E+01  2.75699E+00  2.68544E+00
1.00000E+02 -5.59358E+01  3.97915E+00  3.57728E+01  3.13068E+00  3.93621E+01  1.46464E+01
1.00000E+02  2.81167E+01 -1.73823E+01  3.34133E+01 -2.23863E+01 -4.13246E+00
1.00000E+02  1.71699E+01 -1.58258E+00  4.64817E+01  2.41245E+01
1.00000E+02  3.37737E+01 -2.91320E+01 -2.33298E+01
1.00000E+02  1.53350E+01 -1.81699E+01
1.00000E+02  5.43580E+01
1.00000E+02
```

D Appendix – LSL Format Prompt Gamma Ray Output

```
*cor
*number of energies plus 1
   49
*energy grid (eV) - high to low energy order
 0.5000000E+08  0.3000000E+08  0.2000000E+08  0.1700000E+08  0.1400000E+08
 0.1200000E+08  0.1000000E+08   9000000.       8000000.       7500000.
  7000000.       6500000.       6000000.       5500000.       5000000.
  4500000.       4000000.       3500000.       3000000.       2660000.
  2500000.       2333000.       2000000.       1875000.       1660000.
  1500000.       1330000.       1200000.       1125000.       1000000.
  900000.0       800000.0       700000.0       600000.0       525000.0
  500000.0       450000.0       400000.0       300000.0       200000.0
  150000.0       100000.0       80000.00       60000.00       45000.00
  30000.00       20000.00       10000.00       1000.000
*spectrum number fractions -
   0.00000E+00 0.00000E+00 0.00000E+00 7.17624E-08 3.40990E-07
   2.15267E-05 1.67015E-03 8.40936E-03 1.72543E-02 4.61936E-03
   3.55724E-03 5.82932E-03 7.61868E-03 6.78364E-03 8.77546E-03
   1.20959E-02 1.53346E-02 2.27937E-02 2.09740E-02 1.35183E-02
   1.43027E-02 4.92663E-02 1.53827E-02 3.43175E-02 2.94298E-02
   3.93930E-02 3.49370E-02 2.00205E-02 4.39577E-02 3.61632E-02
   5.27783E-02 5.00014E-02 5.71092E-02 4.77903E-02 4.74301E-02
   3.82547E-02 3.81520E-02 7.32701E-02 5.75146E-02 2.16866E-02
   1.48673E-02 9.10248E-03 2.05195E-02 3.37632E-03 1.26602E-03
   3.28966E-04 1.00229E-04 2.55773E-05
*standard deviation (%)
  92.37442       76.31279       66.02299       59.97667       53.96589
  48.25708       42.48969       37.04626       32.52547       29.26157
  25.76435       21.99784       20.00000       20.00000       20.00000
  20.00000       20.00000       20.00000       20.00000       20.00000
  20.00000       20.00000       20.00000       20.00000       20.00000
  20.25727       20.75147       21.12413       21.52082       22.01440
  22.50493       23.05692       23.68803       24.32566       24.73621
  25.07133       25.56186       26.41813       27.90204       29.47505
  30.95897       32.40774       33.51609       34.78482       42.14988
  52.22706       64.92281       81.49094
 *correlation coefficients - upper triangular
  1.0000    0.41240    0.21365    0.12815    0.61365E-01 0.10903E-01 -0.37460E-01
-0.65499E-01 -0.87938E-01 -0.10420  -0.12245   -0.14472   -0.16105   -0.16553
-0.18295     -0.18211     -0.18113  -0.18020   -0.17953   -0.17901   -0.17833
-0.17678   -0.17498   -0.17324   -0.17074   -0.16642   -0.16034   -0.15540
-0.14960   -0.14798   -0.14904   -0.14965   -0.14982   -0.14952   -0.14890
-0.14787   -0.14566   -0.14116   -0.13406   -0.12837    -0.12439   -0.12141
-0.11913   -0.11609   -0.10302   -0.90090E-01 -0.76804E-01 -0.59182E-01
  1.0000    0.50774    0.35042    0.22681    0.13250    0.49092E-01 -0.20241E-02
-0.42572E-01 -0.71635E-01 -0.10373   -0.14180   -0.17135   -0.18377   -0.25068
-0.24966   -0.24848   -0.24735   -0.24655    -0.24591    -0.24509     -0.24321
-0.24104   -0.23893   -0.23591   -0.23031     -0.22226     -0.21578    -0.20825
-0.20567   -0.20638   -0.20650    -0.20603     -0.20502     -0.20387    -0.20231
-0.19919   -0.19300   -0.18323    -0.17522     -0.16945     -0.16500    -0.16165
-0.15733     -0.13857     -0.12024     -0.10197     -0.78812E-01
  1.0000    0.60229    0.41910    0.28014    0.16248    0.89811E-01  0.33044E-01
-0.69960E-02 -0.50405E-01 -0.10053   -0.14085   -0.16157   -0.28695     -0.28577
-0.28440   -0.28310   -0.28217   -0.28143     -0.28049     -0.27831     -0.27580
-0.27336   -0.26987   -0.26343   -0.25420     -0.24676     -0.23810     -0.23518
-0.23605   -0.23625   -0.23577   -0.23467     -0.23337     -0.23160     -0.22804
-0.22096   -0.20978   -0.20063   -0.19405     -0.18898     -0.18517     -0.18023
-0.15884     -0.13791     -0.11700     -0.90407E-01
  1.0000    0.58195    0.40718    0.26292    0.17413      0.10568      0.58053E-01
 0.72003E-02 -0.50294E-01 -0.97653E-01 -0.12492   -0.29891   -0.29761   -0.29611
-0.29467   -0.29365   -0.29284   -0.29180     -0.28941   -0.28664     -0.28395
-0.28011   -0.27324   -0.26347   -0.25557     -0.24634     -0.24348     -0.24477
-0.24535   -0.24521   -0.24438   -0.24318     -0.24142     -0.23776     -0.23039
-0.21877   -0.20934   -0.20265   -0.19756     -0.19371     -0.18865     -0.16680
-0.14532     -0.12357     -0.95357E-01
  1.0000    0.57454    0.39717    0.28898    0.20691      0.15077      0.91964E-01
 0.27229E-01 -0.27545E-01 -0.62923E-01 -0.29888   -0.29743   -0.29576   -0.29416
-0.29302   -0.29212   -0.29097   -0.28831   -0.28524   -0.28225     -0.27798
-0.27077   -0.26070   -0.25248   -0.24280     -0.24032     -0.24241     -0.24377
-0.24438   -0.24420   -0.24332      -0.24172     -0.23816     -0.23082     -0.21924
-0.21004   -0.20369   -0.19900      -0.19540     -0.19050     -0.16956     -0.14874
-0.12707     -0.97798E-01
  1.0000    0.56273    0.43152      0.33364      0.26784      0.20032      0.12810
 0.65305E-01  0.20326E-01 -0.29005   -0.28843   -0.28656     -0.28477     -0.28350
-0.28249   -0.28120   -0.27823    -0.27479     -0.27145     -0.26668     -0.25917
```

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-0.24895   -0.24051   -0.23046     -0.22860     -0.23182     -0.23428     -0.23599
-0.23675   -0.23638   -0.23507     -0.23176     -0.22467     -0.21350     -0.20491
-0.19924   -0.19527   -0.19215     -0.18763     -0.16865     -0.14941     -0.12849
-0.98523E-01
  1.0000    0.56912    0.45613      0.37990      0.30150      0.21757      0.14383
 0.89579E-01 0.63691E-01 0.83218E-02 -0.45090E-01 -0.96661E-01 -0.13848   -0.16216
-0.17651   -0.19655   -0.21318     -0.22395     -0.23380     -0.23797     -0.23718
-0.23452   -0.22944   -0.25638     -0.26011     -0.26298     -0.26500     -0.26595
-0.26557   -0.26412   -0.26042     -0.25246     -0.23992     -0.23029     -0.22397
-0.21957   -0.21609   -0.21104     -0.18985     -0.16832     -0.14483     -0.11102
  1.0000    0.57041    0.48659      0.40185      0.31329      0.23396      0.17157
 0.14176    0.78141E-01  0.16739E-01 -0.42634E-01 -0.90898E-01 -0.11832   -0.13497
-0.15835   -0.17786   -0.19061     -0.20242     -0.20848     -0.20953     -0.20790
-0.20354   -0.23935   -0.24482     -0.24938     -0.25310     -0.25552     -0.25590
-0.25489   -0.25157   -0.24397     -0.23201     -0.22327     -0.21798     -0.21467
-0.21191     -0.20743     -0.18917     -0.17000     -0.14755     -0.11255
  1.0000    0.58857    0.49840      0.40634      0.32237      0.25237      0.21950
 0.14814    0.79273E-01 0.12641E-01 -0.41609E-01 -0.72485E-01 -0.91259E-01 -0.11766
-0.13977   -0.15427   -0.16779     -0.17558     -0.17836     -0.17770     -0.17398
-0.21870   -0.22611   -0.23257     -0.23817     -0.24224     -0.24349     -0.24298
-0.24011   -0.23295   -0.22172     -0.21404     -0.20994     -0.20788     -0.20595
-0.20214     -0.18731     -0.17090     -0.14978     -0.11363
  1.0000    0.57684    0.48275      0.39562      0.31960      0.28487      0.20735
 0.13258    0.60216E-01  0.12537E-02 -0.32330E-01 -0.52749E-01 -0.81467E-01 -0.10555
-0.12136  -0.13612      -0.14524      -0.14941      -0.14948      -0.14623      -0.19843
-0.20764  -0.21587      -0.22323      -0.22884      -0.23090      -0.23087      -0.22843
-0.22172  -0.21122      -0.20456      -0.20160      -0.20073      -0.19959      -0.19642
-0.18487     -0.17114     -0.15135     -0.11424
  1.0000   0.57433       0.48424       0.40125       0.36517       0.28047       0.19884
0.11986 0.55458E-01 0.18763E-01 -0.35215E-02 -0.34829E-01 -0.61081E-01 -0.78301E-01
-0.94339E-01 -0.10493  -0.11069      -0.11160      -0.10880      -0.17015      -0.18180
-0.19244  -0.20221      -0.20993      -0.21310      -0.21372      -0.21188      -0.20580
-0.19631  -0.19108      -0.18969      -0.19046      -0.19041      -0.18813      -0.18112
-0.17109     -0.15316     -0.11483
  1.0000   0.59181       0.50076       0.46461       0.37146       0.28181       0.19509
 0.12436 0.84063E-01 0.59664E-01 0.25493E-01 -0.30998E-02 -0.21772E-01 -0.39030E-01
-0.51181E-01 -0.58720E-01 -0.60469E-01 -0.57996E-01 -0.13071  -0.14585      -0.15992
-0.17310  -0.18382      -0.18856      -0.19010      -0.18910      -0.18389      -0.17583
-0.17258  -0.17341      -0.17649      -0.17797      -0.17695      -0.17632      -0.17148
-0.15614     -0.11597
  1.0000   0.61372       0.57257       0.46891       0.36927       0.27299       0.19446
 0.14972  0.12259  0.84536E-01  0.52610E-01  0.31678E-01  0.12207E-01 -0.22652E-02
-0.12207E-01 -0.15339E-01 -0.13875E-01 -0.99526E-01 -0.11715  -0.13366      -0.14929
-0.16215  -0.16803      -0.17025      -0.16989      -0.16540      -0.15849      -0.15678
-0.15928  -0.16407      -0.16670      -0.16663      -0.17083      -0.16996      -0.15673
-0.11560
  1.0000   0.68527       0.56822       0.45580       0.34733       0.25899       0.20857
 0.17780   0.13427  0.97412E-01  0.72877E-01  0.49485E-01  0.31449E-01  0.18160E-01
 0.12753E-01  0.12010E-01 -0.88174E-01 -0.10605  -0.12282      -0.13874      -0.15187
-0.15792  -0.16028      -0.16011      -0.15594      -0.14953      -0.14830      -0.15121
-0.15636     -0.15924     -0.15944     -0.16490     -0.16518     -0.15288  -0.11253
  1.0000   0.74602       0.61753       0.49381       0.39326       0.33581       0.30052
 0.25023   0.20731  0.17835      0.15015     0.12706      0.10839      0.99274E-01
 0.94876E-01 -0.24797E-01 -0.44051E-1 -0.62312E-1 -0.79836E-1 -0.94518E-1 -0.10152
-0.10463  -0.10553      -0.10313      -0.99527E-01 -0.10096      -0.10614      -0.11331
-0.11761     -0.11933     -0.13180     -0.13846     -0.13139     -0.95413E-01
  1.0000   0.73852       0.59518       0.47900       0.41260       0.37159       0.31274
 0.26218   0.22766       0.19343       0.16507       0.14163       0.12928       0.12176
-0.21248E-1 -0.40579E-1 -0.58923E-1 -0.76538E-1 -0.91306E-01 -0.98362E-01 -0.10151
-0.10247  -0.10017      -0.96727E-01 -0.98314E-01 -0.10362      -0.11090      -0.11528
-0.11708     -0.12995     -0.13697     -0.13019     -0.94454E-01
  1.0000   0.72730       0.59043       0.51224       0.46373       0.39369       0.33318
 0.29145   0.24942       0.21427   0.18471   0.16823      0.15671     -0.17158E-01
-0.36578E-1 -0.55018E-1 -0.72736E-1 -0.87604E-1 -0.94721E-1 -0.97920E-1 -0.98952E-1
-0.96759E-01 -0.93500E-01 -0.95259E-01 -0.10071     -0.10812  -0.11259      -0.11450
-0.12781  -0.13524      -0.12880      -0.93349E-01
  1.0000   0.73992       0.64550       0.58670       0.50141       0.42742       0.37595
 0.32344   0.27922   0.24152      0.21956   0.20276     -0.13234E-01 -0.32739E-01
-0.51271E-1 -0.69090E-1 -0.84053E-1 -0.91229E-1 -0.94474E-1 -0.95573E-1 -0.93489E-1
-0.90404E-01 -0.92328E-01 -0.97919E-01 -0.10546  -0.11002      -0.11201      -0.12576
-0.13359     -0.12747     -0.92289E-01
  1.0000   0.79796       0.72705       0.62388       0.53417       0.47142       0.40684
 0.35225  0.30531   0.27714      0.25437     -0.10452E-01 -0.30018E-01 -0.48616E-01
-0.66505E-1 -0.81536E-1 -0.88754E-1 -0.92032E-1 -0.93177E-1 -0.91172E-1 -0.88209E-1
-0.90250E-01 -0.95941E-01 -0.10357      -0.10819      -0.11025  -0.12431      -0.13242
-0.12653     -0.91537E-01
  1.0000   0.83596       0.71874       0.61673       0.54520       0.47125       0.40866
 0.35461   0.32169   0.29435  -0.82424E-02 -0.27857E-01 -0.46506E-01 -0.64451E-01
-0.79536E-1 -0.86787E-1 -0.90092E-1 -0.91274E-1 -0.89330E-1 -0.86466E-1 -0.88600E-1
-0.94369E-01 -0.10207  -0.10674      -0.10885      -0.12315      -0.13149      -0.12578
-0.90940E-01
```

```
  1.0000      0.79429      0.68256   0.60410      0.52280      0.45392      0.39429
 0.35765  0.32674 -0.54082E-02 -0.25084E-01 -0.43800E-01 -0.61817E-01 -0.76971E-01
-0.84264E-1 -0.87603E-1 -0.88833E-1 -0.86968E-1 -0.84229E-1 -0.86483E-1 -0.92354E-1
-0.10014  -0.10488  -0.10706     -0.12167  -0.13029     -0.12482     -0.90175E-01
  1.0000      0.80686      0.71533   0.62019      0.53952      0.46945      0.42586
 0.38830 0.11069E-2 -0.18711E-1 -0.37579E-01 -0.55762E-01 -0.71075E-01 -0.78466E-01
-0.81882E-1 -0.83222E-1 -0.81539E-1 -0.79089E-1 -0.81617E-1 -0.87721E-1 -0.95714E-1
-0.10060   -0.10294  -0.11827  -0.12754  -0.12261  -0.88415E-01
  1.0000      0.84638   0.73470      0.64002      0.55761      0.50582      0.46046
 0.86356E-2 -0.11347E-1 -0.30391E-1 -0.48765E-1 -0.64262E-1 -0.71766E-1 -0.75272E-1
-0.76738E-1 -0.75266E-1 -0.73149E-1 -0.75994E-1 -0.82368E-1 -0.90600E-1 -0.95653E-1
-0.98172E-01 -0.11434     -0.12437     -0.12006     -0.86381E-01
  1.0000   0.84229   0.73432   0.64026      0.58078      0.52811      0.15958E-01
-0.41841E-2 -0.23400E-1 -0.41961E-1 -0.57635E-1 -0.65250E-01 -0.68842E-1 0.70432E-1
-0.69164E-1 -0.67372E-1 -0.70525E-1 -0.77161E-1 -0.85626E-1 -0.90843E-1 -0.93538E-1
-0.11051     -0.12128     -0.11757     -0.84403E-1
  1.0000   0.86597   0.75549      0.68520   0.62230      0.26421E-1  0.60514E-02
-0.13409E-1 -0.32236E-1 -0.48166E-1 -0.55937E-1 -0.59655E-1 -0.61421E-1 -0.60445E-1
-0.59116E-1 -0.62710E-1 -0.69721E-1 -0.78518E-1 -0.83971E-1 -0.86916E-1 -0.10505
-0.11687     -0.11403     -0.81576E-1
  1.0000   0.88307   0.80031      0.72558   0.35118E-1  0.14810E-1 -0.46155E-02
-0.23433E-1 -0.39381E-1 -0.47189E-1 -0.50966E-1 -0.52862E-1 -0.52151E-1 -0.51239E-1
-0.55168E-1 -0.62413E-1 -0.71386E-1 -0.76972E-1 -0.80096E-1 -0.98998E-1 -0.11158
-0.10952     -0.78100E-1
  1.0000   0.93311    0.84426  0.43163E-1  0.23145E-1  0.39745E-02 -0.14621E-1
-0.30405E-1 -0.38161E-1 -0.41954E-1 -0.43954E-1 -0.43508E-1 -0.43012E-1 -0.47221E-1
-0.54611E-1 -0.63653E-1 -0.69305E-1 -0.72568E-1 -0.92002E-1 -0.10518 -0.10390
-0.73841E-1
  1.0000   0.94712   0.51272E-1  0.31414E-1  0.12374E-1 -0.61189E-02 -0.21840E-01
-0.29593E-1 -0.33424E-1 -0.35539E-1 -0.35348E-1 -0.35254E-1 -0.39762E-1 -0.47339E-1
-0.56504E-1 -0.62255E-1 -0.65673E-1 -0.85745E-1 -0.99587E-1 -0.99055E-1 -0.70142E-1
  1.0000 0.62639E-1 0.42879E-1  0.23901E-1 0.54360E-02 -0.10296E-1 -0.18090E-1
-0.21997E-1 -0.24281E-1 -0.24437E-1 -0.24890E-1 -0.29834E-1 -0.37712E-1 -0.47099E-1
-0.53021E-1 -0.56671E-1 -0.77734E-1 -0.92562E-1 -0.93054E-1 -0.65523E-1
  1.0000   0.92951      0.80548      0.68123      0.57193      0.51005      0.46520
 0.40771   0.32334   0.20774      0.11488      0.49235E-1  0.18376E-02 -0.23636E-1
-0.42014E-1 -0.71828E-1 -0.91069E-1 -0.93030E-1 -0.66010E-1
  1.0000      0.88120   0.74598      0.62728      0.56007      0.51118      0.44825
 0.35557   0.22852   0.12649      0.54260E-1  0.19969E-02 -0.26316E-1 -0.47130E-1
-0.76874E-1 -0.95599E-1 -0.96873E-1 -0.69427E-1
  1.0000      0.83258      0.70162      0.62748   0.57339      0.50348      0.40025
 0.25876    0.14527    0.64786E-01     -0.63323E-02 -0.25673E-1 -0.49745E-1 -0.80219E-1
-0.99090E-1 -0.10013     -0.72501E-1
  1.0000   0.80313   0.71967      0.65862      0.57946      0.46233      0.30209
 0.17387      0.82787E-1  0.16320E-1 -0.20550E-1 -0.49022E-1 -0.81310E-01 -0.10126
-0.10271     -0.75266E-01
  1.0000    0.83096    0.76155      0.67134      0.53780      0.35574      0.21061
 0.10747  0.31850E-01 -0.10649E-01 -0.44313E-01 -0.79476E-01 -0.10150     -0.10417
-0.77385E-01
  1.0000    0.83863   0.74020      0.59456      0.39660      0.23933      0.12760
 0.45449E-01 -0.10877E-02 -0.38523E-01 -0.76194E-01 -0.10020 -0.10419  -0.78177E-01
  1.0000   0.80353   0.64696   0.43474      0.26668      0.14737      0.59467E-01
 0.93590E-02 -0.31439E-01 -0.71664E-01 -0.97775E-01 -0.10326     -0.78196E-01
  1.0000   0.73378   0.49835   0.31294    0.18153      0.84502E-01  0.28715E-01
-0.17462E-01 -0.62202E-01 -0.92156E-01 -0.10050     -0.77340E-01
  1.0000   0.62900   0.40830      0.25277      0.13773    0.70784E-01  0.13991E-01
-0.40240E-01 -0.78547E-01 -0.93437E-01 -0.74858E-01
  1.0000   0.61713   0.40826   0.25459      0.16412      0.85059E-01  0.10507E-01
-0.46352E-01 -0.76799E-01 -0.70339E-01
  1.0000   0.62851   0.41904   0.29578      0.18638      0.84466E-01  0.21043E-02
-0.51146E-01 -0.65299E-01
  1.0000   0.62807   0.46239   0.31508      0.17986      0.66741E-01 -0.14860E-01
-0.58175E-01
  1.0000  0.68125   0.48331   0.30510      0.15354      0.36686E-01 -0.46102E-01
  1.0000      0.65159      0.42981      0.24081      0.90591E-01 -0.30869E-01
  1.0000      0.61349      0.36921      0.17176     -0.42936E-02
  1.0000      0.57045      0.30184      0.44077E-01
  1.0000      0.51785      0.13033
  1.0000      0.29880
  1.0000
end
```

E Appendix – LSL Format Delayed Gamma Ray Output

```
*cor
*number of energies + 1
   -49
 *energy grid (eV) - high to low energy order
   0.5000000E+08   0.3000000E+08   0.2000000E+08   0.1700000E+08   0.1400000E+08
   0.1200000E+08   0.1000000E+08    9000000.        8000000.        7500000.
    7000000.        6500000.        6000000.        5500000.        5000000.
    4500000.        4000000.        3500000.        3000000.        2660000.
    2500000.        2333000.        2000000.        1875000.        1660000.
    1500000.        1330000.        1200000.        1125000.        1000000.
    900000.0        800000.0        700000.0        600000.0        525000.0
    500000.0        450000.0        400000.0        300000.0        200000.0
    150000.0        100000.0        80000.00        60000.00        45000.00
    30000.00        20000.00        10000.00       0.1000000E-05
*spectrum number fractions -
   0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
   0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
   0.00000E+00 1.30170E-03 1.83797E-03 2.70165E-03 6.48044E-03
   9.83836E-03 1.53126E-02 2.44388E-02 2.23350E-02 1.30531E-02
   1.46107E-02 3.77509E-02 1.65329E-02 3.66744E-02 3.05998E-02
   4.37188E-02 3.64990E-02 2.80729E-02 5.21671E-02 4.59414E-02
   5.09584E-02 5.78900E-02 6.55257E-02 5.68895E-02 3.60669E-02
   4.34404E-02 4.27934E-02 7.75391E-02 5.95847E-02 2.16677E-02
   1.47488E-02 8.80604E-03 2.00329E-02 3.09186E-03 7.67033E-04
   2.34984E-04 7.46814E-05 1.88668E-05
*standard deviation (%)
    100.0000        100.0000        100.0000        100.0000        100.0000
    100.0000        100.0000        100.0000        100.0000        100.0000
    100.0000        100.0000        16.02117        15.14483        14.12357
    12.93757        11.56018        9.954620        8.415668        7.478934
    6.892618        6.008919        5.319580        5.116024        5.082303
    4.721325        4.587551        5.447469        7.171198        7.970987
    9.110368        10.70658        14.54979        38.97043        38.54490
    41.89580        44.28633        42.27082        42.25864        42.42124
    46.58898        54.03873        53.39265        53.45946        74.71307
    101.5013        101.6366        102.2580
 *correlation coefficients - upper triangular
    1.000000       0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00
    1.000000       0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00
    1.000000       0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00
    1.000000       0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
```

```
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
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0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9450000      0.9030000      0.8730000      0.8420000
0.8090000      0.7750000      0.7400000      0.7020000      0.6610000
0.6170000      0.5690000      0.5250000      0.4970000      0.4770000
0.4450000      0.4140000      0.3890000      0.3590000      0.3320000
0.3040000      0.2850000      0.2650000      0.2400000      0.2180000
0.1940000      0.1680000      0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00
 1.000000      0.9540000      0.9230000      0.8900000      0.8560000
0.8210000      0.7840000      0.7440000      0.7020000      0.6560000
0.6060000      0.5610000      0.5310000      0.5110000      0.4780000
0.4450000      0.4190000      0.3890000      0.3600000      0.3310000
0.3110000      0.2900000      0.2640000      0.2400000      0.2150000
0.1880000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00
 1.000000      0.9670000      0.9330000      0.8970000      0.8600000
0.8220000      0.7800000      0.7370000      0.6900000      0.6380000
0.5910000      0.5600000      0.5390000      0.5050000      0.4720000
0.4450000      0.4140000      0.3840000      0.3550000      0.3330000
0.3110000      0.2850000      0.2600000      0.2340000      0.2050000
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9640000      0.9280000      0.8900000      0.8500000
0.8080000      0.7630000      0.7140000      0.6620000      0.6130000
0.5820000      0.5610000      0.5260000      0.4920000      0.4640000
0.4320000      0.4020000      0.3720000      0.3500000      0.3280000
0.3010000      0.2750000      0.2480000      0.2180000      0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9620000      0.9220000      0.8810000      0.8380000
0.7910000      0.7420000      0.6880000      0.6380000      0.6060000
0.5840000      0.5490000      0.5140000      0.4860000      0.4530000
0.4210000      0.3910000      0.3680000      0.3450000      0.3180000
0.2910000      0.2630000      0.2330000      0.0000000E+00  0.0000000E+00
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0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9590000      0.9160000      0.8710000      0.8230000
0.7720000      0.7160000      0.6650000      0.6330000      0.6100000
0.5740000      0.5380000      0.5090000      0.4750000      0.4430000
0.4120000      0.3890000      0.3650000      0.3370000      0.3090000
0.2800000      0.2490000      0.0000000E+00  0.0000000E+00  0.0000000E+00
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0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00
 1.000000      0.9550000      0.9080000      0.8590000      0.8060000
0.7480000      0.6960000      0.6620000      0.6390000      0.6010000
0.5640000      0.5350000      0.5000000      0.4670000      0.4350000
0.4110000      0.3870000      0.3580000      0.3300000      0.3000000
0.2670000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00
 1.000000      0.9510000      0.8990000      0.8440000      0.7840000
0.7300000      0.6950000      0.6710000      0.6330000      0.5940000
0.5640000      0.5280000      0.4940000      0.4610000      0.4370000
0.4120000      0.3810000      0.3520000      0.3210000      0.2870000
```

```
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
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0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9450000      0.8880000      0.8260000      0.7690000
0.7330000      0.7080000      0.6680000      0.6290000      0.5970000
0.5600000      0.5250000      0.4910000      0.4660000      0.4400000
0.4080000      0.3780000      0.3460000      0.3110000      0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9390000      0.8740000      0.8140000      0.7770000
0.7510000      0.7090000      0.6680000      0.6350000      0.5970000
0.5610000      0.5250000      0.4990000      0.4720000      0.4390000
0.4080000      0.3750000      0.3380000      0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9300000      0.8680000      0.8280000      0.8010000
0.7570000      0.7140000      0.6800000      0.6400000      0.6020000
0.5650000      0.5380000      0.5100000      0.4760000      0.4430000
0.4080000      0.3700000      0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00
 1.000000      0.9330000      0.8900000      0.8610000      0.8150000
0.7690000      0.7330000      0.6910000      0.6510000      0.6120000
0.5840000      0.5550000      0.5190000      0.4850000      0.4490000
0.4080000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00
 1.000000      0.9540000      0.9230000      0.8740000      0.8260000
0.7880000      0.7440000      0.7020000      0.6610000      0.6310000
0.6000000      0.5630000      0.5280000      0.4890000      0.4470000
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9670000      0.9160000      0.8660000      0.8260000
0.7800000      0.7370000      0.6940000      0.6640000      0.6320000
0.5940000      0.5570000      0.5180000      0.4740000      0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9460000      0.8950000      0.8540000      0.8070000
0.7620000      0.7190000      0.6870000      0.6550000      0.6160000
0.5780000      0.5380000      0.4940000      0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9450000      0.9030000      0.8530000      0.8060000
0.7610000      0.7280000      0.6950000      0.6540000      0.6150000
0.5730000      0.5270000      0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00
 1.000000      0.9550000      0.9020000      0.8540000      0.8060000
0.7720000      0.7370000      0.6940000      0.6540000      0.6110000
0.5630000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
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0.0000000E+00
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0.7730000      0.7290000      0.6870000      0.6420000      0.5930000
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0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9460000      0.8940000      0.8570000      0.8180000
0.7730000      0.7290000      0.6830000      0.6320000      0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9450000      0.9060000      0.8660000      0.8180000
0.7720000      0.7240000      0.6710000      0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00
 1.000000      0.9580000      0.9160000      0.8660000      0.8180000
0.7670000      0.7120000      0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00
```

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   0.7440000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00
    1.000000       0.9450000      0.8940000      0.8390000      0.7800000
  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
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  0.0000000E+00  0.0000000E+00  0.0000000E+00
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  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00
    1.000000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00
    1.000000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
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    1.000000      0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
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