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The Annular Core Research Reactor (ACRR) Description and Capabilities

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ABSTRACT

The Annular Core Research Reactor (ACRR) is a unique, one-of-a-kind nuclear reactor facility operated by Sandia National Laboratories for the National Nuclear Security Administration that is considered by many to be a national treasure. There is no other research reactor in the world that has the attributes and capabilities comparable to that of the ACRR. The ACRR was specifically designed to meet the irradiation testing needs of the U.S. nuclear weapons program. The ACRR has four major attributes that make it unique: 1) a large dry central cavity; 2) an epithermal neutron flux; 3) a large pulsing capability; and 4) a fueled-ring external cavity with a larger dry cavity. This report presents the unique capabilities of the ACRR and documents some of the more important metrics associated with its operation.

ACKNOWLEDGEMENTS

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ACPR	Annular Core Pulse Reactor
ACRR	Annular Core Research Reactor
Al	aluminum
B	boron
B_4C	Boron carbide
Cd	cadmium
eV	Electron volt
FREC-II	Fueled Ring External Cavity - version 2
FWHM	full-width at half-maximum
Gy	Gray - unit of absorbed dose equal to 100 rad
keV	kilo-electron volt
krad	kilorad - unit of absorbed dose equal to 1000 rad
LB44	44-inch-long lead-boron bucket
MCNP	Monte Carlo N-Particle
MeV	mega-electron volt
MJ	megajoule
ms	milliseconds
MW	megawatts
n/cm^2	units of fluence (neutrons per cm2)
Pb	lead
PCD	photo-conducting detector
PLG	polyethylene-lead-graphite
Poly	polyethylene
rad	unit of absorbed dose equal to 100 erg/g in a specified material
SNL	Sandia National Laboratories
SPND	self-powered neutron detector
TA-V	Technical Area V
TLD	thermoluminescent dosimeter
TRIGA	Training, Research, Isotopes, General Atomics
UO2-BeO	uranium dioxide - beryllium oxide
UZrH	uranium zirconium hydride

1. INTRODUCTION

The Annular Core Research Reactor (ACRR) is a unique, one-of-a-kind nuclear reactor facility operated by Sandia National Laboratories (SNL) for the National Nuclear Security Administration that is considered by many to be a national treasure. There is no other research reactor in the world that has the attributes and capabilities comparable to that of the ACRR. The ACRR was specifically designed to meet the irradiation testing needs of the U.S. nuclear weapons program. The ACRR has four major attributes that make it unique: 1) a large dry central cavity; 2) an epithermal neutron flux; 3) a large pulsing capability; and 4) a fueled-ring external cavity with a larger dry cavity.

The ACRR is typically used to perform irradiation testing when a high neutron fluence is required over a short period of time. Historically, the ACRR has been used for a wide variety of experiment campaigns in addition to supporting its main mission - irradiation services of components for the nuclear weapons program. Some of these campaigns have included radiation damage in materials testing, nuclear pumped laser testing, nuclear fuels testing, space nuclear thermal propulsion testing, and medical isotopes production.

The ACRR is located in Technical Area V (TA-V) at Sandia National Laboratories in Albuquerque, New Mexico. The ACRR is currently fully operational. The reactor, in its current fueled 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 in order to allow for larger pulsing capabilities as compared to other TRIGA-like pulsed reactors. This type of fuel, containing beryllium oxide, is no longer capable of being produced anywhere in the world.

2. ACRR DESCRIPTION

The ACRR can operate in a pulse or steady-state mode. Most customers desire the pulsing capabilities of the reactor. This has allowed the ACRR to have no significant fuel burnup over its 40 years of use. Under the same operating conditions, the reactor fuel is expected to last at least another 40 years. 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 (UZrH) TRIGA fuel as a subcritical multiplier. As currently configured, the FREC-II is not capable of achieving nuclear criticality. FREC-II provides experimenters with a larger test volume, and the fuel arrangement limits the neutron fluence gradient across the test volume. The TRIGA fuel used in FREC-II was originally used in ACRR's predecessor core, the Annular Core Pulse Reactor.

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. Figure 4 shows an experiment package being loaded into the dry central cavity with the assistance of the overhead crane. Another view of the ACRR and FREC-II is shown in Figure 5, with the reactor shut down and the FREC-II (on the left) tilted back in its "decoupled" configuration. Shown on the right in Figure 5 is the radiography tube. Figure 6 shows a detailed 3-D drawing of the ACRR tank and reactor. 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 up to 4 MW. The pool is cooled using a heat rejection system rated to support steady-state operations up to 5 MW.

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 volume of the cavities allows for the possibility of acceleration/deceleration (High-G) apparatus, 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 using 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 adjustment of the neutron-to-gamma dose ratio. Figure 7 shows one of the spectrum modifying buckets for the central cavity, the Cd-Poly bucket.

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 ~300 MJ ($3.50) with a full-width half-maximum (FWHM) of 6.8 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, as in a linear ramp increase in power level from low to high power level.

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

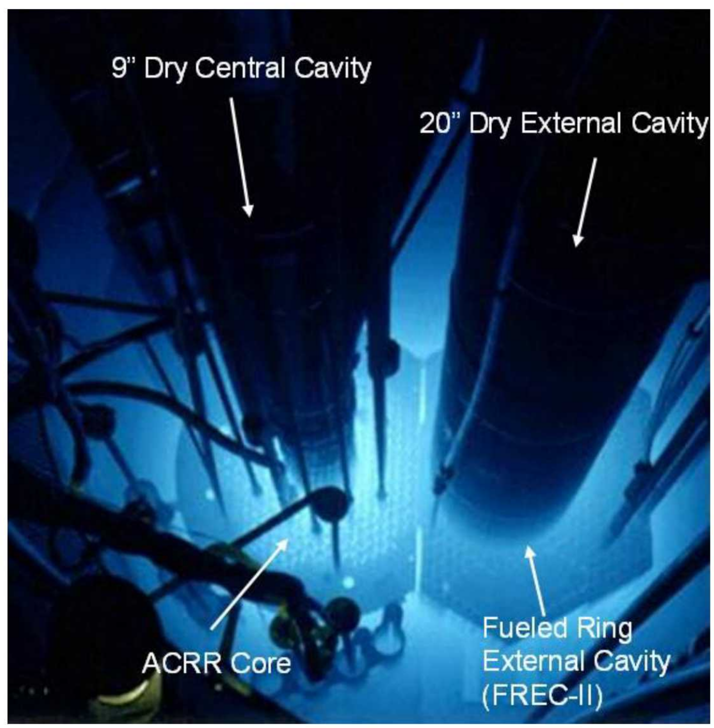

Figure 1. The ACRR and FREC-II Operating at 2-MW Steady-State Power.

Figure 2. The ACRR Tank and High Bay.

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

Figure 4. Experiment Package Loaded into the ACRR Central Cavity.

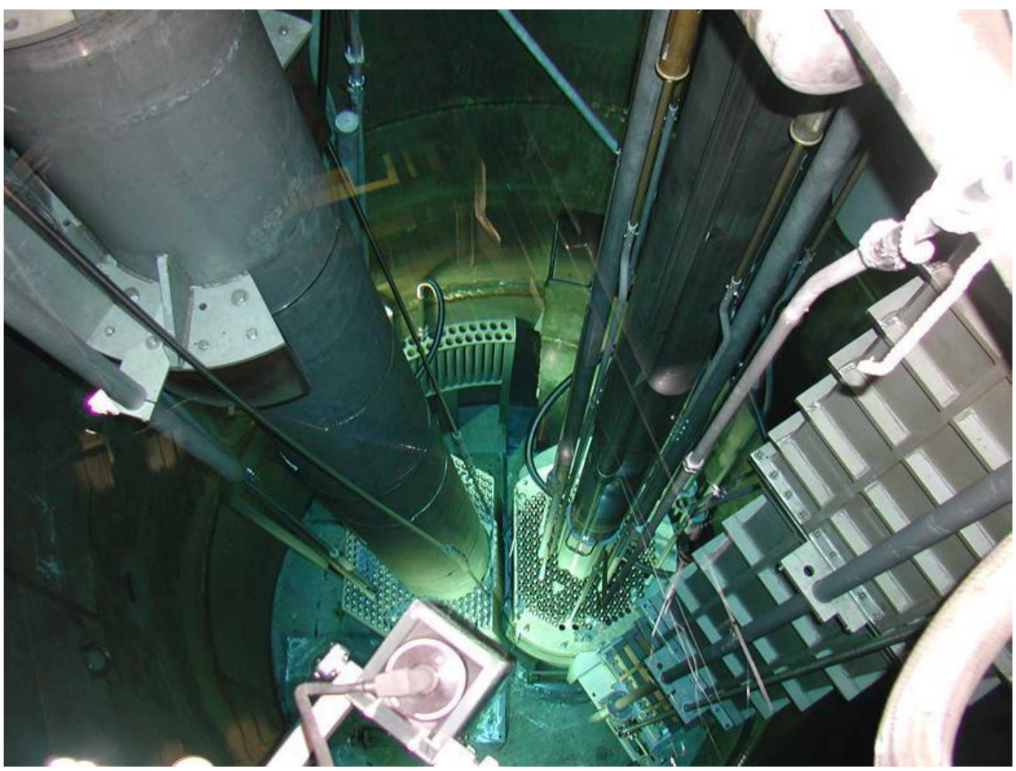

Figure 5. ACRR with FREC-II Decoupled.

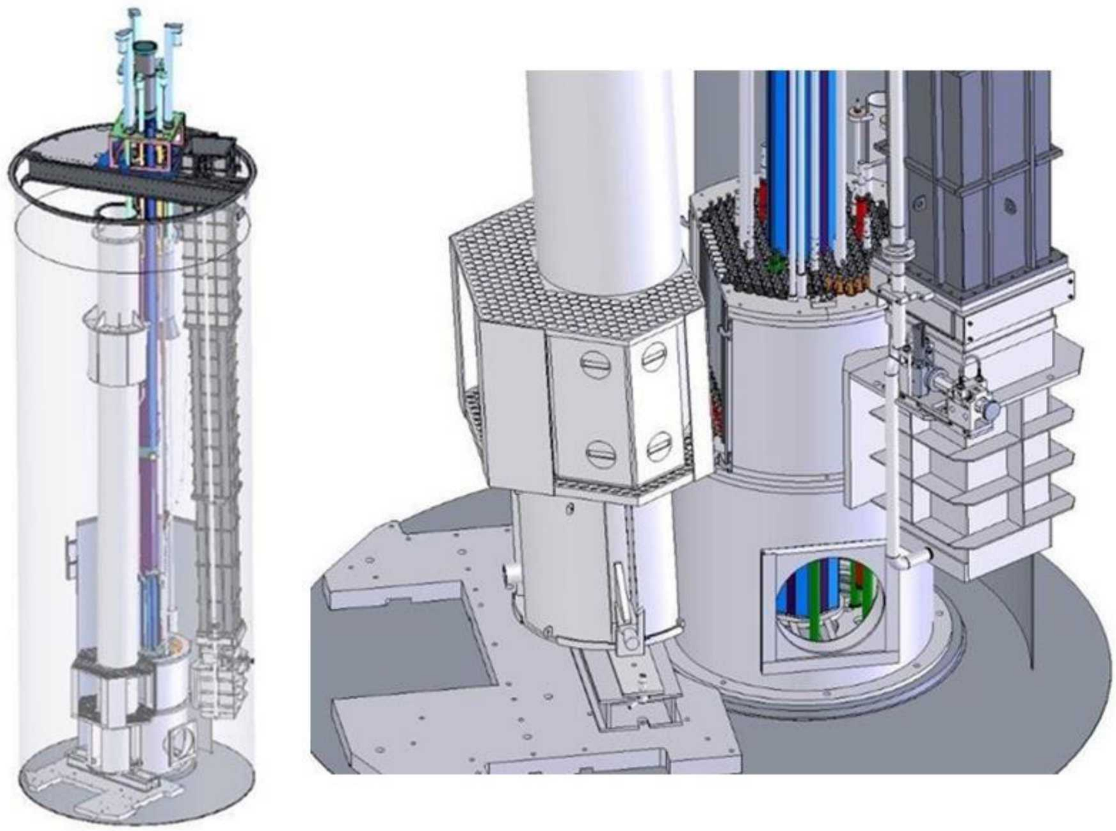

Figure 6. Image of the ACRR Tank, ACRR, and FREC-II in the Decoupled Mode.

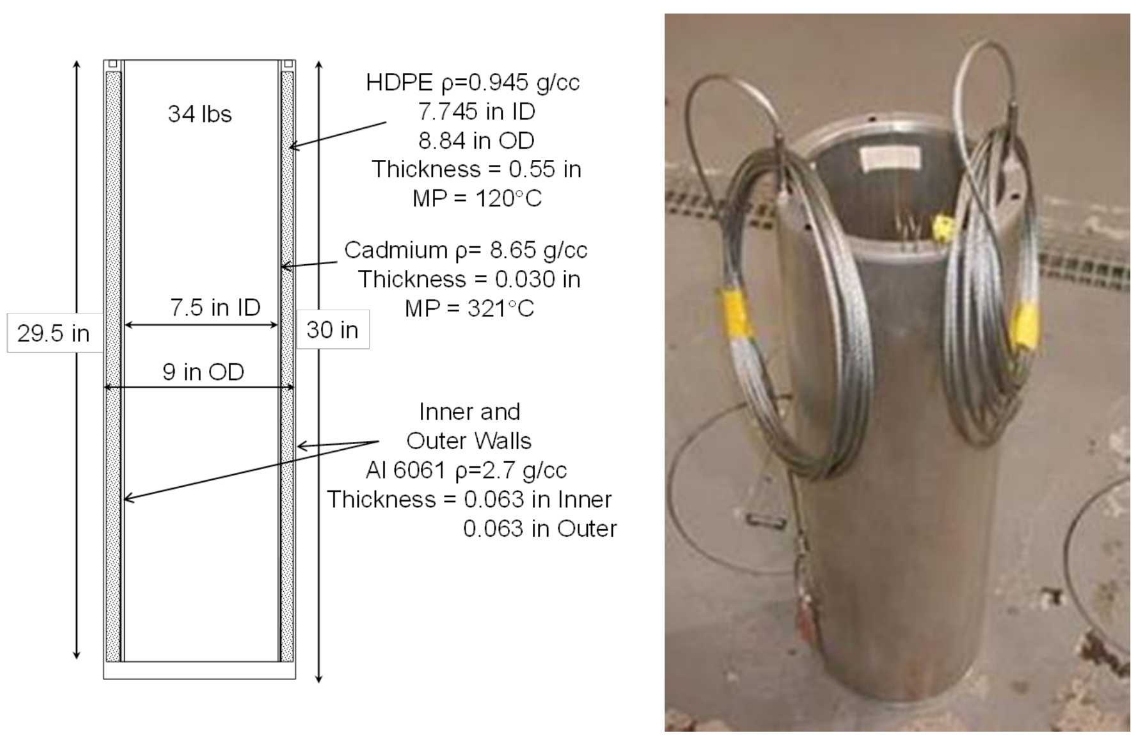

Figure 7. The Cd-Poly Spectrum Modifying Bucket.

3. ACRR MCNP MODEL

The neutronics Monte Carlo code, MCNP [1], is used extensively to perform neutron and gamma-ray transport calculations for the ACRR. Both high-fidelity, and low-fidelity geometric models exist for both the ACRR and the ACRR with the FREC-II in the coupled position [2]. The model has been used to perform keff calculations, neutron and gamma-ray characterization in the cavities using the spectrum modifying buckets, and experiment time dependent radiation response to pulse and steady-state operations. Figure 8 shows the MCNP model of the ACRR. Figure 9 shows the MCNP model of the ACRR with the FREC-II coupled. Neutron and gamma-ray transport calculations are performed for most experiments fielded in the ACRR. These calculations provide both safety basis and operations staff members with important reactivity and heating information to allow for safe operation of the reactor. MCNP calculations also provide the experimenter with detailed response information for the fielded experiment.

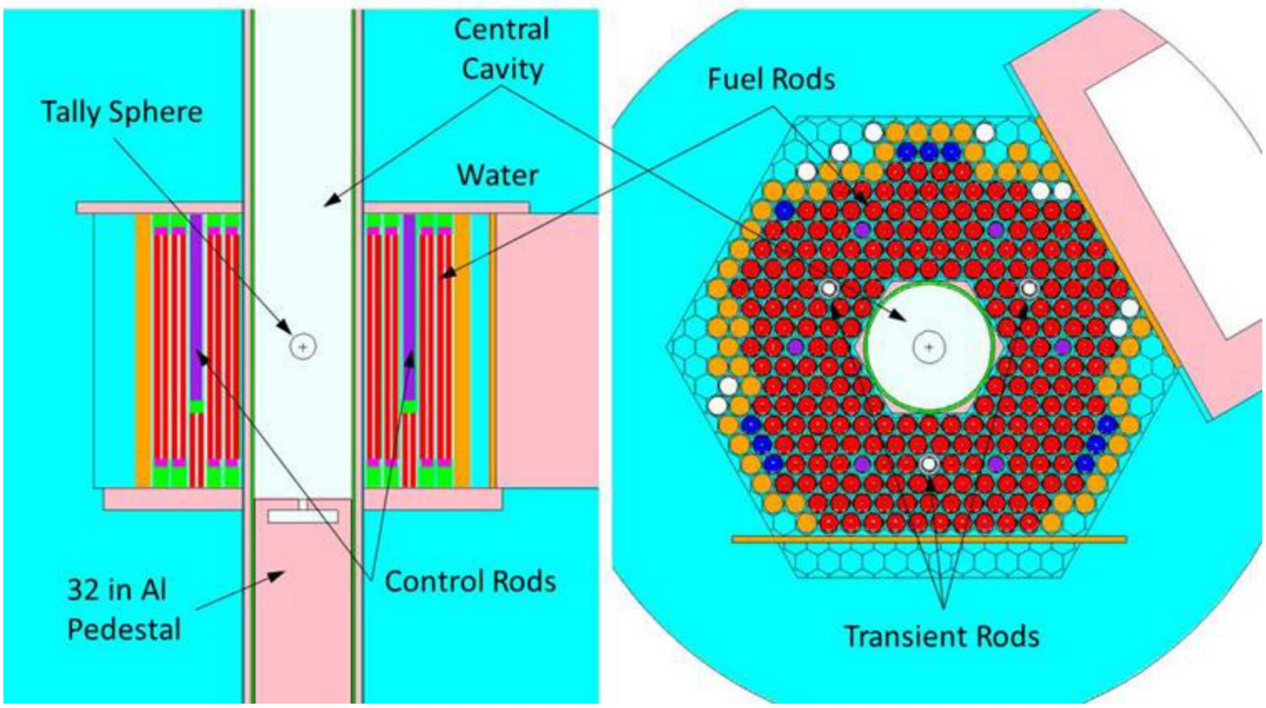

Figure 8. MCNP Model of the ACRR.

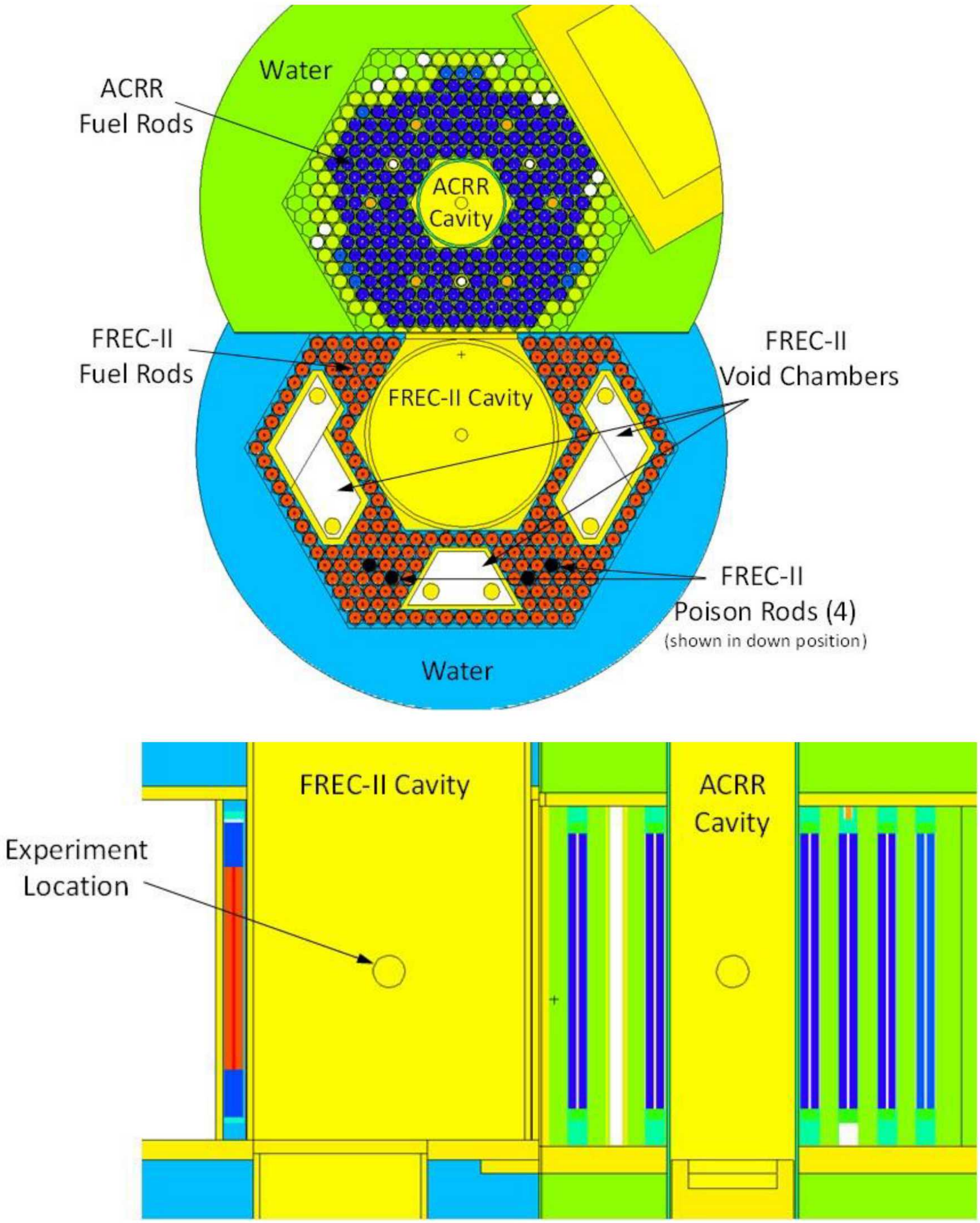

Figure 9. MCNP Model of the ACRR and FREC-II Coupled.

4. CAVITY SPECTRUM MODIFICATION CAPABILITY

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. Polyethylene or water can be added to a bucket environment in an annulus geometry to increase the thermal neutron population. Boron and lead can be used to increase the fast neutron fluence ratio and decrease the gamma-ray fluence, respectively. Boron can be added to a bucket environment in an annulus geometry to remove the thermal neutron population. Gamma rays can be attenuated or increased by adding lead or cadmium, respectively, in an annulus geometry. These perturbations allow for the neutron to gamma ray ratio to be modified in the cavities, adding to the versatility and flexibility of the ACRR to meet the customer's radiation testing requirements.

For a free-field 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 ~8.2E12 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.

For a free-field unmoderated condition, the neutron fluence at the center of the FREC-II cavity at the core axial centerline is ~2.6E12 n/cm^2 per MJ of reactor energy. About 37% of the neutron fluence is above 100 keV and 46% above 10 keV. The 1-MeV damage-equivalent silicon fluence is ~8.8E11 n/cm^2 per MJ of reactor energy. The prompt gamma-ray dose at the same position is ~1.1E3 rad(Si) per MJ. The delayed gamma-ray dose is ~7.0E2 rad(Si) per MJ.

In addition to the free-field irradiation condition (no bucket environment) of the ACRR and FREC-II cavities, several buckets exist and are available for use by the experimenter to allow for neutron and gamma-ray spectrum modification. New buckets can also be built and tested as future needs are required by the experimenters. The irradiation space within each bucket is thoroughly characterized prior to use in order for the experimenter to have the utmost confidence in the neutron and gamma ray irradiation conditions. Characterization involves both MCNP modeling and experimental testing [3-8]. ACRR test measurements in the irradiation volume includes using neutron activation analysis of foils and pellets, irradiation of thermoluminescent dosimeters (TLDs), and active measurements using calorimeters, photo-conducting diodes (PCDs), self-powered neutron detectors (SPNDs), and fission chambers. The neutron energy spectrum is adjusted using least-squares fitting techniques with activation foil measurements to produce the characterized neutron spectrum at the irradiation location within a bucket.

Figures 10 through 14 show the neutron energy spectrum and the prompt gamma energy spectrum for the ACRR cavity free field, PLG bucket, LB44 bucket, Cd-Poly bucket, and the FREC-II cavity free field axial centerline positions. As previously discussed, the use of polyethylene, boron, cadmium, and lead can significantly alter both the neutron spectrum and the gamma-ray spectrum and magnitude. The PLG bucket enhances the thermal neutrons and reduces the gamma-ray intensity as compared to the free field case. LB44 removes the thermal and some of the epithermal neutrons and reduces the gamma-ray intensity as compared to the free field case. Cd-Poly removes the thermal neutrons and enhances the gamma-ray intensity. The FREC-II cavity has a greater thermal neutron component as compared to the ACRR cavity.

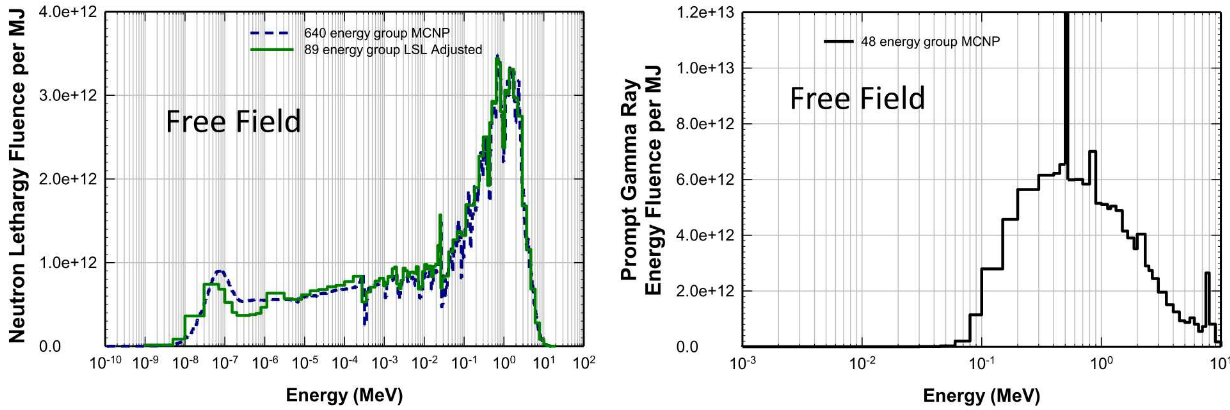

Figure 10. Neutron and Prompt Gamma-Ray Energy Spectra for the Central Cavity Free-Field Environment.

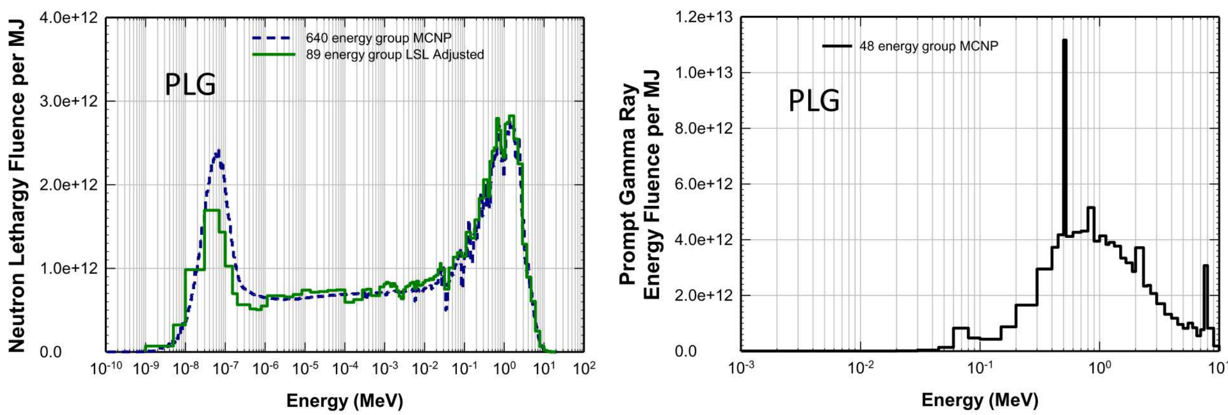

Figure 11. Neutron and Prompt Gamma-Ray Energy Spectra for the Polyethylene-Lead-Graphite (PLG) Bucket Environment.

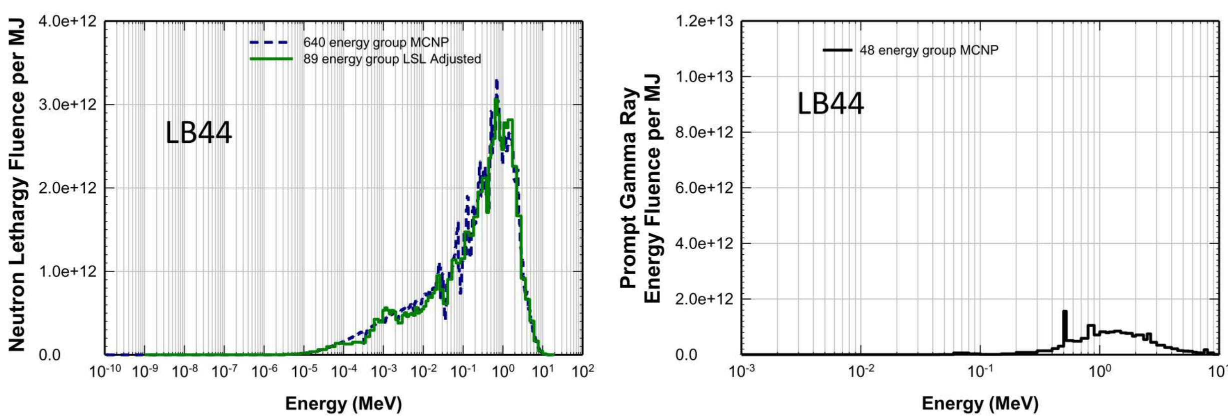

Figure 12. Neutron and Prompt Gamma-Ray Energy Spectra for the Lead-Boron (LB44) Bucket Environment.

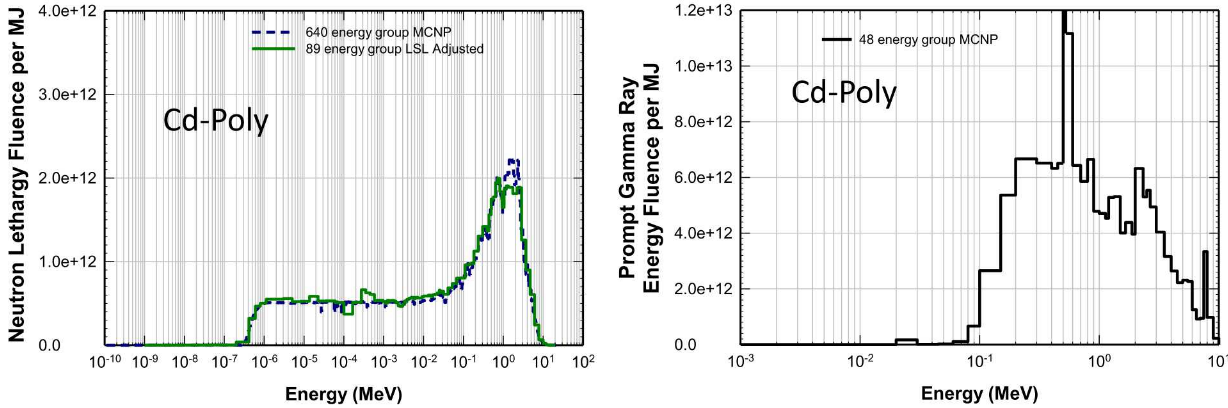

Figure 13. Neutron and Prompt Gamma-Ray Energy Spectra for the Cadmium-Polyethylene (Cd-Poly) Bucket Environment.

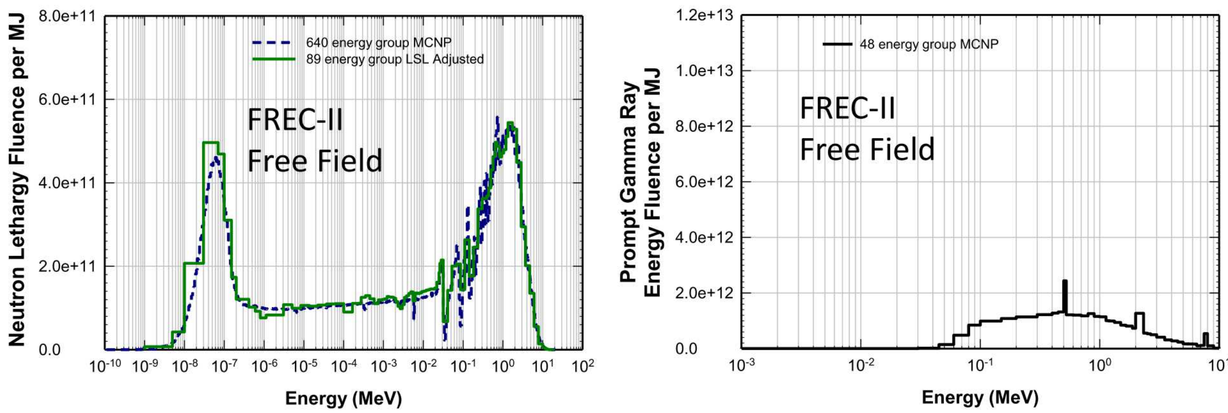

Figure 14. Neutron and Prompt Gamma-Ray Energy Spectra for the FREC-II Cavity Free-Field Environment.

Table 1 shows some of the important metrics associated with the bucket environments that are of interest to experimenters. These metrics include the total neutron fluence, the 1-MeV damage equivalent in silicon (DES) neutron fluence, the prompt gamma-ray dose in silicon, and the ratio of the 1-MeV DES neutron fluence to the prompt gamma-ray dose. From this table the largest 1-MeV DES neutron fluence attainable is ~8.2E12 n/cm^2 per MJ. The largest prompt gamma-ray dose is ~11 krads(Si) per MJ. The 1-MeV DES fluence to gamma-ray dose can be varied by about a factor of 13, with the Cd-Poly bucket having the smallest ratio and the LB44 bucket having the largest ratio.

Table 2 shows the neutron fluence and gamma-ray dose for a 300 MJ pulse for the ACRR and FREC-II free-field environments. For a maximum pulse, the total neutron fluence in the ACRR central cavity is 6.15E15 n/cm^2, the 1-MeV DES neutron fluence is 2.46E15 n/cm^2, and the prompt gamma-ray dose in Si is 2.38E3 krads. For a 300 MJ pulse, the peak power level attainable is ~50,000 MW, corresponding to a neutron flux of 1.0E18 n/cm^2-s.

Table 1. Neutron Fluence and Prompt Gamma-Ray Dose for the Characterized Environments.

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

Table 2. Neutron Fluence and Prompt Gamma-Ray Dose for Free Field ACRR and FREC-II Cavities for a 300 MJ Maximum Pulse.

Environment	Neutron Fluence Total (n/cm^2)	Neutron Fluence 1-MeV DES (n/cm^2)	Prompt Gamma-Ray Dose in Si (krad)
Central Cavity Free Field	6.15E+15	2.46E+15	2.38E+03
FREC-II Free Field - FREC Rods Up	1.19E+15	4.02E+14	5.13E+02

5. PULSING CAPABILITIES

Pulse Mode Capability

The ACRR has unique pulse mode capabilities significantly greater that other pool-type pulse reactors. The three pulse rods can be simultaneously ejected from the core using a pneumatic drive system within ~80 ms. A maximum pulse at the ACRR is a reactivity addition of $3.50, with a pulse width of 6.8 ms, a peak power of ~50,000 MW, and a total reactor energy deposition of 300 MJ. This is at least three times larger than what TRIGA-type reactors can attain. Smaller pulses, as low as 10 MJ, can also be attained with the ACRR. Figure 15 shows the experimental results for several different size pulses for the ACRR. The full-width half-maximum (FWHM) for a pulse is directly proportional to the neutron generation time for the reactor, and inversely proportional to the reactivity added. For reference, 300 MJ pulse ($3.50) would have a FWHM pulse width of ~7 ms; a 100 MJ pulse ($2.05) would have a pulse width of ~14 ms; and a 50 MJ pulse ($1.40) would have a pulse width of ~32 ms. With buckets inserted in the central cavity, the pulse characteristics do not change significantly because the neutron generation time does not change appreciably. With FREC-II coupled to the ACRR and the FREC rods in the "down" position, the pulse characteristics are also similar. With the FREC-II coupled to the ACRR and the FREC rods in the "up" position, the neutron generation time increases to ~32 μs, from ~24 μs for the ACRR with FREC-II decoupled, and the pulse width increases proportionately.

Transient Mode Capability

The ACRR also has unique transient mode capabilities. The three pulse rods can be driven out of the core using stepper motors as opposed to pneumatically. Under these conditions, up to $4.25 of reactivity can be inserted incrementally over time. Power ramps and steady-state transients can be generated for up to 300 MJ of reactor energy. An example is an instantaneous step power of 50 MW that can be held constant for 6 seconds, or 100 MW for 3 seconds in order to achieve the 300 MJ of energy. These types of conditions are typically desirable for advanced fuels testing experiments where the cladding or fuel material integrity of the test specimen is desired to be challenged.

Double Pulse Mode Capability

The ACRR also has unique double-pulse mode capabilities. Using the pneumatic drive system, the three pulse rods can be simultaneously ejected from the core for a single pulse or timed for a unique double pulse. Each of the pulse rods is worth greater than $1.00 of reactivity allowing for one rod to be ejected, followed by the other two. This capability is desirable for experiments where rapid heating is desired in an experiment, followed by an additional pulse.

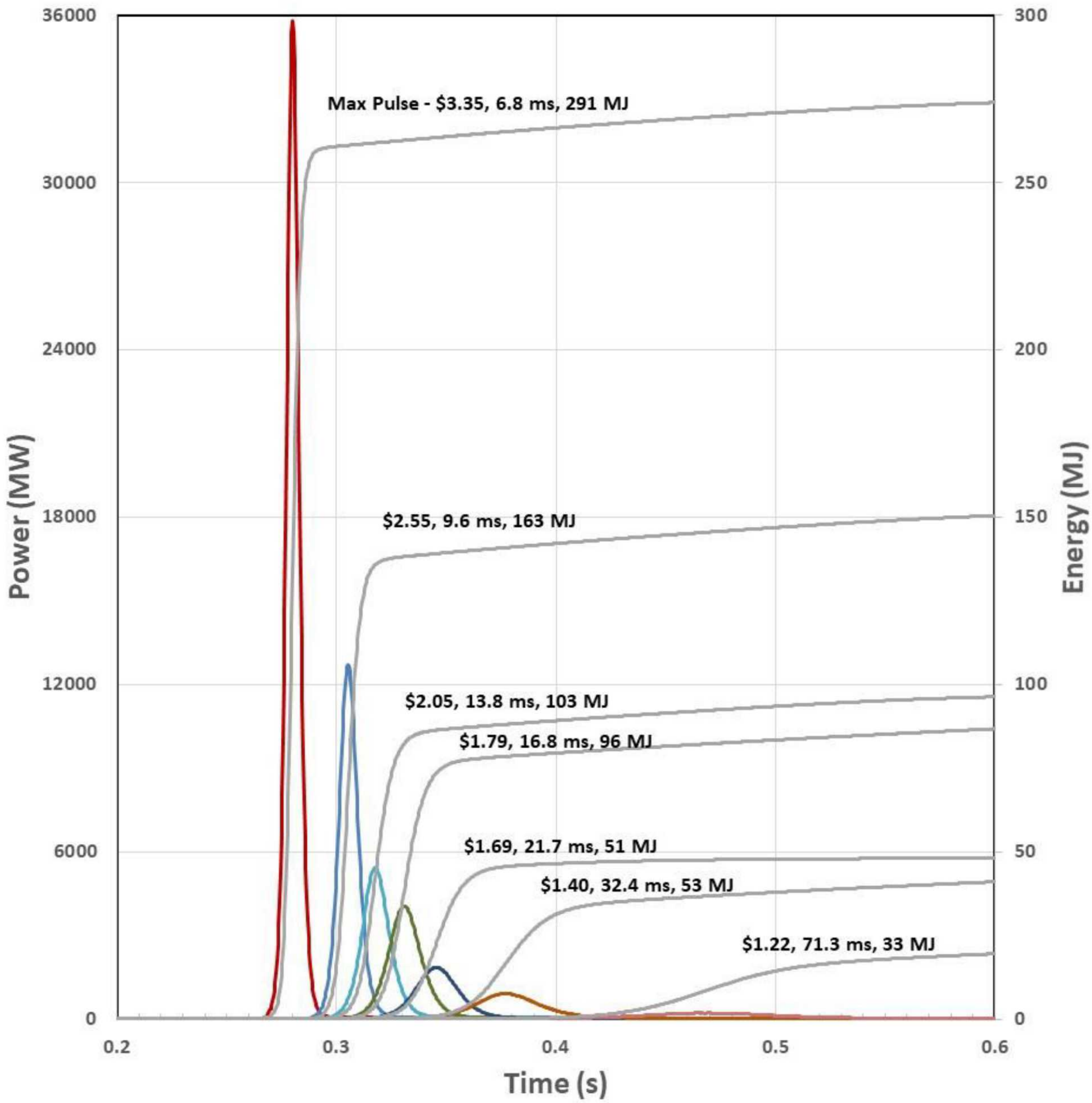

Figure 15. ACRR Pulsing Characteristics.

6. CONCLUSION

The ACRR with its FREC-II subcritical multiplier is a unique research reactor facility unlike any other in the U.S. Its large pulsing capabilities and dry irradiation cavities allow for both passive and active experiments to be fielded at the peak neutron and gamma-ray flux in the core. Its epithermal/fast neutron spectrum in the central cavity allows for neutron spectrum modification and gives experimenters the ability to attain their unique irradiation requirements. The ACRR will continue to provide invaluable pulse and steady-state irradiations services to the U.S. weapons program for at least another 40 years.

7. REFERENCES

1. MCNP-A General Monte Carlo N-Particle Transport Code, Version 5, Technical Report LA-UR-03-1987 (2003)

2. K. R. DePriest, P. J. Cooper, E. J. Parma, "MCNP/MCNPX Model of the Annular Core Research Reactor," Technical Report SAND2006-3067 (2006)

3. E. J. Parma, G. E. Naranjo, L. L. Lippert, D. W. Vehar, "Neutron Environment Characterization of the Central Cavity in the Annular Core Research Reactor," Proceeding of the 15th International Conference on Reactor Dosimetry, EPJ Web Conferences, **106**, 01003 (2016)

4. E. J. Parma, G. E. Naranjo, R. M. Vega, L. L. Lippert, D. W. Vehar, P. J. Griffin, "Radiation Characterization Summary: ACRR Central Cavity Free-Field Environment with the 32-Inch Pedestal at the Core Centerline (ACRR-FF-CC-32-cl)," Technical Report SAND2015-6483 (2015)

5. E. J. Parma, D. W. Vehar, L. L. Lippert, P. J. Griffin, G. E. Naranjo, S. M. Luker, "Radiation Characterization Summary: ACRR Polyethylene-Lead-Graphite (PLG) Bucket Located in the Central Cavity on the 32-Inch Pedestal at the Core Centerline (ACRR-PLG-CC-32-cl)," Technical Report SAND2015-4844 (2015)

6. E. J. Parma, T. J. Quirk, L. L. Lippert, P. J. Griffin, G. E. Naranjo, S. M. Luker, "Radiation Characterization Summary: ACRR 44-Inch Lead-Boron Bucket Located in the Central Cavity on the 32-Inch Pedestal at the Core Centerline (ACRR-LB44-CC-32-cl)," Technical Report SAND2013-3406 (2013)

7. E. J. Parma, G. E. Naranjo, K. I. Kaiser, J. F. Arnold, L. L. Lippert, R. D. Clovis, L. E. Martin, T. J. Quirk, D. W. Vehar, , "Radiation Characterization Summary: ACRR Cadmium-Polyethylene (CdPoly) Bucket Located in the Central Cavity on the 32-Inch Pedestal at the Core Centerline (ACRR-CdPoly-CC-32-cl)," Technical Report SAND2016-10114 (2016)

8. E. J. Parma, G. E. Naranjo, L. L. Lippert, R. D. Clovis, L. E. Martin, K. I. Kaiser, J. Emmer, J. Greenburg, J. O. Klein, T. J. Quirk, D. W. Vehar, P. J. Griffin, "Radiation Characterization Summary: ACRR-FRECII Cavity Free-Field Environment at the Core Centerline (ACRR-FRECII-FF-cl)," Technical Report SAND2017 (2017)

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