SAND2015-9360C

Enhanced Capability for Low Fluence Operations at the Annular Core Research Reactor

K. Kaiser[1], L. Martin[2], and J. Emmer[1]

[1]Senior Nuclear Reactor Engineer & Reactor Operator, Nuclear Facility Operations, Sandia National Laboratories, P.O. Box 5800, MS1142, Albuquerque, New Mexico 87185-1142, USA.

[2]Principal Nuclear Reactor Engineer & Reactor Supervisor, Nuclear Facility Operations, Sandia National Laboratories, P.O. Box 5800, MS1142, Albuquerque, New Mexico 87185-1142, USA.

E-mail contact of main author: kkaiser@sandia.gov

Abstract: Sandia National Laboratories (SNL) Annular Core Research Reactor (ACRR) has expanded the low fluence capability for irradiation of components. The ACRR recently upgraded its wide-range neutron monitoring system to a Neutron-Flux Monitoring Channel DWK 250 from Mirion Technologies. This paper focuses on the reactor operator interface with the new Neutron-Flux Monitoring channels, verification of fluence levels via the use of dosimetry and impact to radiation effects science, ACRR operations, and customers.

1. Introduction

The Annular Core Research Reactor (ACRR) is located at Sandia National Laboratories (SNL) in Albuquerque, New Mexico, USA. The ACRR is licensed for steady-state operations up to 4 MW; however, currently 100 % is set to 2.39 MW. The ACRR also has pulse power and energy capabilities up to 60,000 MW and 500 Mega-Joules (MJ).

The ACRR recently upgraded its wide-range neutron monitoring system. The new system is the Neutron-Flux Monitoring Channel DWK 250 from Mirion Technologies. The new flux monitoring channels significantly improved the signal to noise ratio, which allowed for measuring the neutron flux over a full 12 decades of reactor power. Prior to this upgrade, the lowest statistically repeatable fluence was 5E12 (1 MeV Si equivalent) neutrons per square centimeter [n/cm^2] and the reactor operator would only have a linear power trace beginning at 23.9 watts. This change in power monitoring equipment and reactor operating parameters now allows the ACRR to deliver repeatable integral fluences on the magnitude of 1E7 n/cm^2 with a linear power trace starting at the reactor core's neutron background of 0.005 watts.

The ACRR is a pool type research reactor with a dry 9-inch (~23 cm) central irradiation cavity (see FIG. 1). Experiments are loaded into this cavity and a biological shield plug is inserted above the experimental package. The reactor is positioned 3 ft. (~ 1m) from the bottom of a 28 ft. (~8.5 m) deep stainless steel tank. The tank is 10 ft. (~3.05 m) in diameter and contains approximately 15,000 gallons (~56,775 L) of ultra-pure water. The water provides cooling and moderation for the reactor and serves as a biological shield for personnel working in the reactor bay. Experiments are placed on a support pedestal inserted into the central cavity providing highly accurate and repeatable placements (shown in FIG. 2). Additionally, there is a 20-inch (50.8 cm) diameter sub-critical multiplier positioned so that it may be coupled and driven by the main core. The coupled position is shown in FIG. 1.

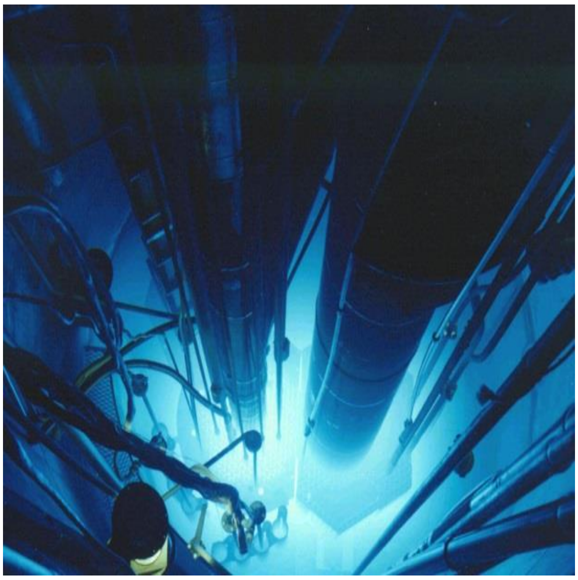

FIG. 1. ACRR during Pulse Operation

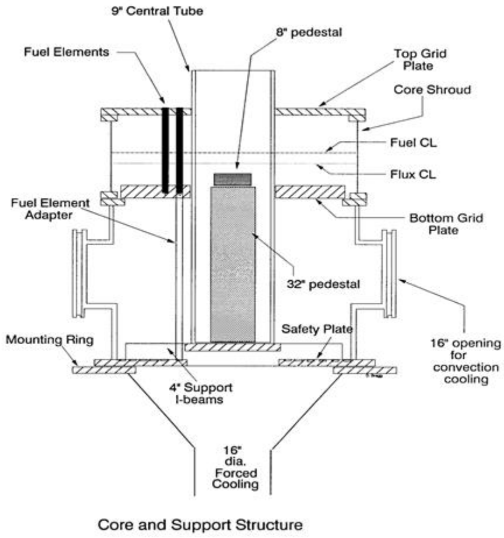

FIG. 2. Core Support Structure

2. Neutron Monitoring

ACRR utilizes a wide-range neutron flux system to monitor several important operational and programmatic reactor parameters. Included are: Technical Safety Requirements (TSRs) for linear/log reactor power indication and interlocks preventing pulsing from high power; operationally necessary indication including startup rate (indication and interlocks), total power integration, defense-in-depth high power shutdowns; and programmatic parameters such as power history and profile.

Rather than having separate instruments for source, intermediate, and power range; ACRR covers all three ranges with two redundant system. The previous power signal processors had been displaying age-related symptoms which may have been an indication of incipient failure. One system exhibited short duration signal drop outs at low power at an increasing frequency while the other drawer exhibited long duration signal drop outs at high power.

The digital system realized new fidelity in the low power range at ACRR. This increased reactor reliability, reduced down time, and expanding programmatic capabilities in the low power ranges.

The DWK 250 outputs several signals to ACRR:

1) Linear power is sent in two 0-20 mA signals, one covering 0.2 to 200 % power and one covering 0.002 to 2 % power. Two linear signals were designed to properly cover six decades.
2) Log power is sent through one 0-20 mA signal covering 1E-8 to 200 % power.
3) Startup rate is sent through one 0-20 mA signal covering -1 to +7 DPM.
4) Seven bistable trips communicate detector signal loss, high startup rate (> +4DPM), greater than 0.1 % power (pulse from high power interlock), high power shutdown (106%), detector high voltage low or high, unit in test mode, and a non-operational signal.

These signals are input to the ACRR Instrumentation and Control System (I&C) through National Instruments Field Point 2000 modules. Parameters are interpolated by LabVIEW software and displayed on the primary reactor operator human-machine interface (HMI). FIG. 3 details the wide-range HMI display screen. This is the focal screen for the reactor operator during critical operations.

FIG. 3. ACRR DAC 4 Wide-range HMI screen shot

The two linear signals are digitally smoothed (in LabVIEW code) over the transition range. Additional LabVIEW programmed smoothing occurs over the unavoidable glitches as the analog electronics shift between decades. During reactor operations, this smoothing is not evident to the operator.

The digitally processed log signal from the DWK 250 is displayed on a log scale using two bar graphs. In a departure from the previous system at ACRR, the linear power chart display is now fed by the detector log signal rather than the linearized signal. The digital processor of the DWK 250 provides perfect undetectable smoothing between count rate and campbelling processes and between decade changes. By displaying the high fidelity log signal (on a linear scale for human factors reasons), reliable reactor power (neutron flux) is visible down to 1E-8 percent power; however, the background level is 2E-7 percent. This is in contrast to the legacy system which only provided indication down to only 1E-3 percent power (23.9 W).

This new fidelity in the low power region has resulted in several unintended benefits to ACRR; while neutron background and decay after steady-state or pulse operations was always evident on the log scale bar graphs, a linear display in digital chart recorder format allows operators to observe the influence of removing reactivity elements during startup. Feedback from installing largely negative or positive experiments in the reactor’s large central cavity is also apparent on the digital chart readout.

The new low power fidelity has opened the window to new experimenter capabilities for ACRR. Experimenters have long requested repeatability in the low dose ranges. Operators are now able to maintain critical reactor operations in the sub 1E-3 percent power ranges and provide low dose to experiment packages.

3. Reactor Dosimetry

Passive dosimetry is the verification that the correct neutron fluence was delivered to the experiment part. Reactor control rod height (± 0.2mm repeatability) was used as an indication of criticality. Typical activation dosimetry at the ACRR includes nickel foils, sulfur pellets, and thermoluminescent dosimetry (TLDs). Calcium fluoride TLDs with a range of 1 rad to 200 krads are used at the ACRR.

The initial low fluence dosimetry operations were performed with a neutron energy spectrum modifier. The dosimetry was placed inside a spectrum modifying bucket (lead-boron). This modification to the spectrum removes most of the thermal neutrons and reduces gamma radiation on the experiment package. Three types of sulfur dosimetry were used for validation of the new wide range neutron monitoring system. TLDs and nickel activation foils were also used; however, results were not as promising.

ACRR typically uses small standard sulfur pellets for operations; however, due to extremely low fluence, two additional types of sulfur pellets were used. A larger bare sulfur was used to increase the amount surface area for enhanced neutron interaction probability and post-activation detection. The other type of sulfur dosimetry was large sulfur clad in aluminum. The aluminum clad prevents detection of other sulfur reactions with lower beta energies. The three types of sulfur were combined with a nickel activation foil and then wrapped in aluminum foil. The foil aids in contamination control and allows practicality when combining dosimetry. FIG. 4 displays the activation foil dosimetry.

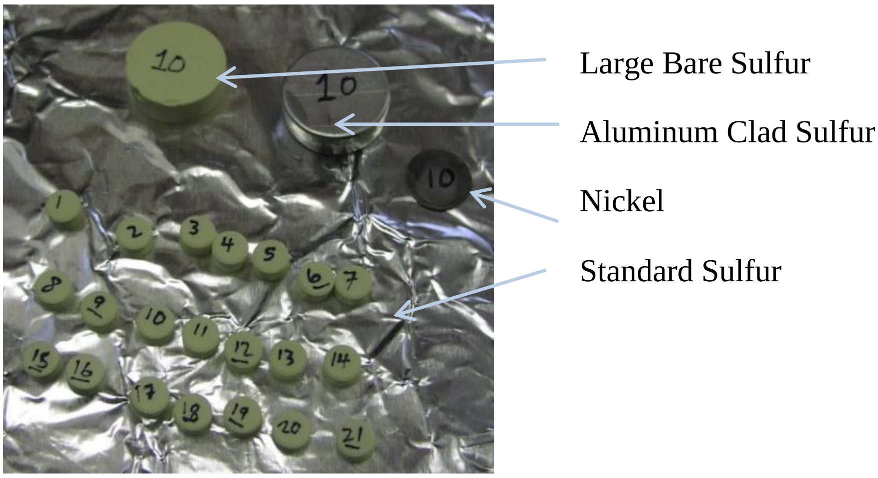

FIG. 4. Activation Foils

The activation foils were then stacked in a consistent arrangement for all the different fluence levels that were tested. FIG. 5 displays the stacked configuration and final dsoimetry configuration with TLDs. TLDs were added in four arragnements each with 4 TLDs to the outside of the aluminium foil wrapped stacked configuration.

FIG. 5. Stacked Dosimetry and Final Configuration

4. Results

The low fluence nickel and sulfur results are displayed in FIG. 6 and FIG. 7, respectively. To establish an initial neutron exposure level in Mega-Joules (MJ) at each decade a 'MJ to fluence' result was used from a prior 1E12 [n/cm^2] operation. The prior operation was intended to deliver an integral reactor energy of 0.5 MJ which resulted in a neutron fluence of 3E12 based on activation dosimetry. A complicating factor in this previous exposure was the lack of data regarding the time the activation foils were in the reactor cavity prior to and after the operation for this reference operation. A value of 1/3 of the 0.5 MJ was selected for the 1E12 exposure. The subsequent decades were than scaled from the 0.17 MJ delivery of 1E12 fluence. Based upon the dosimetry results this value was an average factor of approximately 14 lower than the desired fluence decade. Going forward, operations will adjust the target MJ value by a factor of 14 for low fluence operations; however, this has demonstrated neutron dosimetry capability at the 1E7 decade exposure level. Small standard sulfur data is missing at the 1E8 and 1E11 decades due to overwhelming the counting laboratory. Low activation dosimetry requires a significant period of count time to obtain decent statistics due to the very low level of activation.

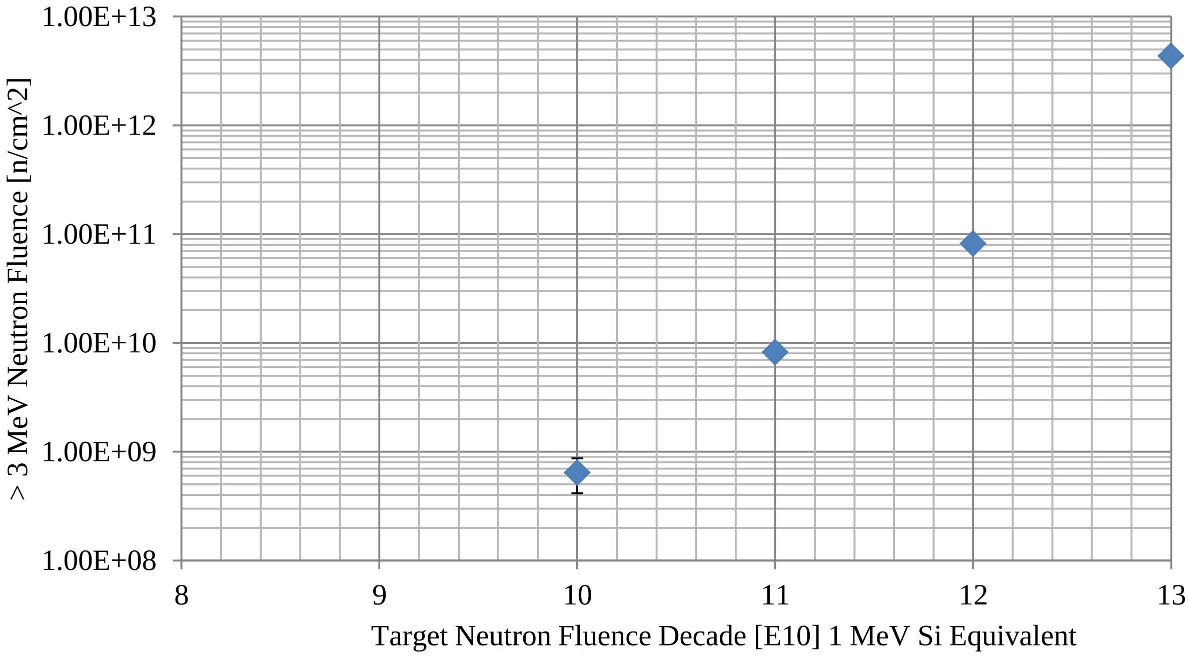

FIG. 6. Nickel Low Fluence Results

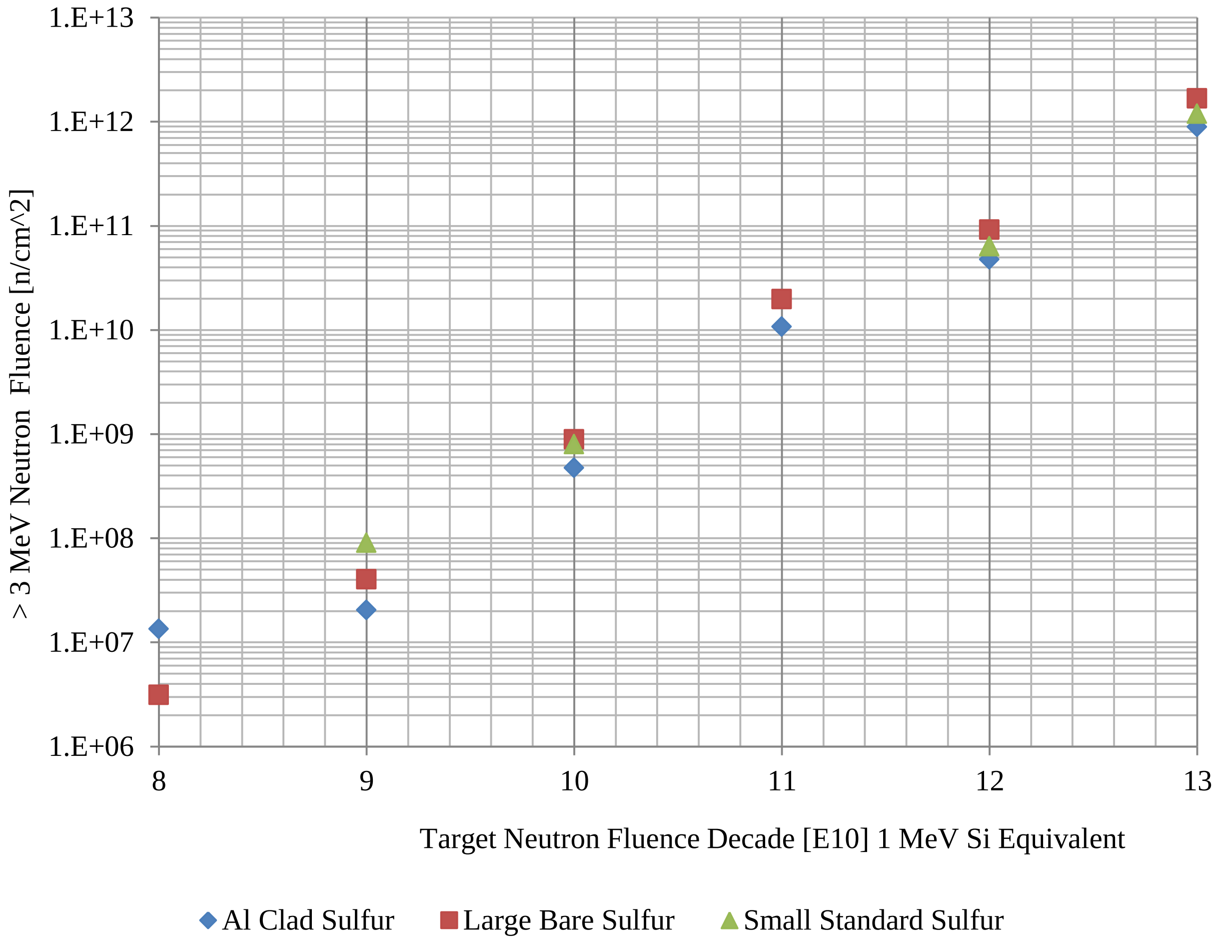

FIG. 7. Sulfur Low Fluence Results

Neutron linearity between measured expended energy (in MJ) and neutron fluence is shown to exist between the ranges of 1E7 through 1E13. ACRR has previously demonstrated linearity between the ranges of 5E12 to 1E17. This new low fluence work has extended the working range from 1E7 though 1E17. Due to the mission of the ACRR, fluence request greater than 1E17 are not very common; therefore, neutron dosimetry verification has not been performed for fluences greater than 1E17. Sulfur dosimetry may be used down to exposures of 1E7 while nickel dosimetry is only viable down to the 1E10 range. The gamma progeny from Co-58 cannot be counted below 1E10 via a gamma spectrum analysis.

FIG. 8 displays the gamma low fluence results. Gamma radiation is linear down to the 1E11 decade; however, linearity breaks down below 1E10 and TLDs can no longer be used to ratio gamma to neutron dose. TLDs will provide a reading down to 1 rad and may be used to quantify the gamma dose. The reason for attempting to use an integral gamma dose to establish the neutron dose would be to increase the throughput of experiments without having to purchase additional equipment to count the extremely low activation sulfur dosimetry pellets which takes a significant amount of time – anywhere from 1 hour up to multiple days. The reason for the breakdown in linearity below 1E10 is due to gamma decay products which are continuously produced in the reactor and the decay level will vary with operational power history. Table 1 displays the dosimetry processing error.

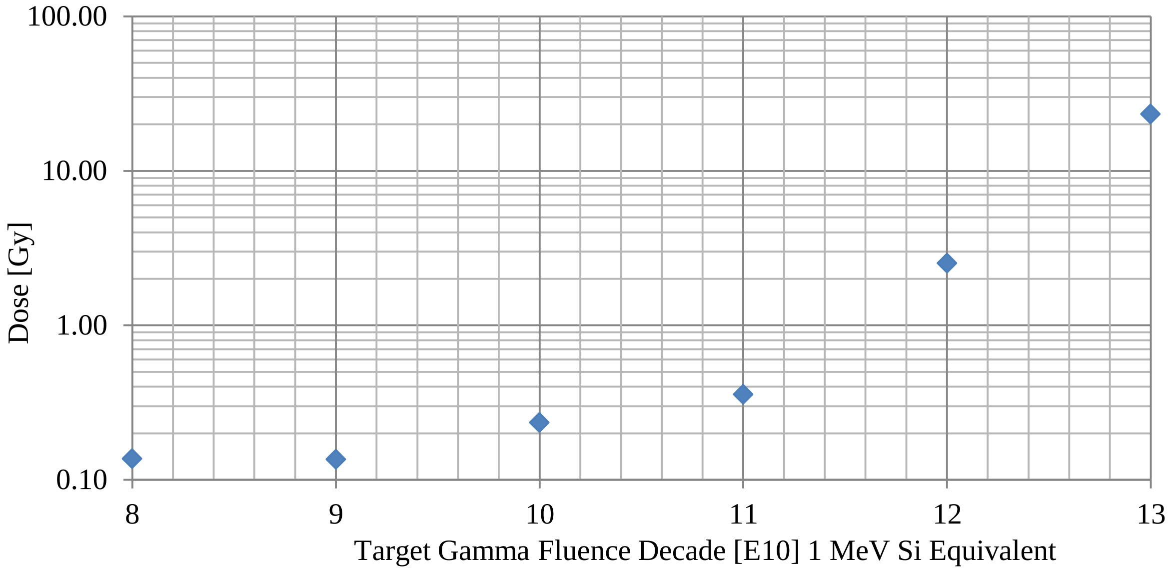

FIG. 8. Gamma Low Fluence Results

TABLE I: DOSIMETRY PROCESSING ERROR

Target Fluence	**1E8**	**1E9**	**1E10**	**1E11**	**1E12**	**1E13**
TLD	4.39 % to 5.68 %					
Nickel	NA	NA	64.9 %	91.3 %	93.97 %	96.91 %
Small Sulfurs	NA	6.03 %	2.99 %	NA	0.33 %	0.34 %
Al Clad Sulfurs	10.53 %	1.64 %	0.80 %	0.32 %	0.32 %	0.32 %
Large Bare Sulfurs	38.33 %	1.89 %	0.55 %	0.32 %	0.32 %	0.32 %

[1]

5. Repeatability

The ability to repeat requested low neutron fluences is highly influenced by how long the experiment has been located within the reactor cavity. The ACRR is uniquely fueled with a uranium dioxide – beryllium oxide (UO_2-BeO) ceramic metal fuel. The presence of beryllium in the ACRR is subject to significant photoneutron effects from a gamma-neutron [Be9(γ,n)Be8] and neutron-2 neutron [9Be(n,2n)Be8] reactions. The photoneutron reactions are produced from delayed gammas in the fission product decay or directly from fission process gammas. ACRR's abundance of beryllium and the long average photoneutron half-life (2.31 h) the neutron 'tail' after operation at power can be significant. The new wide-range monitoring capability has provided the opportunity to run at much lower power levels; however, controlling the amount of time an experiment is in the reactor cavity still needs to be developed. The data collected in support of this paper used a very controlled load and unload time; however, the reactor was only allowed to start up once the dosimetry packet had been loaded and the packet was only allowed to be removed after the reactor had shutdown. The reactor 'up power' ramp is dependent upon numerous variables, most of which are reactor operator dependent. In other words, not all operators drive the reactor at the same start up rate, let alone consistently at said rate every time. FIG. 9 displays an example of a reactor power ramp up to a desired power level. The tail portion of the ramp is also an uncontrollable variable since the power history will drive the photoneutron source strength post operation.

[1] Dosimetry processing results and errors are provided by the Sandia National Laboratories Radiation Metrology Laboratory.

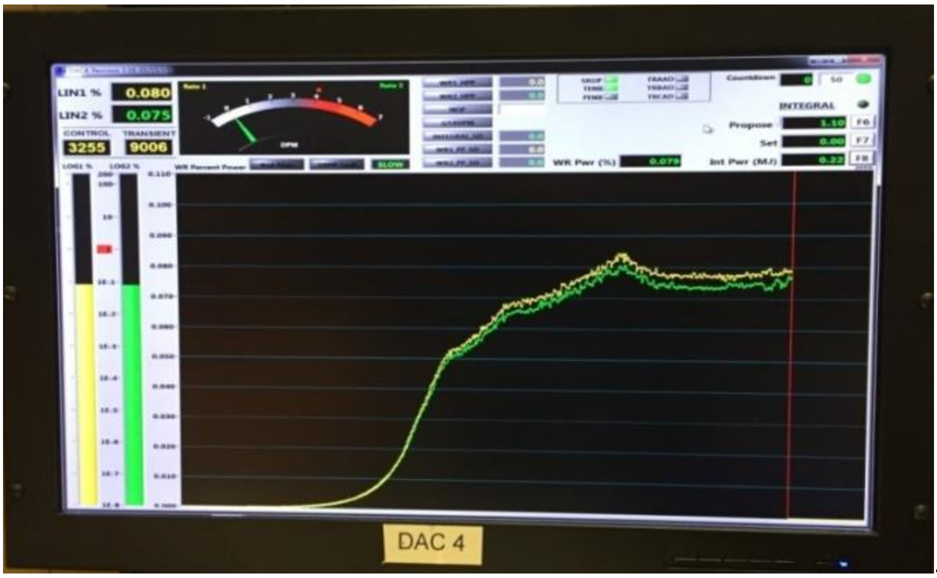

FIG. 9. Reactor Power Ramp

A system which allows loading and unloading while at power removes this tail variable and will provide for even more consistent low fluence operations. ACRR is in the process of designing a rapid load and unloading system for more exposure fidelity in the future.

Photoneutrons present a major repeatability challenge for the ultra-low fluence operations (<1E9). The neutron background is dependent upon the power history and the photoneutron energy spectrum differs from the fission energy spectrum so the actual impact on activation dosimetry needs to be considered. On a typical Monday morning − after no operations for the previous 48 hours − the background will be approximately 2E-7% of 2.39 MW or 0.0047 W. The ACRR background following a typical 280 MJ pulse operation is approximately 1.2 W. The ACRR has not gone through a significant period of no operations with the new wide-range monitors to determine how low the neutron background can be detected. Operations with ultra-low fluence requirements need to be run when the background is near the nominal 0.0047 W; otherwise the background power level may already be at or above the desired power level, which would not correspond to the desired neutron spectrum produced during operations (i.e. fission events). This constraint imposes operational considerations when scheduling customers.

6. Customer Impact

The ability of the ACRR to provide very low (<1E12 n/cm^2) or ultra-low (<1E9 n/cm^2) fluences on a repeatable basis has allowed customers to conduct testing in a more consistent manner. The neutron-to-gamma ratios of concern for many experimenters conducting electronic survivability testing is highly characterized at the ACRR and is highly repeatable down to the gamma baseline decay limit. Many experimenters previously found it necessary to shift to very different neutron sources, such as Californium 252 spontaneous fission spectrum, energetic alpha emitters (radium/polonium/plutonium) homogenously mixed with beryllium or lithium, high energy photon impingement on deuterium, fusion accelerators, or proton accelerators, in order to achieve low level neutron exposures. ACRR remains the only research reactor able to conduct pulse operations up to 60,000 MW with fluences up to 5E15 n/cm^2 per pulse in the United States.