LA-UR-24-26304

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Intended for: American Nuclear Society (ANS) Winter Meeting and Nuclear Technology Expo, 2024-11-18 (Orlando, Florida, United States)

Issued: 2024-06-26

The Prompt Fission Uranium Neutron Spectrum (PFUNS) Experiment: Critical Configurations and Irradiations

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INTRODUCTION

The objective of the Prompt Fission Uranium Neutron Spectrum (PFUNS) experiment is to reduce the uncertainty of the Prompt Fission Neutron Spectrum (PFNS) of ^{235}U above 8 MeV. The experiment was performed at the DOE National Criticality Experiments Research Center (NCERC) at the Nevada National Security Site. To meet the experiment objective, activation foils were placed in a central void region of a critical configuration consisting of concentric highly enriched uranium (HEU) metal hemishells. The set of activation foils were chosen based on threshold reactions to neutron energies across the fission spectrum, but especially those in the high-energy tail of the fission spectrum. PFUNS was performed on the Planet critical assembly machine at NCERC [1] and uses the Rocky Flats (RF) HEU hemishells [2, 3]. PFUNS has similarities to the Measurement of Uranium Subcritical and Critical (MUSiC) experiment [4, 5] conducted at NCERC in 2021, which also used RF hemishells, but contains a large central cavity to allow for a sample plate to be inserted. This large void means that much more HEU is needed to achieve a critical configuration (108 kg for PFUNS versus 59 kg for MUSiC). This work describes the 2024 experiment execution of four critical configurations and two irradiations for the PFUNS project.

BACKGROUND

The ^{235}U Prompt Fission Neutron Spectrum (PFNS) is an important nuclear data observable for many applications including nuclear criticality safety, nuclear energy, nuclear non-proliferation, etc. The PFNS can be measured in the same way as other differential experiments, through the use of a particle accelerator. The ^{235}U PFNS was measured to high precision below 10 MeV by the Chi-Nu collaboration of LANL and LLNL at the Los Alamos Neutron Science Center (LANSCE) [6]. These new data, published in 2022 [7], were included into the PFNS nuclear data evaluation as described in Ref. [8] and builds on a previous evaluation included ENDF/B-VIII.0 [9]. The Chi-Nu data defines the PFNS well until about 10 MeV. Above that, however, extrapolations with the Los Alamos model are currently used [10]. The neutron counts are very low at these energies leading to high statistical uncertainties. The actual neutron counts can also be hard to identify as gamma and cosmic background can be a significant portion of the measured signal. Extrapolation with the Los Alamos model could lead to biased nuclear data, as this model is not from first principles. Moreover, different PFNS models lead to widely different behaviors (orders of magnitude differences) at outgoing-neutron energies above 10 MeV [11]. The PFUNS experiment is designed to focus above 10 MeV where Chi-Nu data are uncertain and unreported. In addition, it will help serve as valuable confirmation of the Chi-Nu measurements below 10 MeV. Thus, these new data would provide crucial input to PFNS evaluation and validation.

The PFUNS experiment was designed to measure activation foils inside a bare HEU system [12]. In 2022, the PFUNS experiment began at NCERC and a critical configuration was established with 108 kg of HEU [13]. At that time, two successful irradiations were performed at lower relative power to determine scaling factors and to confirm neutron field symmetry with direct measurement. Unfortunately, electronic component failures prevented subsequent irradiations at the high power necessary to obtain data on high-energy threshold reactions. Additional work was performed between the 2022 and 2024 operations to ensure that a successful irradiation could be performed. This included permanent relocation of several electronic components further away and out of the line of sight of the Planet assembly. In addition, a large radiation shielding wall was assembled to further reduce radiation dose to components.

EXPERIMENTS

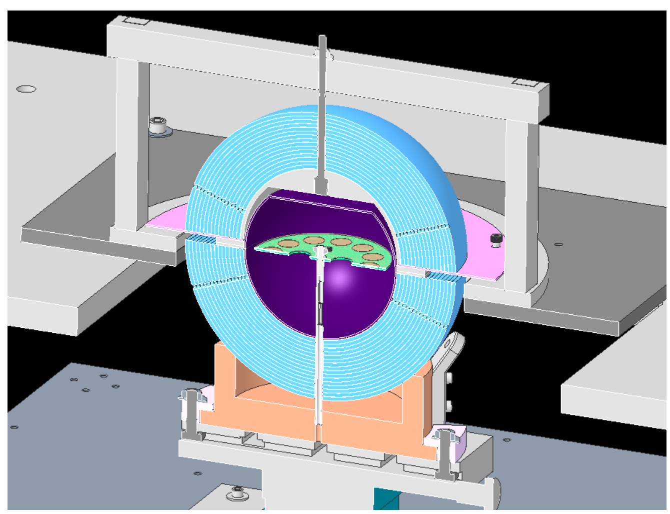

Fig. 1. Cutout view of the PFUNS experiment

Figure 1 shows a model of the PFUNS experiment and Figure 2 shows the experiment loaded on the Planet assembly. As seen in this figure, half of the HEU hemishells are placed on the top stationary platform and half are loaded on a movable platform that can be closed remotely. Four critical configurations were achieved. When 108 kg of HEU was present, the system was slightly supercritical. This is the same configuration that was built in 2022 [13]. It was not clear that this would provide enough reactivity to perform the needed irradiations since additional reactivity is required to overcome the negative temperature feedback. The addition of another hemishell would result in a system with over two dollars of reactivity. In order to be within allowed limits, spacer rings were added for the 114 kg configurations.

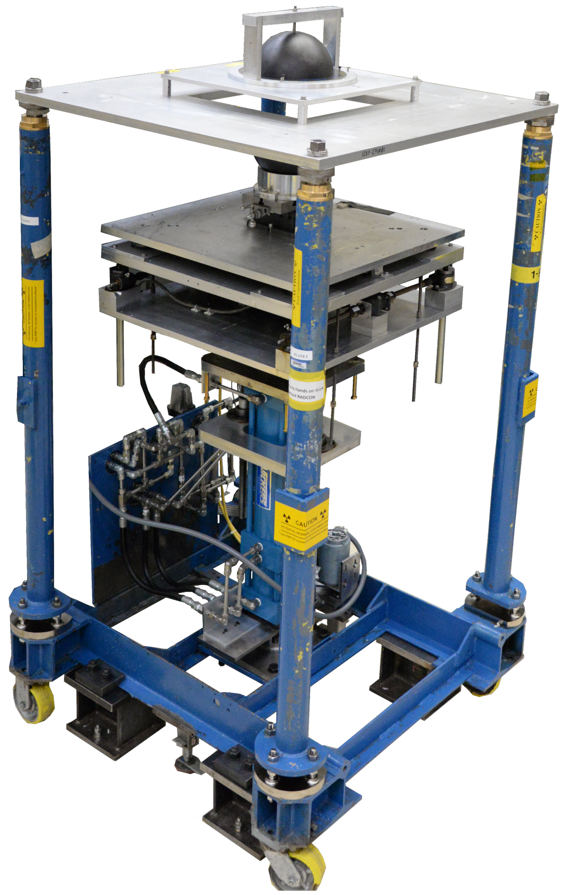

Fig. 2. PFUNS experiment on the Planet assembly.

RESULTS

An approach-to-critical method was used until it was determined that a critical system could be obtained within allowed excess reactivity limits. Once a super-critical configuration was obtained, the reactor period was calculated by measuring the exponential rise in neutron population using ^{3}He (Startup, SU system), and compensated ion chambers (Linear Channel, LC system). Figure 3 shows an example of this for the 108 kg configuration. The data are fit to determine the reactor period. Once the reactor period is obtained, the reactivity of the system can be estimated using the Inhour equation via

$$\rho = \frac{\Lambda}{T\beta_{eff}} + \sum_{i=1}^{6} \frac{(\frac{\beta_i}{\beta})}{1 + \lambda_i T}. \tag{1}$$

TABLE I. Delayed neutron parameters and abundances for fast fission in ^{235}U.

Group i	Decay Constant $\lambda_i(s^{-1})$	Relative Abundance (β_i/β)
1	0.0127 ± 0.0002	0.038 ± 0.003
2	0.0317 ± 0.0008	0.213 ± 0.005
3	0.115 ± 0.003	0.188 ± 0.016
4	0.311 ± 0.008	0.407 ± 0.007
5	1.14 ± 0.081	0.128 ± 0.008
6	3.87 ± 0.369	0.026 ± 0.003

where ρ is the reactivity in dollars, β_{eff} is the effective delayed neutron fraction, Λ is the prompt neutron lifetime of the system in s, $\frac{\beta_{eff}}{\Lambda}$ is the absolute value of the Rossi-α at delayed critical in s^{-1}, T is the reactor period in s, $\frac{\beta_i}{\beta}$ is the relative abundance of precursor group i, and λ_i is the decay constant of precursor group i in s^{-1}. Table I shows the decay constant and relative abundance for each of the six delayed neutron groups for fast fission in ^{235}U used in Equation 1[14].

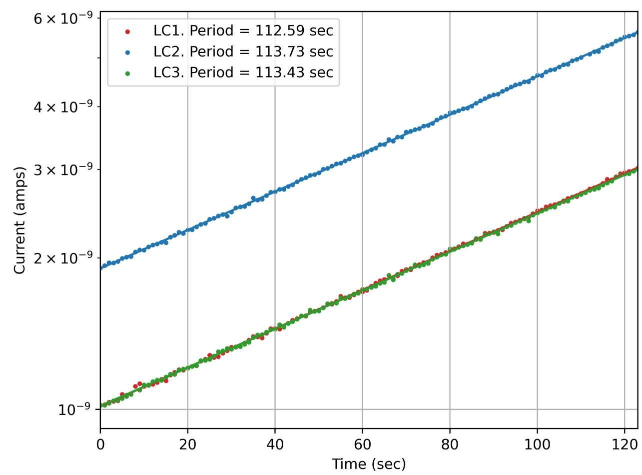

Fig. 3. Linear channel (compensated ion chamber) data for the 108 kg configuration.

A summary of the critical configurations is shown in Table II. Comparisons of the configurations with different spacer rings can be used to calculate a reactivity worth of 1.2 cents/mil.

Two irradiations were performed for the PFUNS 2024 operations; these are referred to by their irradiation times (2 hrs and 12 hrs). Summary information on both irradiations are given in Table III. Both irradiations used the same Rocky Flats shells with a total mass of 114 kg. Different spacers were used for the two configurations, however, to ensure adequate reactivity was available. Both configurations had foils present in the center of the assembly; the foils used in the 12 hr irradiation are shown in Figure 4. The 2 hr irradiation focused on reactions with shorter half-lives and included many fission foils. The 12 hr irradiation included many activation foils with longer half-lives and high-energy thresholds, which will allow for neutron spectrum unfolding (leading to the goal of improved PFNS data). The 12 hr irradiation was run at approximately twice the power level as the 2 hr irradiation,

TABLE II. Overview of PFUNS critical configurations.

HEU		RF33,35-63	RF33,35-64	RF33,35-64	RF33,35-64
Uranium mass (kg)		108	114	114	114
Spacer		None	265 mil	275 mil	285 mil
Reactivity (cents)	LC avg	8.63 ± 0.01	31.90 ± 0.07	19.16 ± 0.04	7.57 ± 0.01
	SU avg	8.30 ± 0.04	31.48 ± 0.06	18.91 ± 0.07	7.35 ± 0.02
Reactor period (sec)	LC avg	113.33 ± 0.20	15.12 ± 0.06	37.31 ± 0.12	133.39 ± 0.26
	SU avg	118.81 ± 0.73	15.53 ± 0.06	38.06 ± 0.21	138.03 ± 0.51

TABLE III. Summary of the 2 hr and 12 hr irradiations.

Date	2/20/2024	2/21/2024
HEU mass (kg)	114	114
Spacer	275 mil	265 mil
Number of foils	20	22
Duration (hrs)	2	12
Temperature rise: center of assembly (°C)	20.2	61.8
Temperature rise: outer surface bottom (°C)	10.1	34.5
Temperature rise: outer surface top (°C)	12	35.7
LC current (amps)	5.20E-07	1.15E-06
LC amp-s	3.80E-03	5.04E-02
RMS3 dose rate (R/hr)	35	72
Fissions	1.60E+16	2.10E+17
Watts	69	153
cents/°K	-0.26	-0.29
Reactivity used (cents)	5	18
Excess reactivity available (cents)	30	43

Fig. 4. Foil loadout for the 12 hr irradiation.

leading to 13 times more total fissions. This also lead to a larger difference in temperature as shown in Table III. The gamma dose rate was measured approximately 10 feet from the experiment; this is reported in Table III as the RMS3 dose rate.

Figure 5 shows the linear channel (compensated ion chamber) and temperature data (measured using Resistance Temperature Detectors) for the 12 hr irradiation. During the irradiation, the neutron population was kept constant by making very small adjustments to the closure distance between the top and bottom stacks of the assembly (usually 0.001-0.002 mils). As the system heats up, additional reactivity must be inserted due to the negative temperature coefficient. As shown in Figure 5, however, the temperature rise gets slower and slower as the irradiation progresses. For the last 4 hrs of the irradiation, the system was at steady-state and no operations were needed (additional reactivity insertion was not needed). The 12 hr irradiation exceeded the PFUNS minimum goal of 3E-02 amp-seconds (which would be roughly 1.25E+17 fissions).

After the irradiations were complete, the foils were retrieved. Each foil was individually counted on High-Purity Germanium (HPGe) detectors. For this work, over 10 HPGe systems were used and counting was performed for 4-6 months. Over 3600 hrs of counting has been performed to date. The

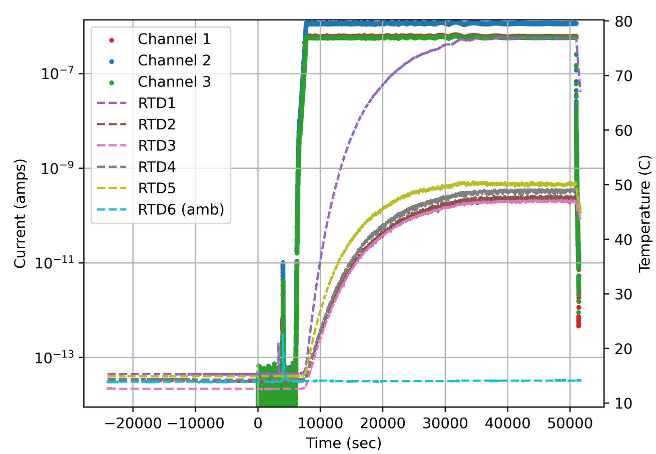

Fig. 5. Linear channel current (points and left y-axis) and temperature (dashed and right y-axis) for the 12 hour irradiation.

results of the foil analysis will be presented in future work.

CONCLUSIONS AND FUTURE WORK

The goal of the PFUNS project is to reduce uncertainty in ^{235}U PFNS at energies at/above 10 MeV. In order to accomplish this, foil irradiations are performed on a bare HEU system. Four critical configurations were measured: one with 108 kg and three with 114 kg of HEU. The first irradiation was performed for 2 hrs and focused on shorter-lived reactions, including many fission foils. The second irradiation was performed for 12 hrs and included longer-lived reactions and will be used for neutron spectrum unfolding. The second irradiation exceeded the established goals to ensure that adequate counting statistics can be achieved. This irradiation resulted in over 2E17 fissions, more than any other operation at NCERC other than the KRUSTY 28 hr experiment [15]. Future work includes analysis of the foil measurements and a benchmark evaluation of the critical configurations.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy (DOE) Nuclear Criticality Safety Program (NCSP), funded and managed by the National Nuclear Security Administration (NNSA) for the DOE. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of the US Department of Energy under Contract No. 89233218CNA000001.

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