INITIAL RESULTS FROM THE AFCI REACTOR-ACCELERATOR COUPLING EXPERIMENTS (RACE) PROJECT

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Abstract

The RACE Project, which is being conducted within the U.S. Department of Energy's Advanced Fuel Cycle Initiative (AFCI), is a series of accelerator-driven subcritical systems (ADSS) experiments. These ADSS experiments are being conducted with a compact, transportable subcritical assembly at the Idaho State University's Idaho Accelerator Center (ISU-IAC) in 2004 and with TRIGA reactors at the University of Texas at Austin in 2005 and at the Texas A&M University in 2006. In these experiments, source neutrons are generated by using electron accelerators to induce bremsstrahlung photon-neutron reactions in heavy-metal targets. These accelerator/target systems produce a source of ~10^{12} n/s, which will then initiate fission reactions in the subcritical systems. This paper includes a description of experiments that have been conducted at the ISU-IAC to develop operating experience and experimental techniques. In addition, initial results are discussed.

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INTRODUCTION

The RACE Project, a university transmutation research project of the U.S. Advanced Fuel Cycle Initiative (AFCI), is a series of accelerator-driven subcritical systems (ADSS) experiments that will be conducted at the Idaho State University's Idaho Accelerator Center (ISU-IAC), at the University of Texas (UT) at Austin, and at the Texas A&M University. In these experiments, an electron accelerator is used to induce bremsstrahlung photoneutron reactions in heavy-metal targets producing a neutron source to initiate fission reactions in the subcritical systems. These systems include:

- a compact, zero-power transportable subassembly at ISU of modular design with multiple target position capability;
- a 1-MW TRIGA reactor at UT-Austin that allows for thermal feedback measurements with a single source location and benchmark experiments with an fresh core; and
- a 1-MW TRIGA modular core at Texas A&M where both multiple target locations and thermal feedback measurements can be conducted in the ultimate test.

In the initial stages of the ISU RACE, which is Phase I of the RACE Project, experiments are being conducted to develop operating experience, procedures, and static and dynamic flux measurement techniques. In this paper we describe the ISU RACE configurations, experimental conditions, and preliminary results of far-subcritical tests. An overview of the RACE Project is in an accompanying paper.[1]

DESCRIPTION OF ISU RACE

The RACE configuration consists of an electron linac, a neutron producing target, a subcritical assembly, a graphite reflector, and a water-filled aluminum vessel. The RACE tests at ISU require the physical movement of fuel elements in the ISU subcritical assembly from the Nuclear Engineering Department to the Idaho Accelerator Center. The neutron source for the first experiments was created by coupling two ~20-MeV electron linacs to produce a total electron energy of more than 30 MeV and a total beam power of less than 1 kW. Neutrons are produced in a water-cooled tungsten (75% tungsten and 25% copper alloy, W-Cu) target aligned horizontally in line with the electron beam. The system produces about 2×10^{-3} neutrons per electron, or 2×10^{10} n/s per μA of electron current at 30 MeV. With a projected time-averaged beam current of 100 μA and electron energy of 30 MeV, we expect to produce a driving source in excess of 10^{12} n/s. The subcritical assembly that will surround this neutron-generating target will consist of 150 flat plates of 20%-enriched uranium-aluminum fuel alloy clad in aluminum inside a water tank. The plates will be arranged in three horizontal rows of two trays with the target in the center. The core is reflected with graphite blocks on all sides. Reactivity and multiplication studies with the Monte Carlo radiation transport code MCNPX[2] indicate that the ISU subcritical assembly should produce a subcritical multiplication of about 10 with k_{eff} of 0.94. Coupling, leakage, and absorption losses between the target and fuel will reduce the expected multiplication from the theoretical value of 14 [$1/(1-k_{eff})$]. We have conducted several far-subcritical developmental experiments with k_{eff} ~0.20 and multiplication just greater than 1. These tests have been conducted to develop operating procedures as well as experience with static and dynamic flux measurements. We are currently completing the design of the full-scale experiment, modeling the coupled system to predict its performance (fission rates, radiation fields, detector responses, fission-product production, activation of the target and other materials, etc.), and developing dynamic instrumentation, including fission chambers and self-powered neutron detectors.

Race Core

The core will be constructed of 6 flat aluminum trays each containing 20 to 30 flat plates of aluminum-clad, 20%-enriched uranium-aluminum alloy. The trays will be arranged 3 high by 2 wide (see Fig. 1). The active, fueled zone of each plate is 0.10 cm thick, 7.0 cm wide, and 61 cm long (0.04 in x 2.75 in x 24 in). The plates are clad in Al, giving them overall dimensions of 0.20 cm x 7.6 cm x 66 cm (0.08 in x 3.0 in x 26 in). Each plate weighs approximately 330.1 ± 4.1 g (based on actual measurements of 8 randomly selected fuel plates) and includes 50.8 g of U. The plates have not been individually characterized, but the total masses of U and ^{235}U are known to be 7.61 kg and 1.51 kg, respectively. The plates will be placed in the trays, separated by aluminum shims (nominally 4 mm thick) (see Fig. 2). The bottom trays will be lowered into the tank on each side of the beam tube, and then slid together. The middle trays will then be stacked on top of the bottom trays and butted up against the beam/target tube. The top trays will then be stacked on the middle trays, and the graphite reflectors will be inserted beside, in front and back, and on top of the fueled core. The remaining space inside the tank, between the fuel plates, around the target, etc. will be filled with de-ionized water.

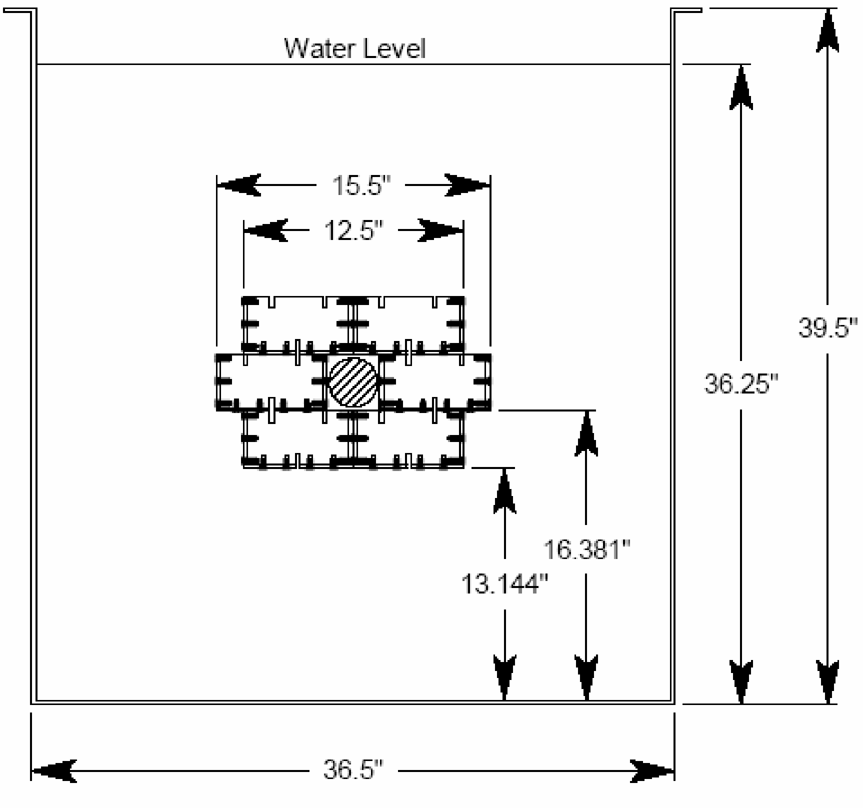

Figure 1. Front view of a cross section of the ISU RACE including the tank, the beam tube/target, and the stacked fuel trays. The cross section is cut to show the ends of the fuel trays. The in-tank graphite reflector and the support stand are not shown.

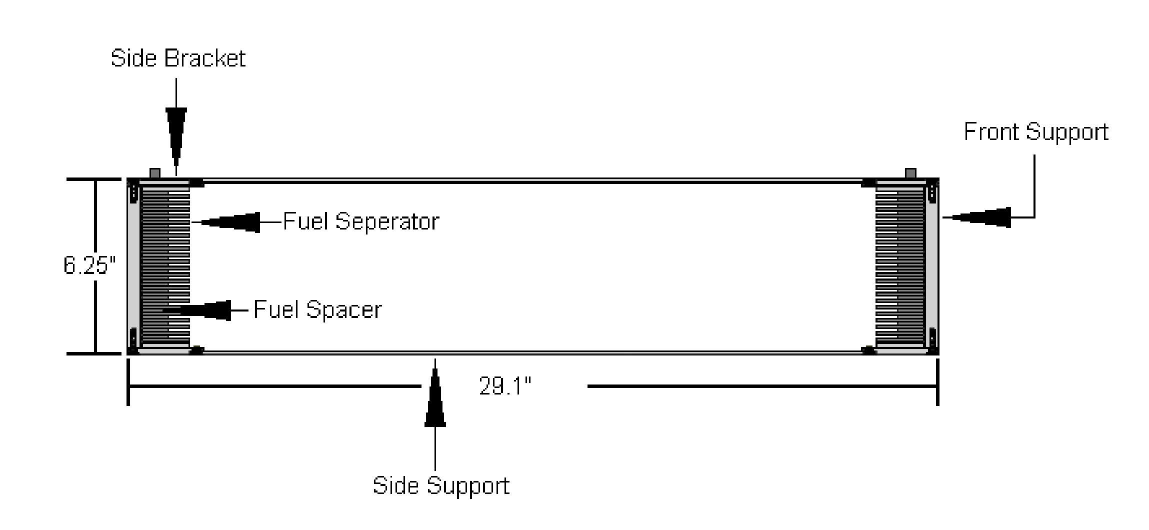

Figure 2. Components and Dimensions of a Modular RACE Fuel Tray (3.24” h) [Alan Hunt design]

Target and Beam Tube

The target was cut from a solid piece of tungsten-copper alloy (75% W and 25% Cu). It is 8.89 cm long by 6.99 cm in diameter (3½ in by 2¾ in). It is welded to one side of a 2¾ in “Conflat” flange, and the other side is welded to a 2.75 in diameter steel tube. This tube is mated to the wall of the Al tank with an O-ring flange (see Fig. 3). With a total beam power of about 3 kW, the face of the target, which is inside the vacuum beam port, will heat up to several hundred C. This heat will be conducted throughout the massive target (> 6 kg) and will be dissipated from its much lower temperature surface by natural circulation of water. This arrangement was tested in air and in water for convective and conductive heat transfer to ensure safe operation in the vicinity of the inner fuel plates. With a core neutron multiplication of 10, fission energy will be just 400 W (0.4 kW), or 0.0026 W/cm^2 from the surfaces of the fuel plates, which will be dissipated easily by natural circulation. Thus, the total power (beam plus fission) of just 3.4 kW that will be deposited in the ISU RACE will be easily dissipated without heating the fuel substantially. The mass of water and graphite in the tank will be about 1.1 tonnes (1100 kg), and the surface area of the tank exposed to ambient air conditions and structure to dissipate beam and fission power will be more than 3.5 m^2, so that the dissipation will be less than 0.1 W/cm^2 (c.f. a 100-Watt light bulb at about 2.5 W/cm^2). The system will not warm significantly during experiments.

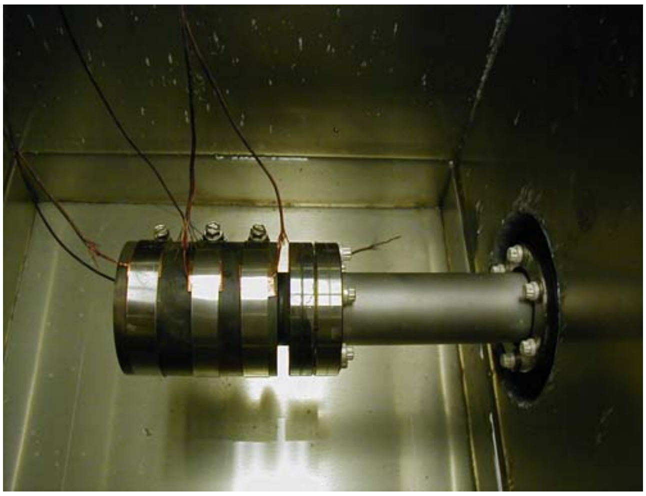

Figure 3. RACE Target Assembly. The tungsten-copper target, flanges, and beam tube inside a small water-filled test tank. The target in this photograph is fitted with thermocouples. The

Tank and Stand

The subcritical assembly is contained in a rectangular tank made of ¼-inch aluminum that is approximately 1.0 m long by 0.93 m wide by 1.0 m high (water depth will be 0.93 m). The tank is placed on a sturdy steel stand to provide structural support as well as a work platform for preparing experiments. The tank was filled with de-ionized water after the fuel trays and graphite bottom and side reflectors were in place.

Accelerator

The principle of the accelerator-driven neutron source is the production of neutrons by photon-neutron reactions in a heavy metal target. The photonuclear reactions are induced by high-energy bremsstrahlung photons produced in the target by a 20 to 40 MeV electron linac (see Fig. 4). These electron-linac produced neutron sources have great flexibility; pulse widths are variable from nanoseconds to ~ 10 microseconds with pulse rates up to several hundred hertz. The neutron source is physically small, with volume ~ 300 cm^3, thus usable flux is relatively high. Yields of ~10^{10} n/pulse for microsecond pulses are easily achieved; thus total average rates are up to ~10^{11}-10^{12} n/sec. The neutron spectrum is similar to a fission spectrum with a high-energy tail similar to a proton spallation spectrum adjusting for the neutron energy end point at ~ 30 MeV. Thus, only a few percent of the source neutrons will be in this high-energy tail. There is little slow neutron contamination from the accelerator/target.

Reactor Physics

Figure 4. The 30-MeV Electron Linac. Peak performance is achieved at 25 MeV. In addition, peak power occurs at less than the maximum energy, so that the accelerator is currently operated at 20 to 25 MeV. The tank and stand are also visible.

Many conceptual arrangements for the RACE experiments have been examined using the MCNPX Monte Carlo radiation transport code and data libraries. These studies have been performed to predict the performance of the system and optimum arrangements of materials for both reactivity and source multiplication. Because of the large target and beam tube in the center of the assembly, we have found it difficult to produce an arrangement with a multiplication value, k-effective (k_{eff}), much greater than 0.94 or 0.95. With a fuel-water core surrounded by a thick graphite reflector, k_{eff} of about 0.94 may be achieved. Reducing the thickness of the reflector to practical values, on the order of 20 to 30 cm (8 to 12 in), will produce k_{eff} of about 0.93. Fuel plates may be assembled in the core in single (each plate is separated from each other plate by water, see Figure 5), double (plates are in pairs), and triple (three plates in contact separated from three more plates by water) arrangements. Parametric studies indicate that the optimum center-to-center spacing for these arrangements is 0.6 cm for single plates and 1.0 cm for double plates. In preparation for conducting the full-core, full-power RACE experiments, we have conducted several experiments with just ten fuel plates (k_{eff} of about 0.2) at low power. These experiments have a source multiplication just greater than 1 and more water in the vicinity of the target. After this experiment has confirmed our ability to conduct the experiments, verified our computations, and demonstrated the performance of measurement, survey, and data acquisition system, we will begin preparing for the full-core RACE. During the loading of the fuel for the full-scale RACE, inverse multiplication measurements experiments will be conducted to verify the transport predictions. In addition, the accelerator will be operated at low energy, low power, and low frequency prior to full-core, high-power testing.

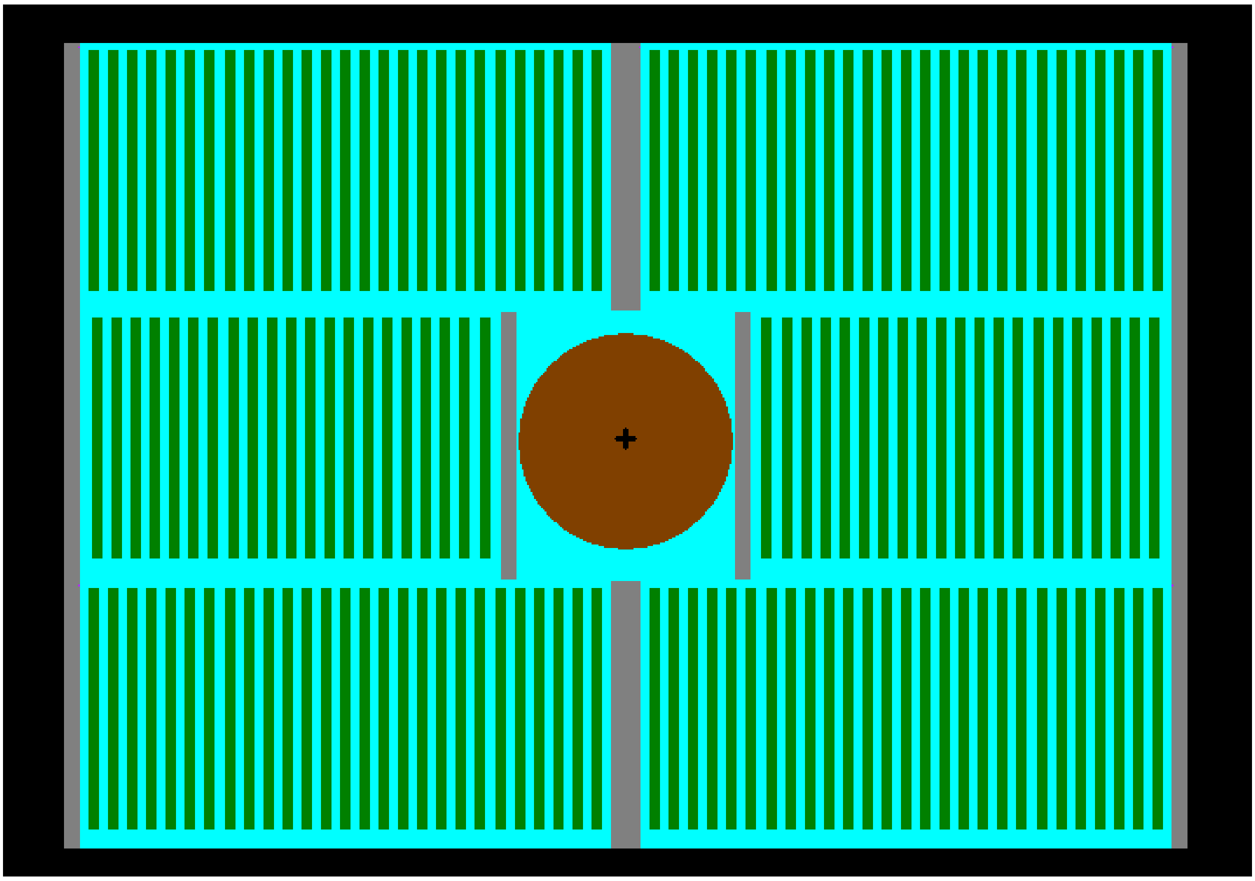

Figure 5. Cross section of an MCNPX model of fuel trays with unequal tray sizes to produce a rectangular core. This is a drawing generated by MCPLOT, it is a horizontal cross section in the XZ plane at Y=0, the axis of the beam tube. Color code: water is blue, target is brown, aluminum is gray, graphite is black, and fuel plates are green.

Instrumentation and Monitoring

A variety of instrumentation and monitoring equipment will be used to measure the production of neutrons and gamma rays from the target, to measure time-dependent neutron flux in and around the core, and to measure the leakage of neutrons and gamma rays out of the experiment and into the experiment bay. In addition, environmental monitoring equipment will be installed in the experiment bay to monitor for fission product leakage from the fuel plates. Instrumentation currently being examined includes BF_3 counters, ^{3}He filled tubes, fission chambers, self-powered neutron detectors, and alpha and beta monitors. Some of this detection equipment has been well qualified through extensive use in the ISU Health Physics program, the Nuclear Engineering program, at the Idaho Accelerator Center, and/or at the Idaho National Laboratory. Other equipment, such as fission chambers for measuring pulsed neutron flux, will be acquired before commencing full-core experiments.

Construction

The tank was constructed, the trays were fabricated, and the graphite reflector "building blocks" were collected and assembled in the tank (Figure 6). In addition, an accelerator and target were assembled and tests were conducted to confirm passive cooling of the target in the vicinity of the fuel plates. When we have received an NRC license, we will assemble the full-core RACE ADSS and begin static and dynamic experiments. In preparation for this testing, we have begun a series of far-subcritical experiments using just 10 of the 150 fuel plates.

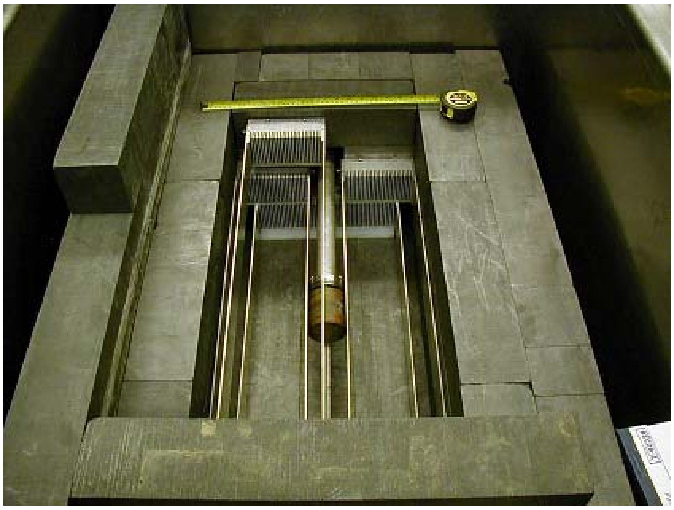

Figure 6. RACE Fuel Trays and Target Inside the Graphite Reflector

First, the system was assembled without fuel plates and beam/target performance was examined in a water-filled tank: neutron production was measured and target cooling was confirmed. Then, ten fuel plates were moved from the basement of the Engineering building to the IAC and installed in two of the top fuel trays (Figure 7). Reactivity and multiplication were measured using accelerator-produced neutrons, and performance was compared to predictions. The results of these experiments were reported to the ISU Radiation Safety Committees and have been reported at an AFCI Semiannual Technical Review Meeting. After discrepancies have been resolved, and after the NRC has granted a license modification to conduct the full-scale tests, the full 150 fuel plates will be moved to the storage location at the IAC.

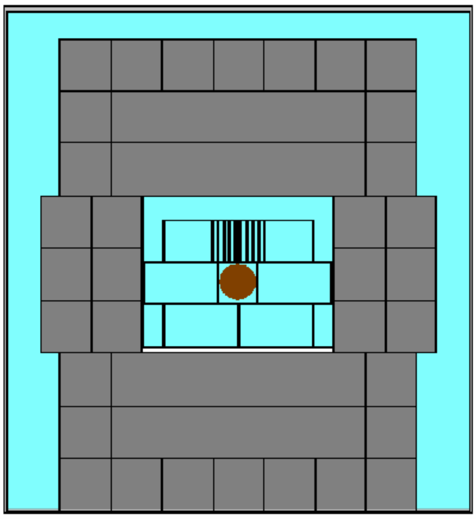

Figure 7. Cross Section of the 10-Plate Experiment from MCNPX

Experiment Plan

The final experiments will include an inverse multiplication measurement experiment using first 10 fuel plates followed by the addition of fuel plates as multiplication increases such that we are confident we will not exceed k_{eff} of 0.95 with any addition of fuel. Each of these steps will require removing and replacing at least the top three layers of the graphite reflector. After the full core has been assembled and reactivity has been verified, initial accelerator-driven experiments will begin. Because the accelerator can be operated at much less than 30 MeV accelerating potential, much less than the nominal 10 mA peak power, narrower pulse width, and as low as 1 Hz frequency, we can conduct initial experiments with essentially a zero-power beam. We will then gradually increase these parameters to verify the performance of the coupled system in terms of target and fuel cooling, radiation fields, neutron production, and activation. Once we have established complete operating parameters and verified that we can predict safe performance at full power, we will be prepared to begin conducting the full-power experiments. Follow-on experiments may include moving fuel trays away from the optimum positions, moving the target away from the center of the core, reducing fuel below 150 plates or changing spacing, moving detectors, and removing or adding reflector elements.

INITIAL EXPERIMENTS

Accelerator Parameters

The accelerator has been operated at reduced conditions to minimize activation of the fuel. The fuel must be transported to the ISU nuclear engineering laboratory the day of the experiment; lower activation reduces exposures and shipping difficulties. The following were typical operating conditions during the first experiments:

Electron Beam Energy	25	MeV
Current (average during each pulse)	80	mA
Pulse width (~fwhm)	3	μs
Frequency	15	Hz
Duration	300	s
Power	90	W
Neutron production	~0.5 to 1 x 10^{11}	n/s

The resulting neutron source, about 3 x 10^{13} neutrons, is sufficient to activate gold and manganese for subsequent analysis of flux and axial flux profiles.

Initial Results

One measurement that allows comparison to ADSS modeling is the measurement of thermal neutron flux profiles by using gold, manganese, or other materials. We have used gold foils and manganese chips for these measurements. Data is still being evaluated. One result is illustrated in Figure 8, which is a comparison of normalized manganese activation with MCNPX results for the current RACE configuration. Differences are being examined.

A technology that will be developed and refined during the international ADSS experiments programs (MUSE, RACE, and TRADE) is the use of time-dependent flux measurements to determine the effective subcriticality of these reactors. At ISU we are developing time-dependent measurement capability as well. Initial experiments included the use of multiple, coupled ^{3}He detectors that were fabricated for a homeland defense prototype. Initial results are illustrated in Figure 9. These results have not correlated well with predicted neutron die-away in our subcritical system. We are likely seeing the result of activation in non-fissile materials surrounding the subcritical assembly.

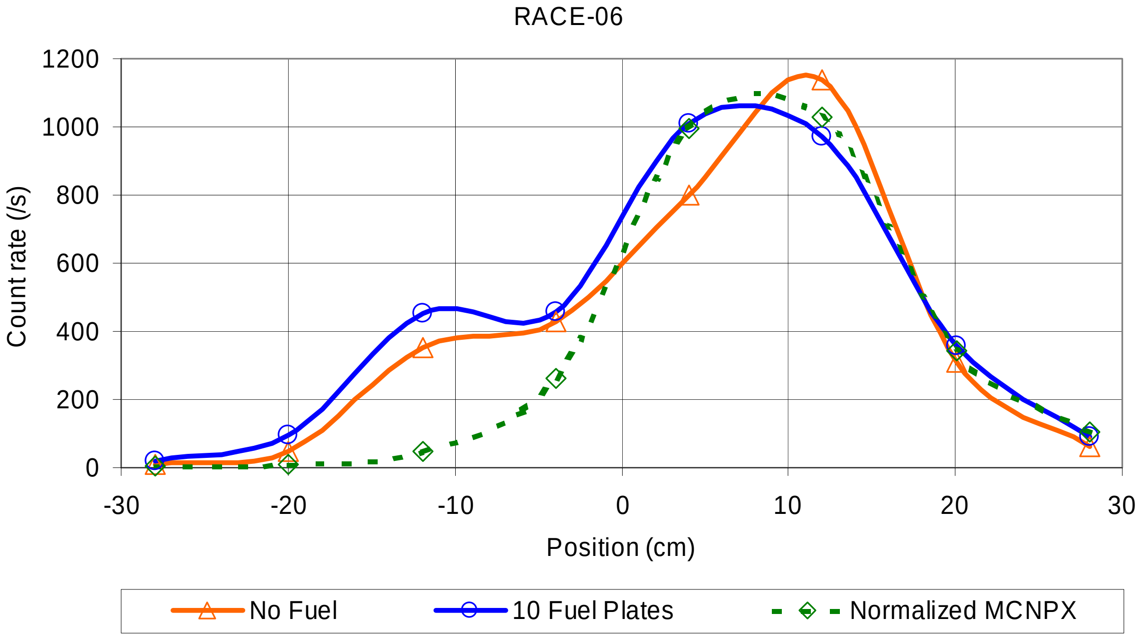

Figure 8. Initial Results: Mn-55 Activation vs. MCNPX. The target face is at 9.14 cm, and the vacuum tube projects to the right.

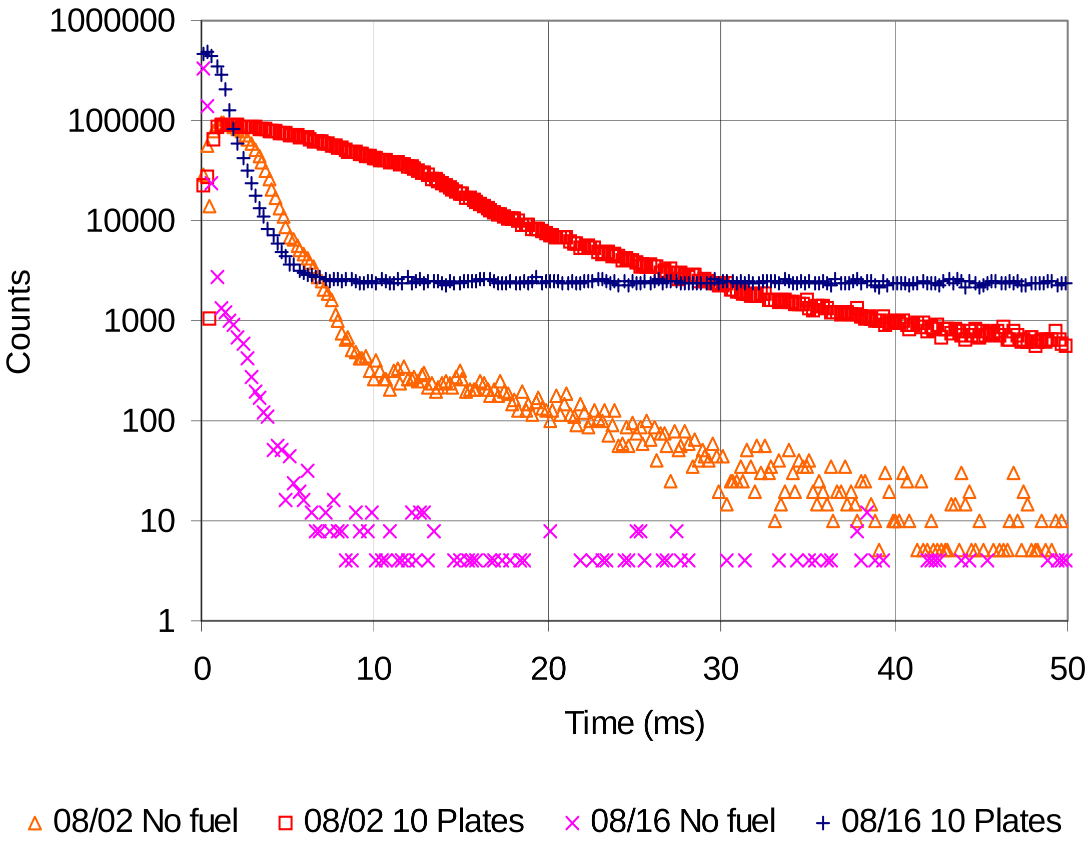

Figure 9. Time-dependent Flux Measurement. Counts are taken on the outside of the reflector using a moderated and shielded 3He detector system.

In addition to the foil activation measurements, we also measured the "Cadmium Ratio," which is a measure of the ratio between the thermal and epithermal flux. The cadmium ratio without fuel was 3.92, and with fuel it was 4.66. We have not studied this ratio further, nor have we compared it to MCNPX calculations. However, this difference in cadmium ratio indicates that we may have different self-shielding in the thick Mn chips that should be investigated.

SUMMARY

Initial experiments have been conducted at the Idaho State University Idaho Accelerator Center to develop operating experience, procedures, and static and dynamic flux measurement techniques for accelerator-driven subcritical systems (ADSS) experiments. A series of these experiments are being conducted in the RACE Project, which is a university transmutation research project of the U.S. Advanced Fuel Cycle Initiative (AFCI). In these experiments, an electron accelerator is used to induce bremsstrahlung photoneutron reactions in heavy-metal targets producing a neutron source to initiate fission reactions in the subcritical systems. Development experiments have begun in Phase I at the Idaho State University's Idaho Accelerator Center (ISU-IAC) with a compact, zero-power transportable subassembly of modular design with multiple target position capability.

Initial results of far-subcritical experiments using just 10 of the 150 ISU fuel plates are summarized herein. These experiments have included flux profiles taken with gold foils and manganese chips as well as time-dependent neutron leakage measurements with a moderated ^{3}He detector system. These experiments are helping to refine techniques before the beginning of full-scale ISU RACE tests, which will commence after the receipt of a license modification from the U.S. Nuclear Regulatory Commission.

REFERENCES

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1. D. BELLER, "Overview of the AFCI Reactor-Accelerator Coupling Experiments (RACE) Project," these Proceedings.

2. MCNPX Team, "MCNPX, Version 2.5.d," *Los Alamos National Laboratory report* LA-UR-03-5916 (August 2003).