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Subcritical Measurements Research Program for Fresh and Spent Material Test Reactor Fuels

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Abstract

A series of subcritical noise measurements were performed on fresh and spent University of Missouri Research Reactor fuel assemblies. These experimental measurements were performed for the purposes of providing benchmark quality data for validating transport theory computer codes and nuclear cross-section data used to perform criticality safety analyses for highly enriched, uranium-aluminum Material Test Reactor fuel assemblies. A mechanical test rig was designed and built to hold up to four fuel assemblies and neutron detectors in a subcritical array. The rig provided researchers with the ability to evaluate the reactivity effects of variable fuel/detector spacing, fuel rotation, and insertion of metal reflector plates into the lattice.

Summary

A collaborative[1] experimental research program was undertaken between Westinghouse, the University of Missouri Research Reactor (MURR) facility, and Oak Ridge National Laboratory (ORNL). The purpose of the program was to characterize the subcritical behavior of a small array of fresh and spent MURR fuel assemblies using the ^{252}Cf source-driven noise technique. The experiments involved using four unirradiated, highly enriched (93.15 wt % ^{235}U) MURR fuel assemblies each containing ~773.5 g ^{235}U, four ^{3}He neutron detectors (4 atm.) and a 0.11 μg ^{252}Cf source ion chamber in a standalone Fresh Water Tank (FWT). An experimental test rig composed of aluminum was constructed to position the fuel, source and detectors at a variety of spacings and orientations while allowing stainless steel, aluminum, lead and borated aluminum plates of varying thickness' to be inserted or removed from the array. One hundred twenty-seven (127) power spectral density noise measurements were performed to measure spectral density ratios and prompt neutron decay constants (α) for subcritical systems which varied in k_{eff} from ~0.65 to ~0.87. Agreement between Monte Carlo calculated and measured spectral ratios from 1-3% was seen for cases involving no reflector plates, stainless steel, aluminum and lead plates. Differences as large as 5% were seen for cases involving borated aluminum plates. Measurements involving combinations of fresh and spent MURR fuels were also performed using the test rig submerged in the MURR reactor weir pool during reactor shutdown. Single and double spent fuel replacement measurements were performed by substituting fresh assemblies with spent assemblies (143 Mw-D burnup) in a 4-assembly array. Lattice reactivity decreases of -1.8 and -3.2 %Δk/k were observed for the single and double replacement cases respectively. Monte Carlo calculated burnup and reactivity estimates of these replacement experiments agreed to within ~7-8%.

Background

An important aspect of performing criticality safety analyses on any type of fissile material containing system is to ensure that the computer codes and neutron cross-section data sets being used for the analysis have been rigorously compared to experimental data to verify their ability to correctly predict reality. This process (known as validation) must be performed by comparing experimentally determined values of reactivity (typically k_{eff}) to those predicted by a given code for the particular fissile isotope, moderation and reflection conditions expected during fuel handling or processing. Many of today's transport theory codes (both probabilistic and deterministic) have been validated against critical (or near critical) experiments for a variety of systems.

For the handling and storage of spent Material Test Reactor (MTR) fuel assemblies in underwater basins at SRS, computer codes used to perform the criticality safety analyses for these systems are traditionally validated using experimental data derived from measurements with fresh fuel assemblies. Since very little experimental data exists for spent fuel assemblies, it has always been viewed that the approximation of fresh fuel contents for spent assemblies is adequate for establishing the fuel handling and storage limits for such fuels. However, several recent studies[2;3] have concluded that the bias and uncertainty for transport codes may be a function of the degree of subcriticality of a given system and that perhaps subcritical measurements[4] should be used for providing experimental data for comparison to computer codes.

In recent years spent fuel storage capacities for both underwater basins and shipping casks have become an important economic factor due to the large increase in fuel receipts at SRS. As a result, the traditional (i.e., very conservative) methods used for establishing criticality safety storage limits for spent fuels have undergone re-evaluation. As part of this re-evaluation, the desire to reduce overall safety margins used for storing and handling spent fuel assemblies has yielded two concepts; (1) reduce the uncertainty in computer code bias uncertainty for MTR fuel assemblies and (2) investigate methods which would allow credit for the burnup of the fuels (both in terms of fission product poisoning and fissile isotope depletion).

In order to address these two issues, a single experimental program was established to perform subcritical reactivity measurements on both fresh and spent MURR fuel assemblies. Due to the inherent difficulties associated with measuring the reactivity of deeply subcritical systems, determination of k_{eff} directly from measurements is not possible. Rather, other quantities related to the degree of subcriticality (such as α, the prompt neutron decay constant) can be measured and related to k_{eff}. Once the determination of measurable quantities (such as α) are made for a subcritical system, corresponding values of k_{eff} can be inferred from these measurements.

The prompt neutron decay constant (α) for subcritical systems can be derived experimentally from a variety of methods[5] all of which involve actively interrogating a fuel assembly with neutrons from an external source and measuring the time-dependent exponential decay of the fundamental mode neutron population N(t). Since the counts measured by the detectors after initial interrogation of the assembly are non-random, (due to the time correlation between neutrons having a common ancestor), this time correlation of events can be observed and measured. For a subcritical system, a logarithmic plot of neutron counts versus time will yield a straight line (background corrected) with a slope equal to $-\alpha$ according to the equation:

$$N = N_0 e^{-at}$$

The $-\alpha t$ term indicates that the neutron population is a decaying exponential function of time and that the system is subcritical. Having obtained an estimate of (α), the reactivity [ρ] associated with this value of (α) can be found knowing the prompt neutron generation time (Λ) and the effective delayed neutron fraction (β_{eff}) according to the following equation:

$$r = -a\Lambda + b_{eff}$$

One difficulty associated with this approach is that while (α) can be measured, Λ and β_{eff} are either calculated quantities or are determined from measurements at or near critical. Also, since the measurements must be performed at a relatively low fission rate (to avoid overlapping of the fission chains) a high detector efficiency is needed and long measurement times may be seen particularly for systems with long prompt neutron lifetimes. The technique, generally referred to as the Rossi-α technique[6], can be useful for measuring subcritical systems with a continuous emitting neutron source and has been utilized for many years in the nuclear industry. Pulsed-neutron techniques have also been used for many years to perform similar types of exponential dieaway measurements. As with Rossi-α measurements, when a fissile assembly is pulsed with a burst of neutrons from an external (pulsed) source, the rate of prompt decay of the neutron flux (or detector count rate) should be proportional to the reactivity which is proportional to α.

Work performed by Mihalczo[7;8] in the late 1960's and early 1970's considered using ^{252}Cf as a randomly pulsed neutron source for active interrogation of fissile assemblies. Mihalczo observed that "if the neutron decay in an assembly takes place in a time shorter than the mean time between neutron-producing disintegrations in a steady state source, the assembly will respond in the same manner as if it were being injected with neutrons from a randomly pulsed source." Proper choice of source disintegration rate will prevent the overlapping of fission chains within the multiplying assembly and determination of (α) is possible. This technique (referred to as the ^{252}Cf source-driven noise method) has several advantages over traditional Rossi-α or pulsed neutron techniques in that it does not require calibration at or near delayed critical and is independent of detector efficiency and relative source intensity.

Development of this technique over the past 20 years[9;10] at ORNL has produced a measurement system capable of analyzing the detector responses in frequency domain by Fourier transforming the time-dependent responses. Frequency domain analysis allows easier removal of signal contributions from background and detector electronics and thus gives a correlated signal which can be related to the prompt neutron decay constant (α) as well as other subcritical reactivity parameters which can be related to k_{eff}. Frequency dependent auto- and cross-correlation functions between pairs of detectors and the source can be measured and complex multiplied to give a particular ratio of densities which can be shown to be proportional to the k_{eff} of a the system (to a first-order approximation).

A very important development in the use of this technique has involved evolution from simple 1-D point kinetics techniques (for calculating some of the key subcritical reactivity parameters) to a generalized, 3-D Monte Carlo method. MCNP-DSP[11] was created to perform a strictly analog neutron and photon transport calculation specifically for the ^{252}Cf source-driven frequency method. The code performs an event-by-event simulation of neutron histories tracking source particles and their progeny until they are either absorbed or escape the system. The code calculates the time (or frequency) dependent detector responses, complex multiplies these responses to obtain spectral densities and averages these densities over many samples. A particular ratio of spectral densities is calculated and compared to those directly measured with the ^{252}Cf source-driven frequency method. If the calculational results differ from those that are measured, the MCNP-DSP model is adjusted to correct for the differences and the MCNP eigenvalues calculated for these two cases represent the inferred or “measured” k_{eff} and the corrected or adjusted k_{eff} of the system. The difference between these two eigenvalues represents the bias of the code and cross-section data set used to perform the calculations. In essence, the bias between the calculated and measured spectral ratios is correlated to a bias in k_{eff}.

Experimental Description

MURR Fuel Assemblies

The MURR fuel assemblies used in these experiments are highly enriched (93.15%) plate-type MTR fuel assemblies. Each fuel assembly is composed of twenty-four (24) curved, thin, uranium aluminum plates clad in aluminum with ~830 grams of total uranium and ~1200 grams of aluminum (clad plus alloy). The meat (or core) region of each plate has a nominal thickness of 0.0508 cm (0.02”) and the uranium is in the chemical form of (UAl_x) particles dispersed in an aluminum matrix. Each meat region is contained in a nominal 0.0381 cm (0.015”) aluminum cladding. The total nominal thickness of each fuel plate is 0.127 cm (0.05”). The 24 fuel plates are held together by a pair 0.381 cm (0.15”) thick aluminum side plates which are grooved to hold the fuel pates. Once stacked inside the side plates, the spaces between the fuel plates act as coolant channels for water to flow through during reactor operation. Figure 1 shows a copy of the manufacturer’s (Babcock & Wilcox) prints[4] detailing how the plates are stacked within the side plates.

All twenty-four fuel pates and the two aluminum slide plates are fastened to an upper and lower end fitting. Both the upper and lower end fittings (they are structurally identical to each other) are made with a 1.8288 cm (0.72”) diameter locating pin hole. This hole is the geometric center of the fuel assembly and allows the assembly to be centered into the reactor during operation from both the top and bottom positions. For these experiments, a locating pin was machined to the same diameter as that used in the MURR reactor for locating each of the four fuel assemblies on to the slide mechanism.

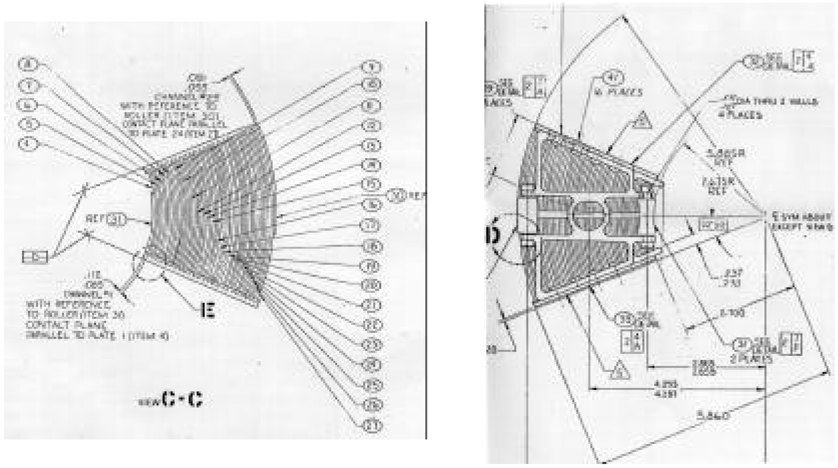

Figure 1.
MURR Fuel Assembly with End Fitting

Experimental Test Rig

A key aspect of this project was the design, construction and use of the experimental test rig. The rig is an aluminum device capable of holding up to four (4) MURR fuel assemblies in vertical positions. The device sits on top of a freestanding aluminum table which was placed either on the bottom of the Fresh Water Tank (FWT) or the reactor weir pool. The FWT is a 213.36 cm (7 ft.) high, 182.88 cm (6 ft.) inside diameter high density polyethylene solid structure with a wall thickness of 1.11125 cm (7/16”). The prototype was designed such that each fuel assembly will be placed inside a thin walled aluminum sleeve with dimensions just large enough for the assembly to be inserted or removed. Figure 2 shows a picture of the test rig inside the empty Fresh Water Tank (FWT).

The tolerances for fuel assembly positioning were a maximum of ±0.15875 cm (±1/16”) as defined in Reference 3. The sleeves were mounted on a slide plate which capable of moving toward or away from the symmetric center of the rig in minimum increments of 1 mm. In addition to the fuel assembly sleeve, each slide plate was also outfitted with a nominal 2.54 cm (1”) diameter schedule 10 aluminum pipe which acts as a dry well for the ^{3}He detector. The detector sleeves had provisions for a 2.54 cm (1”) radial lead shield around the circumference of each detector for shielding needed during the spent fuel measurements. Each detector sleeve was capable of being positioned at five different locations on the aluminum slide plate such that the fuel-to-detector centerline distances can be varied from 7.5 cm to 13.5 cm in increments of 1.5 cm. When in use, each fuel assembly/detector pair moved independently of each other toward or away from the center of the prototype rig.

Each of the four (4) slide mechanisms consisted of an aluminum plate which contains receiver positions for one fuel assembly and one detector dry well. The slide plate was controlled by a threaded screw drive which was operated remotely from above the tank using the hand crank knobs (seen in picture). The drive was calibrated such that one turn on the knob corresponded to 1 mm of slide movement. This mechanism allowed researchers to evaluate the reactivity effects of changing the pitch of the fuel assembly lattice in a variable manner.

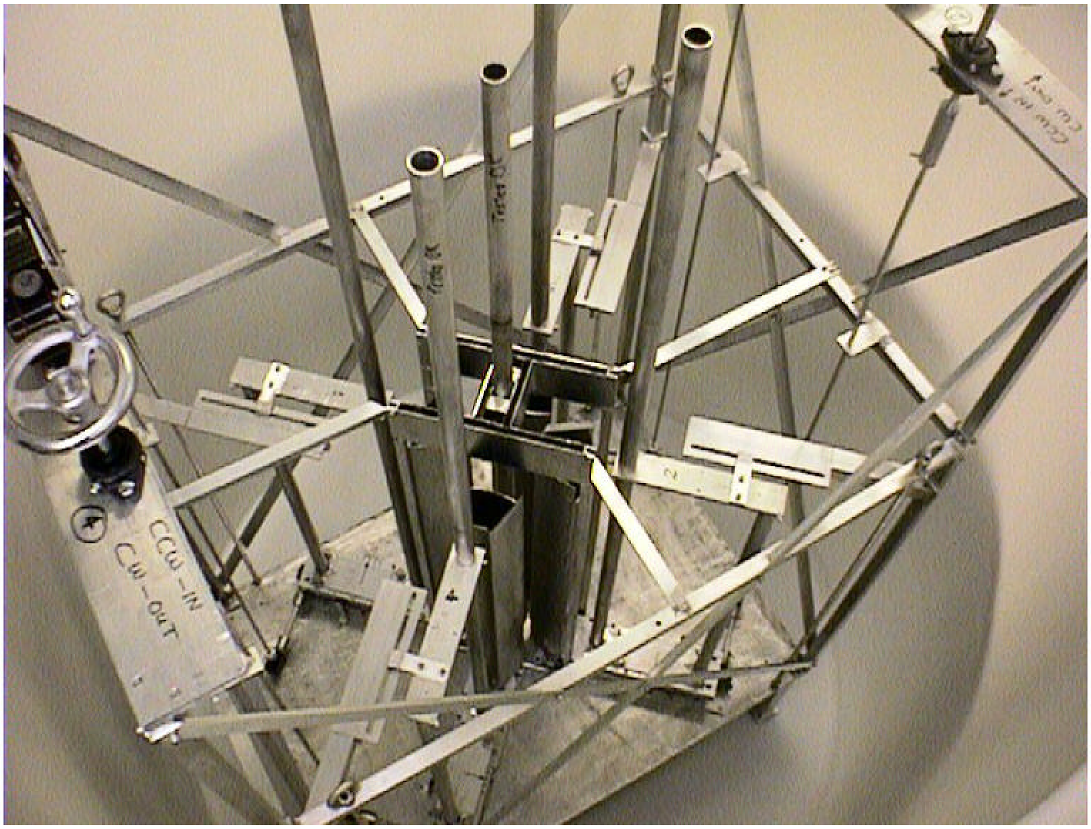

Figure 2.
Test Rig Inside Empty Fresh Water Tank

Evident from Figure 2 are the fuel assembly shrouds, the detector drywells and the aluminum support structure for the "H" cruciform. Also, present were four (4) hand crank knobs (like the one seen in the picture) attached to calibrated mechanical counters. Each slide and crank were calibrated such that one complete turn of the knob translated to 1 mm of slide movement. The mechanical counter readouts were in unit of 0.1 mm such that a change in the counter reading of one (1) unit corresponded to a slide movement of 0.1 mm. Therefore, one complete rotation of the hand crank knob would correspond to 10 units of change in the counter readout.

Prior to the start of the experiments, all five detector drywells (one for the source and four for the detectors), were mechanically locked into the aluminum plate attached to the slide. A fuel assembly was loaded by lowering it into the shroud until it seats on the surface of the assembly base plate. The shroud ensures that once the assembly made contact with the bottom plate, the aluminum locating pin will fit through the 1.8288 cm (0.72") diameter hole in the end fitting (shown in Figure 2). Once seated, the assembly was not in contact with the shroud since both the base plate and surface of the assembly end fitting are precision machined to maintain the assembly vertical. The locating pin maintains the assembly's position relative to the drywells. For clarification, Figure 3 shows a detailed picture of the slides and locating pins used to position the fuel assembly. In these pictures, two of the shrouds have been removed from their base plate for clarity.

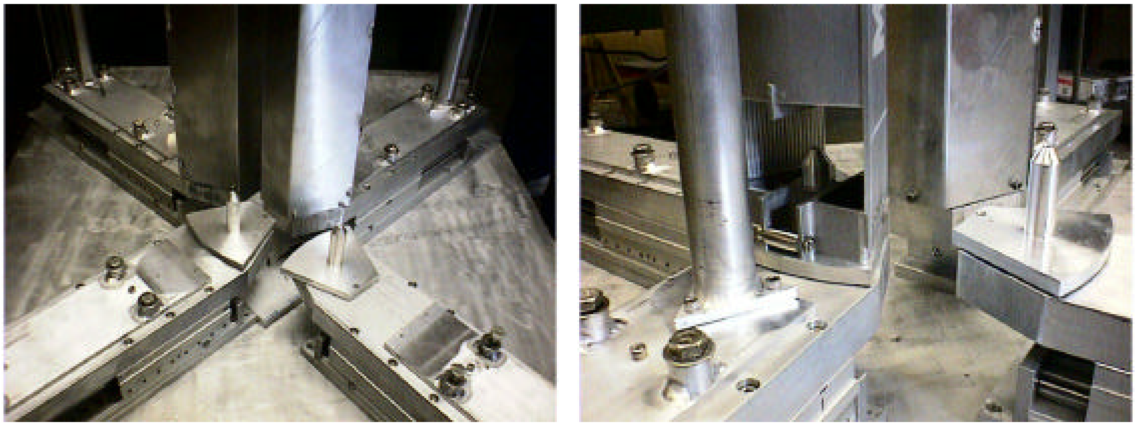

Figure 3.
Pictures of Slides and Fuel Assembly on Locating Pin

Metal Reflector Plates

As seen in Figure 4, the test rig was outfitted with aluminum spacer support brackets capable of holding a variety of metal plates in between the fuel assemblies in a cruciform “H” shape. The plates were positioned upright and shadowed the entire vertical length of the active region of the fuel assemblies with a height of 121.92 cm (48”). The plates were comprised of either stainless steel (304SS), aluminum (AL1100), lead or borated aluminum (boral). The stainless steel and aluminum plates were of two different nominal thicknesses, 0.15875 cm (1/16”) or 0.3175 cm (1/8”). The boral plates were at a fixed thickness of 0.1905 cm (0.075”) whereas the lead plates were either 0.635 cm (1/4”) or 0.9525 cm (3/8”) thick.

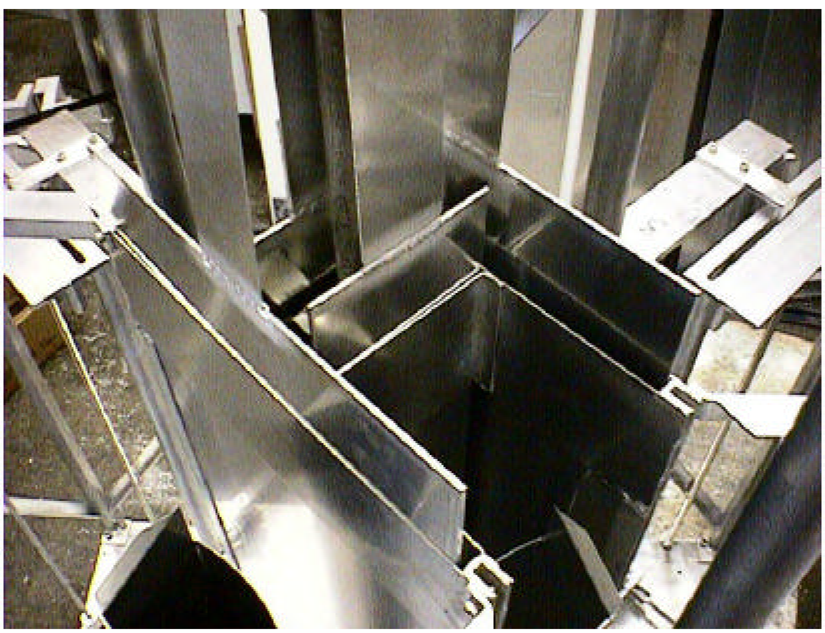

Figure 4.
Cruciform with Metal Reflector Plates

Any plate location (north, south, east or west) was capable of holding up to three (3) plates with a maximum total thickness of 0.9525 cm (3/8"). The individual reflector plates were attached to the aluminum guide sleeve by a set of leaf springs. These springs allowed plates to be stacked one next to each other with essentially no water gap between the plates (other than those which existed as a result of whatever slight amount of curvature existed in the plates due to manufacturing). This feature allowed researchers to determine the subcritical reactivity behavior of the lattice as a function of reflector plate thickness and orientation.

Experimental Subcritical Measurements

Inverse Multiplication Measurements

A series of inverse multiplication measurements were made both during the initial loading of the four MURR fuel assemblies into the test rig, as well as during slide movement which brought the assemblies closer to each other. In order to properly normalize the count rates to determine an inverse multiplication ratio, a series of measurements were performed using two "dummy" MURR fuel assemblies. These measurements involved taking detector count rate measurements at the same slide spacing positions expected during the actual 1/M measurements. This provided a set of initial (baseline) count rates at each position properly accounting for the water displacement affect of the assemblies on detector count rate. The dummy assemblies were removed and the measurements repeated with the actual MURR fuel at the same slide positions. The increase in the fractional count rate as a function of slide position was then calculated and plotted. The results of these measurements are shown in Figure 5. As can be seen from these results, the experimental system remained safely subcritical at all times with a minimum 1/M of 0.126 measured at optimal reactivity.

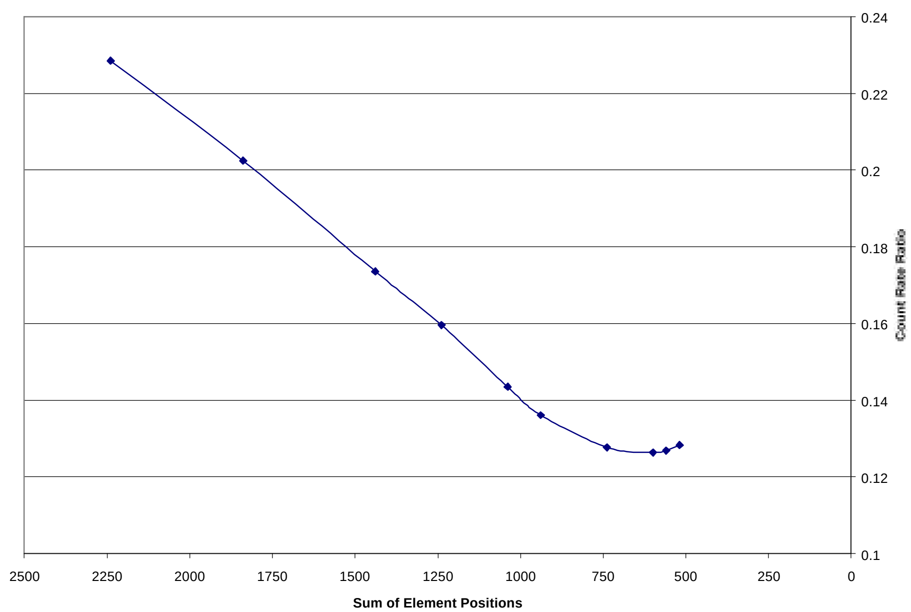

Figure 5.
Inverse Multiplication Measurements for MURR Fuel

Subcritical Noise Measurements in Fresh Water Tank

Over one hundred subcritical measurements were performed in the Fresh Water Tank (FWT) using four unirradiated MURR fuel assemblies over a two-week period. A variety of fuel assembly and detector spacing positions and orientations were measured as well as over fifty experiments which involved the use of metal reflector plates inserted in the subcritical lattice. The tank was filled with deionized water which had a bulk temperature which varied from 74.2 to 74.8 degrees F throughout the course of the experiments. Table 1 summarizes all of the experiments performed in the FWT and Figure 6 shows a picture taken during one of the experiments. Two other papers at this conference will discuss the results and interpretation of the measured and calculated subcritical reactivity parameters.

Table 1.
Summary of Subcritical Measurements Performed in Fresh Water Tank

Description of Experiment Performed	# of Experiments
Initial loading of fuel into test rig	4
Inverse multiplication measurements	10
Fuel spacing variation measurements	9
Axial source repositioning measurements	7
Radial and azimuthal symmetry/asymmetry measurements	11
Detector spacing optimization measurements	6
Fuel assembly rotation measurements	3
Fuel assemblies tilting within shroud measurements	2
Partial voiding of one assembly with forced air bubbles	5
Aluminum plates in lattice	12
304SS plates in lattice	22
Boral plates in lattice	10
Lead plates in lattice	8
Lead collars around detectors	5

Figure 6.
Test Rig for Subcritical Measurements

Subcritical Noise Measurements in Reactor Weir Pool

Also, seven subcritical measurements were performed using combinations of fresh and spent fuel in the MURR reactor weir pool. Due to the increased water depth of the reactor pool (compared to the Fresh Water Tank) the test rig was outfitted with 18 ft. long source tube and detector drywells. Figure 7 shows a picture of the test rig submerged in the reactor weir pool. The first set of measurements involved the same four unirradiated MURR fuels as were used in the FWT (for a reference measurement). Several other measurements followed whereby a single fresh assembly was removed from the array and replaced by a single spent assembly of maximum burnup (143 Mw-D). Since no other aspect of the test rig was changed (i.e., assembly spacing, detector spacing, source location all remained fixed), the observed reactivity decrease could be attributed to the presence of the spent fuel assembly only. A similar set of measurements were also performed using two spent MURR assemblies of maximum burnup.

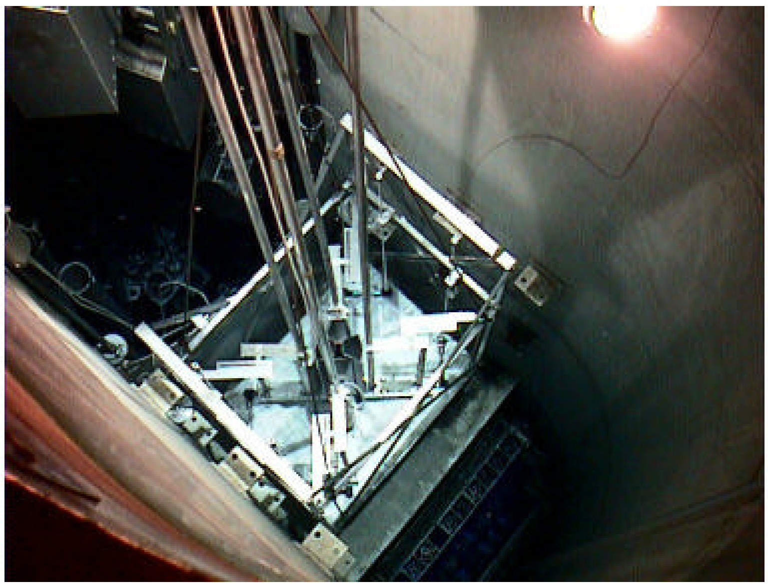

Figure 7.
Test Rig Submerged in Reactor Weir Pool

Table 2 provides a brief summary of some of the measurements performed with fresh and spent fuel assemblies. As can be seen from the results, a small but measurable change in subcritical reactivity was observed for both the single and double spent fuel replacement measurements. Discussion of the differences between measurement and calculation and the generation of the burnup and fission product content data used in the calculations are discussed in another paper at this conference.

Table 2.
Summary of Fresh and Spent Fuel Results

Description of Experiment	Measured Ratio (R_m)	Calculated Ratio (R_c)	Reactivity $(\%\Delta k/k)_c$
4 fresh fuels	0.296 ± 0.003	0.292 ± 0.001	---
3 fresh, 1 spent fuel	0.312 ± 0.003	0.329 ± 0.001	-1.8%
2 fresh, 2 spent fuels	0.327 ± 0.005	0.361 ± 0.001	-3.2%

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