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History and Current Status of the KUCA Dry Core Conversion Project

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ABSTRACT

The Kyoto University Critical Assembly (KUCA) is a multi-core type, thermal spectrum critical assembly consisting of one light-water moderated core and two solid-moderated cores, each fueled with highly enriched uranium (HEU). Starting several years ago, a program sponsored by the DOE/NNSA Office of Material Management and Minimization started an ongoing research program to develop a suitable fuel for the conversion of the reactors to low enriched uranium (LEU). Initial feasibility studies indicated that U7Mo dispersion-type material, compacted into a core then encapsulated to produce a fuel coupon would be a suitable LEU fuel. Using the research capabilities and expertise of Framatome-CERCA™, various designs were tested to determine the best approach to produce the LEU fuel coupons. As the coupon design evolved, complementary analysis and qualification of the LEU coupons continued. This paper presents a concise history of the conversion project, including the initial feasibility analysis, the research and development that led to the LEU fuel coupon design, a summary of the latest analysis results and the status of the KUCA dry cores conversion project.

1 Background

The U.S. Department of Energy (DOE) National Nuclear Security Administration (NNSA) manages the Material Management and Minimization (M^3) Reactor Conversion Program, a continuation of the Reduced Enrichment for Research and Test Reactors (RERTR) Program that was established by the DOE in 1978. The Reactor Conversion program supports the minimization and, to the extent possible, elimination of the use of highly-enriched uranium (HEU) in civil nuclear applications by working to convert research reactors and radioisotope production processes to use low enriched uranium (LEU) fuel and targets throughout the world by developing the technical means to enable research reactors to use LEU fuel (i.e., less than 20% enrichment in ^{235}U). The Kyoto University Critical Assembly (KUCA) at the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS) is currently operating with HEU (93% ^{235}U enrichment) fuel of U.S. origin, but an agreement was reached to convert the KUCA facility to LEU fuel.

2 Description of the facility

KUCA is a multi-core type critical assembly established in 1974 as a facility for the study of reactor physics for researchers at all universities in Japan. The facility has three independent cores: two solid moderated (dry) cores (A and B); and one light water moderated (wet) core (C). The facility also has a pulsed-neutron generator that is used with the A-core for accelerator-driven subcritical experiments.

The subject of this paper, the dry cores, are made up of fuel elements which are assembled from thin fuel "coupons" plus moderator and other materials depending on the experiment. Figure 1 shows the KUCA dry core B including the fuel elements, control rods and removable core section in the shutdown position.

The main fuel material for the solid-moderated cores is 1/16-in. thick, 93% enriched uranium-aluminum alloy fuel. The fuel plates are combined with either polyethylene or graphite moderator plates to form the unit fuel cell. Thin natural uranium and thorium plates can also be used to alter the heavy nuclide composition, and by varying the moderator-to-fissile ratio, a wide range of neutron spectra can be created. Figure 2 shows a schematic representation of a dry core fuel element and the dry core. This capability to have cores with different neutron spectra is one of the unique features of KUCA, and a primary goal of the conversion project is to identify an LEU fuel that would allow KUCA to maintain this capability.

Figure 1. KUCA Dry Core Assembly B

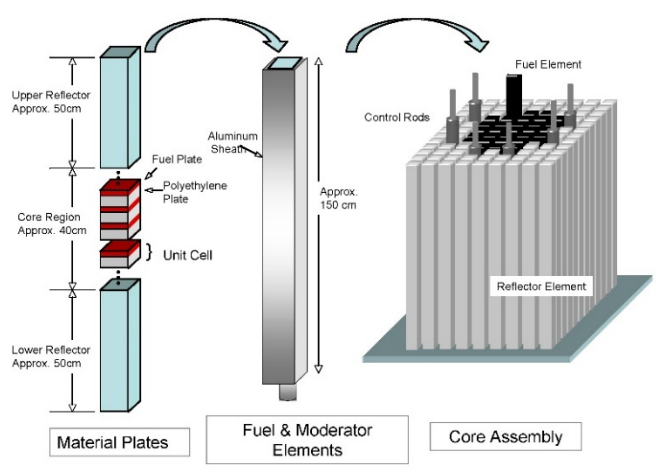

Figure 2. Schematic View of KUCA Dry Core Fuel Element and Assembly

3 Preliminary LEU feasibility studies

3.1 Analysis Approach

Initial feasibility studies on the conversion from HEU to LEU fuel were performed at both Argonne and KURNS. Many of the studies were based on a set of five benchmark configurations published by Pyeon [1] that were characterized by different moderator-to-fuel volume ratios (Vm/Vf) and different H-to-U235 atom ratios (H/U5). This benchmark set allowed analysis of a broad range of neutron spectra that are representative of KUCA dry core flexibility. A primary goal of the feasibility analysis was to identify a fuel that would maintain this ability to construct assemblies with a wide range of neutron spectra. Figure 3 shows one example of a core layout from the benchmark set (designated A3/8"P36EU). Figure 4 shows the cross-sectional view of the respective fuel assemblies and unit cells.

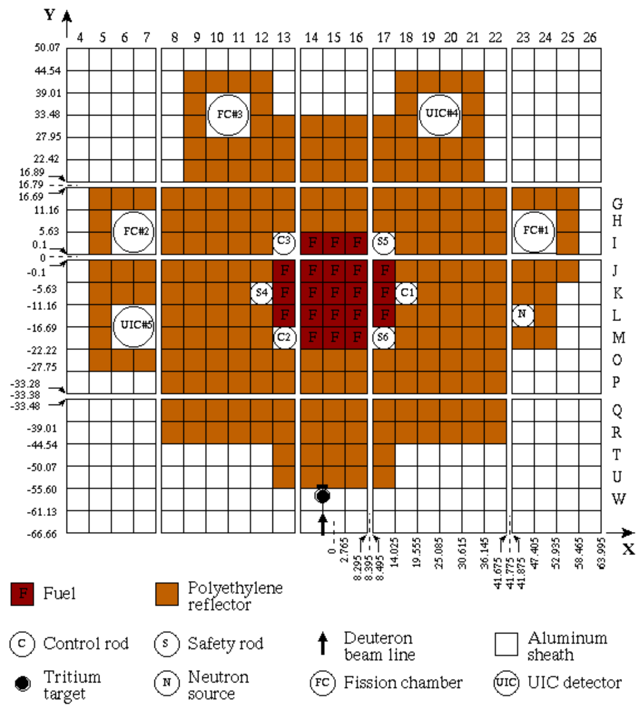

Figure 3. KUCA Dry Core Benchmark Assembly Configuration (A3/8"P36EU)

For the conversion of the KUCA cores, each 1/16-in. (1.5875 mm) HEU plate is replaced with LEU fuel clad by Al on both sides. The LEU coupons were analyzed both with and without a 0.10-in. (2.54-mm) Al edge around the LEU fuel to prevent cracking. The X and Y dimensions of the LEU fuel are the same of the HEU plate being replaced. The thickness of the LEU fuel is determined through iterative calculations. The thickness of the Al clad was set at the lower fabrication limit (i.e., 0.012 in. or 0.3 mm).

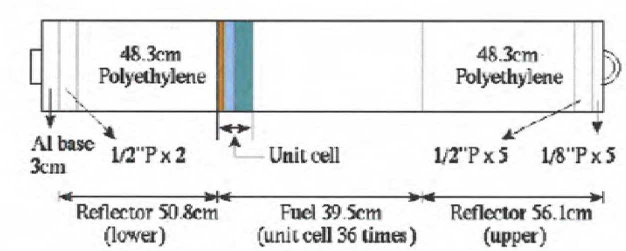

Figure 4. Cross Sectional View of KUCA Benchmark Assembly (A3/8"P36EU)

Iterative calculations are first performed to determine the thickness of the LEU fuel that preserves the central flux spectra for the benchmark configurations. Depending on the result, the reactivity of each assembly can be matched to the HEU value by adding or removing edge assemblies. With this approach both the spectrum and reactivity of each HEU assembly can be matched with LEU.

3.2 Initial feasibility results

Preliminary conversion studies were performed with high density U10Mo monolithic fuel and U_3Si_2-Al. With the U10Mo fuel, to get approximately the same H/U5 atom ratio as the HEU fuel (to preserve the flux spectra), the thickness of the U10Mo foil was determined to be very thin

(~0.012 in. or ~0.3 mm). With this thickness it was possible to preserve both reactivity (with core periphery adjustments) and central flux spectra for the five benchmark assemblies.

In parallel with the Argonne U10Mo studies, KURNS considered the use of U_3Si_2-Al at a density of 4.8 g(U)/cm^3. Results indicated that a coupon core with a thickness of 0.047 in. (1.2 mm) with an aluminum edge around the fuel and thin aluminum on each side could match the neutron spectra for the benchmark cases. However, it would require up to a 35% (depending on the assembly) increase in the fuel loading to achieve criticality with this fuel coupon.

Additional analyses indicated that the use of very thin LEU foils resulted in the reactivity being sensitive to small variations in the foil thickness. Figure 5 show the multiplication factors obtained for KUCA configurations ranging from thermal to fast spectra and compares them to the HEU thermal spectrum cureve.

Due the sensitivity of these thin fuel cores to production tolerances, alternatives were considered. Based on results from other M^3 conversion projects, U7Mo dispersion fuel was identified as a likely candidate. With dispersed U7Mo, the uranium density is smaller than that of the U10Mo monolithic fuel so the sensitivity of the reactivity to the production thickness (based on the ^{235}U density) should be markedly lower. Results of the initial U7Mo studies are given in the following section.

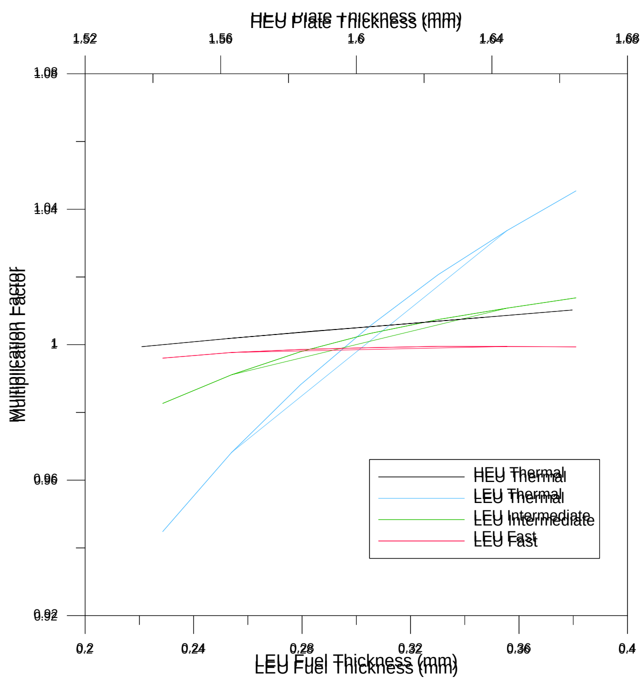

Figure 5. Sensitivity of Assembly k-eff to Fuel Thickness for Various Spectra

3.3 U7Mo analysis results

Two different U7Mo dispersion fuel densities, 8 g(U)/cm^3 and 6 g(U)/cm^3, were initially considered. At 8 g(U)/cm^3 a fuel core thickness of ~ 0.56 mm with no Al edge, giving a U7Mo mass of about 12.6 g per coupon, preserves the central spectra of the benchmark assemblies. This value allowed a reactivity match between the LEU and HEU cores for the benchmark assemblies with the addition of only a limited number of peripheral fuel assemblies, but with additional fuel coupons in each assembly. Using dispersed U7Mo fuel at 8 g(U)/cm^3 reduces the dependence of the core reactivity on production tolerances of the fuel thickness with respect to the case of U10Mo fuel.

At 6 g(U)/cm^3, the central flux spectra was preserved for all of the benchmark configurations by keeping the mass of U7Mo per coupon at 12.6 g. With the lower density, the target coupon mass can be met with a thickness of ~ 0.76 mm. The thicker coupon core further reduces the reactivity dependence on fabrication tolerances. However, the lower density also requires more fuel coupons, either in peripheral assemblies or more coupons per assembly to match the reactivity of the HEU benchmarks. In an attempt to design a coupon that would reduce the total number of coupons needed, a parametric study of the coupon core and clad thicknesses was performed. The analytical solution that proved to be the best compromise was a coupon core with U7Mo thickness of 1.45 mm, with Al clad of 0.4 mm on each side and a 3-mm thick Al edge around the core. This design does not reproduce the full range of flux spectra of the HEU benchmark cores (especially the most thermal spectra) but is still able to produce a wide range of neutron spectra of interest.

4 Initial fuel coupon development

Although the initial parametric studies resulted in a coupon design that would retain most of the flexibility of the KUCA dry cores, it was decided to set the initial specifications for the KUCA dry core LEU coupons to match the physical dimensions of the HEU fuel coupons, nominally 2 x 2 x 1/16-in. thick (5.08 x 5.08 x 0.160 cm). The initial LEU coupons specifications required the coupon core to have a thickness between 0.9 mm and 1.0 mm, with 0.3-mm thick cladding or coating on each side. Framatome-CERCA established a research program to investigate the best cladding or coating technology for the LEU coupons, while at the same time working to adapt their existing compaction process for the coupons cores. Figure 6 shows a comparison of the HEU plates and the initial LEU coupon designs.

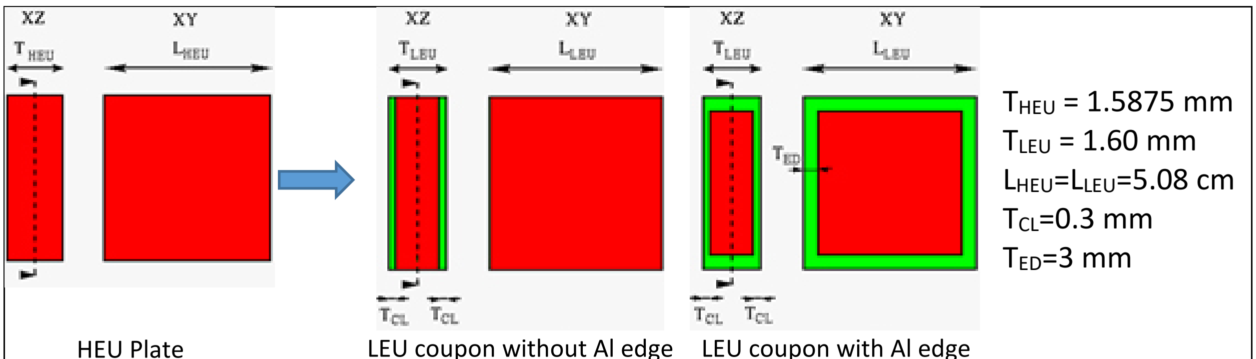

Figure 6. Comparison of HEU Plate and LEU Coupon Design

The coating or cladding material had to be as transparent as possible to neutrons in order to not affect the neutron spectrum of the assemblies in KUCA. Starting with surrogate (non-radioactive) materials a comprehensive test matrix investigated sixteen solutions to the cladding challenge, grouped into four categories: aluminum spray coating, epoxy coating, organic box and aluminum box. Figure 7 shows a summary display of the various techniques that were attempted.

Although several options appeared to be viable solutions, certain features eliminated them from further consideration. The aluminum spray coating could not adequately cover the edges of the coupons, and even when an aluminum frame was put around the coupon, defects in the aluminum spray coating were observed.

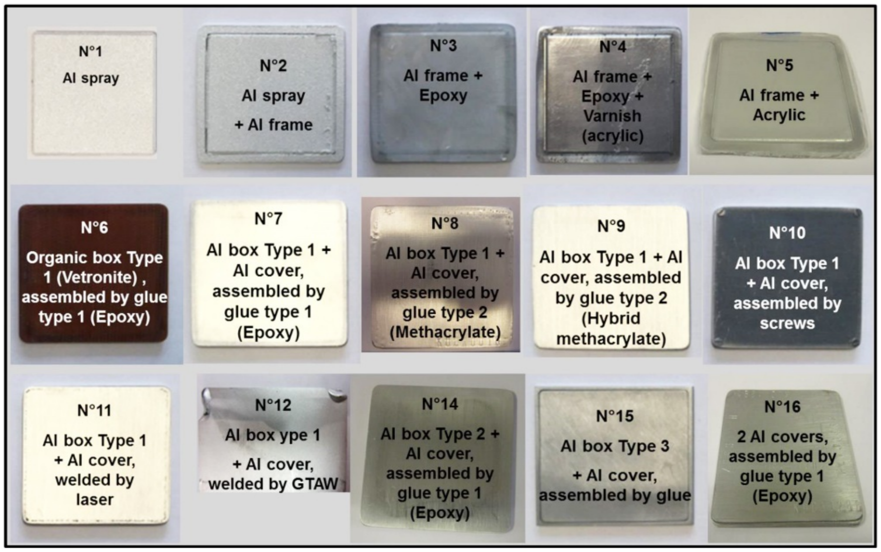

Figure 7. Results of Coating and Cladding Options Study

An organic/epoxy coating was attempted in which the surrogate core was placed in an aluminum frame, and the assembly was coated using a cold molding process. Among the difficulties with this coating were the softness of the material, the inability to tightly control the thickness of the coating within specifications and poor performance under mechanical stress.

An organic box (vitronite) option used a machined cavity to allow the coupon core (surrogate) to be inserted, then a cover is glued into place. This solution was rejected for several reasons, but primarily because it deformed easily under mechanical stress.

The fourth category of cladding options was an aluminum box or an aluminum frame with Al covers on both sides. After testing several different options (shown in Figure 7) the final solution was to: 1) from an aluminum rolled sheet, machine a compartment to hold the coupon core (initially surrogate, followed by DU7Mo, then LEU7Mo); 2) fabricate an aluminum cover that tightly fits into a recess machined into the outer frame of the Al box and completely covers the core; 3) use an automated laser welding system to attach the cover plate to the Al box with a continuous weld along the edges of the cover plate.

After conducting a series of tests and sending surrogate samples to KURNS for examination and handling tests, the aluminum box solution was selected as the best option for enclosing the U7Mo core of the KUCA coupons. Figure 8 shows the pieces of the aluminum box before assembly, and Figure 9 shows a welded coupon.

5 Advanced fuel coupon development

Although the test results using an aluminum box to sheath the coupon core were successful, one significant problem did surface - flatness. Due to the thin nature of the coupons, it was subject to small deformations during the welding process. Considering the stacking arrangement of the coupons in the critical assembly, flatness is an important parameter that must be met. After discussing the issue with KURNS staff, a resolution was proposed to increase the mechanical properties of the coupon by increasing the thickness of the coupon core and the aluminum case. A thick fuel coupon design was developed.

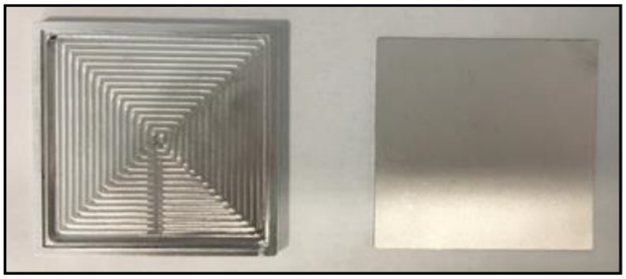

Figure 8. Outer Box and Cover Plate Before Assembly

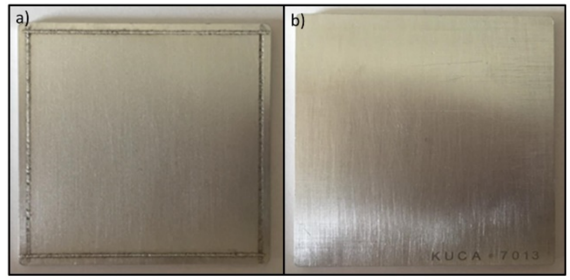

Figure 9. Welded KUCA Dry Fuel Core Coupon

The coupon core thickness was changed from 0.95 mm to 1.45 mm; the length and width remained at 44.80 mm. The minimum side thickness of the aluminum box was increased from 0.3 mm to 0.4 mm, with overall dimensions of 50.8 x 50.8 x 2.40 mm. While the increased thicknesses did improve the flatness of the coupons, the flatness specification of ± 0.10 mm was not always met. Further research by CERCA showed that the flatness could be brought within the specification by using an additional post-welding heat treatment under load applied to the KUCA fuel coupons.

Using the revised specifications, the staff at KURNS began an analysis of the thicker design to see what effect this model would have on the operational and safety characteristics of the KUCA dry cores.

6 Analysis results for proposed LEU thick coupons

The proposed LEU thick coupon design will impact the resonance self-shielding due to the increased fuel meat thickness and also impact the neutron streaming due to increased cladding thickness. Due to this significant change in the fuel coupon design, the compatibility with the present HEU cores may not be fully achieved after LEU conversion. Therefore, the analyses were focused on, under the restriction of the available number of LEU coupons (approximately 3000 coupons), examining the possible variety in achievable critical cores and neutron spectra in the cores after LEU conversion. The critical mass (number of fuel coupons required to construct the critical core) and neutron spectrum in each reactor core was calculated using Monte Carlo code MVP with JENDL-4.0 cross sections. The thickness of the polyethylene moderator plates and the number of LEU coupons in the fuel unit cell and the number of the fuel unit cells in the fuel assembly were systematically changed in the analyses to investigate the critical core configurations. The results are shown in Table 1 and Figure 10. Based on the results, it is expected that six (6) different single region critical cores are achievable, and one core with a harder spectrum is also achievable by creating a zone-type core with approximately 3000 LEU coupons. The core volumes are similar or slightly larger and thus comparable to present HEU cores.

Table 1. Critical Cores of KUCA after LEU Conversion using Thick LEU Coupon Design

Core ID*	#coupon	Note
A4/8"P28 LU	700	Single region core
A3/8"P34 LU	764	Single region core
A2/8"P48 LU	1008	Single region core
A3/16"P56 LU	1288	Single region core
A1/8"P80 LU	2080	Single region core
A3/16"P42 LU-LU	2772	Single region core
A1/8"P50 LU-LU + driver	3044	5x5 Zone core with A3/8"P34 driver fuel

* "xx/yy P" indicates the polyethylene moderator thickness per the fuel cell; "zz" indicates the fuel cell repetitions per the fuel assembly. "LU" or "LU-LU" indicates the number of LEU coupon per fuel cell.

The neutron spectra in the core region (Figure 10) show that a wide variety of neutron spectra are achievable after the conversion. Compared to the current HEU cores, the neutron spectra show slightly harder spectra (rich in fast neutron components) but the LEU fuel is still able to provide a wide variety of neutron spectra. This ensures the continuity of the research capability after the LEU conversion.

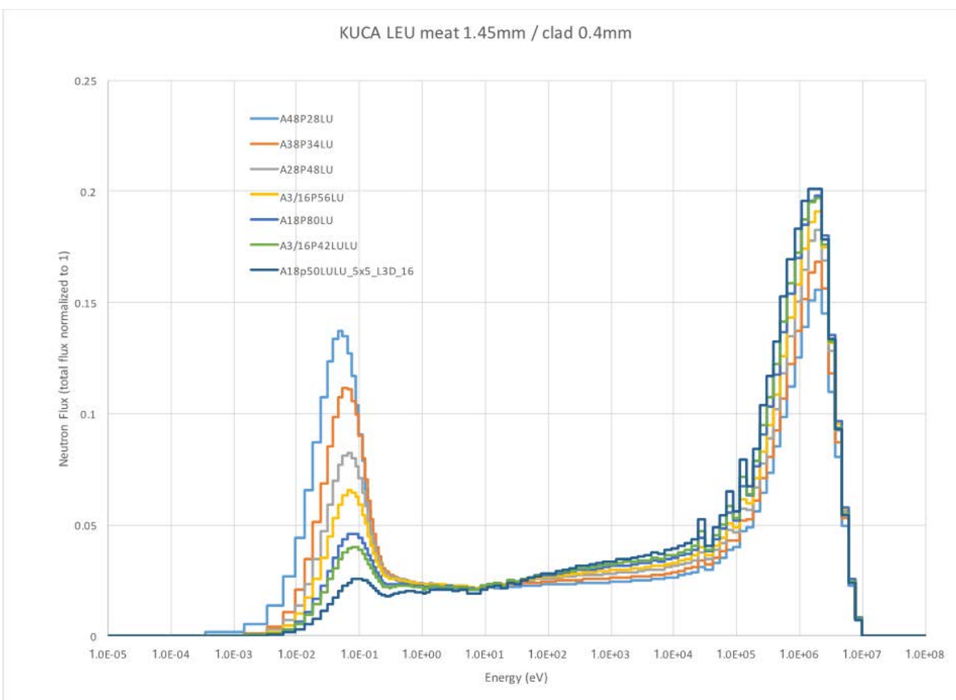

Figure 10. Neutron Spectra of Critical Cores of KUCA after LEU Conversion Using Thick LEU Coupon Design

7 Current status and planned schedule for conversion

The KUCA dry core conversion project is steadily moving towards the goal of fabricating a sufficient number of LEU coupons that will enable assembly of a critical core at KURNS. In spite of some delays caused by the redesign of the LEU coupon to eliminate the flatness problem with the original, thin coupon design, the team at CERCA™ has produced samples with surrogate and depleted uranium cores that meet the new specifications. Fabrication of a small experimental batch of LEU coupons is expected to be completed near the end of CY2019 and shipped to KURNS in early CY2020. At this point in the project, LEU coupon fabrication feasibility has been demonstrated, a well-defined project plan is in place, the necessary equipment has been ordered and a conversion schedule has been established. Production of the first large batch of LEU coupons will begin in CY2020 and lead to the dry core conversion in CY2021.

8 References

[1] C. Pyeon, "Experimental Benchmarks for Accelerator Driven Subcritical Reactor (ADSR) at Kyoto University Critical Assembly (KUCA)," Kyoto University Research Reactor Institute, Japan, November 2007.

9 Acknowledgement

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