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On the Feasibility Study for Utilization of Low Enriched Uranium Fuel at Kyoto University Critical Assembly (KUCA)

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ABSTRACT

This paper describes the status of the feasibility study for utilizing the low enriched uranium (LEU) for the Kyoto University Critical Assembly (KUCA). The KUCA facility is a multi-core type critical assembly used for fundamental research on reactor physics, reactor science and education. KUCA consists of one light-water moderated core (wet core) and two solid-moderated cores (dry cores), and both types of core are currently operated using highly-enriched uranium (HEU) fuel. Due to the variety of neutron spectrum and core composition of KUCA cores, the substitution of the existing HEU with LEU will be a challenge from neutronics point of view. This feasibility study will be pursued within the framework of joint scientific study between Kyoto University Research Reactor Institute (KURRI) and Argonne National Laboratory. Results of preliminary analysis on neutronic characteristics of the KUCA cores with LEU fuel will be described in this paper.

1. Introduction

The increasing interest of nuclear security in recent years are leading to add new activities in the RERTR program in relation with the minimization of highly-enriched uranium (HEU). This lead to the increasing interest in the minimization of HEU fuel in research reactors which were not hitherto been focused in the program, namely, small powered test & research reactors and critical assemblies. However, no notable activity on LEU utilization have been made for critical assemblies currently using HEU fuel. This is considered to be mainly due to the availability of fuel material (non-cladded coupon plates, rods), as well as the variety of core characteristics (for example, wide variety in neutron spectrum) which is far diversified compared to the common

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test & research reactors. Thus there would be significant scientific activities required, especially in the field of reactor physics and fuel fabrication technologies, to accelerate the relevant activities for LEU utilization of namely, small powered test & research reactors and critical assemblies.

In this context, Kyoto University has been jointly discussing with DOE/ANL for the possible cooperation in the activities for utilizing the LEU-based fuel for the Kyoto University Critical Assembly (KUCA) since 2008. The two parties agreed to conduct the joint scientific study for the feasibility study on utilization of LEU fuel in KUCA, which consists of investigation on core neutronics characteristics of possible LEU-fueled cores at KUCA.

The feasibility study is aimed at seeking the possible fuel technology to be adopted for LEU fuel of KUCA, and analysis of core neutronic characteristics using possible fuel candidates will be extensively performed in order to investigate for the possible drawbacks from LEU utilization, such as limitation in core performance including reactor safety and limitation of academic research (discontinuation of specific experiments, etc.), and more importantly, the possible academic and scientific achievement by LEU utilization, such as the possible R&D field which could only be achieved through utilization of LEU fuel.

This paper summarizes the preliminary results of feasibility studies on LEU-fueled KUCA core characteristics for both wet and dry cores. We started from studies on HEU-UAl-compatible LEU fuel material which could be used for conducting critical experiments at KUCA; compatibility in terms of reactivity (criticality) are mainly being verified in this stage.

2. The KUCA Facility

The Kyoto University Critical Assembly (KUCA) (Fig. 1) is a multi-core type, thermal spectrum critical assembly dedicated for the fundamental research and education on reactor physics. KUCA consists of one light-water moderated ("wet") core and two solid-moderated ("dry") cores, both loaded with highly enriched uranium fuels. Pulsed D-T neutron generator is installed in the reactor building and could be used in combination with one of the solid-moderated core (A-core). 100MeV proton beam from the FFAG proton accelerator complex (installed in adjacent building) together with tungsten target could also be used as spallation neutron source in combination with the A-core. The combination of different core types and neutron sources could be considered as the most unique feature of KUCA among the existing critical assemblies.

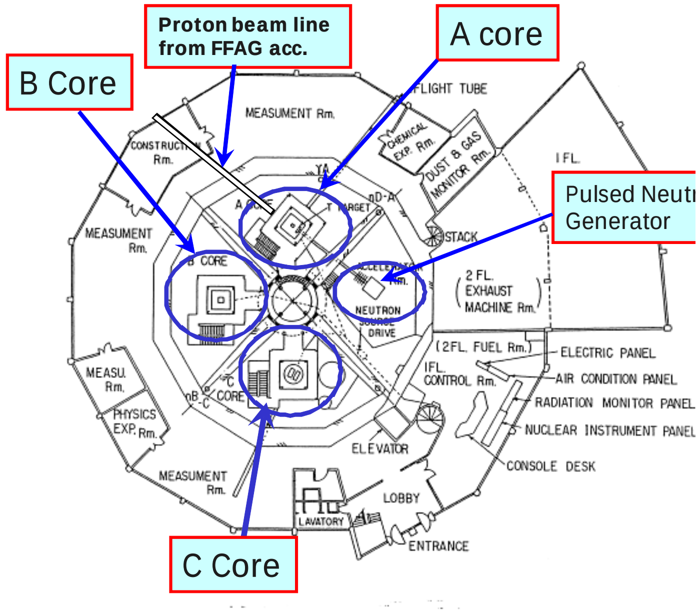


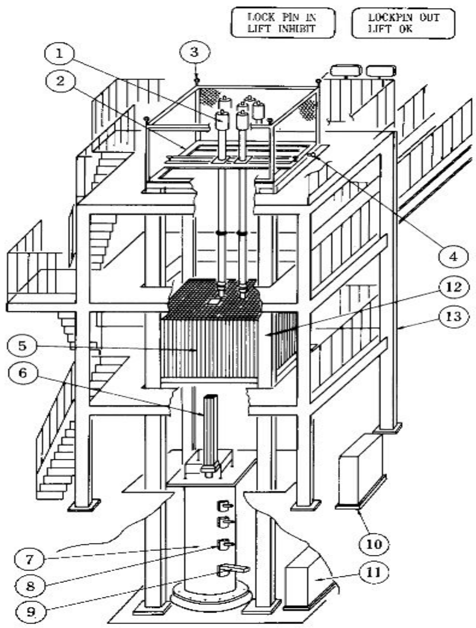
Figure 1: KUCA Facility.

Thanks to the wide variety of available materials and attached facilities, reactor physics experiments on numerous critical and sub-critical configurations have been hitherto successfully conducted at the KUCA[1-4]. KUCA is the only critical assembly owned and operated by university in Japan, and is currently being widely used for joint study among the Japanese universities for the following purposes;

- fundamental studies for reactor physics
- conceptual studies for innovative reactors
- technology development for nuclear engineering
- education & Training
- accelerator-driven subcritical reactor (ADSR) science & technology

2.1 Solid-moderated (Dry) Cores

The overall structure of KUCA solid-moderated core is shown in Fig.2. It mainly consists of core fuel elements, supporting grid for the fuel elements, central removable core section (used as safety shutdown system), control rod and its drive mechanism. The control rod drive mechanism is removable and is transferred to any of the three cores being operated, thus warranting that only one core could be operated at once. Schematic view of the fuel elements and the core is shown in Fig.3. The main fuel material for the solid-moderated core is 1/16”-thick 93% enriched uranium-aluminum alloy fuel (hereafter called as EU plates). 1mm-thick natural uranium metal plates (hereafter called as NU plates) and 1/8”-thick thorium plates could also used in combination with EU plates to alter the heavy nuclide composition (i.e. average enrichment of the fuel, U/Th fraction etc.). The fuel plates are combined with either polyethylene or graphite moderator plates to form the unit fuel cell. By varying the total thickness of the moderator plates, the H/U-235 ratio and consequently the neutron spectrum of the core could be changed so as to cover a wide range of neutron spectrum in interest. Other materials, such as aluminum, beryllium, erbia (coated on graphite plates), Teflon plates could also be used to simulate specific core design.



1	Control Rod Drive
2	Support for Control Rod Drive
3	Lifting Lug
4	Locking Pin for Control Rods
5	Core
6	Central Removable Section of Core
7	Lifting Device for Central Core Section
8	Device for Limiting Upward Core Motion
9	Key Lock Permitting Operation
10	Control Panel for the Oil Hydraulic Lift
11	Hydraulic Unit
12	Core Support Structure
13	Scaffolding

Figure 2: Structure of KUCA Solid-Moderated Core

The unit fuel cells are then piled up to form the core region of approximately 40 to 45 cm in height, depending on the core composition and neutron spectrum. The core region is then "sandwiched" with lower and upper reflectors, and is stacked into aluminum sheaths to form fuel elements. Finally, the fuel elements are arranged onto a core grid plate together with control rods and neutron detectors to construct the core. An example of the actual core is shown in Fig.4.

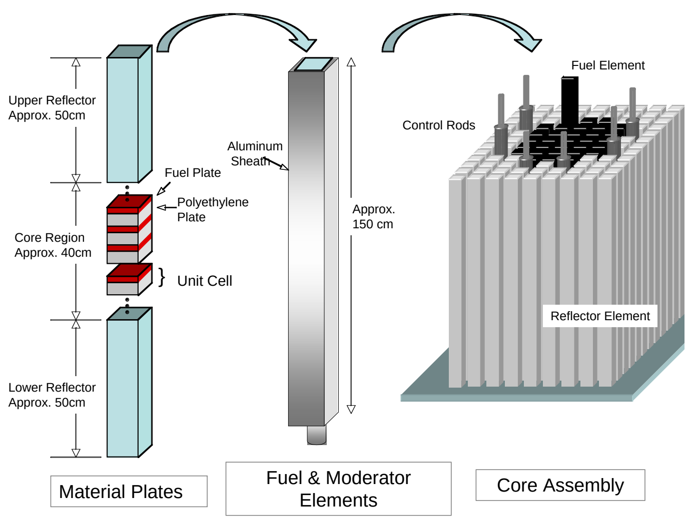


Figure 3: Schematic View of KUCA Solid-Moderated Core and Fuel Elements

Figure 4: KUCA Solid-Moderated Core (B-core), showing fuel elements, control rods and removable section of the core (in shutdown position)

2.2 Light Water-moderated (Wet) Core

The overall structure of the light water-moderate (wet) core is more or less similar to conventional plate-type research reactors; it consists of core tank, grid plate, core (fuel elements and control rod), light water supply system and neutron detectors. The core tank and fuel elements are shown in Fig. 5.

The fuel currently being mainly used is a flat plate-type, aluminum cladded U-Al with 93% enriched uranium. Fuel element is assembled by vertically inserting the fuel plates one by one between two Al side plates of a fuel frame along “grooves”; three types of fuel frame side plates with different groove pitches of approximately 3.0, 3.5 and 4.5mm (named as C30, C35 and C45 fuel frames) are available to change the neutron spectrum in the core region (Fig. 6). Curved fuel plates using 93% and 45% enriched uranium U-Alx have been also used for making annular and cylindrical core for the neutronics study of a specific core design of research reactors, which was also conducted within the RERTR activities. The fuel elements are arranged on a grid plate in an Al core tank and light water is pumped up into the core tank to form the core. In the C core, reactor physics studies on coupled core system, neutronic properties of research reactor cores with reduced enrichment uranium fuel, criticality safety including subcritical measurements and so on have been carried out so far. This core is also being extensively used for the reactor physics education of graduate level students, including leading universities in Japan, Korea and Sweden.

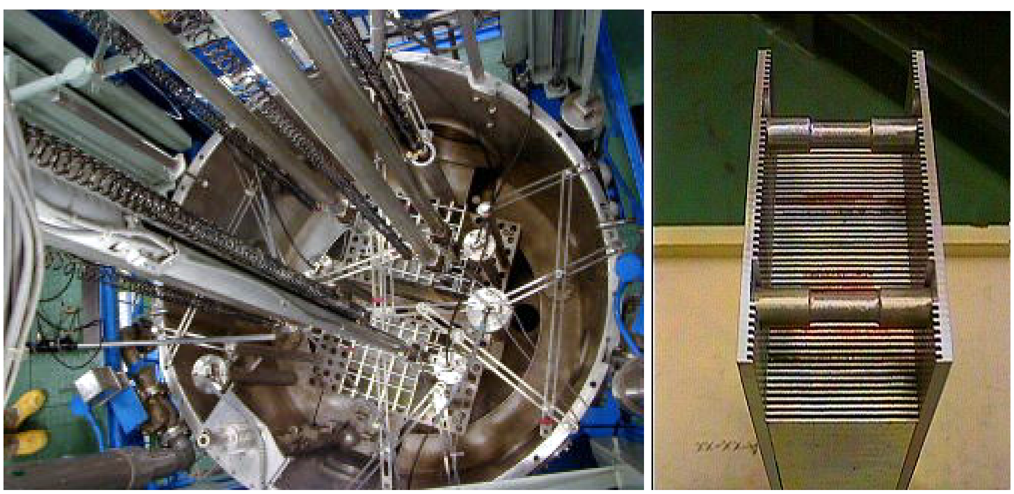
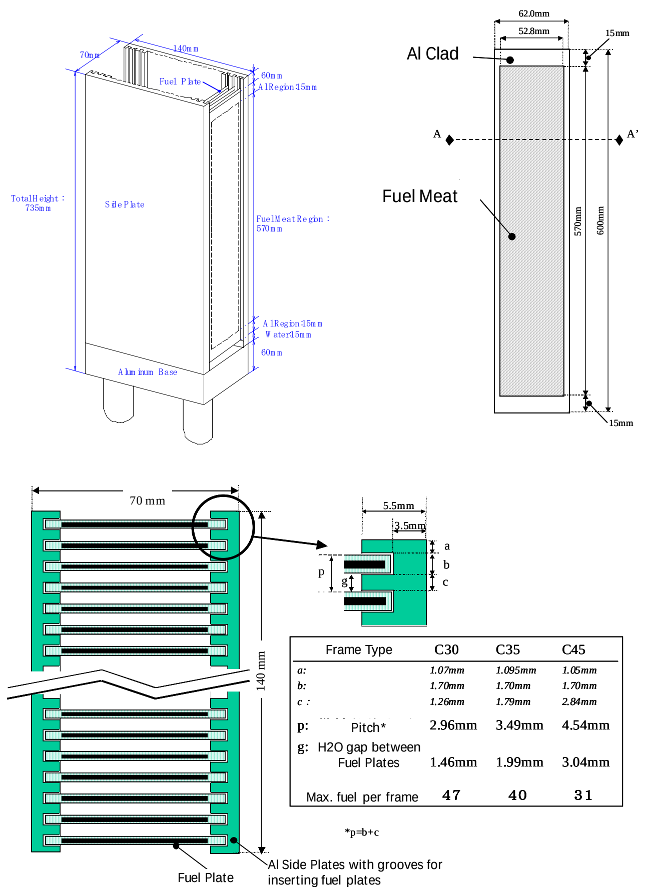


Figure 5: KUCA Light Water-Moderated Core (C-core), showing the core tank and fuel element



Frame Type	C30	C35	C45
a:	*1.07mm*	*1.095mm*	*1.05mm*
b:	*1.70mm*	*1.70mm*	*1.70mm*
c :	*1.26mm*	*1.79mm*	*2.84mm*
p: Pitch*	2.96mm	3.49mm	4.54mm
g: H2O gap between Fuel Plates	1.46mm	1.99mm	3.04mm
Max. fuel per frame	47	40	31

*p=b+c

Figure 6: Structure of KUCA Light Water-Moderated Core (C-core) Flat Plate Fuel Elements

3. Preliminary Results on Feasibility Study

3.1 Wet Core Studies

Due to the similarity of the fuel structure and neutron spectrum to those of conventional research and test reactors, we are starting our investigation from the feasibility of utilizing Al-cladded U-silicide fuels with U density of 3.2gU/cc to 4.8gU/cc as the existing and well-proven fuel technology. Other candidates, such as U-Mo plates and UO2 pins will be investigated in the future. The present results are obtained by deterministic analysis of reactivity change using SRAC code system[5] with 107-energy group JENDL-3.3 as nuclear library. The reactivity change due to LEU utilization is analyzed using the first-order perturbation option of CITATION code. The core configuration was simplified to two-dimensional cylindrical model (RZ model). Figure 7 shows the comparison of neutron spectrum in unit fuel cell of C35 fuel frame. The use of LEU acts to harden the neutron spectrum as a result of decreasing moderation ratio and increasing absorption by U-238 in resonance and thermal energy region. This change in the fuel composition and neutron spectrum leads to the difference in criticality of the core; as shown in Fig. 8, the substitution of the existing HEU fuel plates with U-silicide LEU fuel plates will cause reactivity difference of from about -6%Δk/k to +4%Δk/k, depending on the core type. This difference in the reactivity (i.e. criticality) leads to the change of core volume for critical configuration of about +/- 30% in maximum.

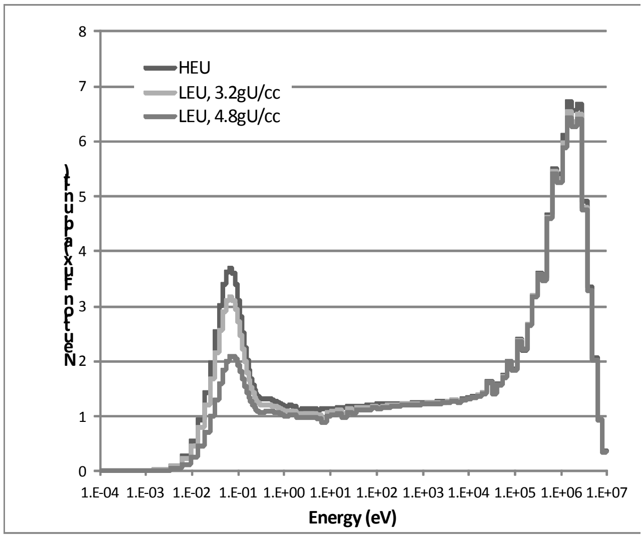


Figure 7: Comparison of C35 fuel cell neutron spectrum

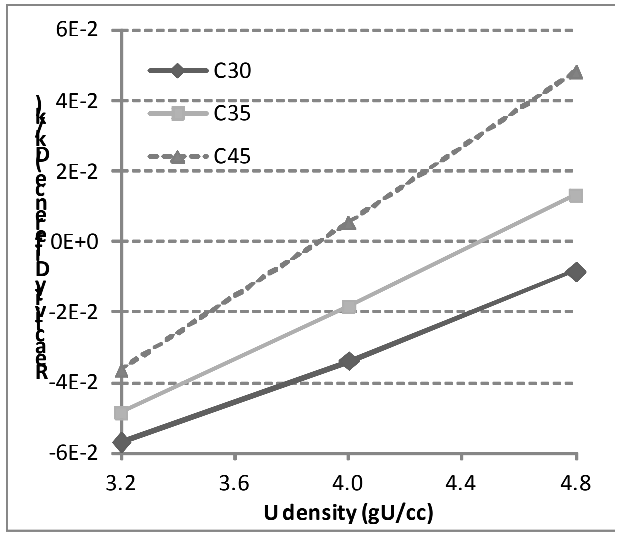
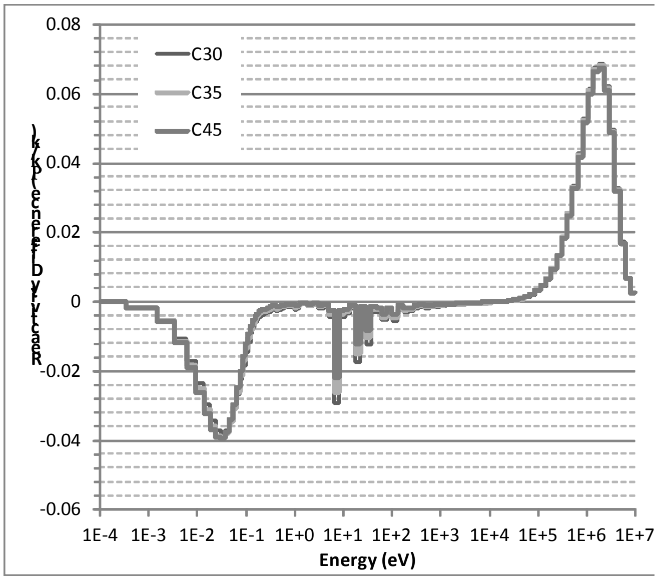


Figure 8: reactivity difference between HEU and LEU with various U density for C35 core

An interesting trend could be seen for the LEU fuel with 4.8gU/cc, where the reactivity change due to LEU fuel can either be negative of positive. This phenomena is caused by the difference in the energy dependent reactivity component as shown in Fig. 9 and Fig. 10. The detailed reactivity component (Fig. 9) could be treated in three energy regions; fast ($E>10^4$eV) region where the production component is dominating, resonance region ($1eV<E<10^4$eV) where the absorption component (of U-238) is dominating, and thermal region ($E<1eV$) where thermal absorption is dominating. As shown in Fig. 10, the total reactivity difference is due to the delicate compensation of large reactivity components. This observation leads to the rather interesting result for considering LEU fuel as a substitute to existing HEU fuel; the compatibility (in terms of reactivity) of the LEU fuel can significantly be different among the cores with different neutron spectrum, and this would be the most significant feature for utilizing LEU in critical assemblies.



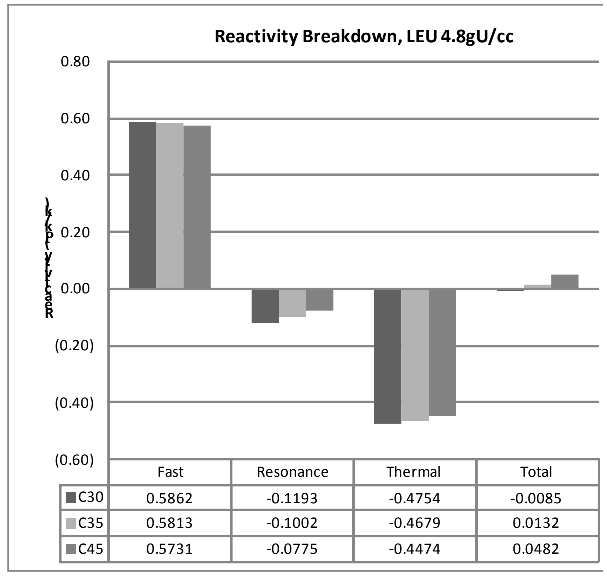


Figure 9: reactivity difference breakdown for LEU fuel, 4.8gU/cc

Figure 10: reactivity difference breakdown by energy region for LEU fuel, 4.8gU/cc

The H/U-235 ratio, which is an index of neutron spectrum in the core, significantly varies with U density of LEU fuel as shown in Fig. 11. Compared to the original range of H/U-235 (i.e. approx. 125 to 250), the use of LEU leads to more harder neutron spectrum in the core. Together with the decreased uranium enrichment, the scientific target of the experiments could be largely affected, shifting more towards neutronic characteristics simulating the power LWR configurations. The detailed investigation on such impact on scientific and academic activities due to LEU utilization remains as future study.

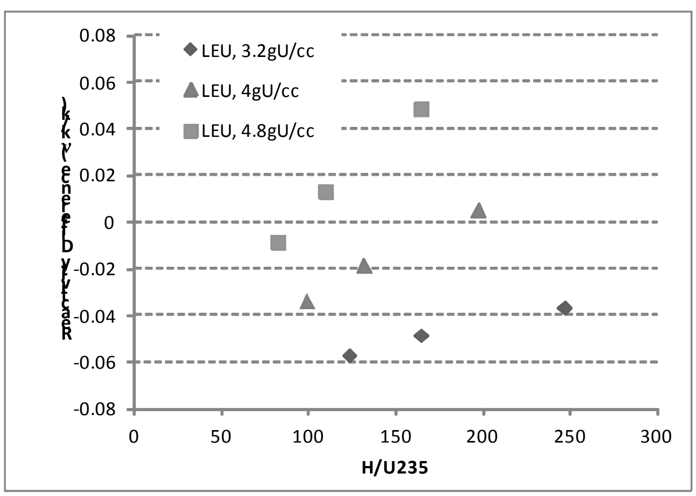


Figure 11: Change in H/U-235 ratio and Associated Reactivity Change due to LEU Utilization

3.2 Dry Core Studies

Due to the flexibility of its design, wider range of neutron spectrum and fuel composition could be achieved in the dry core. The applicability of uncladded fuel plates has been less studied in the conventional conversion studies. Therefore, the selection of appropriate fuel would be more challenging here than the previously described wet core. The results presented here are based on preliminary criticality analysis of a series of polyethylene-moderated/reflected cores with systematically varied H/U-235 ratio, using 19.75wt% LEU fuel of various uranium content. The analysis are based on infinite cell calculations and two-dimensional diffusion core calculations using SRAC code system with 107 energy groups, and full-core criticality calculations using the continuous energy Monte Carlo code MVP[6], using JENDL-3.3 as nuclear data library in all cases.

The U-Al alloy was confirmed to be not applicable as LEU fuel due to its limitation of U density and was rejected as the possible candidate. Therefore, U-9Mo has been selected as the possible candidate in the present preliminary studies. To achieve the same H/U-235 range as the present HEU cores, the U-235 content in the fuel plate was preserved by either mixing U-9Mo with aluminum or by using U-9Mo thin foil.

Figure 12 shows the comparison of k-infinity for various fuel compositions obtained from infinite unit cell calculation. The U-9Mo fuels with different design showed identical k-infinity values lower than the HEU fuel when plotted against H/U-235 ratio of the unit fuel cell. However, some significant difference between the criticality were observed for full core analysis, where an example is shown in Figure 13. In this calculation, 1/16" HEU fuel plates in actual critical cores are substituted by U-9Mo 0.3mm plates to preserve the U-235 content in the unit fuel cell. For comparison, results using fictitious U-Al LEU plate having the same U-235 content as of HEU is shown in the figure. A significant increase in k-effective for U-9Mo thin fuel plate, especially for hard-spectrum cores with small H/U-235 ratio has been observed.

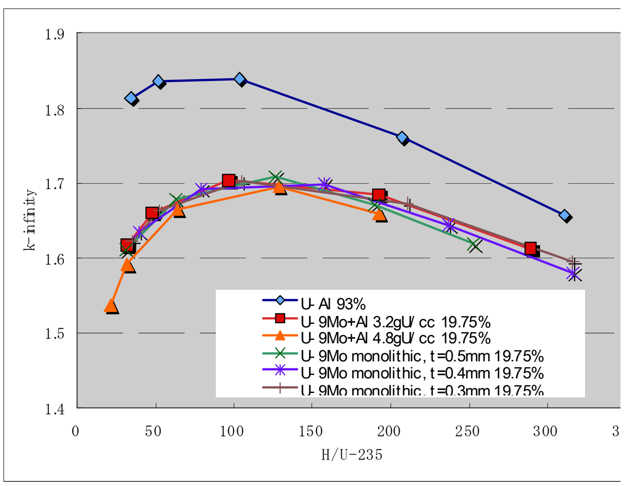


Figure 12: Comparison of k-infinity for dry core unit fuel cell using U-9Mo

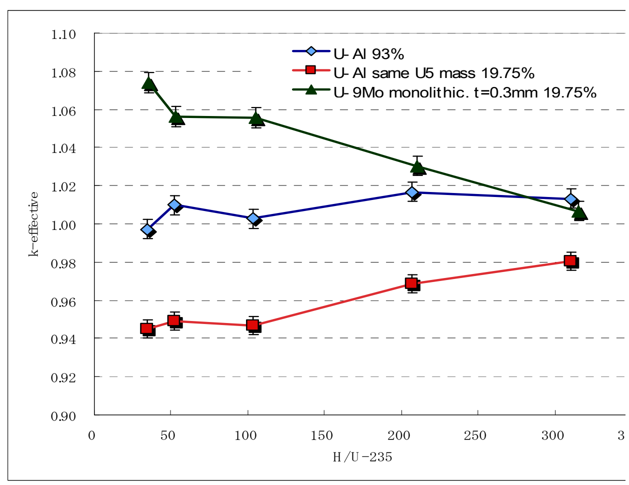


Figure 13: Comparison of k-effective for dry core using LEU

As the change in core volume (i.e. smaller volume) may be possibly contributing to the reactivity increase, a series of calculation using U-9Mo monolithic plates and Al clad has been performed. In the analysis, aluminum clad thickness were varied from 0 (no clad) to 0.065cm (total thickness equivalent to HEU U-Al plate) to change the averaged U density per fuel plate. The U-235 mass per fuel cell (and thus H/U-235) remains unchanged, but the core volume increases with aluminum clad thickness. The results of criticality calculation is shown in Fig. 14 . Significant increase in k-effective by reduction of aluminum clad thickness for hard-spectrum cores with small H/U-235 ratio is observed. Another notable trend is that there might exist an optimal cladding thickness to preserve the compatibility of reactivity with the existing HEU fuel; in this case, cladding thickness of 0.03mm yields almost identical k-effective for all cores investigated. Further analysis, including the effect of core volume (i.e. leakage effect) to the reactivity difference would be required for further understanding of this reactivity change due to LEU utilization.

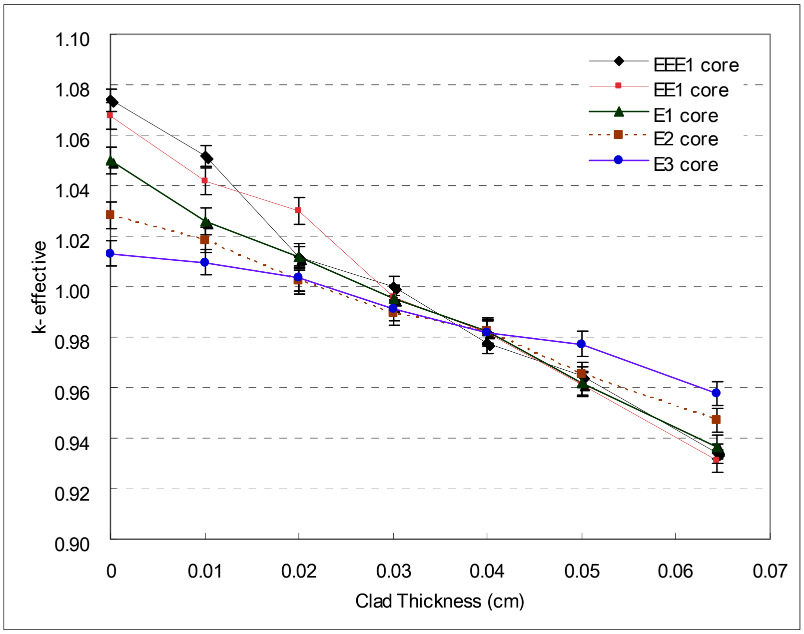


Figure 14: Criticality (k-effective) of dry cores with U-9Mo+Al clad

4. Conclusion and Future Studies

Although the preliminary results of the feasibility study are restricted to specific fuel candidates, they have revealed some notably interesting aspects of LEU utilization in critical assemblies. Due to the possible variation of neutron spectrum and core configuration, there will be no single fuel design to be completely compatible in terms of reactivity and reproductiveness of the currently used HEU cores. Thus careful investigation on the possible drawbacks and benefits, both on core performance and academic/scientific research activities should be done in prior to the actual conversion activities.

The future studies of the present feasibility study would include more detailed analysis of core characteristics using possible fuel candidates, using both deterministic and Monte Carlo codes, investigation on the impact of LEU utilization to safety characteristics, and more importantly, the balance between the drawbacks and benefit in the research activities. The continuity of some of the present research activities unique to KUCA, such as thorium core studies and ADSR studies may be greatly affected by use of LEU, and careful investigation should be made. KUCA is planning to continue operation & utilization to match the expected increasing needs, such as the fundamental research in wide fields of nuclear engineering & science, including nuclear data evaluation, reactor physics, detector development etc., education / training, especially for undergraduate level students, and joint studies with industries, focused on basic studies of next-generation reactor concepts. Therefore, it is of great importance to establish a concrete scientific understanding of the impact of LEU fuel utilization to the future research activities expected to KUCA and to show that significant benefit could be expected by using LEU.

Together with this, technical investigation of the availability of appropriate fuel design including fuel fabrication, fuel transportation and possible modification of the facility required for LEU utilization should be studied and solved. The authors believe that this is an extremely challenging project, but may lead to significant contribution to both reactor technology and nuclear security.

5. References

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