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Neutronic Analysis for Utilization of Low Enriched Uranium Fuel At Light Water Moderated / Reflected Core of Kyoto University Critical Assembly (KUCA)

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ABSTRACT

This paper describes the updated results of the feasibility study for utilizing the low enriched uranium (LEU) at the light water moderated / reflected core (C-core; “wet core”) of the Kyoto University Critical Assembly (KUCA). Due to the variety of neutron spectrum and core composition of KUCA cores, the substitution of the existing HEU fuel with LEU fuel will be of notable interest also from reactor physics, and thus this feasibility study is being pursued within the framework of joint scientific study between Kyoto University Research Reactor Institute (KURRI) and Argonne National Laboratory (ANL). The updated results from Kyoto University on neutronic characteristics analysis of the C-core, using both deterministic and statistical analysis using uranium silicide and U-10Mo as the fuel material, is described in this paper.

1. Introduction

The increasing interest on the minimization of highly-enriched uranium (HEU) in civil nuclear field is currently focused to removal of “gap” materials, and more importantly, on the possible minimization of HEU fuel in low-powered test & research reactors and critical assemblies which were not hitherto been focused in the RERTR program. In spite of such situation, no notable activity have been made for on LEU utilization in critical assemblies currently using HEU fuel.

This is considered to be mostly due to the unavailability of the special fuel material utilized in these facilities (non-cladded coupon plates, rods, etc.), and also due to the variety of core configurations, fuel composition and core characteristics which is far more diversified compared to the conventional test and research reactors. Thus there would be a definite need for significant scientific activities, especially in the field of reactor physics and fuel fabrication technologies, to accelerate the relevant activities for LEU utilization of small powered test & research reactors and critical assemblies.

In this context, Kyoto University is collaborating with DOE/ANL in the studies for utilizing the LEU-based fuel for the Kyoto University Critical Assembly (KUCA). The two parties agreed to conduct the joint scientific study for the feasibility study on utilization of LEU fuel in KUCA, which is aimed at analysis of core neutronic characteristics using possible fuel candidates and to investigate the possible fuel technology to be adopted for LEU fuel of KUCA[1]. Through the study, possible drawbacks from LEU utilization such as limitation in core performance including reactor safety and limitation of academic research, and more importantly, the possible academic and scientific achievement by LEU utilization, would be clarified. Among the ongoing activities of the feasibility study, the results hitherto obtained on LEU-fueled KUCA wet-core characteristics are summarized in this paper.

2. The KUCA Facility and the Light Water-moderated (Wet) Core

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.

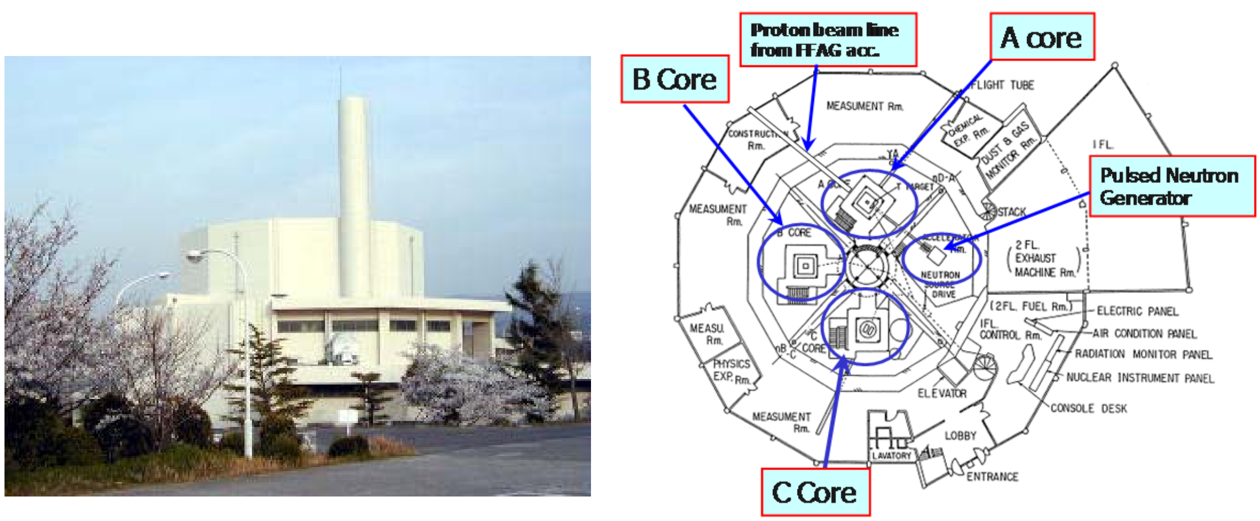


Figure 1: KUCA facility.

The wide variety of available materials and attached facilities enable to perform reactor physics experiments on numerous critical and sub-critical configurations at the KUCA[2-5]. The major topics of the study includes fundamental studies for reactor physics, conceptual studies for innovative reactors, technology development for nuclear engineering, accelerator-driven subcritical reactor (ADSR) science & technology as well as the extensive activities on education and training for graduate-level students.

The overall structure of the light water-moderate (wet) core is more or less similar to conventional plate-type research reactors; it consists of a 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. 2.

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 between two Al side plates of a fuel frame along the grooves of the side plate. 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. 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 including coupled core system, neutronic properties of research reactor cores with reduced enrichment uranium fuel and criticality safety including subcritical measurements 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.

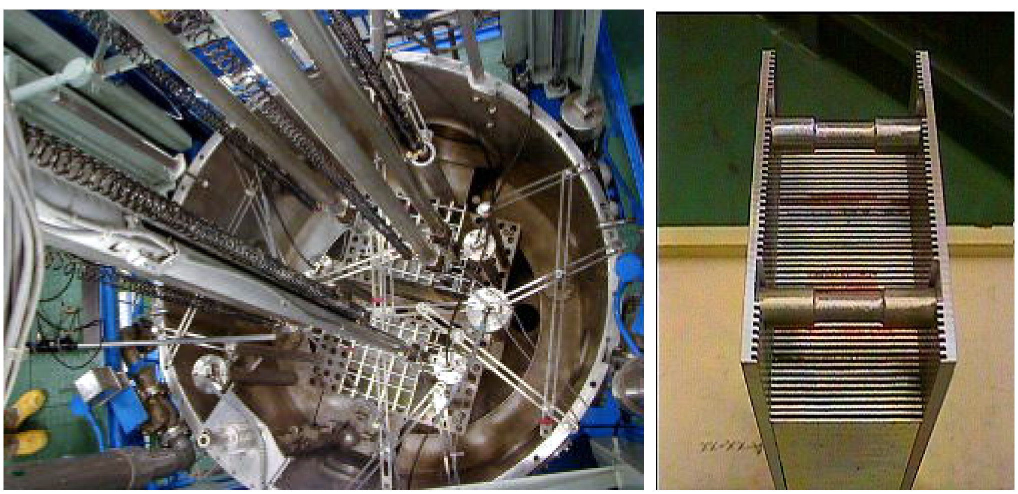


Figure 2: KUCA light water-moderated core (C-core), showing the core tank and fuel element

3. Results of Wet Core Study

3.1 Analysis of Reactivity Difference due to LEU Utilization by Deterministic Calculation

Due to the similarity of the fuel structure and neutron spectrum to those of conventional research and test reactors, we started 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. U-10Mo plates are also investigated in the present study.

The impact on reactivity due to utilization of LEU are first studied based on deterministic analysis of reactivity change using SRAC code system[6] 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, where the change from HEU fuel to LEU fuel is treated as perturbation to the system. The core configuration was simplified to two-dimensional cylindrical model (RZ model), consisting of homogenized fuel region surrounded by light water reflector.

3.1.1 Silicide Fuel

Figure 3 shows the reactivity change due to substitution of the existing HEU fuel plates with U-silicide LEU fuel plates. The utilization of LEU fuel will cause reactivity difference of from about -6%Δk/k to +4%Δk/k, depending on the core type and U density of the fuel meat . It should be noted that for LEU fuel with U density above about 4gU/cc, the reactivity change due to the use of LEU fuel can either be negative of positive depending on the fuel frame type. From the compatibility of reactivity, it would be desirable to adopt the fuel with 4.4gU/cc or 4.8gU/cc.

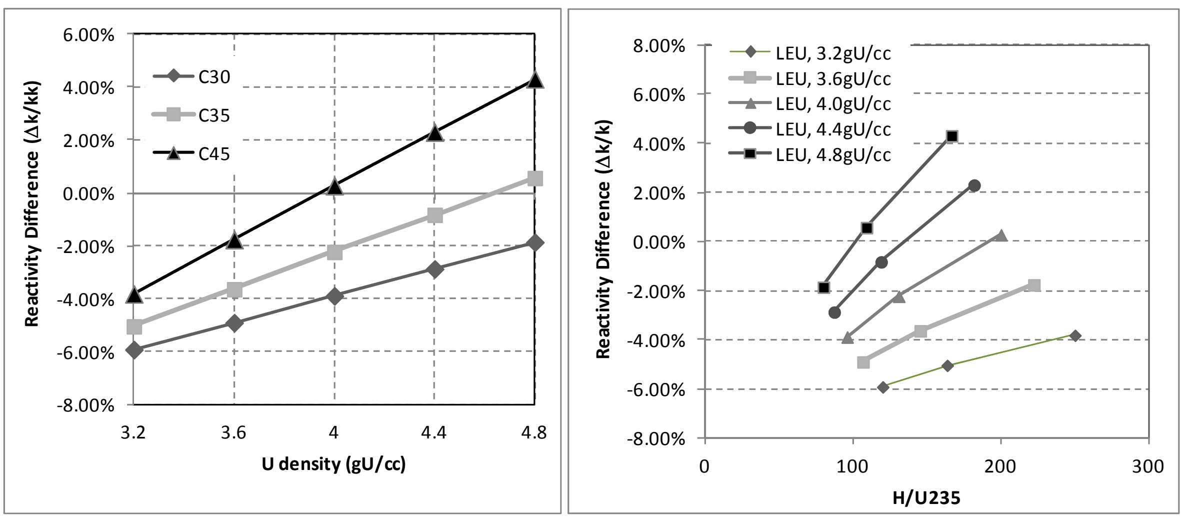


Figure 3: Reactivity difference between HEU and LEU U3Si2-Al with various U density

An example of the detailed energy group breakdown of reactivity difference is shown in Fig. 4. This energy group breakdown is further investigated by dividing it into three energy regions; i.e. the fast ($E>10^4$eV) region where the production (fission) component is dominating, resonance region ($1eV<E<10^4$eV) where the absorption component is dominating, and thermal region ($E<1eV$) where thermal absorption is dominating. The energy region breakdown of the reactivity difference for LEU silicide fuel with 3.2gU/cc and 4.8gU/cc are shown in Fig. 5. The total reactivity difference is due to the compensation of rather large reactivity components, and this is best seen for 4.8gU/cc case. It should be noted that the resulting total reactivity difference is larger for 3.2gU/cc than 4.8gU/cc, even though the reactivity difference is relatively small in each region for 3.2gU/cc.

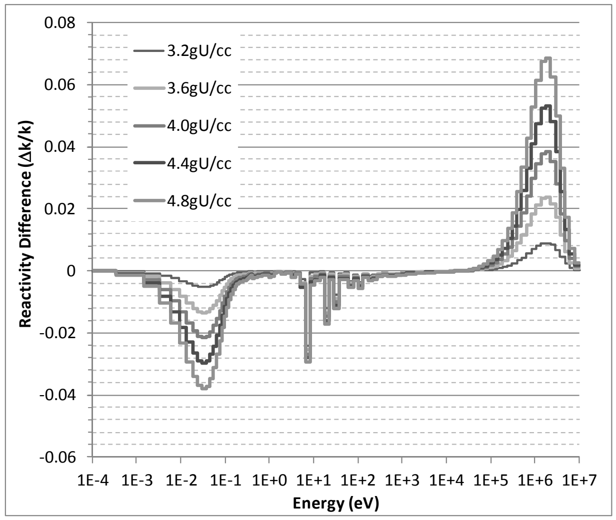
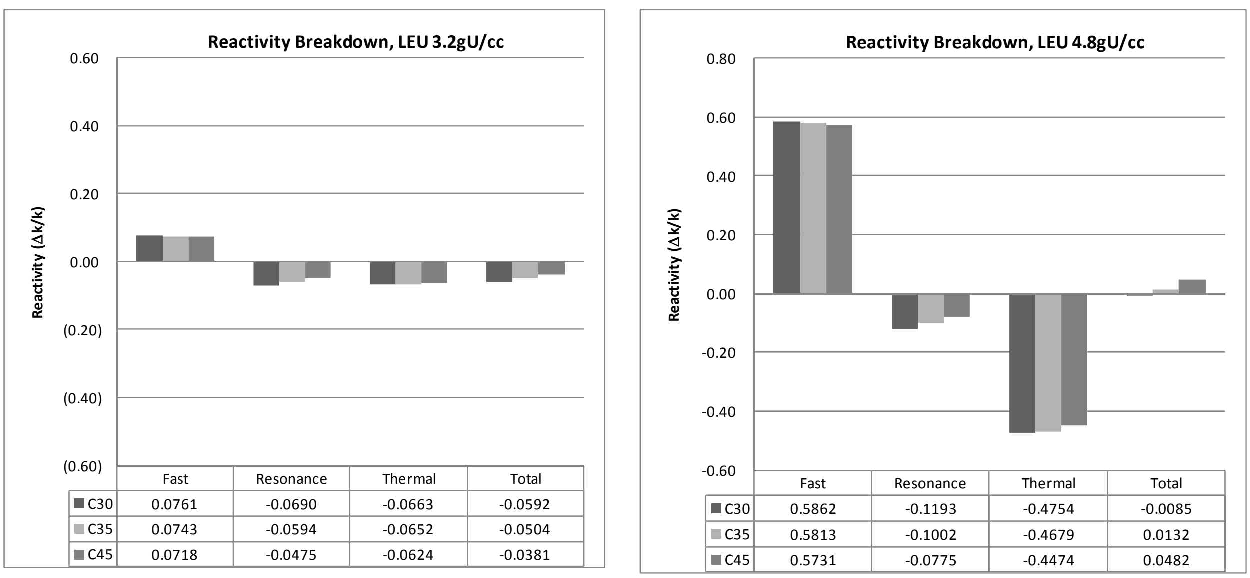


Figure 4: Reactivity difference breakdown for LEU fuel, C30 core



	Fast	Resonance	Thermal	Total
C30	0.0761	-0.0690	-0.0663	-0.0592
C35	0.0743	-0.0594	-0.0652	-0.0504
C45	0.0718	-0.0475	-0.0624	-0.0381

	Fast	Resonance	Thermal	Total
C30	0.5862	-0.1193	-0.4754	-0.0085
C35	0.5813	-0.1002	-0.4679	0.0132
C45	0.5731	-0.0775	-0.4474	0.0482

Figure 5: Reactivity difference breakdown by energy region for LEU fuel, 3.2 and 4.8gU/cc

The cause of such reactivity change from HEU to LEU could be more clearly understood through examination of the sensitivity coefficients. Figures 6 and 7 show the sensitivity coefficients of U-235 and U-238 to k_{eff} of HEU cores, calculated by using SAGEP [7] code, respectively. The current conversion of HEU to LEU leads to increase of both U-235 and U-238 content in the system. The increase of U-235 mostly lead to positive reactivity effect due to the large positive sensitivity to fission cross section in thermal region, which appears as positive "fission" component in the perturbation analysis results as shown in Figures 4 and 5. Increase of U-235 also lead to negative reactivity effect due to increase of thermal capture. More importantly, the increase of U-238 show significant increase of negative contribution througn thermal capture and resonance capture. The different magnitude and balance of the sensitivity coefficient among the cores (i.e. neutron spectrum), together with the change of the U content, results to the energy dependent reactivity difference components shown in Fig. 4.

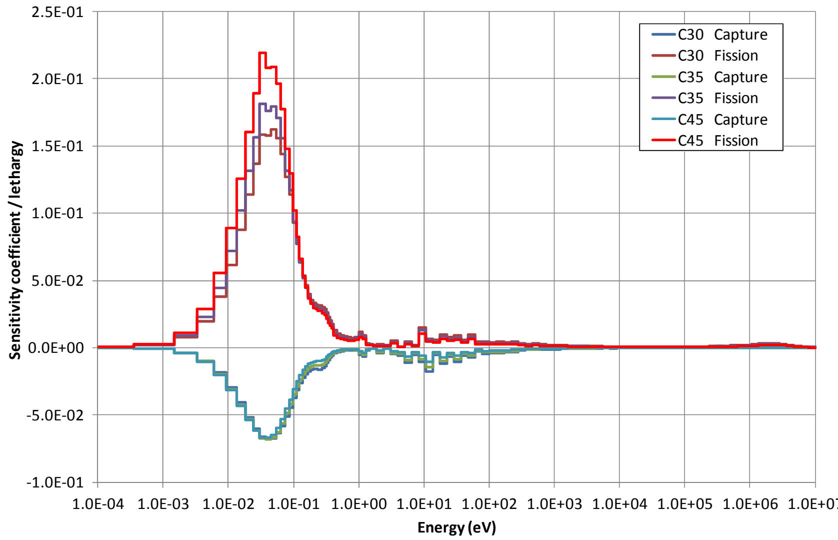


Figure 6 Sensitivity coefficient of U-235 to k_{eff} of HEU core

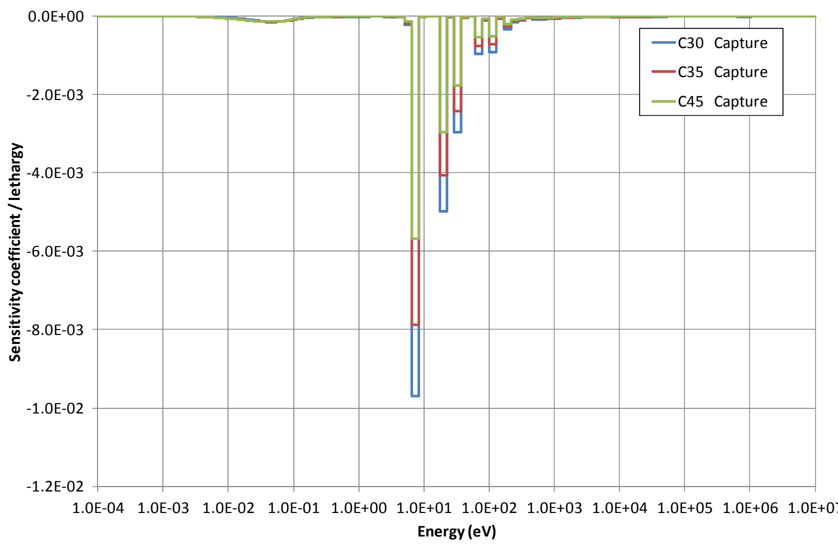


Figure 7: Sensitivity coefficient of U-238 to k_{eff} of HEU core

These examples shows that the compatibility in terms of reactivity of the LEU fuel can significantly be different among the cores with different neutron spectrum and core composition, which is the most significant feature for utilizing LEU in critical assemblies.

3.1.2 U-10Mo Fuel

Among the various U-Mo fuel candidates, monolithic U-10Mo has been selected as the possible candidate in the present study. The material properties of U-10Mo was adopted from Ref.[8], The H/U-235 range was changed by modifying the thickness of the U-10Mo meat thickness.

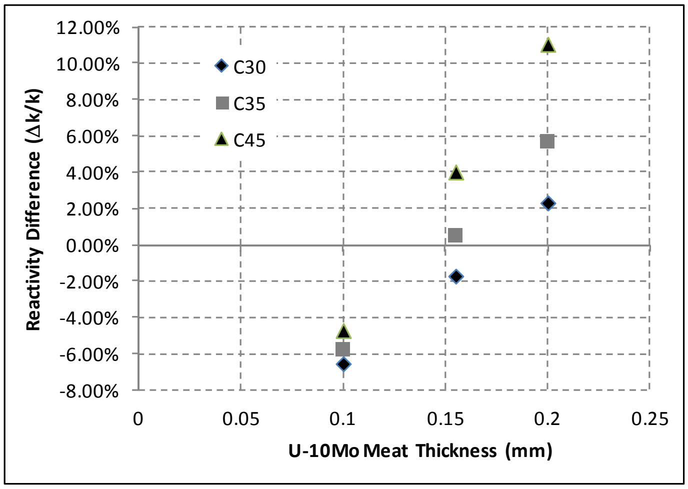


Figure 8: Reactivity difference between HEU and LEU U-10Mo with various meat thickness

Figure 8 shows the reactivity change due to substitution of the existing HEU fuel plates with U-10Mo LEU fuel plates with various U-10Mo meat thickness. Due to the high U density, reduction of fuel meat thickness to less than 0.2mm would be necessary to obtain the compatibility in the reactivity of the core. Fuel meat thickness of 0.155mm, which give approximately the same U content per fuel plate as U3Si2-Al fuel with 4.8gU/cc, shows a modest change in reactivity between -2% and +4%. This reactivity change is very consistent with that obtained for U3Si2-Al fuel with 4.8gU/cc as shown in Fig. 9.

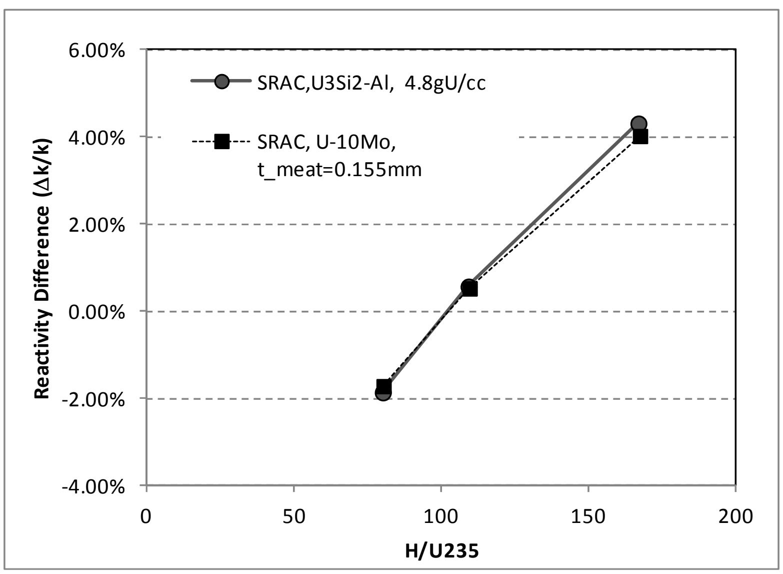


Figure 9: Reactivity difference between HEU and LEU; comparison of U3Si2-Al (4.8gU/cc) and U-10Mo (meat thickness 0.155mm), both LEU fuel having equivalent U content

3.2 Full Core Analysis using MVP Monte Carlo Code

Based on the results of the reactivity difference studies described in Section 3.1, detailed full core analysis was done using the continuous energy Monte Carlo code MVP[9]. The LEU fuel adopted in the full core analysis is U3Si2-Al with 4.8gU/cc and U-10Mo with meat thickness of 0.155mm. Three representative core configurations as shown in Table 1 and Fig. 10 are selected in this study.

Table 1: Selected cores for full core analysis

Core ID	Unit Fuel Cell	Number of Fuel Plates	keff (experimental)
C30G0(4 Rows)	C30 type	330	1.00107
C35G0(4 Rows)	C35 type	424	1.00099
C45G0(4 Rows)	C45 type	544	1.00114

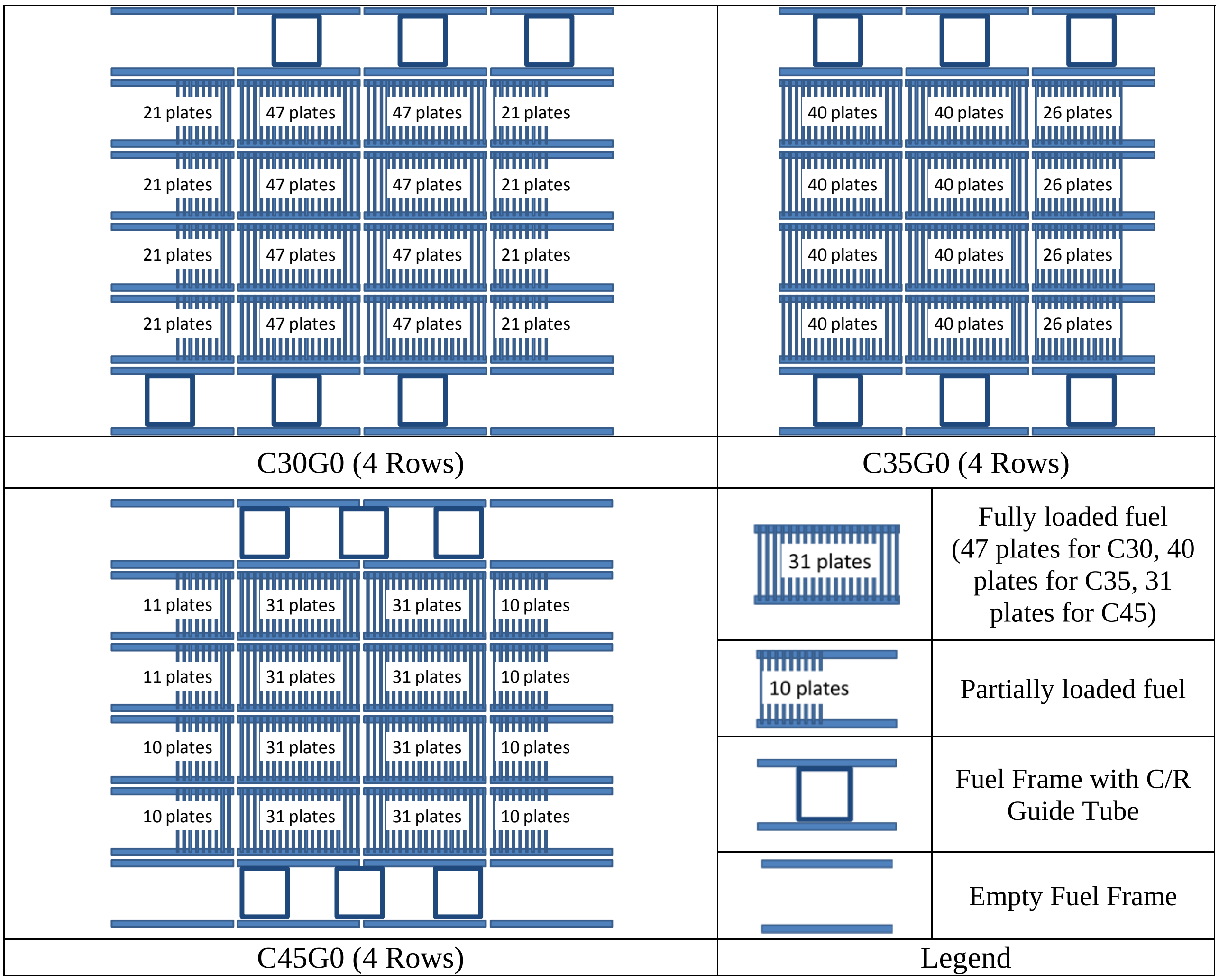


Figure 10: Core configurations (top view of the core)

The detailed structure of the fuel frame and the grid plate was considered in the MVP modeling. The presence of lower support structure of the grid plate was proven to be not significant to the reactivity and thus was not taken into account in the model. The eigenvalue (k-effective) results using JENDl-3.3, JENDL-4.0 and ENDF/B-VII.0 as nuclear libraries are listed in Table 2. The calculated results systematically overestimates experiment by about +0.5 to +0.6%. ENDF/B-VII tends to give larger keff than JENDL results by approximately 100 pcm. Further investigation on this systematic overestimation remains as a future study. Nevertheless, the relative impact of LEU utilization to reactivity is considered to be sufficiently evaluated based on the current model of the C cores.

Table 2: k_{eff} results* for the reference HEU cores

Core ID	k_{eff}, JENDL-3.3	k_{eff}, JENDL-4.0	k_{eff}, ENDF/B-VII.0
C30G0(4 Rows)	1.00729 +/- 0.055%	1.00725 +/- 0.054%	1.00894 +/- 0.053%
C35G0(4 Rows)	1.00790 +/- 0.050%	1.00765 +/- 0.052%	1.00867 +/- 0.052%
C45G0(4 Rows)	1.00639 +/- 0.051%	1.00674 +/- 0.052%	1.00764 +/- 0.052%

* obtained using 10000 neturons/cycle, 320 cycles, 20 skip cycles.

Figure 11 shows the reactivity difference between HEU and LEU cores obtained by MVP full core Monte-Carlo calculation with JENDL-4.0. The reactivity difference due to LEU utilization is from -1.5% to +3% Δk/kk, which is consistent with the SRAC perturbation results shown in Section 3.1. This reactivity difference is estimated to influence the core fuel loading inventory by about 20 to 30% at maximum, and its impact on core performance would be closely investigated in the future studies.

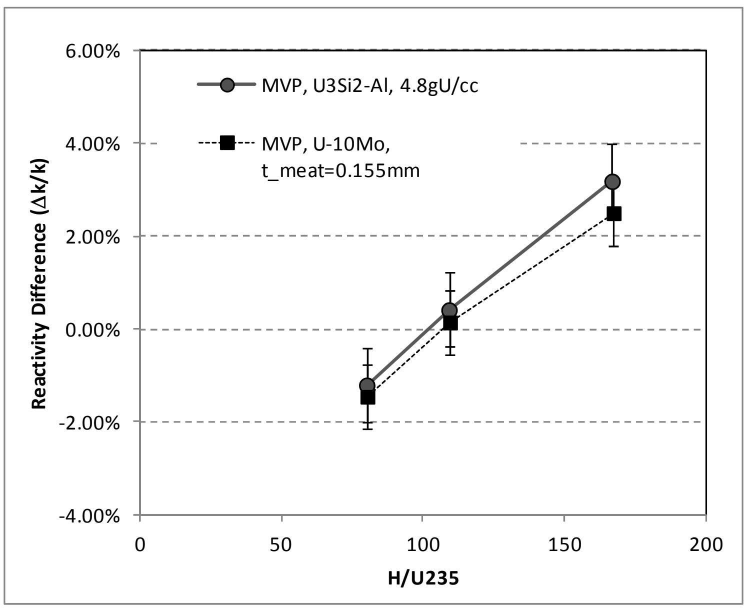


Figure 11: Reactivity difference between HEU and LEU cores by MVP full core Monte-Carlo calculation with JENDL-4.0

4. Conclusion and Future Studies

The future studies of the present feasibility study on wet core (C-core) of KUCA would include more detailed and systematic analysis of core characteristics using possible fuel candidates, including silicide fuel, U-10Mo fuel studied in this paper and also the UO_2 (pin) fuel. Compatibility with the current HEU cores in reactivity would be of primary interest, and investigation on the impact of LEU utilization to safety characteristics, and more importantly, the balance between the drawbacks and benefit in the research activities would follow. Together with these studies, 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 investigated in parallel.

Studies on the dry core conversion, which has been shown to be more challenging[1], is also under progress. As the dry core configurations exhibit more drastic change in the core material composition and neutron spectrum than the wet core, the adequate selection of the LEU fuel material and investigation on the possible benefit of conversion would require significant effort from now on.

We would like to emphasize again that 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 and detector development, and also for human resource development including education and training for graduate course students. We believe that 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 be able to show the significant benefit expected by using LEU.

5. References

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