KUCA CONVERSION PROJECT - CHALLENGES AND ACHIEVEMENTS

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Abstract

On June 2016, the governments of the United States of America and Japan has agreed to convert Kyoto University Critical Assembly (KUCA), located at Osaka, Japan from highly enriched uranium (HEU) fuel to low enriched uranium (LEU) fuel and to return all HEU fuel materials from KUCA to United States. Based on this mutual agreement, Kyoto University has been working extensively with close collaboration with USDOE and MEXT and, especially with support from ANL, FRAMATOME CERCA™ and KAERI on the conversion project, which will be focused on this paper. This LEU conversion project is the first attempt to convert a critical assembly from HEU to LEU. Extensive efforts have been hitherto made to conserve and even extend the capabilities of KUCA experiment after conversion. Preceding the present conversion project, a joint feasibility study on neutronic characteristics of the KUCA LEU cores have been initiated between ANL and Kyoto University, which finally resulted to show the feasibility of converting KUCA with LEU fuel and to preserve the wide variety of neutron spectrum as well as core configuration achievable at the facility. Further investigation in the fuel design resulted to selection of uranium silicide dispersion fuel for Wet core fuel, and uranium molybdenum dispersion fuel for Dry core fuel. The latter posed a significant challenge in coating / cladding technology development to ensure the integrity of the fuel during manipulation for the KUCA operation. Innovative design for Dry core coupon fuel based on “jewelry box” concept has been adopted, which conceals the U7Mo-Al fuel core inside machined aluminum case and aluminum lid fixed by laser welding. Technology development using both surrogate material and depleted U7Mo at FRAMATOME CERCA™ is ongoing. The Dry core coupon fuel fabrication will be the first experience for UMo based fuel production. In order to facilitate the startup of the fabrication project, KAERI has joined this project as a supplier of the U7Mo atomized powder for industrial production of Dry core coupon fuel; the atomized powder will be fabricated at KAERI using LEU metal supplied by USDOE. The conversion project is foreseeing the KUCA conversion to be achieved on calendar year 2021. This conversion is expected to be the first critical facility to be converted to LEU and be a significant achievement for nuclear threat reduction and HEU minimization in civilian sector. Moreover, this would be the first critical reactor to be operated by U7Mo based fuel, which shall be providing invaluable scientific data to research reactor conversion community.

1. INTRODUCTION

This paper aims to present an identification of challenges and achievements on the conversion project of Kyoto University Critical Assembly (KUCA) at the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS) from highly enriched uranium fuel to low enriched uranium (LEU) fuel. The increasing importance in nuclear security in recent years is leading to add new activities in relation with the minimization of highly-enriched uranium (HEU) in civil nuclear field. The conversion project has been officially announced in the Japan-US governmental statement at the fourth Nuclear Security Summit held on 2016. Based on this mutual agreement between the two governments, Kyoto University as the operator of KUCA facility has been working extensively on the LEU conversion project with close collaboration with NNSA Office of Material Management and Minimization, U.S. Department of Energy (USDOE) and Ministry of Education, Culture and Sports (MEXT), Japan and, especially with technical support from Argonne National Laboratory (ANL), Framatome CERCA™ and KAERI. This LEU conversion project is the first attempt to convert a critical assembly from HEU to LEU. Extensive efforts have been hitherto made to conserve and even extend the capabilities of KUCA experiment after conversion.

Prior to the present conversion project, Kyoto University has been collaborating with DOE/ANL for more than 10 years in the studies for utilizing the LEU-based fuel for KUCA. This was aimed to seek for the possible minimization of HEU fuel in low-powered test & research reactors and critical assemblies which were not hitherto been focused in the relevant program such as Reduced Enrichment for Research and Test Reactors (RERTR) progamme. Joint scientific study for the feasibility study on utilization of LEU fuel in KUCA has been conducted, which is focused to analysis of core neutronic characteristics using possible fuel candidates and to investigate the possible fuel technology to be adopted for LEU fuel of KUCA. This joint feasibility study on neutronic analysis have hitherto revealed important findings on the complexity of critical assembly conversion, and identified feasible pathway for the conversion. The major findings of the aforementioned joint feasibility study between ANL and Kyoto University resulted to show the feasibility of converting KUCA with LEU fuel and to preserve the wide variety of neutron spectrum as well as core configuration achievable at the facility. These achievements have acted as a scientific background for the decision to proceed further towards the actual conversion.

The KUCA facility, as described in more detail in the next chapter, has a unique feature that it consists of three cores, of which two utilizes solid moderator such as graphite and polyethylene (called as "Dry" core) and one core utilizing light water for moderator (called as "Wet" core). Investigations in the fuel design through the feasibility study resulted to selection of uranium silicide dispersion fuel for Wet core fuel, and uranium molybdenum dispersion fuel for Dry core fuel. The latter posed a significant challenge in coating / cladding technology development to ensure the integrity of the fuel during manipulation for the KUCA operation. Innovative design for Dry core coupon fuel based on “jewellery box” concept has been adopted, which conceals the U7Mo-Al fuel core inside machined aluminium case and aluminium lid fixed by laser welding. Technology development using both surrogate material and depleted U7Mo at CERCA is being performed as the initial stage of the conversion project of the Dry core.

This paper will provide the description of the KUCA facility, major results of the preliminary studies, and the recent achievement for the Dry core fuel development as well as the future perspectives and challenges of the conversion project.

2. THE KUCA FACILITY

2.1 Facility

The Kyoto University Critical Assembly (KUCA) (Figure 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.

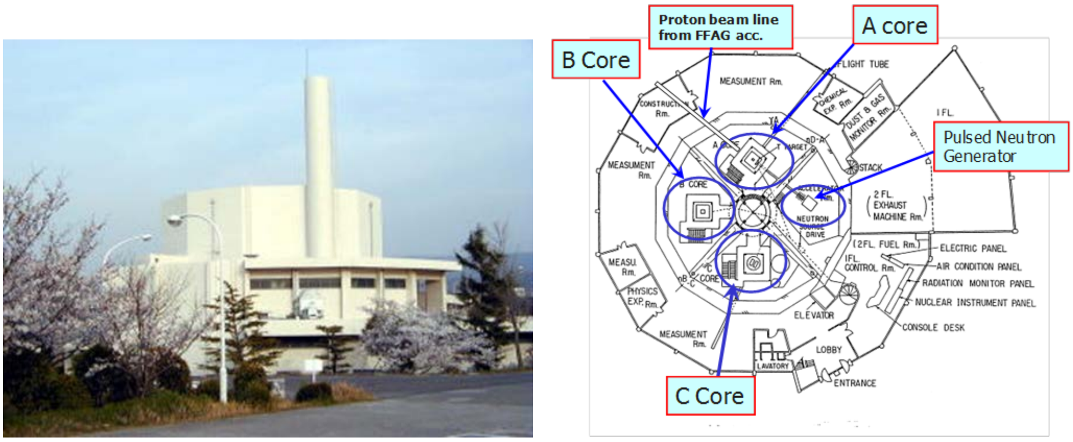
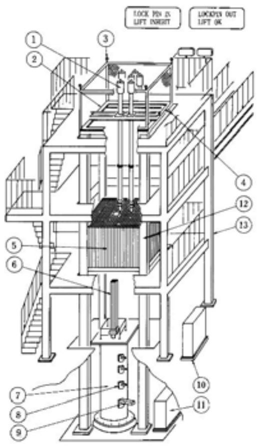


FIG. 1. KUCA Facility.

The wide variety of available materials and attached facilities enable to perform reactor physics experiments as well as educational activities on numerous critical and sub-critical configurations at the KUCA [1-5]. 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 and research institutions. 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.

2.2 Dry core (Solid Moderated Core)

The overall structure of KUCA solid-moderated core is shown in Figure 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 (called as "coupon" fuel). 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

FIG. 2. Structure of the KUCA solid-moderated core (Dry 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. A schematic view of the core is shown in Figure 3.

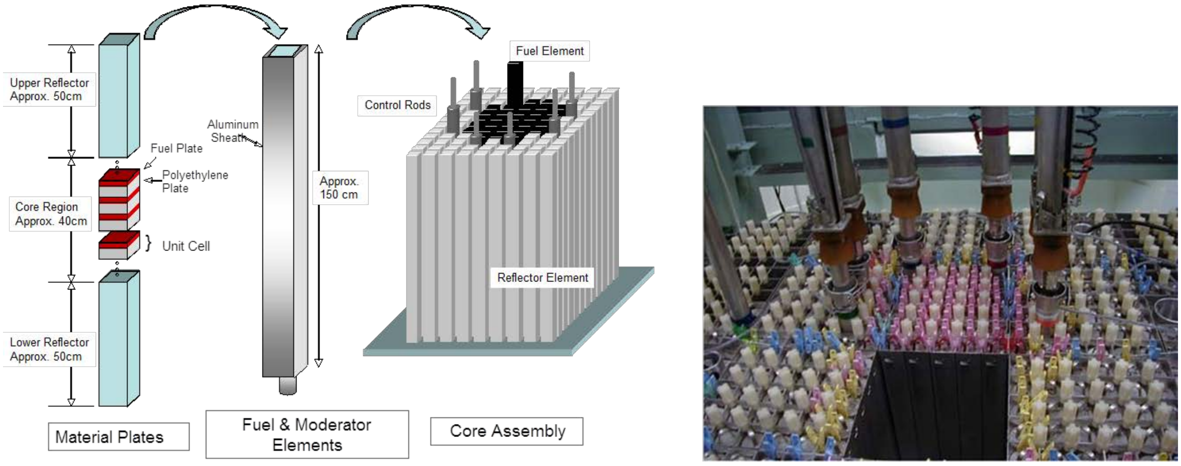


FIG. 3. Schematic view of the KUCA solid-moderated core ("Dry" core).

2.3 Wet core (light water moderated 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 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 Figure 4.

The fuel currently being mainly used is a flat plate-type, aluminium 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.

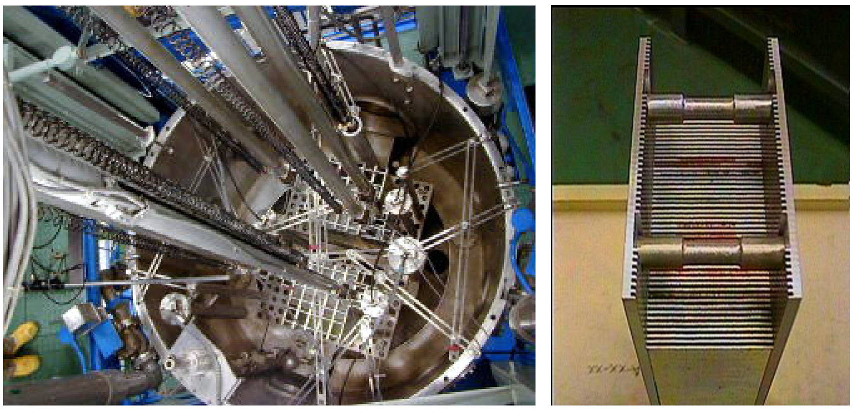


FIG. 4. KUCA light water-moderated core ("Wet" core), showing the core tank and fuel element.

3. PRELIMINARY LEU CONVERSION STUDIES

Initial feasibility studies on the conversion from HEU to LEU fuel were performed by reactor physics / core design specialists at both ANL and KURNS. The major results are shown for Wet core and Dry core studies [6-10].

3.1 Wet Core Studies

Due to the similarity of the fuel structure and neutron spectrum to those of conventional research and test reactors, investigation were commenced by seeking the feasibility of utilizing Al-cladded Uranium-silicide fuels with U density of 3.2gU/cc to 4.8gU/cc as the existing and well-proven fuel technology. The first results were obtained by deterministic analysis of reactivity change using SRAC code system [14] with 107-energy group JENDL-3.3 as nuclear library. The reactivity change due to LEU utilization is analysed using the first-order perturbation option of CITATION code. The core configuration was simplified to two-dimensional cylindrical model (RZ model). 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 Figure. 5, the substitution of the existing HEU fuel plates with U-silicide LEU fuel plates will cause reactivity difference of from about -6%Δk/kk' to +4%Δk/kk', 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, which was considered to be acceptable. Using 4.4gU/cc or 4.8gU/cc can reproduce reactivity within +/- 4%Δk/k, with the C35 core having moderate reactivity change of within 1%Δk/kk'. This result was further confirmed through detailed full core analysis using the continuous energy Monte Carlo code MVP[15]. From this result, the candidate fuel was set to be 4.8gU/cc, which is equivalent to the uranium density utilized in many research reactors and thus is more feasible for the actual fabrication.

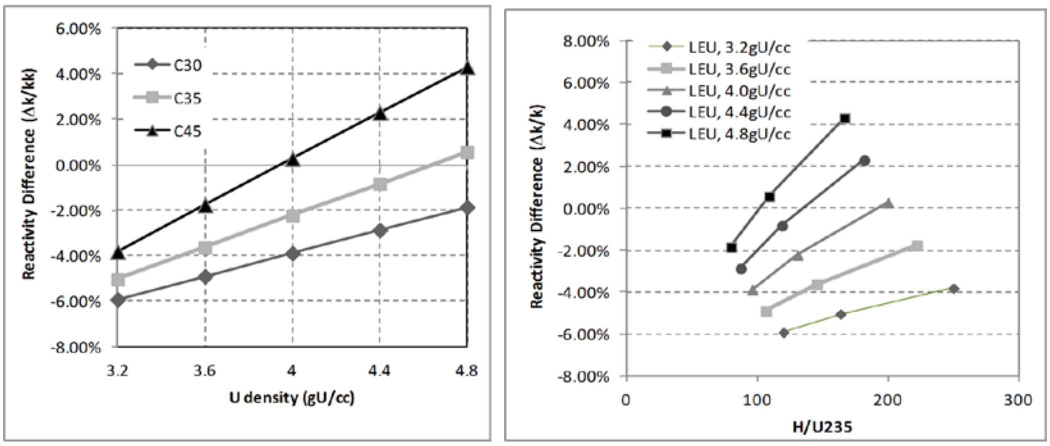


FIG. 5. KUCA Wet core: Reactivity difference between HEU and LEU U_3Si_2-Al with various U density.

The major results from the feasibility studies on LEU conversion of the Wet core hitherto performed could be summarized as follows;

- As the plate type fuel used in the Wet core is similar to those of individual flat-type fuel plates widely used in test and research reactors, existing and proven technology of U-silicide fuel could be applicable,
- Investigation of reactivity, neutron spectrum to check compatibility with HEU cores and to further extend the experimental capability thus performed with U3Si2-Al based fuel design,
- Increase of U density due to use of high density LEU leads to decrease of H/U5 and thus neutron spectrum of the core,
- Gain in reactivity by increasing U density strongly depends on neutron spectrum,

- Uranium loading of 4.8gU/cc allows modest reactivity deviation from present HEU core and also to extend the availability of cores with harder neutron spectrum, and
- Core inventory change estimated to be +/- 30%, which is considered to be practically acceptable.

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 un-cladded 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 criticality analysis has been conducted for a series of polyethylene-moderated / reflected cores with systematically varied H/U-235 ratio, using 19.75wt% LEU fuel of various chemical forms and uranium content but with identical physical dimensions (nominally 2 x 2 x 1/16-in. thick , e.g. 5.08 x 5.08 x 0.16 cm). The preliminary 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 (at KURNS) and MCNP (at ANL). The representative critical cores[11] are shown in Figure 6. 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-Mo (either in the form of UMo-Al dispersion or UMo monolithic) and U_3Si_2-Al dispersion fuel has been selected as the possible candidate in the present preliminary studies, both of them requiring some form of coating or cladding from safety point of view. Further studies confirmed that no significant difference between UMo and U_3Si_2-Al dispersion do exist. This lead to the decision to adopt UMo fuel for the Dry core conversion, which shall result to the first critical reactor to be operated fully with UMo fuel when successfully converted.

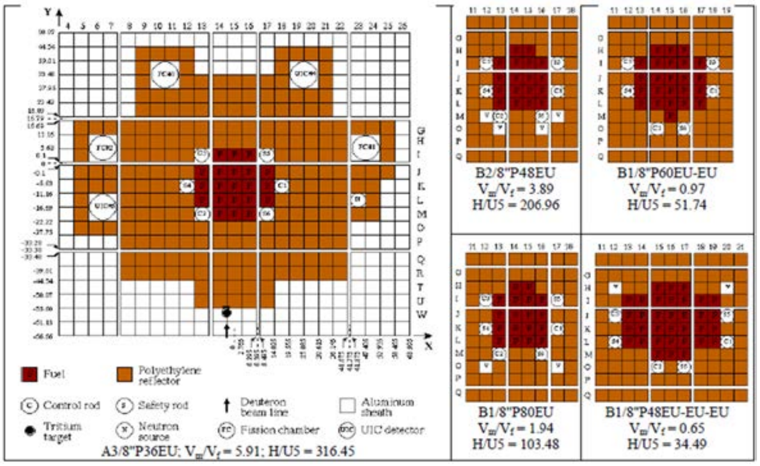


FIG. 6. KUCA Dry core: representative critical cores used for feasibility study.

The major findings from the preliminary feasibility studies could be summarized as follows;

- Criticality analysis show that UMo is a promising candidate for Dry core conversion,
- Adjusting fuel meat thickness to preserve H/U5 (and thus neutron spectrum) generally leads to decrease in reactivity, leading to increase in core loading up to 35%,
- Criticality of LEU dry cores using U-10Mo monolithic very sensitive to fuel thickness increase: fuel thickness increase of 1 mil may result to reactivity increase of 1200pcm for soft spectrum core,
- fuel fabrication feasibility of small sized, Al-cladded or covered coupon should be investigated in detail (fabrication process, tolerance),
- Use of high density fuel may act to extend KUCA dry core capability to fast spectrum experiments: a very promising outcome of the conversion.

4. PRESENT LEU CONVERSION ACTIVITIES

4.1 Wet Core Conversion

Through the preliminary studies, it has been identified that U-Silicide dispersion fuel with 4.8gU/cc (no design change in fuel geometry) allows modest reactivity deviation from HEU cores and extension towards cores with harder spectrum. Based on this result, detailed full core Monte Carlo simulation has been performed to seek for the optimum number of the fuel plate to be fabricated to not only conserve but to potentially extend the experimental capability of the KUCA Wet cores. The results shown in Figure 7 show that the usage of LEU fuel will fully cover the H/U5 range of the present HEU cores and extend the experimental capability towards lower H/U5 range, e.g. cores with higher spectrum. The optimum number of the LEU fuel plates to achieve this has been identified to be around 700 plates.

Discussion with the fuel fabricator, Framatome CERCA, confirmed that there is no major obstacle in terms of fuel fabrication, as the overall design is practically identical to those of fuel plates used in conventional research reactor. Procurement of LEU raw materials will be performed in late CY2019, fabrication to be commenced in CY2020, and the first batch of LEU fuel expected to be introduced to KUCA in CY2021.

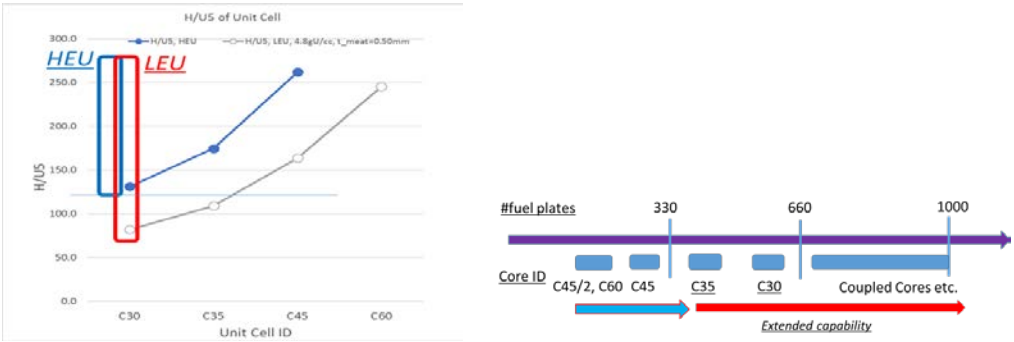


FIG. 7. KUCA Wet core: representative critical cores used for feasibility study.

4.2 Dry Core Conversion

4.2.1 Fuel coupon fabrication technology development[12-13]

The LEU coupons specifications derived from the preliminary studies required the coupon core to have a thickness of approximately 1.0 mm with 0.3-mm thick aluminium cladding or coating on each side. Dedicated research team at Framatome CERCA has investigated sixteen (16) solutions, grouped into four categories: aluminium spray coating, epoxy coating, organic box and aluminium box, to the cladding/coating challenge. Figure 8 shows the test samples with various techniques attempted. After handling test and mechanical tests, the aluminium spray coating, organic/epoxy coating, organic box (vitronite) were rejected due to various reasons (including mechanical, chemical and quality control issues), and the aluminum box (or an aluminum frame) with Al covers on both sides remained as the most viable candidate.

FIG. 8. Results of Coating and Cladding Options Study

After more in-depth study and technical development, the final process has been established to use a machined compartment (box) of aluminium to hold the coupon core, an aluminum cover to completely cover the fuel core, and then 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 (Figure 9). After conducting a series of basic tests at the fabrication lab and examination and handling tests of surrogate samples at KURNS, this design (the "jewellery box" design) was determined as the best option for enclosing the U7Mo-Al dispersion core of the KUCA Dry fuel coupons.

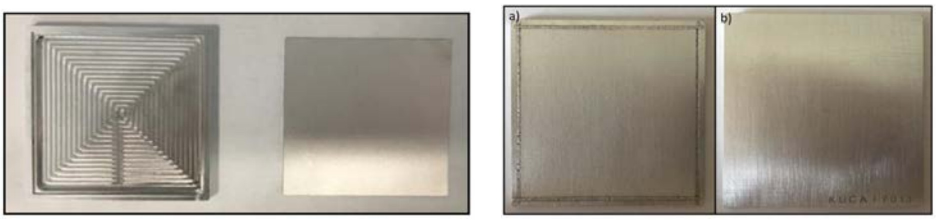


FIG. 9. KUCA Dry LEU fuel design with aluminium box and cover plate.

4.2.2 Fuel coupon design advancement

After the initial success of the jewellery box design approach, detailed investigation of the test samples at KURNS identified that the flatness of the coupon could not be satisfactory achieved due to the thin nature of the coupons, which is sensitive to deformations caused during the welding process (it should be noted that flatness of the coupon is a crucial parameter that must be met for ensuring the experimental accuracy and reliability at KUCA Dry core). The resolution proposed by KURNS was to change the fuel coupon design so as to increase the mechanical properties of the coupon by increasing the thickness of the coupon core and the aluminium case; the coupon core thickness was changed from 0.95 mm to 1.45 mm, and the minimum side thickness of the aluminium box was increased from 0.3 mm to 0.4 mm (resulting to overall dimensions of 50.8 x 50.8 x 2.40 mm). Further research by CERCA showed that the flatness could be further achieved within the specification by using an additional post-welding heat treatment under load applied to the KUCA fuel coupons.

The change in the LEU coupon design will impact the core characteristics of the LEU core through increased resonance self-shielding (due to the increased fuel meat thickness) and also through the increased neutron streaming (due to increased cladding thickness). Thus, the impact of LEU conversion has been re-analysed to examine the possible variety in achievable critical cores and neutron spectra in the cores after LEU conversion, rather than reproducing the HEU cores. Based on the analysis, it is expected that six (6) different single region critical cores having different H/U235 ratio are achievable, and one core with a harder spectrum is also achievable by creating a zone-type core with approximately 3000 LEU coupons.

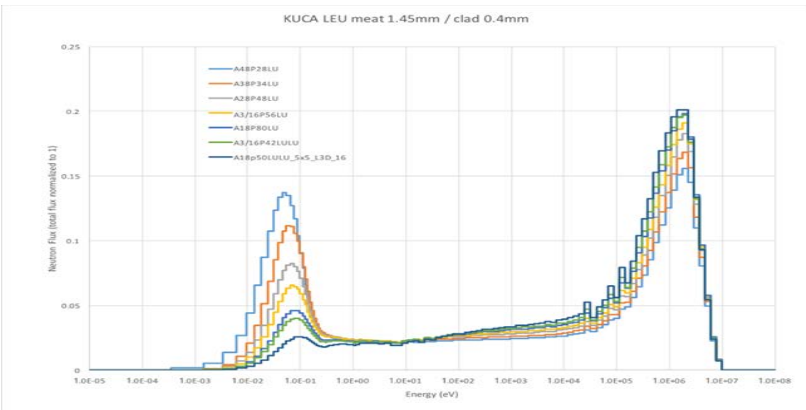


FIG. 10. Neutron spectra of KUCA LEU cores using thick LEU coupon design.

The neutron spectra in the core region (Figure 10) show that a wide variety of neutron spectra are achievable even after the conversion, which ensures the continuity and even the expansion of the research capability after the LEU conversion.

The core volumes are similar or slightly larger and thus comparable to present HEU cores, which is acceptable from operational point of view.

5. CURRENT STATUS AND PLANNED SCHEDULE FOR CONVERSION

Conversion activities for both Wet and Dry cores are steadily proceeding. As for the Wet core conversion, basic design specifications as well as inspection requirement specifications are developed, and the procurement of the raw LEU material is expected to proceed by the end of CY2019. No technical issue for fabrication process is foreseen, and the production of the first large batch (approximately half the amount) to be used in the initial LEU loading will begin in CY2020. This will lead to the Wet core conversion in CY 2021.

As for the Dry core, 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. These samples were successfully inspected and validated by KURNS team on October 2019, and the fabrication technology was confirmed to be well developed so that the mass fabrication of the LEU coupon is basically achievable. Fabrication of a small experimental batch of LEU coupons is expected to be completed near the end of CY2019 and shipped to KURNS in the first or second quarter of CY2020 to be used as experimental material in the present HEU core. Production of the first large batch of LEU coupons will begin in CY2020 and lead to the dry core conversion in CY2021. It should be highlighted that the U7Mo atomized powder to be used for the LEU fuel is to be provided from KAERI to DOE and used for LEU Dry core fuel fabrication at Framatome CERCA as technical contribution of KAERI to KUCA dry core conversion project; a successful multilateral collaboration towards conversion project.

6. CONCLUSIONS AND FUTURE CHALLENGES

The major findings and challenges derived or highlighted from this study include:

- the KUCA conversion project, originally initiated more than ten years ago, is finally commenced as a multilateral international collaboration between United States, France, Korea and Japan;
- analysis show some potential enhancement of experimental capability at KUCA by LEU conversion;
- development of fuel fabrication technology for Dry coupon fuel resulted to significant achievement of new findings, which require further validation and possible improvement;
- Continuous collaboration, frequent communication between the project team members is the key to successfully promote the complicated and challenging project;

Knowledge and experience achieved through this conversion project on the availability of appropriate fuel design including fuel fabrication, fuel transportation and possible modification of the facility required for LEU utilization shall be of significant importance for the future conversion of other critical assemblies and small reactors with specialized fuel design. This conversion is expected to be the first critical facility to be converted to LEU and be a significant achievement for nuclear threat reduction and HEU minimization in civilian sector. Moreover, this would be the first critical reactor to be operated by U7Mo based fuel, which shall be providing invaluable scientific data to research reactor conversion community. The authors believe that the present KUCA conversion is an extremely challenging project, but may lead to significant contribution to both reactor technology and nuclear security.

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