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Conversion of the KUCA "Type-A" Cores to LEU Fuel Preserving Reactivity and Central Flux Spectra

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ABSTRACT

Recent studies [1] demonstrated the feasibility of converting the 93% High Enriched (HEU) KUCA cores to the use of 19.75% Low Enriched (LEU) U-10Mo fuel by preserving the same reactivity. However, with the conversion of the KUCA cores it is preferable to preserve not only the reactivity but other important neutronic features as well. The present paper discusses the feasibility of converting the KUCA cores while preserving the neutron flux spectrum at the core center as well as the reactivity. Initial results indicate that a 12-mil thick U-10Mo foil is a good candidate for the conversion. Preliminary studies were also done on the sensitivity of the KUCA cores to the dimensional tolerances that are likely to be associated with the fabrication of the fuel plates. The results indicate that extremely high fabrication accuracy is required or the reactivity effects could be non-negligible.

1. Introduction

Studies were performed [1] on the feasibility of converting five "type-A" KUCA cores (named as A3/8"P36EU[1], B2/8"P48EU, B1/8"P80EU, B1/8"P60EU-EU and B1/8"P48EU-EU-EU) characterized by different moderator-to-fuel volume ratios (V_m/V_f) and different H-to-U235

[1] In these designators, the letters "A" or "B" refer to two different configurations of gaps between assemblies for flux wire arrangements; the fractional value (e.g., 3/8") specifies the thickness of the polyethylene in the unit cell; the "P" value indicates the number of times the unit cell is repeated in the core region of the assembly (e.g., P36); and the number of times "EU" is repeated indicates the number of uranium plates in the unit cell.

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atom ratios (H/U5) in the fuel unit cell from the use of HEU to LEU fuel. The performed studies demonstrated the feasibility of converting the KUCA cores with the use of U-10Mo fuel by preserving the same reactivity. The present paper discusses the feasibility of converting the same KUCA cores from HEU to LEU while preserving the neutron flux spectrum at the core center as well as the reactivity. Additionally, preliminary studies on the sensitivity of the KUCA cores to the dimensional tolerances that are likely associated with the fabrication of the fuel plates are presented for both the HEU and LEU loadings.

2. HEU and LEU KUCA Configurations

Figure 1 shows the core layouts of the five HEU KUCA configurations under study, while Figure 2 shows the cross-sectional view of the respective fuel assemblies and unit cells (see Refs. 1 and 2 for other details). It is noted that from the first to the last configuration the V_m/V_f ratio (and consequently the H/U5 atom ratio) decreases by a factor of about 10.

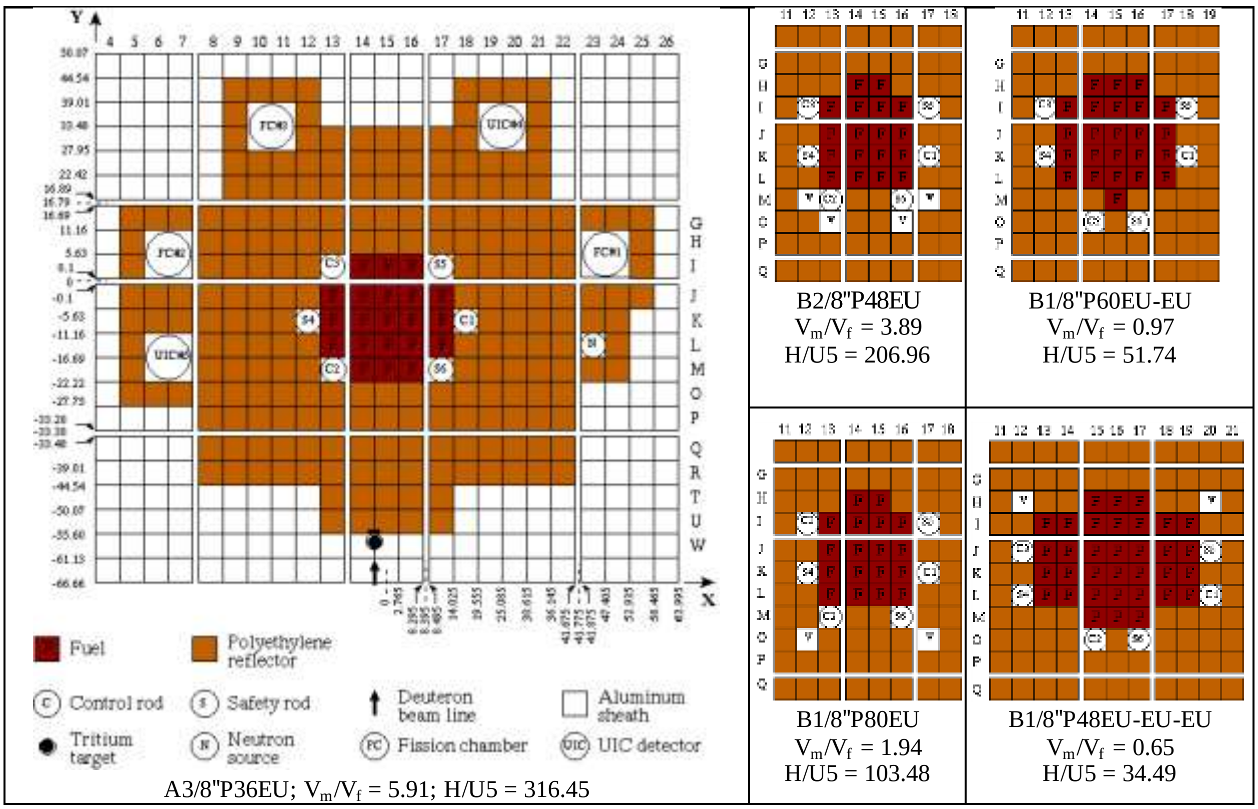


Figure 1. Layouts of the investigated KUCA cores

As done in the past studies on the conversion of the KUCA cores, each 1/16-in. (62.5-mils) HEU plate was replaced with a single U-10Mo foil clad by aluminum (Al) on both sides. The presence of an Al edge all around the LEU foil was considered in order to prevent cracking (see Figure 3 for details). Changing the thickness of the U-10Mo foil, the thickness of the Al clad is adjusted accordingly so that the axial extension (thickness) of the HEU plate being replaced is preserved. All polyethylene plates remain exactly the same as the HEU configuration. Concerning the dimensions, no constraints were found to be imposed by the fabricators, but it was assumed that the thickness of both the U-10Mo foil and Al clad cannot be less than 10 mils. With this constraint, the maximum allowed thickness of the U-10Mo foils would be 42.5 mils. Less well defined are the recommendations on the thickness of the aluminum edge, so that was fixed to 100 mils for the present study.

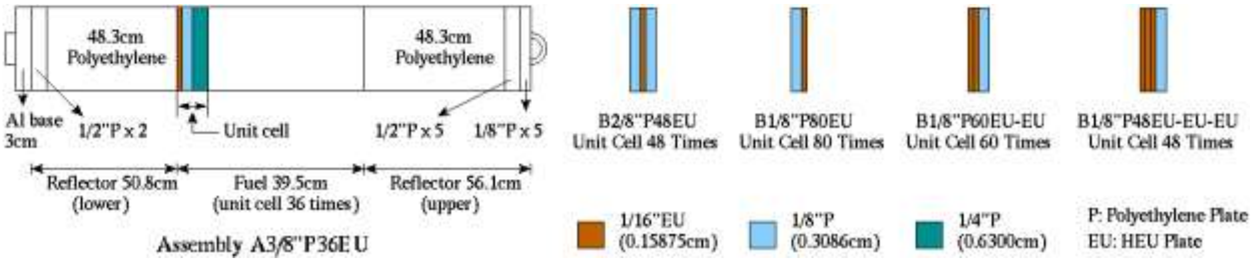


Figure 2. Cross sectional view of the KUCA fuel assemblies

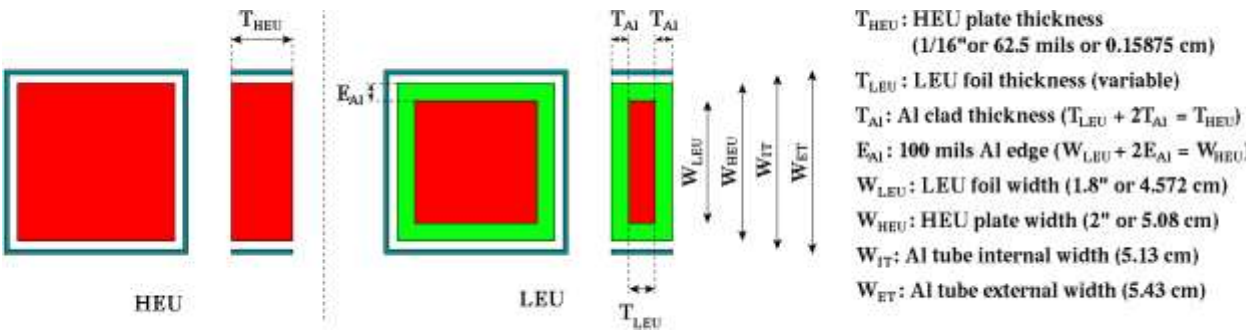


Figure 3. HEU and U-10Mo LEU fuel plates

3. Conversion of the KUCA configuration preserving the reactivity

Using an Al edge around the foil, the thicknesses of the U-10Mo foils that would preserve in the LEU cores approximately the same reactivity as the corresponding HEU configurations were determined as shown in Table 1. All results presented in this paper are obtained for configurations with all control and safety rods fully withdrawn.

Table 1. Calculated (Experimental) k_{eff} Values of HEU and LEU KUCA Configurations

KUCA Configuration	V_m/V_f ; H/U5	k_{eff}: Calculation (Experiment)
A3/8"P36EU	5.91; 316.45	1.00402 ± 0.00006 (1.0008)
A3/8"P36LEU(22)	20.74; 215.78	1.00640 ± 0.00006
B2/8"P48EU	3.89; 206.96	0.99769 ± 0.00006 (1.0010)
B2/8"P48LEU(28)	10.71; 110.88	0.99958 ± 0.00007
B1/8"P80EU	1.94; 103.48	0.99882 ± 0.00007 (1.0015)
B1/8"P80LEU(29)+4*	5.17; 53.53	0.99903 ± 0.00007
B1/8"P60EU-EU	0.97; 51.74	1.00020 ± 0.00007 (1.0010)
B1/8"P60LEU(38)-LEU(38)+6*	1.97; 20.42	1.00053 ± 0.00006
B1/8"P48EU-EU-EU	0.65; 34.49	1.00114 ± 0.00007 (1.0015)
B1/8"P48LEU(38)-LEU(38)-LEU(38)+6*	1.32; 13.62	1.00105 ± 0.00006
*Indicates number of extra assemblies needed to match LEU and HEU reactivities.		

As indicated in Table 1, the configurations with LEU loading are named after the corresponding HEU configurations by changing the designation “EU” to “LEU” and indicating in brackets the thickness in mils of the U-10Mo foil. For the configurations of low V_m/V_f it was found that even increasing the thickness of the U-10Mo foils to the assumed maximum of 42.5 mils would not be enough to assure a reactivity value comparable to that of the corresponding HEU cores. Thus, for these configurations it would be necessary to add a number of peripheral fuel assemblies. Specifically, B1/8"P80LEU(29)+4 is obtained by adding the four fuel assemblies (J,12), (M,14), (M,15) and (J,17); B1/8’’P60LEU(38)-LEU(38)+6 is obtained by adding the six fuel assemblies (H,13), (M,13), (M,14), (M,16), (M,17) and (H,17); and B1/8"P48LEU(38)-LEU(38)-LEU(38)+6 is obtained by adding the six fuel assemblies (H,14), (M,13), (M,14), (M,18), (M,19) and (H,18).

4. Conversion of the KUCA configuration preserving the central flux spectra

Flux spectra were obtained in a central assembly [assembly (K,15) for A3/8"P36 and assembly (J,15) for all other configurations with both HEU and LEU] and were determined as average values in a specific region of the LEU foil (or HEU plate) closest to the core midplane. This region is 1 cm × 1 cm with an axial extension that corresponds to the thickness of the LEU foil (or HEU plate). All flux spectra were obtained in 53 energy groups. The calculations are performed in “homogeneous” mode, i.e. in absence of the external (D-T) neutron source usually present in these configurations.

Figures 4 to 8 show the comparison of the flux spectra determined for the HEU (red line) and LEU (brown line) configurations listed in Table 1. It is observed that the flux spectra in the LEU configurations are quite harder than in the corresponding HEU configurations. This result was expected since the H/U5 ratio of each LEU configuration listed in Table 1 is consistently smaller than in the corresponding HEU core. Flux spectra in the LEU configurations were then calculated for a thickness of the U-10Mo foils that preserves the same H/U5 ratio as in the corresponding HEU configurations and the results are also presented in Figures 4 to 8 (blue line). Taking into account the presence of the Al edge, the value of this thickness is 15.00098 mils.

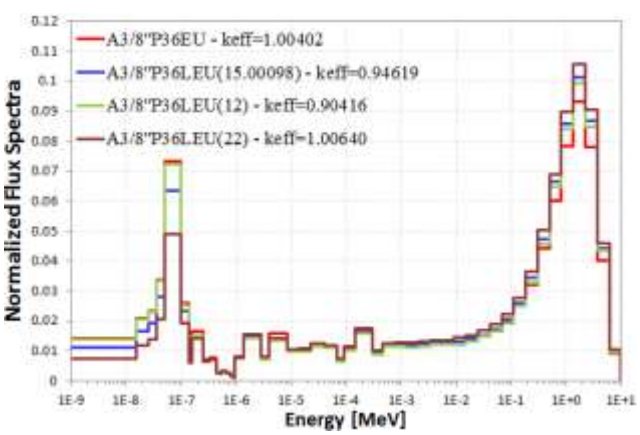


Figure 4. Central flux spectra in A3/8"P36EU and several A3/8"P36LEU

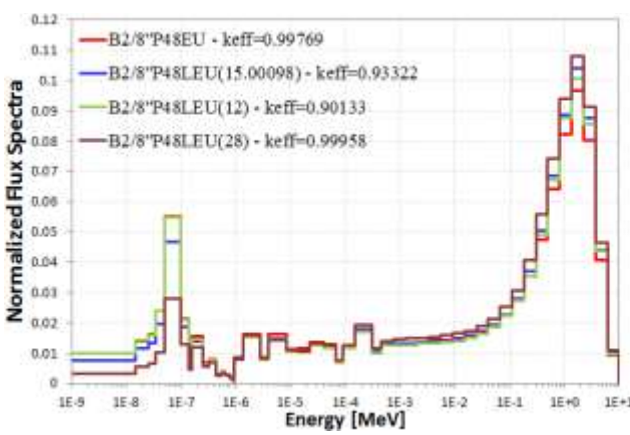


Figure 5. Central flux spectra in B2/8"P48EU and several B2/8"P48LEU

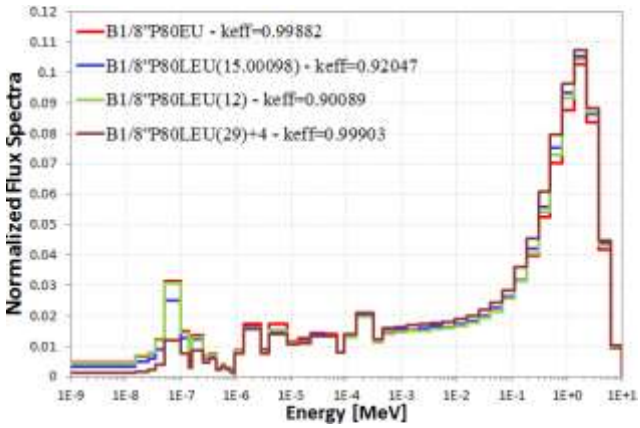


Figure 6. Central flux spectra in B1/8"P80EU and several B1/8"P80LEU

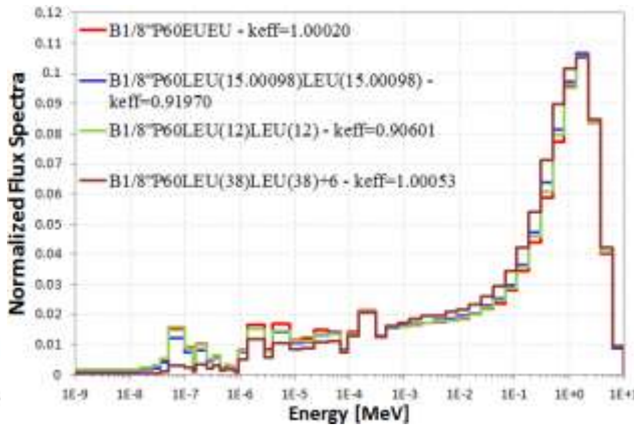


Figure 7. Central flux spectra in B1/8"P60EU-EU and several B1/8"P60LEU-LEU

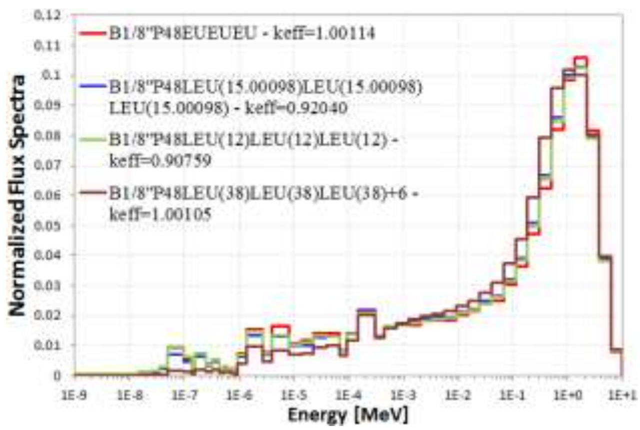
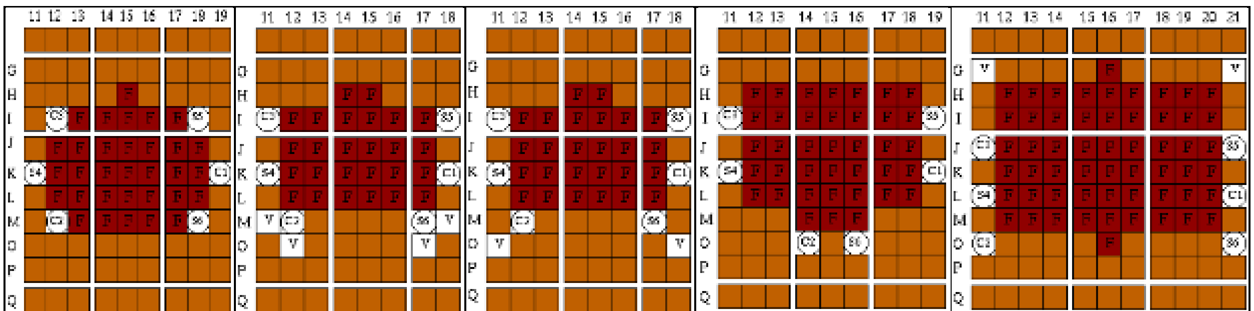


Figure 8. Central flux spectra in B1/8"P48EU-EU-EU and several B1/8"P48LEU-LEU-LEU

It is found that preserving the H/U5 ratio markedly improves the comparison of flux spectra between the LEU and HEU cores with respect to the previous cases. However, the energy flux distribution still remains slightly harder with the LEU loadings. For this reason, the thickness of the LEU foils was reduced further to 12 mils and as can be seen in Figures 4 to 8 the corresponding flux spectra (green line) show quite good agreement with the HEU cores. Particularly, the peak at thermal energies is accurately reproduced while only small discrepancies are observed at high energy. Unfortunately, as indicated in the legend of Figures 4 to 8, using 12-mil thick U-10Mo foils causes the reactivity values to be significantly smaller (discrepancy of the order of 10000 pcm for all cases) in the LEU cores with respect to the HEU cores.

The objective at this point was to increase the reactivity of the LEU configurations with 12-mils thick U-10Mo foils without altering the H/U5 ratio so that the flux spectrum would still be preserved. The simplest way to reach this goal is to add peripheral fuel assemblies to the core. Having to recoup about 10000 pcm for each configuration, the number of assemblies needed can be quite important. Figure 9 shows the layout of the new LEU configurations that would approximately reproduce the reactivity of the HEU cores using 12-mils thick U-10Mo foils. The new configurations are named as A3/8"P36LEU(12)+11, B2/8"P48LEU(12)+8, B1/8"P80LEU(12)+8, B1/8"P60LEU(12)-LEU(12)+14 and B1/8"P48LEU(12)-LEU(12)-

LEU(12)+22 where the '+xx' indicates the number of fuel assemblies that had to be added with respect to the corresponding HEU cores to obtain the desired reactivity value. As shown in Figure 9, besides the additional fuel assemblies, the reactivity increase was also achieved by moving some control or safety rods farther from the core center with respect to the corresponding HEU configurations. It is noted that the reactivity worth of a fuel assembly added at the core periphery is much smaller in the low H/U5 ratio configurations because of the harder spectrum and also because the assemblies are added at an increased distance from the center due to the larger core size with respect to the high H/U5 ratio configurations. Thus, for the configuration B1/8"P60LEU(12)-LEU(12)+14 fourteen fuel assemblies were added at the core periphery with respect to the corresponding HEU cores to get a multiplication factor close to 1, while as many as twenty-two fuel assemblies were needed for B1/8"P48LEU(12)-LEU(12)-LEU(12)+22. However, as shown in Figure 9 even for the high H/U5 configurations the additional fuel assemblies required to increase the reactivity to the desired values correspond to about 50% of the initial core loading. These results make the practicality of the configurations presented in Figure 9 rather questionable.



A3/8"P36LEU(12)+11	B2/8"P48LEU(12)+8	B1/8"P80LEU(12)+8	B1/8"P60LEU(12)-LEU(12)+14	B1/8"P48LEU(12)-LEU(12)-LEU(12)+22
V_m/V_f=38.02 H/U5=395.59	V_m/V_f=25.00 H/U5=258.71	V_m/V_f=12.50 H/U5=129.36	V_m/V_f=6.25 H/U5=64.68	V_m/V_f=4.17 H/U5=43.12

T_{LEU}=12 mils T_{AL}=25.25 mils E_{Al}= 100 mils

Figure 9. Layouts of the LEU KUCA cores reproducing about the same k_{eff} and central flux spectra of the corresponding HEU cores.

Figures 10 to 14 compare the central flux spectra of the KUCA LEU configurations (blue line) presented in Figure 9 with the HEU cores (red lines). As expected, the flux energy distributions at the core center of the LEU configurations are not affected by the addition of peripheral fuel assemblies and consequently the agreement with the HEU cores appears quite satisfactory. It is noted that the LEU configurations presented in Figure 9 offer another relevant advantage besides preserving both reactivity and central flux spectra. These configurations use all 12-mils thick U-10Mo foils so that (contrary to the LEU cores listed in Table 1) the fabrication of a single type of LEU coupon would be suitable in all five cases. The only, unfortunately not irrelevant, disadvantage of the LEU cores shown in Figure 9 is the considerable increase of the core size with respect to the corresponding HEU cores. Additional studies were made in an attempt to eliminate this disadvantage.

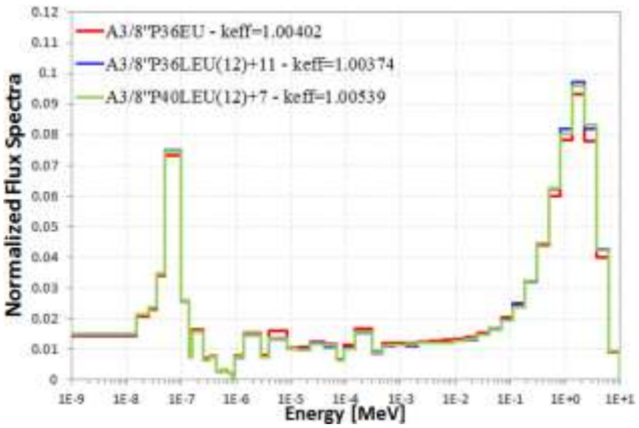


Figure 10. Central flux spectra in A3/8"P36EU, A3/8"P36LEU(12)+11 and A3/8"P40LEU(12)+7

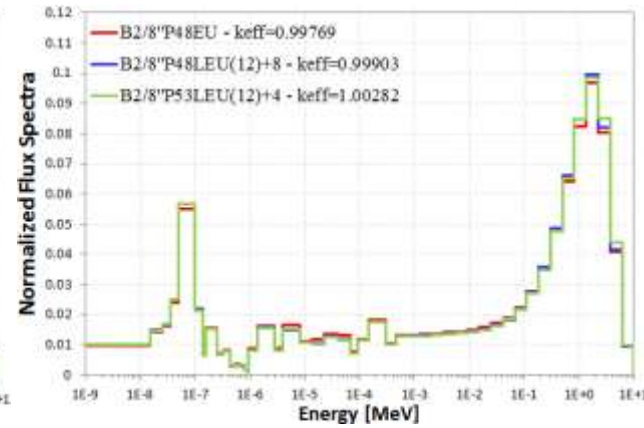


Figure 11. Central flux spectra in B2/8"P48EU, B2/8”P48LEU(12)+8 and B2/8”P53LEU(12)+4

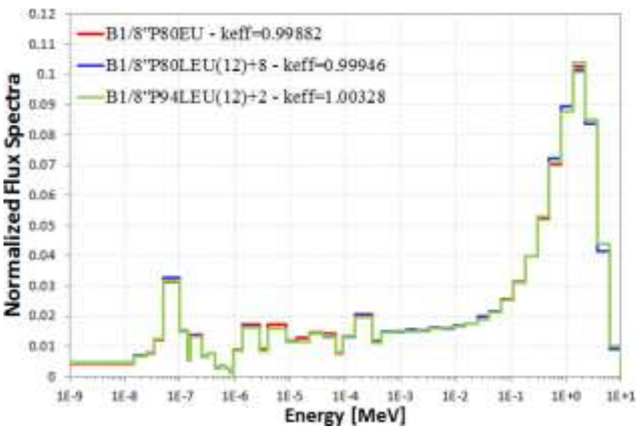


Figure 12. Central flux spectra in B1/8"P80EU, B1/8"P80LEU(12)+8 and B1/8"P94LEU(12)+2

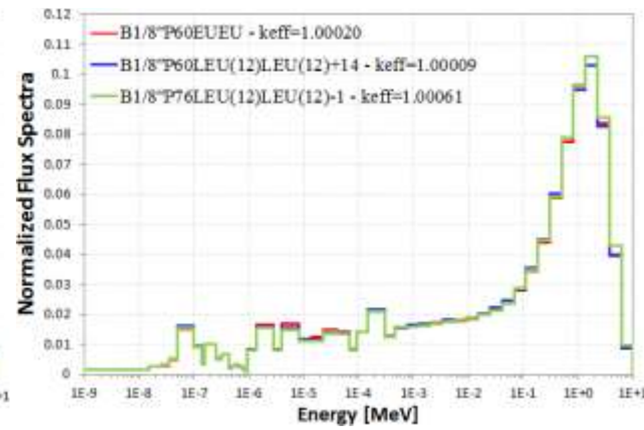


Figure 13. Central flux spectra in B1/8"P60EU-EU, B1/8"P60LEU(12)-LEU(12)+14 and B1/8"P76LEU(12)-LEU(12)-1

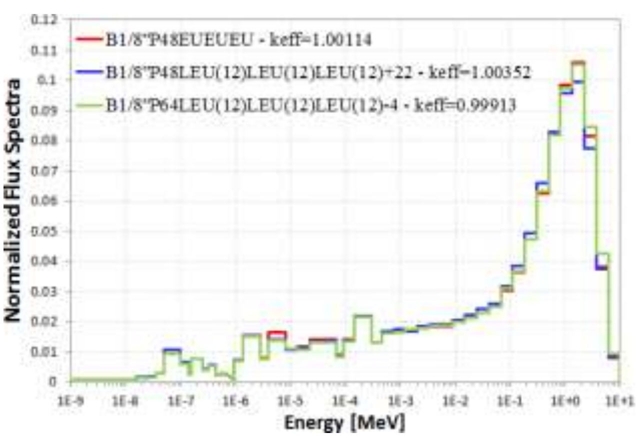


Figure 14. Central flux spectra in B1/8"P48EU-EU-EU, B1/8"P48LEU(12)-LEU(12)-LEU(12)+22 and B1/8"P64LEU(12)-LEU(12)-LEU(12)-4

All LEU cores investigated so far are based on the scheme illustrated in Figure 3 for the fabrication of the LEU coupons. According to this scheme, the total axial extension (thickness) of the coupon is always kept equal to that of the HEU plates being replaced. As mentioned in Section 2, this means that when using thinner U-10Mo foils, the thickness of the Al clad is adjusted so that the total axial extension of 62.5 mils is preserved. Particularly, for the configurations of Figure 9 with 12-mils thick U-10Mo foils, the thickness of the Al clad is 25.25 mils on both sides of the foil. As mentioned in Section 2, it is assumed that the thickness of the Al clad can be as thin as 10 mils. Thus, new LEU configurations were analyzed using 12-mils thick Al clad on both sides of the 12-mils thick U-10Mo foil, leaving the polyethylene plates unchanged. With respect to the previous cores shown in Figure 9, these new configurations keep the same H/U5 ratio but allow an increase in the number of unit cells (ensemble of LEU coupon and polyethylene plates as shown in Figure 2) along the axial height of the core so that the desired reactivity values can be reached while eliminating some peripheral fuel assemblies. Depending on the number of unit cells along the axial height of the core and on the number of peripheral assemblies added/removed with respect to the initial HEU configuration, the new LEU configurations are named A3/8"P40LEU(12)+7, B2/8"P53LEU(12)+4, B1/8"P94LEU(12)+2, B1/8"P76LEU(12)-LEU(12)-1 and B1/8"P64LEU(12)-LEU(12)-LEU(12)-4 and are presented in Figure 15.

It is noted that for the configurations of low H/U5 ratio the reduction of the Al clad to 12 mils saves room for a larger number of unit cells along the core height due to the presence of more LEU coupons in the same unit cell. As an example, for the configuration B1/8"P48LEU(12)-LEU(12)-LEU(12)+22, with three LEU coupons in the same unit cell, reducing the Al clad thickness to 12 mils would save room along the core height for an additional 16 unit cells (i.e. 1/3 more than the initial 48) so that the same reactivity can be achieved by eliminating as many as 26 peripheral fuel assemblies.

In summary, the LEU KUCA configurations shown in Figure 15 preserve the same reactivity and approximately the same flux spectra at the core center (as shown in Figures 10 to 14 with a green line) as the original HEU cores. Additionally, they are obtained by adding or even removing only a limited number of fuel assemblies with respect to the number of assemblies loaded in the HEU cores. Finally, similar to the previous set of LEU cores presented in Figure 9, the LEU cores shown in Figure 15 all use 12-mils thick U-10Mo foils so that the fabrication of a single thickness LEU coupon would be suitable in all five cases. All these findings would make the LEU configurations presented in Figure 15 the best candidates for the conversion of the HEU cores. However, it is recalled that the LEU configurations presented in Figure 15 preserve the reactivity and central flux spectra of the corresponding HEU cores when all control and safety rods are fully withdrawn in both cases (see Section 3). Since the control rod locations in the LEU cases have often changed due to the addition/removal of the peripheral fuel assemblies (see control rod location in the HEU and LEU cores by comparing the layouts of Figure 1 and 15, respectively), it is expected that this will affect the control rod reactivity worth of the LEU cores with respect to the HEU configurations. Consequently, with control rods fully inserted the LEU configurations shown in Figure 15 most likely will no longer preserve the reactivity of the corresponding HEU cores. Finally, the comparison of flux spectra between the HEU and LEU cores should be also carried out in presence of the 14 MeV (D,T) external neutron source and eventually in other important locations (besides the core center) where measurements will likely be performed. All of these results suggest that trying to determine how to best reproduce the neutronic features of the HEU cores with the use of LEU U-10Mo fuel is clearly not an easy task, but the results presented in this paper are certainly encouraging for further analyses.

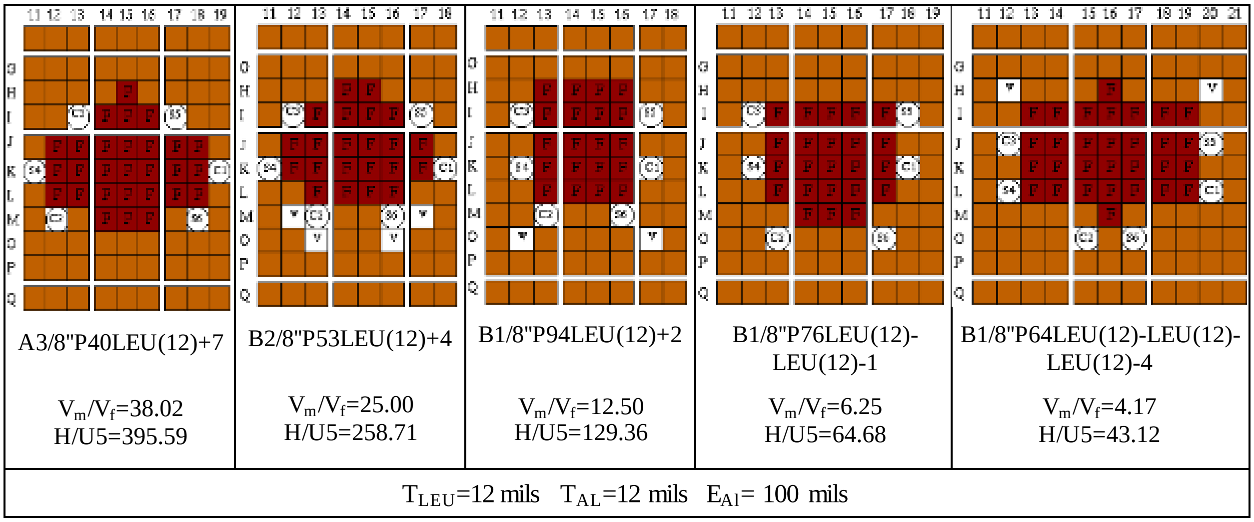


Figure 15. Layouts of the LEU KUCA cores using 12 mils thick U-10Mo foil and Al clad and reproducing about the same k_{eff} and central flux spectra of the corresponding HEU cores.

5. Preliminary sensitivity studies of the KUCA cores to dimensional tolerances of fuel plates

Preliminary studies were performed to address a potential issue associated with the feasibility of converting the KUCA LEU cores using U-10Mo foils. For a given volume of U-10Mo, the U-235 mass is ~5 times higher than in the same volume of the 93% enriched U-Al alloy of the HEU loading currently in use at KUCA. Consequently, the tolerances of the U-10Mo fabrication in principle should only need to be ~1/5 that of U-Al in order to give the same U-235 mass tolerance. On the contrary, considering that the LEU coupon uses very thin U-10Mo foils, the associated sensitivity to manufacturing tolerances will be likely larger than that of U-Al. Thus, sensitivity studies were performed for the KUCA cores both with HEU and LEU fuel in order to determine the maximum dimensional tolerances that would be acceptable during the fabrication of the fuel plates. As a first attempt the sensitivity studies for the LEU cores were performed by taking as a reference the configurations that are listed in Table 1 (i.e., the LEU configurations that preserve only the reactivity of the corresponding HEU cores). The sensitivity of the KUCA cores to the dimensional tolerances (or irregularities) of the plates has been investigated only in terms of reactivity impact. More detailed studies can be envisaged to also take into account the impact on the flux spectra. Also consider that, due to the extremely small dimensions that are involved, the fabrication of the LEU coupons with U-10Mo foils may be affected by several types of irregularities and some of them eventually cannot even be easily reproduced by the calculations, such as surfaces not completely flat or parallel, tiny bumps just on the edge of the foil, etc. Additionally, each coupon may have a different type of irregularity with respect to the other coupons in the same fuel assembly. Since the sensitivity studies assume that all coupons/plates in the cores are affected by the same type of irregularity, the results should be taken just as an indication of the effects due to potential irregularities of the plate fabrication.

Figure 16 shows the multiplication factor values obtained for the LEU KUCA configurations by varying the thickness of the U-10Mo foils from the minimum of 10 mils to the maximum of 42.5 mils. The k_{eff} values corresponding to the nominal dimensions are marked by the symbol "◊" for each configuration. Calculations are performed by changing the dimensions T_{LEU} and T_{Al} in

Figure 3, so that the total axial coupon extension of 62.5 mils is preserved. Consequently, the core height in each calculation remains unchanged as well. From Figure 16, it appears that the reactivity impact of the U-10Mo thickness fabrication tolerances is quite significant but it decreases for the configurations of low V_m/V_f (harder neutron spectra). Particularly, for KUCA A3/8"P36LEU(28) (the configuration with largest V_m/V_f) even a fabrication tolerance as small as 1 mil would have a reactivity impact of 600 – 700 pcm, while the effect decreases to ~200 pcm for B1/8"P48LEU(38)-LEU(38)-LEU(38)+6 (the configuration with lowest V_m/V_f).

For comparison purposes, Figure 17 shows the reactivity impact in the KUCA HEU configurations for changes of 1 to 6 mils on the thickness of the HEU plates. The calculations are performed by modifying the dimension T_{HEU} in Figure 3 and (since all polyethylene plates remain the same) adjusting the core height accordingly. It is observed that with the HEU loading, a 1 mil tolerance on the thickness of the fuel plates would have a reactivity effect of ~200 pcm in the worst case. Note that the volume associated with a 1 mil tolerance is also slightly larger than in the LEU case. Because of the Al edge, a 1 mil increase in the thickness of the LEU U-10Mo foils corresponds to a volume change that is 23% smaller than the volume change associated with a 1 mil increase in the thickness of the HEU plates.

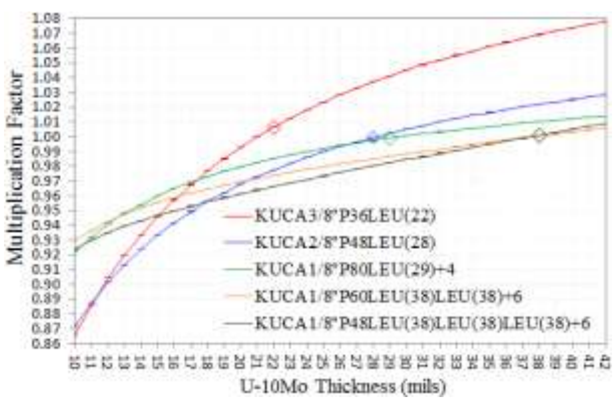


Figure 16. Sensitivity of KUCA LEU k_{eff} values to the tolerances of U-10Mo thickness

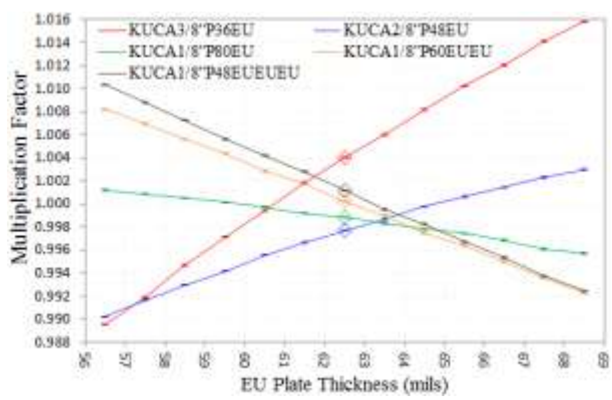


Figure 17. Sensitivity of KUCA HEU k_{eff} values to the tolerances of the fuel plate thickness

Figure 18 shows the impact on the multiplication factor values caused by postulated tolerances on the width of the U-10Mo foils. The calculations are performed by changing the dimension W_{LEU} in Figure 3 and adjusting the extension of the Al edge so that $W_{LEU} + 2E_{Al}$ remains equal to W_{HEU}. From Figure 18 it appears that a 1 mil tolerance on the width of the U-10Mo foils would have a rather small reactivity effect that varies from ~50 pcm in the configuration with largest V_m/V_f to ~20 pcm in the configuration with lowest V_m/V_f. The same tolerance on the width and on the thickness of the U-10Mo foils has a reactivity impact that is smaller in the first case primarily because of the different volumes of U-10Mo involved.

For comparison purposes, Figure 19 shows the reactivity impact in the KUCA HEU configurations for tolerances of 1 to 6 mils on the width of the HEU plates. The calculations are performed by changing the dimension W_{HEU} in Figure 3 for both fuel and polyethylene plates so that V_m/V_f remains unchanged. From Figure 19 it appears that the reactivity effect of a 1 mil tolerance in this case is ~140 pcm for all configurations.

The results discussed in this section make it clear that the fabrication of the LEU coupon should rely on extremely high accuracy. Particularly, the tolerance on the thickness of the U-10Mo foil should be less than 1 mil (which is probably unrealistic) or the reactivity effects could be non-negligible. Also note that the present sensitivity study has been performed by taking as a reference the LEU configurations that are listed in Table 1. A more appropriate sensitivity study would suggest taking as a reference the configurations presented in Figure 15 that preserve both reactivity and flux spectra of the corresponding HEU cores. Since these configurations have a softer spectrum, the reactivity dependence on the dimensional tolerances of the plates is expected to be even stronger.

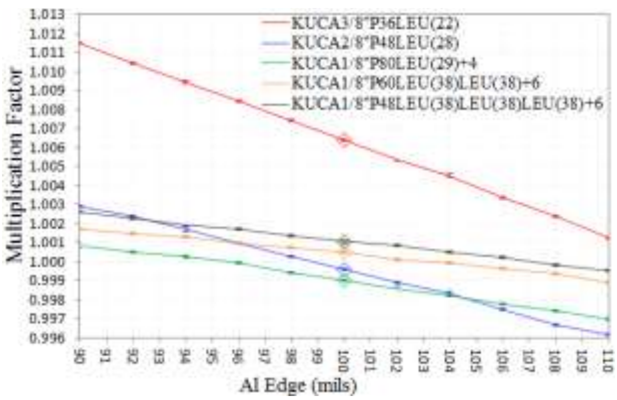


Figure 18. Sensitivity of KUCA LEU k_{eff} values to the tolerances of U-10Mo width

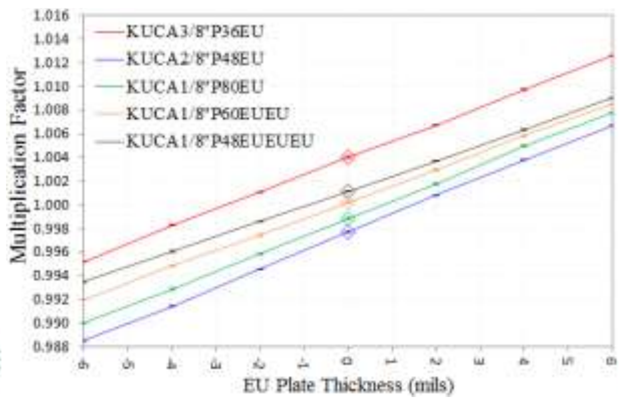


Figure 19. Sensitivity of KUCA HEU k_{eff} values to the tolerances of the fuel and polyethylene plate width

6. Conclusions

Recent studies demonstrated the feasibility of converting five type-A KUCA cores, characterized by different moderator-to-fuel volume ratios (V_m/V_f) and different H/U5 atom ratios in the fuel unit cell, from HEU to LEU (using U-10Mo fuel) by preserving the same reactivity with both loadings. A new set of LEU KUCA configurations was identified in the present paper that also preserves the same flux spectra at the core center as the original HEU cores. These LEU configurations are obtained by adding or removing only a limited number of fuel assemblies with respect to the number of assemblies loaded in the HEU cores and they use all 12-mils thick U-10Mo foils so that the fabrication of a single LEU coupon would be suitable for all configuration loadings. The features examined here certainly put the new set of LEU configurations among the best candidates for the conversion of the HEU cores. However, depending on feedback from the fuel fabricators and from the KUCA experimentalist team, there are still several aspects that require further analysis, such as the comparison of the neutronic features of the HEU and LEU loadings with control rods fully or partially inserted, or in presence of the 14 MeV (D,T) external neutron source and eventually in other important locations besides the core center where measurements will likely be performed. In summary, the work presented in this paper suggests that trying to determine how to best reproduce the neutronics features of the HEU cores with the use of LEU U-10Mo fuel clearly it is not an easy task but the present results are certainly encouraging for further studies.

The preliminary sensitivity studies presented here were performed for the KUCA cores both with HEU and LEU loading in order to determine the maximum dimensional tolerance that would be acceptable during the fabrication of the fuel plates. The results obtained make it clear that the fabrication of the LEU coupon with U-10Mo foils requires extremely high accuracy. In particular, the tolerance on the thickness of the U-10Mo foil should be less than 1 mil (which is probably unrealistic) or the reactivity effects could be non-negligible. Additionally, the present sensitivity study was performed by taking as references the initial set of LEU configurations that preserve only the reactivity of the corresponding HEU cores. By taking as references the set of LEU configurations that preserve both reactivity and flux spectra of the corresponding HEU cores, due to the softer spectrum the reactivity dependence on the dimensional tolerances of the plates is expected to be even stronger.

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