Core Physics Analysis of 100% MOX Core in IRIS

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Abstract

International Reactor Innovative and Secure (IRIS) is an advanced small-to-medium-size (1000 MWt) Pressurized Water Reactor (PWR), targeting deployment around 2015. Its reference core design is based on the current Westinghouse UO_2 fuel with less than 5% ^{235}U, and the analysis has been previously completed confirming good performance. The full MOX fuel core is currently under evaluation as one of the alternatives for the second wave of IRIS reactors. A full 3-D neutronic analysis has been performed to examine main core performance parameters, such as critical boron concentration, peaking factors, discharge burnup, etc. The enhanced moderation of the IRIS fuel lattice facilitates MOX core design, and all the obtained results are within the requirements, confirming viability of this option from the reactor physics standpoint.

KEYWORDS: IRIS, Integral PWR, MOX fuel, enhanced moderation

1. Introduction

IRIS (International Reactor Innovative and Secure) is an advanced small-to-medium-size (1000 MWt) PWR with integral primary system. [1,2] It relies on combining proven and worldwide accepted LWR technology with innovative engineering. While the use of proven technology enables IRIS to target deployment already around 2015, its innovative solutions address all the key requirements for the next generation of reactors. Consistent with its aggressive development and deployment schedule, the "first IRIS" reference design assumes current, licensed fuel technology, i.e., UO_2 fuel with less than 5% ^{235}U enrichment. However, more advanced core configurations are being examined in parallel for the second wave of IRIS reactors. [3] These studies which include evaluation of the full MOX core capability are presented in this paper.

2. IRIS Reference Core Design

2.1 UO_2 Core Design

The IRIS core includes 89 fuel assemblies employing square lattice, standard 17x17 layout (with 264 fuel rods, 24 locations for control rods and the central location for instrumentation), and a standard fuel rod size. The fuel design incorporates standard Westinghouse fuel features, except for the: (a) lattice pitch, which has been increased from 0.496" from to 0.523", thus increasing the moderator-to-fuel volume ratio Vm/Vf from

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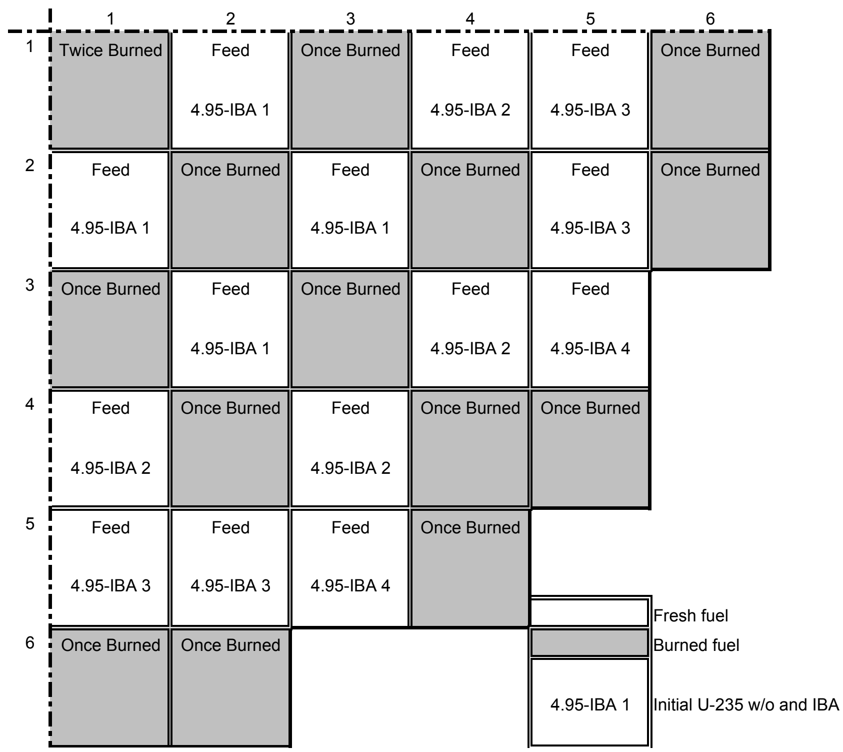
~1.7 typical for standard 17x17 fuel to ~2.0 for IRIS, and (b) plenum volume, which has been roughly doubled, compared to present PWRs. The increased moderation leads to better fuel utilization thus favoring longer cycle length than in a standard PWR, the larger plenum volume eliminates internal rod pressure issues and enable higher fuel burnup.

A reference 2-batch core design and reload strategy have been devised for UO_2 fuel, as depicted in Fig. 1. Erbia (Er_2O_3) is employed as the Integral Burnable Absorber (IBA), at 4 concentrations (IBA 1 through IBA 4 in Fig. 1). Erbia has slower depletion rate than other burnable absorbers employed in PWRs (Gd in Gd_2O_3, gadolinia, and ^{10}B in ZrB_2, IFBA), which makes it suitable for reactivity and power distribution control over the long cycle. Additionally, optimized Er+IFBA configurations are being examined, but this is outside the scope of this paper. The two-batch UO_2 core configuration satisfies all operational and safety constraints, and provides a cycle length of about 3.5 years.

Figure 1: IRIS reference 2-batch UO2 core.



2.2 MOX Core Design

A MOX core design has been developed analogous to the UO_2 core design. The same 2-batch reloading strategy has been used, but the fuel rod size has been slightly reduced (from standard 0.374" to thinner 0.360" rods). The thinner fuel rods further enhance the moderator-to-fuel volume ratio to ~2.3 with respect to ~1.7 of standard PWR fuel. This softens the spectrum making it closer to UO_2 spectrum, and facilitates satisfying safety requirements, which are otherwise challenged in current PWRs with MOX by safety constraints related to reactivity feedback, control rod worth, etc. Additionally, the fissile content has been increased from 4.95% ^{235}U to ~5.5% fissile Pu ($^{239}Pu+^{241}Pu$) to obtain similar cycle length as in the UO_2 core. Radial distribution of burnable absorbers has been kept qualitatively similar, but ZrB_2 (IFBA) instead of erbia is employed, as discussed later.

3. Spectral differences between UO_2 and MOX fuel and effect of the enhanced moderation in IRIS lattice

The spectral differences between UO_2 and MOX fuel have been investigated in 2-D transport calculations with full energy detail but at a single assembly level with reflective boundaries. The fissile content chosen for the assembly study is the same as in the respective core design, namely ^{235}U at 4.95 w/o for the UO_2 fuel and fissile Pu at 5.5 w/o for the MOX fuel. Fuel dimensions and lattice type for IRIS are as indicated above, yielding Vm/Vf of roughly 2.0 for UO_2 and 2.3 for MOX fuel.

In order to assess the impact of the enhanced moderation, calculations are repeated using fuel parameters typical of a standard PWR with Vm/Vf of ~1.7, and results are compared to those obtained for IRIS. The cases analyzed and the associated moderator-to-fuel volume ratios are summarized in Table 1.

Table 1: Moderator-to-fuel volume ratio (Vm/Vf) for UO2 and MOX in IRIS and standard PWR

	UO_2 Fuel Vm/Vf	MOX Fuel Vm/Vf
IRIS	2.0	2.3
Standard PWR	1.7	1.7

The spectrum for the different cases is shown in Fig. 2 at BOC and Fig. 3 at 40 GWd/tHM, representative of the fuel discharge burnup. The MOX spectrum is still substantially harder than the UO2 spectrum for all the analyzed cases; however, the IRIS increased moderation approach yields noticeably softer spectrum than that in a typical PWR. As the fuel depletes, UO_2 and MOX spectra become closer (Fig. 3); this is mainly due to actinide fertilization in UO_2 fuel and Pu depletion in the MOX fuel. On the other hand, the difference in spectrum between IRIS and standard PWR fuel is larger at higher burnup, which reflects the cumulative effect of the spectral softening produced by the enhanced moderation. The implications of the MOX harder spectrum on neutron thermal absorbers behavior are discussed next. The benefits of the enhanced moderation are examined in section 3.2.

Figure 2: Spectrum in UO_2 and MOX with IRIS and standard PWR lattice (BOC)

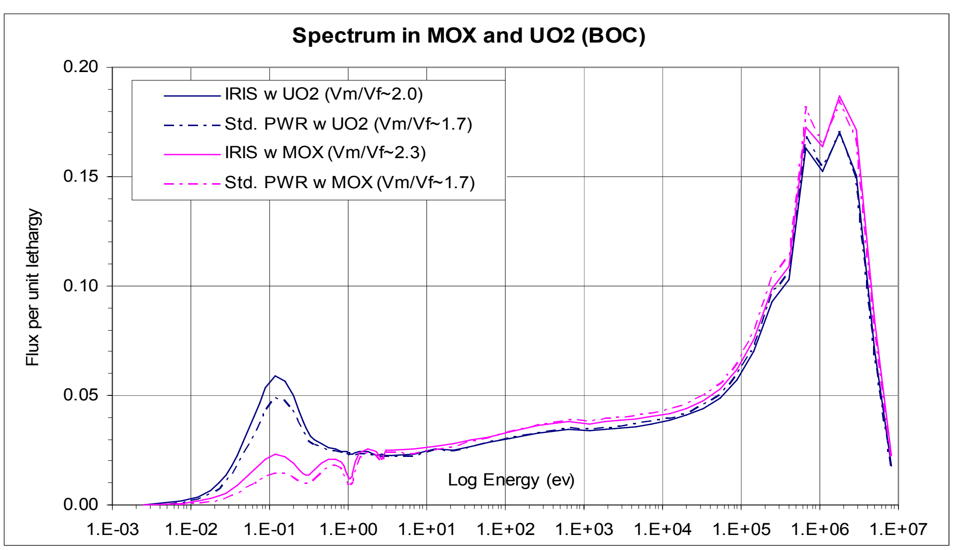
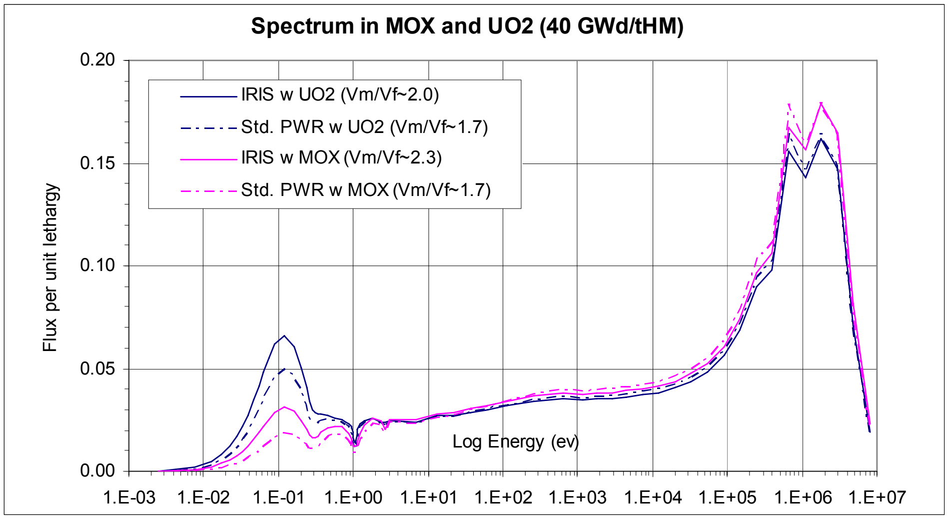


Figure 3: Spectrum in UO_2 and MOX with IRIS and standard PWR lattice (40 GWd/tHM)



3.1 Neutron absorber behavior in MOX fuel

As a result of the harder spectrum, the worth of thermal neutron absorbers (soluble, integral and inside the control rodlets of the control banks) is reduced in the MOX core with respect to the UO_2 core. Therefore, adequate countermeasures are required to maintain the core control capability in the full-MOX core similar to the one in the UO_2 design.

Besides having lower worth, fuel burnable absorbers (BAs) in MOX deplete at a slower rate than in UO_2. The lower worth is partially compensated by the lower excess reactivity in the MOX fuel but the slower depletion rate may lead to a substantial end-of-cycle reactivity penalty if burnable absorbers are not adjusted. The approach taken in IRIS is to use IFBA in the MOX core, in place of erbia which is employed in the UO_2 design. Due to the larger absorption cross-section of IFBA with respect to erbia, and its relatively large concentration, low soluble boron concentration is obtained in the MOX design as in the UO_2 design, notwithstanding the reduced soluble boron worth in the MOX spectrum. Moreover, the slower depletion rate of ^{10}B in the MOX spectrum extends the IFBA reactivity control capabilities to a higher burnup than in UO_2, while reducing the power swing following IFBA consumption. The smoother depletion of IFBA in the MOX spectrum can be appreciated in Fig. 4, comparing K-inf vs. BU of respectively MOX (blue line) and UO_2 (magenta line) fuel assemblies with relatively high IFBA content.

Figure 4: K-inf. vs. BU of IFBA fuel in UO_2 and MOX

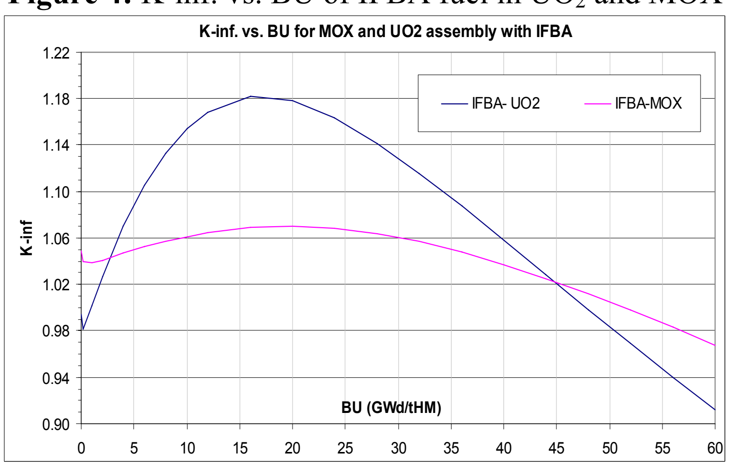
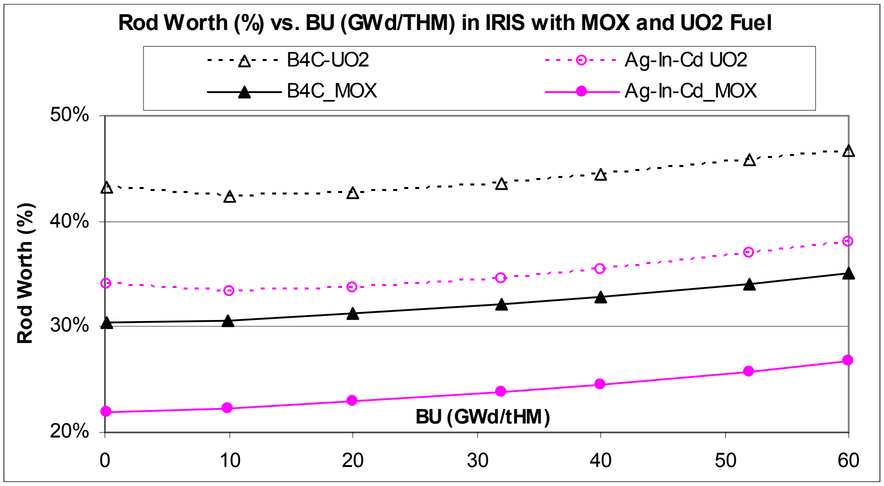


Fig. 5 compares the rod worth of B_4C and Ag-In-Cd banks for the MOX (solid lines) and UO_2 (dotted lines) fuel assemblies. The rod worth in the MOX design is considerably lower. In order to offset this rod worth reduction, more absorptive materials are employed in the control rodlets of the MOX design with respect to their counterpart in the UO_2 core. In particular, it is found in 3-D core simulations that replacing Ag-In-Cd with B_4C banks allows complying with shut-down margin requirements, while leaving some margin available for further bank optimization for reactor control and load following maneuvers.

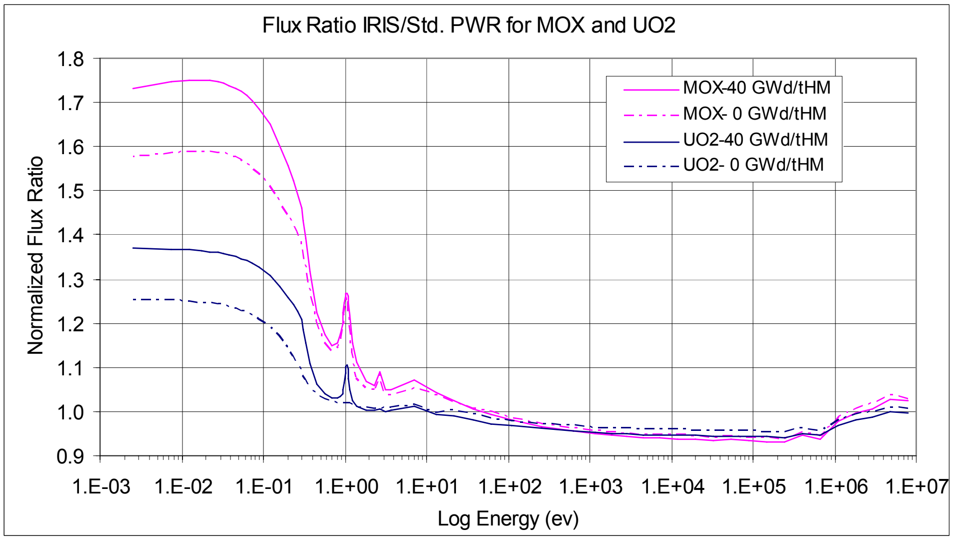
Figure 5: Rod worth vs. BU in UO_2 and MOX (selected materials)



3.2 Benefits of IRIS enhanced moderation

The softening of the neutron spectrum fostered by the IRIS enhanced moderation can be appreciated in Fig. 6, showing the ratio of fluxes for IRIS and standard PWR with either MOX (magenta lines) or UO_2 fuel (blue lines) as a function of the energy. Due to the increased moderation the flux in the thermal range for IRIS lattice is ~30% softer for the UO_2 fuel and over 60% softer for the MOX fuel with respect to standard PWR lattice.

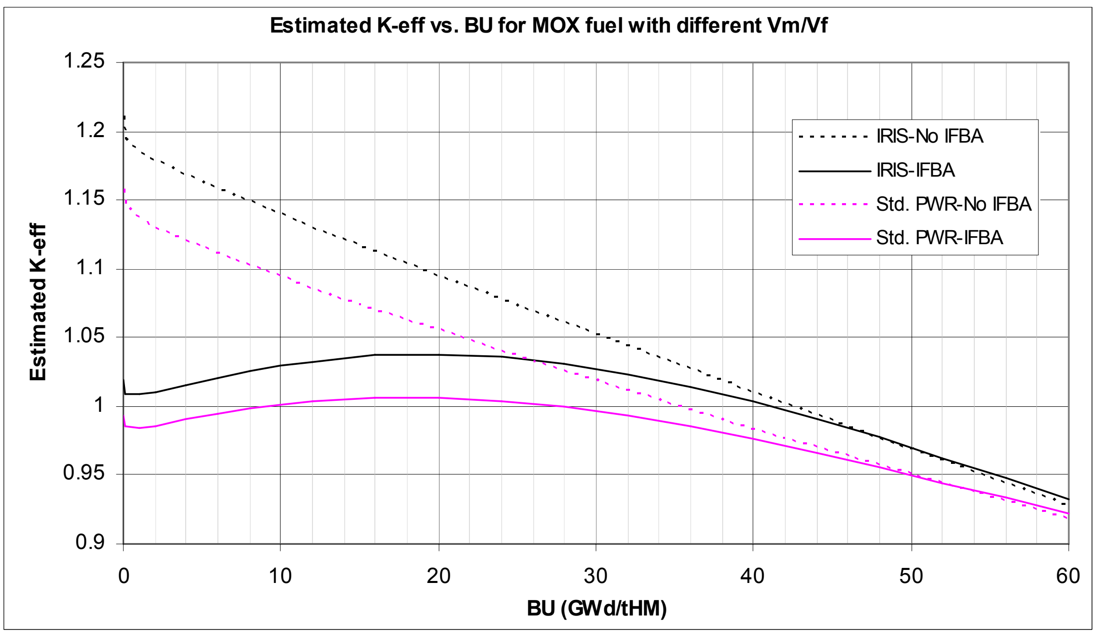
Figure 6: IRIS flux/PWR flux in UO_2 and MOX fuel



This spectrum softening improves neutron economy for the fuel enrichment and discharge burnup typical of commercial PWRs. Already in the UO_2 core this translates into a ~5% increase in the cycle length, which yields significant economic benefits.[4] However, the benefits of the enhanced moderation for the MOX design are of even greater importance.

The first beneficial effect is the increased fuel utilization (discharge burnup), as for the UO_2 core but of a larger magnitude, gained from the further enhanced moderation in IRIS MOX fuel with respect to standard PWR (Vm/Vf is increased from 1.7 to 2.3). The increase in fuel utilization is promoted by more efficient usage of the fuel fissile material, but also by more complete depletion of burnable absorbers in presence of the softer spectrum. The relative importance of these contributions is illustrated in Fig. 7, showing the reactivity of MOX fuel with and without IFBA, for IRIS and a standard PWR. The fuel containing IFBA features relatively high ^{10}B concentration, needed to control reactivity over the long IRIS cycle. The "estimated *K-eff*" corresponds to the *K-inf* of the assembly reduced to account for the neutron leakage.

Figure 7: K-eff of MOX fuel assembly with and without IFBA (IRIS vs standard PWR lattice)



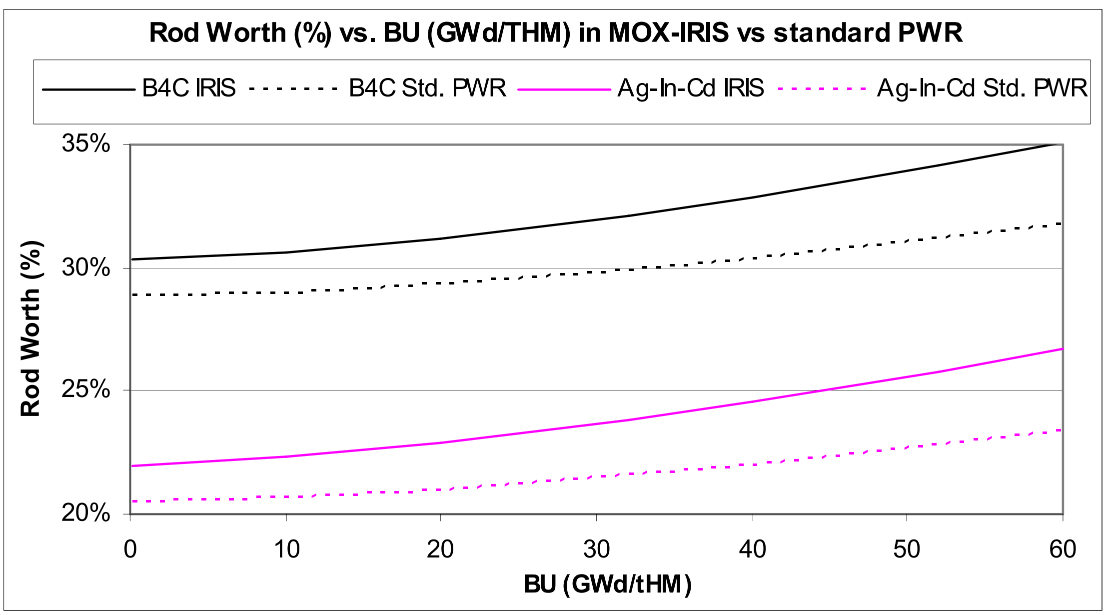
Although the predictions are only qualitative, the assembly study shows a significant improvement in fuel utilization as a consequence of the increased moderation (compare the burnup corresponding to a *k-eff* of 1 for the different fuel types). Moreover, the burnable absorber depletion is considerably more effective than it would have been in a standard PWR fuel lattice, where the high concentration of BA proposed in this study would lead to unacceptable penalty on cycle length.

The enhanced burnable absorber depletion of IRIS expands the range of BA type and loading that can be employed in the fuel, ultimately leading to more flexible operation. Namely, it allows to incorporate heavy BA loading to obtain low soluble boron concentration in the MOX core as well as in the UO_2 core, with benefits from reduced primary system corrosion and volume of liquid wastes, and more favorable reactivity coefficients. Achieving low soluble boron concentration with MOX is more difficult than with UO_2 due to generally reduced boron worth in the harder spectrum. However, due to the enhanced moderation, the reduction of boron worth is mitigated in IRIS, facilitating the low soluble boron concentration.

Another important beneficial effect of the enhanced moderation, and of the increased lattice pitch, concerns the worth of the neutron absorbers contained in the control rodlets of the control banks. Due to the IRIS increased pitch, the space available for the guide tubes of the control rods is larger, ultimately enabling increased diameter of the neutron absorber pellets contained in the control rodlets. The effect of the larger pellets favorably combines with the increased effectiveness of neutron absorbers due to the enhanced moderation to yield higher control rod worth[b] Fig. 8 shows the control rod worth of MOX fuel assembly for IRIS and standard PWR fuel lattice with either B_4C or Ag-In-Cd rodlets.

IRIS has larger worth than standard PWR banks for the two analyzed absorber types, with more significant increase at higher burnup. For the reference two-batch reloading scheme, once-burned fuel assemblies (with higher burnup) are mainly placed under the control rods, with the corresponding larger rod worth increases (right side of Fig. 8). The benefit of the enhanced moderation lattice on rod worth can be exploited to limit the number of banks to be replaced when moving from the UO_2 to full-MOX core design and to improve the reactor control capability during load-following maneuvers.

Figure 8: Rod Worth in MOX for IRIS and standard PWR fuel lattice



3. Full Core Analysis

3.1 Methods Used and Analyses performed

Westinghouse standard core physics analytic tools have been used for this analysis, including the PHOENIX code for cross section generation and the ANC code for 3-D analysis. [5,6] Analysis of several

[b] Rod worth in percent is calculated as $100 \cdot \ln(K_{\infty,unrodded}/K_{\infty,rodded})$

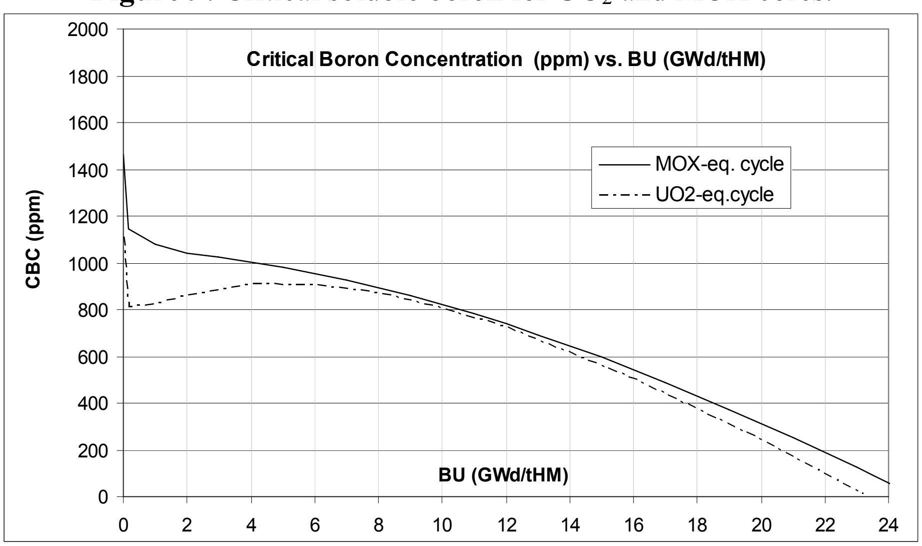
successive cycles starting with cycle 1 and leading to an equilibrium cycle has been performed for both MOX and UO_2 cores. All main reactor physics parameters have been evaluated in each case, and compared to each other, including the critical boron concentration, discharge burnup, peaking factors ($F_{\Delta H}$, F_z, Fq) and reactivity coefficients.

3.2 Results

The critical soluble boron concentration (CBC) for the UO_2 and MOX cores is shown in Fig. 9. CBC is initially higher in MOX core due to reduced effectiveness of neutron absorbers (burnable and soluble) in harder spectrum. The slope later becomes flatter due to conversion of even/fertile Pu isotopes into odd/fissile Pu isotopes. The higher reactivity for MOX fuel at higher specific burnup (GWd/tHM) is offset when converted to "equivalent full power days" by its lower heavy metal loading due to the smaller fuel rods, resulting in approximately equal cycle length.

Fig. 9 shows that CBC is below 1000 ppm for most of the cycle for both the UO_2 and the MOX core. This is a considerably low level of soluble boron, especially when considering the long cycle of operation, ~3.5 years, and additionally for MOX fuel, the reduced worth of boron in the harder spectrum. Beside the benefits from reduced primary system corrosion, the low soluble boron concentration favors lower values of the reactivity coefficients, and in particular of the moderator temperature coefficient (MTC). Fig. 10 shows that MTC is already negative at HZP over the entire cycle for both the UO_2 and the MOX core. Since MTC becomes lower as the power level increases, it ensues that MTC in IRIS is negative over the entire power range, with benefits on safety and reactor control.

Figure 9: Critical soluble boron for UO_2 and MOX cores.



The radial and total peaking factors $F_{\Delta H}$ and F_q are shown in Fig. 11 and Fig. 12, respectively. As suggested by these figures, the harder spectrum in MOX fuel tends to make depletion-related changes more gradual and reduces the spatial relocation of peaking factors over the cycle, reducing the cycle-wise maximum values as well. For the same reason, the maximum $F_{\Delta H}$ and F_q in the MOX core occur at higher burnups than in the UO_2 core. In this specific case, the maximum value of the radial peaking factor $F_{\Delta H}$ is lowered from ~1.52 to ~1.42 and the total peaking factor F_q is reduced from ~1.92 to ~1.72.

Figure 10: Moderator Temperature Coefficient at HZP for UO_2 and MOX cores.

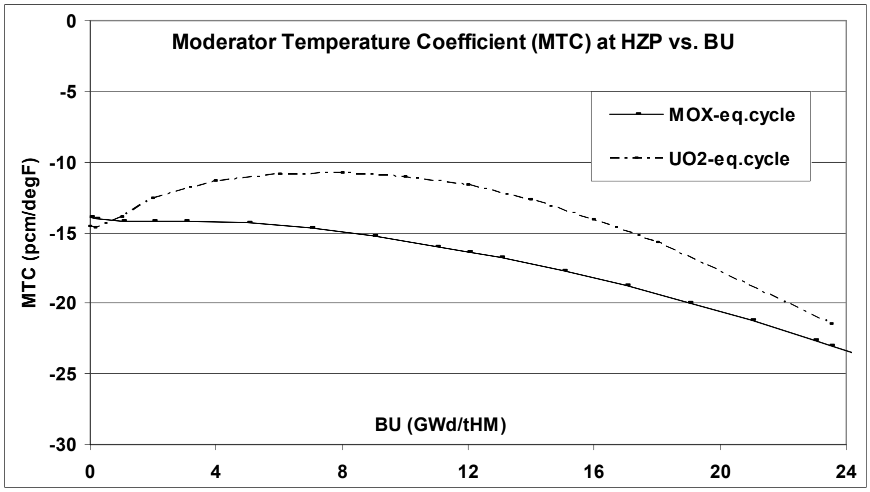


Figure 11: Radial peaking factor $F_{\Delta H}$ for UO_2 and MOX cores.

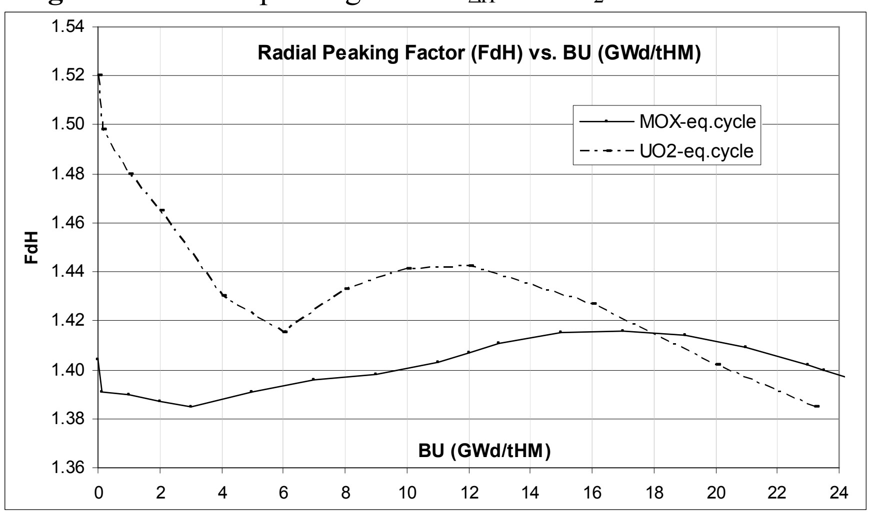
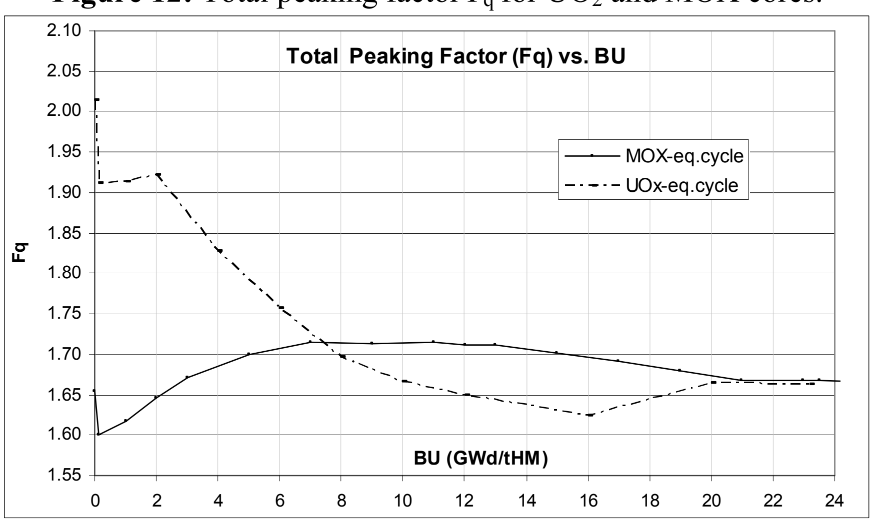


Figure 12: Total peaking factor F_q for UO_2 and MOX cores.



Other parameters including the axial offset, reactivity feedback coefficients, shut-down margin, etc., were examined as well. While the exhaustive safety analysis has not been completed, all main safety and operational requirements have been met.

All the results obtained so far confirm that a 100% MOX core is a viable option in IRIS, moreover, its enhanced moderation lattice makes the use of MOX fuel less challenging relative to its use in present PWRs.

4. Conclusion

In addition to the reference UO_2 core design, MOX core design is being developed for IRIS. IRIS fuel with its somewhat larger lattice pitch, and thus increased moderator-to-fuel ratio, facilitates implementation of a 100% MOX core. Comparison of a 2-batch equilibrium cycle MOX core to the reference equilibrium cycle 2-batch UO_2 core has shown that MOX core provides a comparable performance to the UO_2 core, and satisfies all main safety and operational requirements. Thus, while the reference "first IRIS" design features UO_2 based core, in the long term IRIS may also offer an attractive design for a 100% MOX core, should recycling and use of MOX fuel become the preferred option.

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