K_{eff} AND K_s BURN-UP SWING COMPENSATION IN MYRRHA

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Abstract

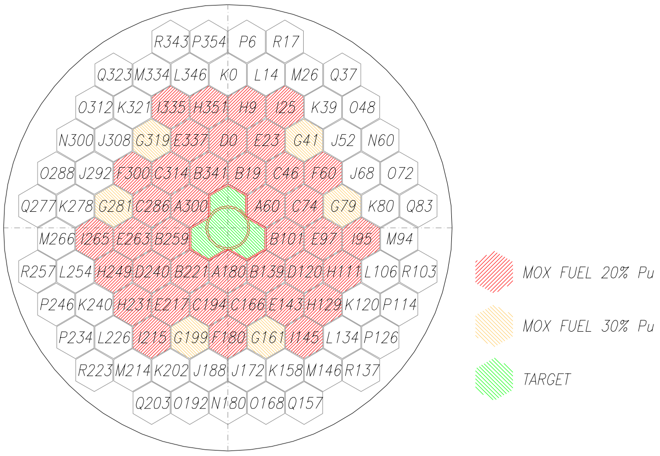
Burn-up for the reference core of MYRRHA over a single cycle of 90 days was estimated with MCNPX and SPECTRUM (an MCNPX postprocessor developed at SCK•CEN). Over this cycle, the source multiplication factor k_s dropped from 0.952 to 0.941 (Dr_s = 1 263 pcm) while the effective multiplication factor k_{eff} dropped from 0.946 to 0.933 (Dr = 1 484 pcm). A number of possible techniques have already been proposed and studied to minimise this burn-up swing such as proton current variation, use of burnable poisons, use of negative void coefficients and multi-batch core operation. We propose the concept of a realistic operational cycle in which voided boxes and/or burnable absorbers (with different levels of enrichment) are used to minimise the burn-up swing in the MYRRHA case. In this paper, we also make an initial assessment of the applicability of these operational cycles to the MYRRHA case.

Introduction

MYRRHA (multi-purpose hybrid research reactor for high-tech application) [1] is an ADS (accelerator-driven system) under development at the Belgian Nuclear Research Centre SCK•CEN in Mol, Belgium, which aims to serve as a basis for the European experimental ADS to provide protons and neutrons for various R&D applications including materials testing, transmutation experiments, etc. The system itself consists of a proton accelerator delivering a 350 MeV, 5 mA proton beam to a liquid Pb-Bi spallation target coupled with a Pb-Bi-cooled, subcritical fast core.

The configuration of the reference core [2] is shown in Figure 1. It consists of 39 fuel assemblies with 30% MOX (in red) and six assemblies with 20% MOX (in orange). The remaining channels are loaded with "dummy" assemblies, which are fuel assembly-like boxes filled with Pb-Bi coolant. The hexagonal fuel assembly for MYRRHA consists of 91 fuel pins, which are surrounded by a hexagonal shroud with an inner plate-to-plate width of 82.0 mm and a wall thickness of 1.75 mm. The cylindrical fuel pin itself has an outer diameter of 6.59 mm and an inner diameter of 5.55 mm. The fuel pellet contained within the pin has a diameter of 5.40 mm without an inner gap. The active length of the fuel is 600 mm. In this configuration, the source multiplication factor k_s is 0.95236 – 0.00028 and the effective multiplication factor k_{eff} is 0.94589 – 0.00020. The targeted operating regime for the system is three months (90 days) of operation followed by one month (30 days) of core reshuffling, loading and maintenance. It is foreseen to have two or three cycles per year (if necessary, followed by a longer maintenance period).

Figure 1. The MYRRHA reference core



For the purpose of burn-up calculations, the active part of a fuel assembly is divided into five equally sized segments. Each cycle of 90 days is then divided into six steps of 15 days. At the beginning of each cycle, the neutron spectrum in the fuel of each assembly segment is calculated using MCNPX [3]. The code SPECTRUM [4] (developed at SCK•CEN as a postprocessor for MCNPX) uses these spectra to calculate ORIGEN libraries [5] for all fuel assembly segments. This way, every segment has a library associated with it specifically for the cycle that we are studying. It is possible to recalculate the library for every burn-up step, but the neutron spectrum and the resulting library do not change enough to justify this approach. For every burn-up step, MCNPX is used to calculate the total flux in every segment for the depletion calculation. The composition of the material after each burn-up step (accounting for 99.99% of absorption in the fuel) is calculated by SPECTRUM using ORIGEN 2.2. This new composition is then used in MCNX for the next burn-up step. The nuclear data used for all calculations is JEF2.2 (unless stated otherwise).

Concept of a realistic operational cycle for MYRRHA

In a normal critical system like a pressurised water reactor (PWR), control is achieved by compensating the excess reactivity of the fuel with anti-reactivity obtained through various means to obtain a total reactivity level of zero. Some of these sources of anti-reactivity are the result of operation and/or the dynamics of the reactor like the xenon and samarium effect, the various temperature feedback mechanisms and the Doppler effect. Some of these effects can actually change as the burn-up of the fuel increases. Other sources are actively varied in time to compensate the excess reactivity of the fuel and to keep the total reactivity of the reactor at zero. In the case of a PWR, this is done by adding boric acid to the coolant of the primary circuit and by using control rods. At beginning of life (BOL), a large amount of positive reactivity is invested in the fuel. The boric acid in the water at BOL compensates most of this positive reactivity. The rest is negated by various other effects. At the end of the cycle, the anti-reactivity associated with the boric acid becomes zero and it is no longer possible to maintain the reactor at a zero reactivity level. At this point, the fuel has lost ~40% of its reactivity due to burn-up. For the following cycle, the fuel elements are reshuffled and new elements are introduced. The entire cycle then repeats itself.

A similar strategy can be adopted for an ADS-like MYRRHA. However, instead of using the normal reactivity ρ associated with the effective multiplication factor k_{eff}, we will use the reactivity ρ_s associated with the source multiplication factor k_s. The definition of this reactivity ρ_s is similar to that of normal reactivity ρ:

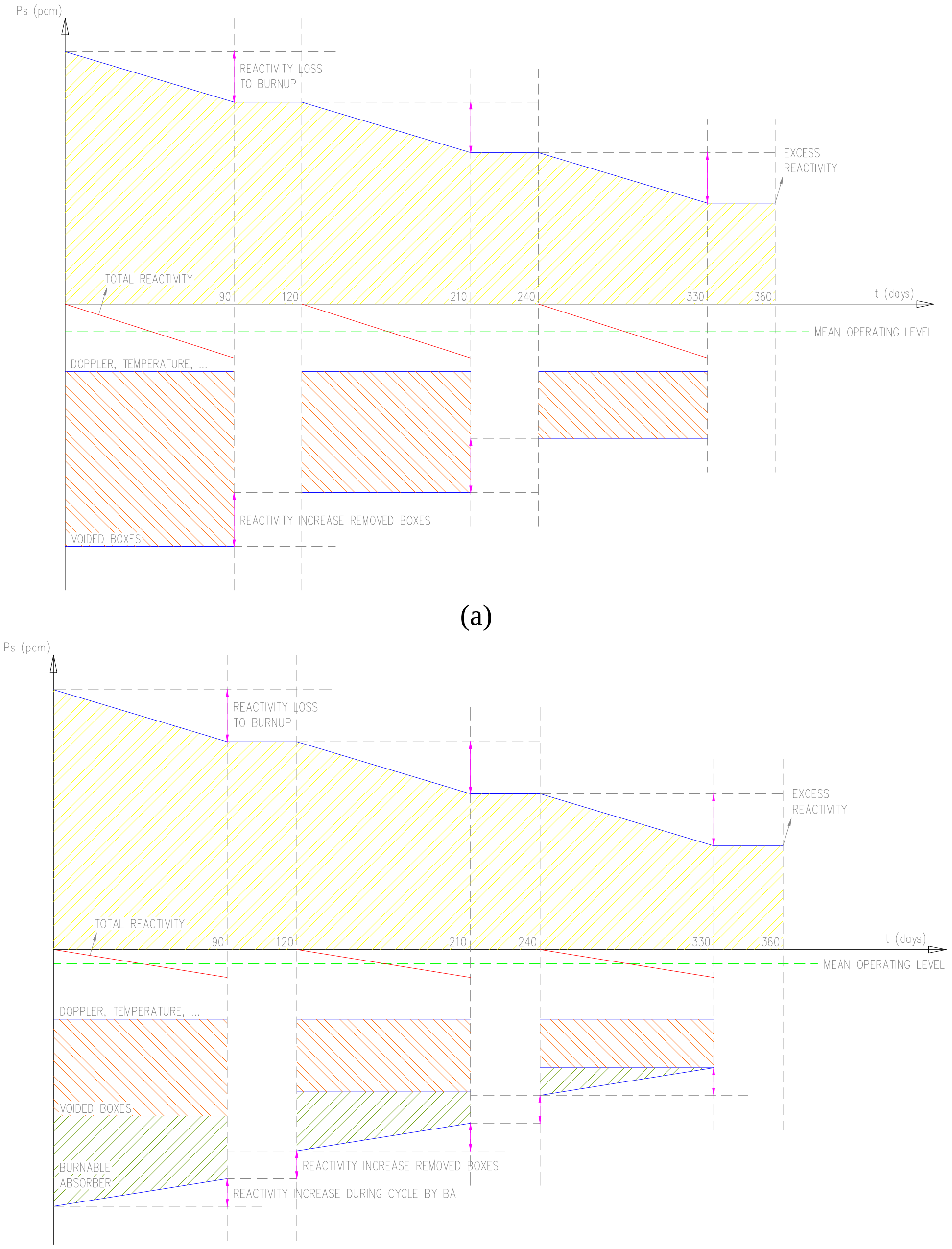
$$\rho_s = \frac{k_s - 1}{k_s} \tag{1}$$

Because ADS is always subcritical, this reactivity ρ_s will always be negative. As such, we cannot speak of positive and negative reactivity without rescaling this reactivity to a certain operating level ρ_{s0}. This value is a reference value for the reactivity and can be chosen freely. A choice for the operating level could be the reactivity ρ_s of the core at the beginning of the cycle, or even the mean value of ρ_s over an entire cycle.

We must insure that the fuel for MYRRHA will at least be able to compensate for all possible reactivity effects and the burn-up of a few cycles. Contrary to the case of a normal reactor where the excess of normal reactivity can be quite high, the maximum amount of reactivity ρ_s introduced by the fuel above the operating level is limited to $|\rho_{s0}|$ and should even be less if we want a sufficient safety margin. If the amount of reactivity introduced by the fuel would be higher than this value, the core could become critical under certain situations. This excess reactivity must be compensated through different means. First of all, there will be the inherent mechanisms that introduce anti-reactivity like the Doppler effect, temperature feedback effects on fuel and moderator/coolant, etc. We also require sources of anti-reactivity that we can actively use to bring the total reactivity back to the operating level. Possibilities would include the use of burnable absorber (either integrated in a fuel assembly or as a separate assembly placed around the core), control rods or fuel assembly-like boxes filled with helium at low pressure (this uses the negative void coefficient of the Pb-Bi coolant to introduce anti-reactivity). These have been shown in the past to be viable options [6,7,8].

The reactivity balance for MYRRHA using some of these techniques would look like Figures 2(a) and 2(b). These balances assume a single year of operation with three cycles of 90 days followed by 30 days of maintenance, with the same configuration of the core. Please note that these figures are not exact and that they are provided to give a sense of how the system would evolve.

Figure 2. Reactivity balances for MYRRHA



(a)

(b)

The first balance [Figure (2a)] depicts the situation in which only voided boxes are used. The voided boxes increase the radial and axial leakage from the core. As a result, fewer neutrons are scattered back into the core, hence lowering the reactivity of the core. It is important to note that these voided boxes are introduced in the reflector around the core. As the radius of the core increases, the effect of these boxes on the total reactivity will decrease (because the centre of the core will be unaffected by the increased leakage caused by the boxes). In the case of Figure 2(a), a number of boxes are added to the core resulting in an amount of anti-reactivity sufficient to compensate for a few cycles. The loss of reactivity during one cycle can now be compensated by removing a few boxes from the core. Because of this, the operating level will not drop below the initial level minus the reactivity loss of a single cycle.

We now obtain an average operating level over a single cycle of about the initial operating level minus half the reactivity lost over the cycle due to burn-up. It would also be possible to design the system so that the average operating level over a single cycle is the operating level we want to achieve over the cycle. We would only need to introduce some extra positive reactivity at the beginning of the cycle equal to half the amount of reactivity lost during a single cycle. This can be achieved by simply removing some voided boxes from the core or by increasing the excess reactivity in the fuel.

Figure 2(b) depicts the situation where voided boxes are used in combination with burnable absorber in the reflector. In this case, B_4C rods are introduced in the reflector (these are not control rods as they cannot be moved during a cycle). The amount of anti-reactivity decreases during the cycle, leading to a higher average operating level as compared to the voided boxes. When the configuration of the core changes a lot from cycle to cycle, the required composition of the rods will change from cycle to cycle (because the reactivity loss due to burn-up will differ from cycle to cycle). It would be necessary to custom-build the required rods for every cycle (the density of the burnable absorber must be adjusted so that the rod represents the right amount of anti-reactivity for that cycle). A solution to this problem would be the use of rods that represent a small amount of anti-reactivity for every cycle (e.g. half the reactivity loss of an average cycle, or 500 to 750 pcm for example). The rest could be compensated by a number of voided boxes. As a result, the total reactivity over a single cycle would only drop by one-half of the amount lost in the situation without burnable absorber [see Figure 2(b)]. Another method to compensate the burn-up swing would be the use of homogeneous poisoning of the core, preferably poisoning that can be adjusted during operation like boric acid in a PWR. A way to achieve homogeneous poisoning would be to incorporate small amounts of the poison in every fuel assembly (either in a single pin or by adding the poison to structural materials of an assembly). As with the rods in the reflector, we must take into account the different configurations of the core. This means that an amount of poison in an assembly that is just right for a given cycle will not necessarily be right for the next cycle. We also have to keep in mind that burnable absorber in the vicinity of the spallation source will have a negative effect on the source.

By using these operational cycles, we can keep operating value within a certain range and increase the residence time of fuel in the core. By using burnable absorbers, we can even reduce this range to half the range without burnable absorber. A compensation technique that can be altered during operation would be the most interesting for controlling the system. Using control rods would be the perfect solution but variation of the accelerator beam current is also an option. However, the latter will raise safety issues as we would need a beam current reserve. As a result, we would have to foresee the possibility of injection of the entire reserve at BOL of the core (represents the worst case scenario as the burn-up of the core is at its minimum). It should be noted that varying the beam current will not directly change the reactivity of the core; it will only allow us to maintain the same flux or power level during the cycle. This is because the power of the system is proportional to the beam current I_p:

$$P = I_p Y \frac{k_s}{1 - k_s} \frac{E_f}{\nu} = -I_p Y \rho_s \frac{E_f}{\nu} \tag{2}$$

In Eq. 2, Y is the neutron yield per proton, E_f is the mean energy released per fission (set to 210 MeV) and ν is the mean number of neutrons released (set to 2.94). As we can see, a reduction of the reactivity by 20%, for example, of its original value will cause the beam current to increase by 20% of its original value if the power over the cycle is to remain constant. So if a core loses 20% of its reactivity per cycle, and if it would operate during three cycles without any compensation of the reactivity loss, then the total amount of beam current required would be 160% of the initial value. When the core uses only voided boxes, this would be only 120% of the initial value. For the case of voided boxes combined with burnable absorber, this becomes 110% (if the burnable absorber compensates for half the reactivity loss). Variation of the beam current can thus be seen as a finetuning technique used in conjunction with other compensating techniques.

All of the above methods (except beam current adjustment) are techniques that can be used to keep the global reactivity level and thus the multiplication of the system as constant as possible. Constant multiplication, however, is not enough. We still need to make sure that we obtain the foreseen flux levels at discrete positions of the core. This can be controlled by fuel element reshuffling during the shutdown period between two cycles. There are two distinctly different refuelling schemes available to us. The first one is the in-out strategy. This involves the loading of new elements in the outer zone of the core and the relocation of older elements towards the centre of the core. This scheme is widely used in PWRs as it flattens the radial flux distribution. It does, however, cause significant neutron leakage from the reactor (something that can be rectified by using an appropriate reflector). The second strategy is the in-out strategy in which new elements are added in the centre of the core and older elements are moved to the outside. This causes neutron leakage to drop drastically but will also cause a radial flux distribution with a large peak in the centre.

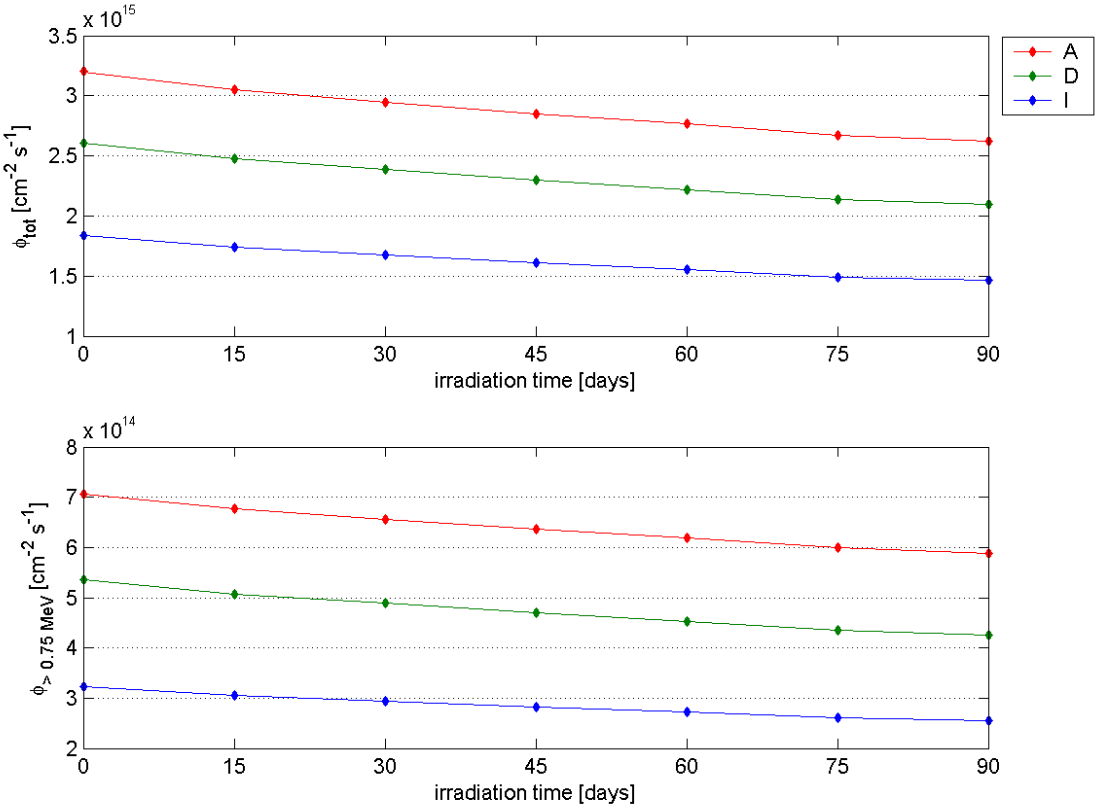
Burn-up in the reference core

Table 1 gives the evolution of the most important parameters (multiplication factors k_s and k_{eff}, reactivity and power of the system) of the reference core during one irradiation cycle. The upper part of Figure 3 shows the evolution of the total flux in the middle of three different assemblies (assembly A close to the source, assembly D in the middle of the core and assembly I on the outside of the core; see Figure 1). The lower part of Figure 3 shows the same for the fast flux ($E_n > 0.75$ MeV). Over this single cycle, the source multiplication factor k_s drops from 0.95236 to 0.94105 while the effective multiplication factor k_{eff} drops from 0.94589 to 0.93279. This equals a total reactivity loss of 1 263 pcm (associated with k_s) or a loss of 1 484 pcm of normal reactivity (associated with k_{eff}). As a result, the reference core of MYRRHA has lost almost 21.3% of its initial power during a single cycle. The total flux drops by ~20%. On the other hand, the fast flux drops by only ~15% compared to the values at the beginning of the cycle.

Table 1. Evolution of multiplication factors, reactivity values and power of the reference core

Time (days)	k_s	k_{eff}	$ɼ_s$ (pcm)	$ɼ$ (pcm)	P (MW)
0	0.95236 – 0.00028	0.94589 – 0.00021	-5 002 – 31	-5 721 – 23	42.80
15	0.94983 – 0.00038		-5 282 – 43		40.45
30	0.94806 – 0.00043		-5 478 – 48		38.87
45	0.94639 – 0.00045		-5 665 – 50		37.33
60	0.94417 – 0.00048		-5 913 – 54		35.87
75	0.94224 – 0.00048		-6 131 – 54		34.46
90	0.94105 – 0.00049	0.93279 – 0.00020	-6 265 – 55	-7 205 – 23	33.69

Figure 3. Flux evolution in the reference core



Modified core calculations

To demonstrate the feasibility of the operational cycles that we proposed earlier, we performed burn-up calculations over two cycles of a modified MYRRHA core (see Figure 4). This modified core was loaded with 45 assemblies with 30% MOX. The six assemblies with 20% MOX in the reference core were thus replaced by higher enriched assemblies providing us with 1 783 pcm of excess reactivity (which should more than suffice to compensate the reactivity loss over a single cycle). This excess reactivity was almost completely compensated by six voided boxes (accounting for 1 421 pcm of anti-reactivity) placed symmetrically around the core. The resulting modified core had slightly higher k_s and k_{eff} values compared to the reference core (see Table 2). The evolution of the multiplication factors k_s and k_{eff} as well as the reactivity and power of the system for this modified core during one irradiation cycle are given in Table 3. Figure 5 gives the evolution of total flux and fast flux (E_n > 0.75 MeV) in the middle of three different assemblies.

Table 2. Multiplication factors and reactivity values in the reference core and modified core

	Reference core	**Full 30% MOX core**	**Adding voided boxes**
k_{eff}	0.94589 – 0.00021	0.96614 – 0.00022	0.94969 – 0.00020
k_s	0.95236 – 0.00028	0.96881 – 0.00019	0.95565 – 0.00026
r **(pcm)**	-5 721 – 24	3 505 – 24	-5 298 – 22
r_s **(pcm)**	-5 002 – 31	-3 219 – 20	-4 640 – 29

Figure 4. The MYRRHA modified core

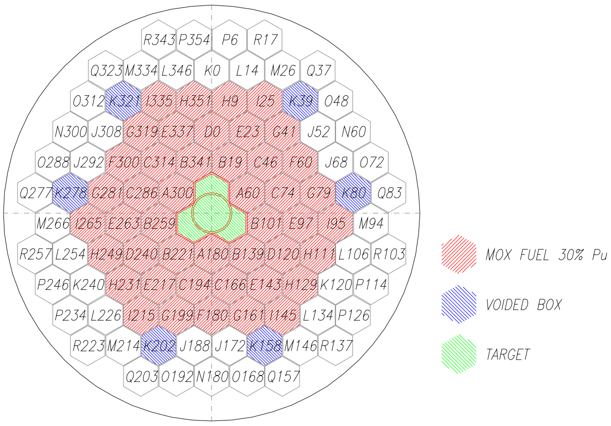


Table 3. Evolution of multiplication factors, reactivity values and power of the modified core

Time (days)	k_s	k_{eff}	r_s (pcm)	r (pcm)	P (MW)
0	0.95565 – 0.00026	0.94969 – 0.00020	-4 640 – 29	-5 298 – 22	46.21
15	0.95329 – 0.00048		-4 899 – 53		43.59
30	0.95053 – 0.00050		-5 204 – 56		40.83
45	0.94942 – 0.00051		-5 327 – 57		39.96
60	0.94762 – 0.00053		-5 528 – 59		38.23
75	0.94629 – 0.00054		-5 676 – 61		37.39
90	0.94367 – 0.00057	0.93611 – 0.00021	-5 969 – 64	-6 825 – 24	35.43
Cooling	-	-	-	-	-
120	0.95682 – 0.00033	0.95118 – 0.00021	-4 513 – 37	-5 133 – 23	47.55

During the first cycle, the source multiplication factor k_s of the modified core dropped from 0.95565 to 0.94367 while the effective multiplication factor k_{eff} dropped from 0.94969 to 093611. This equals a total reactivity loss of 1 329 pcm (associated with k_s) or a loss of 1 527 pcm of normal reactivity (associated with k_{eff}). As with the reference core, this modified core lost over 20% of its initial power during a single cycle. The total and fast flux dropped by ~20%.

At the beginning of the second cycle, the voided box assemblies were removed from the core. As a result, the reactivity of the core went up with 1 456 pcm, compensating the reactivity loss of the first cycle. The source multiplication factor went up to 0.95682 and the initial power of the system reached 48 MWth, which was somewhat higher than at the beginning of the first cycle. In other words, the system reached the power and flux level at the beginning of the first cycle without replacing or adding new fuel assemblies.

Conclusions

We have shown that the operational cycles proposed in this paper are realistic and that they can be applied to the MYRRHA case with ease. In the case studied (two cycles of 90 days using only voided box assemblies), it also appeared that adding new elements after the first cycle was not necessary to reach the operating level of the first cycle at the beginning of the second cycle. Further study will include the addition of burnable absorber to the core.

Figure 5. Flux evolution in the modified core

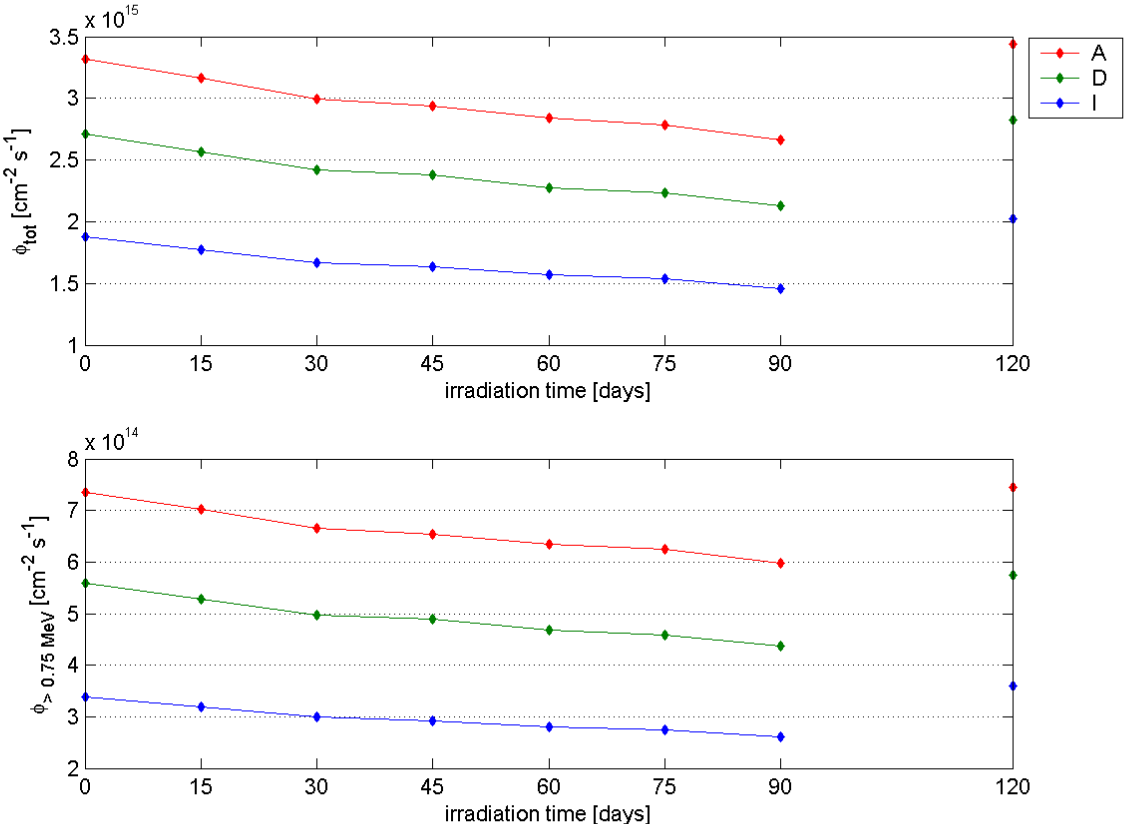


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TABLE OF CONTENTS

CHAIRS: B-H. CHOI, R. SHEFFIELD

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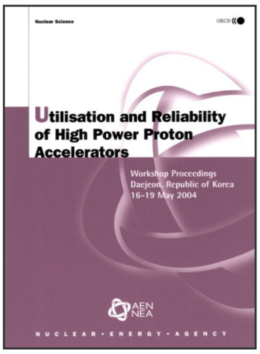

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