AGH University of Science and Technology
Faculty of Energy and Fuels
Department of Nuclear Energy

Adiabatic fuel cycle assessment of LFR core with MOX using MCB system

Study for the LEADER project of European Union's 7th FP EURATOM

AGH WEiP KEJ/2013/4

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Scope

This report describes the work done under the scope of deliverable 05 for the LEADER project, which is part of the European Commission's 7th framework program. It concerns the core performance and fuel cycle assessment of the LFR reactor loaded with MOX fuel (without MA) while applying an advanced Monte Carlo method - MCB. The major goal of the curried out investigation is the definition of LFR core in adiabatic cycle that is characterised by fuel zero breeding. Once system has been defined, the assessment of core physics is done to indicate the core features related to the fuel cycle characterization that leads to the refining of the neutronic and fuel cycle modelling methodology and then brings about an improved core fuel configuration in terms of burnup efficiency. The analysis includes burnup calculations in few-batch fuel reloading, the assessment of the equilibrium fuel composition in the fuel cycle with the actual reloading in a full core calculation, the power distribution with its evolution with burnup, and the modelling of the control rod operation for its influence on the fuel breeding ratio. The fuel zoning was considered by using two options – one with the varied radius of the fuel pellet annular void, and second that applies different zone enrichments of plutonium.

1. **Introduction**

Development of lead cooled fast reactors is being continued in the LEADER project basing on the achievements of its predecessor the ELSY project, where a few core options were investigated. Concerning the fuel cycle strategy, only a single-batch option was analysed, which has a few drawbacks in terms of limited burnup efficiency due to the occurrence of substantial reactivity swing or not favourable power profile evolution with time. As the level of achievable fuel burnup impacts directly the fuel cycle economy an elongation of achievable burnup is one of the major goals for the current step of LFR development. Other important goal that has been formulated during definition of LEADER work program is the application of adiabatic fuel cycle concept to the LFR design. The idea of adiabatic fuel cycle has two major advantages which are elimination of HM waste since all HM is fully recycled with no net breeding or burning, and simplification of fuel reprocessing, which requires no chemical separation but only a removal of fission products followed by an addition of depleted uranium to the required level of plutonium enrichment. In order to achieve these goals it is required to improve the core performance over the irradiation time, which means keeping proper power distribution over time long enough to reach requested burnup level and provide average zero breeding at discharge time.

Although the mixed oxide fuel is the reference fuel in ELSY as well as LEADER projects, the results of core configuration performance optimisation with nitride fuel showed pretty stable time evolution of the core power profile with smaller reactivity swing than that achieved in the reference oxide fuel core. Those features were easier to achieve mainly due to the higher density of the fuel and the proposed introduction of ZrN as the fuel inert matrix with the optimised fuel enrichment and inert matrix fraction zoning. Even if that option cannot be considered technologically matured and validated enough to be considered applicable in the LFR prototype, valuable recommendations from

that study can be adopted also in a MOX fuel core. The improvement that oxide core needs concerns the performance stability of the core along the irradiation time, that can be measured by the power form factors and reactivity swing. That will be possible once we introduce more flexibility concerning the fuel assembly and pin designs as well as few-batch reloading strategy. Since the fuel conversion depends on neutron flux distribution and its spectrum, it is important in design studies to include the modelling of the actual control rod insertion level during the fuel cycle, due to its influence on the neutron flux and spectrum. This is possible in the advanced Monte Carlo code system MCB [1], which has been applied in the current study and it has allowed us to model the CR operation during the cycle herein.

2. **Objectives and study outline**

The major objective of the Deliverable 5 is the definition of LFR core in adiabatic cycle loaded with MOX fuel without MA. Accomplishment of this objective has been done in a few steps as follows:

A. Definition of the adiabatic core concept, which includes its expected features and research direction leading to its realisation.
B. Initial assessment of the staring point core that is based on the FP6 ELSY core regarding the undertaken objective.
C. Specification of the design constrains concerning fuel pin and assembly parameters as well as the reactivity control system.
D. Core configuration development based on the results of performance assessment respectively to the considered configuration.

General definition of the core concept has been formulated in the specification of Task 2.1 of LEADER project according to the development of adiabatic fuel cycle done by ENEA, which later has been developed further in the course of LEADER project itself in the form of core expected features and possible ways of their realization, which then were translated to the core specific configuration and assessed in a design study by means of numerical analysis of the reactor core system. These assessments were drawn for various core configurations starting form the one produced in the ELSY project and then in the course of optimisation process continuing with the improved ones, thus leading to the finally proposed solutions.

The numerical tool used in our design study is a Monte Carlo Burnup calculation system – MCB, whose methodology in application for LFR core analysis is described in Chapter 3.

In Chapter 4 the definition of the adiabatic core concept is presented in terms of expected features and proposed research direction leading to its realisation. It also contains the constraints put on the core parameters and outlines the methodology of the core configuration development.
Chapter 5 comprises the results of the initial neutronic assessment obtained using the final core configuration of ELSY project as the starting point. This

assessment includes considerations of few-batch fuel reloading strategy in equilibrium state, which has involved modification of the fuel enrichments.

In Chapter 6 we present the results of adiabatic fuel cycle study of LFR core configurations which are done for two different approaches of fuel zoning - the first one with few enrichment zones that have been optimized for the maximum average burnup on discharge, and the second one with the uniform enrichment but the annular void of the fuel pins varied from zone to zone – the concept developed by ENEA and JRC and verified herein for its burnup performance.
The comparison of both approaches is presented, where the week and strong sides of them are shown.

Finally, Chapter 7 comprises recommendations and conclusions.

3. **Monte Carlo burnup code system - MCB**

The Monte Carlo Continuous Energy Burn-up Code (MCB) is a general-purpose code for the calculation of nuclide density evolution with time (after burn-up or decay). The code performs the eigenvalue calculations of critical and sub-critical systems as well as the neutron transport calculations in fixed source mode to obtain the reaction rates and energy deposition that are necessary for evaluation of the burn-up. MCB internally integrates the well-known MCNP code (currently - version 5 [2]), which is used for the neutron transport calculations, and novel Transmutation Trajectory Analysis (TTA) module. It forms, analyses and solves on-line the specific transmutation chains and then calculates the nuclide density evolution [3]. The code of version MCB1C became available to the scientific community on a freeware basis through Nuclear Energy Agency Data Bank, Package-ID: NEA-1643 in 2002. The MCB code was applied in many fuel cycle studies of nuclear reactor systems including “PDS-XADS” within the frame of the EU 5th FP, which concerned the lead-bismuth cooled subcritical reactor. The code has been under constant development for twelve years; recently added features concern statistical analysis of burnup, emitted particle collection thus enabling direct He4 production assessment, thermal-hydraulic coupling, power form factors assessment and others [4]. The further development is directed towards improved description of advanced reactors in models that can be more detailed as well as new analytical tools of Monte Carlo burnup analysis. Below the methodology of core design and fuel cycle analysis using MCB is briefly described.

3.1. Transmutation system assessment

The main goal of a burnup code is to calculate the evolution function of material density. In case of MCB, it concerns all possible nuclides that may emerge in the system as a result of nuclide decay, transmutation, or particle emission. The burnup calculation process also includes the fission product breakdown into nuclides, and the formation of helium and hydrogen atoms from alpha particles and protons emissions respectively. There is no required predefined list of nuclides under consideration since all transmutation chains are being formed automatically on-line, based on the physical conditions that

constrain the system under the control of user-defined thresholds. These thresholds concern the contributions to nuclide mass change from the constructed transmutation trajectories.

In a real system under irradiation or decay, the nuclide composition undergoes evolution that generally can be described with a continuous function of time. In MCB, the way of obtaining its approximation leads throughout a time step procedure, which starts from the reaction and decay probabilities assessment of every possible channel by means of stationary neutron transport calculations. In the next step the transmutation chain is formed and then solved to produce the nuclide density table in the required time points

3.2. General features

- The decay schemes of all possible nuclides and their isomeric states are formed and analysed based on the decay data taken from two sources. The first one – TOI.LIB, which is prepared based on "Table of Isotopes"[5], describes decay schemes for over 2400 nuclides and includes nuclide formation in excited states.
- Numerous cross-section libraries and data sets can be loaded into computer memory in support of the adequate calculation of reaction rates and nuclide formation probabilities. The data treatment is separate for every zone, which concerns the cross section temperature, the energy dependent distribution of fission product formation, and the energy dependent formation of isomer nuclides.
- Thermal-hydraulic coupling assessment is possible for gas-cooled systems; application to other cooling media is under development.
- Reaction rates are calculated exclusively by continuous energy method with the usage of the point-wise transport cross-section libraries and, in case of lack of proper library, by using dosimetry cross section library. The contributions to reaction rates are being scored at every instant of neutron collision occurring in cells filled with burnable material. For this, the code uses the track length estimator of neutron flux.
- Fission product yield is calculated from incident energy dependent distributions of fission products prepared separately for every fissionable nuclide.
- Heating is calculated automatically in a similar way as the reaction rates during neutron transport simulation by using heating cross section that is KERMA factors contained by standard cross section tables. The code also calculates automatically the heating from natural decay of nuclides, which allows for consideration of afterheat effects. The energy of decay is taken from the ORIGEN library.
- Time evolution of nuclide densities is calculated with the complete set of linear transmutation chains that is prepared for every zone and time step so it is being automatically adjusted to time evolving transmutation conditions. The code uses extended linear chain method, which is based on the Bateman approach, to solve a set of linear chains prepared on-line that noticeably contribute to nuclide formation. The program calculates transmutation transitions from nuclide to nuclide and prints them out to one of the output files. Transmutation chains that are formed by the code can also be printed for the nuclides of interest.

- Advanced modelling of material processing and system rearrangements is possible, which includes fuel shuffling, reloading and control rod operation (insertion or withdrawal).
- Automatic calculation of various system performance parameters is available including power profiles and form factors, neutron multiplication factors, radiotoxicity, afterheat and others.

4. Adiabatic core concept and its cycle modelling method

4.1. Meaning of fuel cycle strategy

The fuel cycle strategy applicable to a particular nuclear reactor system impacts the management of nuclear fuel as well as of its waste and plays very important role in many aspects of the nuclear system, such as:

- economy
- sustainability
- security of supply
- radiological hazard
- public acceptance
- political acceptance
- proliferation threats

As some aspects of the fuel cycle strategy may favour one cycle feature, they can be unfavourable regarding the other aspect. For example breeding of plutonium is favourable by the sustainability and supply security aspects, while being unfavourable by the proliferation threat aspect. The trade-offs between the different aspects always exist, which may result in the fuel cycle strategy preferences, yet depending on currently available nuclear technology and the phase of the related nuclear industrial system lifecycle. In this regard the fuel breeding is of the highest priority for times when resources of U235 will become scarce. The fuel breeding needs have been the main incentive to undertake the development of Generation IV reactors, in which the number of fast breeders prevail over the other ones. One may think, the maximisation of breeding would be the optimal solution, but the situation is not that simple - the other aspects have to be taken care of. The major concern results form production of MA due to nuclear transmutations that come along with the fuel breeding. The fuel cycle strategy in LFR can serve specific needs of its operator depending on the actual circumstances in nuclear fuel market or regulatory constraints in relation to amount of accumulated plutonium stockpile or even the costs of MA management, including its separation or underground storage. The fuel cycle strategy can also be affected by public factors like their protests against spent fuel transportation to a reprocessing plant. The MA must be properly managed since they increase radiological hazard and can adversely affect the public acceptance for a chosen solution. As transmutation brings MA mass to existence it can also end it, which means that MA can be managed by transmutations within a properly defined fuel cycle strategy. Just here one of the main missions of the LEADER project is located, which is the development of a lead cooled fast neutron reactor system with fuel self-sufficiency and MA management.

4.2. Equilibrium and adiabatic cycle description

Since LFR system is flexible in terms of fuel breeding capabilities it can be designed as a breeder, burner or self-breeder. The adiabatic core concept responds to this issue by proposing a solution in which the nuclear system that comprises a fuel factory, reactor park and final waste repository, once it has reached its equilibrium, needs the external supply of fertile material and turns into waste only fission products. Since LFR is designed for the uranium - plutonium cycle the fertile material must consists of depleted uranium mostly. However, other HM nuclides that comprise nuclear waste from LWR-s may also be included since they are not fuel – at least for LWR-s. Once the cycle needs additional fuel loaded in at the fuel cycle front end or must unload surplus fuel at the back end it cannot be considered adiabatic. But still, that kind of cycle can reach its equilibrium as breeder or burner. The adiabatic cycle characterises self-breeding cores. Summarising, one can distinguish the following fuel cycles strategy applicable to the uranium-plutonium cycle with the respective equilibrium characterisation:

Cycles without external MA loads

A. Adiabatic cycle. The fertile material comprises depleted uranium only, all HM nuclides are recycled, net production of HM nuclides other than fertile is zero, U238 is reduced.
B. Breeding cycle. The fertile material comprises depleted uranium only. The fuel is bred, which then is partially recycled, and partially exported to make the initial load of a new system. U238 is reduced.
C. Burning cycle. At the front end a fresh load plutonium or MOX must be added to the fertile material. The fuel is net burned, which serves reduction of the plutonium stockpile from LWR-s.

Cycles with external MA added at the front end to the recycled fuel

D. Adiabatic cycle. At the front end the fuel is made of the recycled fuel, external MA and depleted uranium. External MA is burned, all remaining HM nuclides are recycled, U238 is reduced.
E. Breeding cycle. At the front end the fuel is made of the recycled fuel, external MA and depleted uranium. The fuel is bred but external MA burned. The fuel is partially recycled, and partially exported to a new system. U238 and MA are reduced.
F. Burning cycle. At the front end the fuel is made of the recycled fuel, depleted uranium and a fresh load plutonium or MOX with MA. The fuel is net burned including external MA, which serves reduction of the plutonium and MA stockpile from LWR-s or fast neutron systems.

Case A is the reference cycle, while cases B and C are a departure from it. This departure may be large on a designer intention or a small one as a result of differences between the calculation model and reality, or due to change in the fuel cycle operational conditions that brake design constrains of the adiabatic cycle. Understanding the way and quantitative consequences of the cycle deviation from its adiabatic state may be important for undertaking required countermeasures in the real operation. Investigation toward that process has

also been curried out. Since the current deliverable deals with LFR core without external MA the cycles D, E and F would not be discussed here but in the follow-up deliverable.

In the adiabatic cycle all heavy metal (HM) nuclides are recycled into the new fuel loads after suitable cooling time, while conserving its total circulating mass. The HM mass deficit at the discharge time is covered by external amount of fertile nuclide - here U238; in practice depleted uranium is applied due to its vast availability. The state of adiabatic equilibrium cannot be reached quickly since it is obtained when the balance or production and destruction of every HM nuclide but the fertile one is established over the applied period of irradiation and cooling. The fertile nuclide is being net destructed during that time but then its missing mass is being admixed during the new fuel production process at the front end of the cycle. The described process of the nuclide evolutions can be also analysed in reference to the fuel composition. Once the equilibrium cycle is established then one can determine quantitatively the equilibrium fuel composition. This, however, should be given with the reference to the time in the period of the entire cycle; over the irradiation and cooling times. Here, we will use mostly the beginning of cycle (BOC).

4.3. Outline of the adiabatic core definition

The general concept of adiabatic core described above can be realized in many ways, but to ensure that the core with assumed configuration conditions along with the fuel cycle parameters is able to reach the adiabatic equilibrium is not straightforward. An efficient fuel cycle modelling procedure is needed at this point in order to avoid a long multi cycle series that brings the fuel to its adiabatic equilibrium in terms of composition and spatial distribution. This procedure in the first phase of cycle analysis should generate the core that satisfies the adiabatic state constraints. However, for competitiveness reasons an optimal configuration should be sought-after in the second phase. A fully-fledged optimisation procedure will not be applied here, since it requires more substantial calculation and modelling effort and is not suitable at the current, initial phase of adiabatic core conceptual modelling. Instead, the optimisation process can be carried out in a simplified form that applies physically justified specification of main parameters, thus reducing the optimisation steps along a single variable. For any option to be carried out, required are the definitions of:

- parameter phase space;
- constraints;
- goal function;
- characteristic functions.

4.3.1. Parameter phase space is made up by the set of variable design parameters and their limits. In our case they are:

- fuel reloading batch scheme - number of fuel batches, optionally zone differentiated.
- parameters setting the fuel distribution in the core:
    - fuel zone divisions
    - fuel enrichment distributions
    - fuel pin annular void radius distribution

- active core height
- irradiation periods
- cooling periods

The fuel recycling will be simplified if the core is loaded with a uniform fuel enrichment. In that case the fuel distribution in the core is done by the variation of fuel pin annular void. In the classical approach the fuel distribution is realized by a fuel enrichment zoning. Detailed analysis of the core performance in both approaches is shown in the next chapters in order to compare weak and strong point of each of them.

4.3.2. Constraints are set in order to satisfy two types of conditions, the first ones are general limitations of the core structure, assumed reactor working conditions and material limits, while the second ones concern satisfaction of adiabatic cycle. They are as follows:

- General limitations of the core:
    - dimensions of the reactor vessel and subassemblies (SA)
    - number of specific SA – fuel, CR, dummy and fixed locations
    - structure material and coolant compositions, densities and temperatures
    - fertile fuel compositions
    - fuel temperature and density
- reactor working conditions and material limits:
    - thermal power
    - power density limit
    - power form factor limits
    - DPA limits
    - peak burnup limit
- adiabatic cycle constraints:
    - invariant cycle to cycle fuel composition, provided the equilibrium has been reached
    - core average fuel breeding over the cycle equals zero
    - invariant cycle to cycle core criticality at the reference time

The constraint for adiabatic cycle of the first bullet is sufficient but requires that equilibrium composition is known, which in practice must be approximated. Two other bullets show supplementary constraints, which must be satisfied in the equilibrium, but they are usually satisfied before the equilibrium is reached once an adiabatic configuration has been defined. Therefore, in our track we were using them in the search for an adiabatic configuration.

4.3.3. Goal function is needed in an optimisation search. Since optimisation should aim at the effectiveness gains, the following function is the most proper:

- average fuel discharge burnup

which for the constrained thermal power is equivalent to

- fuel cycle length

This, however, should be combined with the additional costs of fuel processing when comparing different approaches in regard to the number of required fuel enrichments.

4.3.4. Characteristic functions are used for better understanding of system performance, which should help to carry the search for final configuration. They are useful, particularly for specifying in which direction to move on the phase space in order to satisfy or keep the constraints. Time evolutions are crucial as far as cycle analysis is performed. The evolving functions of interests are:

- criticality
- fuel breeding as distributed over zones
- power profiles

4.4. Adiabatic cycle modelling method using MCB

An adiabatic core that is designed to work in a few-batch fuel reloading scheme, once it has reached the state of equilibrium cycle, all its characteristics are invariant cycle to cycle. This particularly concerns the burnup distribution of the continued fuel batches, which differs from the uniform distribution at BOC of a fresh batch load, since its burnup then equals zero. The burnup distribution is caused by the neutron flux buckling in the core. In order to produce the core model with the equilibrium distribution a few step iterative procedure has been adopted, which, however, differs from the core evolution in a real reactor start-up case. Modelling ideally according to reality would require much longer time just to obtain the equilibrium composition of the reloading fuel. Applying our procedure we can skip a long multi cycle series that brings the fuel to its adiabatic equilibrium in terms of composition and spatial distribution. It involves the methodology of equilibrium fuel composition approximation developed in ENEA and University of Bologna in combination with fuel cycle modelling using MCB system. It is outlined in the subchapters below.

4.4.1. Cross section averaging

The start point core model is used for calculation of all reaction average cross sections for every HM nuclide. The cross section averaging process is obtained over the irradiation period. Here, even if fuel composition differs from the one in the adiabatic equilibrium, the average cross sections will not differ significantly, since the average neutron spectrum will be very similar. That will be true if both cores, the starting point one and the searched one, have similar core materials and structure. In our case that condition is fulfilled.

4.4.2. First approximation of adiabatic fuel composition

The set of averaged cross sections is used as an input for the ENEA procedure of the adiabatic composition calculation. We assume this as the first approximation of adiabatic composition. This procedure requires assumption of the irradiation and cooling times. Because those values later can be a subject of adjustment to satisfy the adiabatic cycle constraints the obtained composition may slightly change due to this. The adiabatic composition is the average one, which means that its local vectors can differ. Yet, the starting point core was loaded with fuels of a few enrichments, therefore the local composition variation from the averaged can be attributed to the initial differentiation of enrichments and to the burnup difference due to the flux buckling.

4.4.3. Next step approximations of the fuel composition using MCB burnup calculations

The adiabatic composition of first approximation is further processed in a few iteration cycle procedure using the preliminary core model of burnup calculation using MCB system. That model is based on the first one but some changes required by general system specification are introduced and the fuel is prepared using the first approximation composition. The fuel cycle in 2-batch reloading scheme is adopted in the following manner:

A. Both fuel batches in the entire core are loaded with the fresh equilibrium fuel at BOC and burned for first sub-cycle.
B. After first sub-cycle the first batch fuel is reloaded and discarded. In its place the fresh fuel is loaded while the second batch is continued in the core.
C. After the second sub-cycle the fuel of the second batch is reloaded since it reached its two sub-cycle residence time. The new fresh fuel is loaded in the second batch locations.
D. Series of two sub-cycles is repeated several times until the power distribution at BOC as well as EOC does not change noticeably cycle to cycle. The last reloaded fuel is then cooled by assumed cooling time and reprocessed. The reprocessing is two step:
    1. entire mass from different regions is blended for a homogenised composition.
    2. the fission product mass is replaced by the fertile material – depleted uranium.

Obtained composition is the adiabatic fuel of the second approximation.

E. The composition of the last approximation is used for new fresh loads of fuel in the next series of cycles as in point D to obtain new approximation. This process is continued until the composition stops changing noticeably

Obtained composition is considered the final adiabatic composition, and the preliminary core becomes the preliminary equilibrium core with 2–batch reloading scheme.

4.4.4. Cycle analysis of the preliminary equilibrium core and configuration improvements

The fuel cycle of the obtained core configuration is then analysed in order to identify what is the cycle breeding status and criticality level. In order to achieve a reliable core configuration the core must be able to be critical over the entire cycle. Therefore, the first issue is to ensure this. The second issue concerns the core being able to work in the adiabatic cycle. Possible Configuration modification that leads to the criticality maintenance is possible by a change of the fuel volume or enrichment. Since the average enrichment is fixed in the adiabatic composition, any configuration change that misses that value will cause the cycle departure from its adiabatic constraints. This kind of exercise leads to a configuration not being sought for in the current study as a final configuration, but still it is worth attention. That situation occurs once the core in hand is limited by volume, as in case of ETDR. The path that leads to the adiabatic cycle must adjust the fuel volume to the criticality needs while keeping the average enrichment bounded to its value resulted from the equilibrium composition.

4.4.5. The adiabatic cycle adjustment

Results of cycle analysis show the core balance during the cycle, where from we can judge if all the adiabatic cycle constraints are satisfied and the power and burnup distributions are favourable. The main issue concerns the breeding gain which is the function of cycle length. The analysis of the reactivity evolution in the core with adiabatic equilibrium fuel shows that at BOC the swing is positive, then in the MOC reaches the maximum and then starts to decline. Similar evolution is observed with the breeding rate, which is positive at the BOC and then around MOC reverses and consumes early gains approaching to zero at the EOC. Since the adiabatic state is characterised by zero breeding, this state can be obtained by extending the cycle length in case of positive breeding gains, or reducing it otherwise. The breeding in this context concerns the mass of all HM nuclides but U238 and a marginal fraction of other residual uranium isotopes, mostly U235, which are present in depleted uranium as the fertile material. These residual uranium isotopes are burnt during irradiation but are built during cooling times from plutonium decay. Plutonium is build during irradiation but decays during cooling times to americium and uranium. The exact measure of breeding gain over the entire cycle requires to calculate the composition changes during both irradiation cooling and refuelling times. As the most important evolution of breeding gain occurs during irradiation, it would be convenient to use a breeding gain measure limited to that time. The best solution is to calculate the changes in mass of all HM nuclides but U238. This equals zero during cooling times. The changes of breeding gain due to the refuelling is limited to the mass fraction addition of residual uranium isotopes and it make a marginal correction as shown in Equation 4.1:

$$BG_{REF} = fima \cdot f_{resU} \quad (4.1)$$

where:

$fima$ is percent average depletion of discharged fuel

f_{resU} is mass fraction of residual uranium in fertile material

Assuming $fima$ as maximum of 7% and 0.2% of residual uranium fraction in depleted uranium as fertile material we got the breeding gain due to refuelling not greater than 0.0014%. In case of applying natural uranium as the fertile material that value will be lower than 0.005%. In both cases we can assume that the breeding gain can be sufficiently well evaluated by mass change of HM without U238. Basing on this assumption, in order to satisfy the adiabatic condition it is needed to obtain zero breeding just over the irradiation cycle.

The issue of favourable core balance has consequences on the cycle effectiveness in terms of average discharge burnup – a factor mutually dependent on the cycle length. The average discharge burnup can be limited by unfavourable power balance that leads to similar distribution of discharge burnup. Since the burnup is limited by its peak value, a levelled-out discharge burnup increases the average one. Otherwise, the unfavourable balance brings limits on cycle efficiency. The process of core power deposition balancing can be carried out in a simple optimisation process along with parallel adjustment of cycle length to ensure the breeding zero. The final definition of the adiabatic core and its cycle parameters will be accomplished once that simple optimisation search is done.

5. **Preliminary assessments using initial core configuration**

As outlined in the previous chapter we start from the preliminary assessments using initial core configuration that will produce results of core physics assessment as well as give us its status concerning the specified constrains.

As the major objective of the relevant deliverable is the definition of LFR core in adiabatic cycle the studies reported herein concern the assessment of various core characteristics that influence the fuel cycle performance, which indicate to what extend the constraints of adiabatic cycle are kept, and show the core ability to achieve desirable burnup level. The definition of LFR core that fulfils major objectives of the LEADER project concern its performance feature.

Once system has been defined, the assessment of core physics is done to indicate the core features related to the fuel cycle characterization that leads to the refining of the neutronic and fuel cycle modelling methodology and then brings about an improved core fuel configuration in terms of burnup efficiency. The analysis includes burnup calculations in few-batch fuel reloading, the assessment of the equilibrium fuel composition in the fuel cycle with the actual reloading in a full core calculation, the power distribution with its evolution with burnup, and the modelling of the control rod operation for its influence on the fuel breeding ratio. The fuel zoning was considered by using two options – one with the varied radius of the fuel pellet annular void, and the second that applies different zone enrichments of plutonium.

6. **Assessments of chosen configurations of LFR adiabatic core**

The fuel cycle analysis in the preliminary LFR core have shown the occurrence of the core criticality deficit. The preliminary core was based on the staring point core configurations (the final one of ELSY). Two factors are responsible - the lower equilibrium fuel enrichment and a larger number of CR assemblies, which reduces the number of fuel assemblies, as related to the starting point core. An additional source of criticality deficit will appear if we increase the annular void in the fuel pins as a measure for the fuel distribution over the zones. This concept, to which we will refer as the pin annular void zoning, has been proposed by ENEA and JRC, as an alternative to the fuel enrichment zoning. The pin annular void zoning requires only the single fuel enrichment during both irradiation and processing. As a counter measure for the criticality deficit the two following changes were introduced in order to increase plutonium load:

- active core height was increased from 120 cm to 140 cm, that is by 16.67%
- assembly lattice as well as fuel rods lattice were slightly tightened – the pitch was reduced by 3.35%, which increases the rod packing by 6.8%
- Both measures bring the fuel volume increase by 20.6%.

The adiabatic core concept has been modelled in two options - the fuel pin annular void zoning and the fuel enrichment zoning. The results of the core configuration final adjustments to satisfy the adiabatic cycle constraints, the core performance and fuel cycle assessments in regard to both options is presented in two subchapters below.

6.1. The adiabatic core with fuel pin annular void zoning

The first adiabatic core applies the uniform enrichment over all regions. The plutonium distribution is made by varied radius of the rod inner void. This reduces the fuel loading in the central zone. The first core is not aimed to be optimal one but should satisfy the adiabatic cycle constraints. The reference core cycle is assumed to have 2-batch reloading scheme in order to increase achievable burnup. The core division is specified in
Table 6. The fuel irradiation

Table 6. Reference 2-batch core zone structure with uniform enrichment; (*with Pu enrichment after correction)

Zone	1	2	3
Fuel pin annular void radius	2 mm	1 mm	1 mm
Nr of fuel assemblies	157	96	174
Nr of CR assemblies	6	6	12
Nr of burnup regions	2x3	2x2	2x3
Fuel assemblies in region	9(10)/30/39	21/27	24/33/30
Pu enrichment (mass)	18,24% (18,17% *)		
Fuel irradiation time	2 x 900 days		
Cooling before recycling	7 years		

time shown in the table was not assumed but resulted from its adjustment to the value that satisfies the adiabatic condition in the process outlined in subchapter 4.4. Here, the loaded fuel has composition obtained in the first approximation process using ENEA methodology. This composition we will refer to as “Fuel Vector A”. This composition is also used for reloading in the burnup distribution adjustment process. The fuel cycle calculation has been done using MCB model with CR-s fully withdrawn. The final burnup distribution adjustment process of the adiabatic core starts with uniform fuel load at the beginning of the first cycle. Since the first load has zero burnup everywhere at BOC, it is not the equilibrium burnup distribution. The process serves bringing the fuel burnup and power distribution to the cycle-to-cycle equilibrium. This adjustment process is needed only for cores that use a few-batch reloading scheme, where a part of the fuel load is continued in the next cycle. An unbalance burnup reflects itself in the power distribution cycle-to-cycle change. Therefore by tracing the power distribution from cycle to cycle we can see if the equilibrium has been reached. In Figure 12 one can see axially average power density factors calculated for every radial region

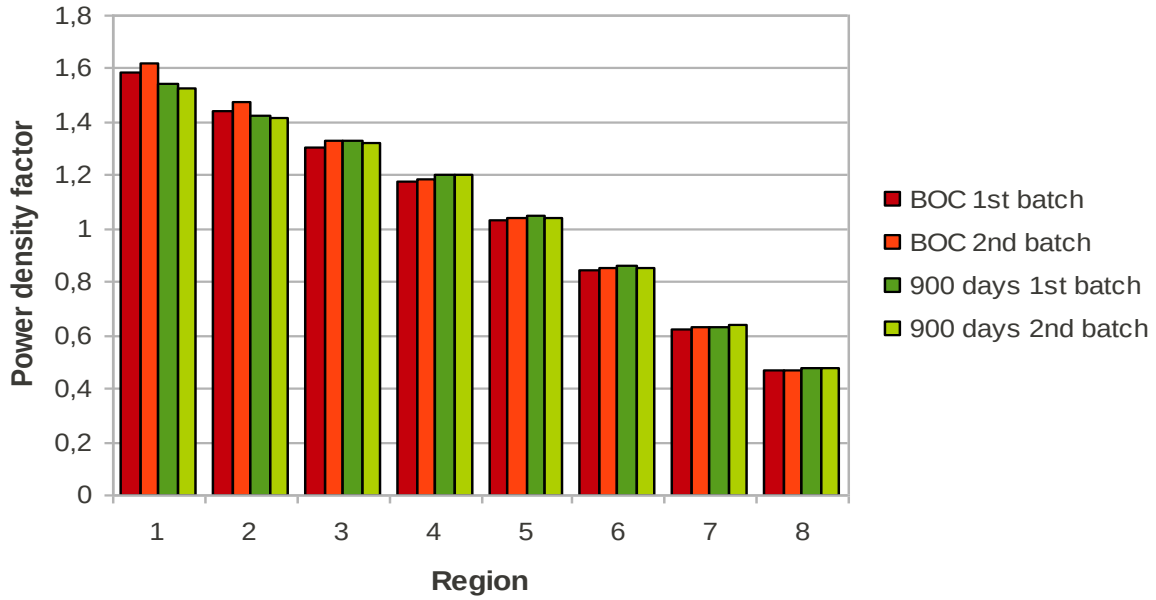

Figure 12. Radial power density factor of fuel pins at the beginning of adjustment; Fuel pin annular void zoning case

during the initial cycle of 900 days. Those power density factors concern the power deposition in the fuel volume not in the rod or assembly volume. That function is used in evaluation of fuel burnup and should not be applied for thermal hydraulic assessment, where the factors related to linear power are needed. In this particular case of the fuel pin annular void zoning they are different due to varied pin cross section area. In Figure 13 one can see the power factors at equilibrium, which has been reached after 5 approximation cycles. Obtained radial power distribution is peaked at the core centre where power density is three times higher than in the most outer region. When the burnup distribution of the continued fuel load reaches its equilibrium the power peaking slightly decreases; the radial form factor of fuel power density

lowers from 1.615 to 1.514. The power distribution on the assembly levels must take into account varied pin cross section. This will be reflected in

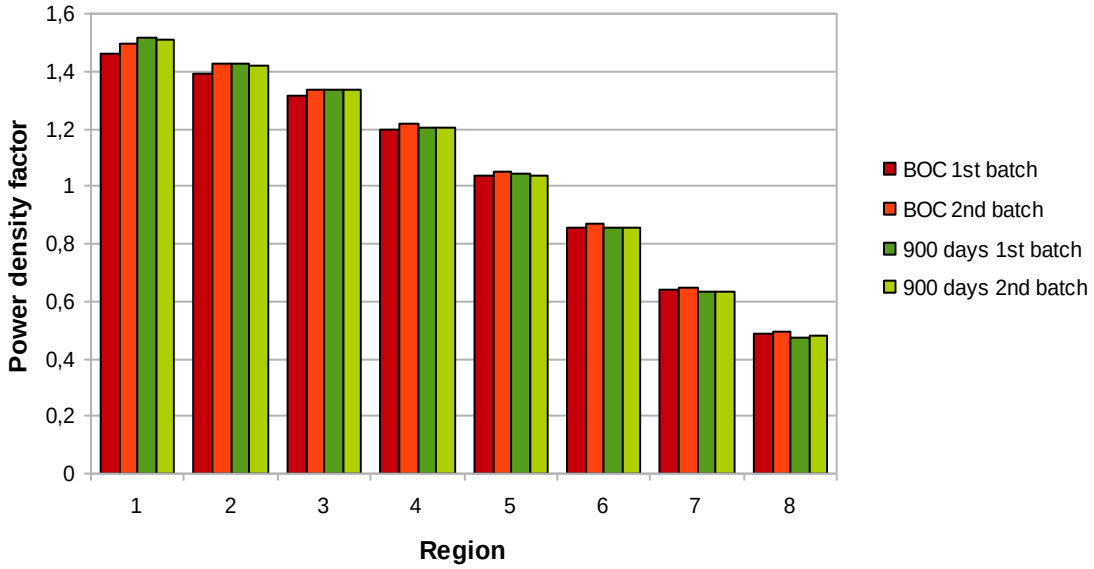

Figure 13. Radial power density factor of fuel pins in equilibrium; adiabatic core with fuel pin annular void zoning

linear power ratings, which are used in thermal hydraulic calculations. The power factors obtained using linear ratings are shown in Figure 14. This shows that the fuel pin annular void zoning can be effectively used for reduction of radial form factors. In our case the radial form factor equals 1.36. This, however, is not helping the core in levelling the discharge burnup distribution, which depends on the local fuel density, not the linear density. The fuel burnup on discharge for the adiabatic cycle was calculated for every burnup region, as shown in Table 7 in terms of MWd/kg as well as FIMA

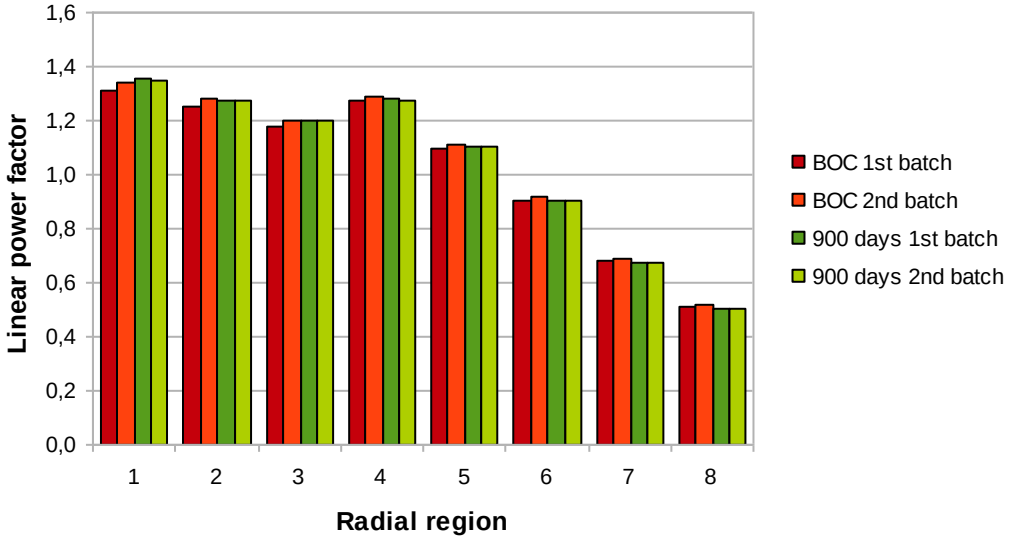

Figure 14. Linear power factor distribution in equilibrium; adiabatic core with fuel pin annular void zoning

Table 7. Burnup distribution in adiabatic core with fuel pin annular void zoning in 2-batch reloading cycle of twice 900 days

Region	Axially average values						
	BURNUP [MWd/kg]			FIMA [%]			
	Fresh fuel	Cont. fuel	Total	Fresh fuel	Cont. fuel	Total	
1	36,65	38,15	74,8	4,05	4,26	8,31	
2	35,02	36,48	71,5	3,87	4,06	7,93	
3	33,25	34,43	67,68	3,63	3,8	7,43	
4	30,32	31,43	61,75	3,31	3,44	6,75	
5	26,69	27,48	54,17	2,86	2,96	5,82	
6	22,23	22,53	44,76	2,35	2,44	4,79	
7	16,52	16,81	33,34	1,77	1,81	3,58	
8	12,58	12,69	25,27	1,33	1,36	2,7	
Core average			52,40			5,71	
1st zone average	34,34	35,66	70,00	3,77	3,95	7,73	
2nd zone average	28,28	29,21	57,49	3,05	3,17	6,22	
3rd zone average	16,74	16,97	33,71	1,78	1,83	3,61	
	Peak values						Axial FF
1	44,20	46,01	90,21	4,88	5,14	10,02	1,206
2	42,34	44,10	86,44	4,68	4,91	9,59	1,209
3	40,30	41,73	82,03	4,40	4,61	9,01	1,212
4	36,93	38,28	75,21	4,03	4,19	8,22	1,218
5	32,67	33,64	66,30	3,50	3,62	7,12	1,224
6	27,28	27,64	54,92	2,88	2,99	5,88	1,227
7	20,19	20,54	40,74	2,16	2,21	4,37	1,222
8	15,28	15,42	30,70	1,62	1,65	3,28	1,215

This 2-batch cycle of 900 days has reached the discharge peak burnup of 90.21 MWd/kg, which is below the specified limit of 100 MWd/kg. The average fuel burnup on discharge equals 52,4 MWd/kg. In the considered 2-batch reloading scheme the fuel is burned over two consecutive cycles, where the fuel of fresh load is burned slightly less than the fuel of continued load. The peak fuel burnup limit of 100MWd/kg has not been reached, which also hinders the average burnup on discharge. The power density does not change significantly during the cycle, since we are dealing with a self-breeder. The fuel breeding gain (BG) is a measure that shows whether the adiabatic cycle constraints are met. The fuel breeding gain obtained in the current case with the fuel vector A is shown in Table 8 with its distribution to zones and time part of the cycle. Time evolution of the birding is shown in Figure 15, where its partial functions that correspond to radial regions show different evolution patterns.

Table 8. Fuel breeding gain distribution in adiabatic core with fuel pin annular void zoning in 2-batch reloading cycle of twice 900 days

	Zone 1	Zone 2	Zone 3	Average
Fresh load	0,55%	0,23%	0,28%	0,36%
Continue load	-0,56%	-0,48%	0,03%	-0,29%
Entire fuel cycle	-0,01%	-0,25%	0,31%	**0,07%**

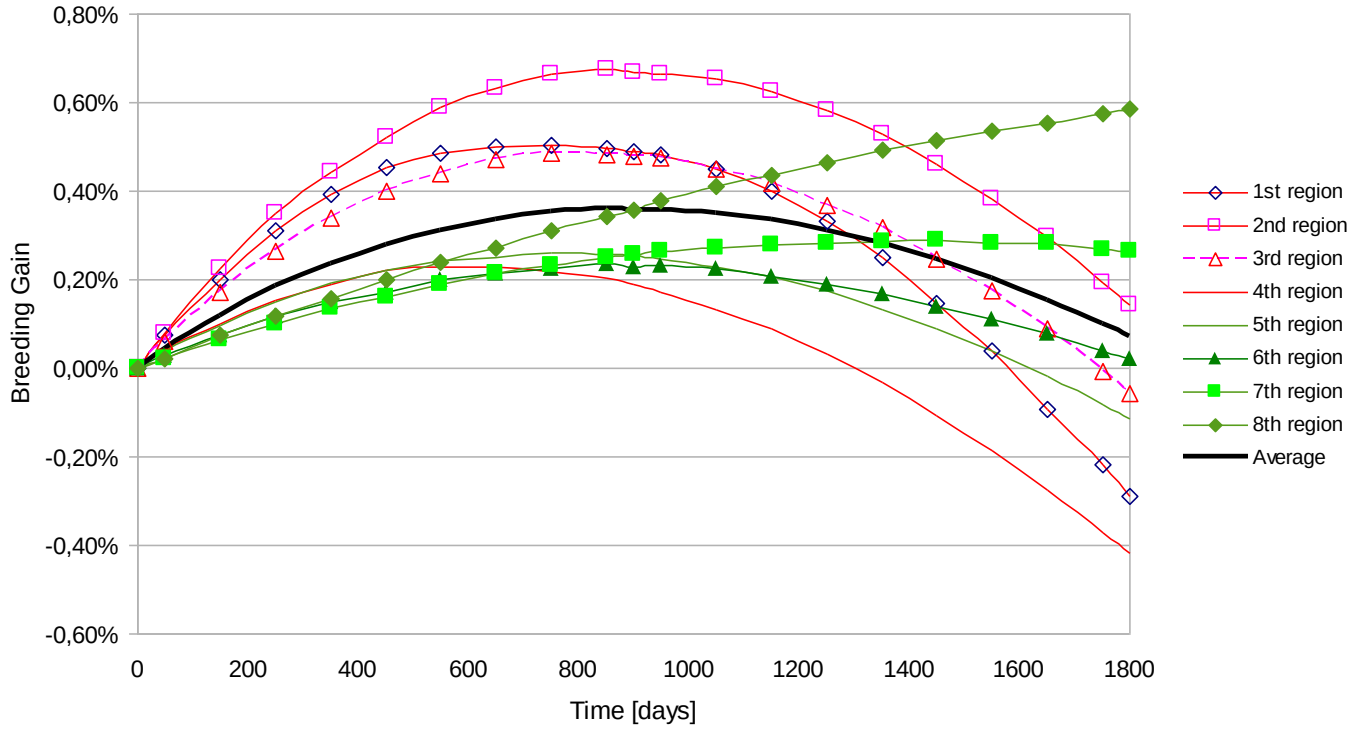

Figure 15. Fuel breeding gain evolution; LFR adiabatic core with fuel pin annular void zoning in 2-batch reloading cycle of twice 900 days

As the average BG is marginally above zero it confirms that the considered cycle is adiabatic within an uncertainty margin. The behaviour obtained here, however, might change when the compensation rods operation is included in our model. Influence of CR on the core cycle characteristics will depend on the reactivity swing that needs compensation. The criticality evolution presented in Figure 16 shows the initial reactivity compensation slightly above 200 pcm, while the reactivity swing over the 900 days cycle needs compensation of about 300 pcm. The reactivity swing in our case is quite small, which usually occurs in few-batch reloading cases. Obtained data implies CR operation in the insertion range that corresponds to the criticality range from 200 to 500 pcm. However, the lower bound operational criticality range in the real case can be higher due to possible discrepancy of criticality level between the calculation model and reality. In an extreme case the CR can operate close to their full insertion. In order to analyse the consequences of CR insertion for the cycle characteristic we have calculated also the adequate fuel cycle with CR fully inserted over entire 2-batch cycle. The comparison of breeding gains for both cases is shown in Figure 17, while Figure 18 shows comparison of reactivity swings. The curve of breeding gain evolution for full CR insertion has been

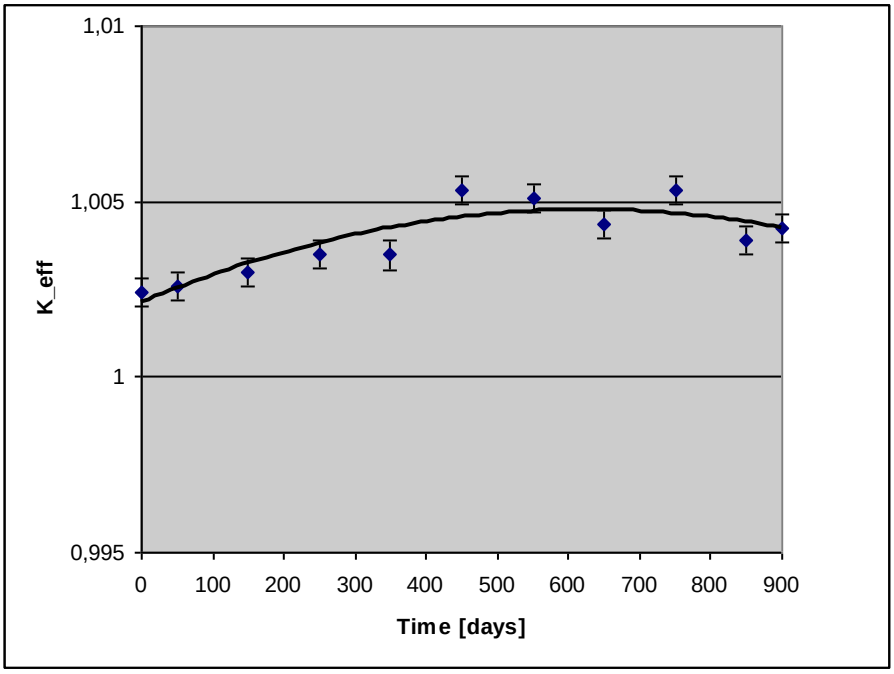

Figure 16. Criticality evolution in adiabatic cycle with fuel pin annular void zoning; Fresh adiabatic fuel load of vector A composition.

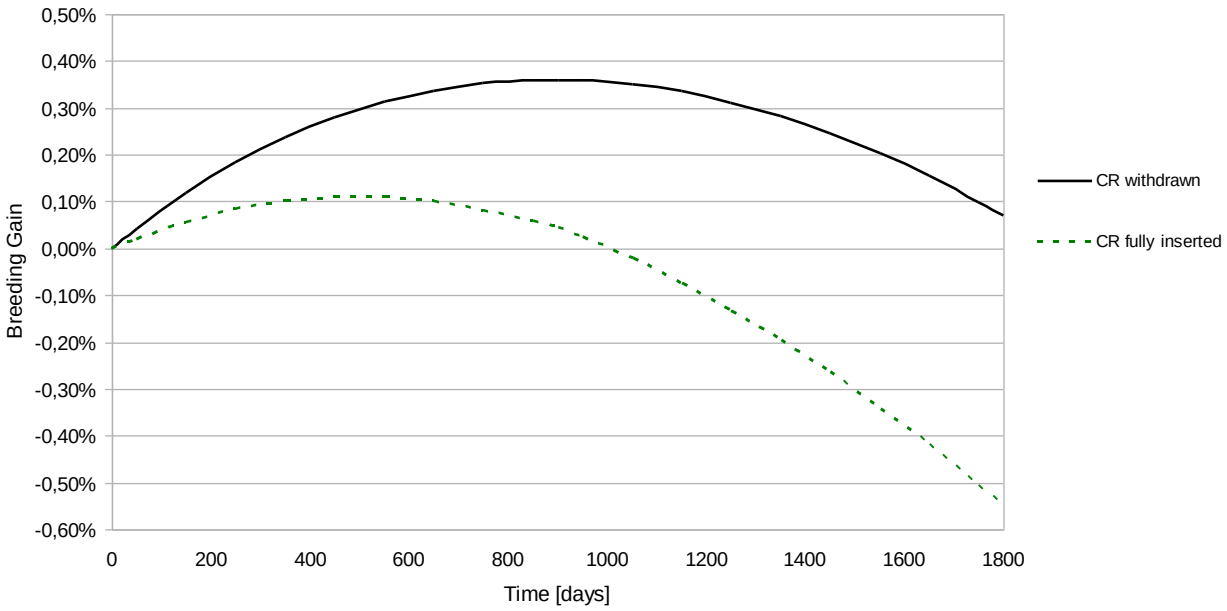

Figure 17. Fuel breeding gain evolution depending on CR insertion. Fresh adiabatic fuel load of vector A composition.

obtained for the core with burnup distribution of the fuel continue load of reference case (with CR withdrawn), therefore it is not the adiabatic state. The deviation form adiabatic state in this case is also confirmed by a negative BG which over entire cycle equals -0.55%, which gives 0,72% of the BG difference between the states of CR withdrawn and fully inserted. This characteristic implies the following recommendation for setting the CR operational margin,

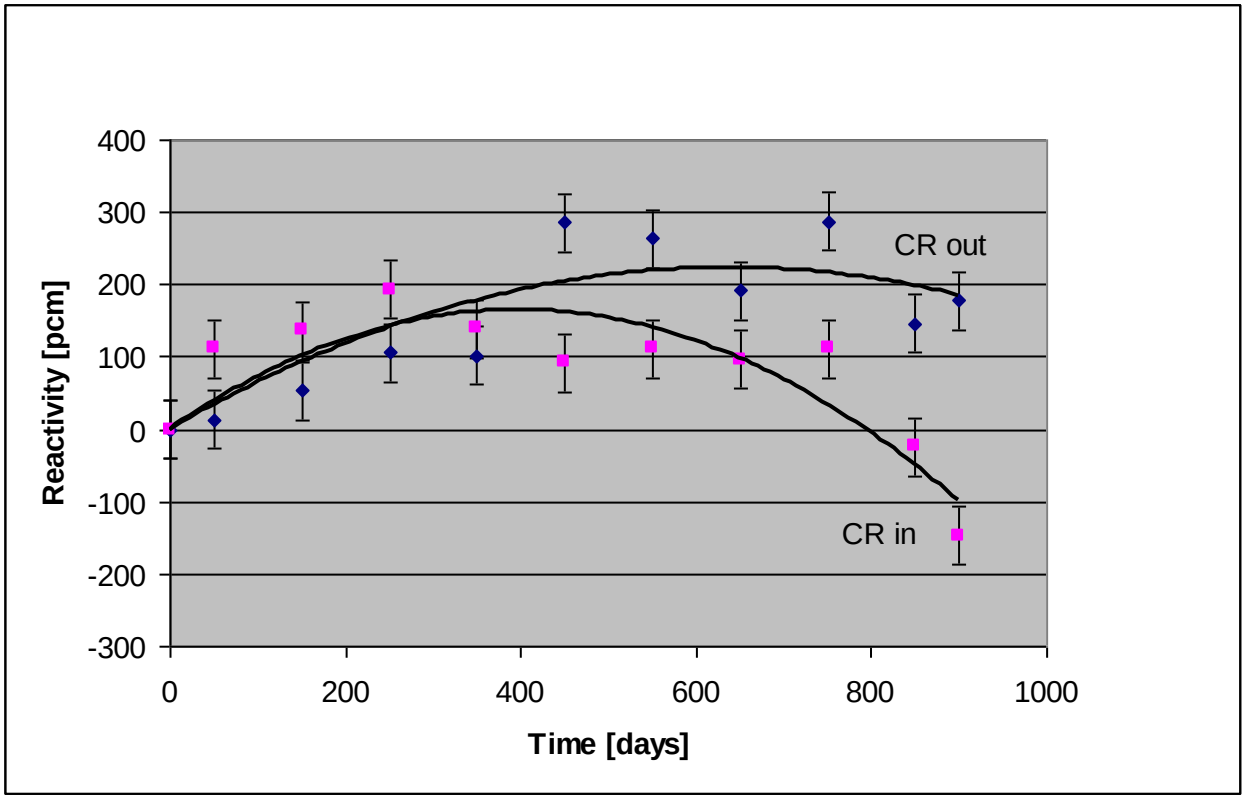

Figure 18. Dependence of CR insertion on the reactivity evolution; Fresh adiabatic fuel load of vector A composition.

whether during designing or in the criticality correction during the actual core loading procedure:

- the CR margin should be set in the low range of reactivity if we need to increase the BG,
- the CR margin should be set in the high range of reactivity if we need to decrease the BG.

In our reference case the margin of required reactivity compensation is about 500 pcm, which is about 10% of the reactivity worth of the operational CR system, which is about 5000 pcm. Therefore breeding gain correction due to the effect of CR operation can be roughly estimated as about - 0.07% which bring the BG value to the zero level. It should be noticed the calculation precision of BG below 0.01% will be overshadowed by the uncertainty in nuclear data, which will be responsible for possibly a higher difference between the designed and measured values.

6.1.1. Adjusting adiabatic composition

The result present in the preceding sections were obtained with the first approximation of adiabatic fuel composition – fuel vector A. Next, the composition final adjustment has been carried out by running a series of unloaded material reprocessing after 7 years of cooling. We will refer to it as "Fuel Vector B". The reprocessing comprises of homogenizing the fuel from all fuel assemblies into one composition, removal of fission products and replacement of FP mass by depleted uranium. This procedure results in the full recycle of HM. The nuclide mass evolutions over the 4-cycle adjustment procedure are shown in Table 9 and Figure 19. It can be noticed that a

Table 9. Nuclide mass evolution in adiabatic composition adjustment process; LFR adiabatic core with fuel pin annular void zoning in 2-batch reloading cycle

Approx. step.	Time [days]	Mass [g]						
		Uranium	Uranium without U238	U233	U234	U235	U236	U238
1st	0	4,2095E+07	2,8143E+05	8,2951E+00	1,2787E+05	5,7551E+04	9,6000E+04	4,1814E+07
	900	4,0603E+07	2,6730E+05	8,2614E+00	1,2128E+05	5,1189E+04	9,4824E+04	4,0336E+07
2nd	900	4,2085E+07	2,7835E+05	8,2050E+00	1,2970E+05	5,2464E+04	9,6180E+04	4,1807E+07
	1800	4,0598E+07	2,6500E+05	7,9640E+00	1,2288E+05	4,7373E+04	9,4739E+04	4,0333E+07
3rd	1800	4,2081E+07	2,7590E+05	7,9525E+00	1,3047E+05	4,9585E+04	9,5838E+04	4,1805E+07
	2700	4,0598E+07	2,6305E+05	7,7905E+00	1,2354E+05	4,5224E+04	9,4284E+04	4,0335E+07
4th	2700	4,2075E+07	2,7418E+05	7,8250E+00	1,3089E+05	4,7940E+04	9,5344E+04	4,1801E+07
	3600	4,0595E+07	2,6159E+05	7,7121E+00	1,2388E+05	4,3982E+04	9,3724E+04	4,0334E+07

Approx. step.	Time [days]	Mass [g]						
		Plutonium	Pu238	Pu239	Pu240	Pu241	Pu242	Pu244
1st	0	9,7568E+06	2,7373E+05	5,2118E+06	3,5980E+06	3,0405E+05	3,6899E+05	1,9418E+02
	900	9,7998E+06	2,6919E+05	5,2301E+06	3,5798E+06	3,5287E+05	3,6764E+05	1,9231E+02
2nd	900	9,7565E+06	2,6319E+05	5,2537E+06	3,5774E+06	2,9527E+05	3,6672E+05	1,9070E+02
	1800	9,8001E+06	2,6145E+05	5,2645E+06	3,5630E+06	3,4554E+05	3,6543E+05	1,8903E+02
3rd	1800	9,7565E+06	2,5790E+05	5,2789E+06	3,5628E+06	2,9225E+05	3,6447E+05	1,8750E+02
	2700	9,7974E+06	2,5734E+05	5,2837E+06	3,5502E+06	3,4274E+05	3,6324E+05	1,8599E+02
4th	2700	9,7559E+06	2,5507E+05	5,2947E+06	3,5526E+06	2,9083E+05	3,6249E+05	1,8468E+02
	3600	9,7953E+06	2,5517E+05	5,2959E+06	3,5413E+06	3,4141E+05	3,6129E+05	1,8331E+02

Approx. step.	Time [days]	Mass [g]							
		Curium	Cm242	Cm243	Cm244	Cm245	Cm246	Cm247	Cm248
1st	0	9,7110E+04	6,4895E+03	1,4614E+03	5,5874E+04	1,6954E+04	1,1854E+04	2,3507E+03	2,1271E+03
	900	1,0957E+05	1,2246E+04	1,4767E+03	6,2708E+04	1,6821E+04	1,1845E+04	2,3497E+03	2,1252E+03
2nd	900	9,5010E+04	6,6458E+03	1,2919E+03	5,4142E+04	1,6633E+04	1,1824E+04	2,3478E+03	2,1257E+03
	1800	1,0780E+05	1,2401E+04	1,3753E+03	6,1300E+04	1,6456E+04	1,1797E+04	2,3457E+03	2,1242E+03
3rd	1800	9,3859E+04	6,6507E+03	1,2493E+03	5,3424E+04	1,6312E+04	1,1757E+04	2,3431E+03	2,1234E+03
	2700	1,0681E+05	1,2398E+04	1,3471E+03	6,0692E+04	1,6193E+04	1,1720E+04	2,3368E+03	2,1221E+03
4th	2700	9,3297E+04	6,6786E+03	1,2378E+03	5,3145E+04	1,6104E+04	1,1680E+04	2,3301E+03	2,1218E+03
	3600	1,0635E+05	1,2410E+04	1,3364E+03	6,0504E+04	1,6019E+04	1,1638E+04	2,3225E+03	2,1199E+03

Approx. step.	Time [days]	Mass [g]					
		Th230	Pa231	Np237	Am241	Am242m	Am243
1st	0	6,3432E+01	4,4414E+00	5,7324E+04	3,9590E+05	1,7921E+04	1,1102E+05
	900	6,2540E+01	4,4171E+00	5,5548E+04	3,4910E+05	2,3439E+04	1,1102E+05
2nd	900	6,4220E+01	4,3624E+00	5,8052E+04	4,0368E+05	2,6511E+04	1,1099E+05
	1800	6,3355E+01	4,3512E+00	5,6121E+04	3,5486E+05	2,9391E+04	1,1112E+05
3rd	1800	6,4977E+01	4,3476E+00	5,8602E+04	4,0545E+05	3,0563E+04	1,1122E+05
	2700	6,4111E+01	4,3474E+00	5,6571E+04	3,5629E+05	3,2144E+04	1,1137E+05
4th	2700	6,5764E+01	4,3520E+00	5,8924E+04	4,0592E+05	3,2375E+04	1,1150E+05
	3600	6,4890E+01	4,3569E+00	5,6848E+04	3,5658E+05	3,3382E+04	1,1158E+05

significant change in mass evolution occurs for Am242m while modest changes occur for U235, U234, Pu238, Pu239, Pu241, Pu242, Np237 and Cm244. The major difference can results form different treatments of Am242m formation in ENEA procedure, which is based on FISPAC, and in MCB, which applies an improved model of metastable nuclide formation process. The differences in

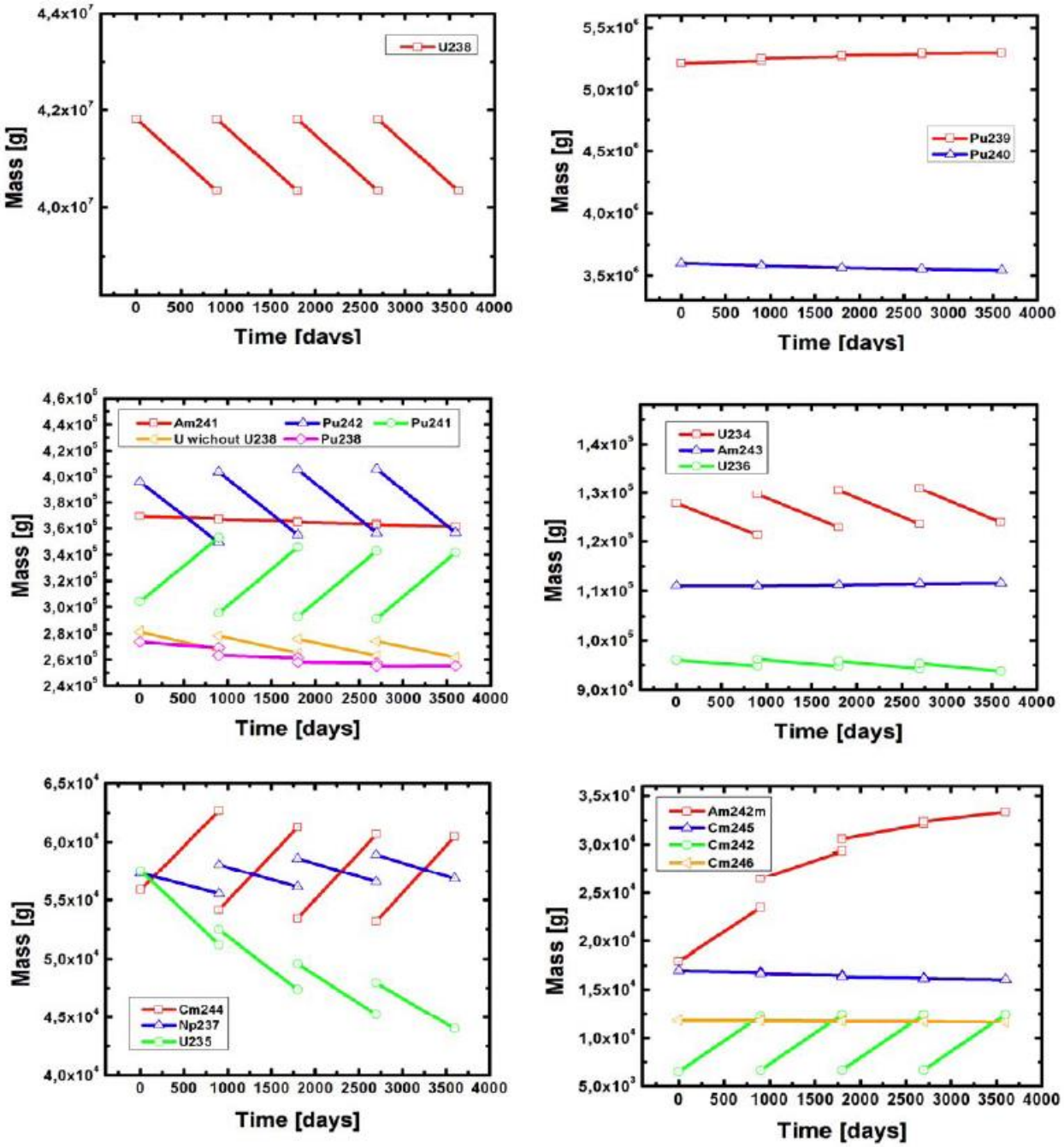

Figure 19. Nuclide mass evolution in adiabatic composition adjustment.

other nuclides are partially caused by different Am242m fraction in the adiabatic composition and subsequent transmutation paths, but also due to differences in the cycle and core models, which has been used in the first approximation process and the current adjustment process with fuel reloading. Change in mass fraction after this adjustment process is shown in Table 10. The increase of Am242m fraction is combined with reduction of curium build-up. Concerning plutonium isotopes, there are some inside trades that favour Pu239, which strongly contributes to reactivity. Thus, the observed fraction changes can imply changes in both criticality and breeding gains. In order to assess the magnitude of that changes a similar analysis of the fuel cycle with the corrected adiabatic composition of fuel vector B has been carried out.

Table 10. Change in the adiabatic composition in the adjustment process with direct simulation of fuel reloading

Nuclide or element	Mass fraction		B/A
	Vector A	Vector B	
	Initial approximation	After adjustment	
Th230	0,00012%	0,00012%	1,036
Pa231	0,00001%	0,00001%	0,977
U233	0,00002%	0,00001%	0,947
U234	0,247%	0,253%	1,025
U235	0,115%	0,094%	0,822
U236	0,181%	0,180%	0,996
U238	79,910%	79,879%	1,000
U	80,452%	80,406%	0,999
Np237	0,109%	0,113%	1,031
Pu238	0,521%	0,481%	0,923
Pu239	9,742%	9,913%	1,018
Pu240	6,773%	6,678%	0,986
Pu241	0,513%	0,485%	0,945
Pu242	0,695%	0,682%	0,982
Pu244	0,00037%	0,00035%	0,950
Pu	18,244%	18,240%	1,000
Am241	0,796%	0,818%	1,028
Am242m	0,026%	0,059%	2,222
Am243	0,209%	0,209%	1,003
Am	1,031%	1,086%	1,054
Cm242	0,00007%	0,00014%	2,060
Cm243	0,0027%	0,0022%	0,804
Cm244	0,0977%	0,0918%	0,940
Cm245	0,0323%	0,0307%	0,949
Cm246	0,0223%	0,0220%	0,986
Cm247	0,0044%	0,0044%	0,993
Cm248	0,0040%	0,0040%	0,997
Cm	0,163%	0,1551%	0,949

Criticality evolution for this case presented in Figure 20 shows that the level of criticality during the cycle is higher by about 500 pcm than in the case of vector A – of the initial approximation of adiabatic fuel composition. Comparing the reactivity evolution in case B, which is shown in Figure 21, with that for case A, one can see similar patterns, with some reduction of the reactivity swing in Case B for CR withdrawn from 300 pcm do 200 pcm. In the case of full CR insertion the reactivity swing is bigger in case B. These effects are not directly caused by the composition change, but rather by the higher criticality

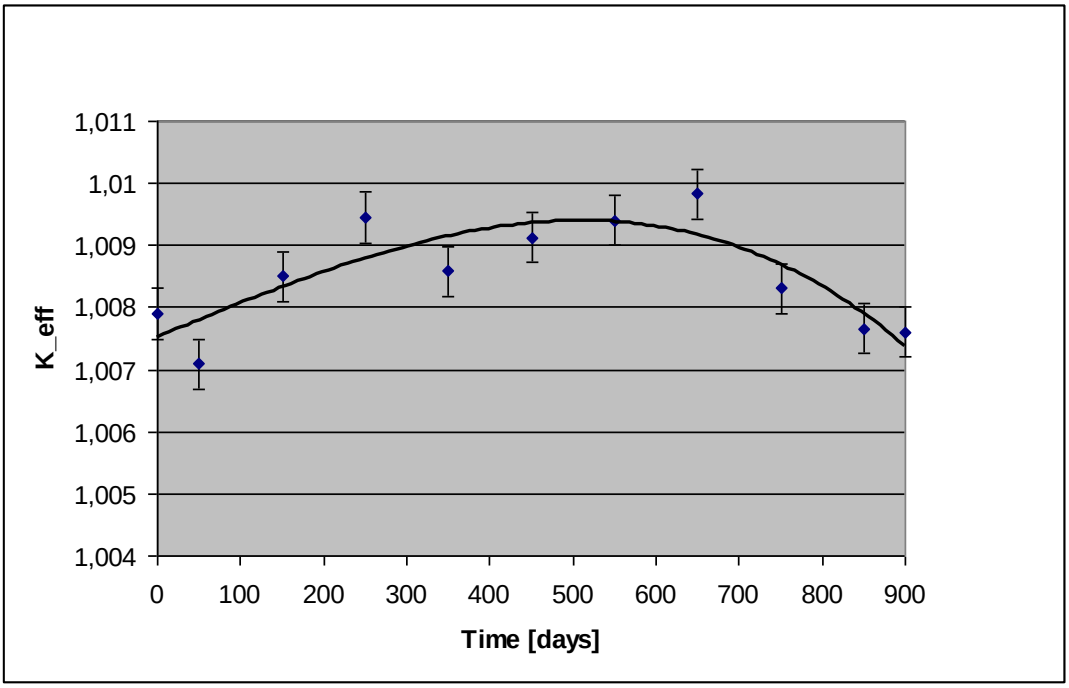

Figure 20. Criticality evolution in adiabatic cycle with fuel pin annular void zoning; Fresh adiabatic fuel load of vector B composition.

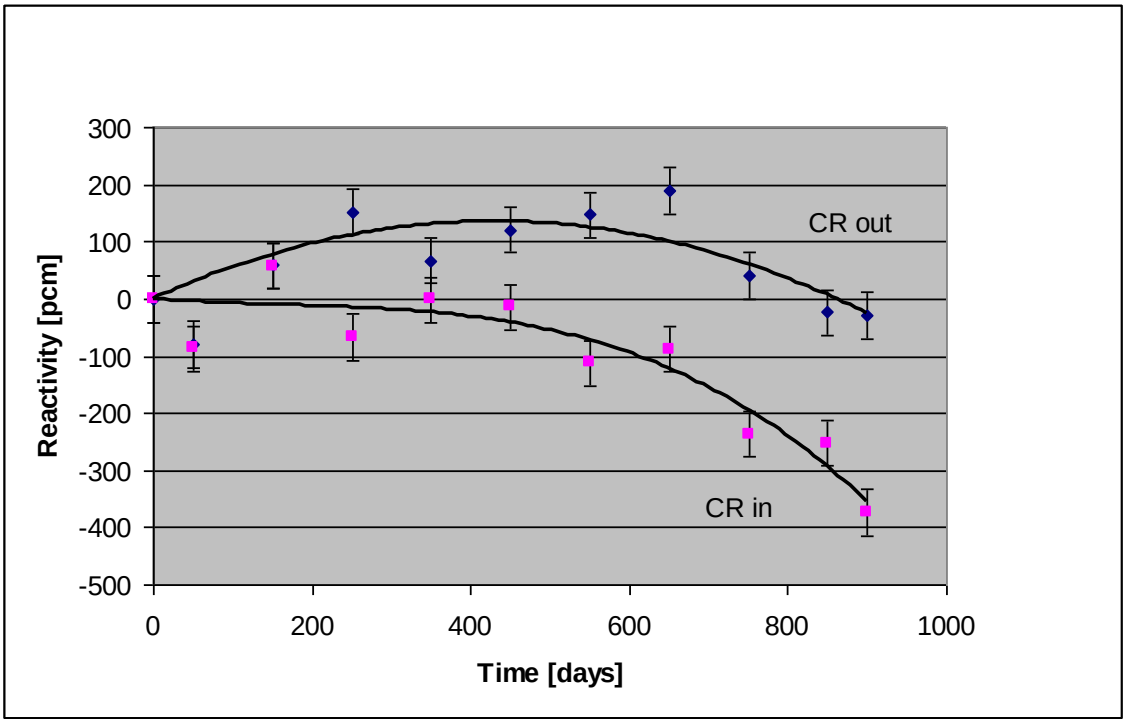

Figure 21. Dependence of CR insertion on the reactivity evolution; Fresh adiabatic fuel load of vector B composition.

level in case B, which also implies small changes in the evolution of breeding gains as shown in Figure 22. The breeding gains in case B at the fuel discharge are -0.13% for CR withdrawn and –0.74% for CR fully inserted, which is lower by number of 0.20% than in case A. The observed differences in breeding gain as well as in reactivity swing can be attributed to the initial levels or criticality,

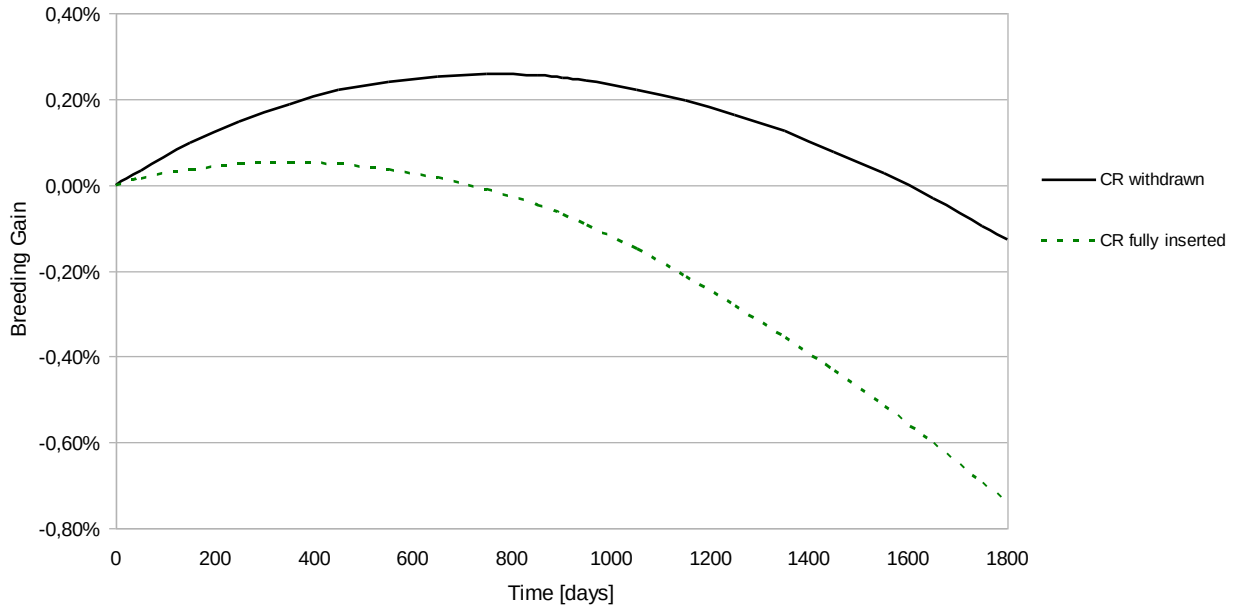

Figure 22. Fuel breeding gain evolution depending on CR insertion. Fresh adiabatic fuel load of vector B composition.

which changes from 1.00254 (±11) in case A to 1.00778 (±11) in case B. This difference is caused by increased fissionability of the fuel vector B as compared to the fuel vector A, mainly due to higher content of Pu239 on the expense of other plutonium isotopes, and Am242m on the expense of curium. The increase of the criticality level occurs even if plutonium enrichment in the fuel fractionally decreased. As the level of initial criticality is a free parameter in the fuel cycle designing process, it can be constrained to the desired level. In general, in every breeder reactor, an increase of fuel enrichments leads to the decrease of breeding gains and vice versa. We can exploiting this rule in our case, by increasing the fraction of admixed depleted uranium in the discharge fuel reprocessing, while keeping the composition of remaining nuclides unchanged. This will impose all desirable changes concurrently and bring the core to its adiabatic equilibrium without changing the cycle length. The first-order sensitivity analysis allows for quantitative approximation of the reactivity sensitivity to fuel enrichment, which can be derived from the definition of criticality. Since criticality is defined as:

$$k_{eff} = \frac{F\Phi}{A\Phi},$$

where the fission operator is fairly proportional to the fuel enrichment:

$$F\Phi \sim \alpha_{enr} \ ,$$

whereas the absorption operator can be assumed independent from the fuel enrichment since in the fast neutron spectrum the absorption cross sections of plutonium does not significantly differ from that of ^{238}U. Therefore, for small changes in the enrichment the first order approximation formula for relation between criticality and enrichment takes the following form:

$$\Delta\alpha_{enr} = \alpha_{enr} \cdot \Delta k_{eff} / k_{eff} .$$

It is irrelevant here, what we assume as a fuel, whether plutonium or all heavy metal nuclides other than U238, since their enrichments are proportional to each other. Therefore the same relation to criticality is valid for both. In our case the criticality equals unity while the required criticality change is:

$$\Delta k_{eff} = -500\, pcm .$$

The plutonium fuel enrichment before correction equals:

$$\alpha_{Pu\_enr} = 18.24\% ,$$

Which gives the required fuel enrichment change:

$$\Delta\alpha_{Pu\_enr} = -0.091\% .$$

This brings the plutonium enrichment of the adiabatic composition after the correction to the following:

$$\alpha_{Pu\_enr} = 18.15\% .$$

The cycle length change, can be also exploited as a mean for adjusting the breeding gain to desired level, since the period elongation reduces the breeding gain. This process might be used in a real operation to adjust the actual BG to the required level. The observed dependence of BG on the CR insertion in the adiabatic cycle indicates the existence of a desirable, self adjusting process that will lead to the composition balance if properly designed. This self adjustment will occur when a positive BG in one cycle will result in a higher criticality at BOC of a new cycle, once the unloaded fuel were reprocessed and reloaded with a higher fuel enrichment, which will have to be compensated during the cycle by a deeper insertion of CRs. This in turn will reduce the BG, possibly to the negative region thus leading to balancing the BGs over longer periods of many cycles around zero.

7. **Conclusions**

Carried out fuel cycle analysis of LRF core concept with uniform fuel enrichment confirms that proposed core configuration can work in the adiabatic cycle with zero fuel breeding in a two-batch reloading scheme. It has been shown that accurate modeling of Am242m is needed in order to obtain the proper adiabatic fuel composition. It has been found that CR insertion level during the fuel cycle influences the breeding gains and should be included in the fuel cycle analysis. The plutonium enrichment of adiabatic fuel is just slightly above 18% which requires the fuel volume enlargement comparing to the LFR preliminary design of ELSY project. It has been realized by the active

core height rise form 120 cm to 140 cm. Reduction of power peaking in the core central region has been realized by the increased pin annular void. This solution has the main advantage of limiting the fuel reprocessing to one material stream, but for given core dimensions a few drawbacks are noticed as follows.

The cycle length is determined by the constrain of zero breeding gain, which results in the adiabatic cycle with the period of 900 days between each batch reloading, while the fuel burnup limit allows for cycles up to 1300 days a batch.

Poor discharge burnup in average of 51,33 MWd/kg results firstly form the cycle length, but also from the higher power peaking in the center, which limits a possible increase of the cycle length do to peak burnup limit of 100MWd/kg. That should be compared with 70 MWd/kg of average burnup, which is achievable in the core with a-few-enrichments zones.

Reduction of the volume for fuel material creates a deficit in reactivity management will complicate the introduction of MA, due to foreseen further reduction of reactivity.

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