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Investigating the Potential of Monolithic UMo for the Conversion of FRM-II

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The use of monolithic UMo fuel of highest density might be a viable option for the conversion of high-flux research reactors from HEU to LEU fuel. One-element-cores are the most challenging like in the case of the German FRM-II. Going beyond linear programming calculations of the past we used the M^3O code to further investigate the potential of monolithic UMo for the conversion of the FRM-II. To better address the full optimization problem and to meet the conversion requirements of a maximized flux, a minimized enrichment, and an attractive cycle length, a broader parameter space study was done for the re-design of the fuel element as a step to a global optimization routine. First results indicate that it might be possible to find a suitable set of design variables to meet the requirements perhaps even by using LEU, while keeping important operational constraints (like power peaking, heat flux etc.).

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1 Introduction

Fortunately, development of high density UMo dispersion fuel has made considerable progress by adding silicon to the matrix and thereby suppressing the growth of porosities. The uranium density of 8 g/cm^3 will allow the conversion of various research reactors to the use of LEU. The operator of FRM-II states that using UMo dispersion fuel would require an enrichment of 50% (HEU) to operate the reactor with the current geometry, while relatively modest flux losses of about 8% will occur.[1]

Since the development of monolithic UMo fuel with a density of up to 16 g/cm^3 is making progress the use of this fuel might be a viable option to further minimize enrichment requirements and thus to foster the international efforts to phase out the usage of civilian HEU and reducing the risks of proliferation and nuclear terrorism.

2 Previous Results

In the case of the FRM-II first results using the M^{3}O-Code, developed in our group, showed that the most straightforward way for a conversion to LEU - the simple replacement of the uranium-silicide-HEU fuel by UMo-monolithic-LEU fuel - yields a reactivity loss at BOL (directly related to k(eff)$_{ini}$) and therefore an unacceptable fuel element lifetime of just a few days. Therefore the usage of monolithic LEU in the current FRM-II fuel element HEU-design is not possible due to these k(eff)$_{ini}$ losses in the core.[2]

Two principle strategies exist, which can also be combined, to increase the initial reactivity of the core. On the one hand one can consider enrichment levels of the monolithic fuel above the LEU limit. The enrichment has to be increased until the required initial k(eff)$_{ini}$ is reached to guarantee an adequate cycle length. In the case of monolithic fuel in the current HEU-geometry an enrichment of 32-33% is necessary to reach the current cycle length of 52 days.[2]

Of course, this procedure of enriching beyond LEU contradicts the international goal for the conversion of research reactors and therefore has to be considered problematic with regard to the politics of non-proliferation. The enrichment level of 20% (19.75%) is not only the international accepted limit for LEU, but assessing the proliferation potential of research reactor fuel shows that this enrichment is the best compromise between U-235 content in the fuel and plutonium production.[3] Hence increasing enrichment should be considered only as an option of last resort.

To compensate the necessary enrichment one can consider on the other hand specific changes of the fuel element and fuel plate geometry, which increase k(eff)$_{ini}$. Such modifications are very limited as long as the most relevant dimensions (inner and outer radius) of the fuel element geometry are considered to be unchangeable. First results of the effects of modest geometrical changes to the fuel element and the fuel plate (active height, meat thickness, cladding thickness, coolant channel thick-

ness) showed that each of these modifications or a combination of them can increase the initial reactivity allowing a reduction of enrichment requirements to achieve the same cycle length.[4][5][6] The combination Mod 6[1] used the same number of fuel plates and a coolant channel thickness like in the HEU-geometry. Only the interior plate geometry and the active height was changed with a reduced cladding thickness of 250 μm and an increased meat thickness of 860 μm with an active height of 80 cm. Results of burnup calculation showed that an enrichment of as low as 22.5% is sufficient to achieve a cycle length of more than 52 days.

These results of tentative changes to the geometry indicated a significant potential for optimization. However, this was restricted to achieve an acceptable cycle length and operational constraints were not sufficiently addressed.

In a second step, we tried to optimize also with respect to minimal flux losses and to meet operational constraints. To that aim we used an iterative linear programming (LP) technique with a linearized objective function $f(\vec{x})$ and linearized constraints $C(\vec{x})$. We considered neutron flux as objective function $f(\vec{x}) = \phi_{th}(\vec{x}))$ only and most variables x_i were kept constant in the LP-process.[2] Based on this procedure two more attractive preliminary conversion option candidates optimized for marginal flux losses and meeting chosen operational constraints were identified.[2][4]

However, for all these previous calculations the initial reactivity to reach an acceptable cycle length was gained by enriching the fuel above 20% in the end. Furthermore, the initial reactivity was not really in the focus of the optimization routine so far. The full optimization problem consist of minimizing enrichment, maximizing flux, and keeping an acceptable cycle length, which means sufficient initial reactivity, while keeping all operational constraints. To this end an global optimization routine is necessary, which can be used to re-optimize the fuel element.

3 New Optimization Strategy

The linear programming technique works with linearized functions for the constraints as well as for the objective function. For an optimization problem with few free variables and slightly nonlinear behavior of the function LP-techniques using an simplex algorithm is robust enough to give reasonable answers.[4]

But in general the optimization of reactor performance is a nonlinear problem, as both objective function and constraints are complex functions of the reactor design variables. If lesser variables are kept constant it becomes necessary not only to iteratively check each step of the algorithm, but to verify the linearizability and to investigate the functional dependance of the objective function $f(\vec{x})$ on each of the variables x_i. Further approaches to the optimization problem would include a wider set of variables as well as additionally choosing k(eff)$_{ini}$ as objective function.

[1] See [5] [6] for more details.

[2] A number of relevant variables x_i are listed in Tab. 1. In the LP process only the meat and cooling channel thickness, the effective density ratio and the transition radius were investigated.

As a next step to address the full optimization problem we started to automatize the generation of input decks and the processing of computer-jobs as a prerequisite to handle the large number of files. With these improved tools we carried out a parameter study varying four geometrical reactor design variables $x_j (j = 4, 5, 6, 9)$ (meat and cladding thickness, thickness of the coolant channel, and height of the fuel element - see table 1) to get k(eff)$_{ini}(x_i, x_j)$ dependent on x_j. For this parameter-space-study the enrichment was kept constant at 19.75% (LEU) and the initial reactivity served as new objective function ($f(\vec{x}) =$ keff$_{ini}(\vec{x})$). The effect on flux performance was also evaluated.[5][6][3]

	x_i	range of parameter	
x_1	Thermal power	20 MW	invariable
x_2	Enrichment	19.75%	invariable
x_3	Eff. uranium density	16 g/cc	invariable
x_4	Meat thickness	$x_4 = 0.40, 0.50, 0.60, 0.70, 0.80, 0.90$ mm	variable
x_5	Cladding thickness	$x_5 = 0.20, 0.25, 0.30, 0.35, 0.40$ mm	variable
x_6	Cooling channel thickness	$x_6 = 1.8, 2.2, 2.6, 3.0, 3.4$ mm	variable
x_7	Inner core radius	6.50 cm	invariable
x_8	Outer core radius	11.45 cm	invariable
x_9	Active core hight	$x_9 = 70.00 - 90.00$ cm (2 cm steps)	variable
x_{10}	Transition radius	10.56 cm	invariable
x_{11}	Density ratio	0.5	invariable

Table 1: Design variables x_i for FRM-II to investigate functional dependencies (parameter-study for LEU usage) on varied variables $x_j (j = 4, 5, 6, 9)$.

Please note, that the procedure of varying several parameters x_j in a broad range may result in combinations of variable values, which might not be feasible due to several practical reasons (certain geometrical combinations, operation parameters like power densities and heat flux, constructional issues).[4] However, the parameter range had to be chosen to cover a broad range (tab.1) to track down trends in the influence on the initial reactivity as objective function.

The influence of the variation of meat, cladding thickness, and cooling channel thickness is shown in fig.1. The figure contains a set of data of 125 simulation

[3]Future work will focus on optimizing the neutron flux again.

[4]In a more detailed analysis it could turn out that very thin plates (e.g. clad 200 μm, meat 400 μm) are not stable with regard to thermohydraulics or that for a very thick plate and wide cooling channel (e.g. clad 400 μm, meat 900 μm, cool. 3.0 mm) the number of plates and therefore the cooling area is too low and results in an unacceptable heat flux or that for very thin cooling channels and very thick plates (e.g. clad 350 μm, meat 900 μm, cool. 1.8 mm) the swelling of the meat during burnup is reducing the cooling channel thickness that the remaining gap is below a critical thickness. (The last exemplary combinations are not very interesting with regard to reactivity gains.)

calculations. Note that each point represents an individual core and fuel plate geometry with different numbers of plates in the core.[5]

As it could be expected, cladding thickness is very important to gain more initial reactivity (k(eff)$_{ini}$). The thinner the cladding the more initial reactivity is gained (fig.1) as the volume gained by reducing the cladding can be filled with fuel if the number of fuel plates is kept constant.

The meat thickness to get an optimum for the initial reactivity lies between 0.7 and 0.9 mm except in the case of very thin cladding and cooling channel, for which a trend to thin meat thicknesses can be observed (fig.2). But in this case (within the studied range) the absolute initial reactivity still is below that one for other combinations.

Regarding the cooling channel thickness it can be observed that variations down to smaller values are not attractive. The optimum can be obtained between 2.6 and 3.4 mm in the studied range. Wider cooling channels in combination with less plates in the fuel element are increasing the moderator to fuel ratio, thermalize the spectrum and therefore can increase the reactivity. If the cooling channel thickness is increased, the more sensitive is k(eff)$_{ini}$ on increasing meat thickness (fig.1).

Varying the active height of the fuel element to increase the initial reactivity can be investigated independently of the variation of the other variables in a first order approximation.[6] Taking the HEU design geometry but with an enrichment of 19,75% the initial reactivity increases relatively linear with increasing active height (fig.3). Increasing the active height and keeping the power level constant reduces the power density in the core and therefore also the flux. This flux decrease can be compensated in principle by a marginal increase of the reactor power. Elongation of the fuel element will also cause changes in the axial flux distribution, which could lead to additional flux losses at the position of the beam tubes entrances. These losses have to be investigated further, but can be compensated as well by a marginal power increase.

Based on these first results of a parametric study two preliminary LEU core geometry variants with an optimized initial reactivity were identified.

The modification LEU 1 was calculated for an unusual thin cladding (200 μm), which has not been tested yet in this form. We chose this modification option to investigate the potential of a development of monolithic fuel with very thin cladding.[7]

[5] Some points are not exactly on the fitcurves, beside the statistical error this is due to an integer number of fuel plates which has to be chosen for each combination of varied parameters. k(eff) is calculated with an absolute error of $\triangle k_{eff} \approx \pm 0.005$ at an 95% confidence interval.

[6] The gain of reactivity by prolonging the fuel element is dominating the effect of an additional variation of cooling channel, meat and cladding thickness on this reactivity gain by prolongation.

[7] Reducing the cladding thickness might be permitted due to the following consideration: In dispersion type fuels the distribution of the fuel particles and therefore the thickness of the meat zone has an uncertainty due to the manufacturing processes, so that parts of the meat can be thicker and fuel particles can be nearer the surface of the plate. Therefore the minimum cladding thickness historically was 250 μm (Al cladding). In monolithic fuel these uncertainties in meat

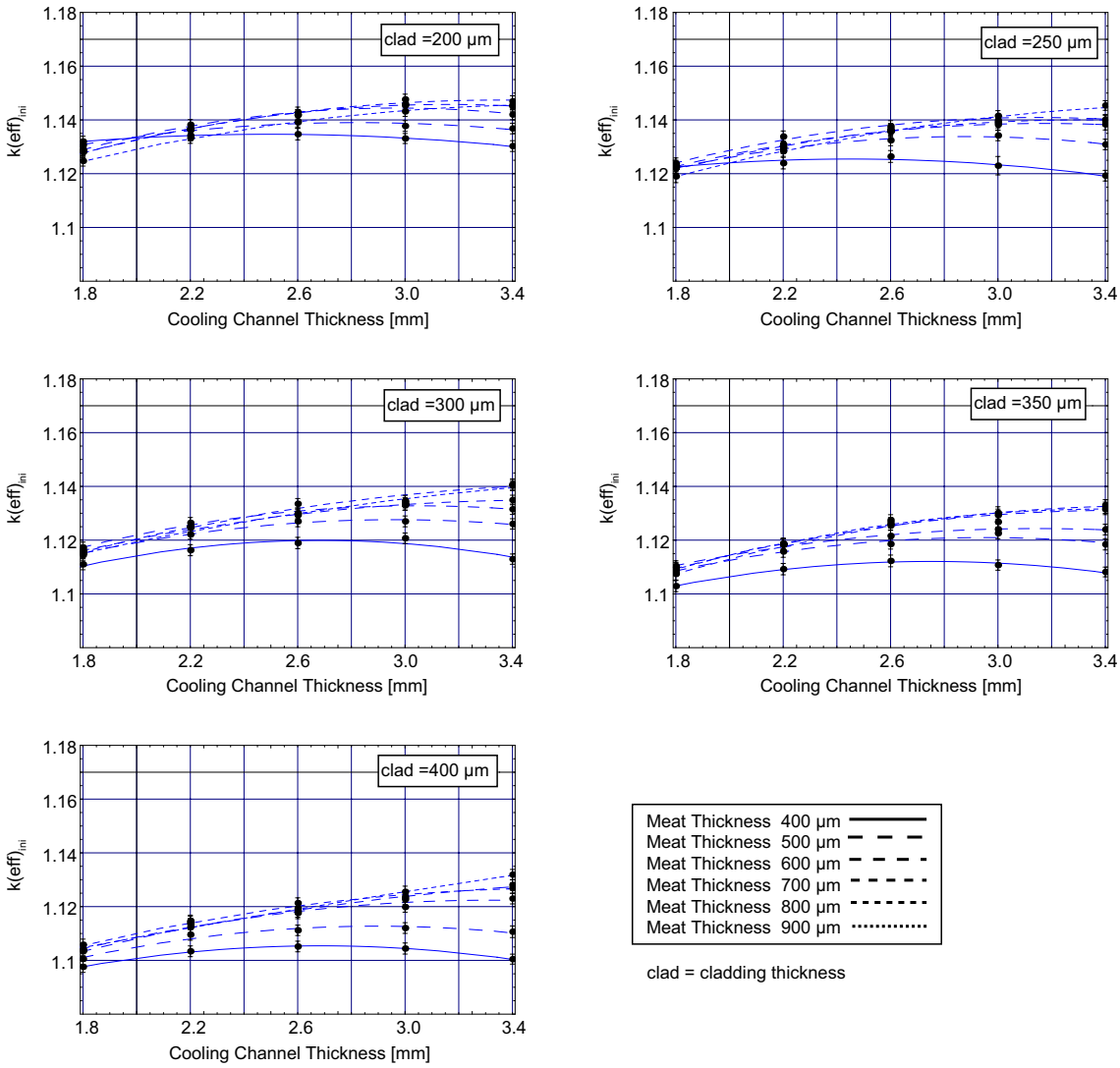

Figure 1: Functional dependance of initial reactivity k(eff)$_{ini}$ on meat thickness, cladding thickness and cooling channel thickness. (Shown: k(eff) over cooling channel thickness.) Number of plates in the fuel element changes accordingly.

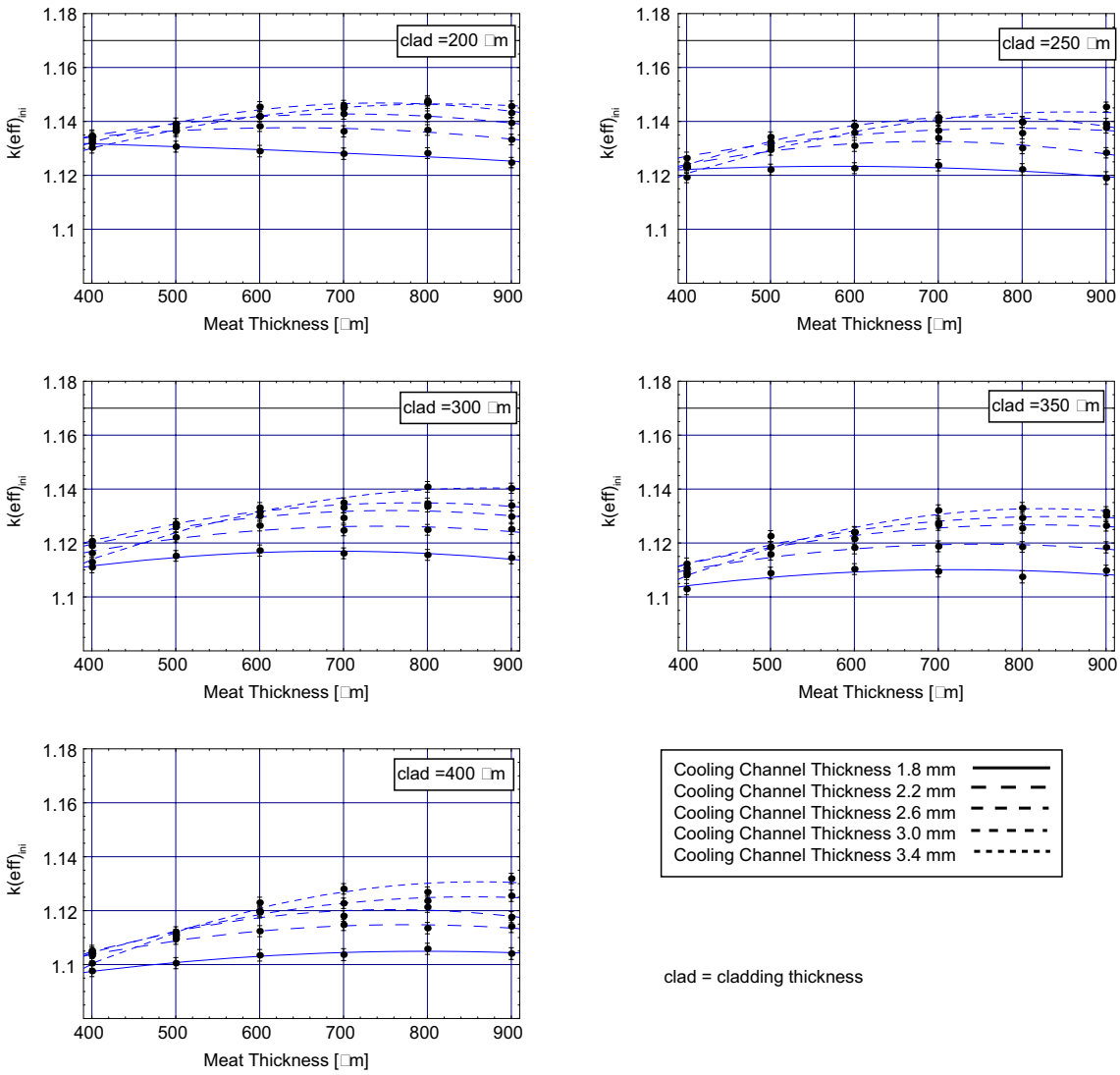

Figure 2: Functional dependance of initial reactivity k(eff)$_{ini}$ on meat thickness, cladding thickness and cooling channel thickness. (Shown: k(eff) over meat thickness.) Number of plates in the fuel element changes accordingly.

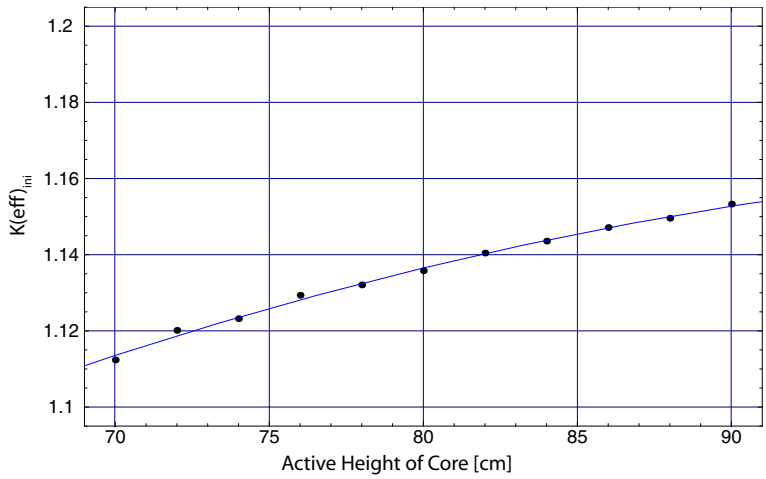

Figure 3: Initial reactivity k(eff)$_{ini}$ in dependence of a variation of the active core height to investigate the functional dependencies of the original geometry with an enrichment of 19,75%.

Recently UMo monolithic fuel miniplates with zircaloy (Zry4) cladding were fabricated with roll bonding in the Argentine fuel development program [7] and were irradiated in RERTR-7A. Cladding thicknesses of as thin as 150-200 μm might be possible with zircaloy. The development and detailed investigation of zircaloy clad fuel could provide a good chance to minimize enrichment requirements for FRM-II conversion further.

Modification LEU 2 is based on modification LEU 1, but uses a cladding thickness of 250 μm as it is used in HFIR reactor at Oak Ridge. This modification has an active height of 84 cm and is longer than the LEU 1 fuel element to compensate losses in the initial reactivity due to a thicker cladding. As in all cases, with an elongation of the active height of the plates in the fuel element the impact on the cooling capability of the system has to be analysed in more detail to find the practical operational constraints.

At first glance, both modifications (LEU 1 and LEU 2) do not have a satisfactory neutron flux with a thermal power of 20 MW (cf. tab. 2). As the flux losses are partly based on a reduced power density in the core, which is caused by the increased active height, these losses could be compensated by increasing the reactor power. With a marginal increase of 10% in reactor power from 20 to 22 MW the flux losses reduce to 7-8% in the maximum and 5-6% at the position of the cold source.

The presented parameter space study shows that it is possible to increase the initial reactivity. However, it does not cover the full parameterspace and will not

thickness are smaller (depending on manufacturing process). The minimum cladding thickness of monolithic fuel could therefore be below the minimum for dispersion type fuel. However, which minimum cladding thickness for monolithic fuel is sufficient has to be investigated further and depends also on the materials used (e.g. Al, Zr). In any case, answering this question is important for all reactor conversions with new fuels.

	HEU	LEU 1		LEU 2	
Thermal power:	20 MW	20 MW	22 MW	20 MW	22 MW
Active Height:	70 cm	80 cm		84 cm	
Meat thickness:	0.60 mm	0.80 mm		0.80 mm	
cladding thickness:	0.38 mm	0.20 mm		0.25 mm	
cooling channel thickness:	2.20 mm	3.00 mm		3.00 mm	
Enrichment	93%	20%		20%	
Relative flux at maximum:	reference	−15.4%	−7,0%	−16.2%	−7.9%
Relative flux at CNS:	reference	−13.7%	−5,1%	−14.7 %	−6.2%

Table 2: Two LEU core geometry variants derived from the functional dependance of design variables and initial reactivity and the original HEU geometry. Flux losses are relative to the HEU design calculated with M^3O.

give a final result for the optimal conversion option with minimized enrichment, maximized flux, and an acceptable cycle length. Other attractive combinations of parameters might be analyzed as well and there are further parameters to be studied. Additionally, option LEU 1 and LEU 2 have to be optimized further not only to maximize flux but also to keep all operational constraints. This further optimization still has to be done.

As it is shown in fig.4 with LEU 1 a cycle length of almost 50 days is achievable, which would not jeopardize the overall performance with regard to the time which is available for experiments. But together with a power increase of 10% to 22 MW the cycle length would drop to about 45 days (fig.4). Comparable cycle lengths would result in case of LEU 2.

4 Conclusions

Monolithic fuel has significant potential for the conversion of single element high flux research reactors. However, a re-design of the fuel elements seems to be necessary as it is clearly shown in the case of FRM-II, if one is striving for simultaneous optimization with respect to maximized flux, minimized enrichment, and an acceptable cycle length while keeping operational constraints. Our new optimization strategy, eventually establishing a global optimization routine, consists in investigating the functional dependence of the variation of certain design parameters on the objective functions. As intermediate step the initial reactivity was chosen as objective function

We carried out a broader parameter space study to find out the functional dependence for varied thickness of meat, cladding as well as cooling channel and active

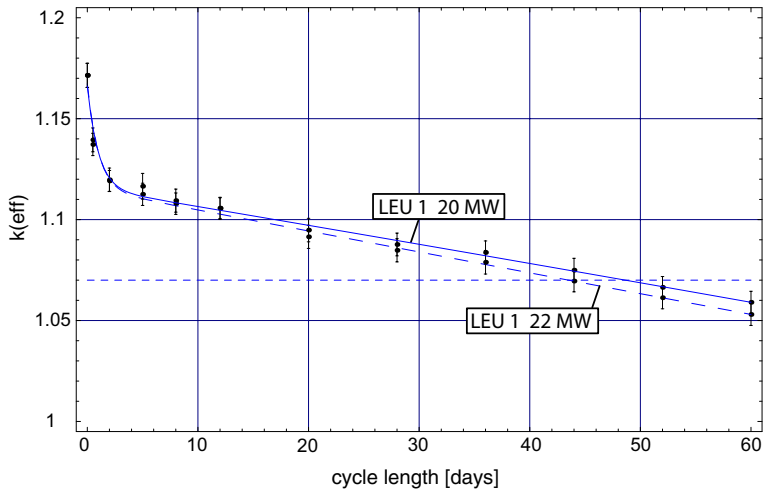

Figure 4: Reactivity of reactor core as a function of cycle length for core design modification LEU 1 with enrichment of 19.75%.

height on the initial reactivity. Thus, we identified two modifications of the fuel element (LEU 1 and LEU 2) as starting points. Optimization with respect to neutron flux still has to be done as well as a more detailed analysis of possible constraints due to reactor safety requirements.

Nevertheless, the preliminary results show in which direction future analysis has to progress, if a minimal enrichment (if possible below 20%) as important objective of international nonproliferation efforts should be achieved:

- Strengthening the development of monolithic UMo LEU fuel with increased meat thickness $> 600\,\mu$m.
- Enabling the development a cladding as thin as possible ($\leq 250\,\mu$m)– eventually based on zircaloy.
- Calculations to simulate reactor neutronics and fuel element performance for optimizing LEU options using cooling channel thicknesses > 2.2 mm. This would include more detailed analysis of the thermohydraulic behavior of the system.

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