VVER-440 FUEL CYCLES POSSIBILITIES USING IMPROVED FA DESIGN

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ABSTRACT

Practically five years cycle has been achieved in the last years at NPP Dukovany. There are two principal means how it could be achieved. First, it is necessary to use fuel assemblies with higher fuel enrichment and second, to use fuel loading with very low leakage. Both these conditions are fulfilled at NPP Dukovany at this time.

It is known, that the fuel cycle economy can be improved by increasing the fuel residence time in the core up to six years. There are at least two ways how this goal could be achieved. The simplest way is to increase enrichment in fuel. There exists a limit, which is 5.0 w% of U^{235}. Taking into account some uncertainty, the calculation maximum is 4.95 w% of U^{235}. The second way is to change fuel assembly design. There are several possibilities, which seem to be suitable from the neutron – physical point of view. The first one is higher mass content of uranium in a fuel assembly. The next possibility is to enlarge pin pitch. The last possibility is to "omit" FA shroud. This is practically unrealistic; anyway, some other structural parts must be introduced.

The basic neutron physical characteristics of these cycles for up-rated power are presented showing that the possibilities of fuel assemblies with this improved design in enlargement of fuel cycles are very promising.

In the end, on the basis of neutron physical characteristics and necessary economical input parameters, a preliminary evaluation of economic contribution of proposals of advanced fuel assemblies on fuel cycle economy is presented.

1. INTRODUCTION

As stated in Abstract, the efficiency of fuel cycle can be improved if six years cycles would be applied. There are at least two ways how this goal could be achieved. The simplest way is to increase fuel enrichment. There exists a limit, which is 5.0 wt% of U^{235}. Taking into account some uncertainty, calculation maximum is 4.95 wt% of U^{235}. The second possibility is to change fuel assembly (and/or fuel pellet) design.

In this paper, both possibilities are checked in different range individually.

2. FUEL ASSEMBLY ONLY WITH HIGHER ENRICHMENT

First, as it has been stated in introduction, we will suppose enrichment of 4.95 w% of U^{235} in some of fuel pins in a fuel assembly. The other characteristics (it means excluding enrichment) are the same as for fuel assembly of Gd-2 or Gd-2M for up-rated power. It seems to be clear that this maximal enrichment can not be applied in all fuel pins because in this case pin power non-uniformity would be very high (more than 1.15), which would create a problem from the point of view of pin power factor in the core. Therefore, enrichment is lower in some pins and **one from possible solutions** is shown in Fig. VIIa, where the maximum value 1.072 was found in pin No: 17 according to Fig. II at FA burn-up of 10000 [MWd/tU]. K_{inf} values of some similar designs are shown in Graph 1K (also with zoom for the beginning of burn-up process) and values of maximum of Fdh (Kr) in Graph 1P (three digits in the name identify lower enrichment in FA). Fuel assemblies (according to Fig. VIIa) have been loaded into core in transient end equilibrium cycles of Dukovany NPP for up-rated power (cycles 27 to 34 of Unit III; ***without change of existing design loadings*** – ***only with a change of overall cycle length***; the same is valid in chapters 3 and 4 and basic characteristics of these cycles are shown in Tables 1r-4r (where in column 1 is cycle number, in column 2 are values for "base" calculation (WFAs of enrichment 4.38 wt% of U^{235} and CA of 4.25 wt% of U^{235})), in column 3 for the variant with WFAs according to Fig. VIIa and CAs acc. to Fig. III, in column 4 for the variant with WFAs acc. to Fig. VIIa and CAs acc. to Fig. VI (Gd-2M) and in column 5 for the variant with WFAs according to Fig. VIIa (but with higher Gd_2O_3 content [5.0 wt%] and CAs according to Fig. III. ***It is seen that fuel cycles prolongation has been achieved, but this prolongation may not be sufficient for six-year cycle***.

3. NEW FUEL ASSEMBLY DESIGN

The other possibility how to extend the fuel cycle (and how potentially achieve six year cycle) is the application of fuel assembly with **an improved design**. There are several possibilities, which seem to be suitable from the neutron – physical point of view. The first is ***higher mass content of uranium in a fuel assembly***. This can be achieved by two ways: first to remove central hole in fuel pellet and second, to enlarge fuel pellet diameter (or both). In our checking, both conditions were applied together. Other characteristics are the same as for FA for up-rated power (Gd2M).

The next possibility ***is to enlarge pin pitch***. It has been also applied. The last possibility ***is to "omit" FA shroud***. This is practically not realistic, in any way, some other structural parts must be introduced; some possibilities were shown on Symposium last year

[3]. As a result of the effort in this year are designs, which are summarized in figures, graphs and tables below.

Fig. IX represents optimum radial profilation found in a FA (it is marked „**QNN**" („**Q3N**" for FA with Gd_2O_3 content of 3,35 wt% and „**Q5N**" for FA with Gd_2O_3 content of 5.0 wt%, respectively - see. further)) ***with maximally four various enrichments and maximum enrichment 4.95 wt% of*** U^{235}.

Graph 4K represents course of multiplication coefficient (k_{inf}) for various FAs namely: **G4442-3** labels FA with increased enrichment up to 4.95 wt% of U^{235} in Gd-2 geometry with ***three various enrichments*** in radial profilation with Gd_2O_3 content of 3.35 wt%, analyzed in year 2007 (also marked **QO3**), **G-QNA-3** labels FA like QO3, however in " a new" geometry (thickness of FA shroud is lowered, FP pitch is increased, fuel pellet diameter is enhanced (central hole is preserved)) also with **three various enrichments** in radial profilation with Gd_2O_3 content of 3.35 wt% - further marked only QNA (without further specification this means Gd_2O_3 content of 3,35 wt%) and **G-QNN-3** is a FA with increased enrichment up to 4.95 wt% of U^{235} in „a new" geometry (thickness of FA shroud is lowered, FP pitch is increased, fuel pellet diameter is enhanced (central hole is preserved)), but with ***four various enrichments*** in radial profilation with Gd_2O_3 content of 3.35 wt% - further marked only **Q3N** (because of resolution of Gd_2O_3 content). Marking **G4442-5**, **G-QNA-5** and **G-QNN-5 indicate** analogical FAs with Gd_2O_3 content of 5.0wt%. **Graph 4K** („**zoom**") represents course of k_{inf} for lower burn-up. For more detailed knowledge, on **graph 5K** are visible differences of k_{inf}, where like a base variant is variant G4442-3; that is why for FA with Gd_2O_3 content 5.0 w% differences of k_{inf} are high – they denote different courses (i.e. rates) of Gd burn-up.

Graph 4P represents maximal relative pin power (precisely fission rate) distribution for mentioned FAs.

Tables 1r-4r show characteristics of fuel cycles loaded with FAs bearing increased enrichment and changed geometry. At first column is mentioned ordinal number of fuel cycle, in 2nd – 5th column quantities for FAs under consideration earlier (i.e. FAs with only increased enrichment) and in column 6th – 9th for FAs with increased enrichment and changed geometry, radial profilation (with four various enrichments): „QNA" represents FA with changed geometry, however ***only with three different enrichment***). „Q3N" represents FA with changed geometry and an optimum radial profilation ***with four various enrichments***), next column sets values for FA marked „Q3N", however fuel part of CA has an average enrichment 4.38 wt% of ^{235}U (like „Gd-2M" fuel) and at last column are values for FA marked „Q5N", which is a FA like „Q3N", however with Gd_2O_3 content of 5.0 wt% (fuel part of CA has an average enrichment again only 4.25 wt% of ^{235}U).

4. NEW FUEL PELLET DESIGN

From the practical point of view as realistic seem to be FA design with only higher UO_2 mass, which means: ***removing of central hole from fuel pellet*** and ***increasing of fuel pellet diameter*** (fuel stack high is unchanged). In our checking, ***both***

conditions were applied simultaneously. Other characteristics are the same as for FA previously mentioned (***Gd-2 geometry*** and ***higher fuel enrichment***).

So, a starting assembly is a FA marked QO3 (see above) and QO5 (idem FA, but with Gd_2O_3 content of 5.0wt%). Here are shown supplemented comparisons for FAs with changed pellets' geometry (bigger pellet diameter without central hole), increased enrichment up to 4.95 wt% of U^{235}, radial profilation with **only three various enrichment** and Gd_2O_3 content of 3.35wt% - marked **Q3S** (like Fig. VIIa), and idem with Gd_2O_3 content of 5.0wt% - marked **Q5S** (see Fig. VIIa for fuel enrichment).

Graph 6K represents course of multiplication coefficient (k_{inf}) for various FAs, namely: **QO3** [G4442-3], **Q3S** [G-QNS-3]**, QO5** [G4442-5] and **Q5S** [G-QNS-5]. **Graph 6K** („**zoom**") represents k_{inf} course for lower burn–up values. **Graph 7K** represents k_{inf} differences regarding to the „first" variant (in legend variant first from the top) in graph FA.

Graph 5P represents for mentioned FAs types values of maximum pin power (precisely fission rate). How follows from the graph, these FAs have always relatively big values of pin power non-uniformity.

Further like in cases newly under consideration, FA types with changed geometry and radial profilation (four various enrichments in FP) ***were also for FAs with increased enrichment*** and ***changed fuel pellets only*** (with three various enrichments in fuel pins of such FA) provided calculations of 27 to 34 cycles as previously. Then an extension of specific cycle is easy to express in difference (gain) of efficient days, which is a measure of contribution of (working) FAs of higher qualities (higher enrichment and changed pellet geometry) on fuel cycle length.

Tables 1s-4s set characteristics of cycles with FAs Gd-2M (QS3) (i.e. „base"), further „ only" increased enrichment in fuel pins (QO3 (and with fuel part of CA with Gd-2M) and QO5) and in the end increased enrichment in FP and in addition changed fuel pellets design only (Q3S (and with fuel part of CA Gd-2M) and Q5S). Excluding "base" FA, all FAs have only three different enrichments in these tables.

It is important to mention, that the cycle's length is not only a criterion, which is necessary to take into account. There are safety limits (F_dh, burn-up of fuel pin or a longitudinal part of fuel pin). Values of burn-up for only selected FAs - Q3S, Q3S (Q3S with Gd-2M FA as a CA) and Q5S are summarized in **Tab. 5s**.

All calculations by MOBY- DICK code were effected in 3D pin-wise mode [2].

5. PRELIMINARY EVALUATION OF ECONOMIC CONTRIBUTION OF PROPOSALS OF ADVANCED FUEL ASSEMBLIES

On the basis of neutron physical characteristics of fuel cycles described above and necessary economical input parameters, a p**reliminary evaluation of economic contribution of proposals of advanced fuel assemblies** on fuel cycle economy is presented.

Conformable with philosophy of work [4], it is possible to write spending on one kWhe ($/kWhe) with discretion of **fuel load costs (C_F)** and **operating costs (C_{op})** in the form:

$$C = C_F + C_{op},$$

where C_F is calculated according to the OECD methodology [5] presented in work [6] and operating costs C_{op} were determined in relation to the reference variant ("base" in table 7, above also marked as QS3) loading of NPP Dukovany with up-rated power and loaded with Gd-2M type fuel assemblies (1444 MWt core power) under the assumption that: C_F / C_{op} = 0.25/0.75, outage time is 40 days and load factor 0.99.

Referential characteristics for economics evaluation (according to [5,6]) are given in table 6.

Where i (in table 6) denotes the following process of fuel cycle:

i = 1 expenses on uranium purchase (U_3O_8 "yellow cake")

i = 2 expenses on conversion (U_3O_8 UF6)

i = 3 expenses on enrichment

i = 4 expenses on fabrication (of fuel pellets and fuel assemblies)

i = 5 expenses on transport and storage of spent fuel

The unit prices of single processes are as follows:

P_1 = price per kg of U_3O_8, (yellow cake),

P_2 = price per kg U in UF_6,

P_3 = price per SWU,

P_4 = price for fuel assembly fabrication recalculated to one kg of U in this assembly,

P_5 = transport and storage price recalculated on one kg of U in spent fuel.

Process „P_5 is understood as a sum of spending on transport and storage in temporary storage (an „interim storage"). Inventory costs in long - term storage is impossible to evaluate at present time, usually only „ legislatively" a price increase is supposed [kWhe]. This price increase of relative expenses is not included in our calculations.

The necessary input data and economics characteristics of advanced fuel assemblies for 105% of core nominal power are provided in table 7.

Modification of cycle length was carried out at calculation with the aim of preservation of zero boric acid at the cycle end. Average cycle length was counted from last four cycles 31 as far as 34. From here, the average number of WFA loaded was 63 and the average number of CA loaded was 9.

Relative expense (relative price) CF for specific cycles are plotted in Graph 8 and its single components are shown in Table 7 under marking P_i (Graph 8-1 displays component P_1, Graph 8-3 displays component P_3). As it can be seen from individual components, relative price is determined by percentage changes in uranium price and SWU price.

In spite of influence of different types of fresh loaded FAs isn't expressive, it is possible *in terms of selected model* to state these findings:

- enrichment increasing leads to decrease of specific load costs;

- increasing of fuel pellet diameter leads to decrease of specific load costs;

- enrichment increasing in CA lowers specific load costs;

- increasing of Gd_2O_3 burnable absorber content increases specific load costs.

5. DISCUSSION

The values shown in Tables 1 – 5s cannot be supposed to be quite real because pin power non-uniformity is too high. As stated above, although not yet proved, ***application of FAs with higher enrichment and improved design*** (see Tables 1(r, s)-4(r, s)) ***could lead to full six years cycle.***

From preliminary economical evaluations seems **to be more promising fuel assemblies with improved fuel design then those with only increased fuel enrichment**.

Anyway, it is clear that FAs have still potential in sense of the fuel cycle economy.

6. CONCLUSIONS

Although only preliminary analyses described in the paper have been performed, it can be concluded that temporary design of VVER-440 FA is not optimal (as it is well known) and it exists a great potential how to increase FA reactivity, which is a necessary condition in achieving full six years loading strategy. (Potential in lowering core neutron leakage is practically exhausted as is also the possibility in reducing neutron absorption in construction parts of a FA.)

Design change (it means FA "like" "KARKAS" type) seems to be more encouraging than an attempt still to increase fuel enrichment.

This was supported by preliminary economical evaluation of cycles with fuel assemblies with improved design.

Of course, both possibilities (or their combination) must be proved on very well designed loading strategies.

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Figures and Graphs

Fig. I Calculation scheme of an „asymptotic“ fuel assembly

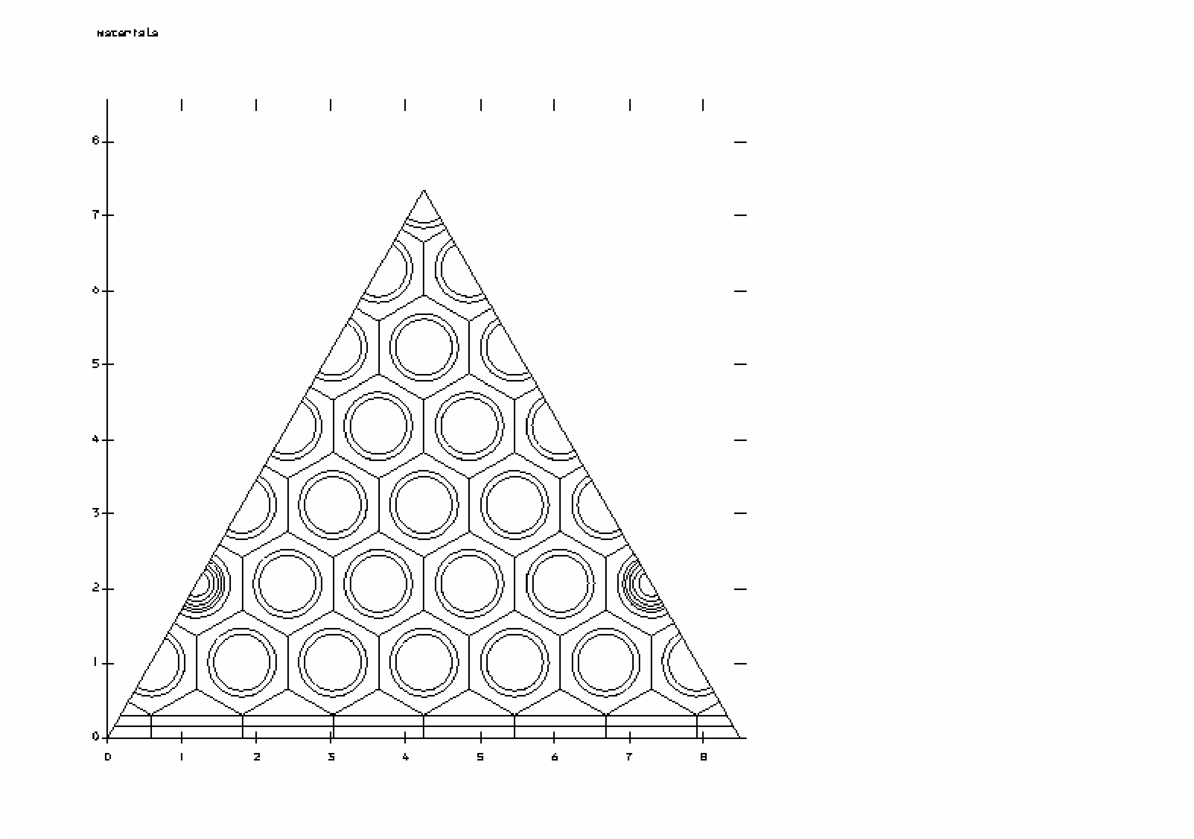


Fig.II Numeration of fuel rods

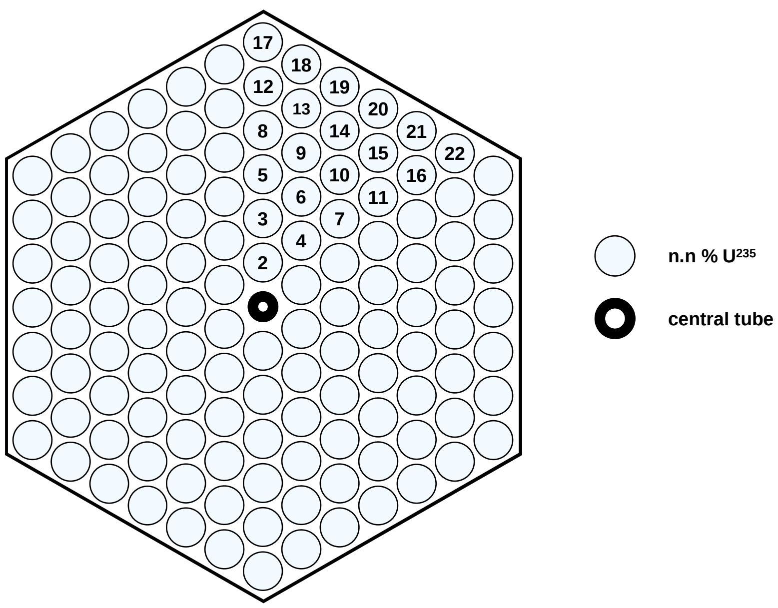


Fig.III Fuel enrichment [w%U^{235}] in fuel rods of Russian design of FA „Gd-2“
(average enrichment 4.247619 w%U^{235})

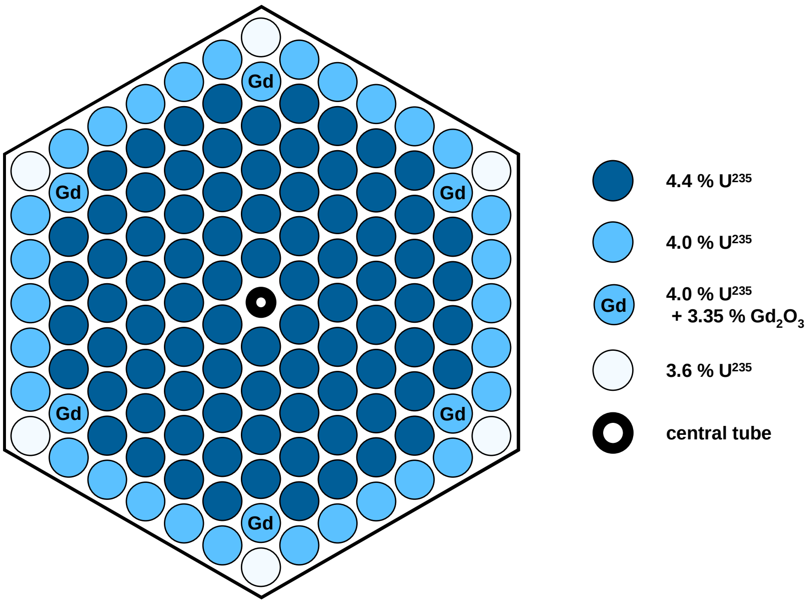


Fig.VI Fuel enrichment [w%U^{235}] in fuel rods of modified design of FA Gd-2 „Gd2M“ (*average enrichment 4.380952 w%U^{235}*) for uprated power

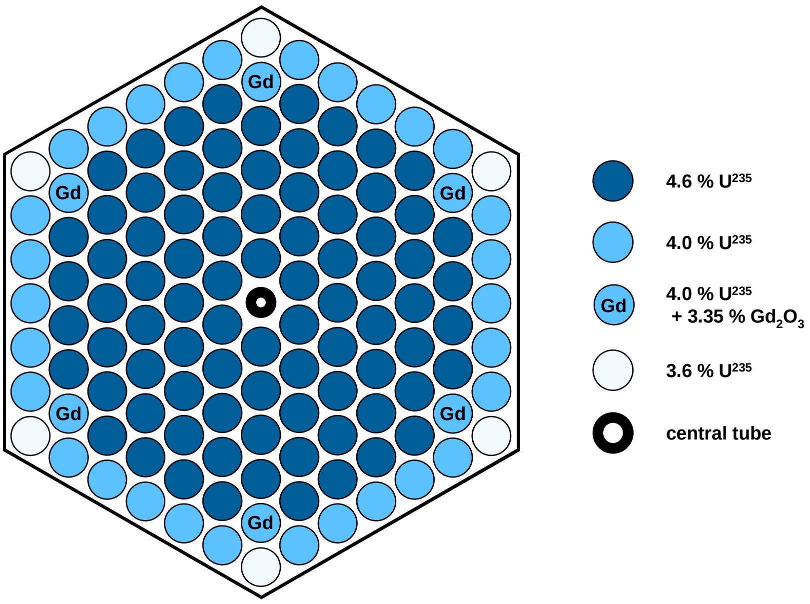


Fig.VIIa Fuel enrichment [w%U235] in fuel rods of modified design of FA Gd-2 „Gd2Max“ (*average enrichment „4.757143“ w%U235*) for six-year cycle

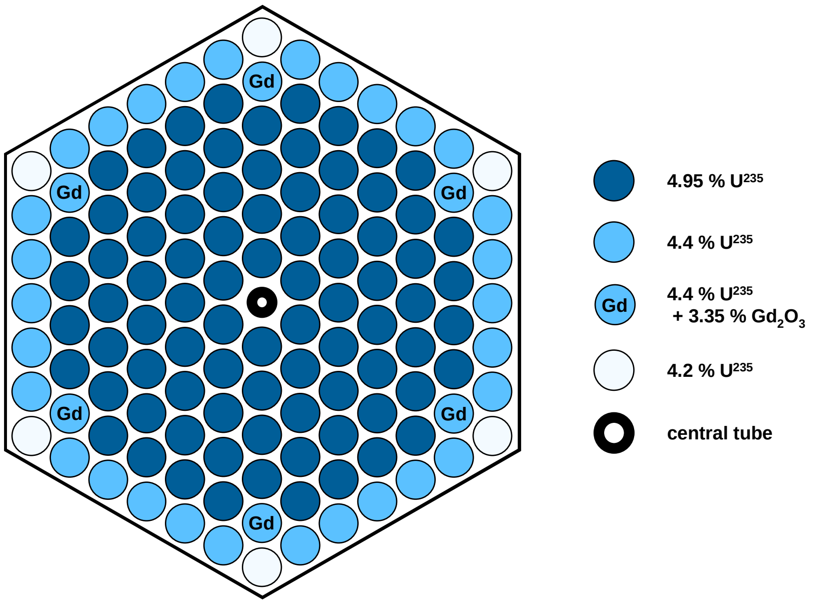
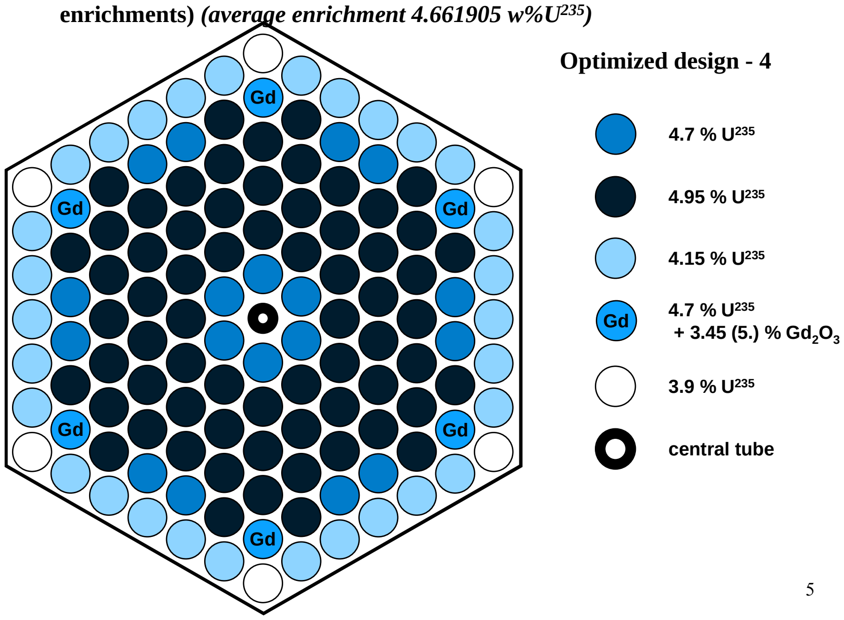
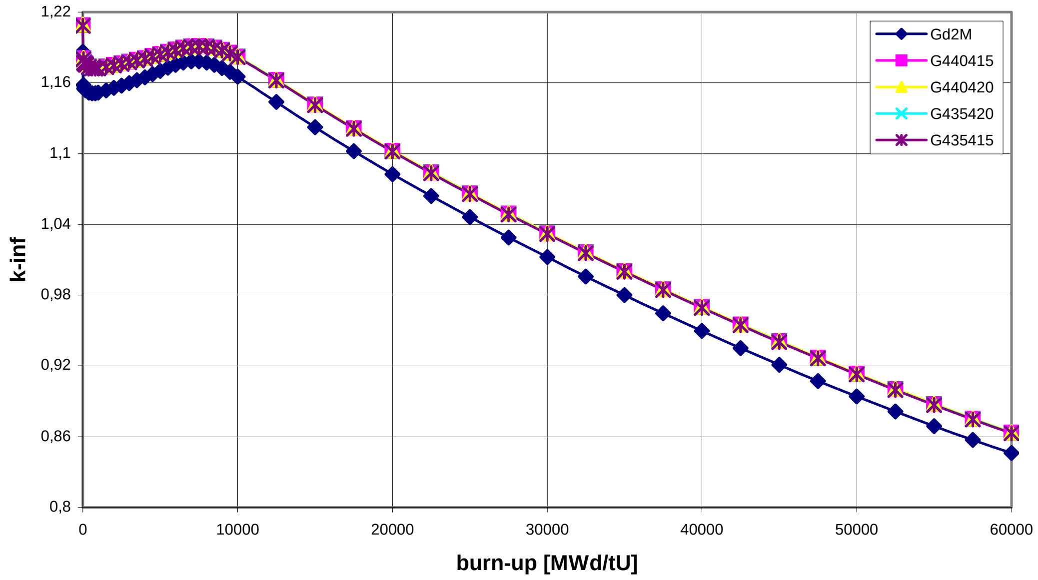


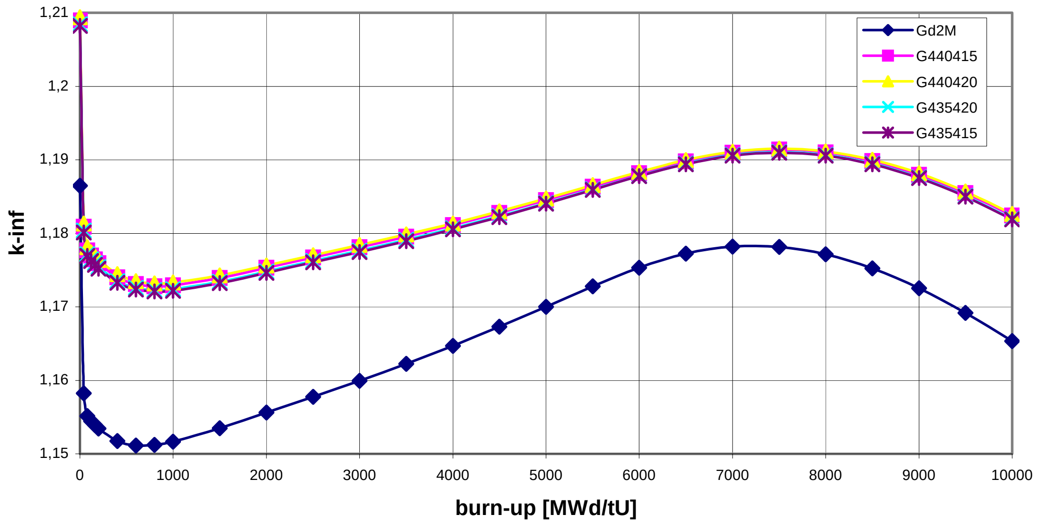
Fig. IX Fuel enrichment [w%U235] in fuel rods of FA design „Gd-x“ „optimized“ from the point of view of radial profilation (with four different enrichments) (*average enrichment 4.661905 w%U235*)



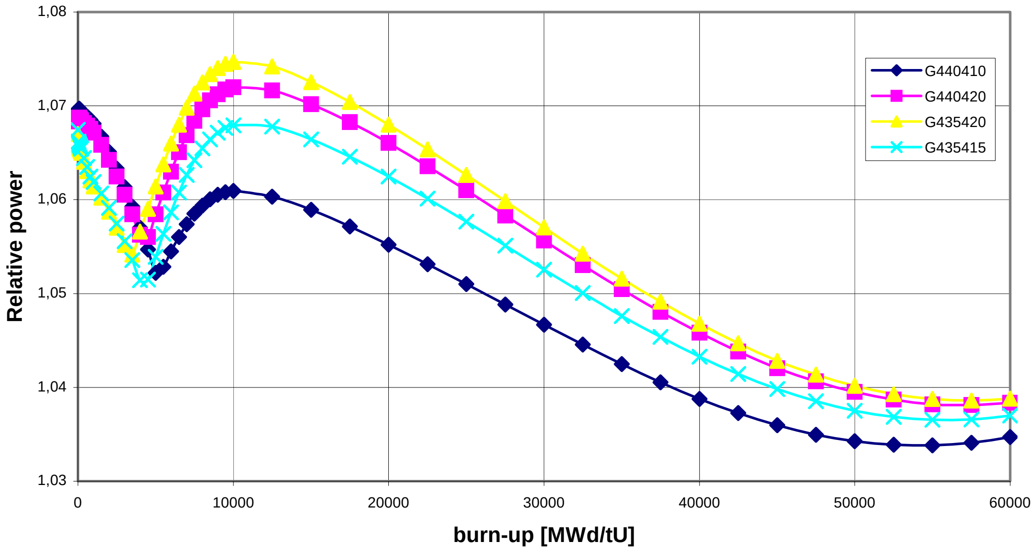
Graph 1 K-inf FAs with higher enrichment and different profilation [Gd_2O_3 content 3.35 w%]



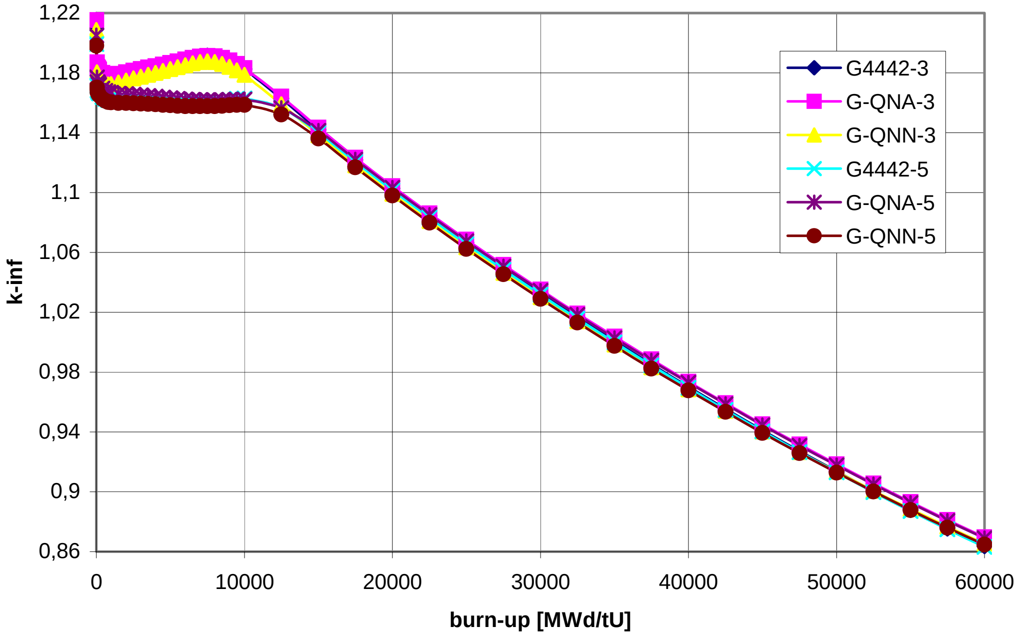
Graph 1K (zoom) K-inf FAs with higher enrichment and different profilation [Gd_2O_3 content 3.35 w%]



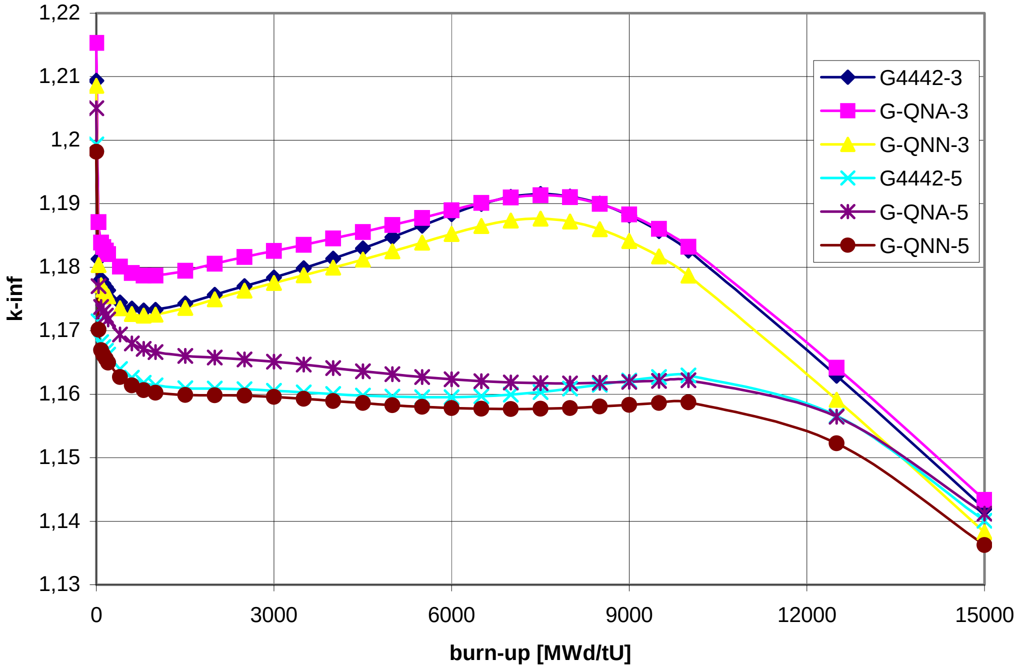
Graph 1P Maximal relative power in FPs of FAs with higher enrichment and different profilation [Gd_2O_3 content 3.35 w%]



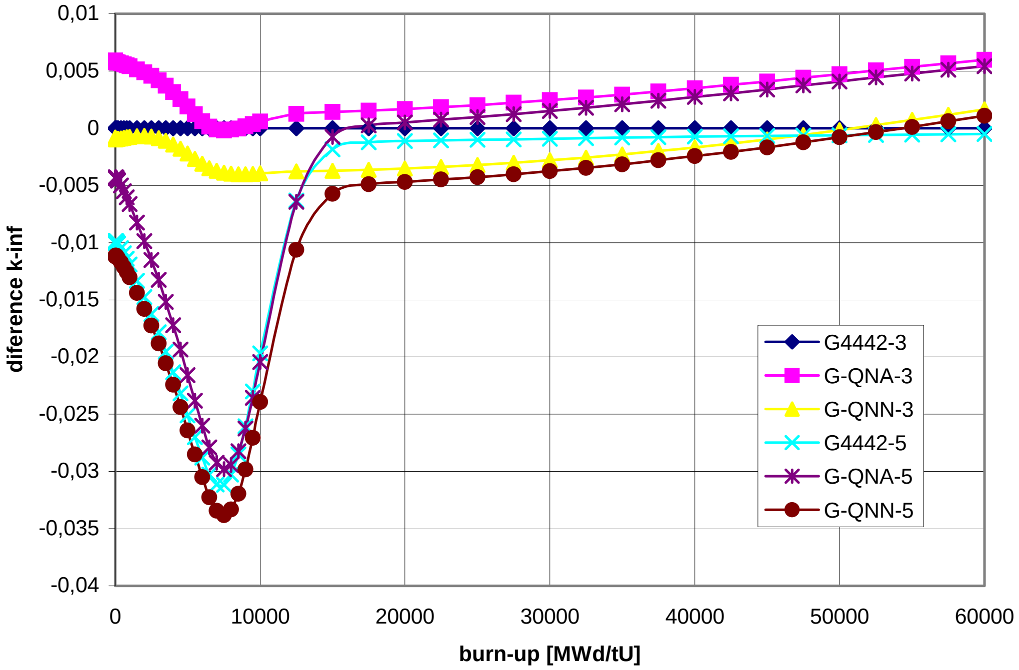
Graph 4K K-inf of FAs with higher enrichment; different profilation and geometry, Gd_2O_3 content 3.35wt% and 5.0 wt%



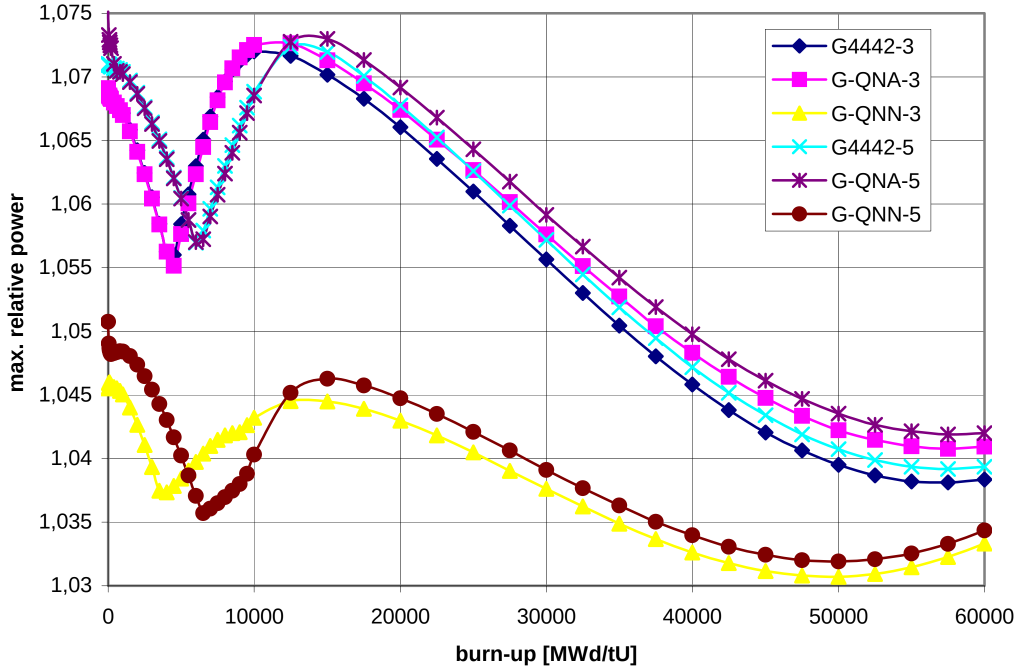
Graph 4K (zoom) K-inf of FAs with higher enrichment; different profilation and geometry, Gd_2O_3 content 3.35wt% and 5.0 wt%



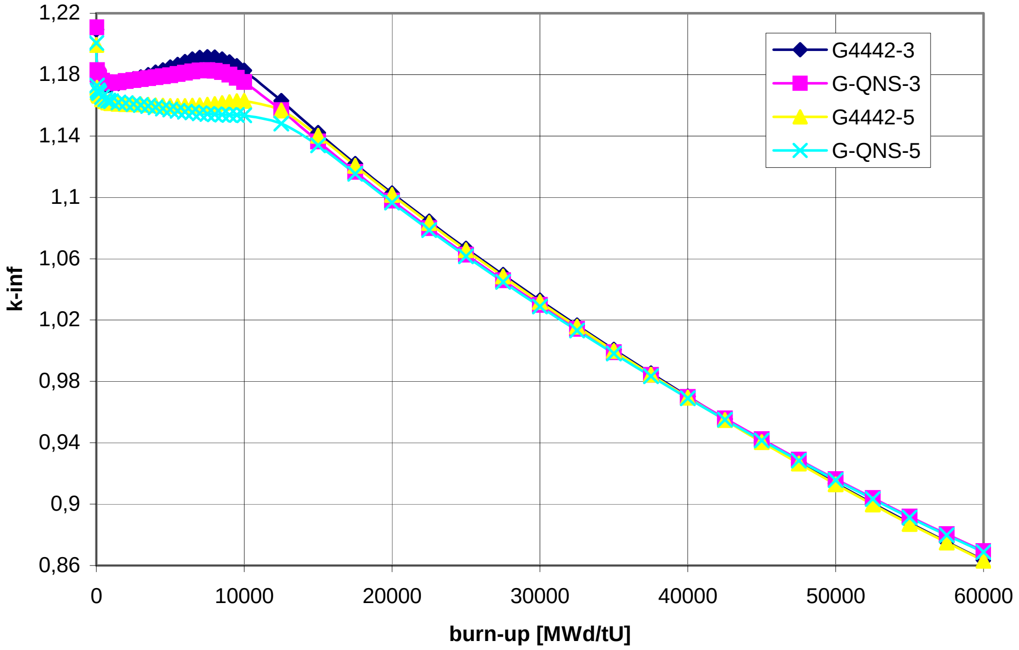
Graph 5K K-inf difference in FA with higher enrichment; different profilation and geomety, Gd_2O_3 content of 3.35wt% and 5.0 wt%



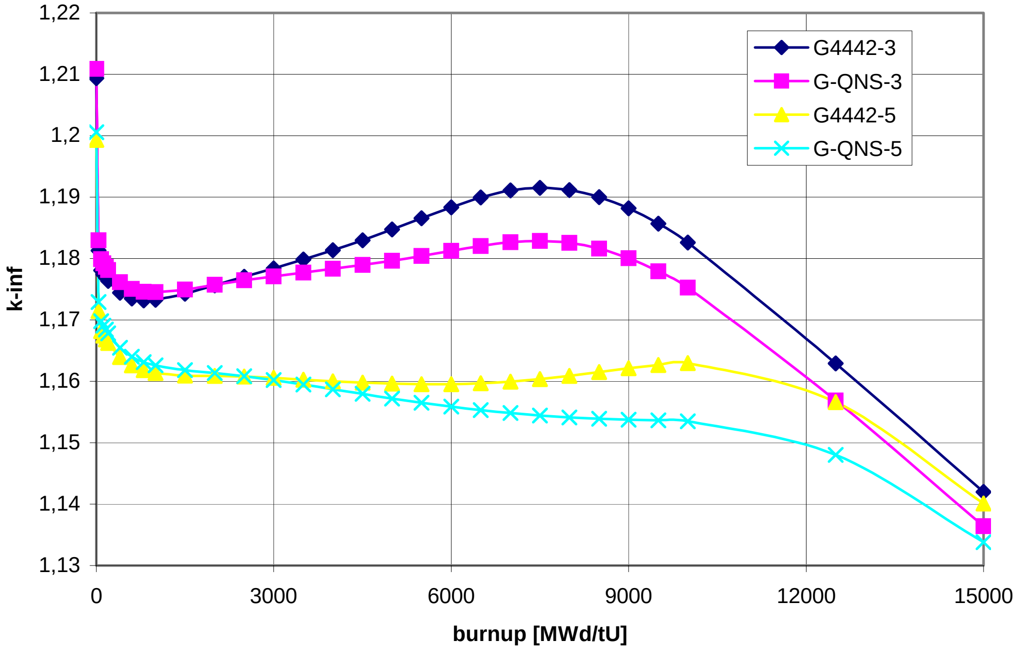
Graph 4P Max. rel. power of FP in FAs with higher enrichment; different profilation and geometry, Gd_2O_3 content 3.35wt% and 5.0 wt%



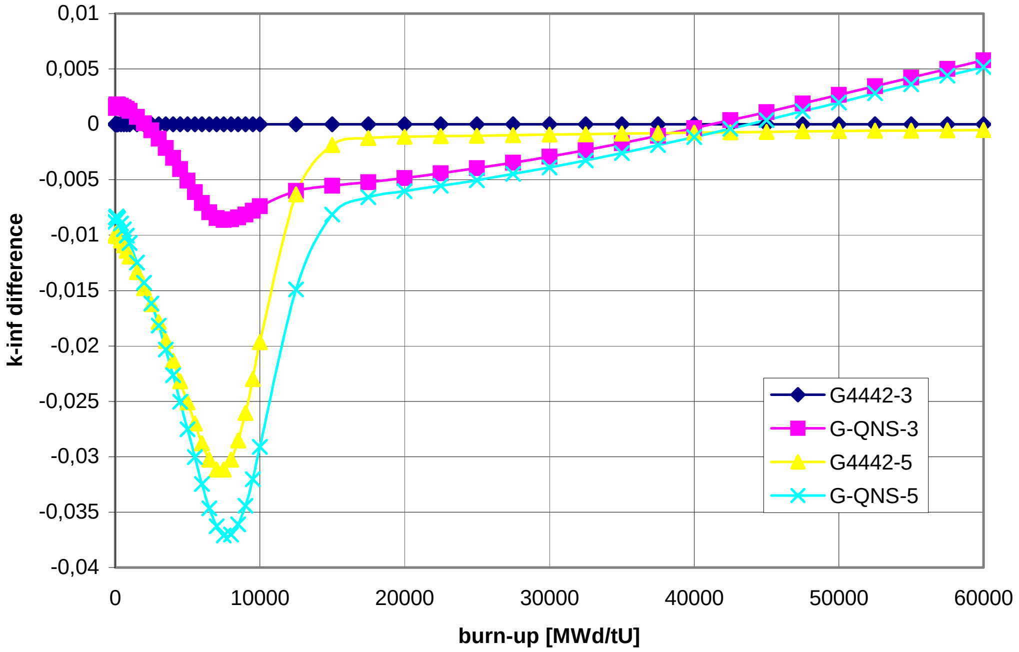
Graph 6K K-inf of FA with higher enrichment; different fuel pellet geometry, Gd_2O_3 content 3.35wt% and 5.0 wt%



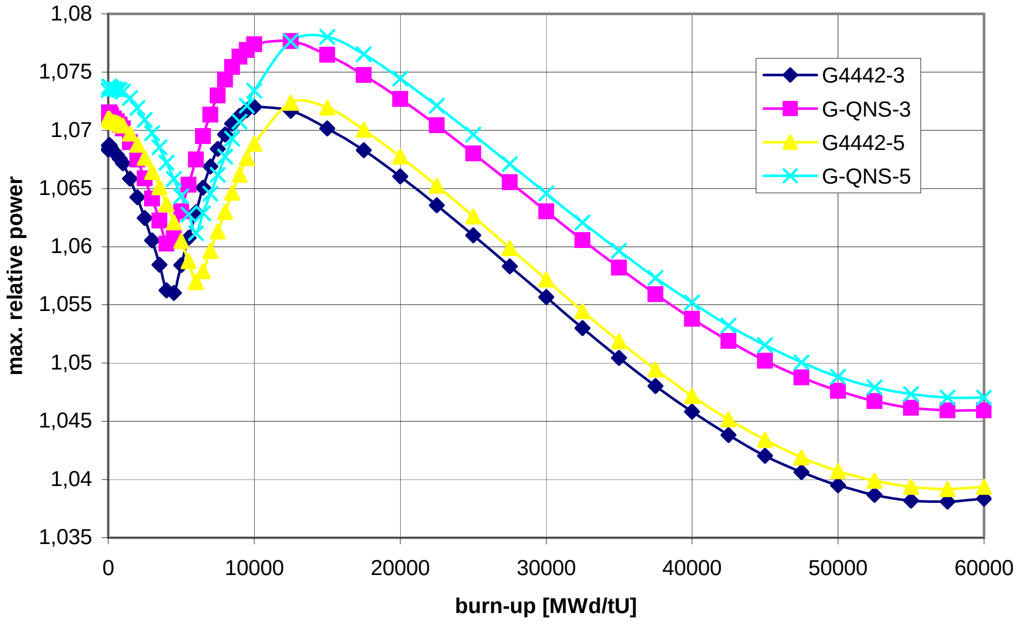
Graph 6K (zoom) K-inf of FA with higher enrichment; different fuel pellet geometry, Gd_2O_3 content 3.35wt% and 5.0 wt%



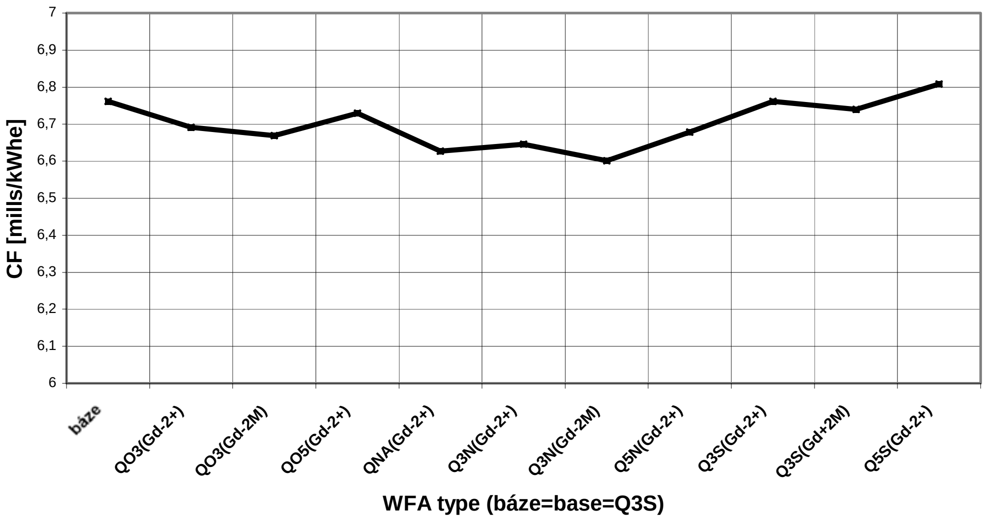
Graph 7K K-inf difference in FA with higher enrichment; different fuel pellet geometry, Gd_2O_3 content 3.35wt% and 5.0 wt%



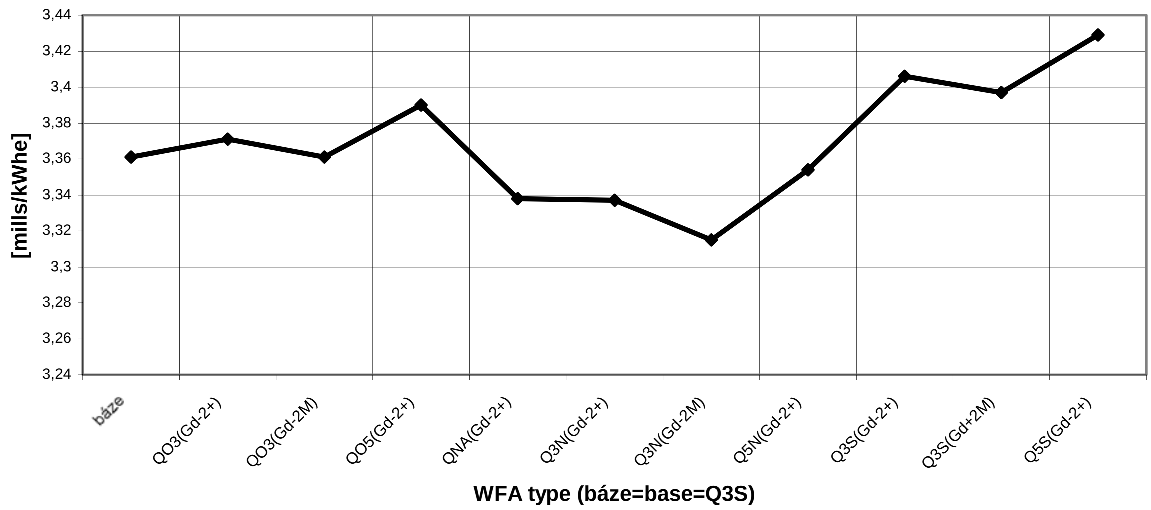
Graph 5P Max. rel. power of FP in FAs with higher enrichment; different fuel pellet geometry, Gd_2O_3 content 3.35wt% and 5.0 wt%



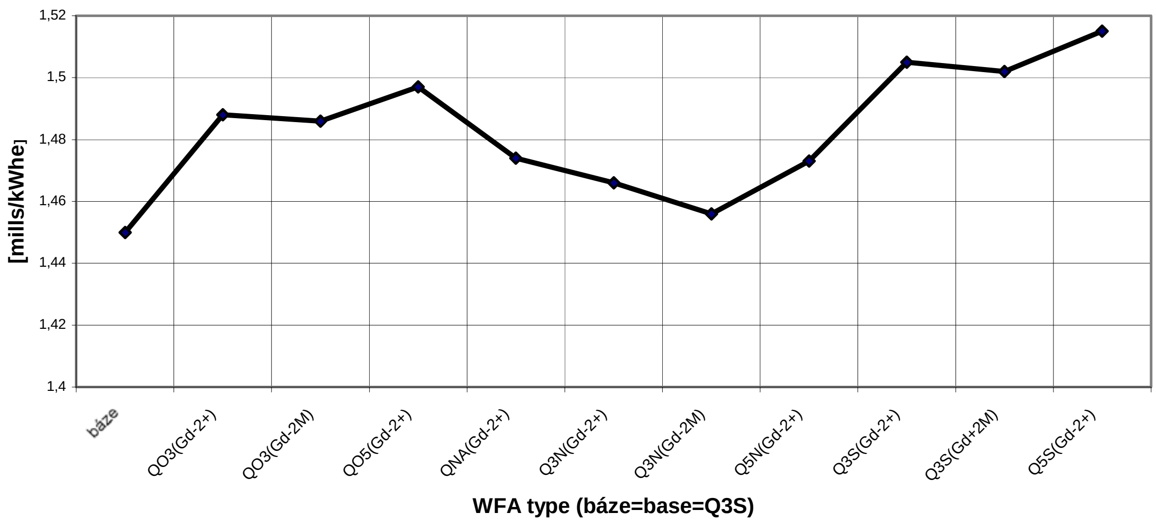
Graph 8 KWhe specific price "CF"



Graph 8-1 Ratio of uranium purchase (P1) on specific load costs [mills/kWhe]



Graph 8-3 Ratio of separation work (P3) on specific load costs [mills/kWhe]



Tables

Tab. 1r Cycles length with FAs with higher enrichment

cycle\ FA	***Base (QS3)***	***QO3 (Gd-2+)***	***QO3 (Gd-2M)***	***QO5 (Gd-2+)***	**QNA (Gd-2+)**	**Q3N (Gd-2+)**	**Q3N (Gd-2M)**	**Q5N (Gd-2+)**
27	*326*	*341*	*342*	*336*	349	345	347	340
28	*326*	*346*	*348*	*344*	361	355	356	353
29	*328*	*357*	*360*	*356*	376	369	372	368
30	*328*	*357*	*359*	*355*	379	372	374	370
31	*328*	*348*	*350*	*346*	369	362	365	361
32	*327*	*353*	*356*	*352*	374	367	369	365
33	*326*	*353*	*355*	*351*	374	367	370	365
34	*326*	*349*	*351*	*346*	369	362	364	360

Tab. 2r Difference (profit) in cycles length with FAs with higher fuel enrichment in relation with base variant (base [Gd2M] QS3)

cycle\ FA	***Base (QS3)***	***QO3 (Gd-2+)***	***QO3 (Gd-2M)***	***QO5 (Gd-2+)***	**QNA (Gd-2+)**	**Q3N (Gd-2+)**	**Q3N (Gd-2M)**	**Q5N (Gd-2+)**
27	*0*	*15*	*16*	*10*	23	19	21	14
28	*0*	*20*	*22*	*18*	35	29	30	27
29	*0*	*29*	*32*	*28*	48	41	44	40
30	*0*	*29*	*31*	*27*	51	44	46	42
31	*0*	*20*	*22*	*18*	41	34	37	33
32	*0*	*26*	*29*	*25*	47	40	42	38
33	*0*	*27*	*29*	*25*	48	41	44	39
34	*0*	*23*	*25*	*20*	43	36	38	34

Tab. 3r Residual boric acid concentration after power stretch-out at fuel cycle length found for FAs with higher fuel enrichment

cycle\ FA	***Base (QS3)***	***QO3 (Gd-2+)***	***QO3 (Gd-2M)***	***QO5 (Gd-2+)***	**QNA (Gd-2+)**	**Q3N (Gd-2+)**	**Q3N (Gd-2M)**	**Q5N (Gd-2+)**
27	*+0.026*	*+0.000*	*+0.010*	*+0.001*	+0.001	+0.005	-0.004	-0.007
28	*-0.013*	*+0.000*	*-0.001*	*+0.001*	-0.004	-0.000	+0.004	-0.005
29	*+0.061*	*-0.001*	*-0.007*	*-0.002*	+0.002	+0.008	+0.008	+0.008
30	*+0.082*	*+0.002*	*-0.004*	*+0.001*	+0.008	+0.006	+0.008	+0.007
31	*-0.041*	*-0.002*	*+0.002*	*+0.005*	+0.001	+0.004	-0.005	-0.007
32	*-0.027*	*+0.007*	*-0.008*	*-0.011*	+0.006	+0.006	+0.001	-0.007
33	*+0.008*	*+0.009*	*+0.006*	*-0.002*	+0.007	+0.008	-0.005	+0.002
34	*-0.062*	*-0.011*	*-0.012*	*+0.001*	+0.005	+0.005	-0.001	+0.002

Tab. 4r Maximum Fdh (K_r) in cycles with FAs with higher fuel enrichment (value in bracket gives burn-up [in FPD] where this maximum occurs)

cycle\FA	*Base (QS3)*	*QO3 (Gd-2+)*	*QO3 (Gd-2M)*	*QO5 (Gd-2+)*
27	*1.519 (2*)*	*1.557 (200*)*	*1.556 (200)*	*1.541 (240*)*
28	*1.511 (0)*	*1.563 (180*)*	*1.561 (160*)*	*1.543 (240)*
29	*1.518 (2)*	*1.548 (160)*	*1.544 (140*)*	*1.543 (0)*
30	*1.497 (2)*	*1.539 (160*)*	*1.537 (160*)*	*1.517 (240)*
31	*1.514 (0)*	*1.542 (180)*	*1.539 (180*)*	*1.525 (8,260)*
32	*1.500 (2)*	*1.537 (180)*	*1.535 (180*)*	*1.523 (4)*
33	*1.511 (2*)*	*1.539 (180*)*	*1.537 (180*)*	*1.532 (4*)*
34	*1.510 (0)*	*1.542 (140*)*	*1.540 (160*)*	*1.528 (4*)*
cycle\FA	**QNA (Gd-2+)**	**Q3N (Gd-2+)**	**Q3N (Gd-2M)**	**Q5N (Gd-2+)**
27	1.592 (220)	1.530 (220*)	1.528 (220*)	1.516 (260*)
28	1.588 (180)	1.539 (180*)	1.537 (160*)	1.524 (2*)
29	1.558 (140*)	1.535 (140)	1.532 (140)	1.522 (0)
30	1.542 (180)	1.515 (180)	1.513 (160*)	1.484 (240*)
31	1.543 (180)	1.516 (180)	1.513 (180)	1.500 (4*)
32	1.538 (180)	1.512 (180)	1.510 (180)	1.496 (4*)
33	1.541 (200)	1.516 (180*)	1.514 (180)	1.499 (6*)
34	1.541 (140*)	1.512 (180)	1.510 (180)	1.502 (4*)

[*] means that value shown has been found in more consecutive time steps [in FPD]; the first from these steps is marked

Tab. 1s Cycles length of different FAs with higher enrichment

cycle\ FA	***Base (QS3)***	**QO3 (Gd-2+)**	**QO3 (Gd-2M)**	**QO5 (Gd-2+)**	**Q3S (Gd-2+)**	**Q3S (Gd-2M)**	**Q5S (Gd-2+)**
27	*326*	341	342	336	344	346	337
28	*326*	346	348	344	356	357	354
29	*328*	357	360	356	374	377	373
30	*328*	357	359	355	379	381	377
31	*328*	348	350	346	370	373	368
32	*327*	353	356	352	374	376	371
33	*326*	353	355	351	375	377	373
34	*326*	349	351	346	369	371	366

Tab. 2s Difference (profit) in cycles length with FAs with higher fuel enrichment in relation with base variant (base [Gd2M] QS3)

cycle\ FA	***Base (QS3)***	**QO3 (Gd-2+)**	**QO3 (Gd-2M)**	**QO5 (Gd-2+)**	**Q3S (Gd-2+)**	**Q3S (Gd-2M)**	**Q5S (Gd-2+)**
27	*0*	15	16	10	18	20	11
28	*0*	20	22	18	30	31	28
29	*0*	29	32	28	46	49	45

30	*0*	29	31	27	51	53	49
31	*0*	20	22	18	42	45	40
32	*0*	26	29	25	47	49	44
33	*0*	27	29	25	49	51	47
34	*0*	23	25	20	43	45	40

Tab. 3s Residual boric acid concentration after power stretch-out at fuel cycle length found for FAs with higher fuel enrichment

cycle\ FA	***Base (QS3)***	**QO3 (Gd-2+)**	**QO3 (Gd-2M)**	**QO5 (Gd-2+)**	**Q3S (Gd-2+)**	**Q3S (Gd-2M)**	**Q5S (Gd-2+)**
27	*+0.026*	+0.000	+0.010	+0.001	+0.000	-0.008	+0.002
28	*-0.013*	+0.000	-0.001	+0.001	-0.002	+0.003	-0.003
29	*+0.061*	-0.001	-0.007	-0.002	+0.007	-0.005	-0.007
30	*+0.082*	+0.002	-0.004	+0.001	+0.005	+0.009	-0.004
31	*-0.041*	-0.002	+0.002	+0.005	+0.003	-0.003	-0.004
32	*-0.027*	+0.007	-0.008	-0.011	+0.002	+0.000	+0.000
33	*+0.008*	+0.009	+0.006	-0.002	-0.002	+0.007	-0.006
34	*-0.062*	-0.011	-0.012	+0.001	-0.002	+0.008	+0.004

Tab. 4s Maximum F_dh (K_r) in cycles with FAs with higher fuel enrichment (value in bracket gives burn-up [in FPD] where this maximum occurs)

cycle\FA	***Base (QS3)***	**QO3 (Gd-2+)**	**QO3 (Gd-2M)**	**QO5 (Gd-2+)**
27	*1.519 (2*)*	1.557 (200*)	1.556 (200)	1.541 (240*)
28	*1.511 (0)*	1.563 (180*)	1.561 (160*)	1.543 (240)
29	*1.518 (2)*	1.548 (160)	1.544 (140*)	1.543 (0)
30	*1.497 (2)*	1.539 (160*)	1.537 (160*)	1.517 (240)
31	*1.514 (0)*	1.542 (180)	1.539 (180*)	1.525 (8,260)
32	*1.500 (2)*	1.537 (180)	1.535 (180*)	1.523 (4)
33	*1.511 (2*)*	1.539 (180*)	1.537 (180*)	1.532 (4*)
34	*1.510 (0)*	1.542 (140*)	1.540 (160*)	1.528 (4*)
cycle\FA		**Q3S (Gd-2+)**	**Q3S (Gd-2M)**	**Q5S (Gd-2+)**
27		1.615 (220*)	1.616 (220)	1.601 (260*)
28		1.598 (180)	1.596 (180*)	1.581 (4*)
29		1.557 (180)	1.555 (180)	1.557 (2)
30		1.530 (200)	1.528 (200)	1.524 (260)
31		1.539 (220)	1.537 (220)	1.541 (320)
32		1.527 (160*)	1.525 (180)	1.520 (4*)
33		1.532 (220*)	1.531 (220*)	1.549 (6*)
34		1.536 (160*)	1.534 (160*)	1.524 (2*)

* means that value shown has been found in more consecutive time steps [in FPD]; the first from these steps is marked

Tab. 5s Max. burn-up values [MWd/tU] **of FA, FP and an axial mesh of FP in „equilibrium“ cycles (33. a 34.) with different FA types**

Cycle	**33.**	**34.**	**33.**	**34.**	**33.**	**34.**
FA **Fuel Part of CA**	**Q3S (Gd-2+)**	**Q3S (Gd-2+)**	**Q3S (Gd-2M)**	**Q3S (Gd-2M)**	**Q5S (Gd-2+)**	**Q5S (Gd-2+)**
Bu_q	59110	56410	59350	57750	58760	56370
Bu_r	64880	65050	65140	65320	64540	64610
Bu_o	72230	71970	72350	72070	71950	71700

Tab. 6 Referential characteristics for economics evaluation (according to [5,6])

Loss factor for conversion	0.5 w/o
Loses at production	0.0 w/o
Uranium tails assay for enrichment	0.3 w/o
P_i **Price per unit of single processes of fuel cycle**	100, 12, 90, 318.8, 230 $ on kg
s_i **Escalation ratio of single processes of fuel cycle**	0.012, 0.012, 0.012, 0.012, 0.012.
l_i **Material loses of single processes of fuel cycle**	0.0, 0.005, 0.0, 0.01, 0.0
t_i **Lead or lag time of processes of fuel cycle**	2.0, 1.5, 1.0, 0.5, 5.0 years

Tab. 7 Input data and economics characteristics of advanced fuel assemblies for 105% of core nominal power

	Base	**QO3(Gd-2+)**	**QO3(Gd-2M)**	**QO5(Gd-2+)**	**QNA(Gd-2+)**	**Q3N(Gd-2+)**	**Q3N(Gd-2M)**	**Q5N(Gd-2+)**	**Q3S(Gd-2+)**	**Q3S(Gd+2M)**	**Q5S(Gd-2+)**
Enrichment WFA [wt%]	4,38	4,757	4,757	4,757	4,757	4,662	4,662	4,662	4,757	4,757	4,757
Enrichment CA [wt%]	4,25	4,25	4,38	4,25	4,25	4,25	4,38	4,25	4,25	4,38	4,25
Average Enrichment	4,3644	4,6963	4,7119	4,6963	4,6991	4,61499	4,6149	4,61499	4,6991	4,7149	4,7
WFA fuel mass [kg]	126,7	126,7	126,7	126,7	133,66	133,66	133,66	133,66	136,9	136,9	136,9
CA fuel mass HRK [kg]	120,5	120,5	120,5	120,5	120,5	120,5	120,5	120,5	120,5	120,5	120,5
Average cycle length [FPD]	326,75	350,75	353	348,75	371,5	364,5	367	362,75	372	374,25	369,5
CF [mills/kWhe]	6,762	6,692	6,669	6,73	6,627	6,646	6,601	6,679	6,762	6,74	6,808
C_{op} [mills/kWhe]	9,785	9,708	9,702	9,714	9,653	9,671	9,664	9,676	9,652	9,646	9,658

CF + C_{op} [mills/kWhe]	16,547	16,4	16,37	16,444	16,28	16,317	16,265	16,354	16,414	16,386	16,466
[kgU/(MWe*day)]	0,597	0,598	0,597	0,602	0,593	0,593	0,589	0,596	0,605	0,603	0,609
[SWU/(MWe*day)]	0,36	0,37	0,369	0,372	0,366	0,364	0,362	0,366	0,374	0,373	0,376
P1 [mills/kWhe]	3,361	3,371	3,361	3,39	3,338	3,337	3,315	3,354	3,406	3,397	3,429
P2 [mills/kWhe]	0,332	0,333	0,332	0,335	0,33	0,329	0,327	0,331	0,336	0,335	0,339
P3 [mills/kWhe]	1,45	1,488	1,486	1,497	1,474	1,466	1,456	1,473	1,505	1,502	1,515
P4 [mills/kWhe]	0,835	0,774	0,769	0,778	0,766	0,781	0,775	0,784	0,781	0,777	0,787
P5 [mills/kWhe]	0,784	0,726	0,722	0,731	0,719	0,733	0,728	0,736	0,733	0,729	0,738